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POWER OPTIMIZATION IN THE STAR-LM MODULAR NATURAL CONVECTION REACTOR SYSTEM

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ABSTRACT

STAR-LM is a modular, factory-fabricated, overland transportable, proliferation resistant, autonomous load following, and passively safe liquid metal-cooled fast reactor system that utilizes inert lead-bismuth eutectic coolant combined with 100+% natural circulation heat transport to achieve radial design simplification, enhanced reliability, and cost savings. STAR-LM has the potential to meet all of the U.S. DOE Generation IV goals of sustainable energy development, safety and reliability, and economics. Previous development of STAR-LM resulted in a 300 MWt modular pool type reactor in which modular steam generators are immersed directly inside the primary coolant and the core is part of a reactor module/flow-thru fuel cartridge that provides no access to fuel during the core lifetime. Recent concept development has focused on raising the power achievable in a small module size based on preserving key criteria for: i) full spectrum of modes of module transport from factory to site (including rail transport); ii) ultralong core cartridge lifetime; iii) 100% natural circulation heat transport; and iv) coolant and cladding peak temperatures well within the existing (mainly Russian) database for lead-bismuth eutectic coolant and ferritic steel core materials. For example, natural circulation is found to be capable of transporting 400 MWt in a fully transportable module size with 15 year core life (at 100% capacity factor; 100,000 MWd/tonne average burnup; 1.5 peaking factor) with a core outlet temperature of 489 C, peak cladding inner surface temperature of 580 C, and steam outlet superheat of 82 C at 10 MPa.

NOMENCLATURE

A	=	flow area, m^2
c	=	specific heat, J/(Kg•K)
F	=	frictional term
g	=	gravitational acceleration, m/s^2
L_{diff}	=	difference in elevation between cooled and heated zone thermal centers, m
Q	=	total reactor power, W
u	=	velocity, m/s
β	=	$-\frac{1}{\rho}\frac{dp}{dT} = \text{compressibility}, K^{-1}$
ΔT	=	temperature rise through heated zone, K
ρ	=	density, Kg/m^3

INTRODUCTION

The Secure Transportable Autonomous Reactor (STAR) project at Argonne National Laboratory addresses the needs of developing countries and independent 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 heavy liquid metal. Two designs are:

STAR-LM (Liquid Metal)[1-2] for electricity production utilizing lead-bismuth eutectic coolant (55 wt% Bi ñ 45 wt% Pb; T_{melt} = 125 C; T_{boil} = 1670 C); and

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STAR-H2 as a nuclear heat source for production of hydrogen via water cracking with optional capability for potable water production from brackish or salt water desalinization as well as optional electricity generation. Consistent with the higher temperatures required by water cracking thermochemical cycles, STAR-H2 utilizes lead coolant (T_{melt} = 327 C; T_{boil} = 1740 C).

Lead-bismuth eutectic (LBE) and lead do not react exothermically or vigorously with water or steam; they do not burn when exposed to air. Use of heavy liquid metal coolant therefore realistically enables radical simplification in system design, greater reliability, and cost savings for fast spectrum reactors including elimination of the need for an intermediate coolant system. Furthermore, the high coolant boiling temperature eliminates the entire class of accident involving coolant boiling. Traditional benefits of liquid metal coolants (compact system design, low system pressure, and separate coolant and working fluids) are also preserved.

The STAR-LM concept described here is a power reactor that embodies modularity, factory fabrication, full overland transportability from the factory to the site, fast construction and startup, autonomous operation/load following, proliferation resistance, and passive safety. STAR-LM addresses the low end of the spectrum of core power where design simplifications and innovations are expected to be necessary in order to realize cost savings and achieve favorable economics. Thus, it is complementary to the higher power 300 MWe sodium cooled Advanced Fast Reactor ñ 300 (AFR-300) also under development at Argonne.

A power level of 300 MWt was originally identified in a criterion for a small modular reactor. Accordingly, STAR-LM was originally developed to meet this criterion. However, it was subsequently realized that the original concept was sufficiently robust to enable a significant increase in power further enhancing the economic advantages of STAR-LM and offering customers flexibility. Recent STAR-LM development has focused on raising the power achievable in a small size module. The objective of the present work is to increase the module power to a new goal of 400 MWt.

KEY FEATURES OF STAR-LM

STAR-LM utilizes inert lead-bismuth eutectic (LBE) for primary coolant enabling elimination of the need for an intermediate coolant system realistically providing radical simplification in system design, greater reliability, and cost savings. Modular steam generators are immersed directly inside the primary coolant in a pool-type configuration to produce superheated steam (Figures 1-3).

The core resides inside of a reactor module. A fast neutron spectrum core with high thermal conductivity transuranic nitride fuel achieves a realistic ultralong core refueling interval of 15 years or more for minimization of the radioactive waste stream, proliferation resistance, and high capacity factor .

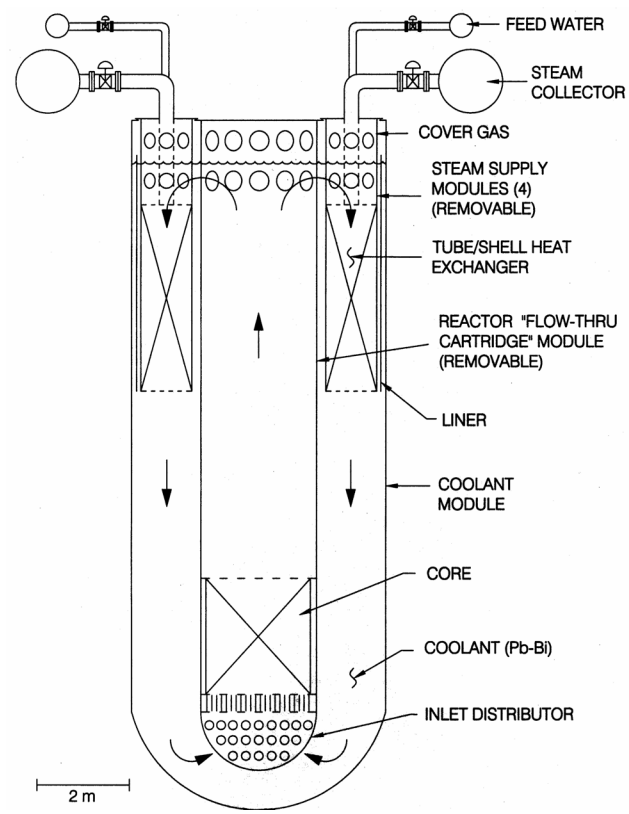

Figure 1. Illustration of STAR-LM Reactor.

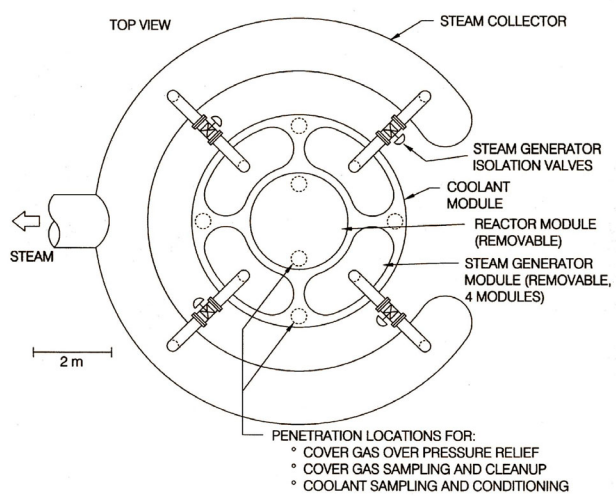

Figure 2. Plan View of STAR-LM Reactor Showing Arrangement of Removable Modular Steam Generators.

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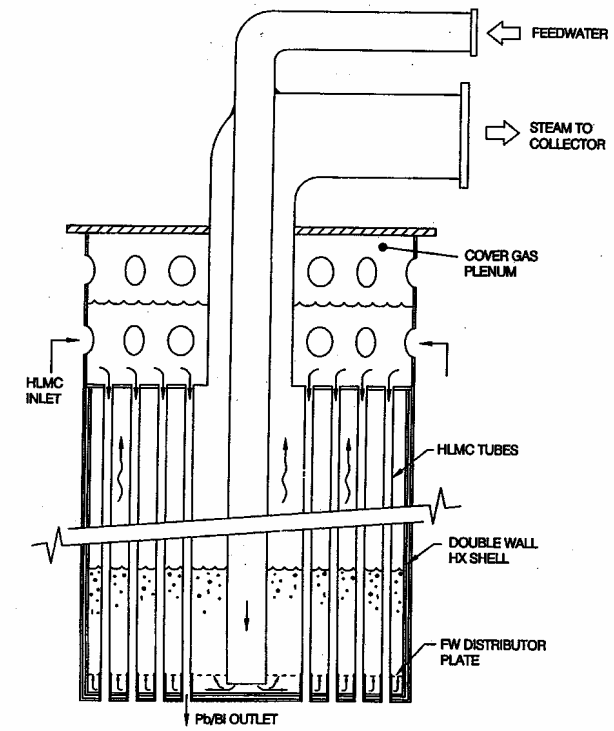

Figure 3. Illustration of STAR-LM Once-Through Tube/Shell Steam Generator Module for Production of Superheated Steam.

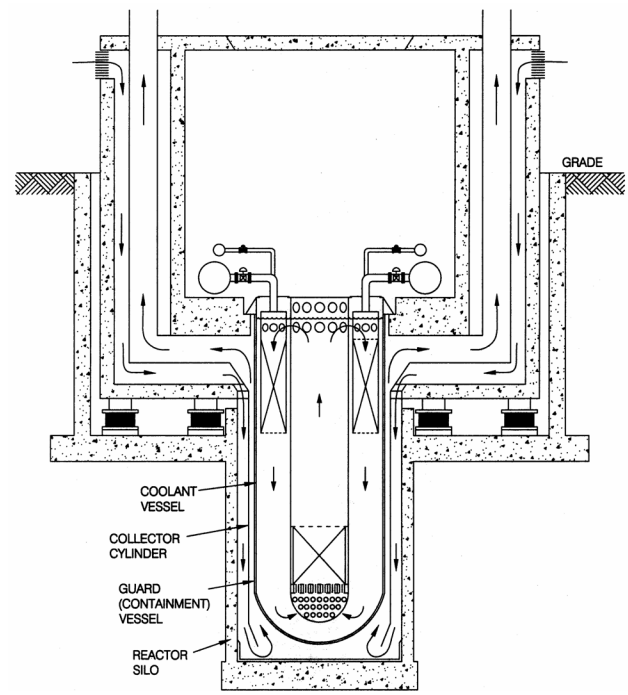

Figure 4. Illustration of STAR-LM Reactor Exterior Cooling System and Seismic Isolation Approach.

The core is a single assembly and is not composed of removable subassemblies as in traditional liquid-metal-cooled fast reactors. The reactor module is functionally a proliferation-resistant ì flow-thru fuel cartridgeî that affords no access to any core materials during the ultralong core lifetime. Following the core life, the used reactor module is removed from the coolant module vessel and is transported from the site to a secure consortia-owned Regional Fuel Cycle Support Center for reprocessing under international oversight.

The ultralong core life is achieved with a low power density core limiting average burnup to 100000 MWd/tonne (peaking factor of 1.5).[4-5] The core low power density facilitates heat removal by coolant through large hydraulic diameter coolant channels reducing the core pressure drop. More than 100% of the nominal core power can be transported from the low-power density/low pressure drop core to the steam generators by natural circulation of the primary coolant.[6] STAR-LM does not incorporate any main circulation pumps in the primary circuit. Elimination of main coolant pumps further enhances simplification, reliability, economics, and passive safety.

The fast spectrum core provides strong negative reactivity feedbacks for autonomous load following[7] and passive accident termination by inherent core power shutdown.[8] Autonomous operation represents an additional significant simplification that reduces operator workload accompanied by a further enhancement in reliability. Simplification of the control system and operator requirements should result in further cost savings.

STAR-LM incorporates a Reactor Exterior Cooling System (RECS) that passively cools the outside of the containment/guard vessel with air driven by natural circulation (Figure 4), in the event that all modular steam generators are unavailable for heat removal.[8,9]

Postulated end-of-spectrum events such as a loss-of-heat sink accident are terminated passively due to inherent shutdown of core power due to strong negative reactivity feedbacks and passive removal of afterheat to the inexhaustible air heat sink by the RECS.[8] The high density of the heavy liquid metal coolant plus provision of an escape path for vapor through the gap between the coolant module vessel and an inner liner eliminates concerns about steam generator tube rupture.[1,10] A seismic isolation approach (Figure 4) eliminates concerns about seismic and pool sloshing-related loads.[1,11]

INCREASE IN NOMINAL OPERATING POWER

Recent concept development to raise the power achievable in a small module size has been carried out within the constraints of preserving the key criteria: factory fabrication; full transportability from factory to site; fast construction and startup; 100+% natural circulation heat transport; ultralong core cartridge lifetime; and coolant and cladding peak temperatures well within the existing (mainly Russian) database for LBE coolant and ferritic steel core and structural materials. A goal was set to increase the nominal power from 300 to 400 MWt.

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Observing the criteria for factory fabrication and overland transportability mainly relates to the transportation of vessels. Overland rail transportability from the factory to the site limits the height to 19 meters and the width to 6.1 meters.[12] Core radial dimensions are constrained by the limitation on the vessel diameter. A core diameter of 2.0 meters is retained.

To meet the limitation on fuel specific power and not exceed the 100000 MWd/tonne average burnup limit, the fuel mass must be increased from 27500 to 35300 Kilograms. After investigating the effects of greater active zone heights, it was decided to maintain the original 2.0 meter active core height and increase the fuel mass by changing the fuel rod dimensions and spacing. The fuel rod diameter is enlarged from 1.27 to 1.91 centimeters and the triangular pitch-to-diameter ratio from 1.475 to 1.50 while maintaining the gap thickness occupied by the cladding-fuel pellet LBE bond. The fuel smeared density rises from 0.66 to 0.78. The hydraulic diameter for LBE flow through the core grows from 1.78 to 2.82 centimeters. This reduces the already low pressure drop through the core. Retaining the same 2.0 meter active core height and 0.5 meter fission gas plenum height further contributes to the low core pressure drop.

The coolant velocity through the heated zone from natural circulation varies as

$$u = \left(\frac{Qg\beta L_{diff}}{2\rho cAF} \right)^{1/3} \tag{1}$$

such that the temperature rise across the heated zone is

$$\Delta T = \frac{Q}{\rho cuA} = \left(\frac{Q}{\rho cA} \right)^{2/3} \left(\frac{\alpha F}{g\beta L_{diff}} \right)^{1/3} . \tag{2}$$

To tend to offset the effect of higher reactor module power, the vertical height difference between the center elevations of the steam generator tubes and active core is increased from 6.25 to 9.0 meters. This thermal centers separation height observes the constraint on vessel height for overland rail transport.

To raise the plant efficiency, the secondary side (water/steam) working pressure is raised from 7 to 10 Megapascals and the steam generator tube height is increased from 3 to 4 meters to further enhance steam superheating and plant efficiency.

A steam generator tube wall thickness of 2 millimeters was originally selected for STAR-LM. The single wall thickness is increased to 3 millimeters to better resist corrosion attack.

To reduce LBE coolant frictional losses inside the taller steam generator tubes, the steam generator tube inner diameter is increased. Figure 5 shows the effects of steam generator tube inner diameter and pitch-to-diameter ratio upon the peak cladding temperature at the top of the active core. Most of the benefit to be gained from enlarging the tube diameter is realized in going from an original inner diameter of 1.27 centimeters and pitch-to-diameter ratio of 1.35 to a larger diameter of 1.80 centimeters and tighter pitch-to-diameter ratio of 1.20. These values are selected for the higher power STAR-LM design.

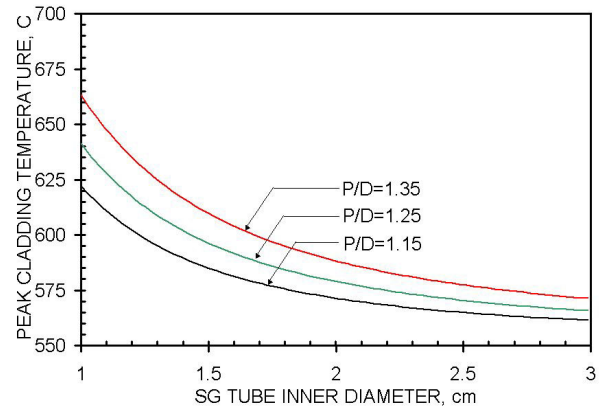

Figure 5. Effects of Steam Generator Tube Size and Pitch-to-Diameter Ratio on Peak Cladding Temperature for 400 MWt STAR-LM.

Table 1 compares the changes in the STAR-LM design conditions for the 300 and 400 MWt variants. Calculated thermal hydraulic conditions for the two designs are compared in Table 2. The peak cladding temperature of 580 degrees Celsius remains within the range where ferritic stainless steels such as HT9 can be used as a structural material together with formation and maintenance of a corrosion inhibiting oxide layer upon the structure by means of control of the level of oxygen dissolved in the coolant.

SUMMARY

The STAR-LM concept has been extended from the original 300 MWt design to include a new design generating a greater module thermal power of 400 MWt thereby offering flexibility to customers. Achievement of a greater 400 MWt power from a small module of similar size further improves the economics and cost savings of STAR-LM. The original STAR-LM concept has been found to be robust with respect to power increase. Even further increases in power are feasible.

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Table 1. Change in STAR-LM Design Conditions for Power Increase

Core Thermal Power, MWt	300	400
Core Diameter, m	2.5	2.5
Core Active (Heated) Zone Height, m	2.0	2.0
Fission Gas Plenum Height, m	0.5	0.5
Fuel Rod Cladding Outer Diameter, cm	1.27	1.91
Fuel Rod Triangular Pitch-to-Diameter Ratio	1.48	1.50
Core Hydraulic Diameter, m	1.78	2.82
Nitride Fuel Smeared Density	0.66	0.78
Core Fuel Mass, Kg	27500	35300
Steam Pressure, MPa	7.0	10
Saturation Temperature, C	286	311
Feedwater Subcooling, C	20	20
Height Difference between SG and Core Thermal Centers, m	6.25	9.0
Steam Generator Tube Height, m	3.0	4.0
SG Tube Inner Diameter, m	1.27	1.80
SG Tube Thickness, mm	2	3
SG Tube Triangular Pitch-to-Diameter Ratio	1.35	1.20

Table 2. Change in STAR-LM Thermal Hydraulic Conditions for Power Increase.

Core Thermal Power, MWt	300	400
Core Inlet Temperature, C	291	320
Core Outlet Temperature, C	474	489
Mean Temperature Rise Across Core, C	185	169
Peak Cladding Outer Surface Temperature, C	506	558
Peak Cladding Inner Surface Temperature, C	516	580
Steam Superheat, C	61	82
Coolant Velocity in Core, m/s	0.38	0.54

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