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MHTGR LICENSING APPROACH AND PLANT RESPONSE TO OFF NORMAL EVENTS

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MHTGR LICENSING APPROACH AND PLANT RESPONSE TO OFF NORMAL EVENTS

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ABSTRACT

The MHTGR design meets stringent top-level regulatory and user safety requirements that require that the normal and off-normal operation of the plant not disturb the public's day-to-day activities. Quantitative, generic top-level regulatory criteria have been specified from US NRC and EPA sources to guide the design. The user has further specified that these be met at the plant boundary. A probabilistic risk assessment has been utilized to select licensing basis events that cover a wide spectrum of events. The events have been grouped into three frequency regimes governed by the 10CFR50 App. I, 10CFR100, and PAG risk and dose criteria.

The MHTGR fuel has been designed to limit the primary circuit activities to levels that, even if completely released, are within those allowed by 10CFR100. The focus of the safety approach has then been centered on retaining the radionuclide inventory within the fuel by removing core heat, controlling chemical attack, and by controlling heat generation. The core geometry, core power, core power density, heat removal geometry, and heat sinks are designed to provide passive core temperatures during accidents. To limit the potential for chemical attack of the MHTGR core, the primary coolant boundary is designed to make large ingress of air and water very unlikely. Furthermore, the fuel particle coatings are highly impervious to oxidizing agents that do enter the primary coolant. The core heat generation is controlled by the large negative temperature coefficient and by insertion of control material to maintain a subcritical core configuration during the span of the accidents. Thus, the three key safety functions have been accomplished by relying on the inherent characteristics of the MHTGR so that the response is largely passive and relatively simple.

ACKNOWLEDGEMENTS

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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 Plant Operation, 2) Maintain Plant Protection, 3) Maintain Control of Radionuclide Release, and 4) Maintain Emergency Preparedness.

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 by retention of radionuclides within the fuel particles with minimal reliance on active design features or operator 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 (especially in the selection of core size and geometry, power density, and vessel type); the basis for each element is described below.

First, the philosophy requires that control of radionuclides be accomplished with minimal reliance on active systems or operator 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. Arguments 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 by the retention of radionuclides within the coated fuel particle rather than reliance on secondary barriers (such as the primary coolant boundary or the reactor building). Proof of containment is dramatically simplified if arguments can center on issues associated with fuel particle coating integrity alone.

TOP-LEVEL REGULATORY CRITERIA AND USER SAFETY REQUIREMENTS

Top-level criteria and requirements are defined primarily 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 (Ref. 2, 3). The top-level regulatory criteria are the basis for plant licensability with the Preliminary Safety Information Document (PSID) and the Probabilistic Risk Assessment (PRA) presenting how the design meets these criteria.

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.

2. Top-level regulatory criteria should be independent of reactor type and site.

3. Top-level regulatory criteria should be quantifiable.

The first basis ensures that the criteria are fundamental to the protection of the public and the environment. The second, consistent with the first, requires that the criteria be stated in terms which do not discriminate among reactor types and sites. Finally, the third basis ensures that compliance with the selected criteria can be demonstrated through measurement or calculation.

Through comparison with the selection bases, the following regulatory sources have been found to contain numerically-expressed criteria or limits which appropriately form top-level regulatory criteria.

1. 51 FR 28044 - 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 numerical consequence or risk values contained within the above regulatory sources are the top-level regulatory criteria for the MHTGR (Ref. 1).

The utility/user group has specified an additional safety requirement (Ref. 2) 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 16000 m (10 miles) for US 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, 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 EPA Protective Action Guidelines (PAGs) of 5 rem thyroid and 1 rem whole body doses evaluated at the 425 m.

LICENSING BASIS EVENTS

For the purpose of deriving the regulatory licensing bases of the MHTGR, 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 US regulatory process. Licensing basis events are used to demonstrate compliance with dose criteria for a spectrum of off-normal events.

For the MHTGR, selection of licensing basis events (LBEs) is based on the probabilistic risk assessment. The use of the 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.

The initial step in the selection of LBEs is to establish a frequency-consequence risk plot defining three regions bounded in frequency by three agreed-upon mean frequencies and in consequence, by allocated dose limits related to 10CFR50 Appendix I, 10CFR100, or the PAGs. Figure 1 provides this plot as established for the MHTGR.

Those families of events in the PRA having the potential for radionuclide releases or consequences in excess of those allowed by the top-level regulatory criteria were it not for design selections that function to control the release of radionuclides are those selected as LBEs. Depending upon their predicted frequency, the selected events are encompassed by 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 PSID 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 which might occur in a large population of MHTGRs (approximately 200). The families of events selected as DBEs at this stage in the MHTGR design are listed in Table 1. These DBEs are evaluated conservatively in the PSID 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).

PLANT RESPONSE TO OFF-NORMAL EVENTS

As an introduction to the plant response to off normal events an illustration of the MHTGR safety characteristics is made. To do this, the available fission product inventory is compared to the allowable activity release from the plant that would satisfy the long-term 10CFR100 and PAG thyroid dose limits. To keep the example simple, only the dominant contributor, I-131, is considered. The allowables for I-131 release are obtained from the dose limits using a conservative USNRC Regulatory Guide 1.4 weather dispersion factor. The result is an allowable I-131 release of 250 Ci and 8 Ci for the 10CFR100 and PAG thyroid doses of 150 and 5 rem, respectively.

In comparison, the MHTGR fission product inventories of I-131 are given below for an equilibrium core:

	Location	Maximum Expected I-131 Inventories (Ci)
Core	Within fuel particles	9.0×10^6
Vessels	Plateout in circuit	20
	Circulating	0.018

As shown above even if all of the plateout and circulating activity is released, the total release is an order of magnitude lower than the 10CFR100 limits. Therefore, the safety approach is focused logically on limiting the fractional release from fuel particles to less than 3×10^{-5} (250 divided by 9×10^6) and to less than 1×10^{-6} (8 divided by 9×10^6) for the 10CFR100 and PAG doses, respectively.

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. Three functions have been identified which, when accomplished, assure that radionuclide retention within the fuel remains acceptable:

1. Remove core heat
2. Control chemical attack
3. Control heat generation

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 one of which can, and in certain LBEs do, perform the function of removing core heat. However, while this multiplicity of systems capable of performing these functions 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 and the fractional release from the fuel.

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 the passive cooling pathway from the core to the environment. Figure 2 presents the temperature transients for two DBEs, 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 Figure 3 the fuel must exceed approximately 2100°C before thermal decomposition of the silicon carbide coating results in significant failure. The normal peak fuel temperature is much lower at 1100°C.

Therefore, in the case of the depressurized conduction cooldown DBE, the release of I-131 from the fuel particles is limited by the passive heat removal to 2×10^{-5} of the fuel inventory. This fraction is further reduced to 6×10^{-6} since the release is slow so that the overall release fraction considering only fuel retention meets the 3×10^{-5} 10CFR100 allowable. Additional passive retention mechanisms within the vessel and building reduce this further to 6×10^{-10}, thereby also easily meeting the 1×10^{-6} PAG allowable.

Control Chemical Attack

The inherent features for controlling chemical attack of the fuel by water include the non-reacting cooling, a water-graphite reaction that is endothermic and requires 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 core cooling systems.

The high quality of the fuel particle coatings limits the I-131 inventory available for release due to water chemical attack for any LBE to those particles with initially failed particles (from either in-service failure or manufacturing defects). The fraction available is 2×10^{-4} of the full inventory. This is further reduced by a factor of .015 since not all the iodine will be released if the fuel kernel is hydrolyzed. The total retention due to the fuel is then 3×10^{-6}, meeting the 3×10^{-5} 10CFR100 allowable. Other additional retention mechanisms limit I-131 release by limiting the amount of water entering the core and by retention in the vessel and surrounding buildings to give an overall release fraction of 6×10^{-8}, which meets the 1×10^{-6} PAG allowable.

The inherent features for controlling chemical attack of the fuel by air include the non-reacting coolant, the embedded ceramic fuel particles, the nuclear grade vessel, and the below grade vessel silo. Figure 4 presents the fraction of the core graphite reacted for two sizes of primary coolant leaks without forced core cooling (one DBE and one EPBE) considering the amount of air available in the reactor cavity silo. As shown the fraction reacted is less than 10^{-4} of the core. No oxidation of the embedded fuel particles is predicted for any LBE.

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 and large thermal margins. These inherent characteristics cause the reactor to inherently shutdown. As shown in Fig. 5 for a pressurized conduction cooldown without any control insertion, fuel temperatures remain low. 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. The reactivity systems can maintain the core subcritical with margin for the maximum water ingress.

In conclusion, the passive safety features of the design prevent and mitigate radionuclide release over a wide spectrum of off-normal events. Preliminary analysis has shown that for the release mechanisms and the associated severe accidents considered, the regulatory and user criteria can be met by relying largely on the HTGR fuel performance attributes. Attenuation of release by other barriers such as the reactor vessel and reactor building provides additional margin in meeting the 10CFR100 and PAG dose requirements.

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2. U.S. Department of Energy. Top-Level Regulatory Criteria for the Standard HTGR. HTGR-85-002, Rev. 1, June 1985.

3. Gas-Cooled Reactor Associates. Utility/User Requirements for the Modular High Temperature Gas-Cooled Reactor Plant. GCRA 86-002, Rev. 1, March 1986.

4. U.S. Nuclear Regulatory Commission. Safety Goals for the Operation of Nuclear Power Plants; Policy Statement. Federal Register, Vol. 51, No. 149, August 4, 1986, pp. 28044-28049.

TABLE 1
MHTGR DESIGN BASIS EVENTS

Design Basis Event
Loss of forced core cooling
Main loop transient without control rod trip
Control rod withdrawal without main loop cooling
Control rod withdrawal without forced core cooling
Earthquake
Moisture inleakage
Moisture inleakage without forced core cooling
Moisture inleakage with moisture monitor failure
Moisture inleakage with steam generator dump failure
Primary coolant leak
Primary coolant leak without forced core cooling

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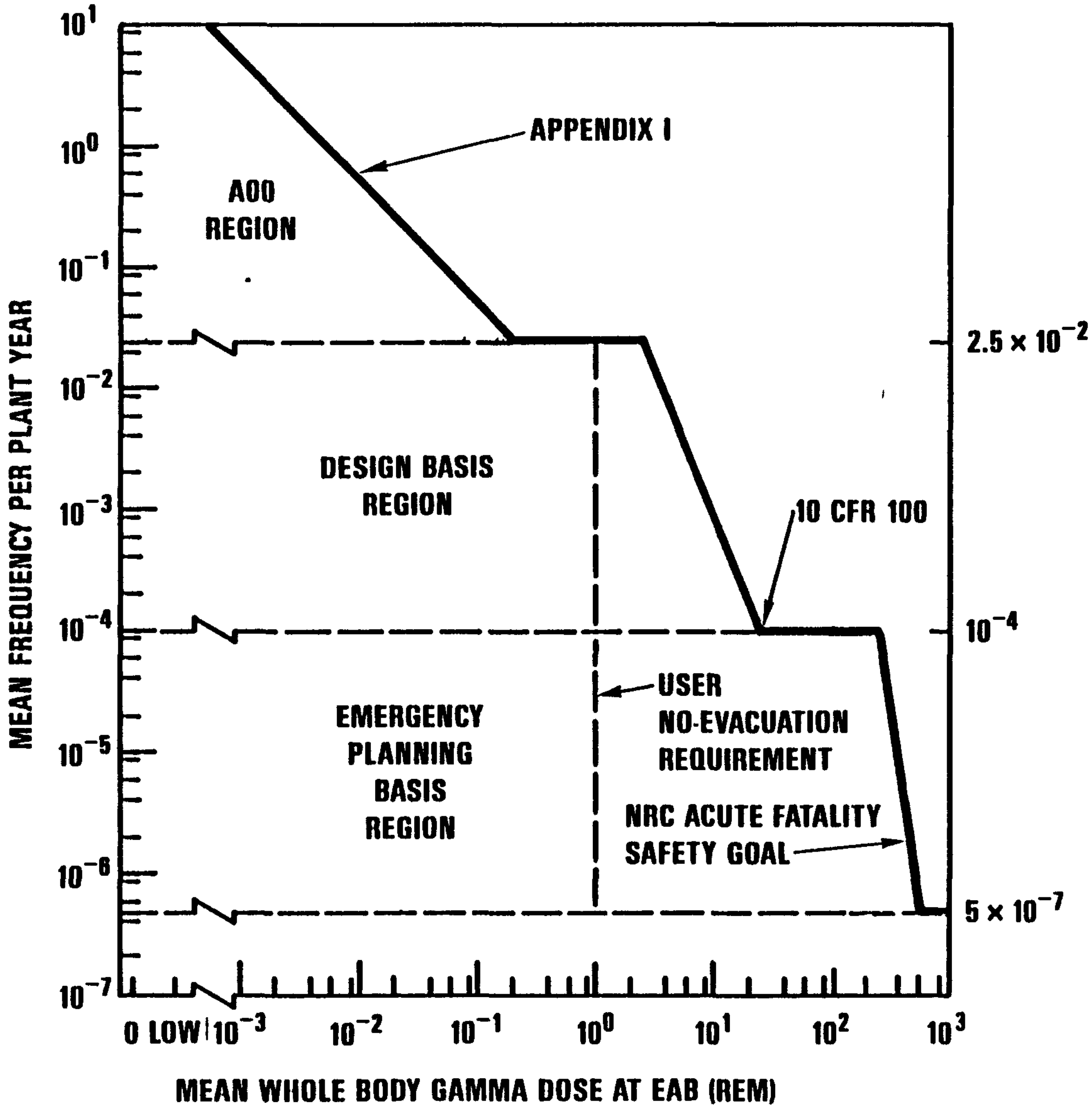
LICENSING BASIS REGIONS



H-775(1)
9-3-86

FIGURE 1

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350 MW(t) TRANSIENTS DURING DEPRESSURIZED AND PRESSURIZED CONDUCTION COOLDOWN

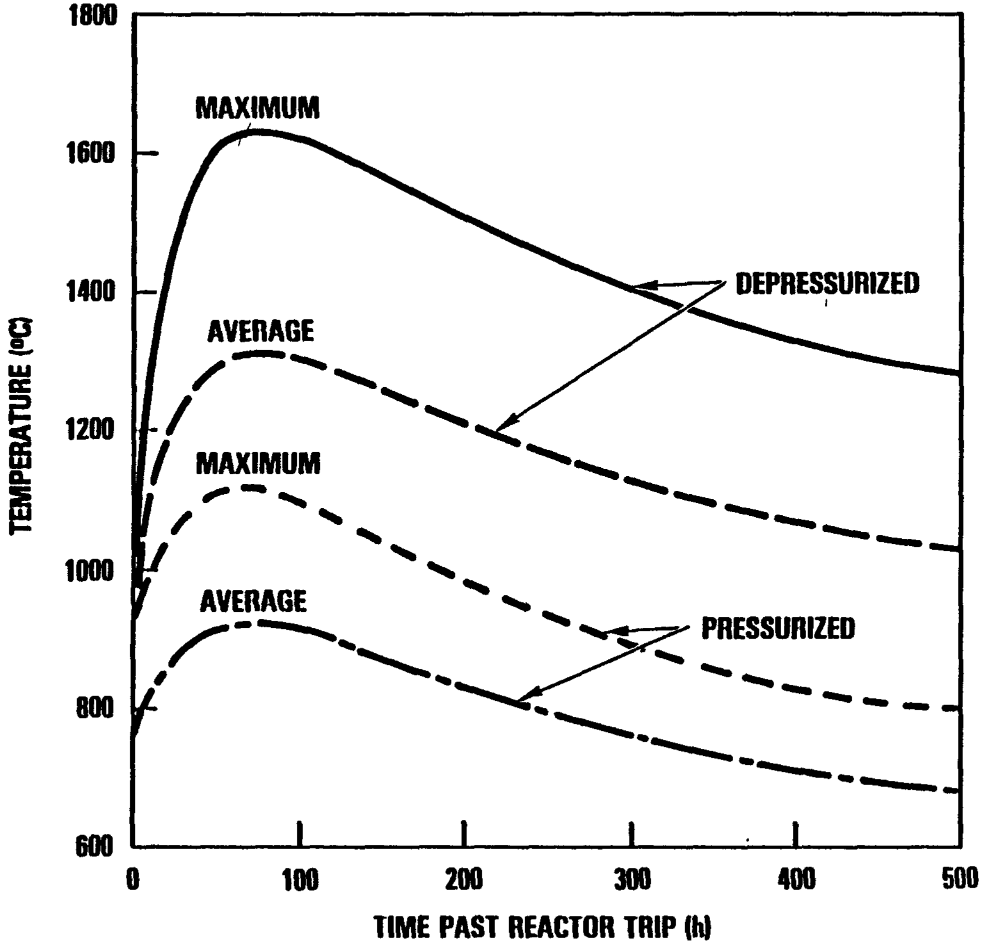

FIGURE 2

H-534(1)
2-7-86

COATED FUEL PARTICLES MAINTAIN INTEGRITY AT HIGH TEMPERATURES

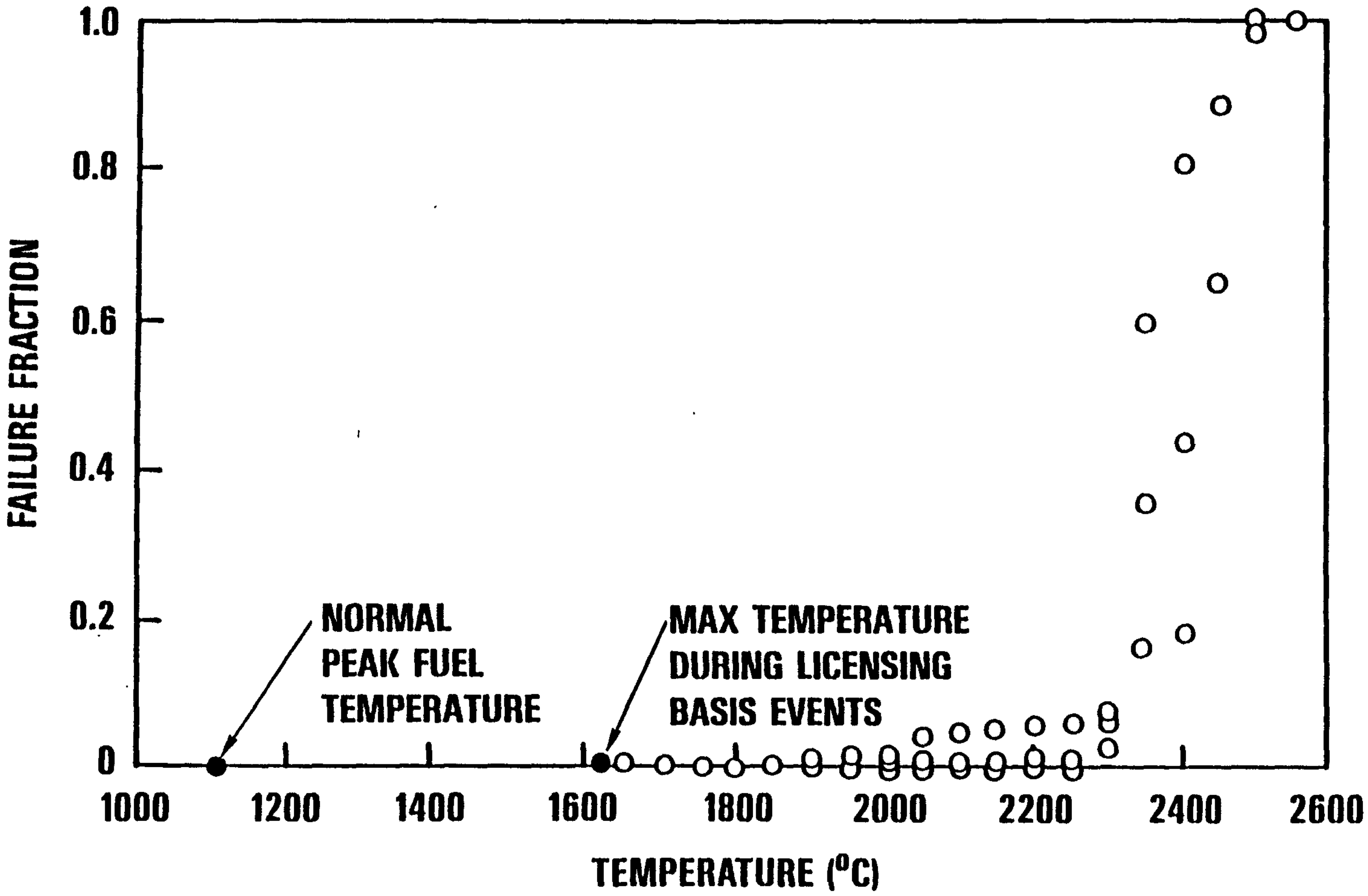

FIGURE 3

H-293(4)
7-11-85

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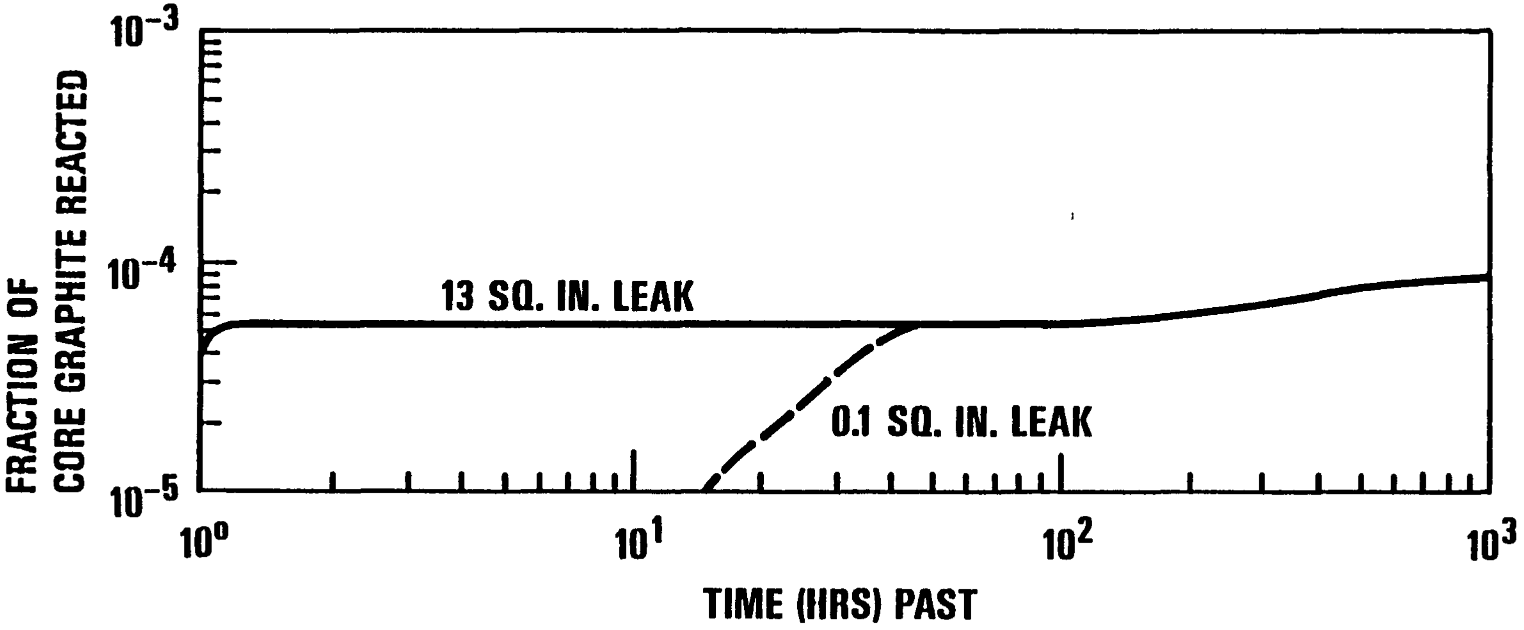
LIMITED AIR-GRAPHITE REACTION RETAINS RADIONUCLIDES IN CORE



PRIMARY COOLANT LEAK LEADING TO CONDUCTION COOLDOWN

FIGURE 4

H-558(11)
3-7-86

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ACCEPTABLE PRESSURIZED CONDUCTION COOLDOWN TEMPERATURES WITH AND WITHOUT REACTOR TRIP

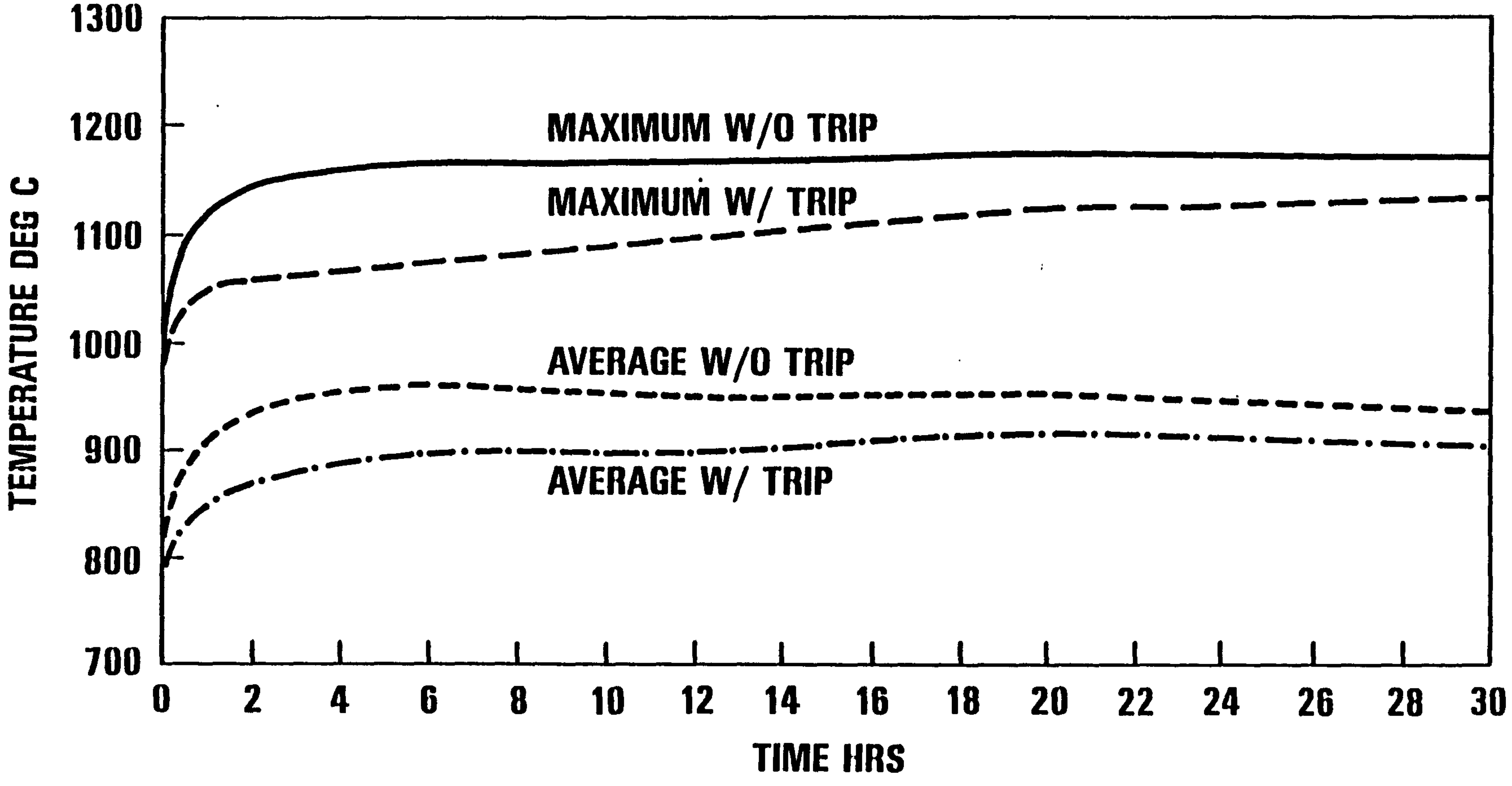

FIGURE 5

H-558(2)
3-7-86