

ICONE
Conference Paper

American Society of Mechanical Engineers (ASME) owns all copyright and publication subject to this requirement: "Verbatim reproduction of this paper by anyone will be permitted by ASME provided appropriate credit is given to the author(s) and ASME."

ICONE 10-22291

**AUTONOMOUS LOAD FOLLOWING AND OPERATIONAL ASPECTS OF THE
STAR-LM HLMC NATURAL CONVECTION REACTOR**

James J. Sienicki
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439, USA
email: sienicki@anl.gov

Plamen V. Petkov
University of Illinois at Urbana Champaign
Nuclear Plasma and Radiological
Engineering Department
103 Goodwin
207 NEL
Urbana, IL 61801, USA

KEYWORDS: Generation IV, Advanced Reactors, Autonomous Operation, Load Following, Heavy Liquid Metal Coolant, Lead-Bismuth Eutectic

ABSTRACT

STAR-LM is a 300 to 400 MWt class modular, fully transportable, proliferation resistant, and passively safe reactor system that offers developing nations and power producers nearly autonomous operation for very long term. Autonomous load following is the ability of the reactor core power to adjust itself to match the heat removal as a consequence of inherent physical phenomena. STAR-LM achieves autonomous load following through the utilization of a fast neutron spectrum core, inert lead-bismuth eutectic primary coolant, high thermal conductivity transuranic nitride fuel, and 100+% natural circulation heat transport of the primary coolant. To investigate and demonstrate autonomous operation as well as other operational aspects, representative operational transients are analyzed for the 300 MWt STAR-LM design using a coupled thermal hydraulics-neutron kinetics plant dynamics analysis computer code. Autonomous load following without reactivity effects from control rods is demonstrated for decrease-in-turbine load and increase-in-turbine load transients. For initial startup, startup from hot standby, and normal shutdown transients effected by withdrawal or insertion of shutdown rods, the reactor transitions stably to the desired steady state.

INTRODUCTION

The Secure Transportable Autonomous Reactor (STAR) project at Argonne National Laboratory (ANL) addresses the needs of developing countries and power producers for economical, proliferation-resistant, sustainable, multi-purpose energy systems which operate nearly autonomously for very

long term based upon small, modular, passively safe, fast spectrum reactors cooled with inert heavy liquid metal. STAR-LM (Liquid Metal)¹⁻³ is a 300 to 400 MWt class power reactor that utilizes lead-bismuth eutectic coolant (55 wt% Bi-45 wt% Pb; $T_{melt} = 125\text{ C}$; $T_{boil} = 1670\text{ C}$). STAR-LM has 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 core⁴ with high thermal conductivity transuranic nitride fuel, inert lead-bismuth eutectic (LBE) coolant,⁵ 100+% natural circulation heat transport, redundant passive natural circulation guard/containment vessel air cooling, and seismic isolation where required by the site to realistically achieve radical design simplification, greater reliability, and enhanced passive safety. The use of inert LBE primary coolant enables elimination of the need for an intermediate heat transport system.

Modular steam generators are immersed directly inside the primary circuit to produce superheated steam and provide a tighter, more effective, coupling between the primary and working (water/steam) circuits. Reliance upon natural circulation heat transport of the primary coolant eliminates the need for main circulation pumps.

Autonomous load following, that is, the ability of the reactor core power to adjust itself to match heat removal, is a consequence of the fast core with its strong reactivity feedbacks. Power changes occur solely due to the effects of physical phenomena alone without any operation of control rods or any

inherent reactivity feedback from control rods induced by temperature variations. This behavior offers the prospect for radical simplifications in plant control strategies whereby inherent reactivity feedbacks restore the balance between power generation and heat removal as well as provide passive reactivity shutdown in accidents involving failure to scram. In many instances, it would not be necessary for operators to change the reactor power by means of altering the location of control rods. Elimination of an intermediate cooling system, primary coolant main circulation pumps, as well as other systems represent significant simplifications that reduce the number of components and thereby enhance reliability. Autonomous operation is an additional significant simplification that reduces operator workload accompanied by a further enhancement in reliability. Simplification of the control system and operator requirements should lead to further cost savings.

The main purpose of the present work is to investigate the autonomous load following and other operational behavior of the STAR-LM reactor concept for a representative set of operational transients using a coupled thermal hydraulics-neutron kinetics plant dynamics analysis computer code.

ANALYSIS APPROACH

Calculations were carried out for the 300 MWt STAR-LM design using the THSTAR (Thermal Hydraulics for System Transient Analysis of Reactors) computer code. The code and its application to STAR-LM, including the nodalization scheme and the neutron kinetics reactivity feedback coefficients assumed, are described in a companion paper on passive safety.⁶

The complete secondary side is not modeled in the analysis. A detailed steam generator model describing separate subcooled, saturated liquid continuous, saturated vapor continuous, and superheated regions is incorporated in which the remainder of the secondary side is represented by specified pressure, feedwater flowrate, and feedwater temperature boundary conditions.

All calculations model autonomous operation whereby deliberate reactor startup and shutdown are effected by the motion of shutdown rods to introduce positive or negative reactivity, but control rods are not used and have no effect during operational transients or postulated 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.

ANALYSIS OF OPERATIONAL TRANSIENTS

Decrease-in-Turbine Load. Because the coupled thermal hydraulics-neutronics code does not include a complete model of the secondary side, it is not possible to calculate in detail the variation in secondary side conditions due to an imposed change in electricity demand from the electric power grid as well as turbine-supporting components. However, the effect of such a change is to alter the amount of heat being removed from the

primary coolant system by the steam generators. A change in turbine load may thus be modeled sufficiently well by an imposed change in the heat removal rate by the steam generators.

The thermal hydraulic portion of the code has been deliberately developed with an option whereby the user may specify the time dependent heat removal by the steam generators. During each timestep, the code calculates the required feedwater flowrate to achieve the specified heat removal rate, given the current conditions of LBE coolant and water/steam passing through the steam generators. This option has been used in the change-in-turbine load calculations.

A reduction in turbine load was modeled by a 50 percent decrease in the steam generator heat removal over 50 seconds (Figure 1). In a secondary side system, this corresponds to partially closing the turbine regulatory/throttle valves to reduce the steam flow area by 50 percent. The time dependent feedwater flowrate calculated by the code to achieve the specified heat removal is shown in Figure 2 for an assumed unvarying feedwater inlet temperature.

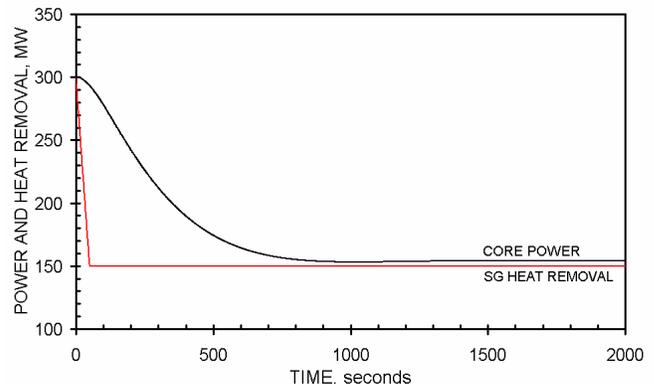


Figure 1. Core Power and Heat Removal by Steam Generators for Decrease in Turbine Load.

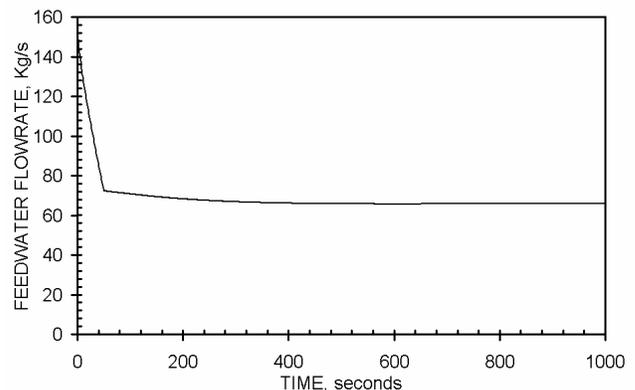


Figure 2. Feedwater Flowrate for Decrease in Turbine Load.

The reduction in heat removal immediately causes a rapid rise in the temperature of LBE coolant exiting at the bottom of the steam generator tubes (Figure 3) as well as along the tube height and decreases the driving force from buoyancy. The lower coolant velocity causes the core outlet-inlet temperature difference to rise resulting in higher outlet temperatures and an increase in the mean coolant and fuel temperatures (Figure 4). Strong negative reactivity feedbacks from fuel Doppler, fuel axial expansion, and core radial expansion cause the net reactivity to be negative (Figure 5) attaining a maximum negative value of -1.5 cents at 233 seconds. The core power responds to the negative reactivity by decreasing with time. Most of the reduction in power occurs over 600 seconds; the core power essentially balances the heat removed by the steam generators after 900 seconds (Figure 1). The peak cladding temperature (Figure 6) attains a maximum of 555 degrees Centigrade and decreases to a new steady state value of 550 degrees Centigrade.

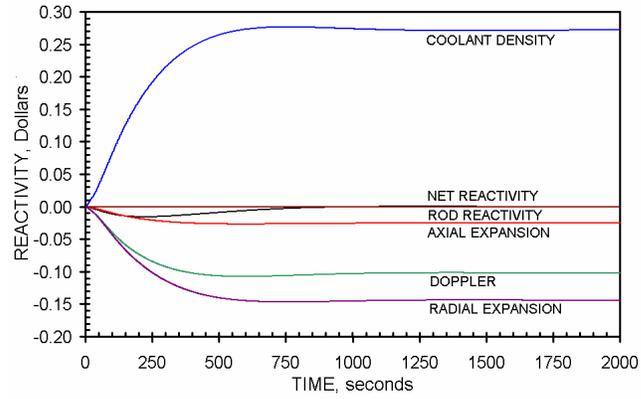


Figure 5. Reactivity Contributions and Net Reactivity for Decrease in Turbine Load.

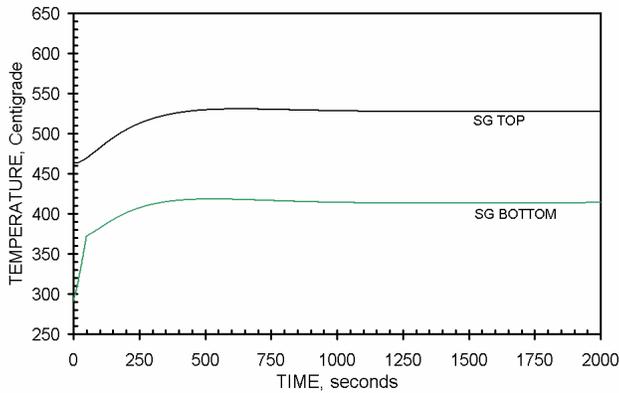


Figure 3. Coolant Temperatures at Top and Bottom of Steam Generators for Decrease in Turbine Load.

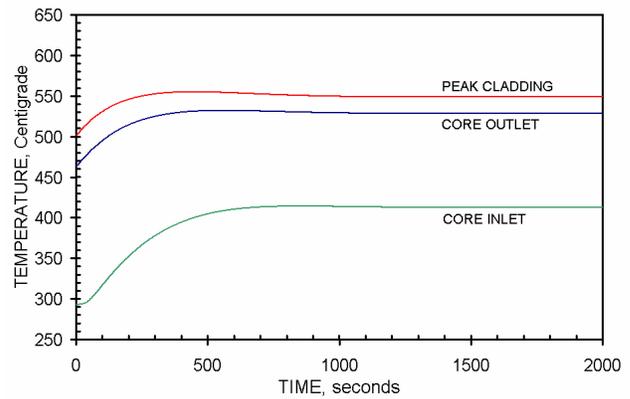


Figure 6. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Decrease in Turbine Load.

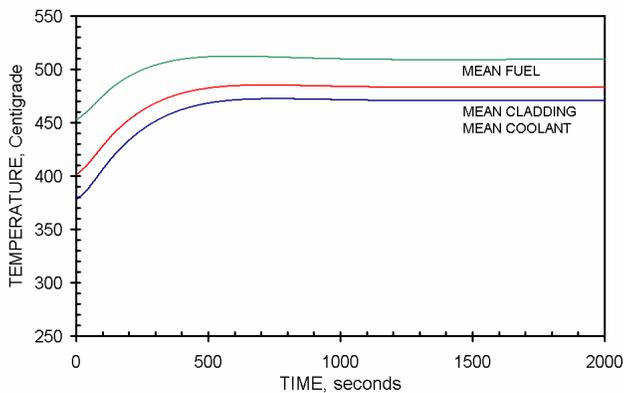


Figure 4. Mean Fuel, Cladding, and Coolant Temperatures for Decrease in Turbine Load.

Increase in Turbine Load. Increases in load demand complement decreases; it is necessary to demonstrate the ability of the reactor to passively restore the initial nominal operating conditions when an increase in load back to 100 percent follows a decrease from 100 percent. Cases simulating an increase in turbine load are thus calculated as variations of the calculation of a decrease in heat removal by the steam generators from 100 to 50 percent in which the heat removal is subsequently increased from 50 to 100 percent. The increase in heat removal is assumed to begin 7250 seconds after the initial reduction in heat removal from nominal power; that is, two hours after the heat removal has been decreased to 50 percent nominal. This waiting time has been chosen to enable the system to attain a steady state corresponding to heat removal at 50 percent nominal.

Results calculated for an assumed fast increase in heat removal over a time interval of 100 seconds are shown in Figures 7 through 9. In many respects, the phenomena are

similar to those for the decrease in heat removal but with temperature rises and power decreases replaced by temperature reductions and power increases.

The net effect of the time dependent reductions in mean fuel, core outlet, and core inlet temperature is an increase in the net reactivity to a peak value of 1.9 cents at about 7530 seconds. The positive reactivity causes the power to increase. The net reactivity subsequently decreases to zero at 8060 seconds. At this time, the power has risen to 296 MWt. It continues to increase, effectively reaching 300 MWt by 12600 seconds.

Results for the slow increase in heat removal are presented in Figures 10 and 11. The heat removed by the steam generators is assumed to increase linearly with time over nineteen hours to observe an arbitrary 5.6 degree Centigrade per hour mean coolant temperature rise limitation.. It is assumed that such a smooth increase can be achieved through control of the secondary side by the operators or an automatic control system.

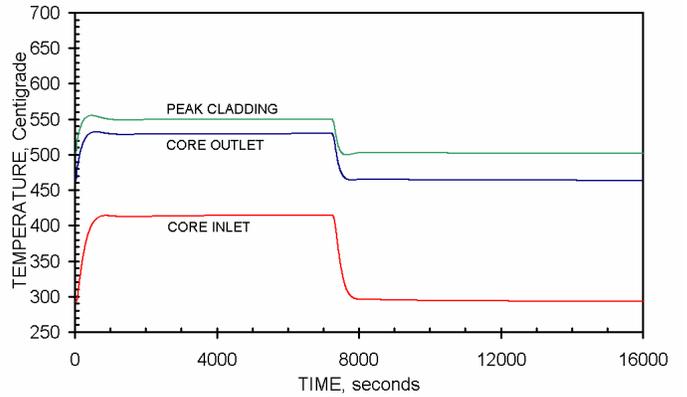


Figure 7. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Fast Increase in Turbine Load Following Decrease in Turbine Load.

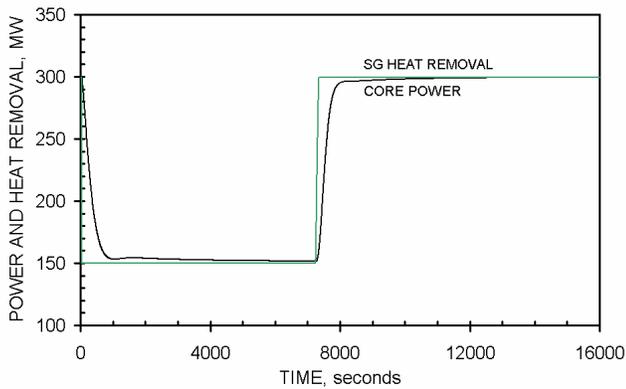


Figure 8. Core Power and Heat Removal by Steam Generators for Fast Increase in Turbine Load Following Decrease in Turbine Load.

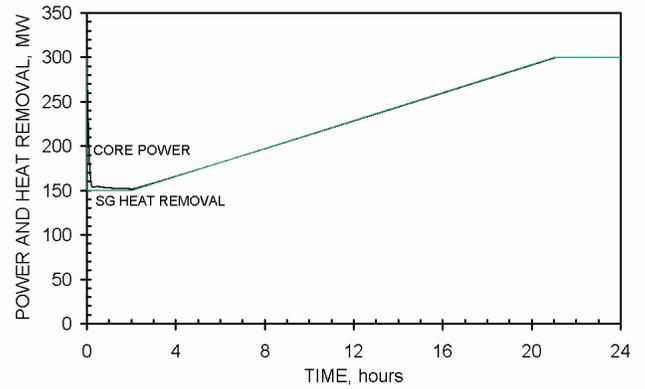


Figure 10. Core Power and Heat Removal by Steam Generators for Slow Increase in Turbine Load Following Decrease in Turbine Load.

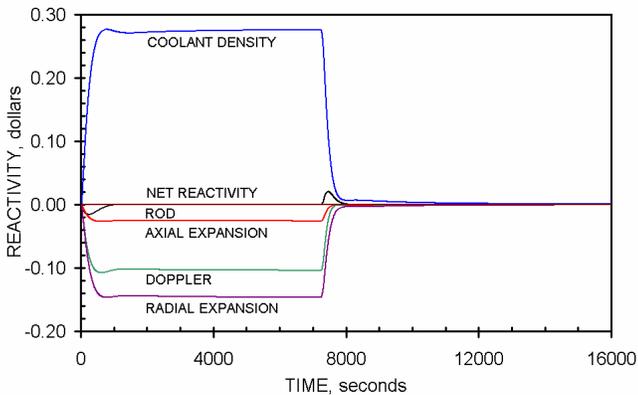


Figure 9. Reactivity Contributions and Net Reactivity for Fast Increase in Turbine Load Following Decrease in Turbine Load.

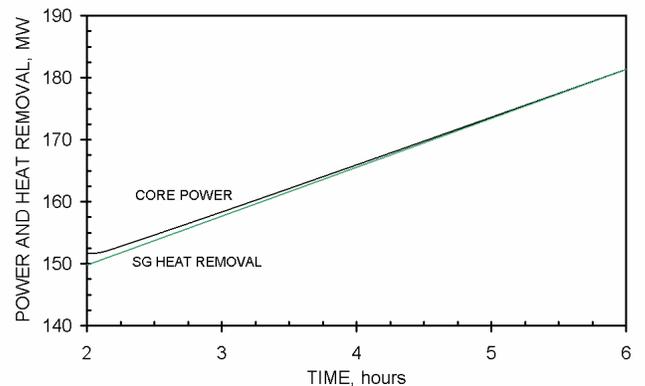


Figure 11. Core Power and Heat Removal by Steam Generators for Slow Increase in Turbine Load Following Decrease in Turbine Load.

The rise in the heat removal rate is so mild that a significant mismatch between heat removal and core power never develops. The rate of change in heat removal is so slow that the net reactivity remains close to zero. The time dependent core power virtually equals the heat removal rate by three hours following the onset of load increase and remains equal to the heat removal rate thereafter.

Initial Startup. Startup encompasses at least two distinct stages. The first consists of adding reactivity to bring the reactor from a deeply subcritical state (e.g., tens of dollars of negative reactivity) to being critical but with essentially zero power. It is assumed that this is accomplished by means of withdrawal of shutdown rods. The second stage is the one presently being calculated in which relatively smaller amounts of reactivity are added to raise the reactor power to the desired nominal operating level. It is expected that there will be a limitation upon the system heatup rate during startup. For example, in certain U.S. pressurized water reactors, the temperature rise rate during startup is limited to 5.6 C (10 degrees Fahrenheit) per hour or less based on thermal stresses associated with the reactor vessel. At this time, analysis of the STAR-LM design is not sufficiently developed that an analogous criterion can be stated for the HLMC system. The low pressure liquid metal-cooled system would be expected to impose less of a constraint from heatup induced stresses. A temperature rise rate limitation of 6 C per hour upon the mean coolant temperature is arbitrarily assumed, since it represents a restriction that forces startup to take many hours. Positive reactivity is assumed to be added in equal steps of a size sufficiently small not to violate the 6 C per hour criterion for the mean coolant temperature

It is assumed that the heavy liquid metal coolant has been heated to a temperature representing a sufficient temperature margin above the LBE freezing point. Since the generation of significant fission power must be accompanied by heat removal through the steam generators, it is assumed that feedwater is flowing to the steam generators. The initial LBE coolant temperature is thus expected to be in proximity to the feedwater temperature. The secondary side conditions are dependent upon the startup procedure for operation of the nuclear power plant. The initial flow state of the LBE coolant is dependent upon how non-nuclear heating has been provided to the reactor. The coolant may be circulating with a nonzero velocity dependent upon the locations of the sources for heating as well as heat removal. In addition to the steam generators, heat is also being removed, albeit at a low rate, by the Reactor Exterior Cooling System and from the upper closure head.

The question is sometimes asked about how the natural convection HLMC system responds to startup from a state of zero velocity and flowrate of the LBE coolant. As noted above, this initial condition is unrealistic. In spite of this, in order to respond to the question, it was desired to begin from such a state in the present analysis. However, the code fails to execute when presented with a zero or negligibly small initial condition

for the velocity in the core region. It was attempted to approximate such a state by beginning with a nominal power steady state, decreasing the core power with time to an extremely small value, and subsequently maintaining this small power while holding the feedwater flowrate and temperature unvarying with time. The purpose was to calculate a new steady state in which the total power is sufficiently small such that the core velocity is negligible. Unfortunately, this approach was unsuccessful for power levels below 0.06 percent nominal which was the smallest value for which the code iteration converged to produce a low power steady state. Therefore, initial startup was calculated from the initial conditions of flow and temperature equivalent to a power level of 0.06 percent nominal with a core velocity of 2.78 centimeters per second.

Going from the 0.06 percent nominal steady state to the one at nominal power, the reactivity change due to the inherent feedbacks is ≈ 26.9 cents. Thus, to calculate the startup transients, it is assumed that the reactor initially has zero reactivity and that 26.9 cents of positive reactivity is added by withdrawal of shutdown rods.

Figures 12 through 15 show the long-term results calculated when the reactivity addition of 26.9 cents is carried out in 22 steps of 1.22 cents each over 1 second followed by a one hour waiting interval. The first reactivity insertion begins at 100 seconds on the figures. The average rise rate of the mean coolant temperature over the 21 hours following the onset of startup is 5.3 C per hour thereby satisfying the 6 C per hour assumed criterion. Of course, after each reactivity insertion, much higher instantaneous rates are attained but the magnitude of each individual temperature increase during any single hour is limited to a maximum of 12 C locally and 6 C on the average.

Figures 12 through 15 do not resolve the system behavior following each individual reactivity insertion. Thus, the two curves in Figure 12 appear to be identical for all times. The results calculated for the sixth reactivity insertion after 5 hours plus 104 seconds are shown in Figures 16 and 17. The core power is observed to rise to a new steady state value in about 600 seconds (10 minutes). The steam generator heat removal lags slightly behind the power. Over the same 600 second time frame, the temperatures also increase to new steady state values.

One can ask how the natural circulation HLMC reactor system will respond if startup is attempted over a short time (e.g., a few seconds). Of course, this is not how one would realistically start up the reactor. Such a calculation is more representative of a postulated accident in which shutdown rods are unintentionally withdrawn.

A calculation was carried out in which the reactor is in the initial startup state at 0.06 percent nominal power and 26.9 cents of positive reactivity is added linearly over a timescale of only 5 seconds. The results are shown in Figures 18 and 19. The reactivity insertion begins at an absolute time of 50 seconds in the figures. The power is observed to rise to a peak of 309 MWt at 442 seconds following the onset of reactivity insertion and then decrease toward the steady state value of 300 MWt

approaching the steady state value after about 600 seconds (10 minutes) following the reactivity insertion. During the rapid rise in power, the heat removal through the steam generators lags the power by 62 seconds. Significantly, the overshoot of the nominal power level of 300 MWt is small amounting to only 9 MW. The peak cladding and core outlet temperatures attain most of the steady state values over an interval of about 300 seconds. The coolant inlet temperature does not begin to increase until 167 seconds following the initiation of the reactivity addition. This delay includes the effect of the time required for coolant heated in the core to transit to the lower plenum. The inlet temperature attains most of its nominal steady state value over 300 seconds.

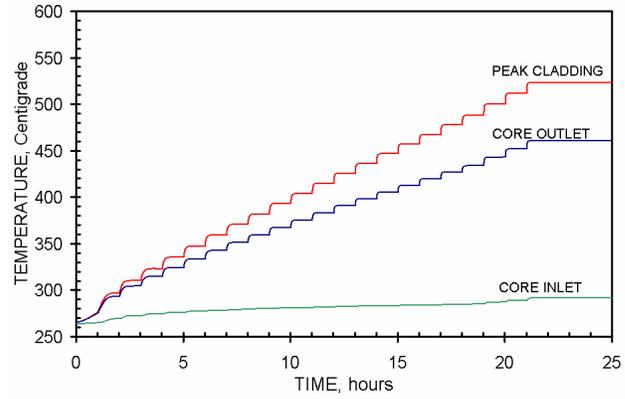


Figure 14. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Initial Startup from Critical State.

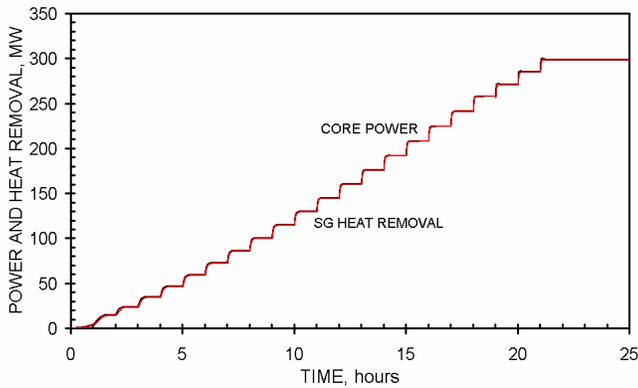


Figure 12. Core Power and Heat Removal by Steam Generators for Initial Startup from Critical State.

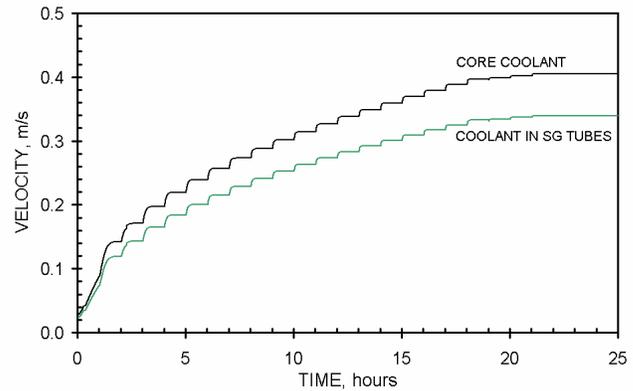


Figure 15. Coolant Velocity for Initial Startup from Critical State.

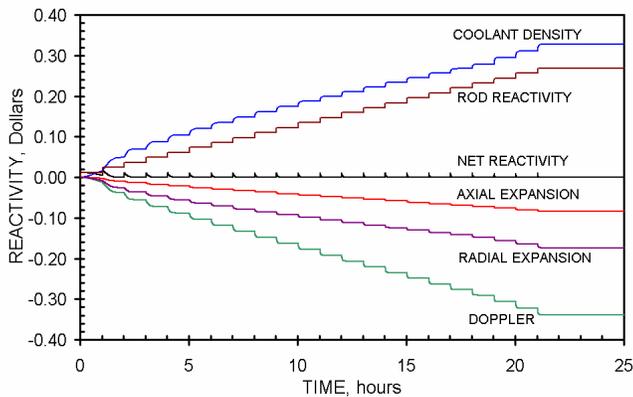


Figure 13. Reactivity Contributions and Net Reactivity for Initial Startup from Critical State.

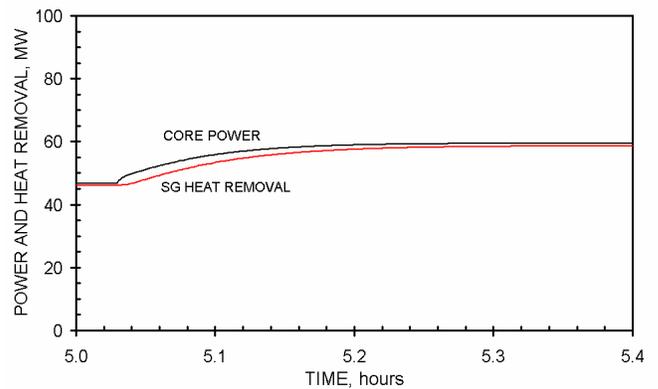


Figure 16. Core Power and Heat Removal by Steam Generators for Individual Reactivity Insertion During Initial Startup.

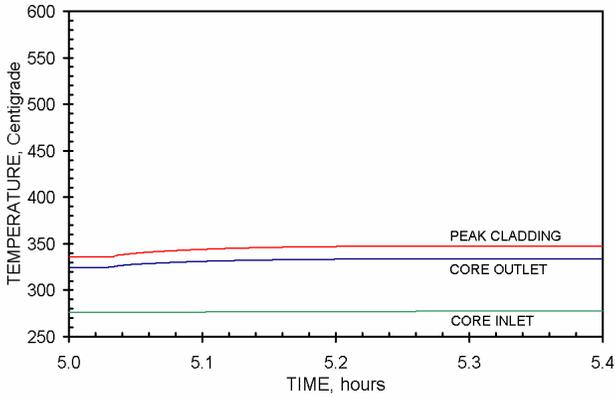


Figure 17. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Individual Reactivity Insertion During Initial Startup.

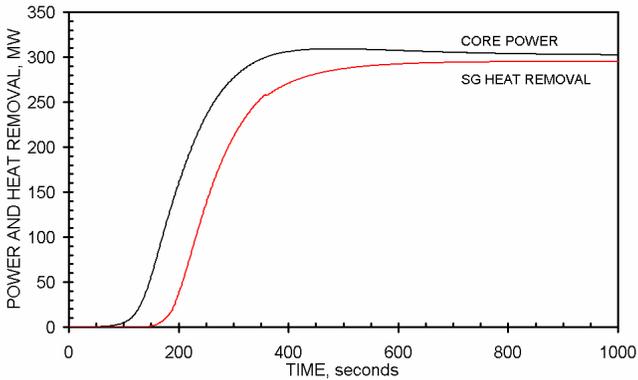


Figure 18. Core Power and Heat Removal by Steam Generators for Fast Initial Startup from Critical State.

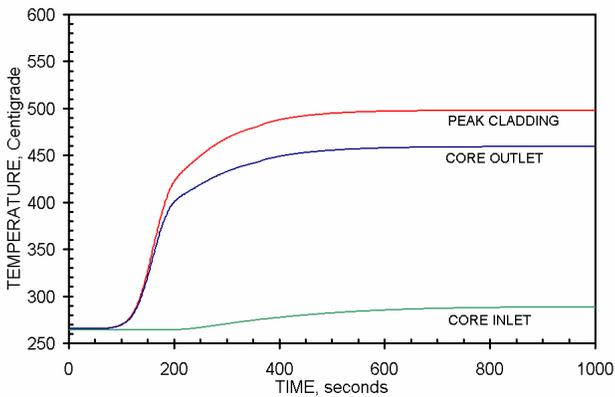


Figure 19. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Fast Initial Startup from Critical State.

Normal Shutdown. Shutdown involves the insertion of negative reactivity in order to terminate the fission reaction and place the reactor in a deeply subcritical state. When calculating shutdown, the questions arise of what is the rate at which reactivity must be inserted and what is the total amount of reactivity that must be inserted. Of course, the design of the shutdown or control rods and their insertion mechanisms provides a limitation upon the insertion rate and amount. There is also the question of how quickly the fission power generation must be terminated so as to limit the afterheat produced following the generation of a shutdown signal. Furthermore, one can distinguish between scram situations in which a relatively rapid shutdown is effected and a more gradual reduction/termination of fission power. The STAR-LM design is not well enough developed that criteria for shutdown can be stated. Thus, the approach taken here has been to assume that negative reactivity is inserted over a time interval of 5 seconds and vary the amount of reactivity inserted. Figures 20 through 23 present the dependencies upon the total reactivity inserted; the reactivities are measured in dollars.

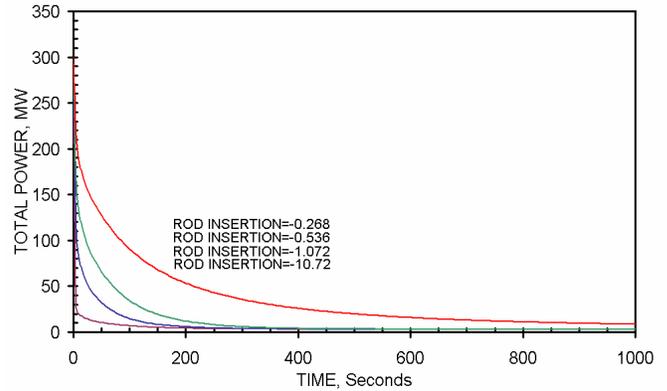


Figure 20. Effects of Total Reactivity Inserted Upon Total Power During Shutdown; Reactivity Insertions are in Dollars.

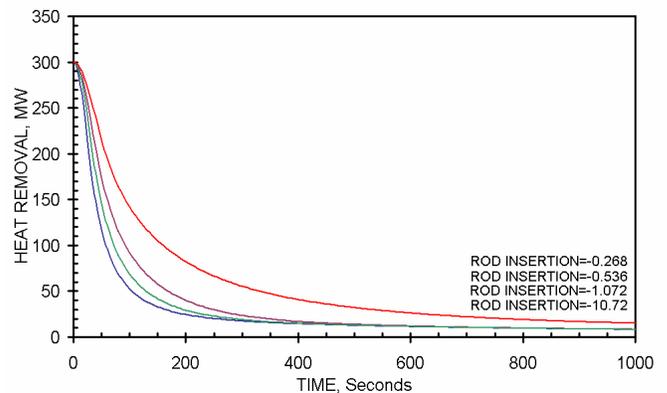


Figure 21. Effects of Total Reactivity Inserted Upon Heat Removal by Steam Generators During Shutdown; Reactivity Insertions are in Dollars.

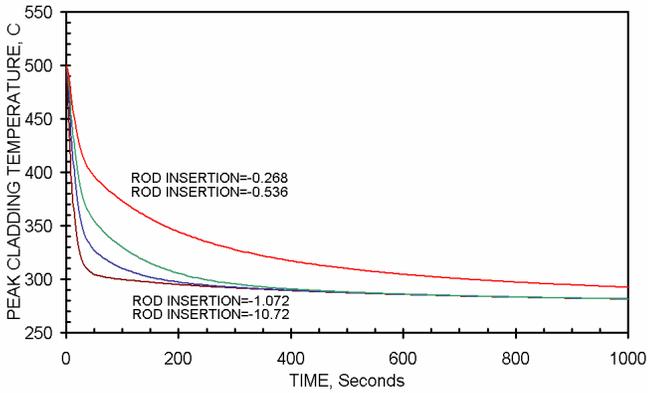


Figure 22. Effects of Total Reactivity Inserted Upon Peak Cladding Temperature during Shutdown; Reactivity Insertions are in Dollars.

Startup from Hot Standby. The term, hot standby, implies that the reactor has been operated for a long enough time that the coolant module vessel, steam generators, and other reactor structures have been heated to operating temperatures prior to the reactor being temporarily rendered subcritical in a hot standby mode. The natural way to calculate startup in this case is to first simulate placing the reactor in a hot standby state by calculating shutdown from the nominal power steady state following a long period of operation. This was done by calculating a shutdown case in which 0.538 dollars of negative reactivity is inserted in 5 seconds to bring the reactor subcritical. The hot standby state thus realized varies with time due to the decay of the fission power and decay heat. In the interest of beginning startup at higher system temperatures, only a short waiting time of 600 seconds (10 minutes) in hot standby mode was assumed corresponding roughly to the time for the fission power to decay to a negligibly small value. In particular, the fission power has fallen to 0.02 percent nominal and the decay heat is 1.06 percent nominal. The peak cladding temperature is 285 degrees Centigrade; the core outlet temperature is virtually identical, while the core inlet temperature equals 278 degrees Centigrade.

To calculate a slow startup from hot standby, 26.9 cents of positive reactivity is first added over five seconds to bring the reactor to a critical state. Subsequently, a short waiting period of 100 seconds is observed to allow variables to tend to stabilize. A small step reactivity insertion of 1.22 cents over one second is then made to initiate the fission reaction. Following a one hour wait, another small step change in reactivity is made at 1.2 hour. This causes the fission power to increase at a significantly greater rate and reach 3.4 percent nominal power by 2 hours. Another hour delay is observed before the next reactivity addition is made. The cycle of small reactivity addition over 1 second followed by an hour delay is repeated until the nominal operating conditions are achieved. The

purpose is to observe the assumed 6 degree Centigrade per hour limitation on the rate of rise of the mean coolant temperature.

The resulting increases in system temperature and coolant flowrate to nominal operating conditions are shown in Figures 23 and 24. The hour long waiting time is more than long enough for the system to achieve a new steady state.

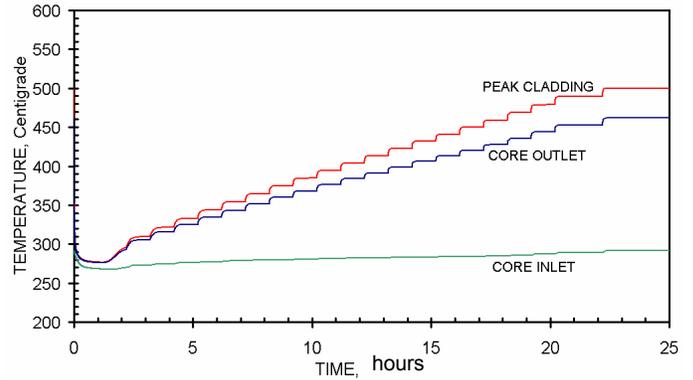


Figure 23. Peak Cladding, Core Outlet, and Core Inlet Temperatures for Slow Startup from Hot Standby.

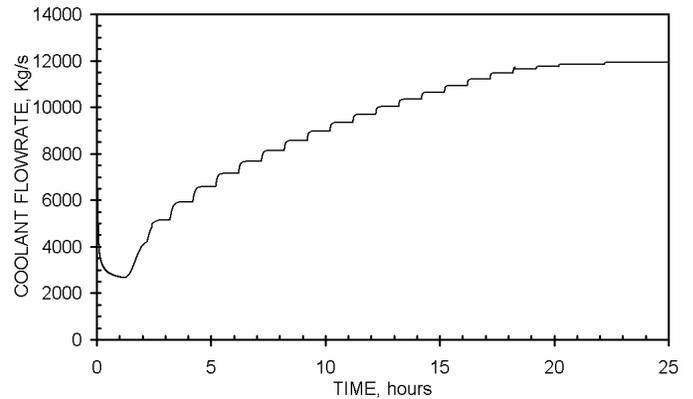


Figure 24. Coolant Flowrate for Slow Startup from Hot Standby.

Figure 25 shows the power and heat removal for a fast startup from hot standby in which 0.538 dollars of reactivity is added between 600 and 605 seconds. The total power peaks at a value of 309 MW at 1090 seconds. After 750 seconds, the heat removed by the steam generators shows a similar rise rate. Equilibrium between the core power and heat removal is essentially established by 1400 seconds.

At 605 seconds, the net reactivity is 0.251 dollar. Heatup of the fuel and coolant decreases the net reactivity to virtually zero by 1400 seconds. By 1200 seconds, the temperatures have essentially attained the nominal operating values. The

coolant flowrate and velocity begin to increase after 650 seconds and rise most rapidly after 750 seconds. By 1000 seconds, the flowrate/velocity has essentially achieved the nominal steady state value.

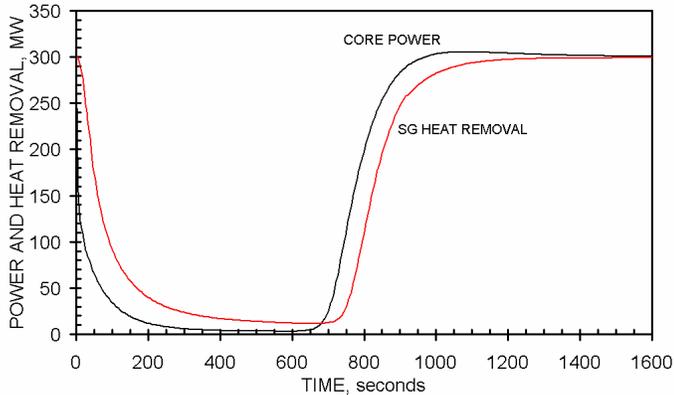


Figure 25. Core Power and Heat Removal by Steam Generators for Fast Startup from Hot Standby.

SUMMARY

The change-in-turbine load calculations demonstrate that the STAR-LM reactor passively follows the load without operation of controls rods. The reactor power autonomously adjusts itself to balance the heat removal from the reactor. The timescale over which the power changes to match the load is about 600 seconds.

The calculations of all of the initial startup and startup from hot standby transients exhibit stable reactor behavior in which the flowrate and temperature rise continuously to the nominal steady state values. No oscillations in flow or temperature are calculated. No overshoots in flowrate or temperature are calculated. There are no oscillations in core power. For the extreme case in which the total reactivity required to bring the reactor to the nominal steady state is assumed to be added in only five seconds, the total power exhibits only a slight overshoot of the nominal power by 3 percent; thereafter, the power soon decreases toward the nominal value.

The shutdown calculations show that the core power decreases monotonically following the insertion of negative reactivity. For example, inserting ~ 10.8 dollars of reactivity over 5 seconds brings the power down from 300 to 19 MW by 10 seconds. In all cases, the reactor transitions stably to a quasi-steady state involving natural circulation of the LBE coolant at the decay heat power level.

At the current time, the design of the STAR-LM secondary (water/steam) side is incomplete. The plant dynamics code models the steam generators accounting for water heatup and boiling, and steam superheating. However, the remainder of the secondary side is modeled as only secondary side pressure as

well as feedwater flowrate and temperature boundary conditions. For the particular scenarios calculated in the present study, this was not a shortcoming as the behavior of secondary side components beyond the steam generators has minimal impact.

There are other scenarios where the secondary side transient response could influence the results. For example, autonomous load following could be limited by the secondary side behavior at low heat removal levels.

A further lesson of the present study is the requirement to design a secondary side that seeks to preserve autonomous operation and passive safety to the greatest extent, consistent with economic and reliability considerations.

ACKNOWLEDGEMENTS

This work was funded by the Japan Nuclear Cycle Development Institute (JNC). The authors are grateful to Drs. Yoichiro Umetsu and Takatsugu Mihara of JNC. Bruce W. Spencer of Argonne National Laboratory (ANL) was the innovator of STAR-LM. Unfortunately, he passed away on March 1, 2001, following an unsuccessful battle with cancer during which he continued to work to advance STAR-LM. The authors appreciate the continuing support of David J. Hill, David C. Wade and Jordi Roglans of ANL. This work was carried out while the second author was a Visiting Scientist in the Reactor Analysis and Engineering Division at ANL. Reactivity feedback coefficients for STAR-LM were calculated by R. N. Hill and J. A. Stillman (ANL/RAE). J. E. Cahalan (ANL/RAE) adapted the TSPK point kinetics module from SAS4A/SASSYS for usage with the THSTAR thermal hydraulics calculation. The authors are indebted to him for continuing assistance and advice concerning TSPK. The manuscript was prepared by Kathleen S. Rank.

REFERENCES

1. B. W. Spencer, D. C. Wade, D. J. Hill, J. J. Sienicki, and M. T. Farmer, "Thermal-Hydraulic Development of a Small, Simplified, Proliferation-Resistant Reactor," 10th Annual Engineering and Science Conference, "From the World's First NPP to the XXI Century Power," Obninsk, Russia, June 28-July 2, 1999, The Nuclear Society of Russia (1999)
2. B. W. Spencer, R. N. Hill, D. C. Wade, D. J. Hill, J. J. Sienicki, H. S. Khalil, J. E. Cahalan, M. T. Farmer, V. A. Maroni, and L. Leibowitz, "An Advanced Modular HLMC Reactor Concept Featuring Economy, Safety, and Proliferation Resistance," ICONE-8145, Proceedings of ICONE-8, 8th International Conference on Nuclear Engineering, Baltimore, April 2-6, 2000.
3. J. J. Sienicki and B. W. Spencer, "Power Optimization in the STAR-LM Generation IV Modular, Natural Convection Reactor System," ICONE 10-22294, Proceedings of ICONE 10, Tenth International

- Conference on Nuclear Engineering, Arlington, April 14-18, 2002.
4. R. N. Hill, J. E. Cahalan, H. S. Khalil, and D. C. Wade, "Development of Small, Fast Reactor Core Designs Using Lead-Based Coolant," Proceedings of the International Conference on Future Nuclear Systems, Global '99, "Nuclear Technology-Bridging the Millennia," Jackson Hole, Wyoming, August 29-September 3, 1999.
 5. B. W. Spencer, "The Rush to Heavy Liquid Metal Reactor Coolants-Gimmick or Reasoned," ICONE-8428, Proceedings of ICONE 8, 8th International Conference on Nuclear Engineering, Baltimore, April 2-6, 2000.
 6. J. J. Sienicki and P. V. Petkov, "Passive Safety of the STAR-LM HLHC Natural Convection Reactor," ICONE 10-22290, Proceedings of ICONE 10, Tenth International Conference on Nuclear Engineering, Arlington, April 14-18, 2002.