Conf-9205125--1

GA-A--20789-Rev.1

DE92 014131

INNOVATIVE SAFETY FEATURES OF THE MODULAR HTGR

by
F.A. Silady and W.A. Simon

APRIL 1992

GENERAL ATOMICS

DISCLAIMER

GA–A20789
Rev. 1

INNOVATIVE SAFETY FEATURES OF THE MODULAR HTGR

by
F.A. Silady and W.A. Simon

This is a preprint of a paper to be presented at the 1992 Edison Electric Institute (EEI) Engineering and Operating Computer Committee (E&OCC) Forum, May 17-20, 1992, Denver, Colorado

Work Supported by
Department of Energy
Contract No. DE-AC03-89SF17885

GENERAL ATOMICS PROJECT 7600
APRIL 1992

GENERAL ATOMICS

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

INNOVATIVE SAFETY FEATURES OF THE MODULAR HTGR

By F. A. Silady and W. A. Simon

ABSTRACT

The Modular High Temperature Gas-Cooled Reactor (MHTGR) is an advanced reactor concept under development through a cooperative program involving the U.S. Government, the nuclear industry, and the utilities. Near-term development is focused on electricity generation. The top-level safety requirement is that the plant's operation not disturb the normal day-to-day activities of the public. Quantitatively, this requires that the design meet the U.S. Environmental Protection Agency's Protective Action Guides at the site boundary and hence preclude the need for sheltering or evacuation of the public. To meet these stringent safety requirements and at the same time provide a cost competitive design requires the innovative use of the basic high temperature gas-cooled reactor features of ceramic fuel, helium coolant, and a graphite moderator. The specific fuel composition and core size and configuration have been selected to use the natural characteristics of these materials to develop significantly higher margins of safety.

The innovative safety features of the MHTGR are reviewed by examining the safety response to events challenging the functions relied on to retain radionuclides within the coated fuel particles. A broad range of challenges to core heat removal are examined, including a loss of helium pressure and a simultaneous loss of forced cooling of the core. The challenges to control of heat generation consider not only the failure to insert the reactivity control systems but also the withdrawal of control rods. Finally, challenges to control of chemical attack of the ceramic-coated fuel are considered, including catastrophic failure of the steam generator, which allows water ingress, or failure of the pressure vessels, which allows air ingress. The plant's

response to these extreme challenges is not dependent on operator action, and the events considered encompass conceivable operator errors.

I. Background

Under the sponsorship of the U.S. Department of Energy (DOE), four U.S. corporations - General Atomics, ABB-Combustion Engineering Nuclear Power, Bechtel National, Inc., and Stone & Webster Engineering Corporation - along with Oak Ridge National Laboratory and with utility input through Gas-Cooled Reactor Associates are developing a Modular High Temperature Gas-Cooled Reactor (MHTGR) that can provide safe, economic, and reliable power for the next generation of power plants. The design is responsive to the public's concern about nuclear safety, the investors' concern about protection of their investment and the operators' concern about ever-increasing costs of operation and maintenance.

Various innovative features have been introduced to address those concerns. Plant design and the safety characteristics are building on 30 years of gas-cooled reactor experience and proven technology, utilizing the unique properties of graphite reactors and coated particle fuel.

II. Plant Description

The reference MHTGR plant consists of four identical 350 MW(t) reactor modules. Each module is housed in a vertical cylindrical concrete silo embedded underground (Fig. 1). Each silo serves as an independent vented confinement structure. The four reactor structures form part of the nuclear island along with other structures which house systems for helium purification, shutdown cooling, hot cell maintenance, power conditioning, and heating, ventilating, and air conditioning. A storage array cooled by natural circulating air is provided to accommodate on-site storage of spent fuel in an adjacent reactor service area. The four reactor structures and the reactor service area are covered by a common enclosure which allows sharing of auxiliary cranes and fuel handling equipment.

The energy conversion area, or turbine island, is nonsafety-related and is separated from the nuclear island so that conventional, fossil-fired equipment and standards can be used in its construction and operation. It is located adjacent to the nuclear island so the main steam and feedwater connections between the turbine building and the individual reactor structures will be

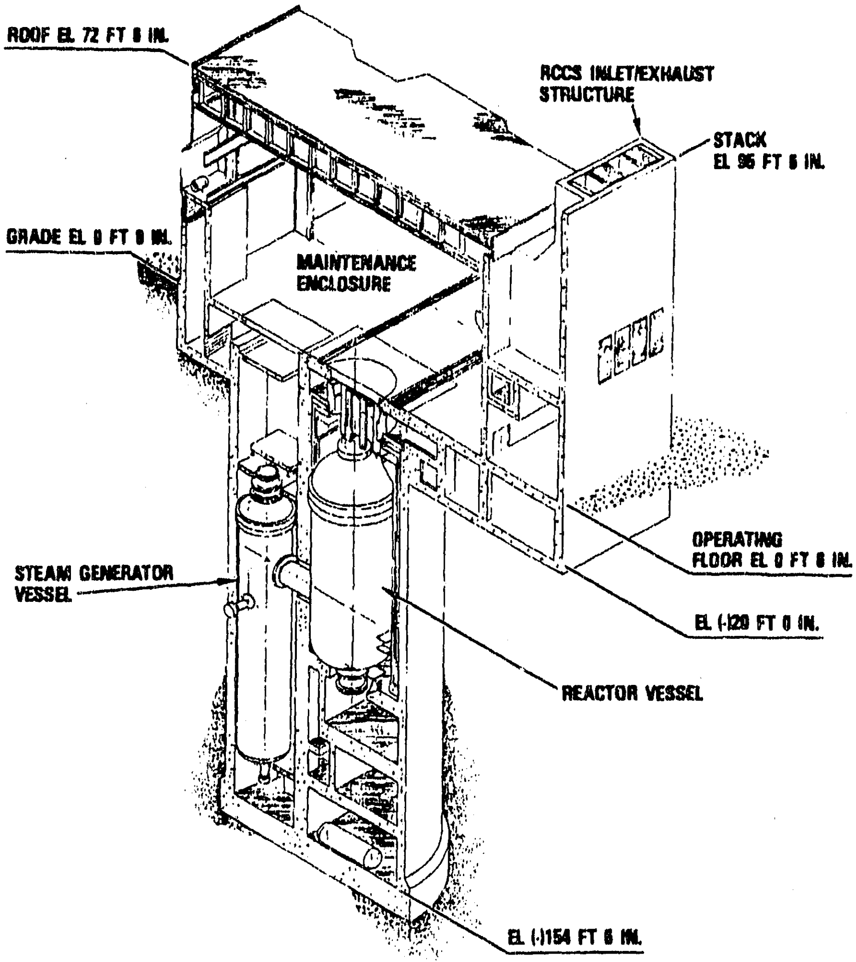

Figure 1 Reactor Building Cutaway

as short and direct as possible. The reference energy conversion area incorporates two 275 MW(e) non-reheat turbine generator sets, each connected to a pair of reactors. Four stages of feedwater heating are used to optimize the turbine cycle.

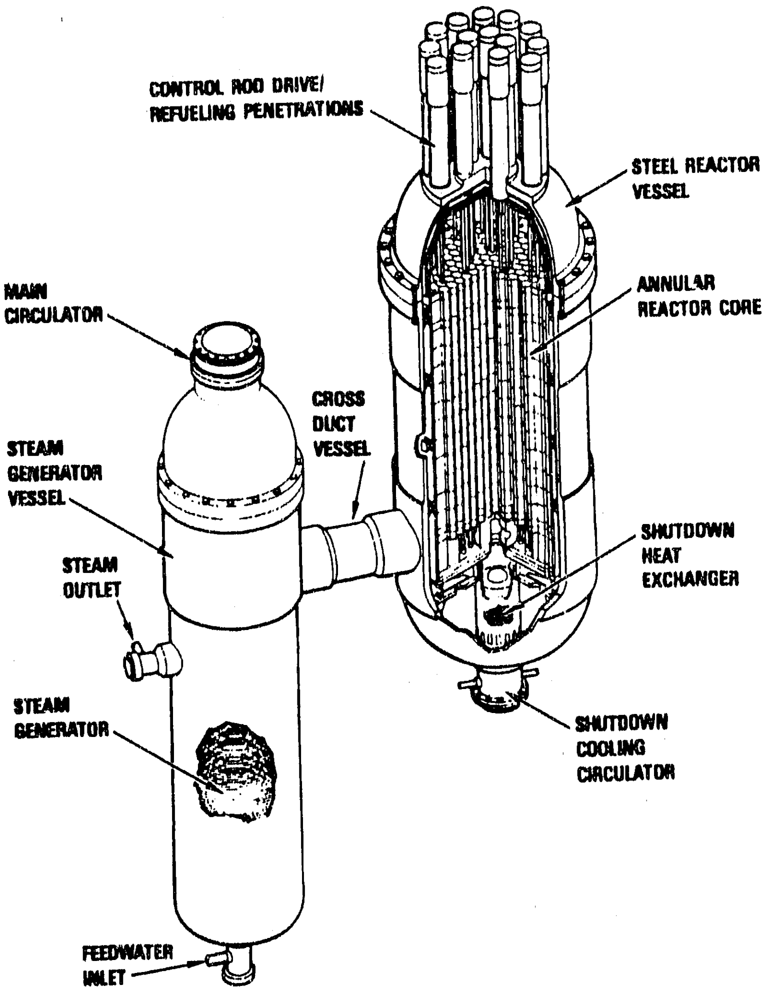

Figure 2 MHTGR Single Module Reactor Arrangement

Figure 2 shows the physical arrangement of a single reactor module. The primary system components are contained within three steel vessels: a reactor vessel, a steam generator vessel, and a connecting cross vessel. The reactor core consists of an assembly of hexagonal prismatic graphite blocks identical to use employed at the Fort St. Vrain Nuclear Generating Station. The active region of the core consists of fuel blocks arranged in three annular rings (Fig. 3). The center and outer portions of the core are made from unfueled reflector blocks. The core assembly is surrounded by a steel core barrel and contained inside the uninsulated reactor vessel.

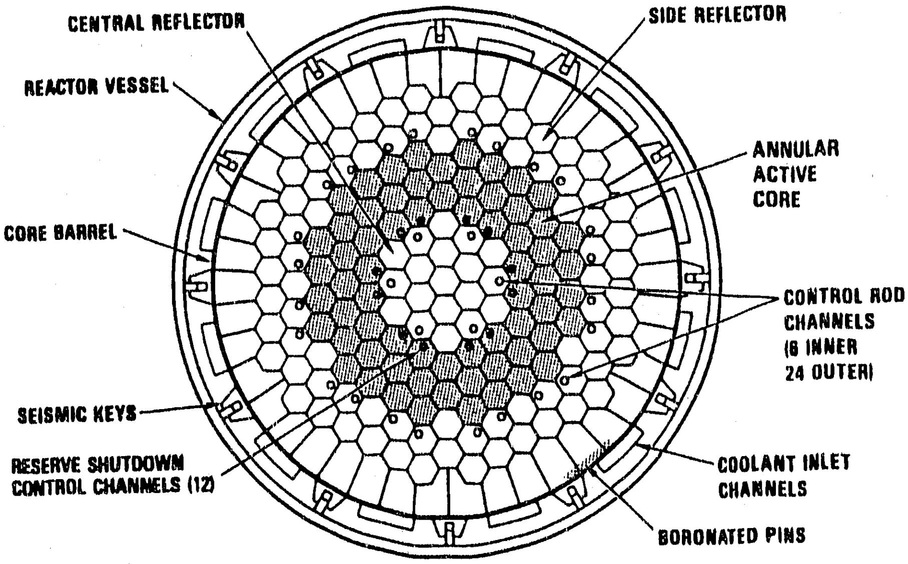

Figure 3 Reactor Core Plan View

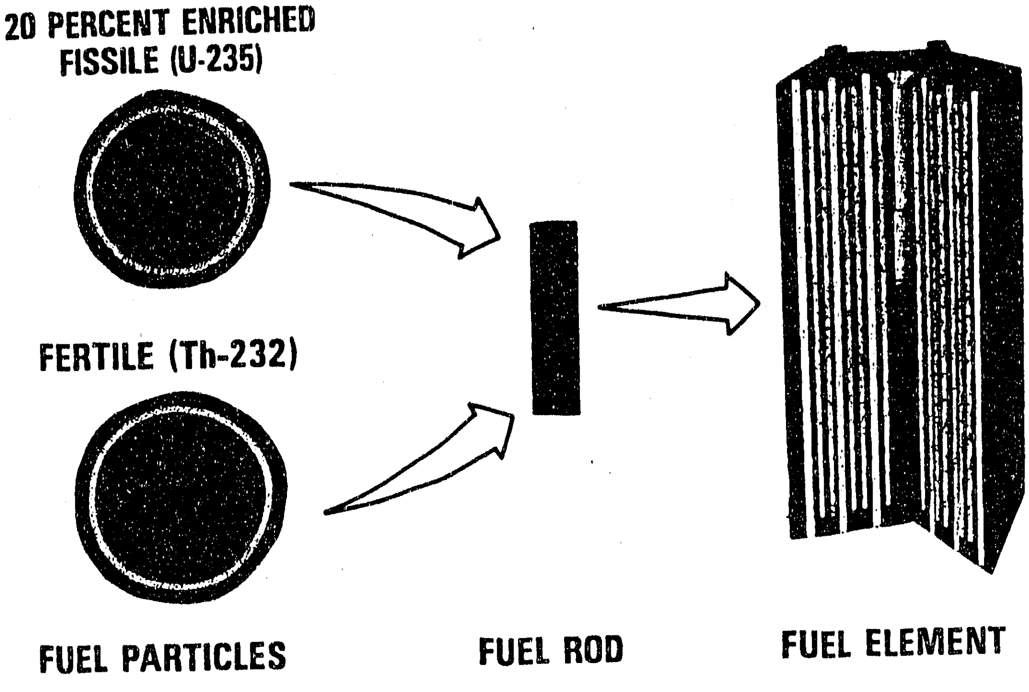

Figure 4 MHTGR Fuel Components

The fuel consists of two types of coated particles: fissile particles containing 20%-enriched uranium oxycarbide kernels and fertile particles, containing thorium oxide kernels. The particles are bonded together to form fuel rods which are inserted in blind vertical holes in the graphite fuel blocks as shown in Fig. 4. Vertical coolant holes also pass through the fuel blocks. The fuel cycle is a once-through, three-year cycle with one-half of the core refueled every 20 months. The core reactivity is controlled by control rods in the inner and outer reflectors. A reserve shutdown system provides a diverse reactivity control capability using boron pellets stored in hoppers above special channels in the core.

Helium flows downward through the core to a plenum at the bottom of the core, and then through the inner part of the coaxial cross-duct vessel to the steam generator vessel. Helium flows downward over a helical tube steam generator bundle. Feedwater enters at the bottom of the steam generator, and steam exits at the top. Cool helium flows upward around the outside of the tube bundle to a single stage, axial compressor driven by an electric motor equipped with magnetic bearings. Shrouds and flow devices direct the helium to the outer part of the cross vessel. After reentering the reactor vessel, the helium flows upward along the outside of the core barrel to the top of the core. A simplified flow diagram including the secondary side of the plant is shown in Fig. 5.

For availability and maintenance requirements, a separate shutdown cooling system (SCS) is provided as a backup to the primary heat transport system. A shutdown heat exchanger and a shutdown cooling circulator are mounted on the bottom of the reactor vessel. The heat removal systems allow hands-on module maintenance to begin within 24 hours after plant shutdown.

A reactor cavity cooling system (RCCS) is located in the concrete structure external to the reactor vessel to remove heat radiated from the vessel during normal operation as well as all normal events when forced core cooling is unavailable. The RCCS consists of above-grade intake structures (see Fig.1) that naturally convect outside air down through enclosed ducts and panels that surround the below-grade core cavity before returning the warmed air through above-

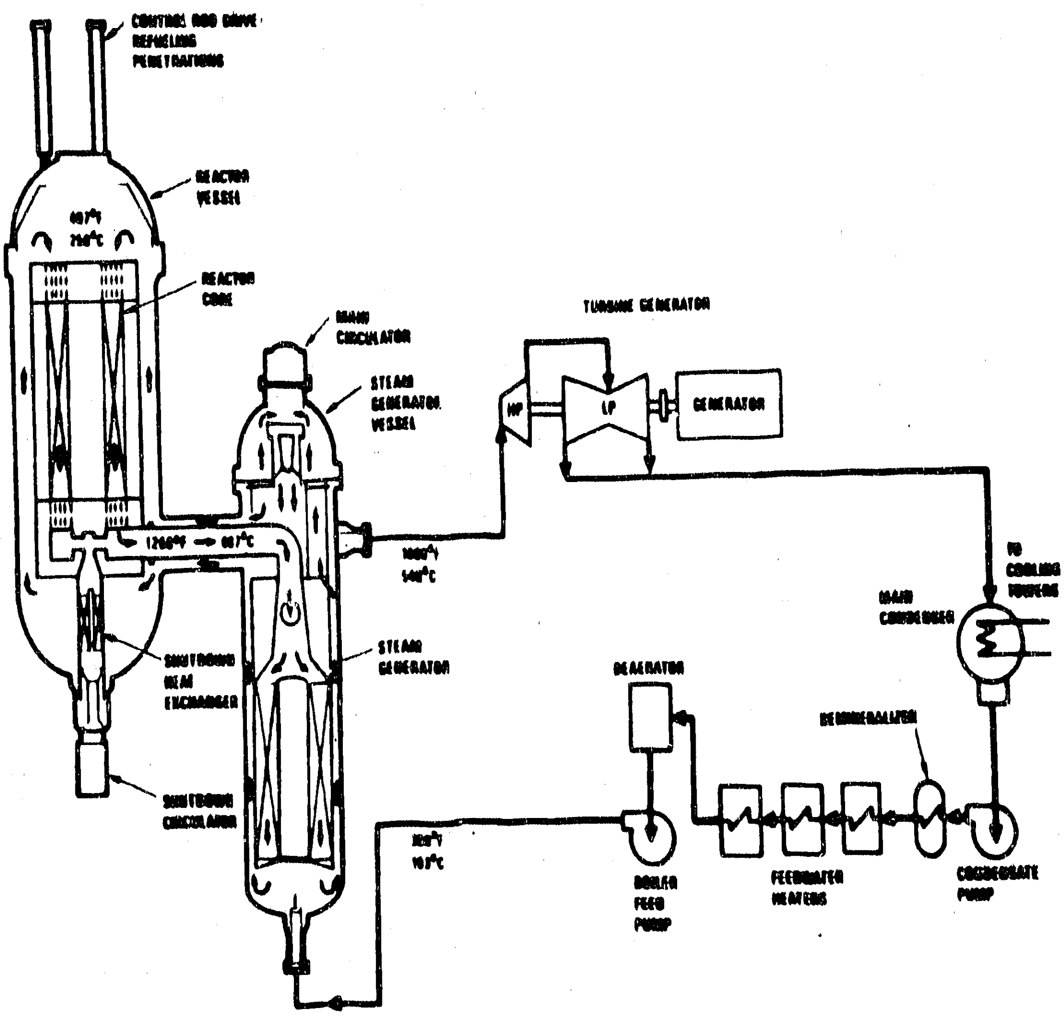

Figure 5 MHTGR Simplified Flow Diagram

grade outflow structures. The core heat is transferred by conduction, convection, and radiation to the RCCS. This system is completely passive and has no controls, valves, circulating fans, or other active components.

The plant control, data, and instrumentation system is an integrated, modern commercial microprocessor-based distributed control system that enables the multiple-reactor, multiple-turbine plant to be automatically controlled and operated from a single control room with two operators. The plant control, data, and instrumentation system performs control, monitoring, and data management functions given automatic and/or plant operator generated commands. Digital computers are used for control, data processing, and signal transmission.

The reactor protection system which is separate and functionally independent from the plant control system senses plant process variables, detects abnormal plant conditions, and initiates plant protective actions. Each reactor module has a separate and independent reactor protection system which consists of four separate (redundant) safety channels and redundant two-out-of-four coincidence solid-state logic to command initiation of a protective action. The protective action initiation signal is sent to separate and redundant actuation devices.

III. Safety Requirements

The design of the MHTGR has been guided by specific quantified utility/user requirements (Ref. 1) that cover safety, performance, availability and economics. They also incorporate established top level regulatory requirements (Ref. 2) for the protection of the public. The overall safety requirement to not disturb the normal day-to-day activities of the public has been quantified by the utility/user group to require that the top level regulatory criteria be satisfied at the plant boundary. In this way the emergency planning zone, which is generally 10 miles for U.S. light-water reactors, is reduced to the MHTGR's 425m Exclusion Area Boundary (EAB). This allows the utility/user to limit emergency drills to the area and personnel within its control. Thus the need for offsite drills for sheltering and evacuation is obviated. The specific quantitative requirements are those of the Environmental Protection Agency's Protective Action Guidelines (PAGs) evaluated at the 425m EAB.

IV. Safety Innovations of the MHTGR

To meet these stringent safety requirements and at the same time provide a cost competitive design requires the innovative combination of the basic high temperature gas-cooled reactor features of ceramic coated fuel, helium coolant, and graphite moderator and a unique core configuration. The inherent or intrinsic properties of this combination are:

- Coated fuel particle - The multiple ceramic coatings surrounding the fuel kernels constitute tiny independent pressure vessels which contain fission products. These coatings are capable of maintaining their integrity to very high temperatures in excess of 2000°C.
- Helium coolant - The inert and single phase helium coolant has several advantages. No flashing or boiling of coolant is possible, pressure measurements are certain, no coolant level measurements are required and pump cavitation cannot occur. Further, there are no reactivity effects associated with the helium coolant and no chemical or energetic reactions between coolant and fuel or cladding is possible.
- Graphite core - The strength of the graphite core and the stability of the ceramic fuel coating at high temperatures results in a wide margin between operating temperatures and temperatures that would result in core damage. Further, the high heat capacity and low power density of the core result in very slow and predictable temperature transients.

- Core Configuration - Selection of core geometry, core power density and core power level to assure that fuel temperatures cannot reach the integrity limit of the coated particles even if all active cooling fails.

The innovative approach taken in the design of the MHTGR is to rely on the coated fuel particles for meeting the 10CFR100 doses and on other additional, largely passive retention barriers for meeting the more restrictive PAG doses. First and foremost, high-quality fuel is relied on to minimize releases during normal operation. For example, even if all the plateout and circulating activity within the primary circuit is released, the total release is an order of magnitude lower than the 10CFR100 limits (Ref.3).

Three functions must be accomplished to ensure that radionuclide retention within the fuel remains acceptable during off-normal conditions: (1) remove core heat, (2) control heat generation, and (3) control chemical attack. The innovative manner in which the MHTGR meets each of the three key safety functions is discussed briefly by examining selected licensing basis events (LBEs) with frequency $>5x10^{-7}$/year. Further, the ultimate capability of the MHTGR is demonstrated by examining events of still lower frequency that have been evaluated for NRC in the safety risk assessment to provide assurance that the plant's residual risk is negligible.

Removal of Core Heat

The inherent features for heat removal include the intrinsic core geometry and power densities, the internals and vessel, and the passive cooling pathway from the core to the environment, as illustrated in Figs. 6 and 7. Figure 8 shows the best-estimate temperature transients for two LBEs, one with the primary system pressurized and one with it depressurized,

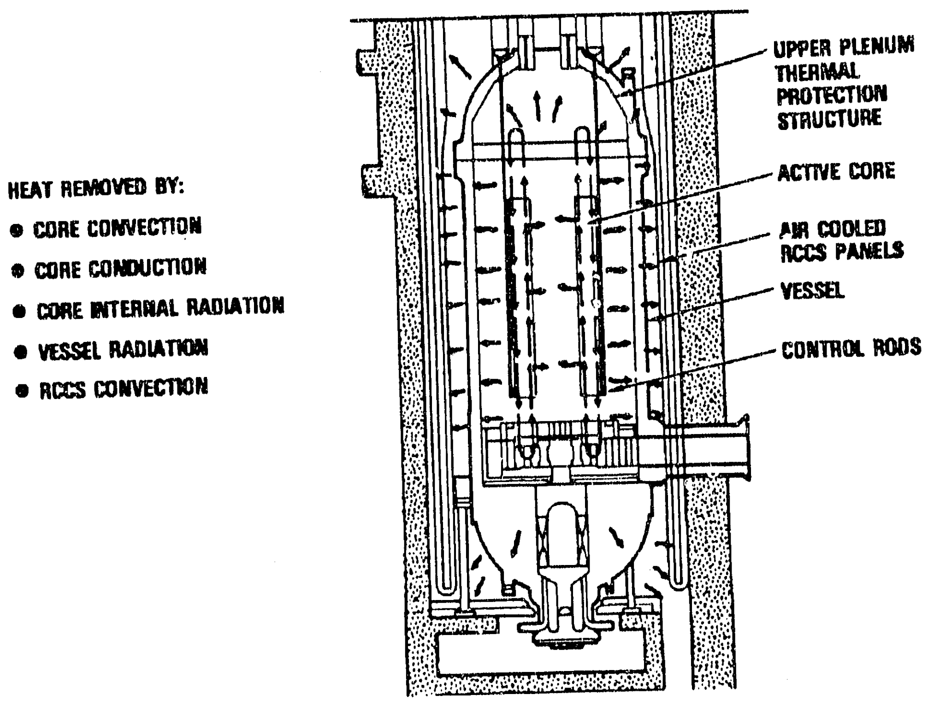

Figure 6 MHTGR Pressurized-Conduction Cooldown Heat Flow Path

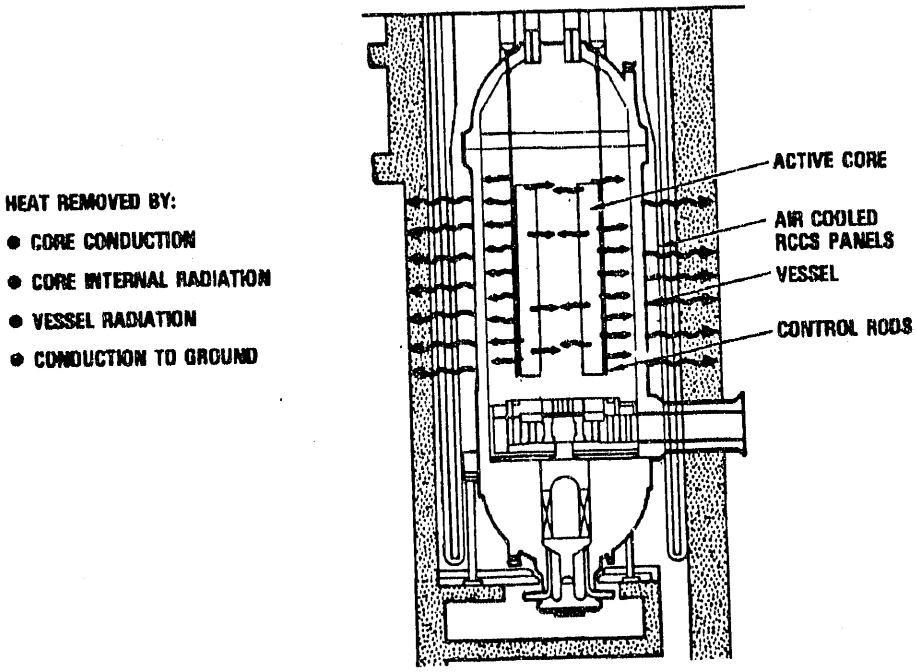

Figure 7 Depressurized-Conduction Cooldown Heat Flow Paths

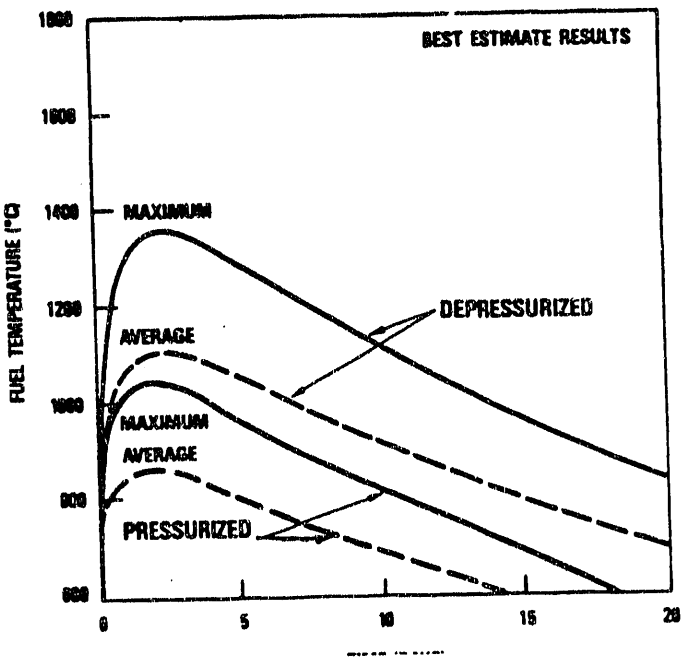

Figure 8 MHTGR Fuel Temperatures With Passive Heat Removal During Loss Of Forced Cooling.

in which the first two independent means of forced cooling are unavailable. Passive heat removal by conduction, radiation, and natural convection from the core through the vessel to the RCCS limits fuel temperatures to acceptable levels.

Passive heat removal is possible because of the large thermal margins in the fuel. As shown in Fig. 9 the fuel must exceed approximately 2000°C before thermal decomposition for the silicon carbide coating results in significant failure. The normal peak fuel temperature is about 1100°C.

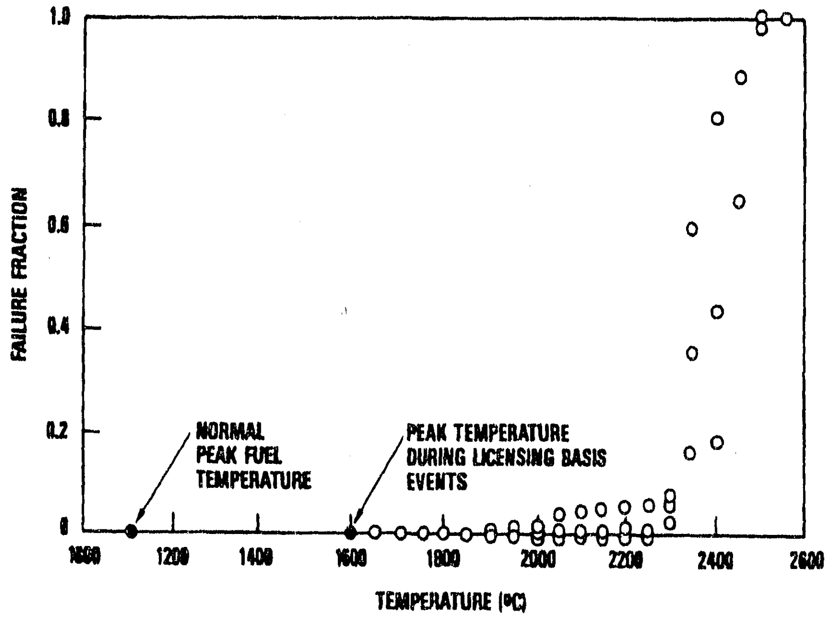

Figure 9 Integrity Of MHTGR Coated Fuel Particles During Temperature Ramp Tests In Which Fuel Was Heated From 1100 To 2500 °C In Times Ranging From 8 to 80 hours.

The passive means of core heat removal to protect the fuel is a major departure from previous HTGRs. As shown in Figure 10, previous HTGRs, even the small 115 MW Peach Bottom HTGR, with their cylindrical cores could not passively keep the fuel temperatures below an acceptable level in the unlikely event of a loss of forced cooling and a loss of coolant pressure. Only the MHTGR passively assures fuel integrity under these rare accidents.

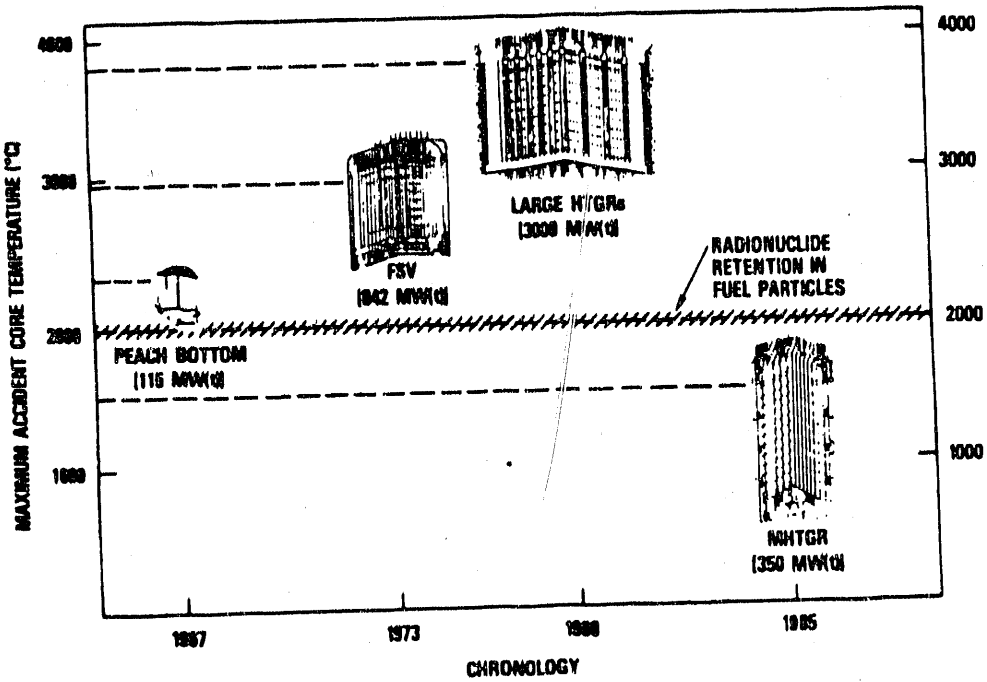

Figure 10 The MHTGR Represents A Fundamental Change In Reactor Safety Philosophy - Sized To Tolerate Even A Severe Accident

Finally, the ultimate and unprecedented capability of the MHTGR to withstand challenges of heat removal is shown in Fig. 11, where the passive air-cooled RCCS panels are assumed to be completely ineffective. As shown in the figure, the maximum core temperature is affected very little and remains within acceptable levels as the heat is transferred into the building and ground.

Control of Heat Generation

The inherent features that control reactivity and thus heat generation, include a strong negative temperature coefficient, a single phase (no void coefficient), and neutronically inert coolant. These characteristics cause the reactor to inherently shut down at higher than normal fuel temperatures. As shown in Fig. 12, for a pressurized conduction cooldown, fuel temperatures remain low and within acceptable limits regardless of whether reactor trip occurs and even if all control rods are withdrawn (a reactivity addition of approximately 3%). The temperatures without reactor trip remain within acceptable limits for periods of time approaching

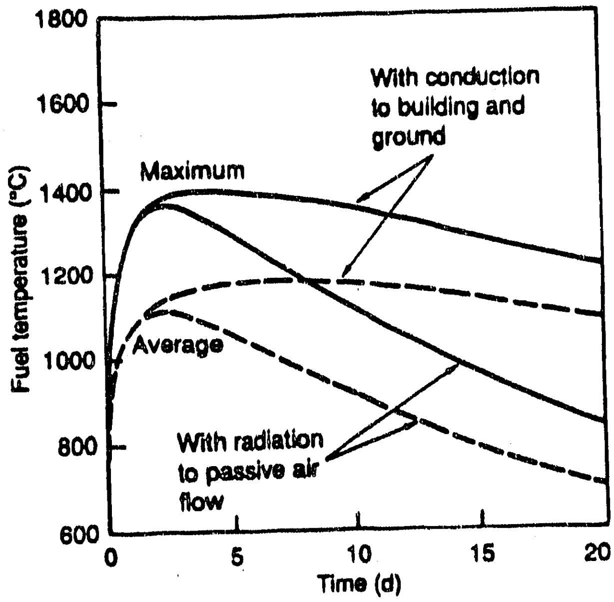

Figure 11 MHTGR Fuel Temperatures (Best Estimate) During Loss Of Forced Cooling At Depressurized Conditions With And Without The Passive Air-Cooling System.

several days. Accidental ingress of water is limited by the amount of steam the core can physically hold (724 kg pressurized and 63 kg depressurized) and bounded by the preceding reactivity addition. Furthermore, as discussed earlier, the plant protection system, which is separate from the operational system and includes two diverse reactivity control systems that are gravity inserted and highly reliable for protecting against even rarer events.

Control of Chemical Attack

The inherent features for controlling chemical attack of the fuel by water include the nonreacting coolant, a water-graphite reaction that is endothermic and requires temperatures above the average normal operating conditions, and the silicon carbide coatings on the fuel. The MHTGR design features that limit water ingress and its consequences include the limited sources of water, reliable detection and isolation systems, and two forced convection core-cooling systems. The circulator magnetic bearings eliminate the source of water that was the dominant contributor to the low capacity factor of the Fort St. Vrain HTGR.

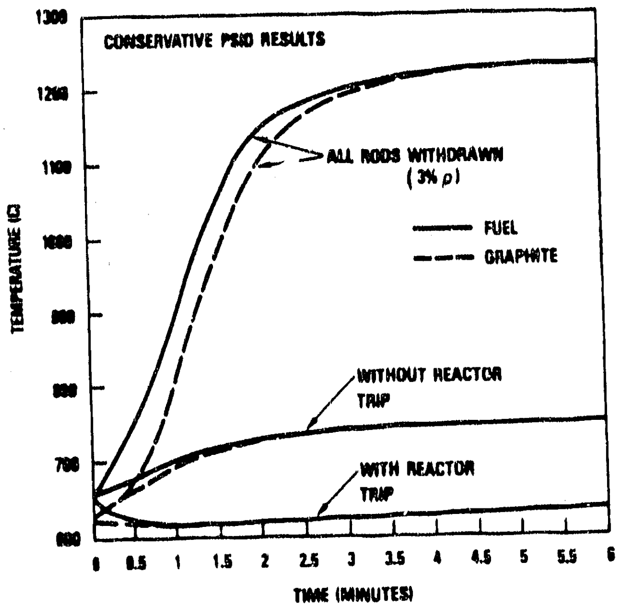

Figure 12 Control Of MHTGR Fuel Temperature By Negative Temperature Coefficient During Loss Of Forced Cooling.

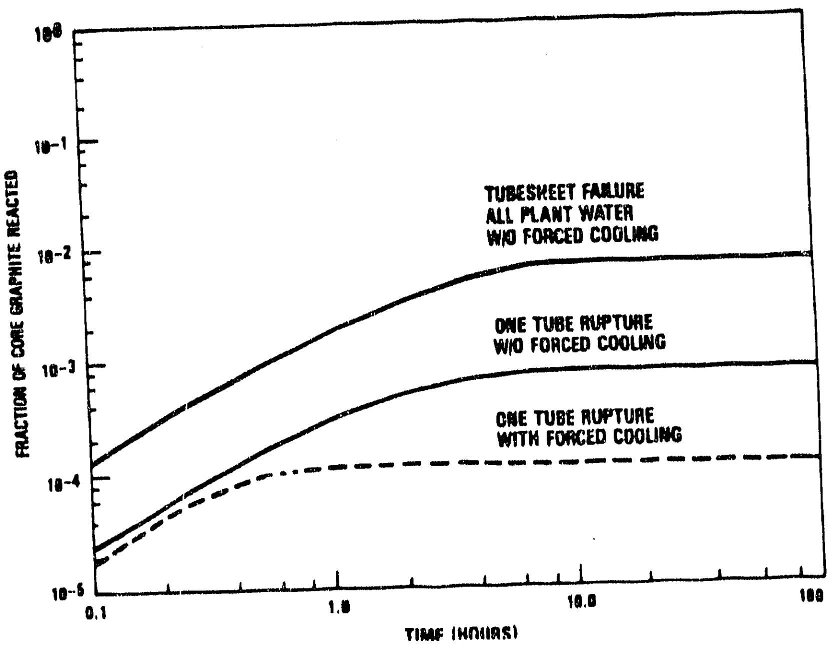

Figure 13 Integrity Assurance Of MHTGR Coated Fuel Particles During Water Ingress.

Figure 13 shows the time-dependent fraction of the core graphite oxidized for two LBEs and a very rare bounding event that challenges the control of chemical attack. In all cases, whether forced cooling is available or lost or whether one or more steam generator tubes fails, the impact on the core graphite is small even without successful moisture detection. Furthermore, and most importantly, the high quality of the fuel particle coatings limits the radionuclide inventory available for release because of water chemical attack to those particles with initially failed coatings (from either in-service failure or manufacturing defects).

The inherent features for controlling chemical attack of the fuel by air include the nonreacting coolant, the embedded ceramic fuel particles, the nuclear-grade vessel, and the below-grade reactor silo. Figure 14 shows the fraction of the core graphite reacted by air ingress following primary coolant leaks without forced core cooling (two LBEs and two extremely rare bounding events). As shown, the fraction reacted is very small in all cases. The primary reason for the small amount of oxidation is the large resistance to flow that the coolant holes provide (L/D > 700). Once again, the impact on the core graphite is small, and the fuel remains intact.

Safety Importance of Operator Actions

By minimizing the need to rely on active systems or operator actions, the safety evaluations are simplified and need only consider the integrity and natural behavior of the passive reactor materials, not the reliability of pumps, valves, and their associated services or the probability of an operator taking correct actions. Furthermore, with emphasis on a passive safety design, the plant is insensitive to incorrect operator actions; thus the human-machine interface is largely removed from the safety consideration.

The MHTGR safety approach of placing primary emphasis on retention of the radionuclides within the coated fuel particles narrows the assessment of incorrect operator errors

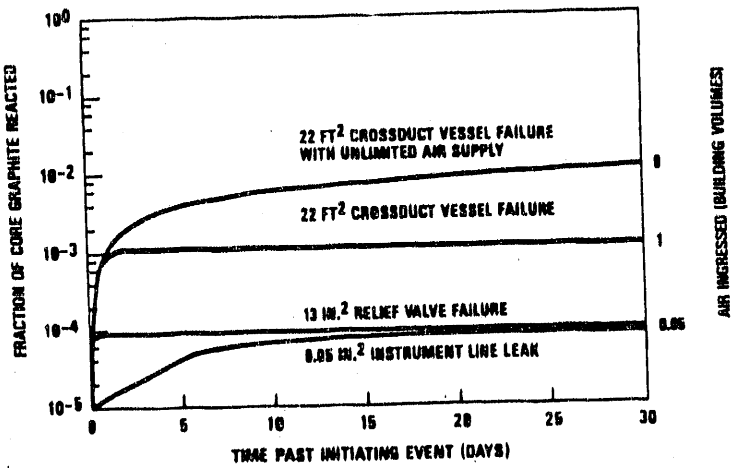

Figure 14 Insignificant Oxidation Of MHTGR Graphite Limited By Air Mass Transfer And Core Temperatures.

to the same three key functions discussed previously. No events have been identified in which an action by the operator can defeat the natural behavior of the passive feature.

The results of the safety risk assessment has concluded that the risk is below that received from commonly accepted activities even for very infrequent events. Essentially, there is an intrinsic consequence cap that corresponds to the retention of the radionuclides within the fuel particles. Thus the passive safety features of the design prevent and mitigate radionuclide release over a wide spectrum of off-normal events, including failure of active systems, operator errors of omission and commission and acts of sabotage.

V. Development Status

During 1988, the NRC staff completed a lengthy review of the MHTGR conceptual design and its safety characteristics. The national laboratories and other NRC consultants independently verified the safety calculations. The staff review concluded that the design had the potential to meet the Advanced Reactor policy in that it took advantage of passive features to achieve a degree of safety at least at least as high as the current generation of reactors. The NRC staff completed their draft of the Safety Evaluation Report (SER) in August 1988. The

Advisory Committee on Reactor Safeguards (ACRS) subsequently reviewed the draft SER and generally concurred with the NRC staff that the technical issues identified in the SER can be adequately addressed in subsequent design and technology development programs.

The draft SER (NUREG-1338) was released February 28, 1989. The draft states that several areas are contingent on a further review of a mechanistic siting source, accident selection, and emergency planning, as well as the acceptability of the MHTGR's containment system.

Development of the preliminary design of the four-module standardized commercial plant is progressing under sponsorship of the DOE. The principal contractors include Bechtel, Combustion Engineering, General Atomics, and Stone & Webster. Oak Ridge National Laboratory provides technical support while Gas-Cooled Reactor Associates represents utility interests.

In addition to pursuing the MHTGR for commercial electricity generation, the U.S. government is also actively pursuing the MHTGR for application in defense material production. As would be expected, the two designs exhibit extensive commonalities, with the main distinguishing feature being in the core design area (high enriched fuel and target assemblies versus proliferation-resistant low enriched fuel). The MHTGR New Production Reactor (MHTGR-NPR) is also currently in the preliminary design phase. With aggressive plans for deployment of this reactor near the turn of the century, the NPR will proceed in the lead role if a positive decision is made to commit to construction. Thus, the strategy for commercializing the MHTGR is intimately tied to the Production Reactor Program.

The two programs are being coordinated to maximize benefits from the NPR program to the commercial design. These benefits are not limited to the design itself, but extend to project infrastructure, technology development, and design acceptance. It is planned that transfer of know-how to the commercial program be accomplished by utilizing experienced staff as they become available from the defense program. Furthermore, the strategy requires that the Production Reactor conduct necessary performance testing, results of which can be utilized to support licensing and certification of the commercial design as the fastest path to a certified commercial plant at minimum development cost.

In order to implement this optimum strategy, interactions with the NRC are underway now to agree on a licensing plan and the resolution of licensing issues. In addition, the design development of the commercial program will proceed in parallel with the pacing Production Reactor. This is necessary to adapt the detailed component and system designs as they evolve on the defense program. Thus, carefully planned coordination between the two MHTGR programs will be implemented to avoid technological duplication and facilitate certification of the commercial design (Ref.4).

V. Summary

The MHTGR has been developed to respond to the changing environment that requires increased margins of safety that rely on the basic laws of nature and the integrity of passive design features. The MHTGR uses the intrinsic or inherent properties of the HTGR features of ceramic coated fuel, helium coolant, and a graphite moderator configured in an innovative manner. The fundamental choice of retaining the radionuclides at their source within the fuel dramatically simplifies proof of containment. This coupled with the relatively small power of the annular ceramic core within an uninsulated steel vessel to provide innovative passive heat removal assures radionuclide retention even if the primary coolant boundary is breached and the coolant is lost - the core will not melt. Thus, an unprecedented level of safety has been made available by the full innovative implementation of the basic HTGR features in the MHTGR.

The authors would like to thank the U.S. Department of Energy for approval to publish this work, which was supported by the San Francisco Operations Office Contract DE-AC03-89SF17885.

References

1. *Utility/User Requirements for the Modular High Temperature Gas-Cooled Reactor Plant,* Report GCRA-002, Rev. 3, Gas-Cooled Reactor Associates, June 1987.
2. *Top-Level Regulatory Criteria for the Standard MHTGR,* DOE Report DOE-HTGR-85002, Rev. 2, October 1986.
3. Silady, F. A. and A. C. Millunzi, *Safety Aspects of the Modular High Temperature Gas-Cooled Reactor,* Nuclear Safety, Vol. 31, No. 2, April-June 1990.
4. Simon, W. A. and J-D. Wistrom, *Status of Modular High Temperature Gas-Cooled Reactor Development,* GA-A20597, July 1991.

END

DATE FILMED

7/14/92