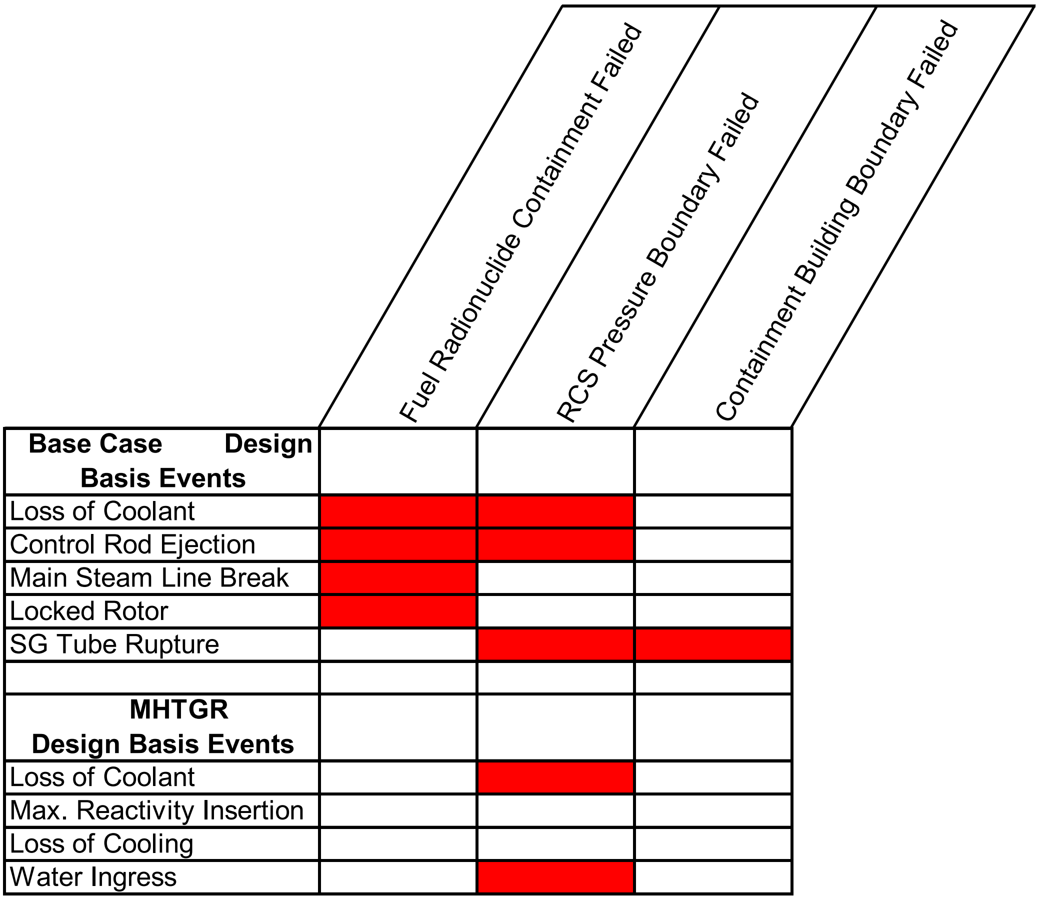
Appendix

COMPARISON BETWEEN THE SAFETY CHARACTERISTICS AND FEATURES OF WATER REACTORS AND THOSE OF MODULAR HIGH TEMPERATURE GAS COOLED REACTORS

As stated earlier, in the recommended process the requirements for a specific type of reactor (e.g. MHTGR) are to be generated through a critical interpretation of the ‘objectives’ and ‘essential means’ associated with each level of defence in depth (see Table 3.1) for the reactors upon which the existing requirements are based. This requires a full understanding of the safety characteristics and features of the specific type of reactor under consideration as well as those of the water reactors on which the existing requirements were based. The applicability of an existing requirement must then be determined by a comparative evaluation of the two types of reactors. The purpose of this appendix is to provide a summary comparison of MHTGR safety characteristics and features with those of water reactors. Nothing presented here should be interpreted as criticism of the safety case for existing water reactors. Their performance speaks for itself as they have demonstrated a very high level of safety over many thousands of reactors years of operation. The water reactor safety case has been based upon highly reliable active systems to maintain the system parameters within the required envelope at all times and to respond rapidly as warranted for specific event conditions. The MHTGR safety case utilizes the characteristics of HTGR fuel and core materials in conjunction with a passive design approach to avoid reliance on active systems, and thus takes a very different approach. Some of the key differences are summarized below, with representative characteristics from existing reactors upon which the current requirements are based referred to as the base case.

A.1. ALLOWED CONDITIONS WITHIN THE DESIGN BASIS

In the base case, fuel failure in the form of limited melting and/or cladding failure is allowed within the design basis, as long as a core geometry that is capable of being cooled is maintained. A comparison of allowed conditions within the design basis between the base case and MHTGR is shown in Fig. A.1. As shown in the figure, the combined effect of the initiating event and system response is allowed to fail two radionuclide containment boundaries in several events for the base case. MHTGR design practice has been to preclude failure of any barrier except that associated with the initiating event. This difference, in conjunction with the ineffectiveness of a typical LWR containment design for MHTGR conditions requires a different approach to radionuclide containment than has been used in the base case.

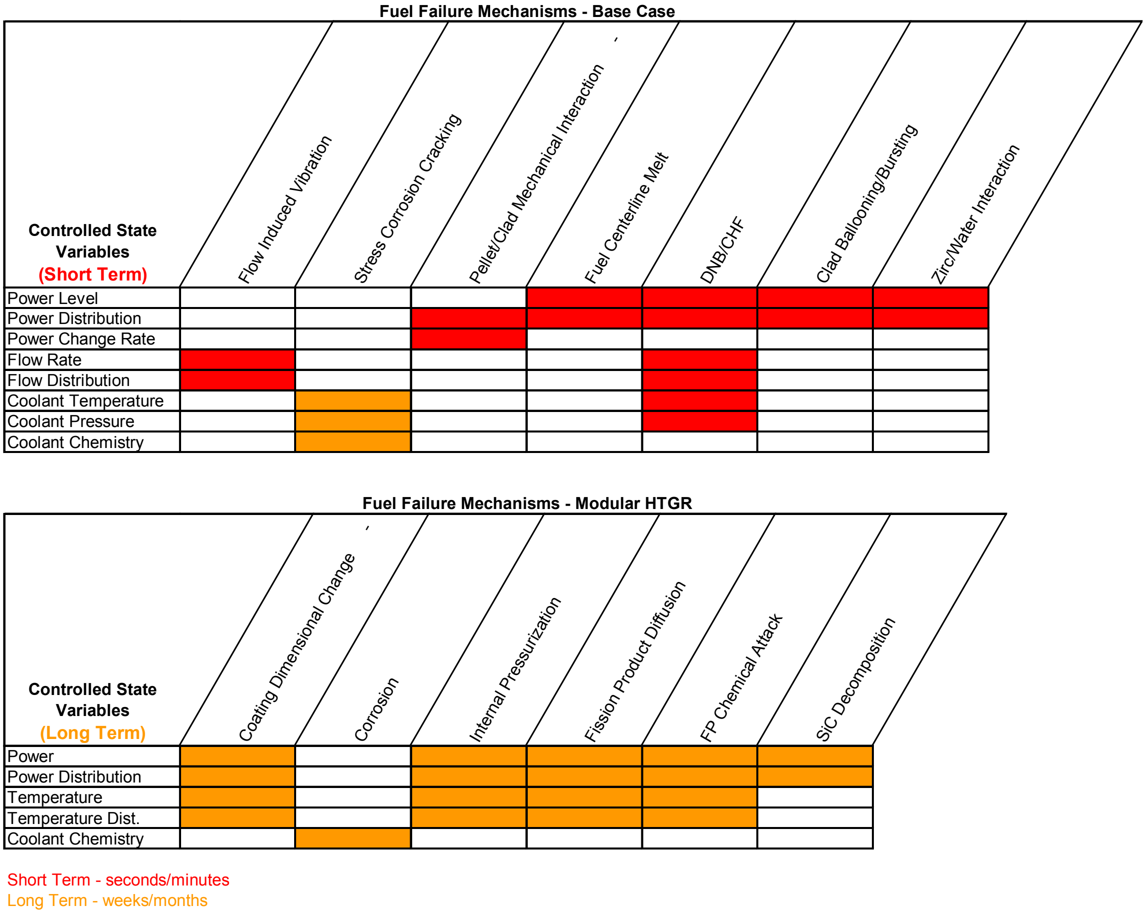


Base Case Design Basis Events	Fuel Radionuclide Containment Failed	RCS Pressure Boundary Failed	Containment Building Boundary Failed
Loss of Coolant	🟥	🟥	
Control Rod Ejection	🟥	🟥	
Main Steam Line Break	🟥		
Locked Rotor	🟥		
SG Tube Rupture		🟥	🟥
MHTGR Design Basis Events			
Loss of Coolant		🟥	
Max. Reactivity Insertion			
Loss of Cooling			
Water Ingress		🟥	

FIG. A.1. Table which compares the allowed conditions within the design basis for a water reactor and for an MHTGR.

A.2. FUEL FAILURE MECHANISMS

A comparison of fuel failure mechanisms for the base case and MHTGR is shown in Figure A.2. While there are a comparable number of mechanisms for fuel failure, there is a major difference with regard to the implications for safety, particularly with regard to the need for protection systems. As indicated in the figure, many of the mechanisms in the base case can cause fuel failure in the short term (seconds to minutes after the allowed envelope is exceeded). This leads to safety requirements for maintaining the allowed operating envelope on a moment-to-moment basis, and requirements for immediate response of mitigation systems. The last two mechanisms (clad ballooning/bursting and zirconium/water reaction) relate to loss of coolant accident conditions, where the residual fission and short term decay heat distribution is important and thus power level and power distribution just prior to the event are the primary operational state variables of interest. In the case of the MHTGR, the failure mechanisms are for the most part related to long term operational conditions of the fuel. In the case of a loss of coolant, the slow response results in reaching a peak temperature days after the initiation of the event, thus operational state variables in the short term prior to the event are of little importance from a safety standpoint. This is discussed further below.



Fuel Failure Mechanisms - Base Case

Controlled State Variables (Short Term)	Flow Induced Vibration	Stress Corrosion Cracking	Pellet/Clad Mechanical Interaction	Fuel Centerline Melt	DNB/CHF	Clad Ballooning/Bursting	Zirc/Water Interaction
Power Level				🟥	🟥	🟥	🟥
Power Distribution			🟥	🟥	🟥	🟥	🟥
Power Change Rate			🟥				
Flow Rate	🟥				🟥		
Flow Distribution	🟥				🟥		
Coolant Temperature		🟧			🟥		
Coolant Pressure		🟧			🟥		
Coolant Chemistry		🟧					

Fuel Failure Mechanisms - Modular HTGR

Controlled State Variables (Long Term)	Coating Dimensional Change	Corrosion	Internal Pressurization	Fission Product Diffusion	FP Chemical Attack	SiC Decomposition
Power	🟧		🟧	🟧	🟧	🟧
Power Distribution	🟧		🟧	🟧	🟧	🟧
Temperature	🟧		🟧	🟧	🟧	
Temperature Dist.	🟧		🟧	🟧	🟧	
Coolant Chemistry		🟧				

Short Term - seconds/minutes
Long Term - weeks/months

FIG. A.2. Table which compares fuel failure mechanisms for a water reactor and for an MHTGR.

A.3. CORE TEMPERATURE MARGINS AND THERMAL RESPONSE

The combined effects of large temperature margins and slow thermal response are a central safety aspect of MHTGR, allowing major simplification of the operational safety requirements. Figure A.3 illustrates typical margins to fuel structural limits for the base case in comparison to an MHTGR. In the base case, the structural limit is taken as the onset of rapid oxidation of the zircaloy cladding at approximately 1200ºC. The onset of cladding ballooning and bursting in the base case typically occurs at a lower temperature, but is a function of design specific internal pressurisation and cladding mechanical properties. The chemical decomposition of silicon carbide, which becomes important around 2200ºC was taken as the structural limit for the MHTGR fuel. As with the base case, other mechanisms such as diffusion of some fission products through the coatings begins at lower temperatures, affected by coating properties and fuel operating history. Note that the average fuel temperature in the reference case is higher than for the MHTGR even though the coolant temperature is considerably lower. This is due to the much higher power densities in the base case, which cause a large temperature rise across the cladding/fuel pellet gap and within the fuel pellet.

Typical margins to fuel melt limits are illustrated in Fig. A.4. The fuel melting temperature includes an allowance for a reduction of the melting point with fuel burnup. In the base case the design peak fuel temperature at full power is seen to be relatively close to the centreline melting limit. As with the fuel average temperature, the fuel maximum temperature is much higher for the base case due to the much higher power density. Protecting against this limit for the base case requires monitoring of power level and power distribution on a momentary basis. The large margins for the MHTGR are a primary reason that fuel melting is not a credible condition.

The full power core adiabatic heatup rate is a hypothetical figure of merit for comparing thermal response. It is the rate of increase in temperature that would occur if the reactor core were operated at full power with no heat removal. The values for the base case and a typical MHTGR, both with and without coolant present, are shown in Fig. A.5. The heatup rates for the base case are higher by between one and two orders of magnitude, depending on whether the coolant is present or not. The absence of the coolant has no significant effect on the response of the MHTGR. This difference, which is the combined result of the low power density and high heat capacity of the MHTGR, translates into a very slow response to conditions involving a mismatch between heat generation and removal. This characteristic, in conjunction with the large thermal margins and a limitation on rated thermal power, constitutes the essence of the passive safety characteristics of MHTGR.

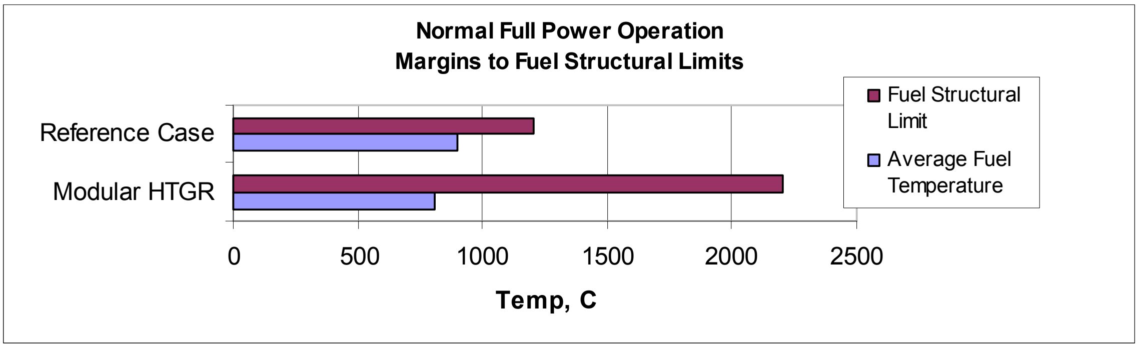


FIG. A.3. Comparison of margins to the structural limits for fuel for a water reactor and for an MHTGR.

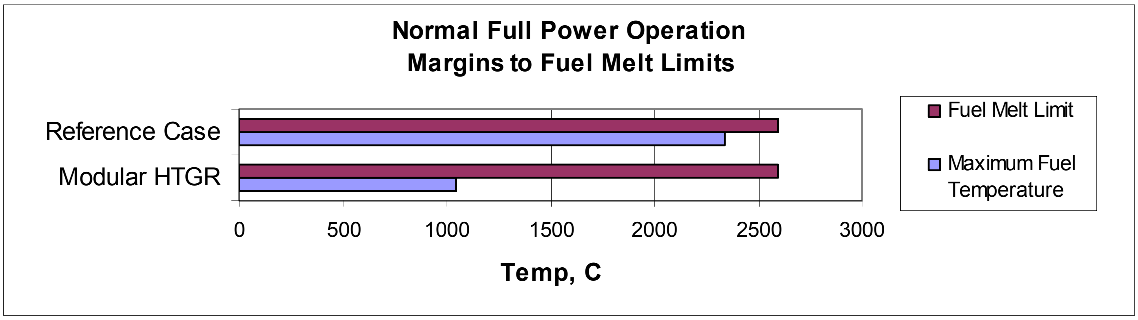


FIG. A.4. Comparison between the margins to the melt limits for fuel for a water reactor and for an MHTGR.

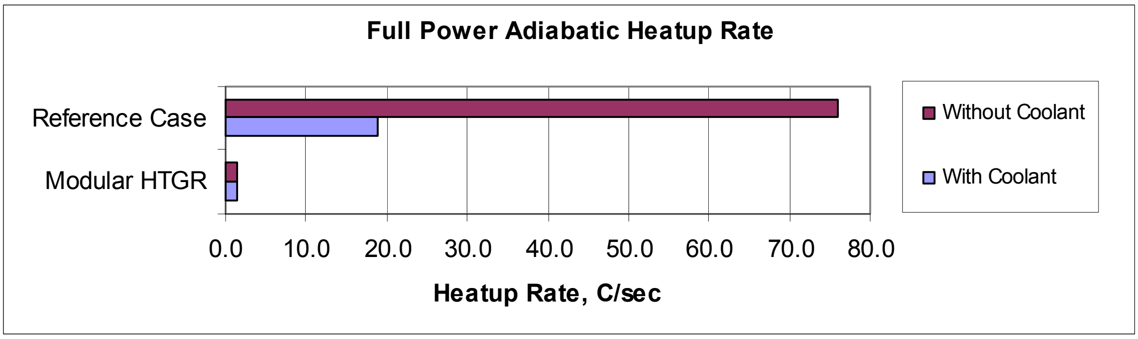


FIG. A.5. Comparison showing the full power, adiabatic heatup rates for a water reactor and for an MHTGR.

A.4. OPERATIONAL IMPLICATIONS OF SLOW THERMAL RESPONSE

The long slow thermal response and large thermal margins of MHTGR opens the possibility of major simplifications of operational safety requirements. For example, the peak temperature on a loss of coolant with sustained loss of active cooling systems is reached days after the initiation of the event. The temperature distributions of interest with regard to fuel performance during the event are determined by the heat transfer characteristics for heat removal through the walls of the reactor vessel, and thus are effectively decoupled from the temperature distribution in the core prior to the event.

In addition, the power distribution affecting the event temperature distribution is the distribution of the longterm decay heat. This is determined by the longterm core power distribution, and not significantly affected by the shortterm core power distribution prior to the event. This effect is illustrated in Figure A-6, which shows decay heat levels, as a function of duration of full power operation prior to shutdown, for several times after shutdown. The shortterm decay heat levels, of importance to the safety case for existing water reactors, are shown as the top set of curves. In this case levels approach equilibrium within minutes to hours of operation prior to shutdown, thus the decay power distribution is strongly influenced by the shortterm power distribution prior to shutdown. For the longterm decay heat of importance to the MHTGR safety case, days to weeks of operation are required to approach equilibrium, and the shortterm power distribution prior to shutdown has no significant effect.

The factors discussed above, in conjunction with the importance of controlling the integrated temperature, fluence and burnup history of the fuel, point to potential for a major simplification of operational safety requirements relative to existing water reactor plants. It is important to maintain the longterm core power and temperature distributions within an allowed envelope, but shortterm operational variations may be shown to be of no safety significance. Thus time compensated control and protection systems with restrictive requirements on accuracy and response times and resulting surveillance requirements typical of existing water reactors may be eliminated.

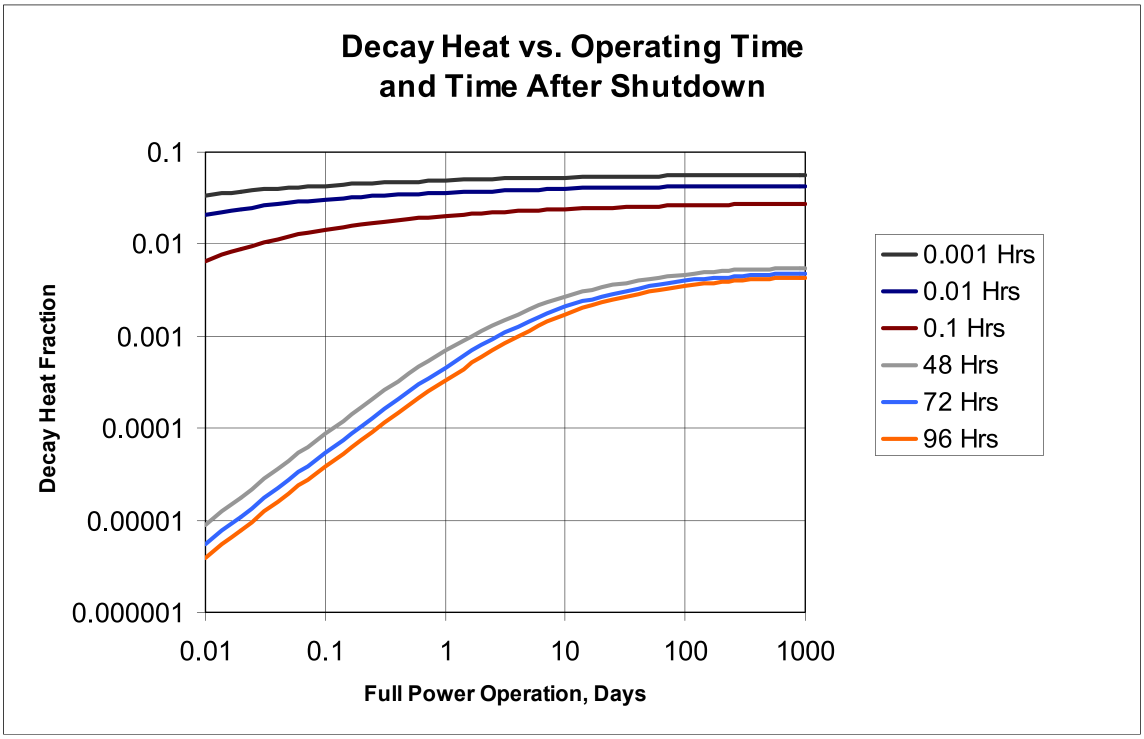


FIG. A.6. Comparison between the decay heat characteristic of importance to safety for water reactors (top set of curves) and for an MHTGCR (bottom set of curves).