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SAFETY ASPECTS OF THE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR (MHTGR)

by
F.A. SILADY and A.C. MILLUNZI*

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F. A. Silady
(GENERAL ATOMICS)
and
A. C. Millunzi
(USDOE)

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 and cogeneration uses such as water desalination. The design utilizes the basic high-temperature gas-cooled reactor (HTGR) features of ceramic fuel, helium coolant, and a graphite moderator. However, the specific size and configuration are selected to utilize the natural characteristics of these materials to develop a significantly higher margin of safety than current generation reactors. The qualitative 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 hence precluding the need for sheltering or evacuation of the public.

The MHTGR safety response to events challenging the functions relied on to retain radionuclides within the coated fuel particles has been evaluated. A broad range of challenges to core heat removal have been examined which include a loss of helium pressure and a simultaneous loss of forced cooling of the core. The challenges to control of heat generation have considered not only the failure to insert the reactivity control systems, but the withdrawal of control rods. Finally,, challenges to control chemical attack of the ceramic coated fuel have been considered, including catastrophic failure of the steam generator allowing water ingress or of the pressure vessels allowing air ingress. The plant's response to these extreme challenges is not dependent on operator action and the events considered encompass conceivable operator errors. In the same vein, reliance on radionuclide retention within the fuel particle and on passive features to perform a few key functions to maintain the fuel within acceptable conditions also reduces susceptibility to external events, site-specific events, and to acts of sabotage and terrorism.

INTRODUCTION AND DESIGN OVERVIEW

Under the sponsorship of the U.S. Department of Energy (DOE), four U.S. corporations, General Atomics; Combustion Engineering; Bechtel National; and Stone & Webster Engineering Corporation; along with Oak Ridge National Laboratory, and utility input through Gas Cooled Reactor Associates are developing a MHTGR that can provide safe, economic, and reliable power for the next generation of power plants.

The MHTGR design is based upon generic gas-cooled reactor experience, as well as specific HTGR programs and projects. These include the 52 carbon dioxide-cooled developed in the United Kingdom and the five helium cooled reactors built in Western Europe and the United States.

The MHTGR is being designed to meet the rigorous requirements established by the NRC and the electric utility/user industry for a second generation power source of the late 1990s. The plant is expected to be equally attractive for deployment and operation in the United States, other major industrialized nations, and the developing nations of the world.

The typical MHTGR plant includes an arrangement of four identical modular reactor units located in a single reactor building. The plant is divided into two major areas: a Nuclear Island (NI) containing the four reactor modules and an energy conversion area (ECA) containing two turbine generators. Each of the reactor modules produces a thermal output of 350 MW(t). The reactor modules are paired to feed the turbine generators to produce 538 MW(e) net of electric power. The steam conditions are similar to those of a modern fossil-fired plant.

Each reactor module is housed in adjacent, but separate, reinforced concrete structures located below grade and under a common roof structure. The below-grade location provides significant design benefits by reducing the seismic amplifications typical of above-grade structures.

The overall reactor configuration is shown in Fig. 1. The reactor components are contained within three steel vessels: a reactor vessel, a steam generator vessel, and a connecting cross duct vessel. The reactor vessel is approximately the same size as that of a large boiling water reactor and contains the core, reflector, and associated supports. Top mounted penetrations house the control rod drive mechanisms and the hoppers containing boron carbide pellets for reserve shutdown. The penetrations are also used as access for refueling and inspection.

The heat transfer during power operation or normal decay heat removal operation is accomplished by helium which is heated as it flows down through the core. It is collected in a plenum below the core and flows through a coaxial hot duct inside the cross vessel to a once-through helical bundle steam generator. After flowing downward over the steam generator tubes, the cool helium flows upward in an annulus between the steam generator vessel and a shroud leading to the main circulator inlet.

The main circulator is a submerged electric motor driven, two stage axial compressor with active magnetic bearings. The helium is discharged from the circulator and flows through the annulus of the cross vessel and hot duct and then upward to the top plenum over the core.

In order to meet 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 plant maintenance to begin within 24 h after plant shutdown.

A reactor cavity cooling system (RCCS) is located in the concrete structure external to the reactor vessel to remove plant residual heat. This system is totally passive and provides a heat sink if the forced cooling systems are inoperative. The heat is transferred by means of conduction, convection, and radiation from the core to the RCCS. This system has no controls, valves, circulating fans, or other active components.

The reactor core and the surrounding graphite neutron reflectors are supported on a steel core support plate at the lower end of the reactor vessel. A horizontal cross section of the reactor core and vessel internals is shown in Fig. 2. The reactor core contains graphite fuel blocks that are hexagonal in cross section. The fuel (Fig. 3) is in the form of coated particles of low enriched fissile uranium oxycarbide and fertile thorium oxide. The fuel particles are bonded together in fuel rods which are contained in sealed vertical holes in the fuel blocks. These fuel blocks are stacked in columns to form an annular shaped core. Unfueled graphite blocks fill the center and surround the active core to form the reflector. Key reactor core design parameters are shown in Table 1.

SAFETY PHILOSOPHY

The overall safety philosophy guiding the design of the MHTGR is to produce a safe, economical plant design which meets NRC and user requirements by providing defense-in-depth through the pursuit of four goals: (1) maintain safe plant operation, (2) maintain plant protection, (3) maintain control of radionuclide release, and (4) maintain emergency preparedness.

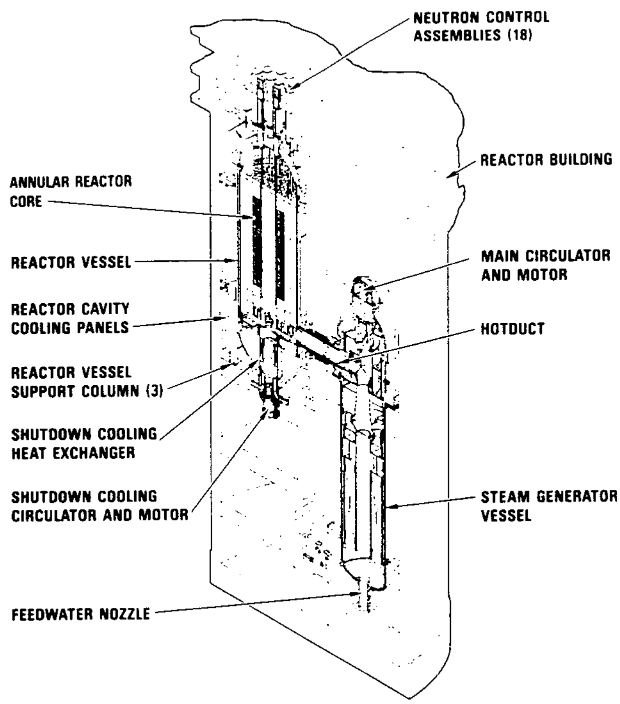

Fig. 1. 350 MW(t) MHTGR isometric

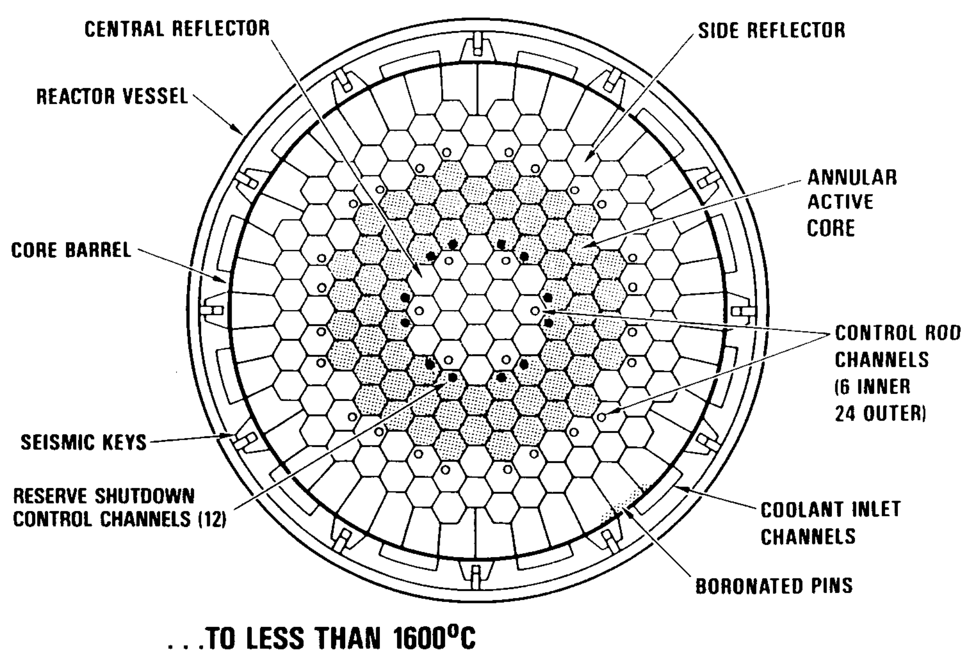

Fig. 2. 350 MW(t) modular reactor core cross section

TABLE 1 PLANT AND CORE PARAMETERS	
Thermal power (4 modules)	1400 MW(t)
Electrical output	588 MW(e) gross; 538 MW(e) net
Net efficiency	38.4%
Steam conditions	538°C (1000°F)/16.6 MPa (2400 psig)
Core exit helium temperature	687°C (1268°F)
Cold helium temperature	259°C (498°F)
Core power density	5.9 W/cm^3
Annular core diameters	
Outer	3.5 m
Inner	1.6 m
Core height	7.9 m
Number of columns in active core	66
Number of fuel elements per column	10

With regard to the achievement of NRC criteria for the accomplishment of the first two goals, measures are taken in the design of the MHTGR to minimize defects in the fuel so that normal operational releases or any accidental releases of primary circuit activity are low and worker exposures are minimized.

The unique aspect of the MHTGR, however, is the approach which has been taken to achieve the third goal and thereby minimize the design requirements from the fourth goal. To accomplish this with high assurance, the design of the MHTGR has been guided by the additional philosophy that control of radionuclide releases be accomplished primarily by retention of radionuclides within the fuel particles with minimal reliance on active design features or operation actions. The overall intent is to provide a simple safety case that will provide high confidence that the safety criteria are met. This approach is consistent with the NRC's Policy on Advanced Reactors (Ref. 1). There are two key elements to this philosophy which have had a profound impact on the design of the MHTGR.

First, the philosophy requires that control of radionuclides be accomplished with minimal reliance on active systems or operation actions. By minimizing the need to rely on active systems or operator actions, the safety case centers on the behavior of the laws of physics and on the integrity of passive design features. Studies need not center on an assessment of the reliability of pumps, valves, and their associated services or on the probability of an operator taking various actions, given the associated uncertainties involved in such assessments.

Second, the philosophy requires control of releases primarily by the retention of radionuclides within the coated fuel particle and with decreasing reliance on secondary barriers (such as the primary coolant boundary or the reactor building). Proof of containment is dramatically simplified if evaluations center on issues associated with fuel particle coating integrity. This proof is further simplified if the evaluations are based on easily understood and modeled transient characteristics. Specifically, the MHTGR's single phase coolant and low power density, refractory, annular core preclude core melt, large internally generated energetics, geometric reconfigurations, and their associated phenomenological uncertainties.

TOP-LEVEL REGULATORY CRITERIA AND USER SAFETY REQUIREMENTS

Top-level criteria and requirements are defined from two sources: the regulator, whose concern is primarily public health and safety and the user, whose concern is all encompassing (e.g., safety, performance, availability, and economics). Each of the four goals has been quantified by a series of top-level criteria and requirements (Refs. 2 and 3). The top-level regulatory criteria are the basis for plant licensability.

The following bases were adopted for the selection of top-level regulatory criteria:

1. Top-level regulatory criteria should be a necessary and sufficient set of direct statements of acceptable health and safety consequences or risks to individuals or the public. This ensures that the criteria are fundamental to the protection of the public and the environment.
2. Top-level regulatory criteria should be independent of reactor type and site.
3. Top-level regulatory criteria should be quantifiable to ensure that compliance can be demonstrated through measurement or calculation.

The following regulatory sources have been found to contain numerically-expressed criteria or limits which appropriately form top-level regulatory criteria:

1. 51FR28044 – Policy Statement on Safety Goals for the Operation of Nuclear Power Plants.
2. 10CFR20 – Standards for Protection Against Radiation.
3. 10CFR50, Appendix I – Numerical Guides for Design Objectives ... to Meet the Criteria "As Low As Reasonably Achievable" for Radioactive Material ... in Effluents.

4. 40CFR190 – Environmental Radiation Protection Standards for Nuclear Power Operations.

5. 10CFR100 – Reactor Site Criteria.

6. EPA-520/1-75-001 – Manual of Protective Action Guides for Protective Actions for Nuclear Incidents.

The utility/user group has specified an additional safety requirement (Ref. 3) that is more restrictive in that item 6 above of the top-level regulatory criteria is to be satisfied at the plant boundary. In this way the emergency planning zone, which is generally 16,000 m (10 miles) for United States light-water reactors (LWRs), is reduced to the MHTGR's 425 m Exclusion Area Boundary (EAB). This allows the utility/user to limit emergency drills to the area and personnel within its control. The need for offsite sheltering and evacuation is obviated, and the public's normal day-to-day activities are not disturbed by the proximity of the MHTGR plant. The specific quantitative user requirements are the Environmental Protection Agency (EPA) Protective Action Guidelines (PAGs) of 5 rem thyroid and 1 rem whole body doses evaluated at the 425 m EAB.

LICENSING BASIS EVENTS

For the purpose of deriving the regulatory licensing bases for the design, the probabilistic bases for the design have been cast in a framework and format similar to that of traditional licensing approaches. Postulation of a set of bounding licensing basis events is one of the key elements in the traditional regulatory process. Licensing basis events (LBEs) are used to demonstrate compliance with dose criteria for a spectrum of off-normal events. The use of PRA for LBE selection provides a basis for judging, in a quantitative manner, the frequency of the entire event sequence and, therefore, the appropriate dose or risk criteria to be applied.

Figure 4 provides the frequency-consequence risk plot defining three regions bounded by three frequencies and by corresponding consequence limits related to 10CFR50 Appendix I, 10CFR100 or the PAGs. Depending upon their predicted frequency, selected events are assigned to one of the following three categories:

1. Anticipated Operational Occurrences (AOOs) – These are families of events expected to occur once or more in the plant lifetime. Their dose consequences are realistically analyzed in the SARs to demonstrate compliance with 10CFR50 Appendix I.

2. Design Basis Events (DBEs) – These are families of events lower in frequency than AOOs that are not expected to occur in the lifetime of one plant but

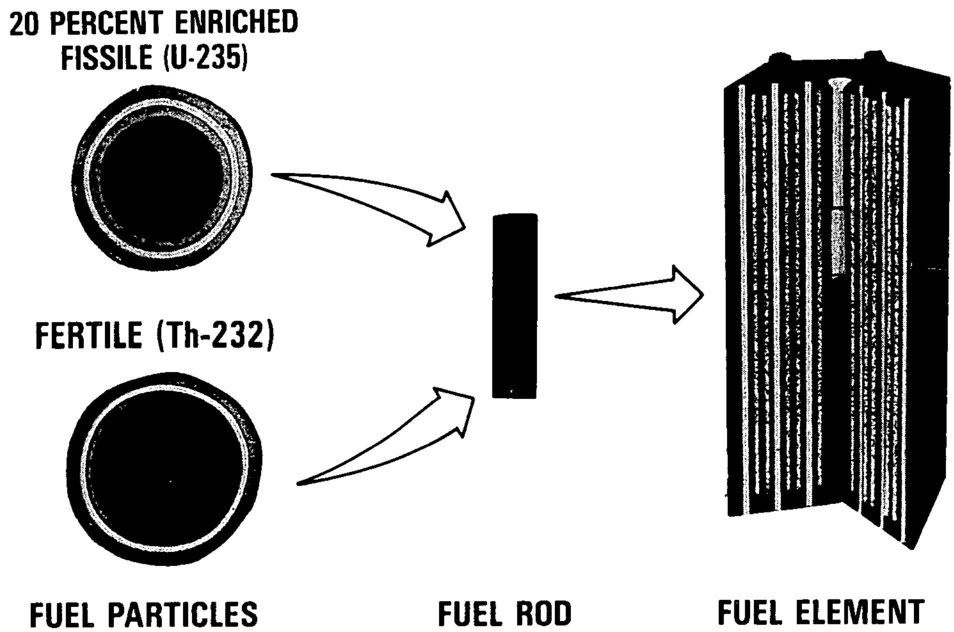

Fig. 3. MHTGR fuel components

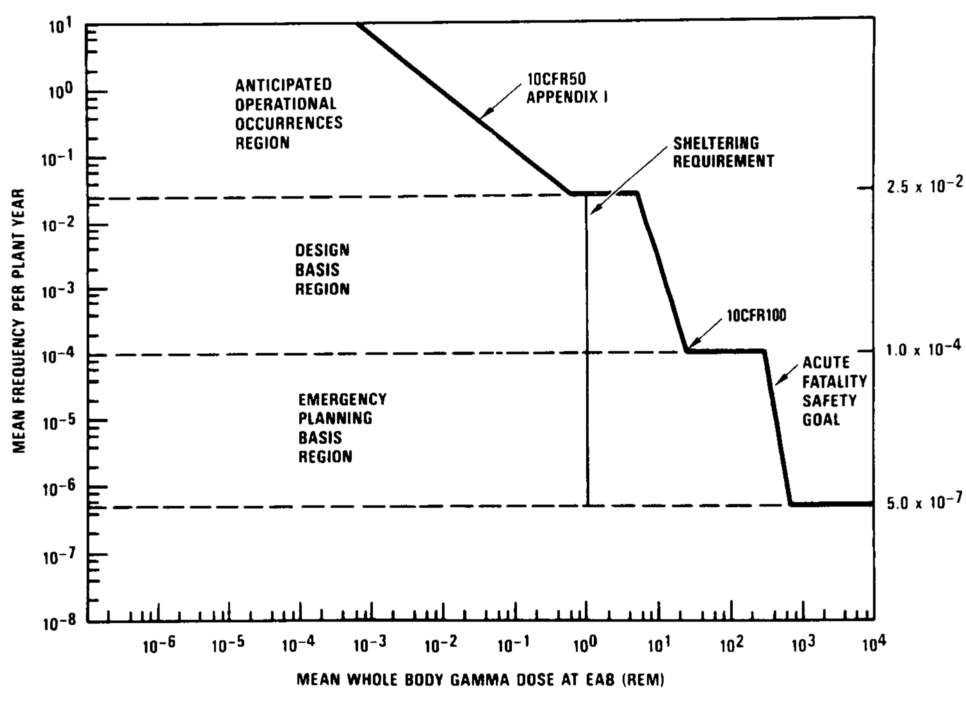

Fig. 4. Top-level regulatory criteria for mean frequency range/dose limits at site boundary

which might occur in a large population of MHTGRs. The DBEs are evaluated conservatively in the SARs against the 10CFR100 dose criteria.

3. Emergency Planning Basis Events (EPBEs) – These are families of events lower in frequency than DBEs that are not expected to occur in the lifetime of a large number of MHTGRs. The EPBE consequences are analyzed realistically in the PRA for emergency planning purposes and environmental protection assessments.

In addition to demonstrating compliance with the dose limits of the top-level regulatory criteria and the user safety requirements, the LBEs are considered collectively to show compliance with the NRC Policy Statement on Safety Goals (Ref. 4).

SAFETY DESIGN APPROACH AND RESULTS

The 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. For example, even if all of the plateout and circulating activity is released, the total release is an order of magnitude lower than the 10CFR100 limits. Three functions have been identified which, when accomplished, assure that radionuclide retention within the fuel remains acceptable:

1. Remove core heat.

2. Control heat generation.

3. Control chemical attack.

There are many ways these functions can be accomplished, and the various LBEs utilize different design selections to perform the same function depending upon the accident scenario. Generally, the less frequent LBEs rely more heavily on passive design features. For example, the MHTGR has three independent and diverse cooling systems, any of which can perform the function of removing core heat. However, while this multiplicity of systems contributes to increasing the margin of safety for the MHTGR and is considered in the LBE analyses, the MHTGR safety design approach emphasizes a minimum set of largely passive design features which, by themselves, are sufficient to accomplish these functions. How the MHTGR meets each of the three key safety functions is now briefly discussed by examining selected LBEs. Further, the ultimate capability of the MHTGR is demonstrated by examining events of still lower frequency that have been evaluated for the NRC to provide assurance that the plant's residual risk is negligible.

Remove Core Heat

The inherent features for heat removal include the intrinsic core dimensions and power densities of the reactor core, internals and vessel, and passive cooling pathway from the core to the environment as illustrated in Figs. 5 and 6. Figure 7 presents the best estimate temperature transients for two LBEs, one with the primary system pressurized and one depressurized, 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 reactor cavity cooling system limit fuel temperatures to acceptable levels.

Passive heat removal is possible due to the large thermal margins in the fuel. As shown in Fig. 8, 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 much lower at 1100°C.

Finally, the ultimate and unprecedented capability of the MHTGR to withstand challenges to heat removal is demonstrated in Fig. 9 where the passive air-cooled RCCS panels are assumed to be completely ineffective. As shown, the maximum core temperature are little effected and remain within acceptable levels as the heat is transferred into the building and ground. Note, also, that removal of core heat in the MHTGR is largely independent of maintaining any coolant flow path geometry.

Control Heat Generation

The inherent features that control reactivity include a strong negative temperature coefficient, a single phase (no void coefficient) and neutronically inert coolant. These characteristics cause the reactor to inherently shutdown. As shown in Fig. 10 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 ~3%). Accidental ingress of water is limited by the amount of steam the core can physically hold (724 Kg pressurized and 63 Kg depressurized) and is, therefore, bounded by the above reactivity addition. Furthermore, the plant protection system, which is separate from the operational system, includes two diverse reactivity control systems that are gravity inserted and highly reliable to protect against even rarer events.

Control 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

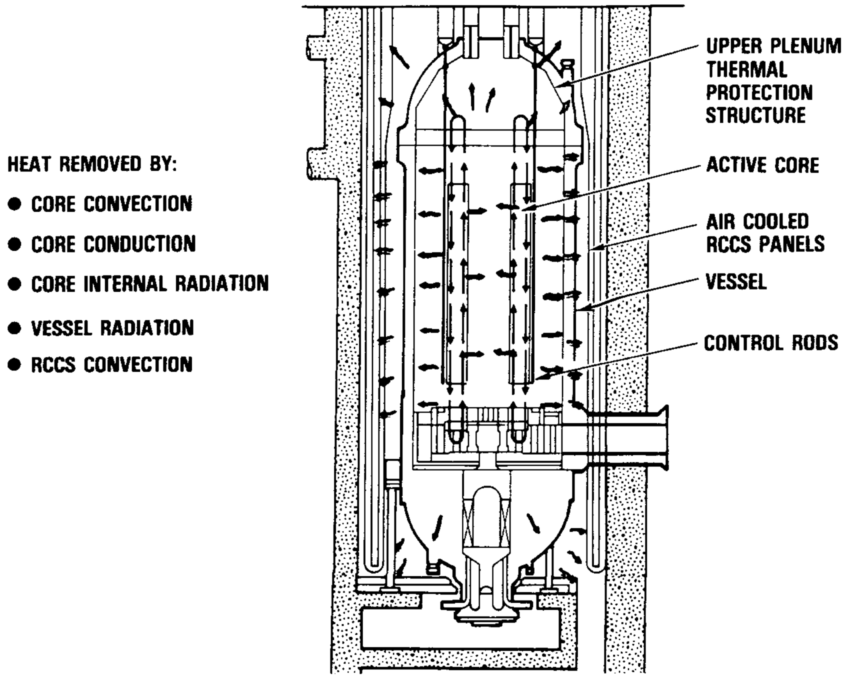

Fig. 5. MHTGR pressurized conduction cooldown heat flow paths

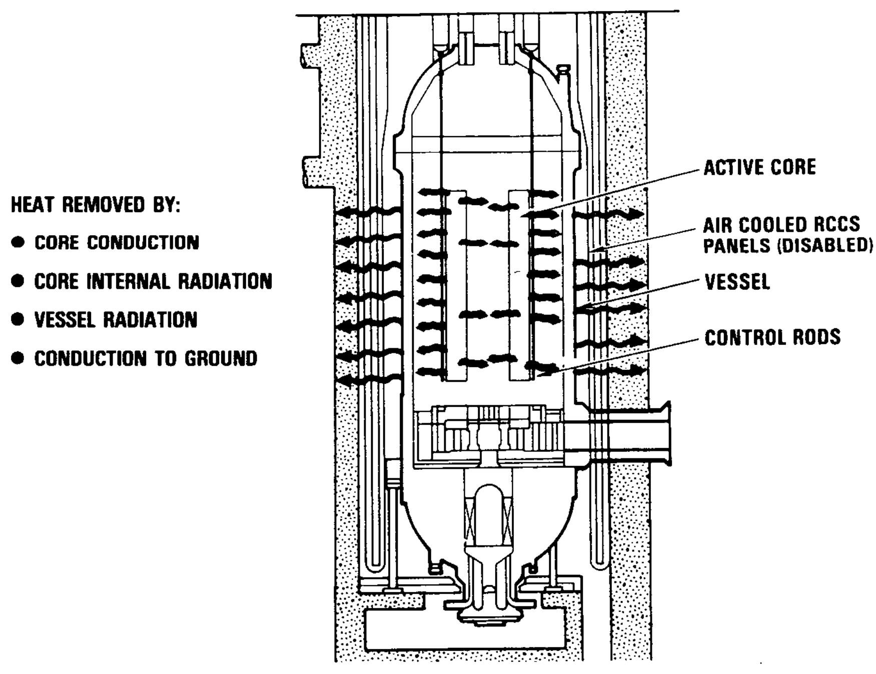

Fig. 6. Depressurized conduction cooldown heat flow paths

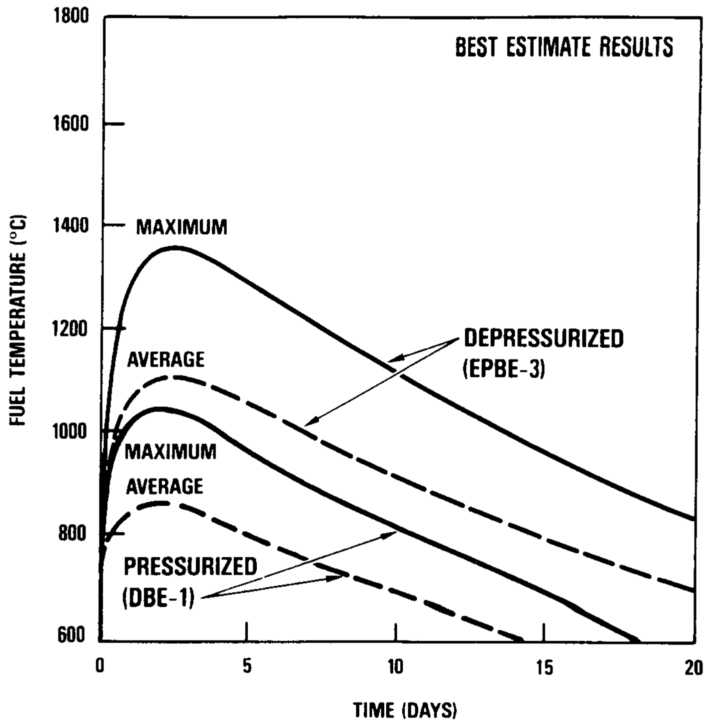

Fig. 7. MHTGR fuel temperatures (best estimate) with passive heat removal during loss of forced cooling

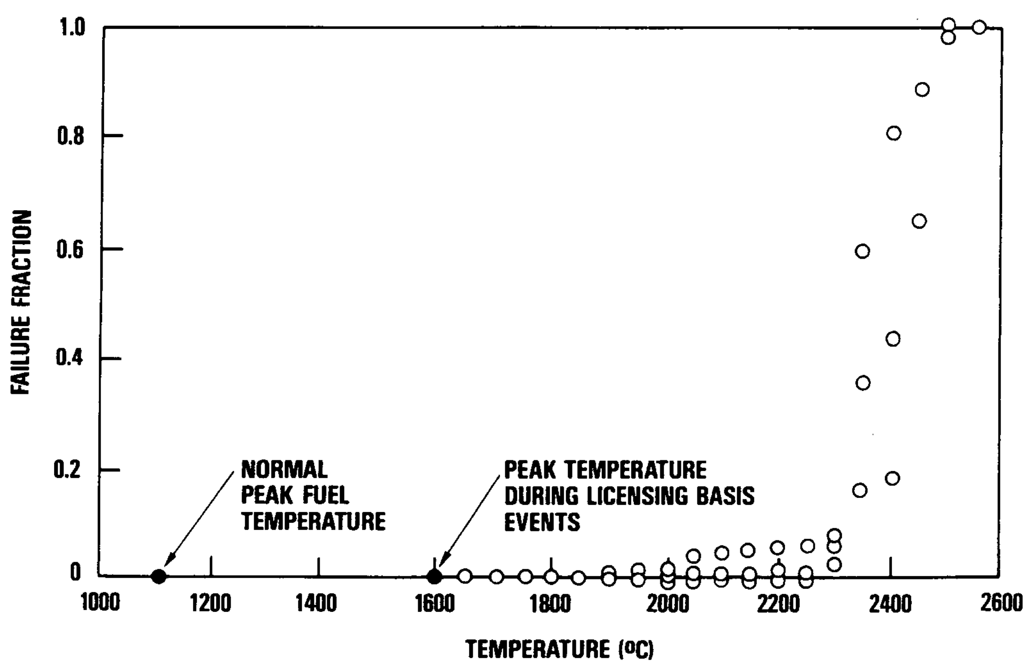

Fig. 8. Integrity of MHTGR coated fuel particles at high temperatures

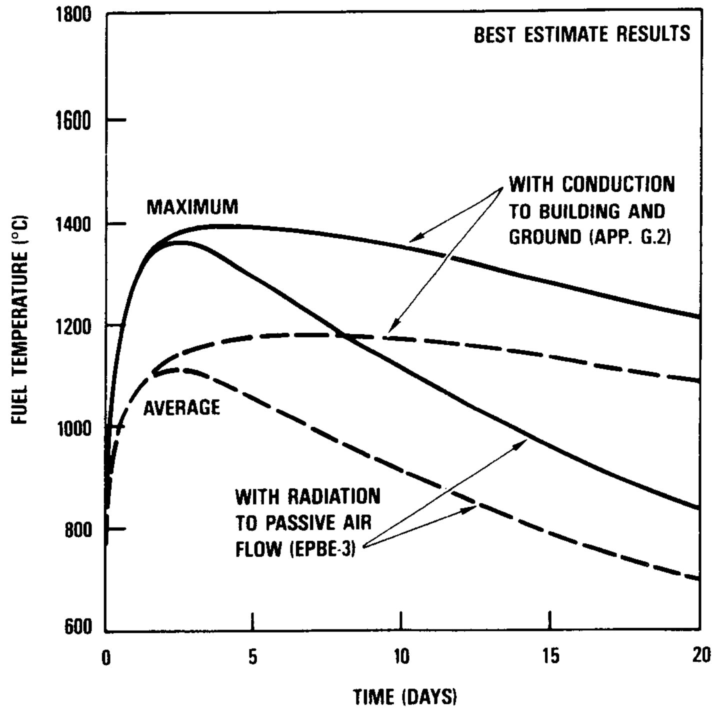

Fig. 9. MHTGR fuel temperatures (best estimate) during loss of forced cooling at depressurized conditions with and without the passive air cooling system

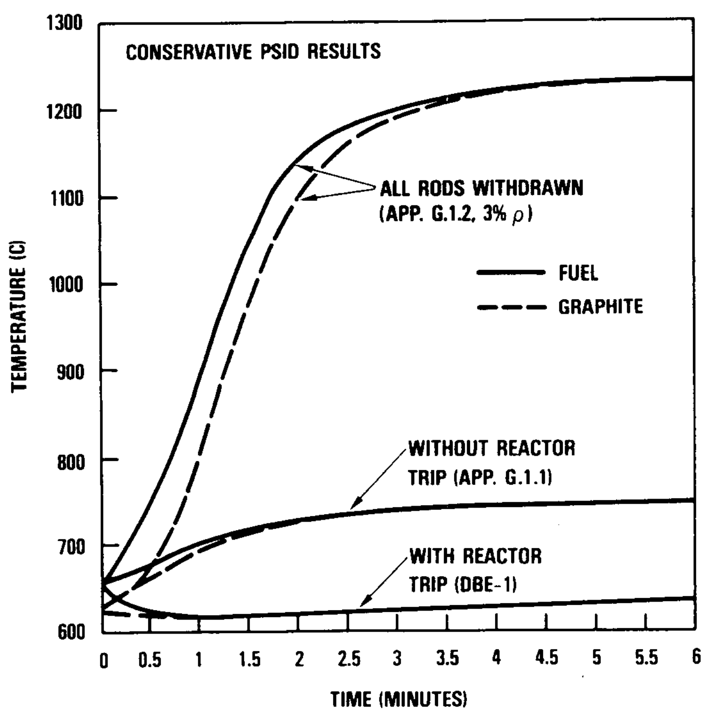

Fig. 10. Control of MHTGR fuel temperature by negative temperature coefficient during loss of forced cooling

temperatures above the average normal operating conditions and the silicon carbide coatings on the fuel itself. 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.

Figure 11 presents the time-dependent fraction of the core graphite oxidized for two LBEs and a very rare bounding event that challenge the control of chemical attack. In all cases, whether forced cooling is available or lost or whether one or more steam generator tubes fail, 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 due to 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 12 presents 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 operation actions, the safety evaluations are more transparent and need only consider the integrity of and natural behavior of the passive reactor materials not on the reliability of pumps, valves, and their associated services nor on 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 largely removing the man-machine interface from the safety discussion.

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 to the same three key functions discussed above. As shown in Fig. 13, the broad spectrum of events considered bounds potential operator errors. No events have been identified in which an action by the operator can defeat the natural behavior of the passive feature. Similar conclusions can be drawn for intentional, malevolent acts of sabotage as extreme as the willful destruction of the reactor vessel in a catastrophic fashion.

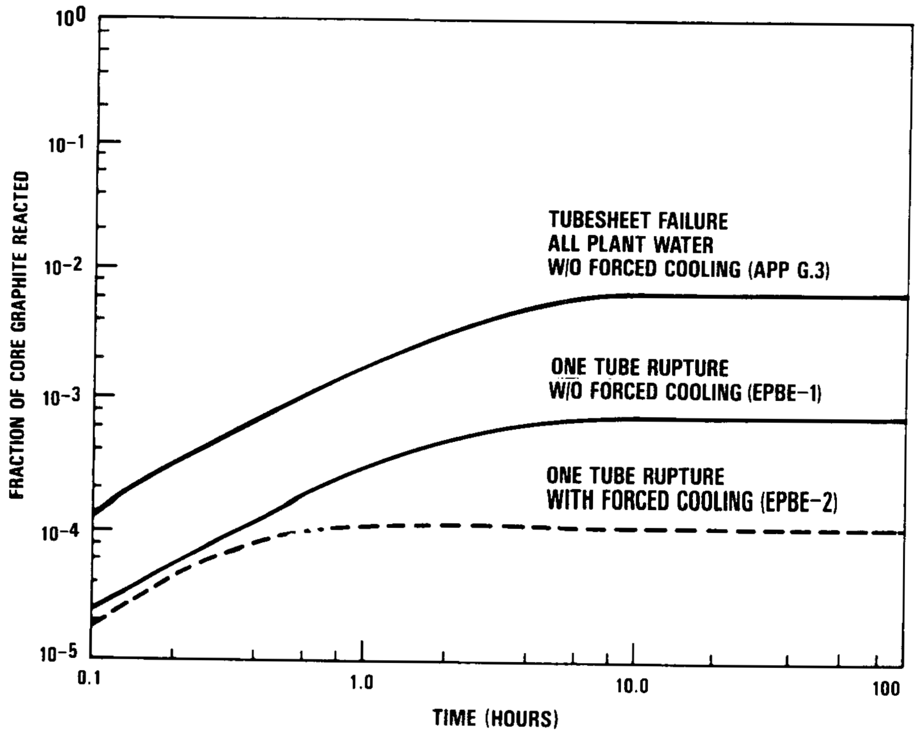

Fig. 11. Integrity assurance of MHTGR coated fuel particles during water ingress

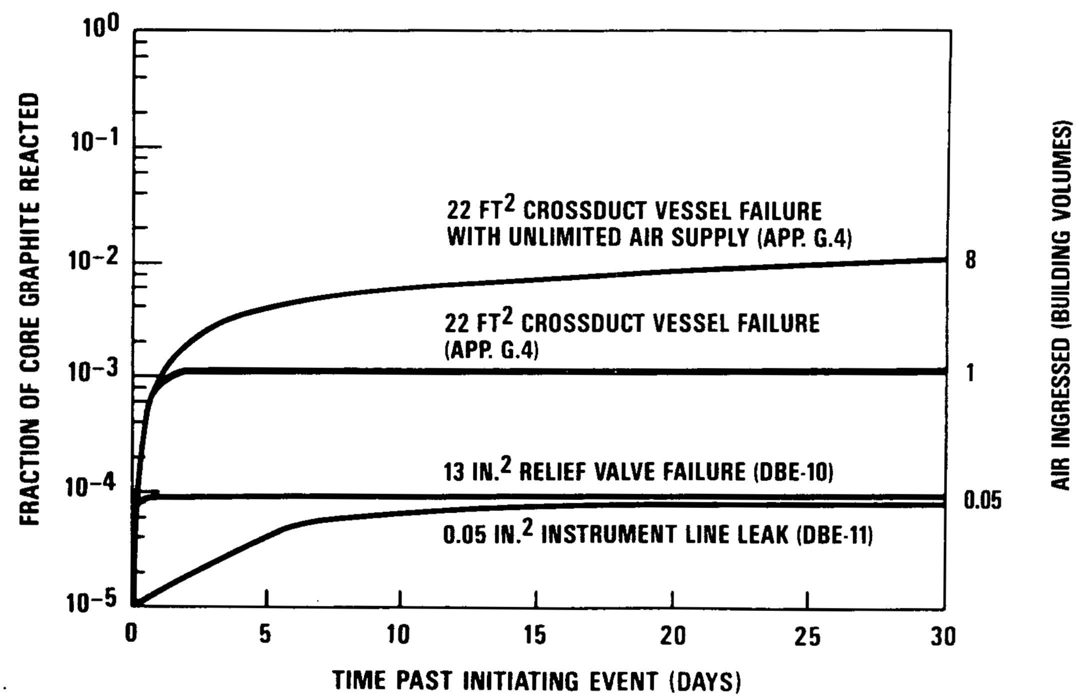

Fig. 12. Insignificant oxidation of MHTGR graphite limited by air mass transfer and core temperatures

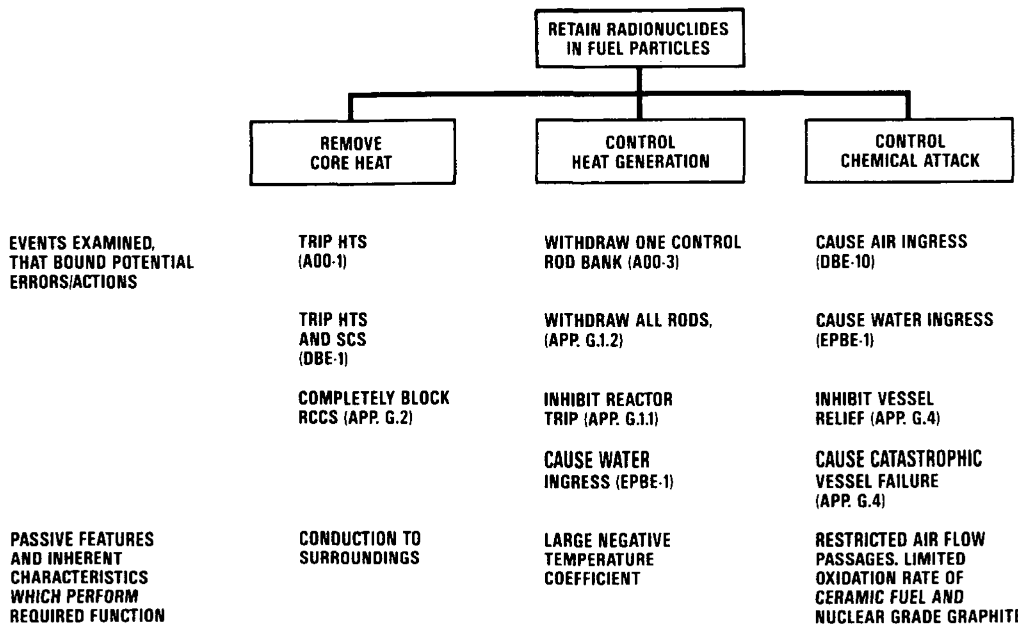

Fig. 13. Assessment of MHTGR sensitivity to operator errors and sabotage

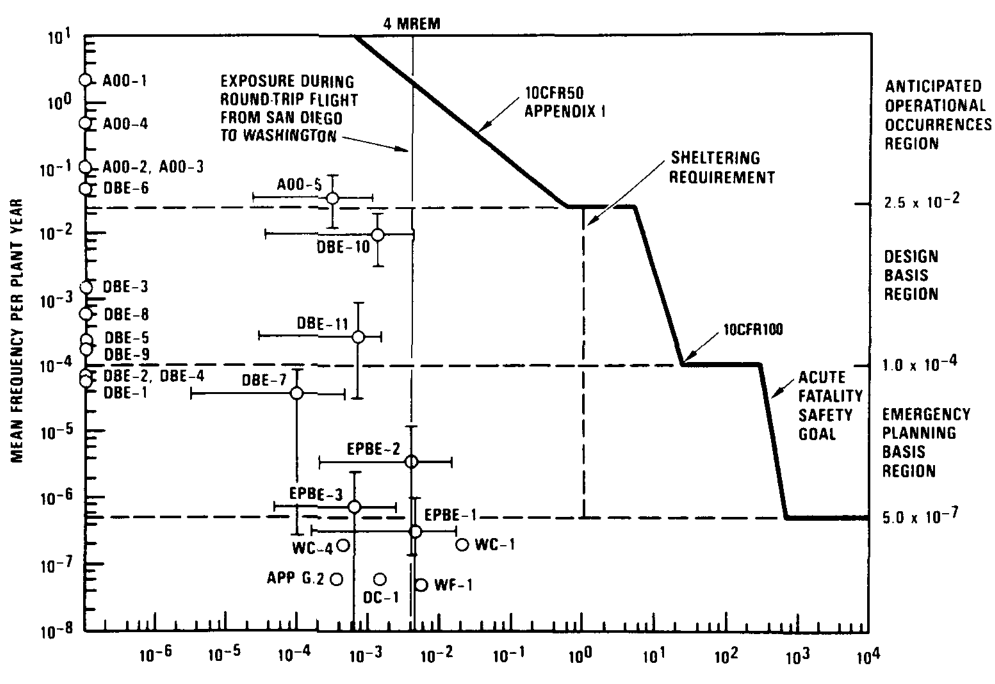

Fig. 14. Comparison of MHTGR risk to top-level safety requirements

The results of the PRA are depicted in Fig. 14 in comparison to the top safety criteria. As shown, 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 which include failure of active systems, operator errors of omission, and commission and acts of sabotage.

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