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SSTAR Lead-Cooled, Small Modular Fast Reactor for Deployment at Remote Sites - System Thermal Hydraulic Development

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Abstract- *Analyses are investigating the viability of a 20 MWe (45 MWt) proliferation-resistant and passively safe small, modular, liquid metal fast reactor concept for deployment at remote sites. The concept combines the benefits of molten lead coolant, transuranic nitride fuel, and natural circulation heat transport to enhance passive safety and operate at higher temperatures than traditional liquid metal fast reactors. It achieves a 20-year core lifetime with cassette core refueling to enhance proliferation resistance, is fissile self-sufficient by creating as much fissile fuel as it consumes, has a high fuel discharge burnup exceeding that of operating light water reactors, autonomously changes its power without operation of control rods to match the demand from the electric power grid, and employs supercritical carbon dioxide Brayton cycle power conversion to achieve a 44 % efficiency at a core outlet temperature of 566 °C.*

I. INTRODUCTION

Research and development is in progress to determine the viability of a small modular Lead-Cooled Fast Reactor (LFR) concept known as the Small Secure Transportable Autonomous Reactor (SSTAR). One mission of SSTAR is to provide incremental electricity generation to match the needs of developing nations and especially remote communities without major electrical grid connections such as exist in the states of Alaska or Hawaii, island nations of the Pacific Basin (e.g., Indonesia), and elsewhere. This represents a niche market within which capital and operating costs per unit energy that are higher than those for large-scale nuclear power plants (NPPs) may be competitive.

Power levels in the range of 10 to 100 MWe are of interest. For example, the "Report to Congress on Small Modular Reactors," U.S. Department of Energy, May 2001[1] states that *"In considering possible replacement power plants, it appears that units less than 50 MWe would represent the majority of Alaskan generating capability, with units of 10 MWe or less being the most widely applicable."* The concept currently under investigation has a power level of 20 MWe (45 MWt). The SSTAR LFR incorporates favorable attributes similar to those that have been identified for the LFR at larger scale.[2,3] Key features and goals of SSTAR include:

- Proliferation resistance:
    - Core lifetime/refueling interval of 20 years;
    - Core is a single cassette and is not composed of individual removable fuel assemblies;
    - Access to fuel is restricted during the core lifetime;
    - Refueling equipment is present at the site only during refueling operations at the end of the core lifetime;
    - Transuranic fuel which is self protective in the safeguards sense;
- Molten lead (Pb) primary coolant and nitride fuel:
    - Passive safety and potential to operate at higher system temperatures than traditional liquid metal-cooled fast reactors;
- Autonomous operation:

- Core power adjusts itself to heat demand from the reactor system due to large inherent reactivity feedbacks of the fast spectrum core without operator motion of control rods;
- Active adjustment of control rods for startup, shutdown, and burnup compensation over the core lifetime;

- Fissile self-sufficiency:
  - Conversion ratio near unity;
  - Realization of a sustainable closed fuel cycle;
- Supercritical carbon dioxide (S-CO_2) gas turbine Brayton cycle power converter:
  - Higher plant efficiency than a Rankine saturated steam cycle at the same core outlet temperature;
  - Reduced balance of plant footprint, costs, and staffing requirements;
- Natural circulation primary coolant heat transport:
  - Eliminates main coolant pumps and loss-of-flow accidents;
- Factory fabrication:
  - All reactor and balance of plant components including reactor and guard vessels;
  - Reduced costs and improved quality control;
- Factory assembly of components into transportable modules:
  - Short modular installation and assembly times at the site;
- Full transportability by barge or rail, or possibly by road;
- Flexibility to be adapted to generate other energy products:
  - Production of desalinated water or hydrogen.

The use of lead coolant enhances passive safety. Lead is chemically inert; that is, it does not react chemically with the CO_2 working fluid above ~ 250 °C. Lead does not react vigorously with air or water/steam. Lead has a high boiling temperature of 1740 °C (1670 °C for Pb-Bi eutectic). *As a consequence, under all operational transients and postulated accidents, the SSTAR core and heat exchangers remain covered by ambient pressure single-phase primary coolant and single-phase natural circulation removes the core power.*

The use of nitride fuel offer several potential improvements that are well suited to the LFR and also enhances passive safety. Nitride has a high melting temperature (> 2600 °C for UN) as well as a high temperature for decomposition (> 1350 °C for mixed nitride, ($U_{0.8}$, $Pu_{0.2}$)N). Its high thermal conductivity together with the Pb bond between the fuel pellets and cladding reduce the fuel-coolant temperature difference. Nitride is compatible with a fast neutron spectrum and provides a high atom density. The nitrogen is enriched in N^{15} to eliminate parasitic reactions in N^{14} and waste disposal problems associated with C^{14} production. In addition, nitride fuel is compatible with both the ferritic-martensitic stainless steel cladding and Pb coolant; nitrogen is insoluble in Pb. The nitride pellets are bonded to the cladding by molten Pb. Nitride further offers low irradiation-induced swelling and fission gas release.

The lead coolant and nitride fuel together provide the potential to operate the LFR reactor system at higher temperatures than traditional liquid metal-cooled fast reactors, provided that corrosion-resistant structural materials capable of maintaining sufficient strength over the long core lifetime can be developed. A peak cladding temperature of 650 °C is assumed as the limiting condition in the present analysis.

II. SUMMARY OF NEUTRONICS ANALYSES

A power level of 20 MWe (45 MWt) is selected because it represents an optimal value for an assumed compact core with a core fuel volume fraction that allows natural circulation heat transport at nominal power. The neutronics analyses are discussed in a companion paper.[4] A 20-year core life, fixed fuel volume fraction of 0.55, fuel smeared density of 90 %, and core height-to-diameter ratio of 0.8 are assumed. Transuranic (TRU) fuel feed from LWR spent fuel following a 25-year cooling time is assumed. This allows for decay of the Pu^{241} isotope. The core incorporates five distinct TRU enrichment zones including a central low-enrichment region to reduce the peak-to-average power ratio and burnup reactivity swing. The assumed fuel volume fraction of 0.55 is high, but when combined with a large pin diameter, it is shown in the thermal hydraulics analysis below to be low enough to facilitate natural circulation heat transport from the core to the in-vessel Pb-to-CO_2 heat exchangers (HXs).

Given a fixed core power level, Figure 1 shows the results of calculations of the average discharge burnup and burnup reactivity swing versus active core diameter for a simplified

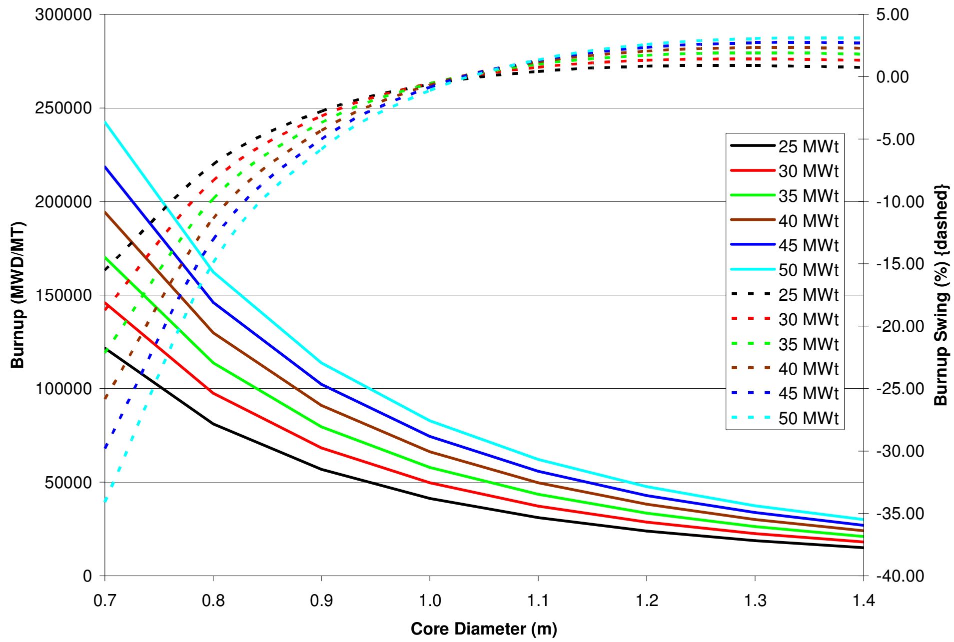

Figure 1. Average Discharge Burnup and Burnup Reactivity Swing versus Active Core Diameter.

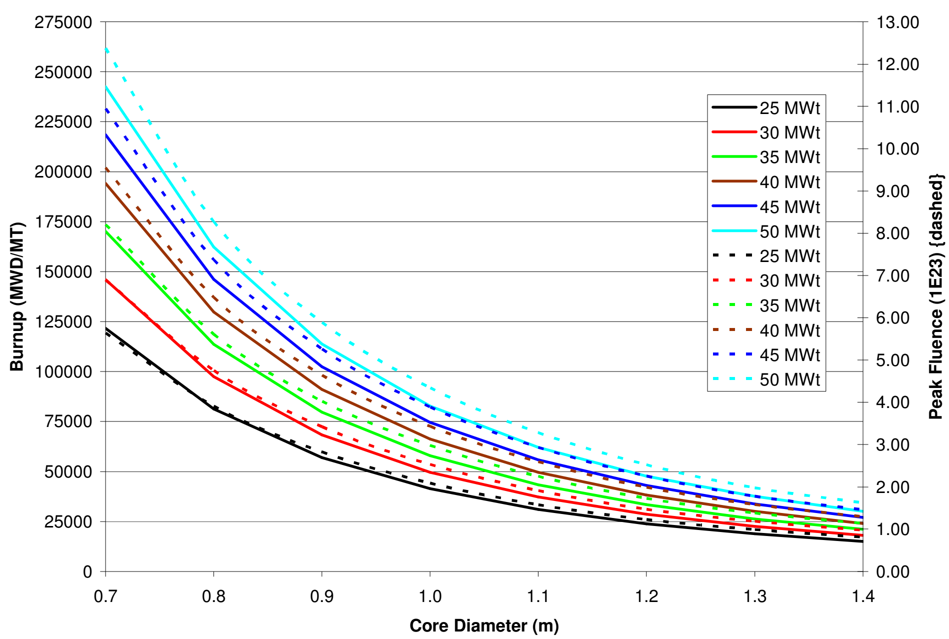

Figure 2. Average Discharge Burnup and Peak Fast Fluence versus Active Core Diameter.

cylindrical core geometry (height-to-diameter ratio = 0.8) assuming a fuel volume fraction of 0.55 and an 90 % nitride fuel smeared density. It is desired to limit the burnup reactivity swing over the core lifetime to less than one dollar. It is observed that for a fuel volume fraction of 0.55, the burnup reactivity swing exhibits a minimum at an active core diameter of about 1.0 m. Figure 2 plots the average discharge burnup as well as the peak fast fluence versus the active core diameter. Increasing the core thermal power directly increases the average discharge burnup. However, the maximum power is limited by the requirement that the peak fast fluence remain below the assumed limit of 4.0×10^{23} neutrons/cm^2.

This limitation is encountered for core powers of about 45 to 50 MWt. Thus, for the assumed 0.55 fuel volume fraction, a core diameter of about 1.0 m minimizes the burnup reactivity swing and a power level of about 45 MWt maximizes the average discharge burnup. More detailed calculations were performed using the DIF3D/REBUS-3 code package. Table 1 shows core conditions and the calculated core neutronics performance.

The reference fuel form consists of nitride pellets bonded by molten Pb to oxide dispersion-strengthened silicon-enhanced ferritic-martensitic stainless steel cladding. The fuel pins are arranged on a triangular pitch with a pitch-to-diameter ratio of 1.121. The fuel pins have a large diameter of 2.5 cm that provides a large hydraulic diameter for Pb coolant flow reducing the frictional pressure drop through the core as required for natural circulation. The core is a single open cassette of fuel pins and is not composed of individual removable assemblies.

III. SYSTEM THERMAL HYDRAULIC DEVELOPMENT

Figure 3 shows the primary coolant system configuration. The Pb coolant flows upwards through the core and the above-core riser region interior to the above-core shroud. Coolant flows through the holes in the shroud and enters the modular in-reactor heat exchangers to flow downwards over the exterior of double-walled circular tubes arranged on a triangular pitch through which the S-CO_2 flows upwards. Heat is thus transferred from Pb to S-CO_2 in a countercurrent regime. The Pb exits the heat exchangers to flow downwards through the downcomer to enter the reactor vessel lower head. A flow distributor head provides for an approximately uniform pressure boundary condition beneath the core.

Table 1. SSTAR Core Conditions and Performance

Core Diameter, m	1.02
Active Core Height, m	0.8
Nitride Fuel Smeared Density, %	90
Fuel Volume Fraction	0.55
Cladding Volume Fraction	0.16
Bond Volume Fraction	0.10
Coolant Volume Fraction	0.18
Fuel Pin Diameter, cm	2.5
Fuel Pin Pitch-to-Diameter Ratio	1.121
Cladding Thickness, mm	1.0
Average Power Density, W/cm^3	69
Specific Power, KW/Kg HM	10
Peak Power Density, W/cm^3	119
Average Discharge Burnup, MWd/Kg HM	72
Peak Discharge Burnup, MWd/Kg HM	120
Peak Fast Fluence, n/cm^2	4.0×10^{23}
BOC to EOC Burnup Swing, % delta rho	0.13
Maximum Burnup Swing, % delta rho	0.36
Estimated Delayed Neutron Fraction	0.00375
BOC to EOC burnup Swing, $	0.35
Maximum Burnup Swing, $	0.96

The SSTAR reactor system thermal hydraulic development has been carried out to meet the following requirements and constraints:

- Power level = 45 MWt;
- Full transportability by barge or rail, or road, if possible;
- Natural circulation heat transport of primary coolant at power levels up to and exceeding 100 % nominal;
- Core dimensions and fuel volume fraction from core neutronics analyses;
- Peak cladding temperature equal to 650 °C;
- Maximize S-CO_2 Brayton cycle efficiency;
- Fission gas plenum height above active core is conservatively set to 1.75 times the active core height, for the fuel pin cladding material, ODS F/M SSt or another material, yet to be selected;
- Pb coolant channels about 1 cm or more in diameter to reduce potential for plugging by contaminants;
- Space for incorporation of cylindrical liner and annular gap escape path for CO_2 vapor/gas between in-vessel Pb-to-

CO_2 heat exchangers and reactor vessel inner surface;

- Space for multi-plate thermal radiation heat shield between bottom of upper head/cover and Pb free surface;
- Adequate coolant temperature margin above the freezing temperature;
- Removal of decay heat from outside of guard/containment vessel to the atmospheric heat sink by natural circulation of air.

Vessel size is constrained by conflicting goals. Rail transportability imposes a size limitation upon the reactor vessel and guard vessel of 6.1 m (20 feet) in diameter and 18.9 m (62 feet) in height. Alternately, the vessel height (18.3 m) and diameter (3.23 m) are determined by the need to fit the following components inside of the vessel and to provide sufficient driving head for single-phase natural circulation heat transport between the elevations of the in-reactor heat exchangers and the active core:

- 1.02 m active core diameter;
- 0.297 m reflector thickness;
- 2.54 cm core shroud thickness interior to downcomer;
- 5.72 cm thick gap between reactor vessel inner surface and 1.27 cm thick cylindrical liner to provide escape path to Pb free surface for CO_2 void, in the event of HX tube rupture;
- 5.08 cm thick reactor vessel;
- Kidney-shaped Pb-to-CO2 heat exchangers must fit inside of the annulus between the shroud and reactor vessel, and provide sufficient heat exchange performance to realize a significant Brayton cycle efficiency.

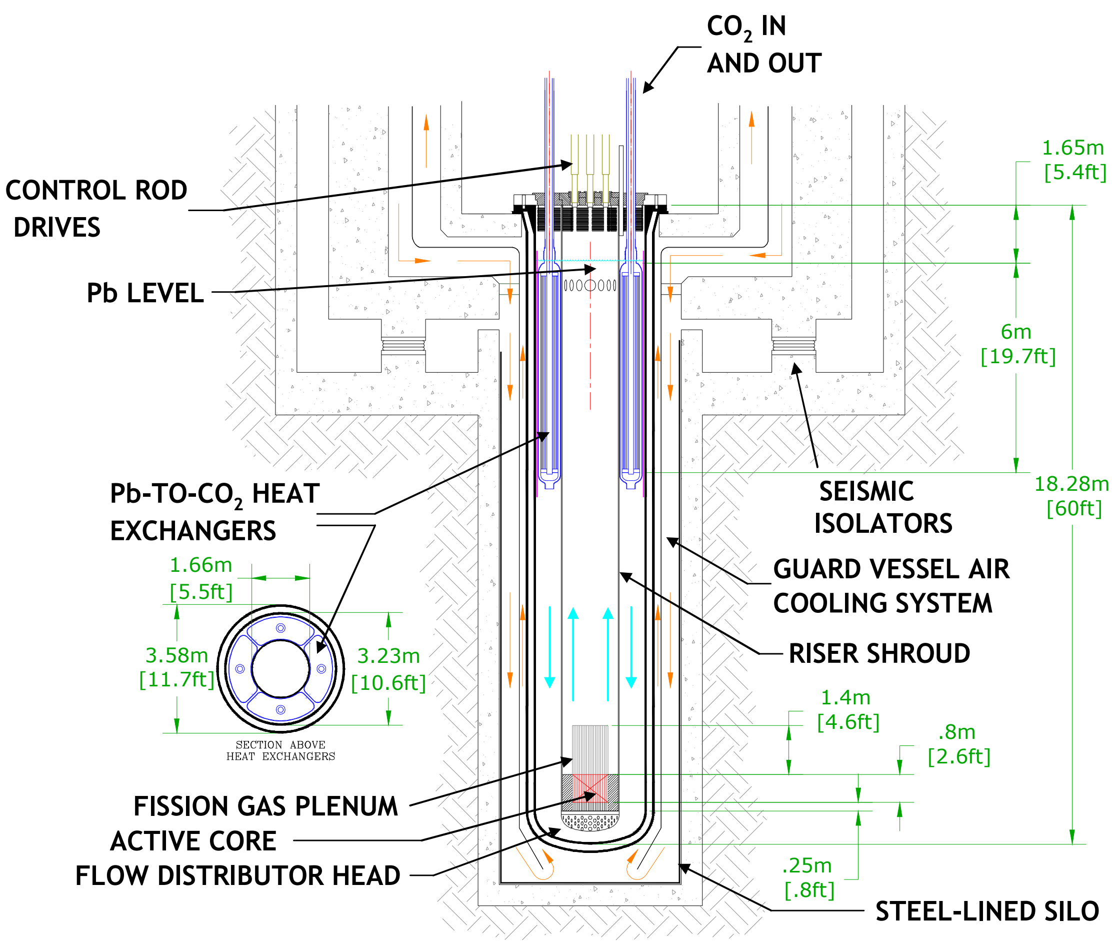

Figure 3. Illustration of SSTAR LFR.

The fuel pin cladding outer diameter is selected to minimize the peak cladding temperature for a fixed fuel volume fraction, fuel smeared density, and Pb core inlet temperature. Figure 4 shows the relationship between the fuel pin pitch-to-diameter ratio for a triangular lattice and the fuel pin diameter, for a fixed fuel volume fraction equal to 0.55, smear density of 90 %, and cladding thickness equal to 1.0 mm. The dependency of the peak cladding temperature (PCT) upon the fuel pin diameter for different core inlet temperatures is presented in Figure 5. A fuel pin diameter of 2.5 cm is selected. Figure 6 shows the dependency of peak cladding temperature upon core inlet temperature; for a 2.5 cm pin diameter, the PCT equals 650 °C for a core inlet temperature of 420 °C. As observed from Figure 7 the peak fuel centerline temperature is equal to 953 °C for the selected core inlet temperature and fuel pin diameter. Table 2 lists conditions calculated for SSTAR. The triangular pitch-to-diameter ratio of the in-reactor heat exchanger tubes has been selected to provide the 650 °C PCT at a 420 °C core inlet temperature.

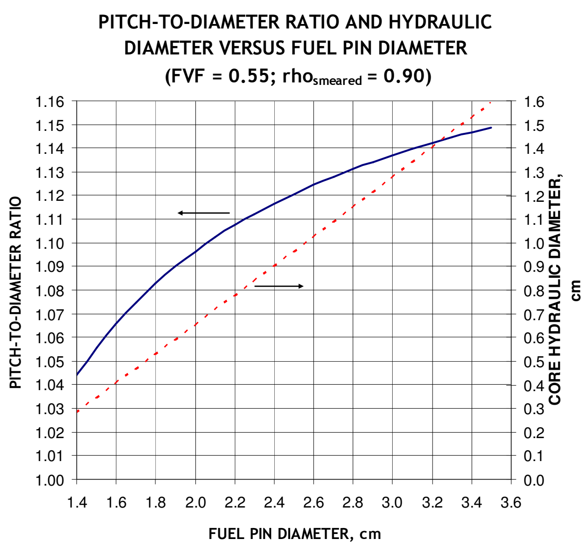

Figure 4. Relationship Between Fuel Pin Diameter and Triangular Pitch-to-Diameter Ratio for 0.55 Fuel Volume Fraction, 90 % Fuel Smeared Density, and 1.0 mm Cladding Thickness.

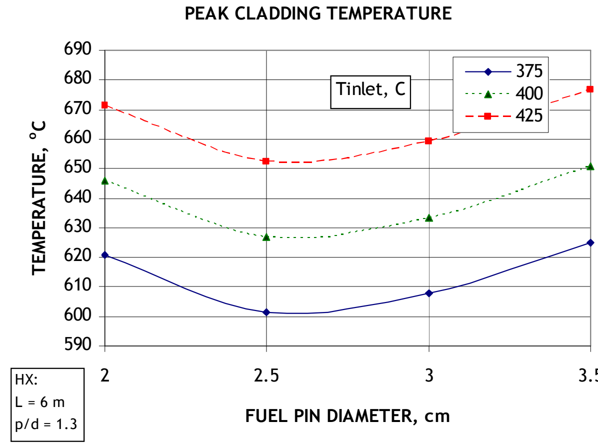

Figure 5. Peak Cladding Temperature versus Fuel Pin Outer Diameter.

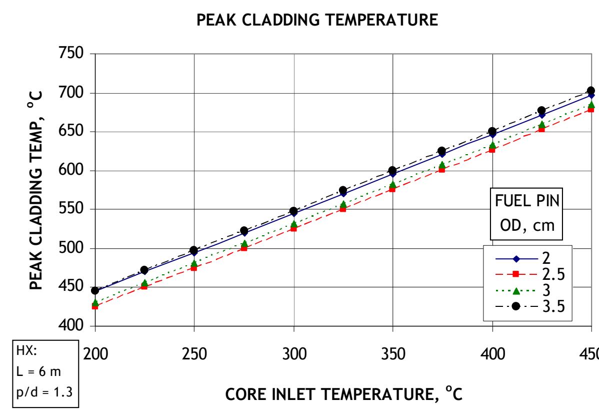

Figure 6. Peak Cladding Temperature versus Core Inlet Temperature.

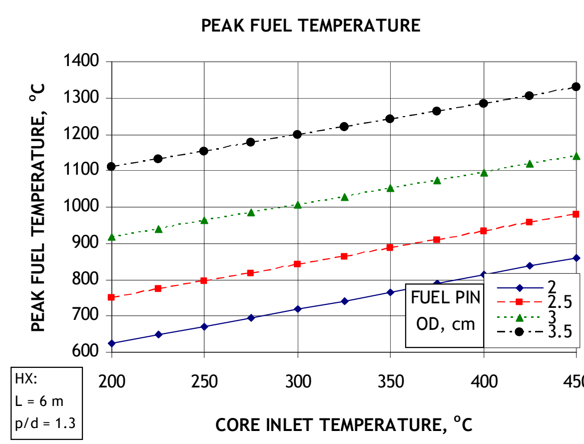

Figure 7. Peak Fuel Centerline Temperature versus Core Inlet Temperature.

Table 2. SSTAR Operating Conditions

Power, MWe (MWt)	19.8 (45)
Reactor Vessel Height, m (feet)	18.3 (60.0)
Reactor Vessel Outer Diameter, m (feet)	3.23 (10.6)
Active Core Diameter, m (feet)	1.02 (3.35)
Active Core Height, m (feet)	0.80 (2.62)
Active Core Height-to-Diameter Ratio	0.8
Fuel Volume Fraction	0.55
Fuel Pin Outer Diameter, cm	2.5
Fuel Pin Pitch-to-Diameter Ratio	1.121
Core Hydraulic Diameter, cm	0.964
Cladding Thickness, mm	1.0
Fuel Smeared Density, %	905
HX Tube Height, m	6.0
HX Tube Outer Diameter, cm	1.4
HX Tube Inner Diameter, cm	1.0
HX Tube Pitch-to-Diameter Ratio	1.242
HX Hydraulic Diameter for Pb Flow, cm	0.983
HX-Core Thermal Centers Separation Height, m	12.2
Peak Fuel Temperature, °C	953
Peak Cladding Temperature, °C	650
Core Outlet Temperature, °C	566
Maximum S-CO_2 Temperature, °C	553
Core Inlet Temperature, °C	420
Core Coolant Velocity, m/s	0.896
Pb Coolant Flowrate, Kg/s	2125
CO_2 Flowrate, Kg/s	242
CO_2 Mass in Brayton Cycle, Kg	8712
S-CO_2 Brayton Cycle Efficiency, %	44.4
Plant Efficiency, %	44.0

The SSTAR reactor is coupled to a supercritical carbon dioxide (S-CO_2) Brayton cycle power converter that provides a greater cycle efficiency than a helium ideal gas Brayton cycle or a Rankine saturated steam cycle operating at the same core outlet temperature. The general features of the S-CO_2 Brayton cycle are discussed in the literature[5-7]. The present discussion shall therefore be limited to SSTAR-specific attributes. Figure 8 is a schematic of SSTAR coupled to the S-CO_2 Brayton cycle showing the heat transfer paths as well alternative control mechanisms for the S-CO_2 Brayton cycle. The turbine and two compressors are connected via a common shaft. This enhances the cycle efficiency and reduces the required generator power. Conditions for the turbine and compressors are presented in Table 3. The turbomachinery components are observed to have remarkably small sizes suggesting that the plant footprint might be reduced relative to a helium ideal gas Brayton cycle or a Rankine saturated steam cycle. The power conversion plant also incorporates a shutdown cooling compressor to circulate CO_2 through the in-reactor heat exchangers and a shutdown cooler to reject decay heat while allowing S-CO_2 Brayton cycle components to be isolated for maintenance or repair.

The two recuperators and cooler are assumed to consist of Printed Circuit Heat Exchangers (PCHEs) in which 1.0 mm semi-circular channels are chemically etched into plates that are subsequently hot isostatically pressured together at sufficiently high temperature and pressure. Use of PCHEs offers the potential for savings in the recuperator and cooler volumes relative to traditional shell-and-tube heat exchangers. It also offers the potential for enhanced reliability and reduced requirements for inspection through elimination of the concerns about tube failures typical of shell-and-tube heat exchangers.

For the present analysis, it is assumed that the etched-plate manufacturing process limits the plate width to 0.6 m. To obtain the required heat exchange area, twelve such PCHEs are incorporated to realize each of the high temperature recuperator (HTR), low temperature recuperator (LTR), and cooler heat exchanger units. A concept was developed whereby the three components are assembled from three transportable modules. Each module consists of twelve PCHEs in total: four PCHEs with 2.0 m long channels belonging to the high temperature recuperator (located at the top); four PCHEs with 2.0 m long channels belonging to the low temperature recuperator (in the middle); and four PCHEs with 1.6 m long channels of the cooler (at the bottom). The PCHEs of each transportable module are supported by a steel space frame.

Pressures and temperatures calculated for the Pb and S-CO_2 circuits are shown on the schematic in Figure 9. A S-CO_2 Brayton cycle efficiency of 44.4 % is calculated. Subtracting off the pumping power requirement for the cooling water flowing through the cooler where heat is rejected from the cycle, a net plant efficiency of 44.0 % is obtained.

Figure 10 shows a plan view of an arrangement of S-CO_2 Brayton cycle components inside of the turbine generator building. The turbine and two main compressors are housed inside of a power conversion unit coupled to a commercially available generator through a gearbox. The inventory control volume consists of a number of cylindrical tanks connected to manifolds.

Table 3. Results of Turbine and Compressor Analyses for 45 MWt SSTAR

	Turbine	Compressor No. 1	Compressor No. 2
Power, MW	31.2	4.83	5.74
Number of Stages	5	10	10
Rotational Speed, rev/s	180	180	180
Length without Casing, m	0.41	0.26	0.13
Maximum Diameter without Casing, m	0.38	0.14	0.21
Minimum Hub Diameter, m	0.214	0.108	0.184
Maximum Hub Diameter, m	0.288	0.116	0.194
Minimum Blade Height, cm	3.1	1.3	0.5
Maximum Blade Height, cm	4.4	1.9	1.0
Minimum Blade Chord, cm	3.3	1.2	0.6
Maximum Blade Chord, cm	5.1	1.5	0.8
CO_2 Flowrate, Kg/s	242	162	80
Efficiency without Secondary Losses, %	96.0	92.4	90.5
Assumed Secondary Losses, %	5.0	5.0	5.0
Net Efficiency, %	91.0	87.4	85.5

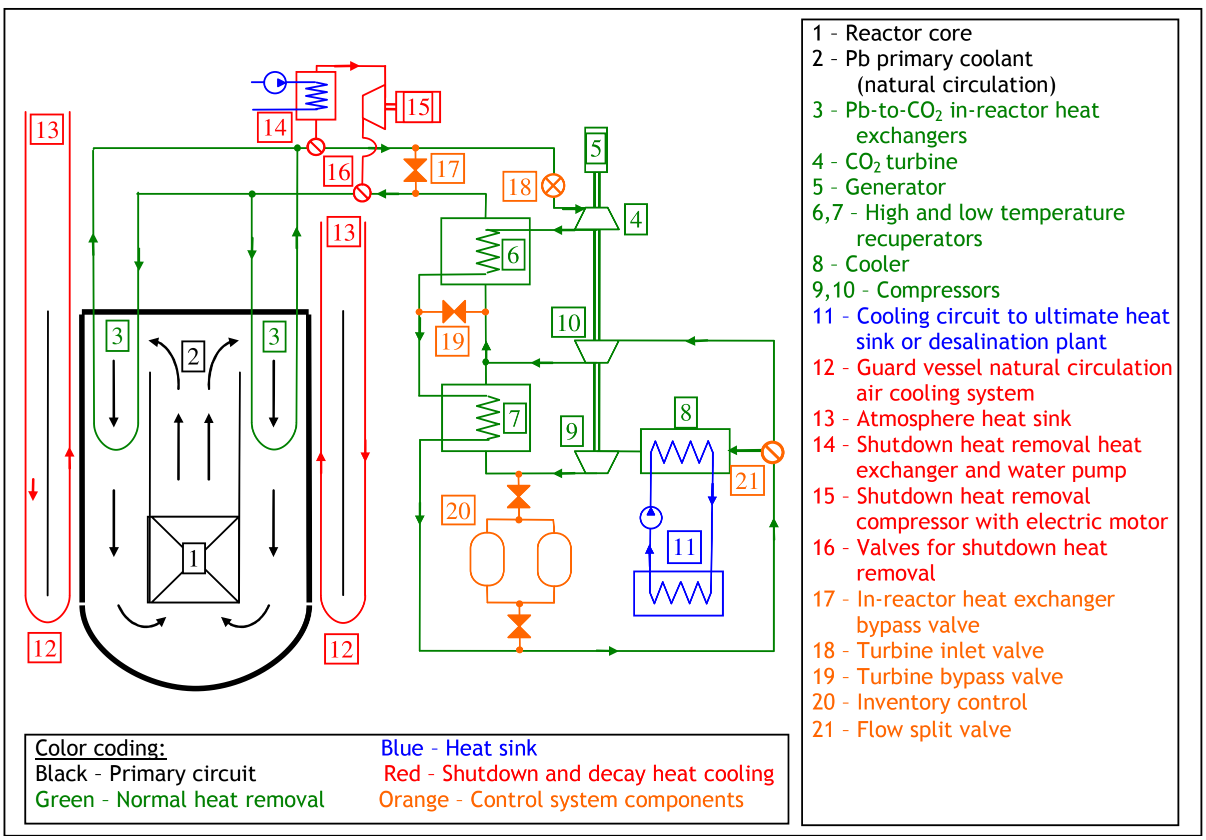

Figure 8. Schematic Illustration of SSTAR Coupled to S-CO_2 Brayton Cycle Showing Normal, Shutdown, and Emergency Heat Transfer Paths.

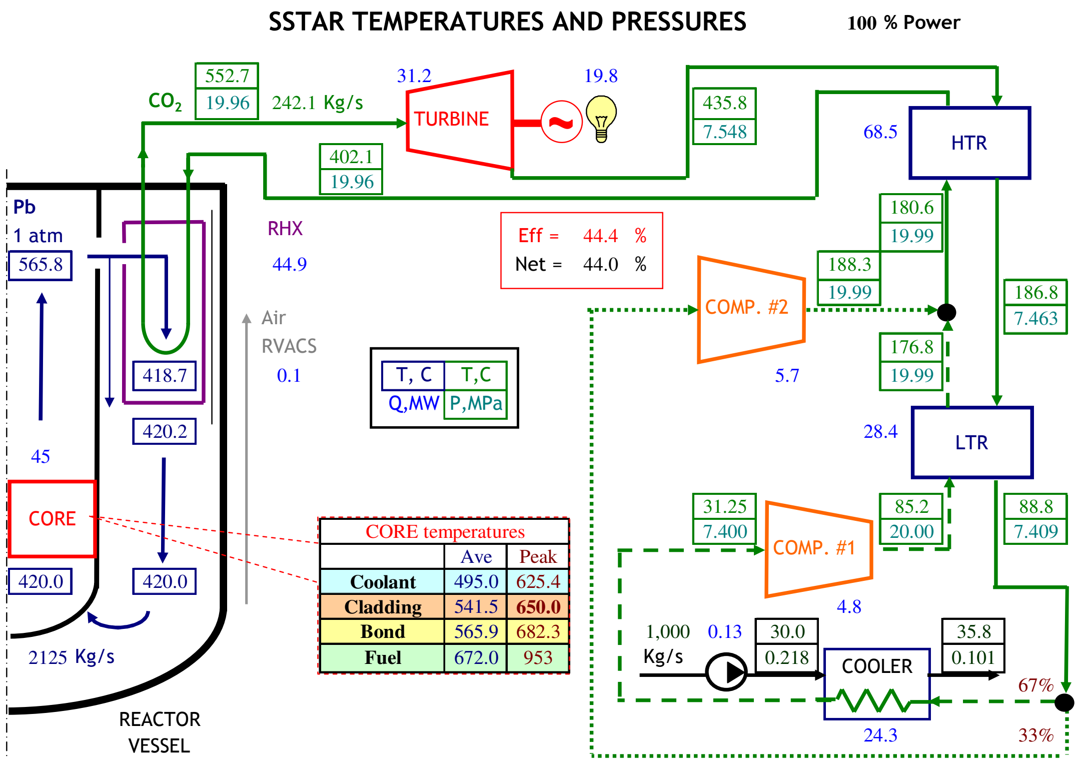

Figure 9. Schematic Illustration of SSTAR Coupled to S-CO_2 Brayton Cycle Showing Temperature, Pressures, Flowrates, and Heat Exchange Rates.

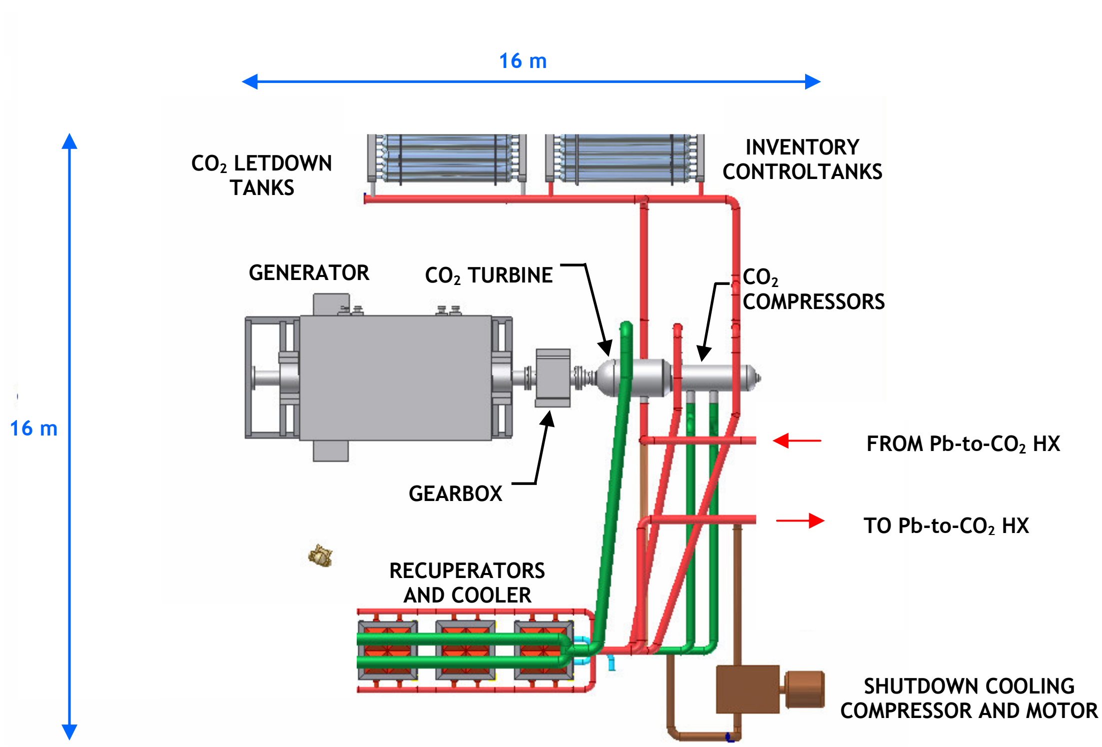

Figure 10. SSTAR S-CO_2 Brayton Cycle Layout.

IV. SUMMARY

Results of preconceptual core neutronics and system thermal hydraulics calculations indicate that a SSTAR Pb-cooled, single-phase natural circulation, proliferation resistant, and passively safe small modular fast reactor concept with a 20-year core lifetime, good core reactor physics performance, good system thermal hydraulics performance, and a high plant efficiency of 44 % ($S-CO_2$ gas turbine Brayton cycle efficiency of 44.4 %) may be viable at an electrical power level of 20 MWe (45 MWt). In particular, the SSTAR concept achieves a maximum average discharge burnup of 72 MWd/Kg HM, a maximum burnup reactivity swing during the 20-year core lifetime of less than one dollar, and a mean core temperature rise of 146 °C while the peak fuel pin cladding structural temperature is limited to 650 °C.

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REFERENCES

1. U.S. DEPARTMENT OF ENERGY, OFFICE OF NUCLEAR ENERGY, SCIENCE AND TECHNOLOGY, "Report to Congress on Small Modular Reactors," May 2001.

2. J. J. SIENICKI, A.V. Moisseytsev, D.C. Wade, M.T. Farmer, C.P. Tzanos, J.A. Stillman, J.W. Holland, P.V. Petkov, I.U. Therios, R.F. Kulak, and Q.U. Wu, "The STAR-LM Lead-Cooled Closed Fuel Cycle Fast Reactor with a Supercritical Carbon Dioxide Brayton Cycle Advanced Power Converter," *Russian Forum for Science and Technology FAST NEUTRON REACTORS, The Second International Conference on Heavy Liquid Metal Coolants in Nuclear Technologies (HLMC-2003)*, Paper 2105, Obninsk, Russia, December 8-12, 2003.

3. D.C. WADE, R. Doctor, J.J. Sienicki, R. Faibish, A. Moisseytsev, and D. Matonis, " STAR-H2: A Long-Refueling Interval Battery Reactor for Hydrogen and Water Supply to Cities of Developing Countries," *5th International Conference on Nuclear Options in Countries with Small and Medium Electricity Grids*, Dubrovnik, Croatia, May 16-20, 2004.

4. W.S. YANG, M.A. Smith, A.V. Moisseytsev, J.J. Sienicki, and D.C. Wade, "Lead-Cooled, Long-Life Fast Reactor Design for Remote Deployment," *2005 International Conference on Advances in Nuclear Power Plants, ICAPP 2005*, Seoul, May 15-19, 2005.

5. V. DOSTAL, M.J. Driscoll, P. Hejzlar, and N.E. Todreas, "A Supercritical CO_2 Gas Turbine Power Cycle for Next Generation Nuclear Reactors," ICONE 10-22192, *Proceedings of ICONE10, Tenth International Conference on Nuclear Engineering*, Arlington, April 14-18, 2002.

6. A.V. MOISSEYTSEV, J.J. Sienicki, and D.C. Wade, "Cycle Analysis of Supercritical Carbon Dioxide Gas Turbine Brayton Cycle Power Conversion System for Liquid Metal-Cooled Fast Reactors," ICONE11-36023, *11th International Conference on Nuclear Engineering*, Tokyo, April 20-23, 2003.

7. A.V. MOISSEYTSEV, J.J. Sienicki, and D.C. Wade, "Turbine Design for a Supercritical Carbon Dioxide Gas Turbine Brayton Cycle," Paper 3064, *Proceedings of ICAPP '03, 2003 International Congress on Advances in Nuclear Power Plants*, Córdoba, Spain, May 4-7, 2003.