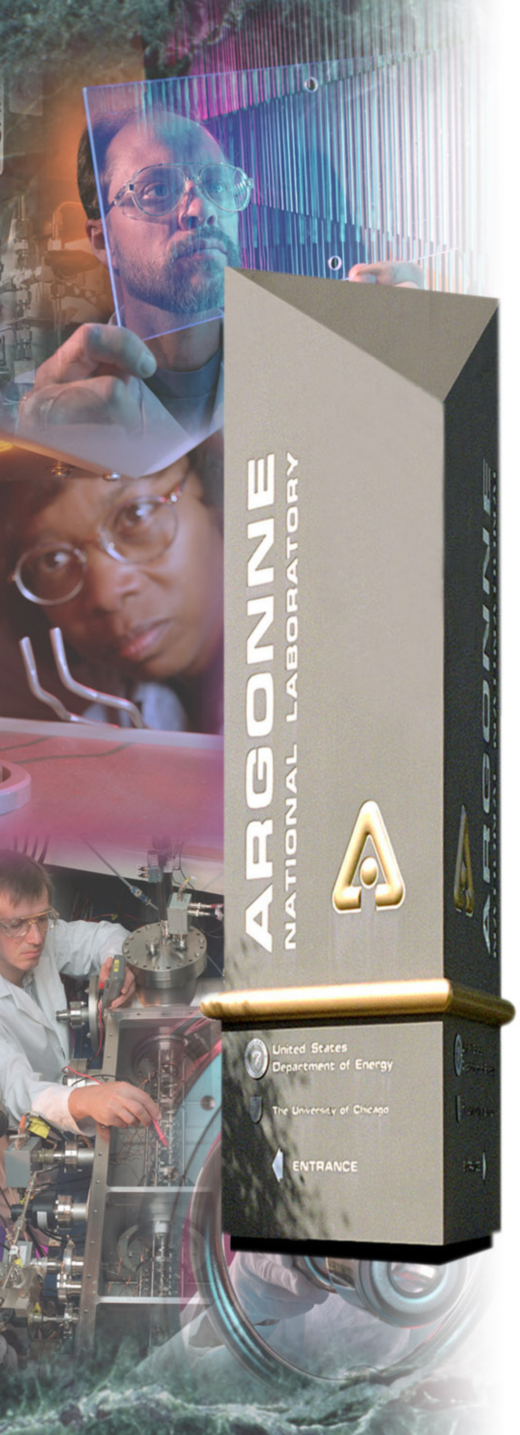

A Small Secure Transportable Autonomous Lead-Cooled Fast Reactor for Deployment at Remote Sites

by

James J. Sienicki, Micheal A. Smith,
Anton V. Moisseytsev, Won Sik Yang,
and David C. Wade
Argonne National Laboratory
sienicki@anl.gov

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Small Modular Reactors for Remote Sites

- **Mission - Electricity generation to match needs of developing nations and remote communities without electrical grid connections**
  - Alaska, Hawaii, island nations of the Pacific Basin (Indonesia), and elsewhere
  - Niche market within which costs that are higher than those for large-scale nuclear power plants are competitive
- **"Report to Congress on Small Modular Reactors," U.S. Department of Energy, May 2001**
  - "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."

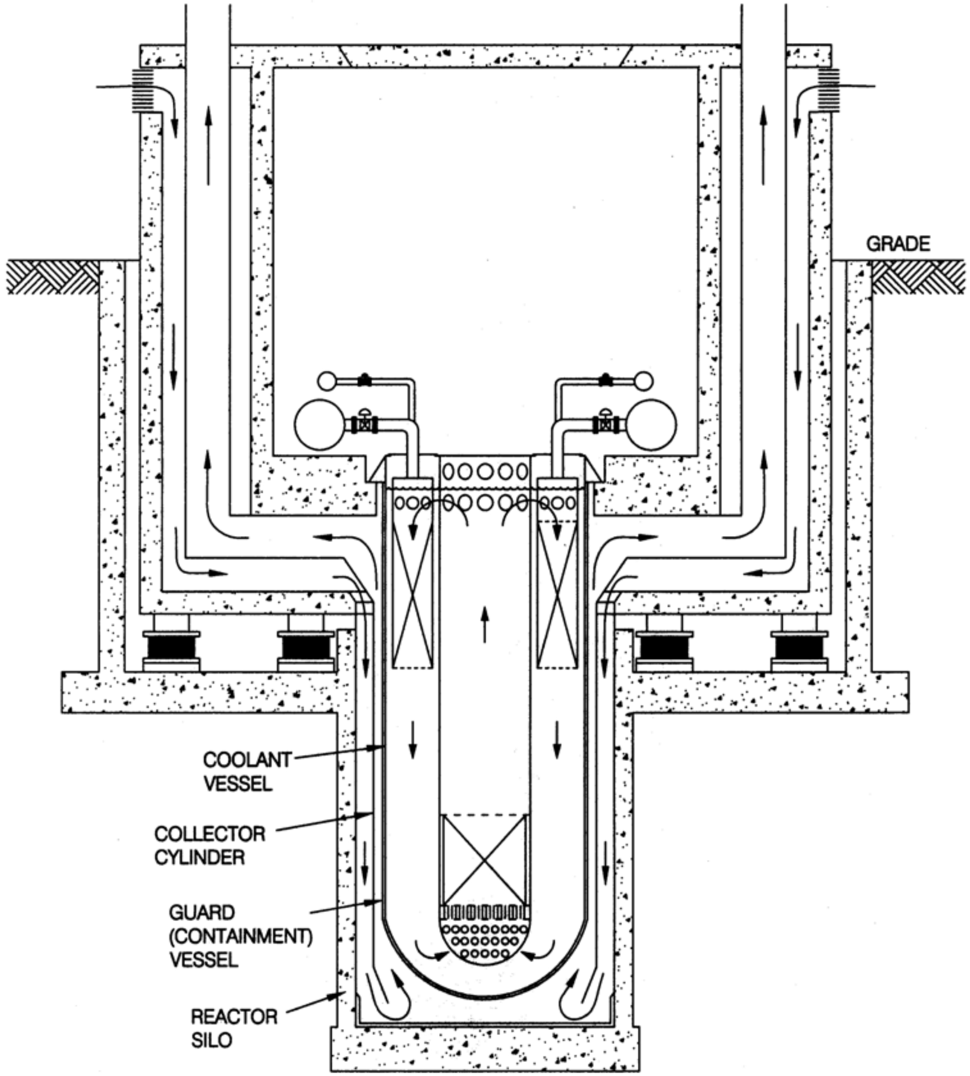
Small Secure Transportable Autonomous Reactor (SSTAR)

- **Current concept under investigation is 18 MWe (45 MWt)**
- **Proliferation resistance**
  - Core lifetime/refueling interval of 15, 20, or 30 years
  - Restrict access to fuel during core lifetime
  - Transuranic fuel – Self protective in the safeguards sense
- **Molten lead (Pb) primary coolant – Nitride fuel**
  - Passive safety
- **Autonomous operation**
  - Core power adjusts itself to heat removal from reactor system due to large inherent reactivity feedbacks without operator motion of control rods
  - Active adjustment of control rods for burnup compensation, startup, and shutdown
- **Fissile self-sufficient (Conversion ratio near unity)**
  - Realization of sustainable closed fuel cycle

Small Secure Transportable Autonomous Reactor (SSTAR)

- **Utilizes supercritical carbon dioxide (S-CO_2) gas turbine Brayton cycle power converter**
  - Higher plant efficiency than Rankine saturated steam cycle
  - Reduce balance of plant costs
- **Natural circulation primary coolant heat transport**
  - Eliminate main coolant pumps
- **Factory fabrication**
  - All reactor and balance of plant components including reactor and guard vessels
- **Assembly of components into transportable modules**
  - Short modular installation and assembly times at site
- **Full transportability by barge, rail, or road**
- **Flexibility to be adapted to generate other energy products**
  - Desalinated water or hydrogen

Illustration of Lead-Cooled Fast Reactor



Pb Coolant

- **Enhanced passive safety**
  - Chemically inert – Does not react chemically with CO_2 working fluid above ~ 250 °C. Does not react vigorously with air or water/steam
  - High boiling temperature of 1740 °C for Pb (1670 °C for Pb-Bi eutectic) - Core and heat exchangers remain covered by ambient pressure single-phase primary coolant and single-phase natural circulation removes core power under all operational and postulated accident conditions
- **Potential to operate at higher temperatures than traditional liquid metal-cooled fast reactors**
  - Peak cladding temperature of ~ 650 °C
- **Two lead-bismuth eutectic (LBE)-cooled land prototypes and ten submarine reactors were operated in Russia providing about 80 reactor years experience**
  - Development of coolant technology and control of structural material corrosion

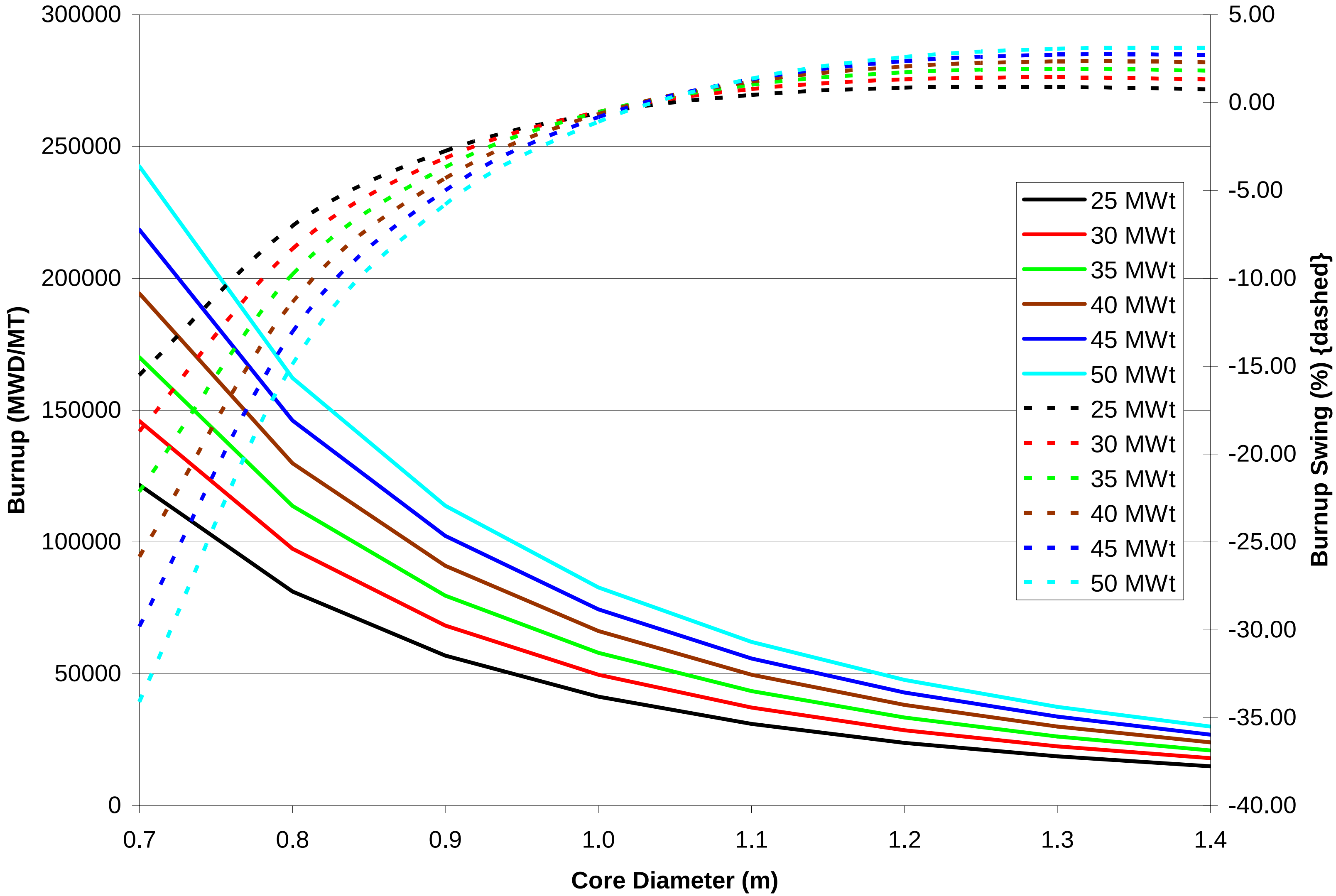
Nitride Fuel

- **Enhanced passive safety**
  - High melting temperature (> 2600 °C for UN)
  - High temperature for significant decomposition of nitride (> 1500 °C)
  - High thermal conductivity that together with Pb bond between fuel and cladding reduces the fuel-coolant temperature difference
- **Compatible with fast neutron spectrum**
  - High atom density
  - Nitrogen is enriched in N^{15} to eliminate parasitic captures
- **Compatible with ferritic-martensitic stainless steel cladding and Pb coolant**
  - N is insoluble in Pb
  - Bonded to cladding by molten Pb
- **Low irradiation-induced swelling and fission gas release**

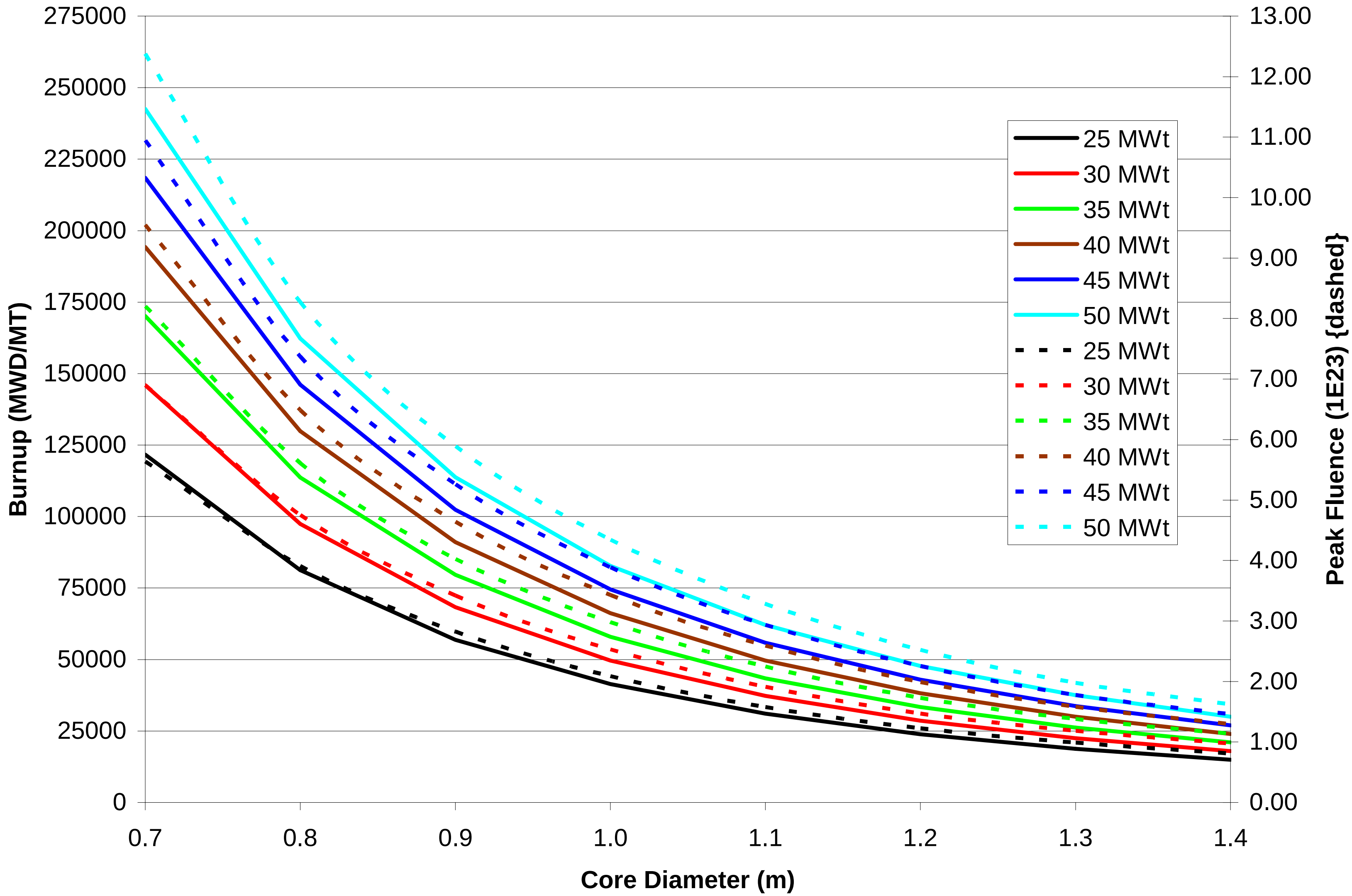
18 MWe (45 MWt)

- **Optimal power level for a 20 year core lifetime, fixed fuel volume fraction of 0.55, fuel smeared density of 85 %, and core height-to-diameter ratio of 0.8**
  - Minimizes maximum burnup reactivity swing over core lifetime
  - Maximizes average discharge burnup limited by fluence limit
- **Transuranic (TRU) fuel feed from LWR spent fuel following 25-year cooling time - Allows for decay of Pu^{241} isotope**
- **Low enrichment central region to reduce burnup swing**
- **Fuel volume fraction of 0.55 is low enough to facilitate natural circulation heat transport from core to Pb-to-CO_2 heat exchangers**
- **Seek to minimize burnup reactivity swing to less than one dollar**
- **Seek to maximize average discharge burnup**
  - Target of 100 MWd/Kg Heavy Metal
- **Fast neutron fluence limit of 4.0 x 10^{23} n/cm^2 on ferritic-martensitic stainless steel cladding**

Average Discharge Burnup and Burnup Reactivity Swing versus Core Size



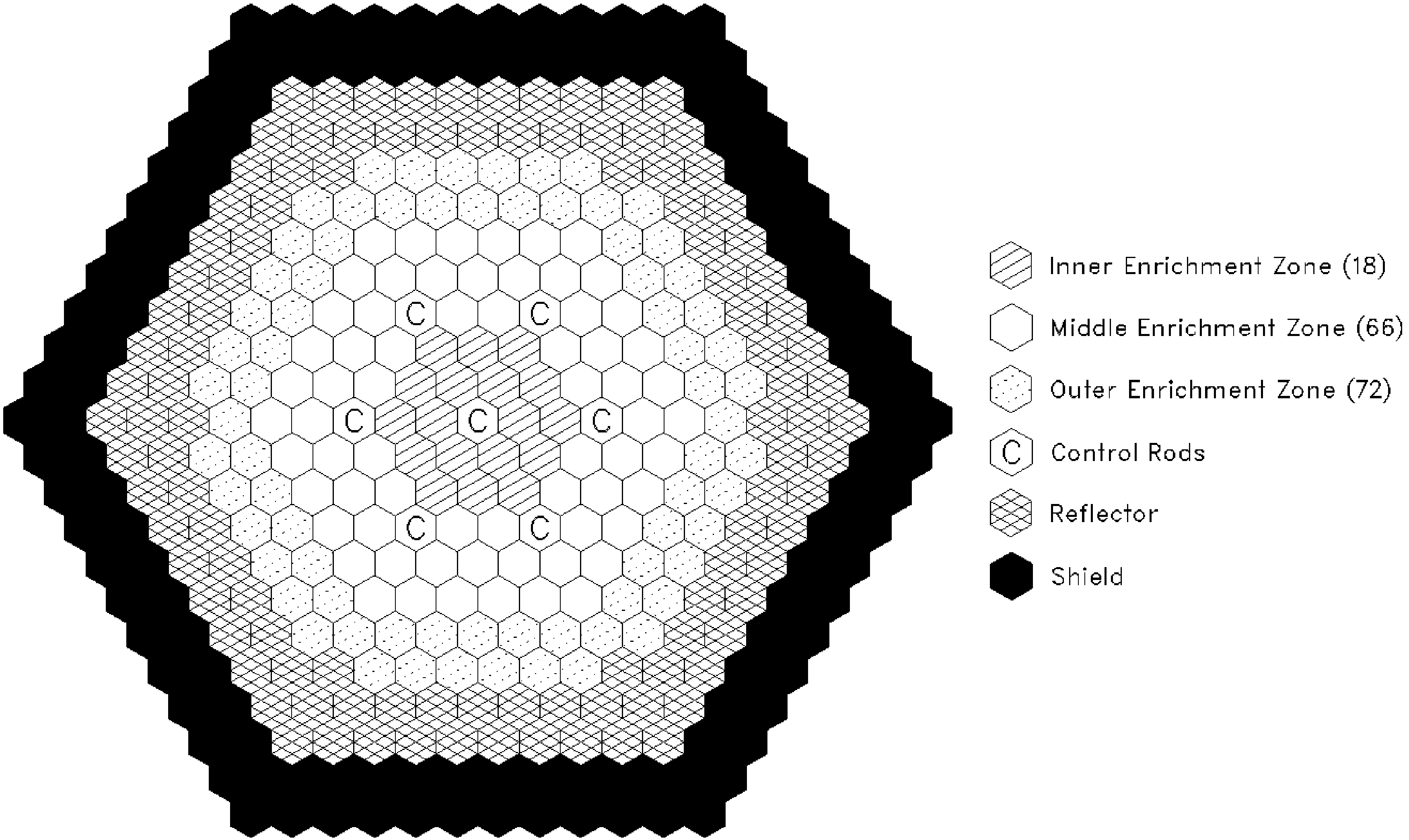
Average Discharge Burnup and Peak Fluence versus Core Size



SSTAR Core Neutronics Analyses

- **Active core diameter of about 1.0 meter minimizes the burnup reactivity swing for 20 year core lifetime, 0.55 fuel volume fraction, and 85 % fuel smeared density**
  - For fixed active core diameter, raising the core power increases the average discharge burnup
- **Average discharge burnup is limited by the peak fast fluence limit**
  - Occurs at a core power of about 45 to 50 MWt for 20 year lifetime
- **45 MWt selected as optimum**
  - Specific to assumed 20 year core lifetime, fuel volume fraction of 0.55, and 85 % smeared density
- **More detailed geometry calculations were performed for 45 MWt core to determine core performance**

Assumed Core Layout/Nodalization



45 MWt SSTAR Neutronics Conditions

Core Diameter (m)	1.02
Active Core Height (cm)	80
Fuel Smear Density (%)	85
Fuel Volume Fraction	0.55
Cladding Volume Fraction	0.16
Bond Volume Fraction	0.10
Coolant Volume Fraction	0.18

45 MWt SSTAR Neutronics Performance

Average Power Density (W/cm^3)	69
Specific Power (KW/KgHM)	10
Peak Power Density (W/cm^3)	119
Peak Linear Power (W/cm)	411
Average Discharge Burnup (MWd/Kg)	72
Peak Discharge Burnup (MWd/Kg)	120
Peak Fast Fluence (10^{23} n/cm^2)	3.6
BOC to EOC Burnup Swing (% delta rho)	0.13
Maximum Burnup Swing (% delta rho)	0.36
Estimated Delayed Neutron Fraction (Beta)	0.00375
BOC to EOC Burnup Swing ($)	0.35
Maximum Burnup Swing ($)	0.96

Supercritical Carbon Dioxide Gas Turbine Brayton Cycle Power Conversion

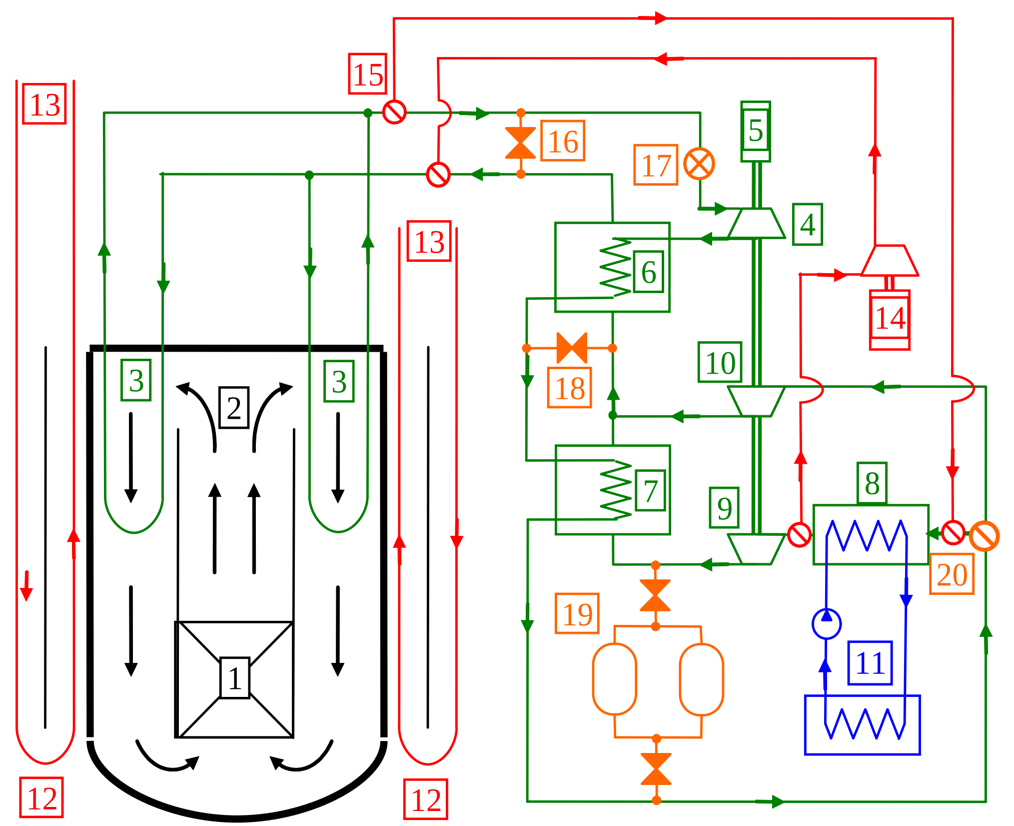
- **Potential improvements over traditional Rankine saturated steam cycle**
  - Higher cycle efficiency at operating temperatures attainable with Pb primary coolant
  - Smaller and simpler secondary side components than Rankine cycle with potential for cost and staffing reductions – Turbine and compressors have remarkably small sizes
  - Waste heat can be partially rejected at high temperatures for other applications such as desalination
- **Potential benefits follow from high density and low work required to compress S-CO_2 immediately above the critical point**
- **A commercial-scale S-CO_2 Brayton cycle plant has never been constructed and operated – Significant development and demonstration required**

Supercritical Carbon Dioxide Gas Turbine Brayton Cycle Power Conversion

- **Remarkably small turbine and compressor sizes reflecting high S-CO_2 density**

Fluid	Location	Pressure, MPa	Temperature, ° C	Density, Kg/m^3
S-CO_2(SSTAR)	Critical point Cooler outlet Compressor outlet Turbine inlet Turbine outlet	7.37 7.40 20.0 19.99 7.44	30.98 31.25 84.0 541 420	468 369 567 126 56.8
Helium (Eskom PBMR)	Cooler outlet/ Compressor inlet Compressor outlet	2.6 7.0	27 104	4.17 8.93
Water		0.1	20	998
Lead		0.1	495	10400
Sodium		0.1	420	828

Schematic of SSTAR Coupled to S-CO_2 Brayton Cycle Showing Heat Transfer Paths

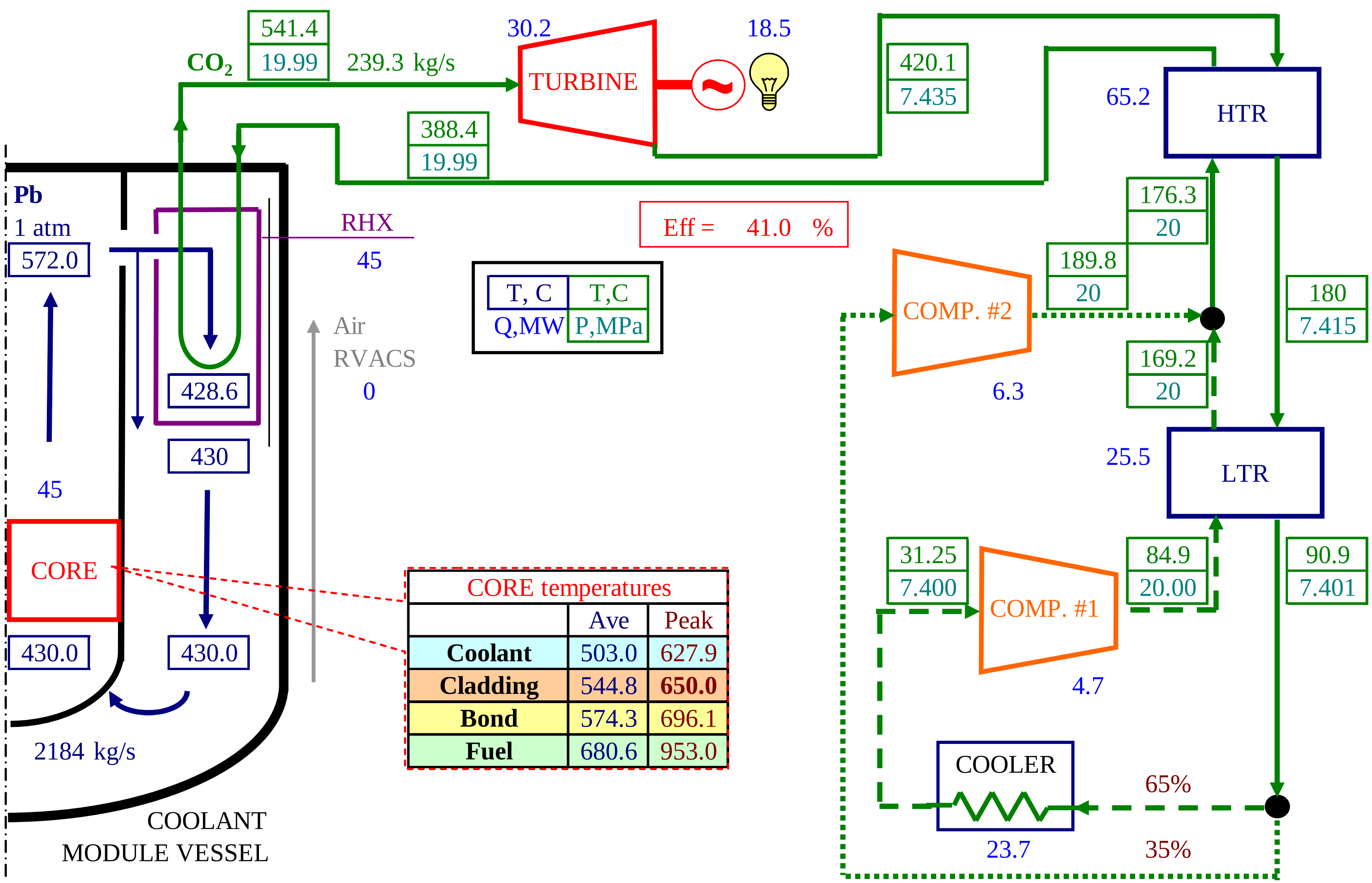


1 – Reactor core
2 – Pb primary coolant (natural circulation)
3 – Pb-to-CO_2 in-reactor heat exchanger
4 – CO_2 turbine
5 – Generator
6,7 – High and low temperature recuperators
8 – Cooler
9,10 – Compressors
11 – Cooling circuit to ultimate heat sink or desalination plant
12 – Guard vessel natural circulation air cooling system
13 – Atmosphere heat sink
14 – Normal shutdown heat removal compressor with electric motor
15 – Valves for shutdown heat removal
16 – In-reactor heat exchanger bypass valve
17 – Turbine inlet valve
18 – Turbine bypass valve
19 – Inventory control
20 – Flow split valve

Color coding:
Black – Primary circuit
Green – Normal heat removal
Blue – Heat sink
Red – Shutdown/emergency heat removal
Orange – Control system components

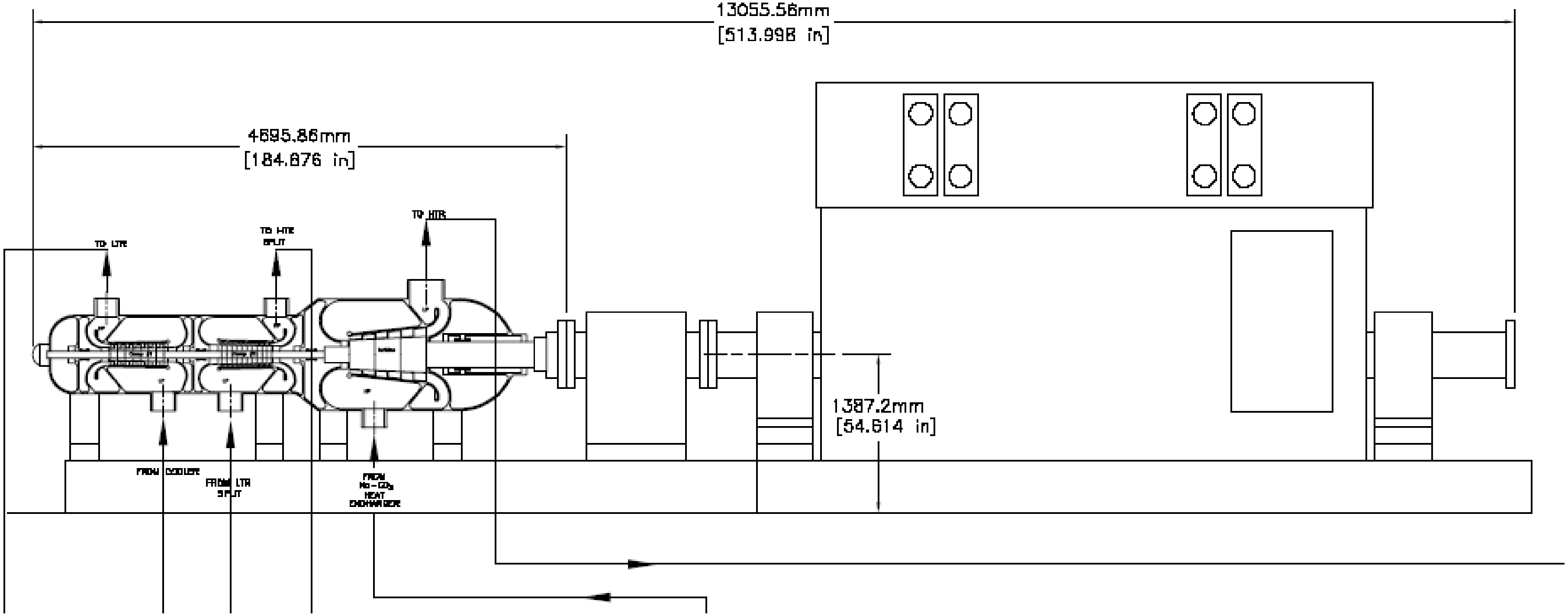
Schematic of SSTAR Coupled to S-CO_2 Brayton Cycle Showing Nominal Conditions

SSTAR CONCEPT TEMPERATURES AND PRESSURES 100 % POWER

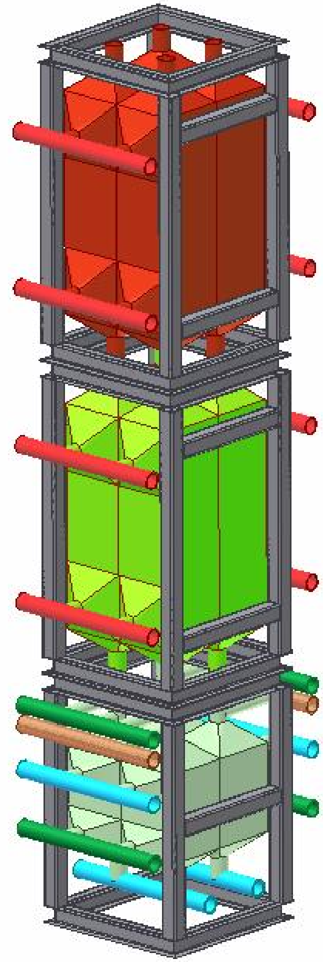


CORE temperatures		
	Ave	Peak
Coolant	503.0	627.9
Cladding	544.8	650.0
Bond	574.3	696.1
Fuel	680.6	953.0

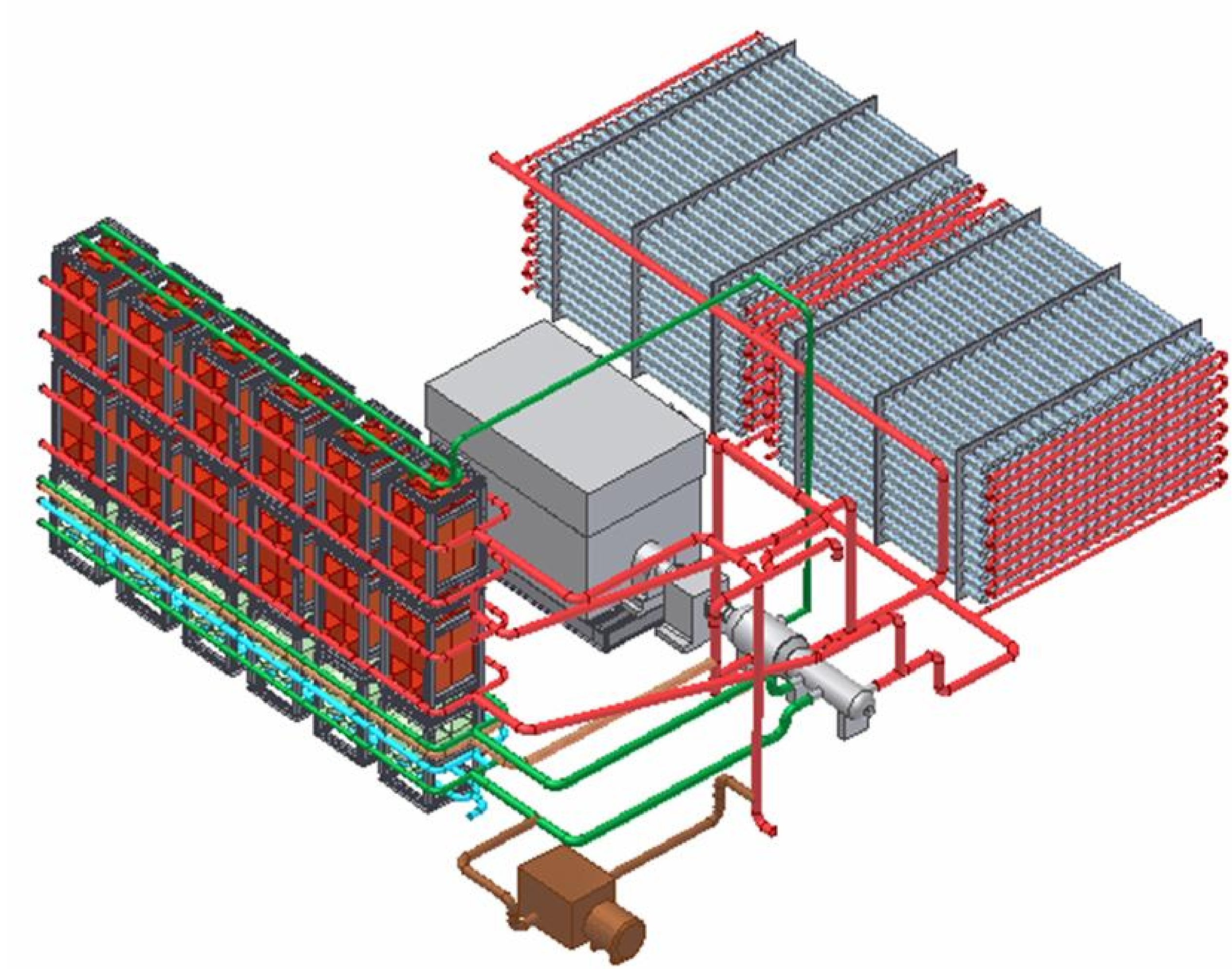
$S\text{-}CO_2$ Power Conversion Unit Housing Turbine and Two Compressors Connected to Generator



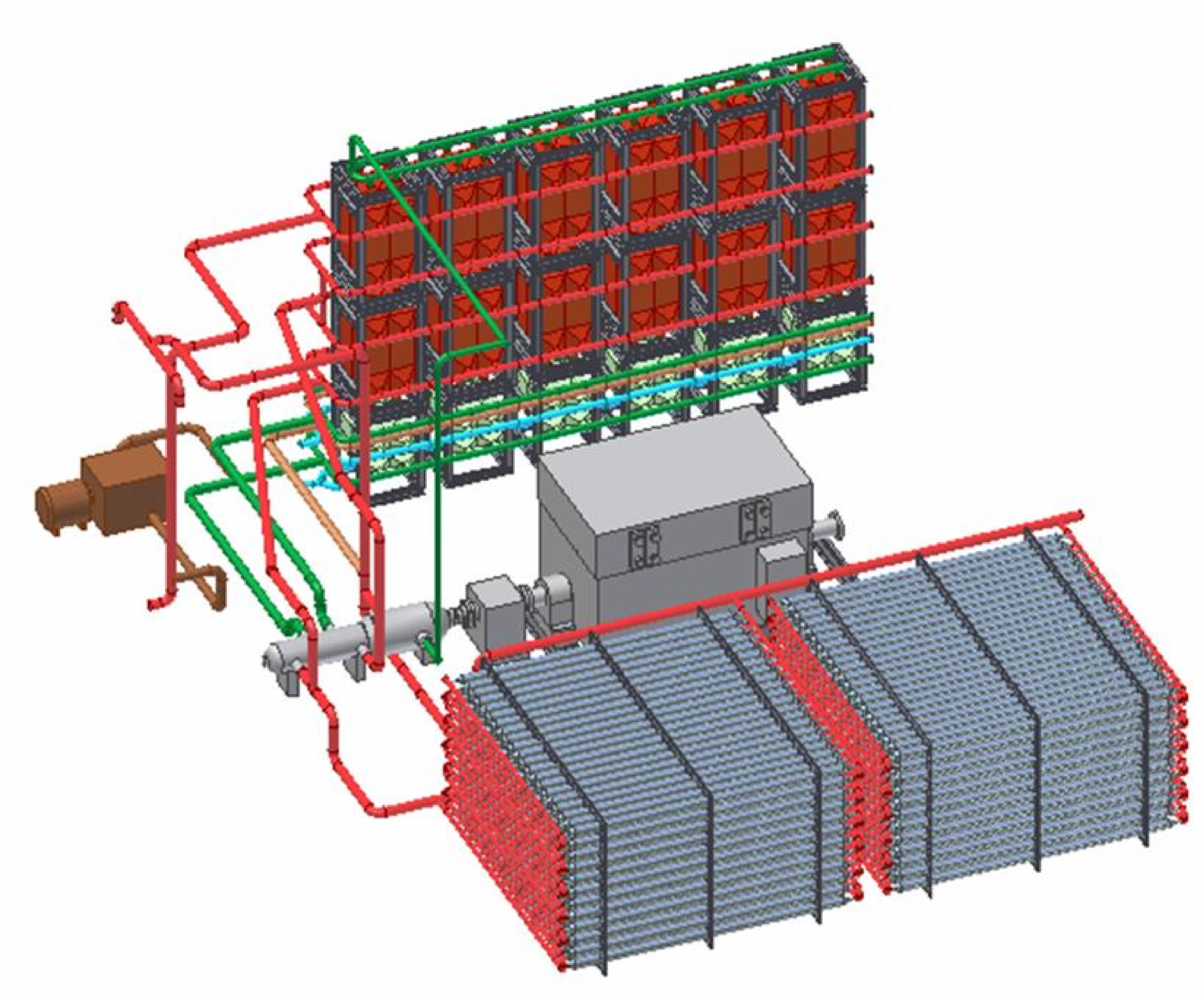
Transportable Module with Printed Circuit Heat Exchangers for HTR, LTR, and Cooler



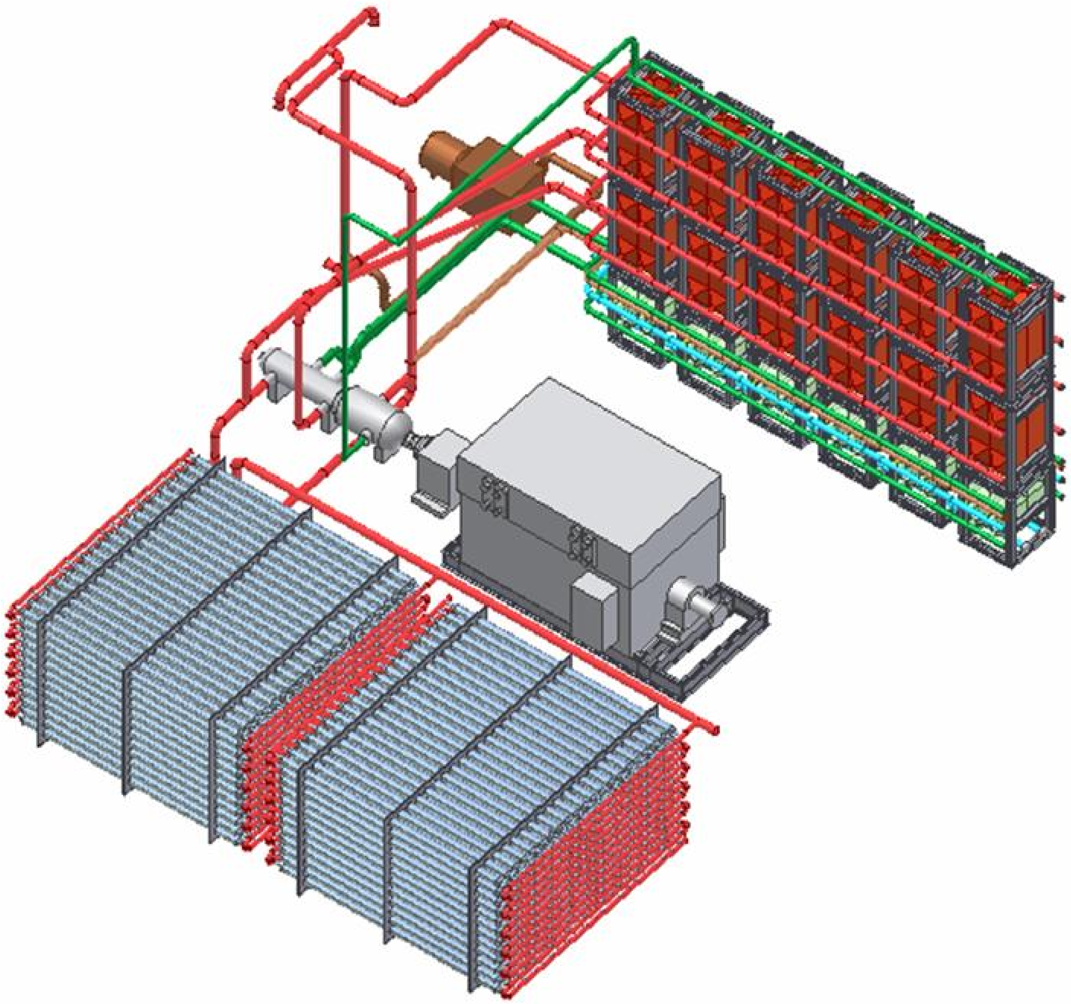
Supercritical CO_2 Brayton Cycle Layout



Supercritical CO_2 Brayton Cycle Layout



Supercritical CO_2 Brayton Cycle Layout

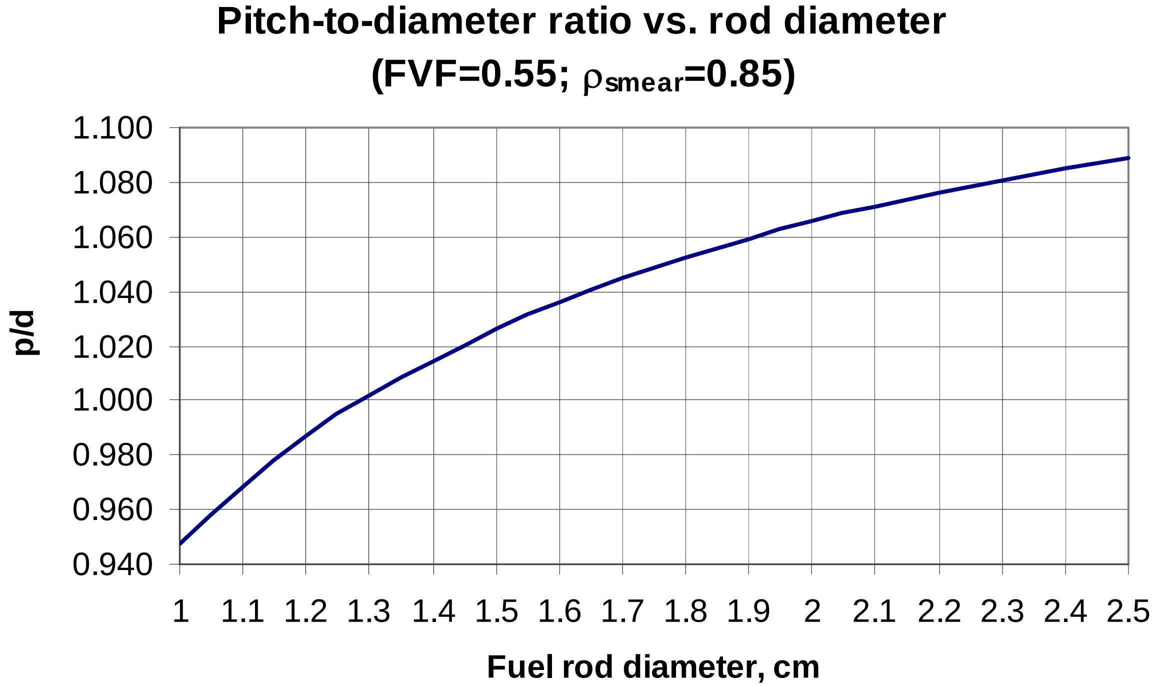


What determines the reactor vessel size?

- **Transportability by road assumed as a goal**
  - Approximate flatbed trailer size limitations are a 12.2 m (40 feet) length by 2.4 m width (8 feet)
  - Greater widths are possible for an oversized load
- **Need to fit core and other components inside of vessel diameter**
  - 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
  - Annular Pb-to-CO_2 heat exchangers must fit inside of annulus and provide sufficient heat exchange performance to realize a significant Brayton cycle efficiency

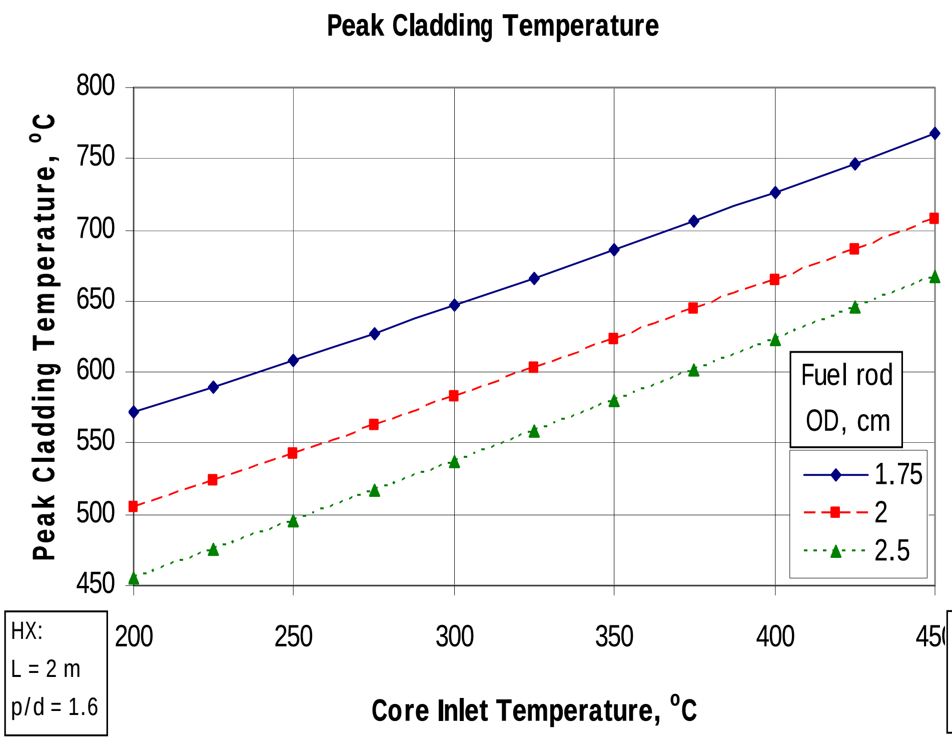
What determines the fuel pin diameter?

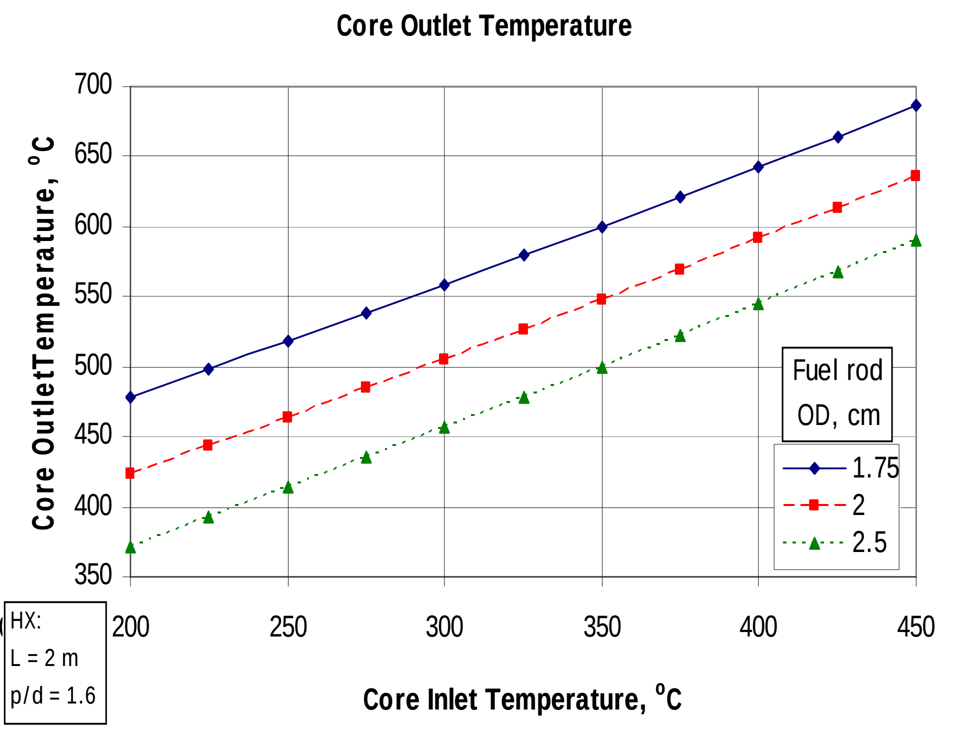
- **Optimal value that minimizes the peak cladding temperature for a fixed fuel volume fraction of 0.55, fuel smeared density of 85 %, and Pb core inlet temperature**
  - Assume fixed cladding thickness = 0.1 cm
- **Relationship between fuel pin diameter and pitch-to-diameter ratio**



What determines the fuel pin diameter?

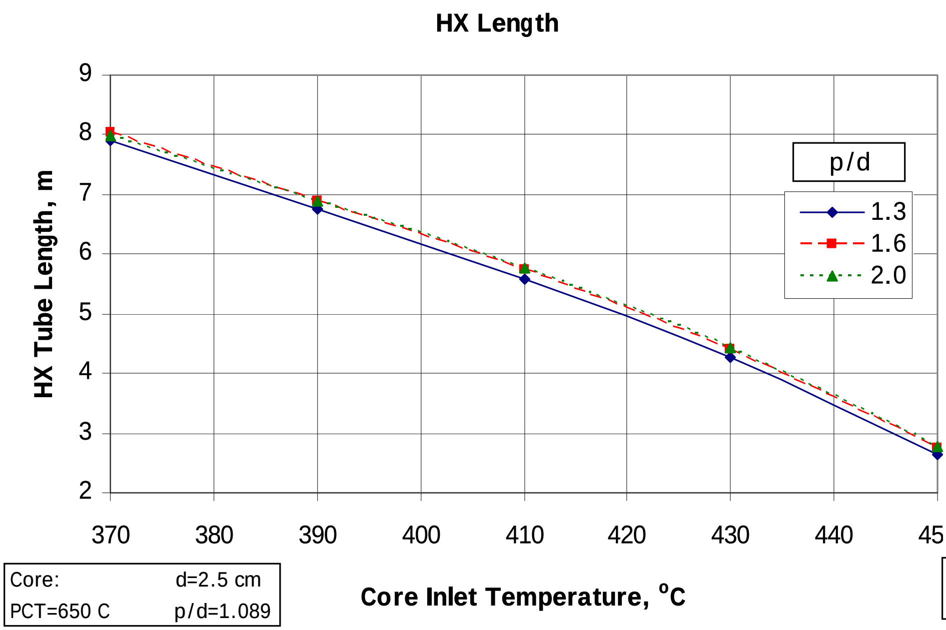
- **Also minimizes the core outlet temperature**
  - Calculations temporarily reduced frictional losses in Pb-to-CO_2 heat exchangers

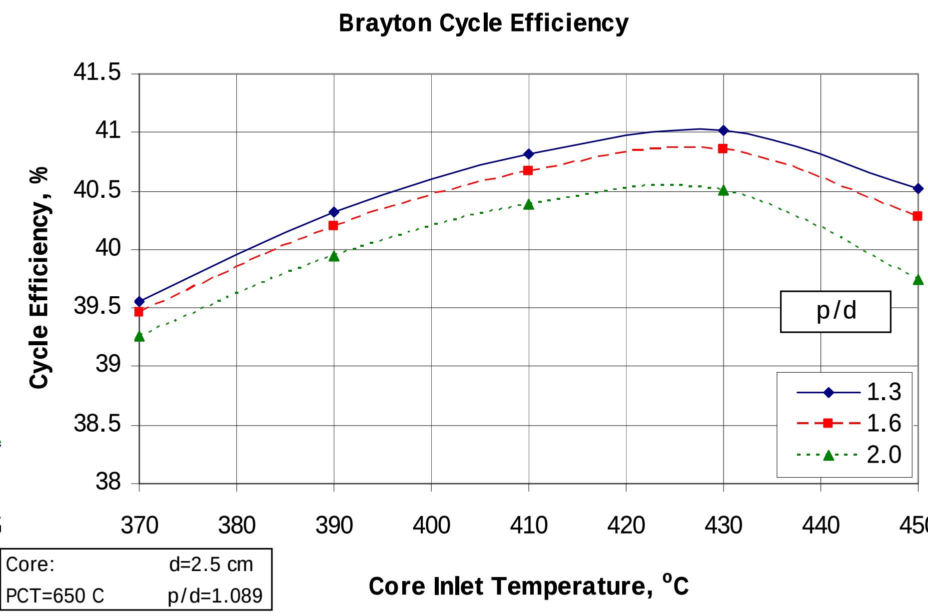




What determines the HX tube dimensions?

- **Tube length and pitch-to-diameter ratio that provide 650 °C peak cladding temperature and maximize Brayton cycle efficiency**





45 MWt SSTAR Thermal Hydraulics Analyses

• Power	45 MWt (18.5 MWe)
• Reactor vessel height	12.19 m (40.0 feet)
• Reactor vessel outer diameter	3.23 m (10.6 feet)
• Active core diameter	1.02 m (3.35 feet)
• Active core height	0.80 m (2.62 feet)
• Active core height-to-diameter ratio	0.8
• Fuel volume fraction	0.55
• Fuel pin outer diameter	2.5 cm
• Fuel pin pitch-to-diameter ratio	1.089
• Core hydraulic diameter	0.769 cm
• Cladding thickness	0.1 cm
• Fuel smeared density	85 %

45 MWt SSTAR Thermal Hydraulics Analyses

• HX tube height	4.26 m
• HX tube outer diameter	1.4 mm
• HX tube inner diameter	1.0 mm
• HX tube pitch-to-diameter ratio	1.3
• HX hydraulic diameter for Pb flow	1.21 cm
• HX-core thermal centers separation height	6.95 m
• Peak cladding temperature	650 ☜C
• Core outlet temperature	572 ☜C
• Maximum S-CO_2 temperature	541 ☜C
• Core inlet temperature	430 ☜C
• Core coolant velocity	1.09 m/s
• Pb coolant flowrate	2184 Kg/s
• CO_2 flowrate	239 Kg/s
• Brayton cycle efficiency	41.0 %

Summary

- **Results of preconceptual core neutronics and system thermal hydraulics calculations indicate that a single-phase natural circulation SSTAR small modular fast reactor concept with a 20-year core lifetime, good core reactor physics performance, good system thermal hydraulics performance, and a high S-CO_2 gas turbine Brayton cycle efficiency of 40 % may be viable at an electrical power level of 18 MWe (45 MWt)**
  - Maximum average discharge burnup = 72 MWd/Kg HM
  - Maximum burnup reactivity swing during 20 year core lifetime is less than one dollar
  - Mean core temperature rise is 142 ☜C while the peak cladding structural temperature is limited to 650 ☜C