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PASSIVE SAFETY OF THE STAR-LM HLMC NATURAL CONVECTION REACTOR

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ABSTRACT

The STAR-LM 300 to 400 MWt class modular, factory fabricated, fully transportable, proliferation resistant, autonomous, reactor system achieves passive safety by taking advantage of the intrinsic benefits of inert lead-bismuth eutectic heavy liquid metal coolant, 100+% natural circulation heat transport, a fast neutron spectrum core utilizing high thermal conductivity transuranic nitride fuel, redundant passive air cooling of the outside of the guard/containment vessel driven by natural circulation, and seismic isolation where required by site conditions.

Postulated loss-of-heat sink without scram, overcooling without scram, and unprotected transient overpower accidents are analyzed for the 300 MWt STAR-LM design using a coupled thermal hydraulics-neutron kinetics plant dynamics analysis computer code. In all cases, STAR-LM is calculated to exhibit passive safety with peak cladding and coolant temperatures remaining within the existing database for lead-bismuth eutectic coolant and ferritic steel core materials.

INTRODUCTION

The Secure Transportable Autonomous Reactor-Liquid Metal (STAR-LM) is a modular, factory-fabricated, overland transportable, proliferation-resistant, autonomous load following, and passively safe reactor concept having the potential to meet all of the United States Department of Energy Generation IV goals of sustainable energy development, safety and reliability, and economics. STAR-LM takes advantage of the intrinsic properties of a fast neutron spectrum core utilizing high thermal conductivity transuranic nitride fuel, inert lead-bismuth eutectic (LBE) coolant, 100+% natural circulation heat transport (i.e., natural circulation is capable of removing more than 100 percent of the nominal core power), natural circulation vessel air cooling, and seismic isolation to realistically achieve radical design simplification, greater reliability, cost savings, and enhanced passive safety. STAR-LM was originally developed to meet a criterion of 300 MWt power.[1,2] The original concept is robust; increase in the core power from a single small size module to 400 MWt is described in a companion paper.[3]

The main purpose of the present work is to investigate and demonstrate the passive safety features of STAR-LM for a representative set of postulated accidents using a coupled thermal hydraulics-neutron kinetics plant dynamics analysis computer code.

PASSIVE SAFETY FEATURES OF STAR-LM

Realization and enhancement of passive safety of STAR-LM involves the following.

Heavy Liquid Metal Coolant. STAR-LM takes advantage of the intrinsic properties of lead-bismuth eutectic (55 wt% Bi-45 wt% Pb; T_{melt} = 125 °C; T_{boil} = 1670 °C) heavy liquid metal coolant.[4] Lead-bismuth eutectic (LBE) does not interact vigorously or exothermically with water or steam; LBE coolant does not burn when exposed to air. This behavior eliminates an entire class of events associated with metal-water reactions that have had to be addressed with sodium-cooled reactors. The need for an intermediate heat transport circuit required with sodium cooled systems is eliminated. Elimination of an intermediate heat transport system eliminates a whole class of failures that would otherwise need to be considered in a risk assessment. Modular steam generators are directly immersed inside the primary coolant in a pool-type configuration to produce superheated steam.

The high boiling temperature of LBE facilitates operation of a low pressure system at high temperatures and essentially eliminates the entire class of events involving coolant void formation due to coolant overheating that have been encountered for certain sodium-cooled reactor designs.

The high density of the heavy liquid metal coolant (10200 Kg/m^3) together with the provision of an escape path for vapor between the coolant module vessel and an inner cylindrical liner mitigates the effects of a steam generator tube rupture event. A postulated steam generator tube rupture accident was analyzed[5] to assess if a significant amount of steam void could be transported into the core. It was concluded that the high coolant density retards and limits void growth resulting from the blowdown of steam into the LBE coolant such that the large bubble formed at the bottom of the affected steam generator tube would break up into smaller bubbles most, if not all, of which would rise benignly to the cover gas through the coolant module vessel-liner gap without being swept into the core.[5]

100+% Natural Circulation Heat Transport. The low power density core facilitates heat removal by the LBE coolant through large hydraulic diameter coolant channels reducing the core pressure drop such that more than 400 MWt can be transported from the core to the steam generator by natural circulation of the primary coolant.[3,6] Elimination of main circulation pumps eliminates an entire class of accidents involving reduction/loss of forced flow that would otherwise need to be addressed in a risk assessment and enhances simplification, reliability, economics, and passive safety. The core design features an open core without individual subassemblies; accidents involving blockage of a subassembly have been eliminated.

Fast Neutron Spectrum Core. The fast spectrum core with transuranic nitride fuel and LBE coolant provides strong negative reactivity feedbacks[7,8] that enable autonomous load following[9] and passive accident termination by inherent core power shutdown.[10]

Reactor Exterior Cooling System (RECS). Redundant passive heat removal is provided by cooling the outside of the guard/containment vessel with air driven by natural circulation, in the event that all of the modular steam generators are unavailable for heat removal. Reactor afterheat is passively removed to the inexhaustible atmospheric air heat sink.

The RECS incorporates removable steel block venetian conductors that provide a steel conduction path between the coolant module and guard vessels eliminating the significant thermal resistance across a gaseous gap inherent in traditional reactor vessel air cooling systems.[2,11]

Seismic Isolation. A nuclear island containing the modular reactor system, steam and feedwater piping, RECS, and containment volume is supported by seismic isolators eliminating concerns about seismic and pool sloshing-related loads where required by site conditions. An analysis has been carried out to determine the required number and type of isolators.[12] It was concluded that seven pairs of three-dimensional isolators provide sufficient isolation. Code calculations demonstrate that the isolators reduce the vertical floor acceleration at the upper basemat from 0.8 to 0.3 g and the horizontal acceleration from 1.2 to 0.2 g during a 0.3 g horizontal/0.2 g vertical Safe Shutdown Earthquake.[12]

ANALYSIS OF ACCIDENT SCENARIOS

To quantify the passive safety of STAR-LM, calculations have been carried out of the response of the 300 MWt STAR-LM reactor to postulated accident scenarios. For this purpose, a new, coupled, transient, thermal hydraulic-neutron kinetics, plant dynamics analysis computer code was developed that can efficiently calculate conditions involving pure natural circulation as well as recriticality from zero or very low fission power. The code is named THSTAR (Thermal Hydraulics for System Transient Analysis of Reactors). The LBE coolant and steel structures are represented with control volumes; one dimensional flow is modeled through each coolant control volume. The nodalization employed for STAR-LM is shown in Figure 1. The complete secondary side is not modeled in the analysis. A detailed steam generator model is incorporated in which the remainder of the secondary side is represented by a specified time dependent pressure as well as feedwater flowrate and temperature. Reactor core kinetics is calculated using the TSPK point kinetics module from the SAS4A/SASSYS computer code.[13]

All steel structures are modeled with thermophysical properties for HT9 alloy. Reactivity feedback kinetics coefficients are shown in Table 1. Reactivity feedbacks from the Doppler effect and fuel axial expansion are modeled as the respective reactivity coefficients times the difference in the current time dependent and initial mean fuel temperatures. Feedbacks from the effects of changing coolant density and core radial expansion are similarly calculated in terms of the feedback coefficients times the difference in the current time dependent and initial mean value of the core coolant outlet and inlet temperatures. The radial expansion coefficient (Table 1) corresponds to linear thermal expansion of HT9 spacer grids that expand and increase the separation between fuel rods as the coolant temperature rises.

Table 1. Neutron Kinetics Reactivity Feedback Coefficients Assumed in Analysis.

Delayed Neutron Fraction	3.10×10^{-3}
Prompt Neutron Lifetime, s	5.74×10^{-7}
Coolant Density Feedback, cents/°C	0.294
Doppler Feedback, cents/°C	-0.182
Axial Expansion Feedback, cents/°C	-0.0452
Radial Expansion Feedback, cents/°C	-0.156

All analyses model autonomous operation whereby deliberate reactor startup and shutdown are effected by the motion of shutdown rods but control rods are not utilized and have no effect during transients or accidents. In particular, no reactivity effects are assumed either from operation of control rods or inherent reactivity withdrawal/insertion due to heatup/cooldown of control rods or control rod drivelines.

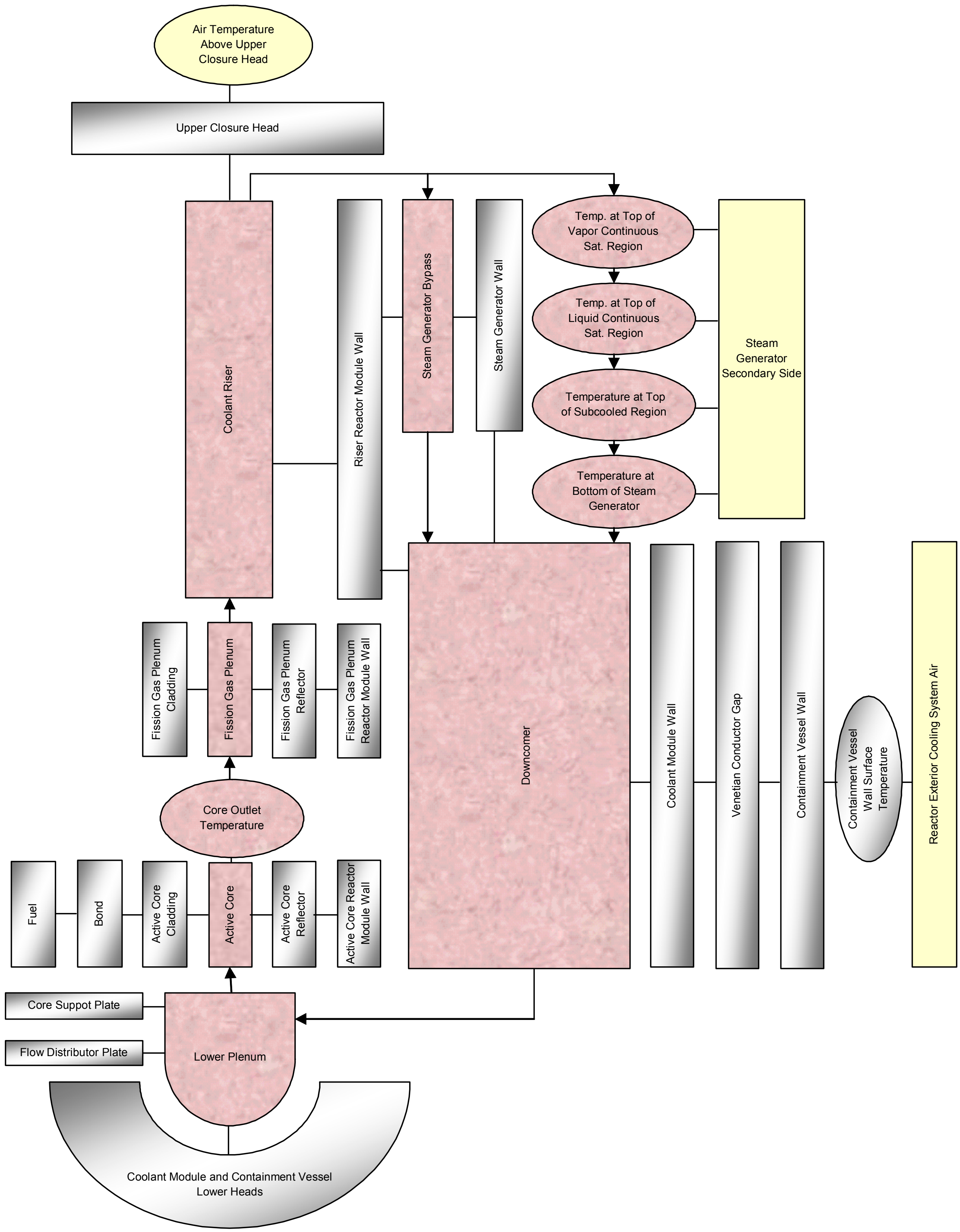

Figure 1. Schematic of Primary Coolant and Structure Control Volumes and Temperatures.

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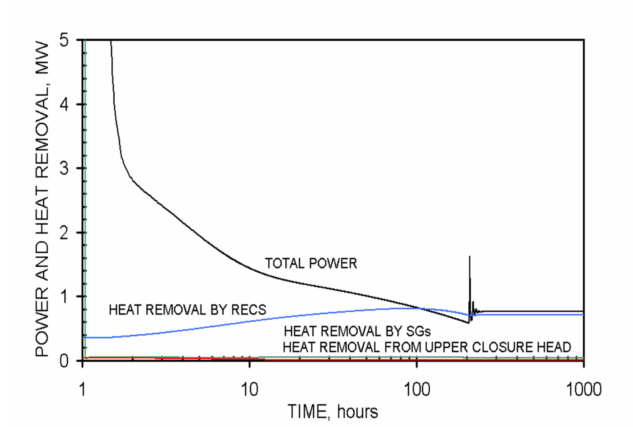

Figure 2. Total Power and Heat Removal for Loss-of-Heat Sink Without Scram.

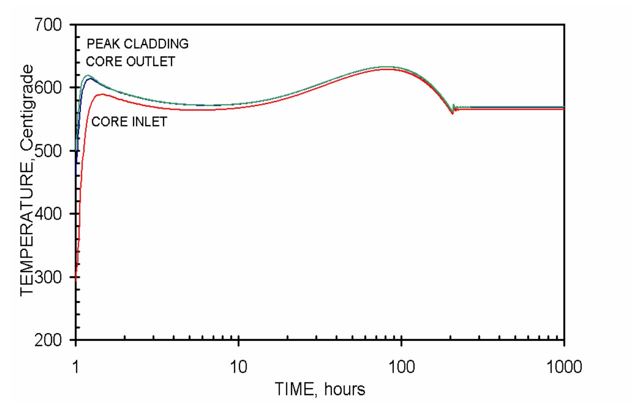

Figure 3. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Loss-of-Heat Sink Without Scram.

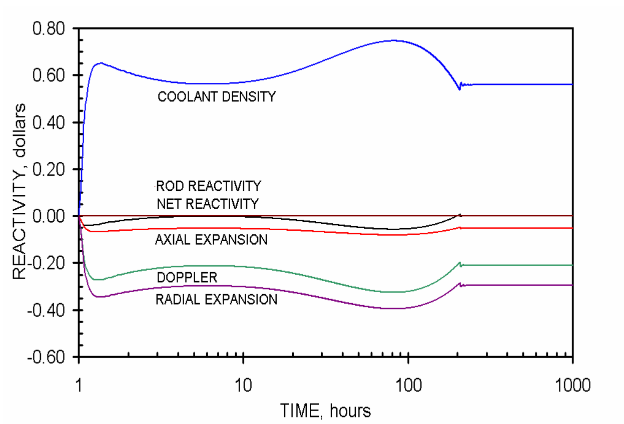

Figure 4. Reactivity Contributions and Net Reactivity for Loss-of-Heat Sink Without Scram.

<u>Loss-of-Heat Sink Without Scram</u>. A complete loss-of-heat sink was initiated by decreasing the feedwater flowrate to the steam generators to zero while holding the feedwater temperature unvarying. In particular, the feedwater flowrate is linearly reduced to 1 percent of the nominal value over a five second time interval and then further reduced from 1 to 0.01 percent of the nominal flowrate over the next sixty seconds. Thus, the feedwater flow through the steam generators is reduced to a negligible fraction, 0.0001, of the nominal value. This is a small enough value to approximate the complete loss of heat removal. Results for the entire accident are shown in Figures 2 through 4; for convenience in plotting, the accident is initiated at a time of 1 hour. Following the postulated loss-of-heat removal through the steam generators, the fuel and coolant temperatures rise. Strong negative reactivity feedbacks from fuel Doppler, fuel axial expansion, and core radial expansion more than offset the positive feedback from decreasing coolant density and cause the net reactivity to become negative and the fission power to decrease and go to zero after 65 minutes following accident initiation. The decrease in power causes the differences between the peak cladding temperatures, core outlet temperature, and core inlet temperature to decrease. A local maximum in the peak cladding temperature of 614 degrees Centigrade is attained after 15 minutes into the accident after which the temperatures temporarily decrease due to the effects of structural heat sinks.

At 83 hours following accident initiation, the temperatures rise to a peak of 633 °C at which the heat removal to air by the RECS exceeds the decay heat power. As the decay heat decreases, the RECS subsequently cools the system to a temperature of about 567 °C at which the net reactivity is zero.

Afterwards, the fission reaction begins again after 205 hours but the power peaks temporarily at only 0.54 percent nominal. Figures 5 through 7 present the reactor behavior over the time interval (180 to 250 hours) during which the reactivity again becomes positive, the fission reaction commences once more, and the power and temperature tend to steady values. By 250 hours, the total power and system temperatures have become unvarying with time. The fission power slowly increases with time in order to offset the decrease in decay heat power, and to maintain a balance between the total power generation and the heat removal by the RECS. The total power remains equal to an extremely low power level of only 0.25 percent nominal while the peak cladding temperature remains equal to 569 °C.

<u>Overcooling Event Without Scram</u>. Due to the inherent reactivity feedbacks, decreasing the reactor coolant and fuel temperatures results in an increase in reactivity. Thus, it is necessary to determine the response of the reactor to events that tend to reduce the temperatures of the LBE coolant and nitride fuel. An overcooling event without scram due to a loss of a feedwater heater was calculated by increasing the feedwater subcooling from the nominal value of 20 °C to a significantly greater value of 120 °C. Results are shown in Figures 8 through 10; the linear reduction in feedwater temperature begins at 50 seconds and ends at 86 seconds. The feedwater flowrate is maintained at the nominal value.

As the feedwater temperature decreases, the heat removed by the steam generators immediately begins to increase and exhibits a linear rise with time until the subcooling attains the maximum value when the heat removal peaks at 354 MW. Due

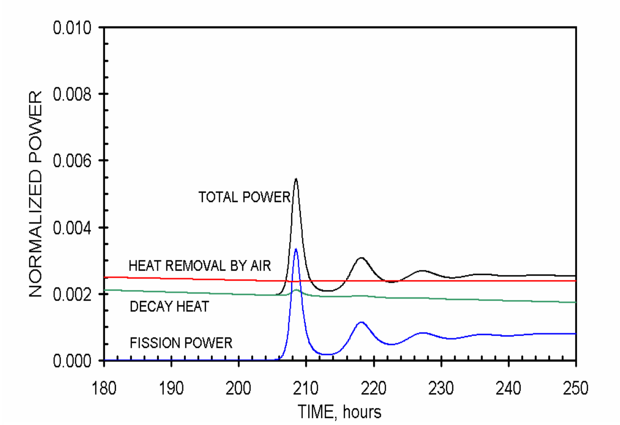

Figure 5. Total Power, Fission Power, Decay Heat, and Heat Removal by Air Surrounding Restart of Fission Power for Loss-of-Heat Sink Without Scram.

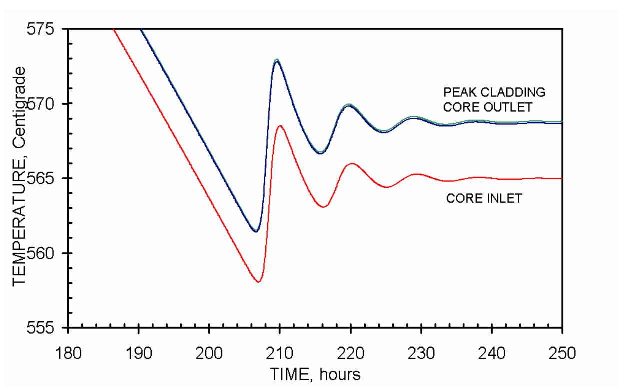

Figure 6. Peak Cladding, Core Outlet, and Core Inlet Temperatures Surrounding Restart of Fission Power for Loss-of-Heat Sink Without Scram.

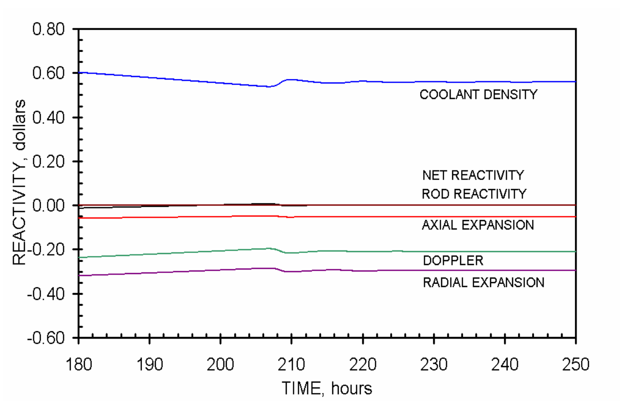

Figure 7. Reactivity Contributions and Net Reactivity Surrounding Restart of Fission Power for Loss-of-Heat Sink Without Scram

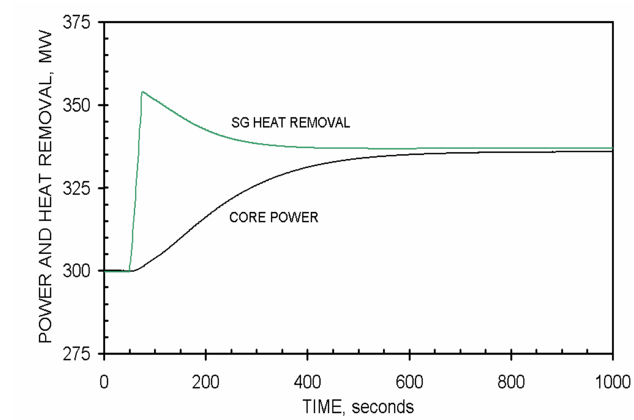

Figure 8. Core Power and Heat Removed by Steam Generators for Overcooling Event.

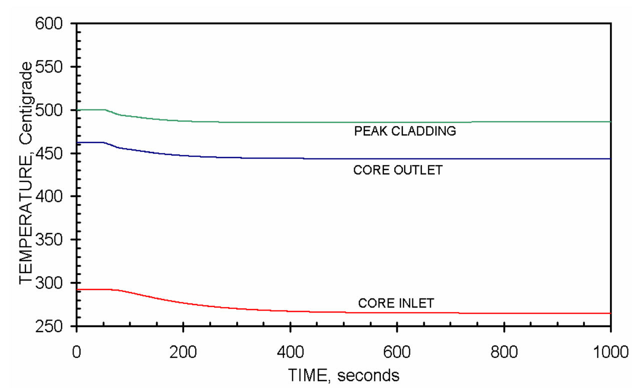

Figure 9. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Overcooling Event.

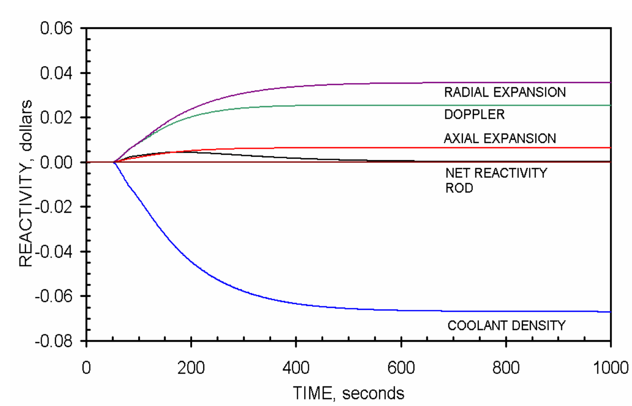

Figure 10. Reactivity Contributions and Net Reactivity for Overcooling Event.

to the increased subcooling, the height of the superheated region inside the steam generators decreases to only several centimeters and the steam superheat falls from 61 to only 4 °C. Beginning at 50 seconds, the temperature of LBE coolant exiting the bottom of the steam generator tubes decreases rapidly with time. The peak cladding, core outlet, and core inlet temperatures as well as the temperature of coolant entering the top of the SG tubes all exhibit gradual decreases with time causing a net positive but small reactivity feedback from 50 to about 620 seconds. The peak value of reactivity attained is only 0.5 cent.

In response to the reactivity rise, the core power rises with time over an interval of about 600 seconds as the reactor tends toward a new steady state at a power level of 338 MWt (1.13 times nominal power). Over the same time frame, the heat removed by the steam generators decreases toward the new steady state core power. The temperature of LBE coolant exiting the steam generator tubes decreases by only 26 °C from 291 to 265 °C when the feedwater temperature is reduced by 100 °C. The design of the secondary side will need to incorporate provisions to cope with the greater than nominal heat transfer rates.

Unprotected Transient Overpower. A deterministic definition of a transient overpower accident for a HLMC reactor depends upon the control strategy for the reactor as well as the properties of the control rods or mechanisms, if any. If a core design can be achieved with minimal burnup reactivity swing and the reactor can be operated in a truly autonomous mode, there may not be any need for reactivity control using control rods. Such a HLMC reactor might be designed with only shutdown rods that are removed to start up the reactor and inserted to effect shutdown. The need for reactivity control would be eliminated thereby eliminating the whole class of accidents associated with the postulated unintended addition of reactivity.

The STAR-LM conceptual design is not well enough developed at this time to justify a need to analyze a transient overpower event or deterministically formulate the conditions for one. Therefore, the approach taken here is simply to prescribe a reference reactivity increase and insertion rate based

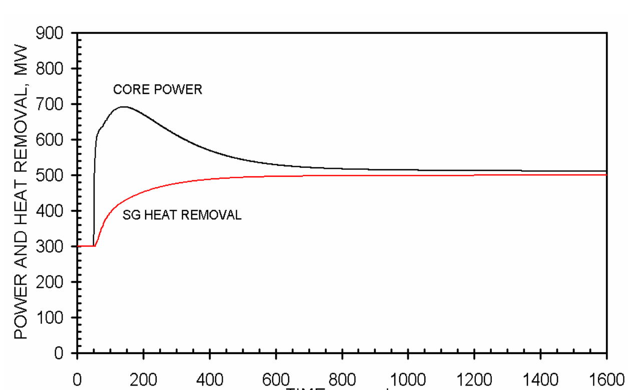

Figure 11. Core Power and Heat Removed by Steam Generators for 30 cents per second/30 cents Total Unprotected Transient Overpower.

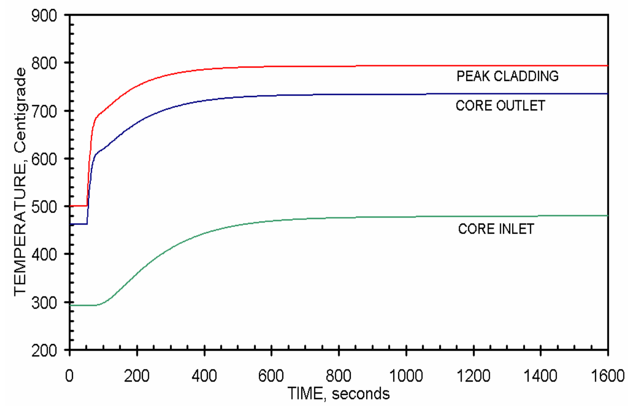

Figure 12. Peak Cladding, Core Outlet, and Core Inlet Temperatures for 30 cents per second/30 cents Total Unprotected Transient Overpower.

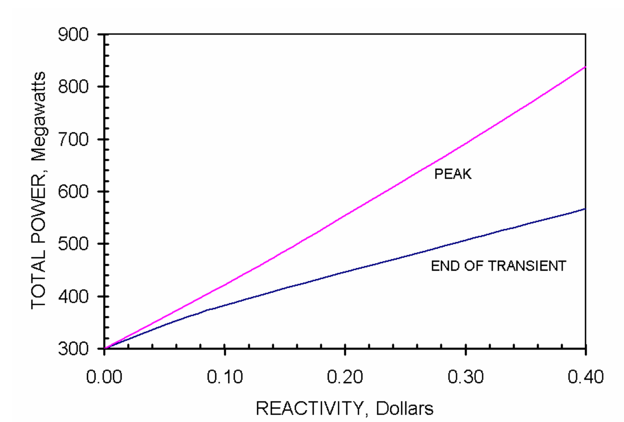

Figure 13. Core Power Attained Following Unprotected Transient Overpower versus Total Reactivity Inserted

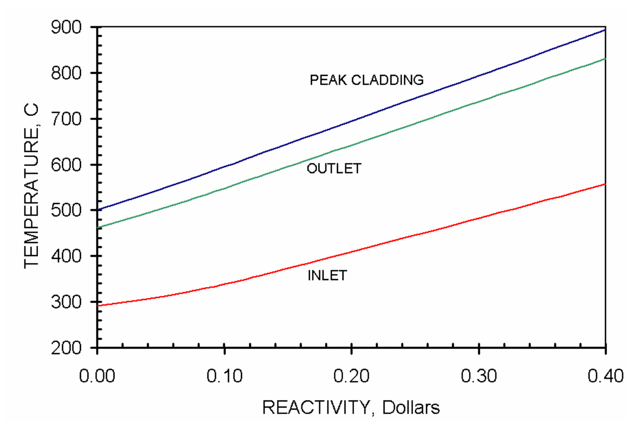

Figure 14. Steady State Peak Cladding, Core Outlet, and Core Inlet Temperatures Attained Following Unprotected Transient Overpower versus Total Reactivity Inserted.

upon what has been assumed in previous analyses for a mature liquid metal cooled fast reactor design. For the higher power 760 MWe Super-PRISM sodium-cooled reactor design, there are nine primary control rods, three secondary control rods, and three gas expansion modules (GEMS). One rod has a maximum runout rate of 2 cents per second up to a maximum of 2 cents. In analyses, this was multiplied by the 15 rods to obtain a maximum reactivity insertion of 30 cents over one second.

Thus, it was decided to investigate how the STAR-LM reactor would respond to the insertion of 30 cents of reactivity during one second. A number of other calculations have also been carried out varying the total reactivity inserted as well as the insertion time.

Figures 11 and 12 show the results calculated for a 30 cent reactivity insertion over 1 second beginning at a time of 50 seconds. The power peak at 692 MWt (2.31 times nominal) at 143 seconds. Although the power rises to a local peak and then decreases toward a new steady state, the system temperatures increase monotonically toward maximum values representative of the new steady state at the long-term steady state power. Heat removed by the steam generators also rises gradually during the transient (Figure 11).

Results are insensitive to the insertion time. The peak power decreases from 692 to 691 to 682 MWt, as the insertion time is increased from 1 to 15 to 150 seconds, respectively. The same new higher power steady state is attained, irrespective of the insertion rate.

Figures 13 and 14 show the dependencies upon total reactivity inserted for a common insertion time of one second. It is observed that the peak cladding temperature attained does not exceed 650 ∞C, representative of the existing (mainly Russian) database for LBE coolant and ferritic steel core materials, if the reactivity insertion is limited to values of 15 cents or less. This insertion conservatively defines a range of transient overpower accidents that are passively accommodated by the STAR-LM design without the attainment of excessive temperatures.

SUMMARY

Following a postulated loss-of-steam generator heat sink accident without scram, the 300 MWt STAR-LM reactor is calculated to passively shut itself down to an extremely low power level of 0.25 percent nominal due to inherent negative reactivity feedbacks. The strong negative reactivity contributions of fuel Doppler, fuel axial expansion, and core radial expansion with increasing temperature more than offset the positive reactivity effect of a decrease in the coolant density. Over the long-term of beyond 250 hours following the onset of the accident, the peak cladding temperature remains equal to 569 ∞C at which the net reactivity is very small. At this temperature, the heat removal to air by the Reactor Exterior Cooling System is balanced by the total power production consisting of decay heat plus nonzero fission power that slowly rises with time to offset the decrease in the decay heat. The peak cladding temperature temporarily exceeds 569 C during the first 200 hours attaining a peak of 633 ∞C at 83 hours.

The calculation of an overcooling event without scram due to loss of a feedwater heater demonstrates a very stable and benign reactor behavior in which the power and system temperatures tend gradually and monotonically toward a new steady state. The power does not exhibit any transient peaks. For a reduction in feedwater inlet temperature by 100 ∞C, the power increases by only 13% and the LBE coolant temperature exiting the steam generators decreases by only 26 ∞C.

It remains to be determined whether a transient overpower accident due to withdrawal of control rods will be a realistic scenario for STAR-LM. Nonetheless, the STAR-LM reactor system could withstand unprotected transient overpower events that insert up to 15 cents of positive reactivity over 1 second without the peak cladding temperature exceeding 650 ∞C. For this amount of reactivity insertion, the system transitions to a new steady state at a higher power of 139% nominal.

In all cases, STAR-LM is calculated to exhibit the behavior required for passive safety with the peak cladding and coolant temperatures remaining within the existing (mainly Russian) database for LBE coolant and ferritic stainless steel core materials.

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