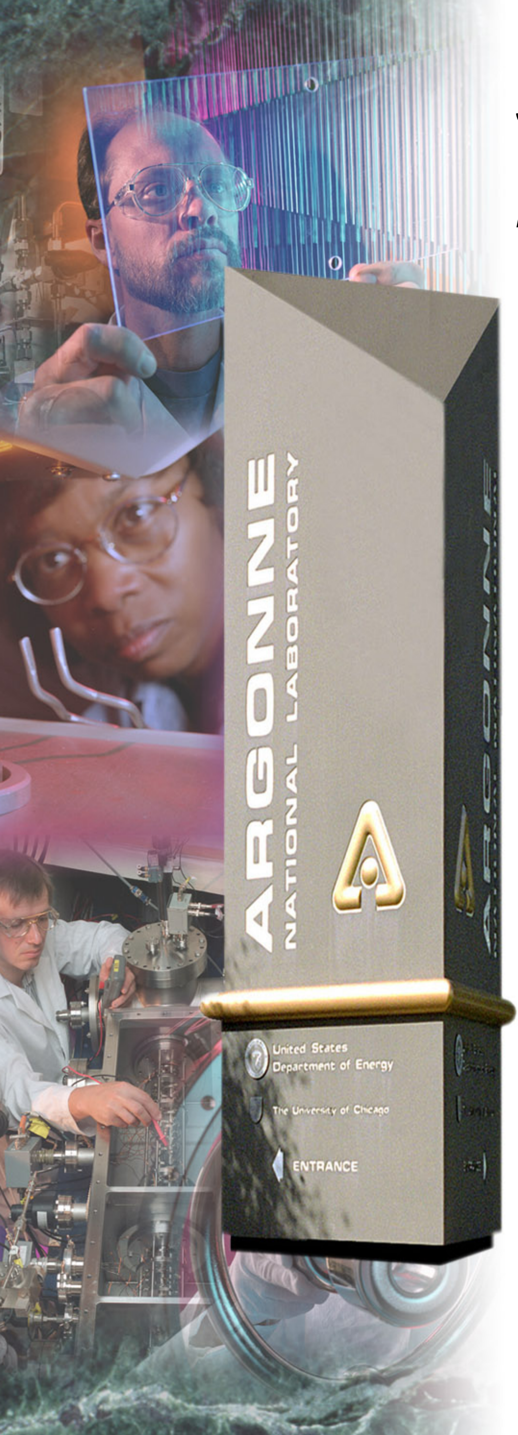

SSTAR LEAD-COOLED, SMALL MODULAR FAST REACTOR WITH NITRIDE FUEL

by

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Workshop on Advanced Reactors with Innovative Fuels

ARWIF-2005

Oak Ridge,

February 16-18,2005

Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Small Secure Transportable Autonomous Reactor (SSTAR)

- **Mission - Electricity generation to match needs of developing nations and especially remote communities or industrial operations (e.g., mining) without major electrical grid connections**
  - Alaska, Hawaii, island nations of the Pacific Basin (e.g., Indonesia), and elsewhere
  - Possible niche market within which costs per unit energy that are higher than those for large-scale nuclear power plants may be 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 20 MWe (45 MWt)**
- **Proliferation resistance**
  - Core lifetime/refueling interval of 20 years
  - Core is a single cassette and is not composed of individual removable fuel assemblies
  - Restrict access to fuel during core lifetime
  - Refueling equipment present at site only during refueling
  - Transuranic fuel – Self protective in the safeguards sense
- **Molten lead (Pb) primary coolant – Nitride fuel**
  - Passive safety
  - Potential to operate at higher temperatures than traditional LMRs
- **Fissile self-sufficiency**
  - Conversion ratio near unity
  - Realization of sustainable closed fuel cycle

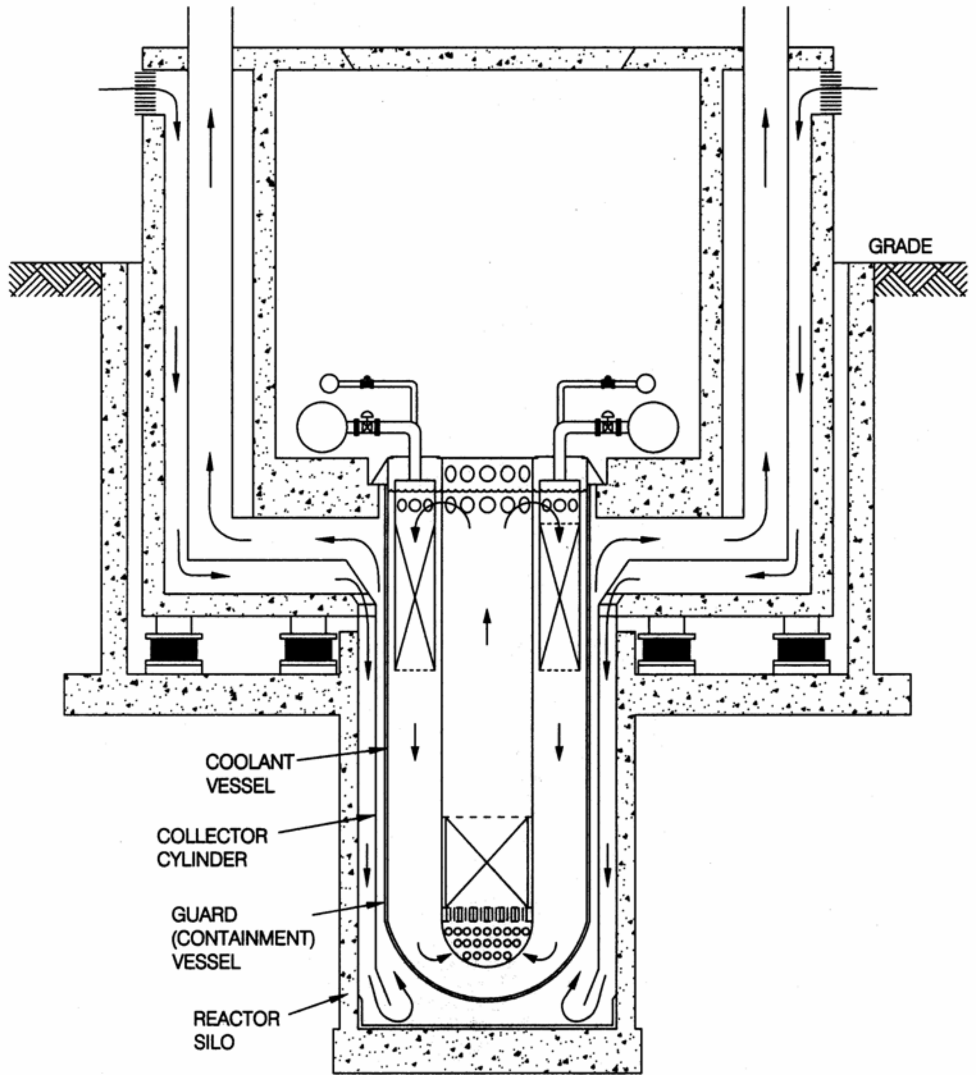
Small Secure Transportable Autonomous Reactor (SSTAR)

- **Autonomous operation**
  - Core power adjusts itself to heat removal from reactor system due to large inherent reactivity feedbacks of fast spectrum core without operator motion of control rods
  - Active adjustment of shutdown rods for startup and shutdown, and compensation/control rods for burnup compensation
- **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 footprint, costs, and staffing requirements
- **Natural circulation primary coolant heat transport**
  - Eliminate main coolant pumps and loss-of-flow accidents

Small Secure Transportable Autonomous Reactor (SSTAR)

- **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 site
- **Full transportability by barge or rail, or possibly by road**
  - Overland transport to remote sites
- **Flexibility to be adapted to generate other energy products**
  - Desalinated water
  - Hydrogen

Illustration of Lead-Cooled Fast Reactor



Pb Coolant

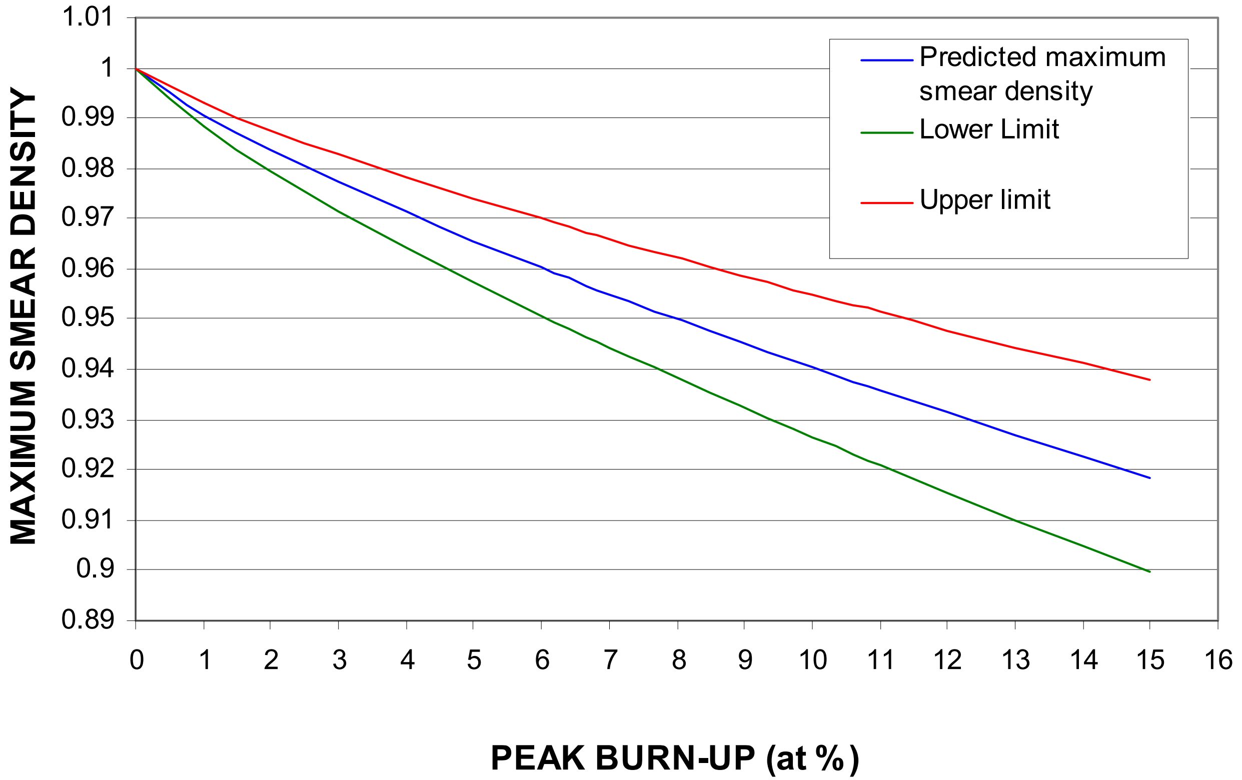
- **Enhanced passive safety**
  - Chemically inert – Does not react chemically with CO_2 working fluid above ~ 250 °C. Does not react vigorously with air or water/steam
  - High boiling temperature of 1740 °C for Pb (1670 °C for Pb-Bi eutectic) - *Core and heat exchangers remain covered by ambient pressure 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**
  - Goal of 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 (> 1400 °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 reactions in N^{14} and waste disposal problems associated with C^{14} production
- **Compatible with ferritic/martensitic stainless steel cladding and Pb coolant**
  - Nitrogen is insoluble in Pb
  - Bonded to cladding by molten Pb
- **Low irradiation-induced swelling and fission gas release**

Maximum Smeared Density for Nitride Fuel

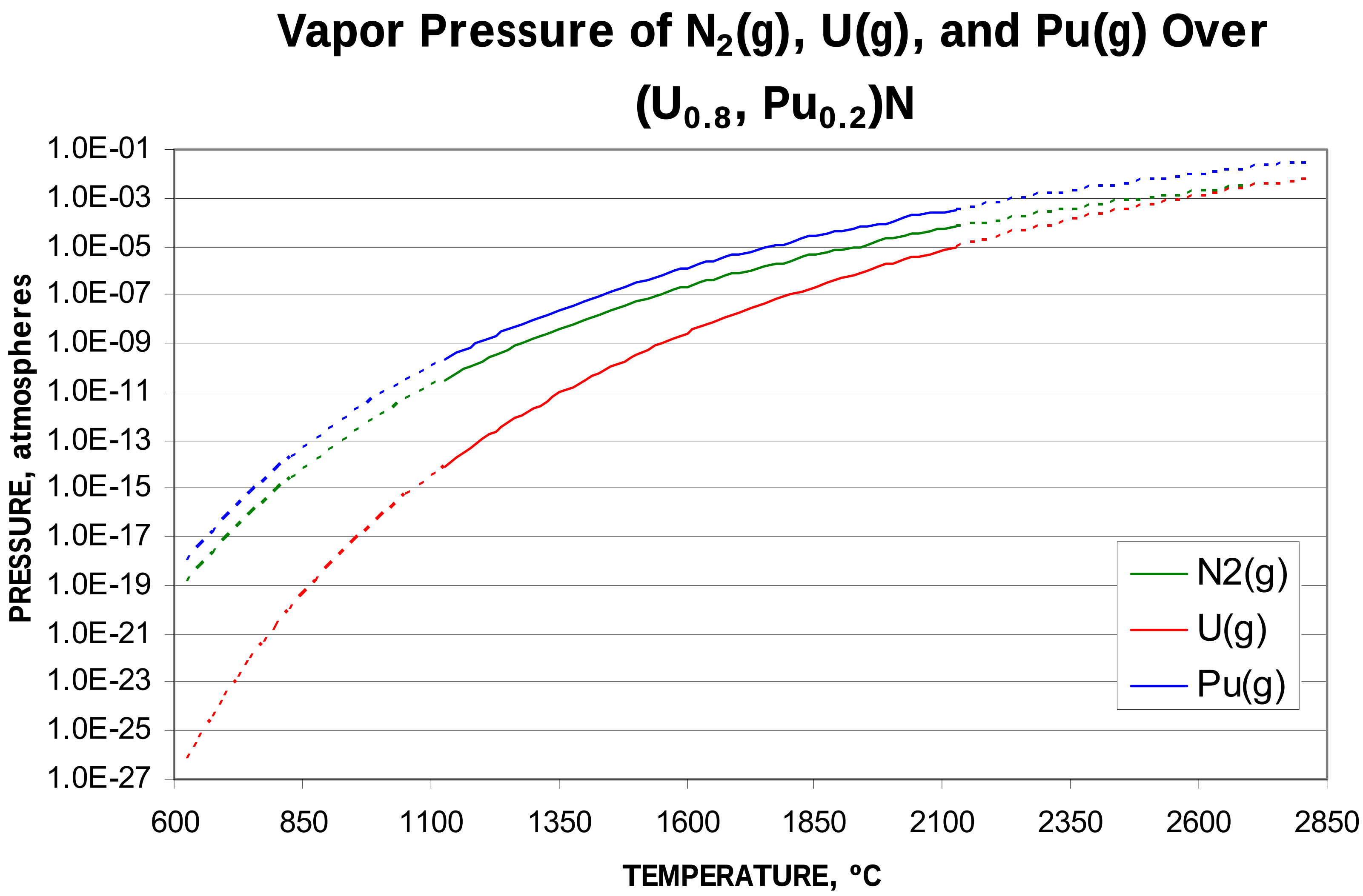
- **Smeared density of 90 % is selected for SSTAR for which the peak burnup = 12 atom %**



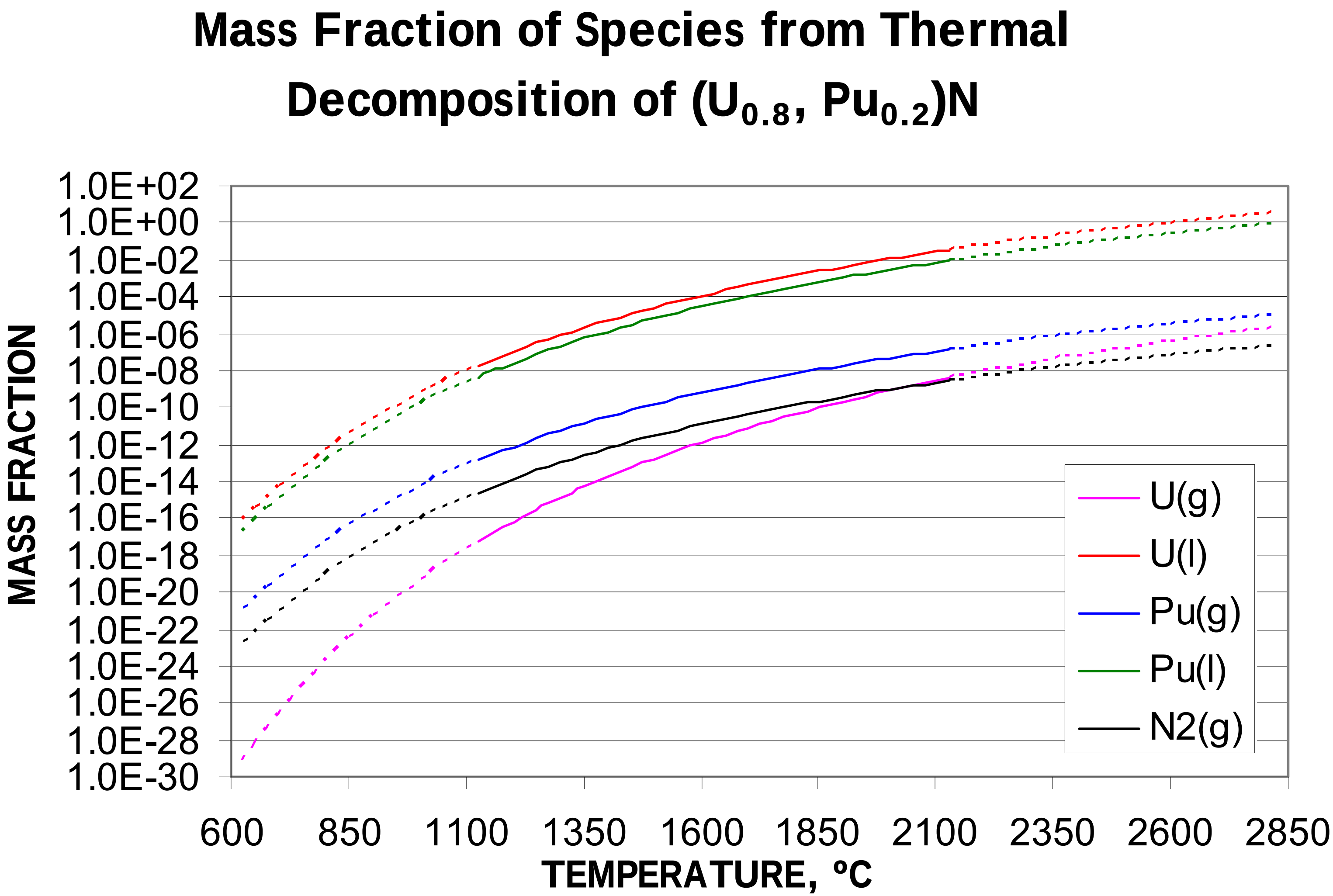
Analysis of Nitride Fuel Thermal Decomposition

- **Calculate mass of each vapor species assuming ideal behavior, measured vapor pressures versus temperature, and fission gas plenum volume per fuel volume**
  - Need to extrapolate vapor pressures outside of measurement range
- **Assuming stoichiometry, vapor species mass is subtracted from decomposed condensed phase mass**
- **Fission gas plenum-to-active core height ratio = 3.5**
  - Conservative assumption based on F/M stainless steel cladding with HT9 mechanical behavior
- **Fuel smeared density = 90 %**
- **Ignore suppression of vaporization by nitrogen fill gas**

Analysis of $(U_{0.8}, Pu_{0.2})N$ Thermal Decomposition



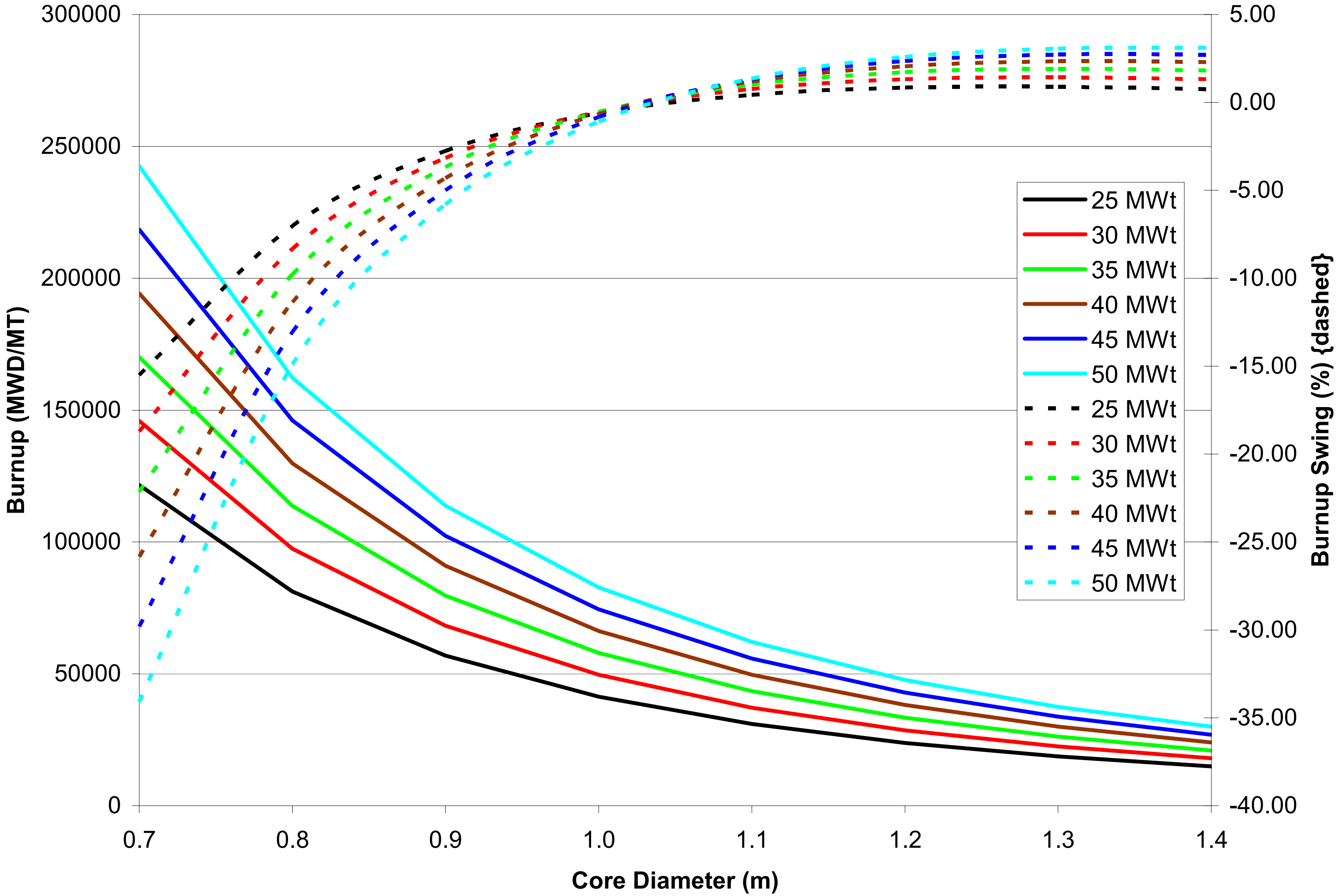
Analysis of $(U_{0.8}, Pu_{0.2})N$ Thermal Decomposition



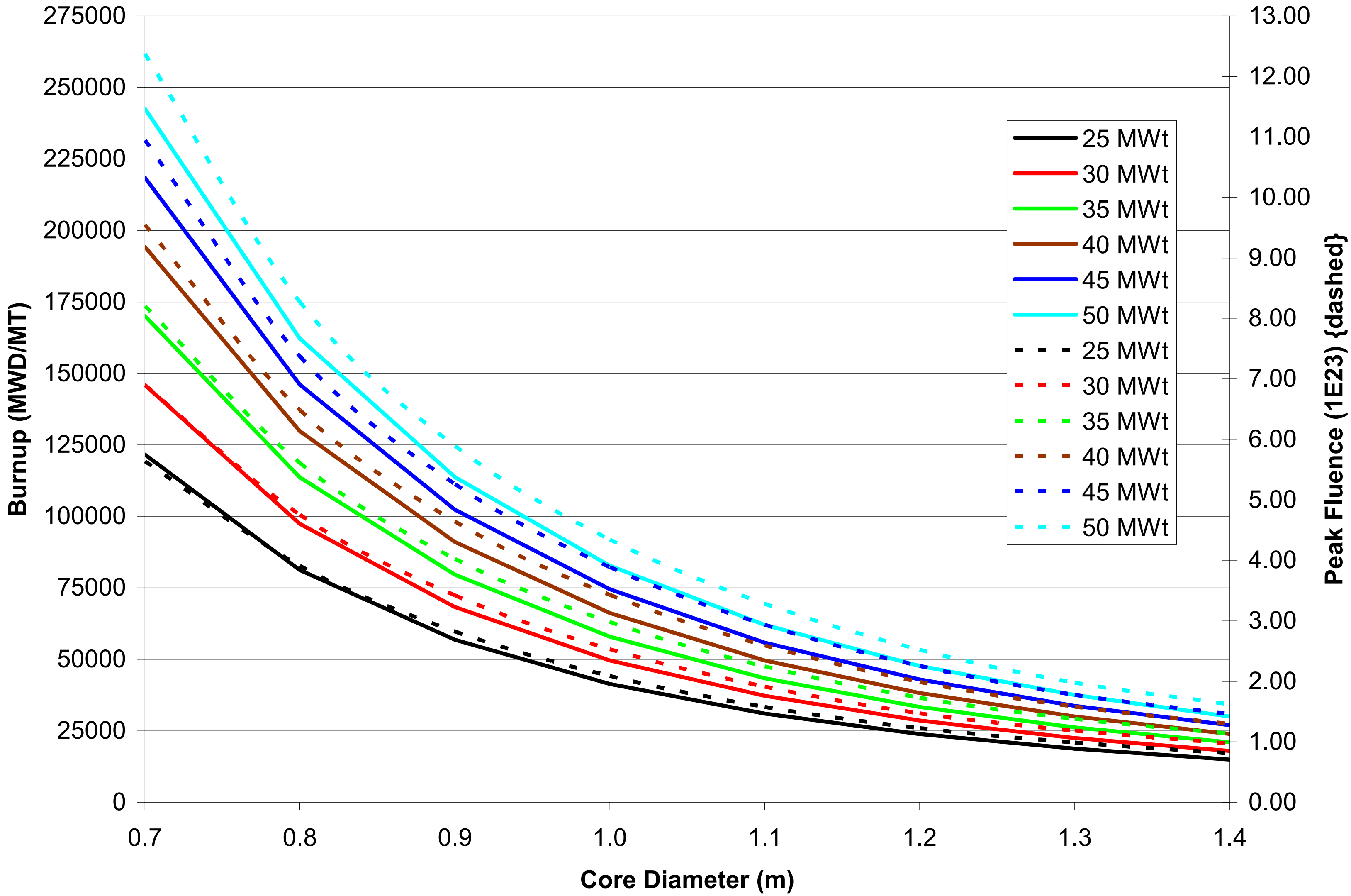
20 MWe (45 MWt) – Neutronics Analysis

- **Assume 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**
- **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 reactivity swing**
- **Seek to minimize burnup reactivity swing to less than one dollar**
- **Fuel volume fraction of 0.55 is low enough to facilitate natural circulation heat transport from core to Pb-to-CO_2 heat exchangers**
- **Burnup reactivity swing exhibits minimum at an active core diameter of about 1.0 m**
- **For this diameter, maximum power limited to 45 to 50 MWt by peak fast neutron fluence limit of 4.0×10^{23} n/cm^2 on ferritic-martensitic stainless steel**

Average Discharge Burnup and Burnup Reactivity Swing versus Core Size



Average Discharge Burnup and Peak Fluence versus Core Size



45 MWt SSTAR Neutronics Conditions

Core Diameter, m	1.02
Active Core Height, cm	80
Fuel Smear Density, %	90
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
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
BOC to EOC Burnup Swing, $	0.35
Maximum Burnup Swing, $	0.96

45 MWt SSTAR Reactivity Feedback Coefficients

	BOC	POC ~ 13 years	EOC
Delayed Neutron Fraction	0.0035	0.0034	0.0034
Prompt Neutron Lifetime, s	1.8×10^{-07}	1.8×10^{-07}	1.8×10^{-07}
Coolant Density, cents/°C	-0.002	0.003	0.002
Core Radial Expansion, cents/°C	-0.16	-0.16	-0.16
Axial Expansion, cents/°C	-0.06	-0.06	-0.06
Fuel Doppler, cents/°C	-0.12	-0.12	-0.11
Coolant Void Worth, $	-0.99	-0.45	-0.71

Fuel Pin Cladding Mechanical Analyses

- **LFR coolant technology database indicates that Si-enhanced ferritic/martensitic stainless steel might resist attack by flowing molten Pb up to temperatures of about 650 ☜C**
- **SSTAR goal is peak cladding temperature = 650 ☜C**
- **HT9 stainless steel taken as representative of Si-enhanced F/M SSt for mechanical behavior**
- **Assume HT9 mechanical properties to investigate viability for application to SSTAR cladding**

Assumed Design Criteria for HT9 Cladding

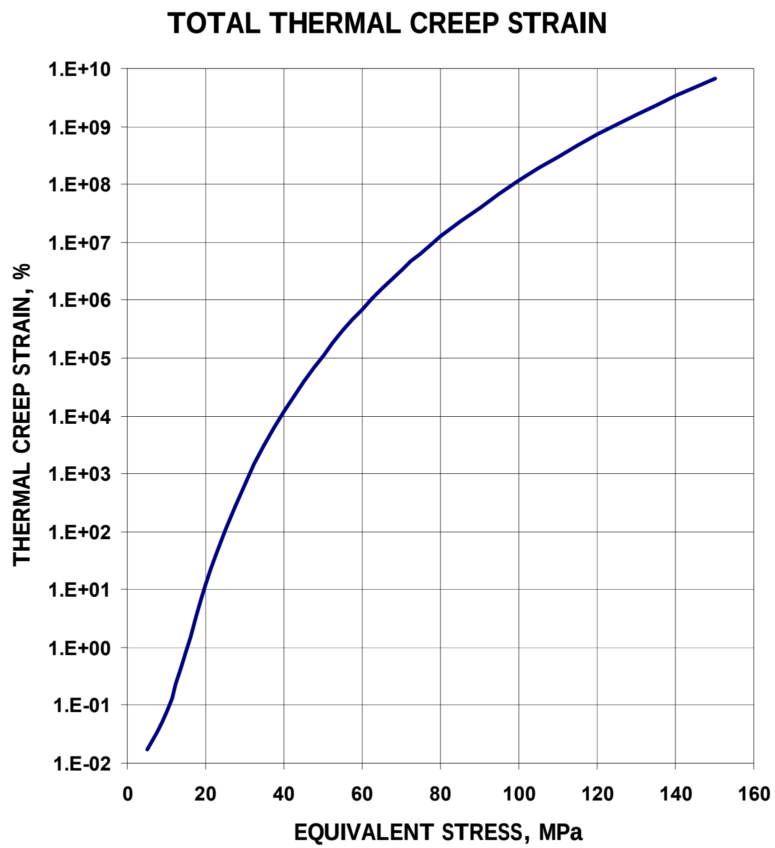
- **Thermal component of plastic hoop strain, ε_{THN} <0.01 = 1.0 %**
  - Thermal creep is what damages fuel pin cladding
  - Thermal creep strain consists of primary, steady state, and tertiary components
- **Cumulative damage function,** $CDF = \int_{o}^{t} \frac{dt}{t_{rupture}} < 0.05$
  - Value of 0.05 is specified to limit fuel pin failures in a statistical sense
- **Radially averaged hoop stress, σ_H < 150 MPa**
  - Purpose is to preclude unstable plastic deformation
  - Strain rates increase rapidly when cladding is subjected to stresses above this level

Fuel Pin Cladding Mechanical Analyses

- **Analyze most severely stressed pin over 20-year core lifetime**
- **Location of power peak/hot channel varies with time**
  - Moves from outer part of core to core center
- **Assume hot channel pin at EOC has average channel conditions for first 90 % of core life followed by hot channel conditions for last 10 % of core life**
- **Assume peak cladding temperature at middle of wall thickness equals 589 ☜C for first 18 years and 638 ☜C for final 2 years**
- **Assume that pressure loading from fission gas release increases linearly with time to final value**

Fuel Pin Cladding Mechanical Analyses

- **Total thermal creep strain criterion is most restrictive and limits cladding hoop stress to 15 MPa**



Selection of Fission Gas Plenum Height

- **1.0 % thermal strain requirement limits cladding hoop stress to ~ 15 MPa for peak cladding temperature criterion of 650 ☜C**
- **To limit hoop stress to such a small value requires a large fission gas plenum volume/height of ~ 2.4 m or greater**
- **Fission gas plenum pressure depends upon gas release from nitride fuel**
- **Fraction of gas released assumed given by correlation of Rogozkin, Steppennova, and Proshkin (Atomic Energy, Vol. 95, No. 3, p. 624, 2003)**
  - $F=3.05\ B^{1.92}\ \exp\left(-4130/RT_{fuel}\right)$
  - B = burnup in atom %, R = 1.98 cal/(mol-K), T_{fuel} = fuel centerline temperature
- **For T_{fuel} = 953 ☜C, release fraction, F = 0.28**

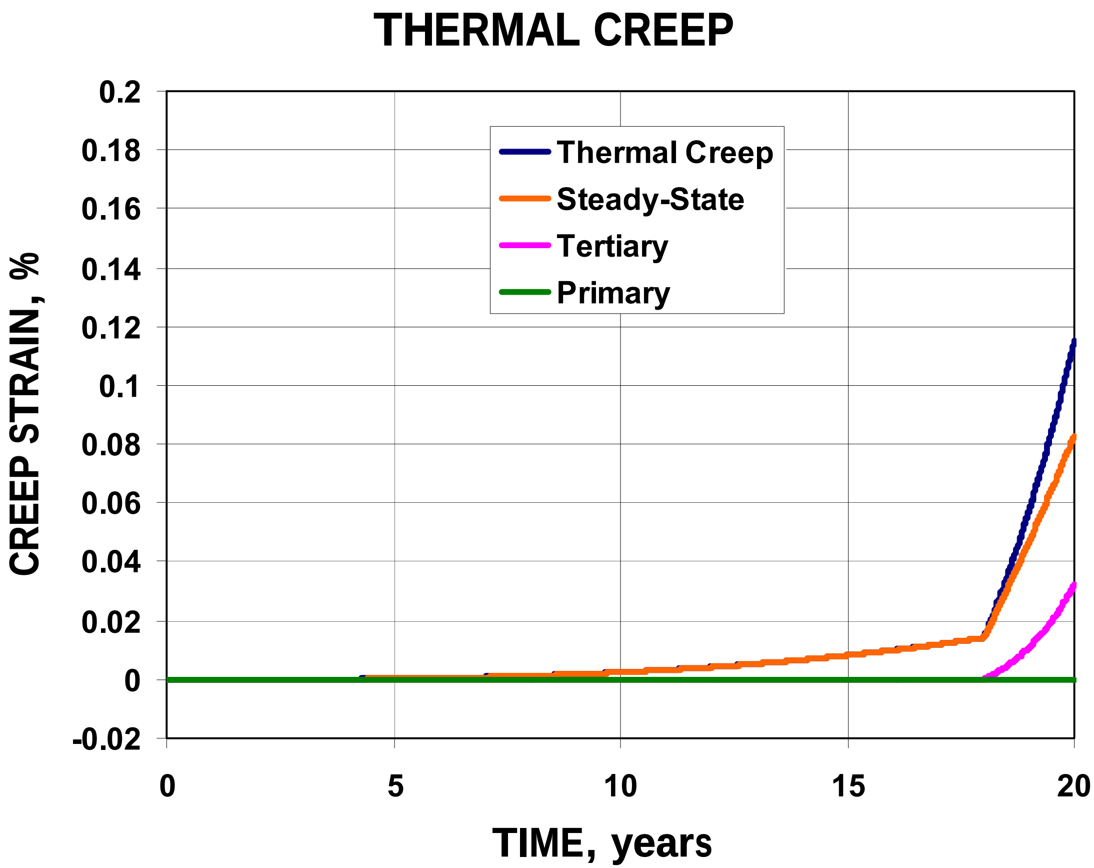
Selection of Fission Gas Plenum Height

- **Fuel pin cladding hoop stress versus fission gas plenum height for 28 % fission gas release and 595 ☜C hot channel outlet temperature**

Plenum Height, m	Internal Pressure, MPa	Cladding Hoop Stress, MPa
0.8	3.23	38.7
1.0	2.58	31.0
1.6	1.61	19.4
2.8	0.92	11.1
3.2	0.81	9.68
3.6	0.12	8.61

- **Fission gas plenum height of 2.8 m selected for SSTAR**

Time Dependent Thermal Creep Strain for Hot Channel Fuel Pin Cladding at End-of-Core Life



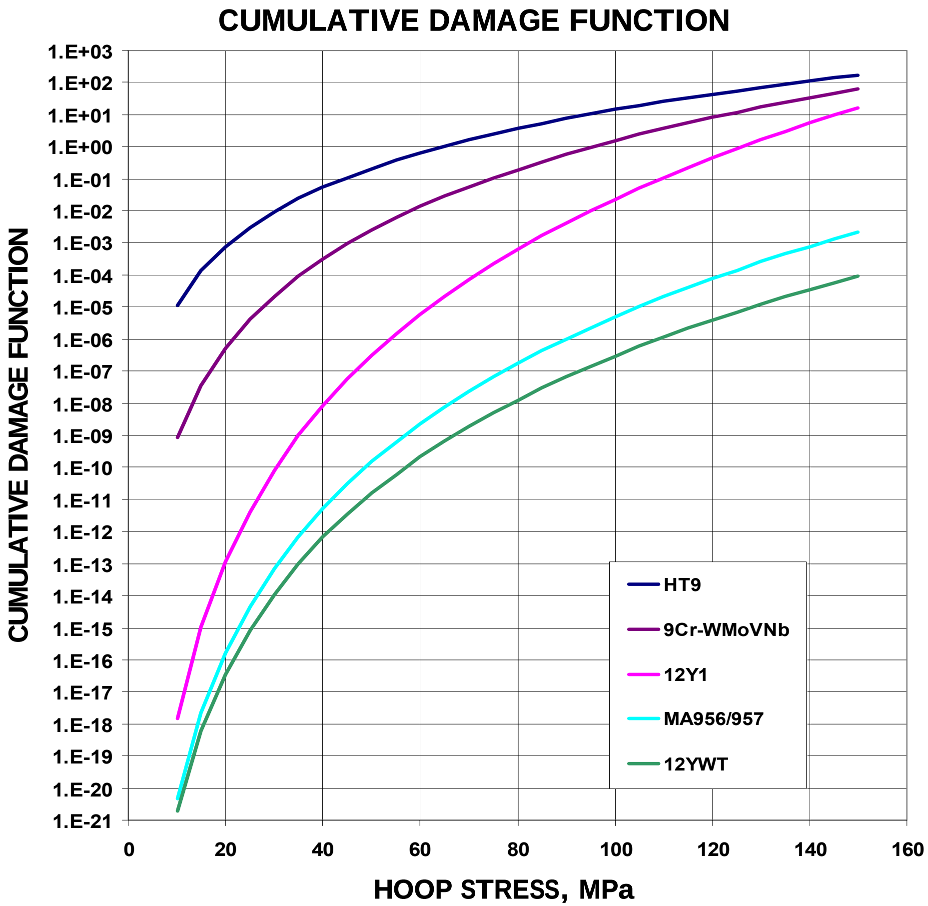
- **Total creep strain limited to 0.12 % but large creep rates are calculated during final 10 % of lifetime – Undesirable regime**

Possible Solution – Oxide Dispersion Strengthened (ODS) Cladding Material

- **ODS materials offer prospect of greater strength at temperatures above 600 ☜C**
- **Examples (Klueh et. al., Journal of Nuclear Materials, Vol. 307-311, p. 773, 2002)**
  - Fe-12Cr-2.5W-0.35Ti-0.25Y_2O_3 (Designated 12YWT)
  - Fe-12Cr-0.25Y_2O_3 (Designated 12Y1)
- **Assumption of 12YWT mechanical properties results in CDF of 1 X 10^{-4} for cladding hoop stress of 150 MPa**
  - Would enable short height fission gas plenum (e.g., one-fourth of active core height)

Comparison of ODS Materials

- **Cumulative damage function for hot channel fuel pin cladding at EOC**



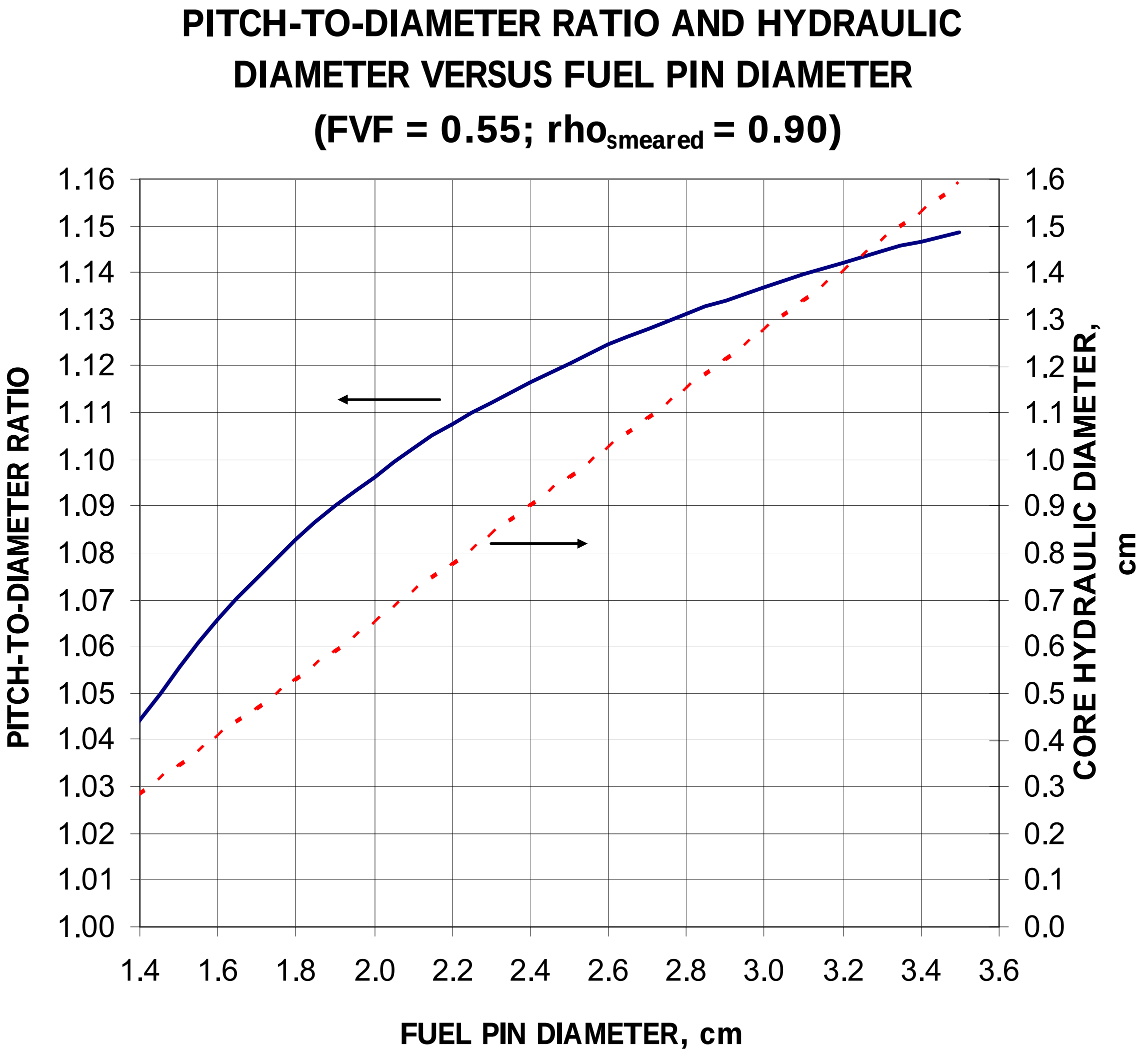
System Thermal Hydraulic Analyses - What Determines the Reactor Vessel Size?

- **Transportability by rail and possibly by road assumed as a goal**
  - Assumed size limitations are 18.9 m (62 feet) length by 6.1 m width (20 feet)
- **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
  - Kidney-shaped Pb-to-CO_2 heat exchangers must fit inside of annulus between shroud and cylindrical liner, and provide sufficient heat exchange performance to realize a significant Brayton cycle efficiency

Optimization of Fuel Pin Diameter and HX Tube Dimensions

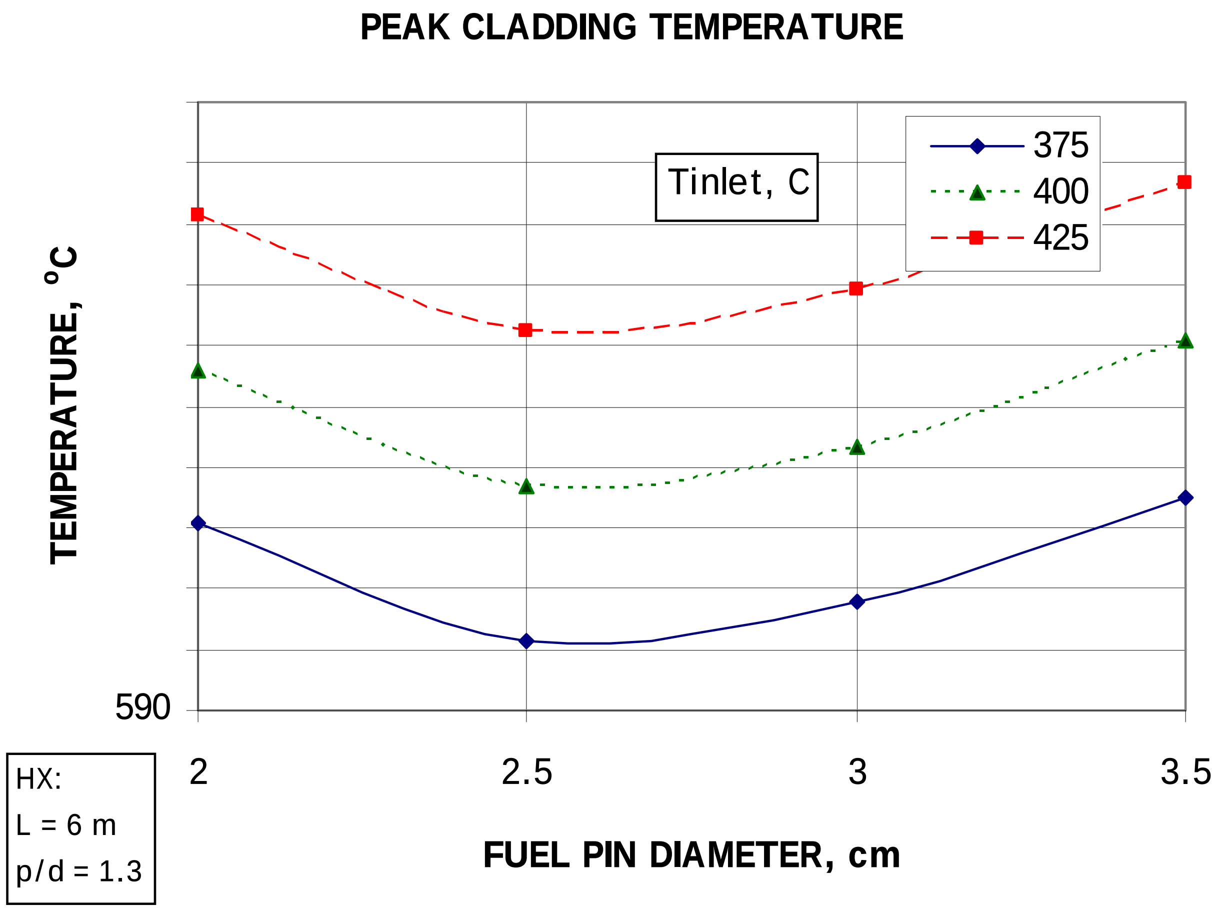
- **Determine optimal fuel pin diameter that minimizes the peak cladding temperature for a fixed fuel volume fraction of 0.55, fuel smeared density of 90 %, and fixed Pb core inlet temperature**
  - Assume fixed cladding thickness = 1.0 mm
- **A unique relation exists between the fuel pin diameter and the triangular pitch-to-diameter ratio for fixed fuel volume fraction and smeared density**
- **Optimal fuel pin diameter determined to be 2.5 cm**
- **Fuel pin pitch-to-diameter ratio = 1.121**
- **Determine HX tube height and pitch-to-diameter ratio that maximize S-CO_2 Brayton cycle efficiency for fixed tube diameter and thickness**
- **HX tube height determined to be 6 m and p/d = 1.242**
- **Core inlet temperature = 420 °C provides PCT = 650 °C**

Relationship Between Fuel Pin Diameter and Pitch-to-Diameter Ratio



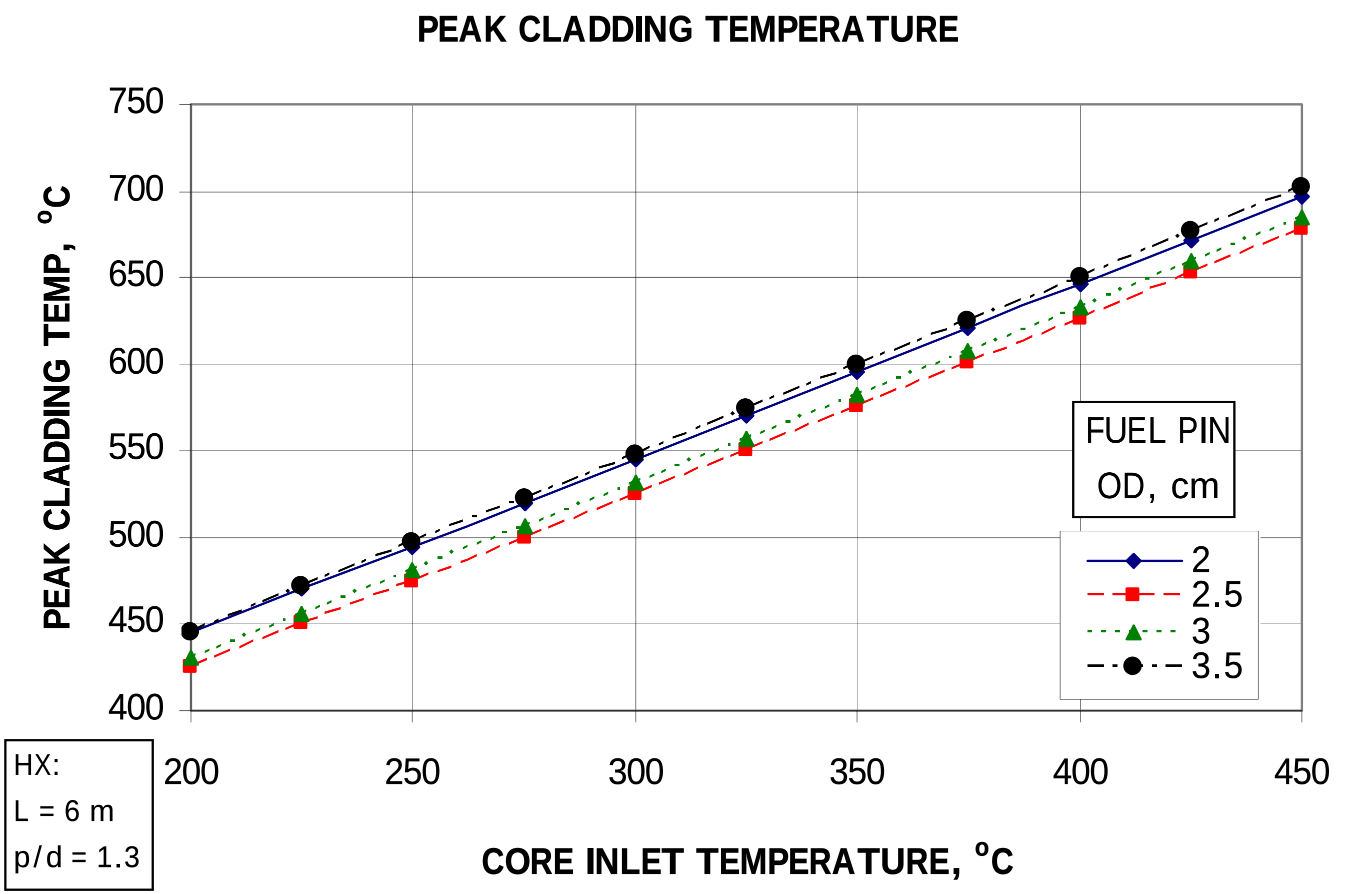
Optimization of Fuel Pin Diameter

- **Select fuel pin diameter = 2.5 cm that minimizes the peak cladding temperature**



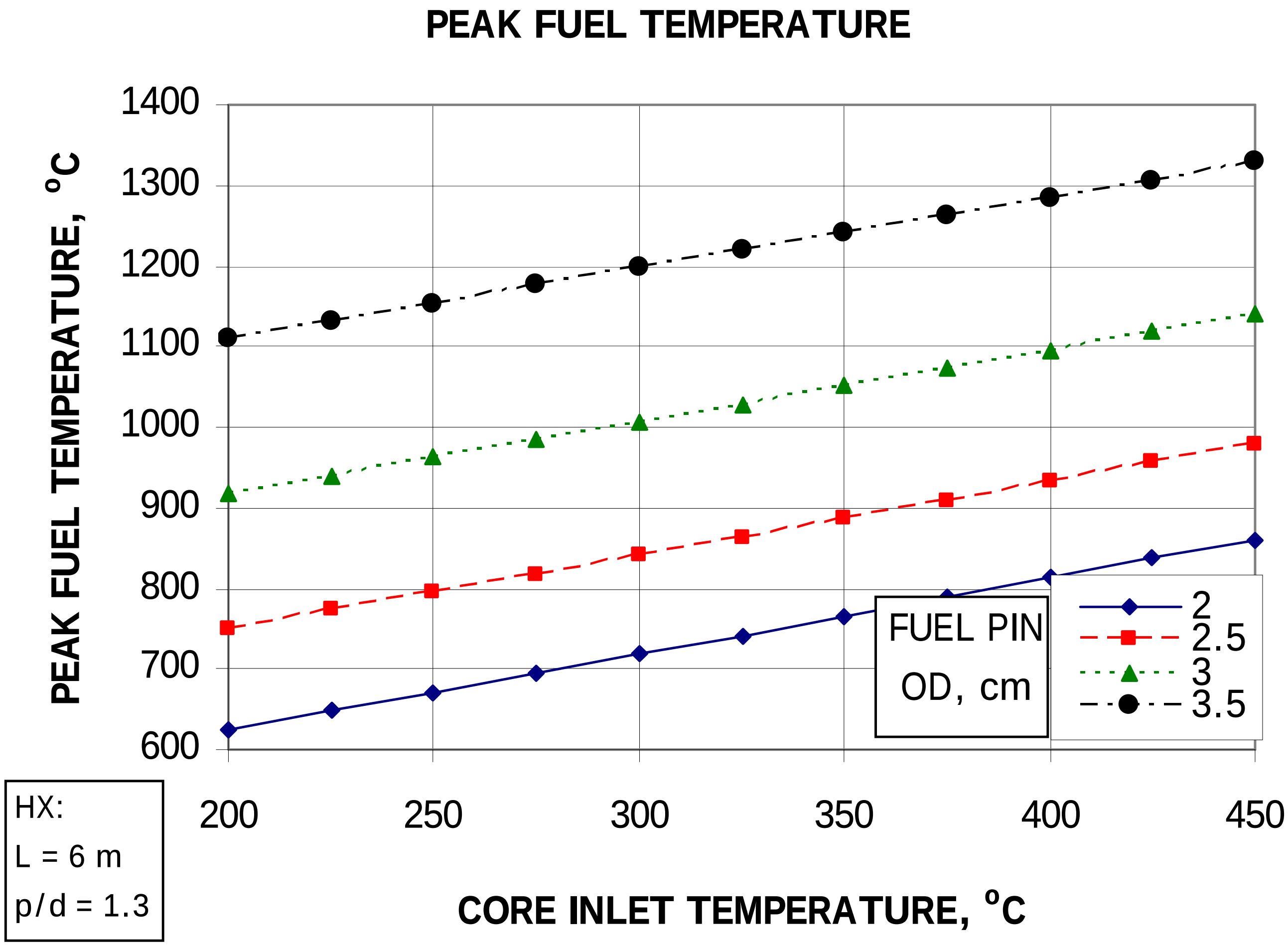
Selection of Core Inlet Temperature

- **Select core inlet temperature = 420 °C that provides a peak cladding temperature of 650 °C**

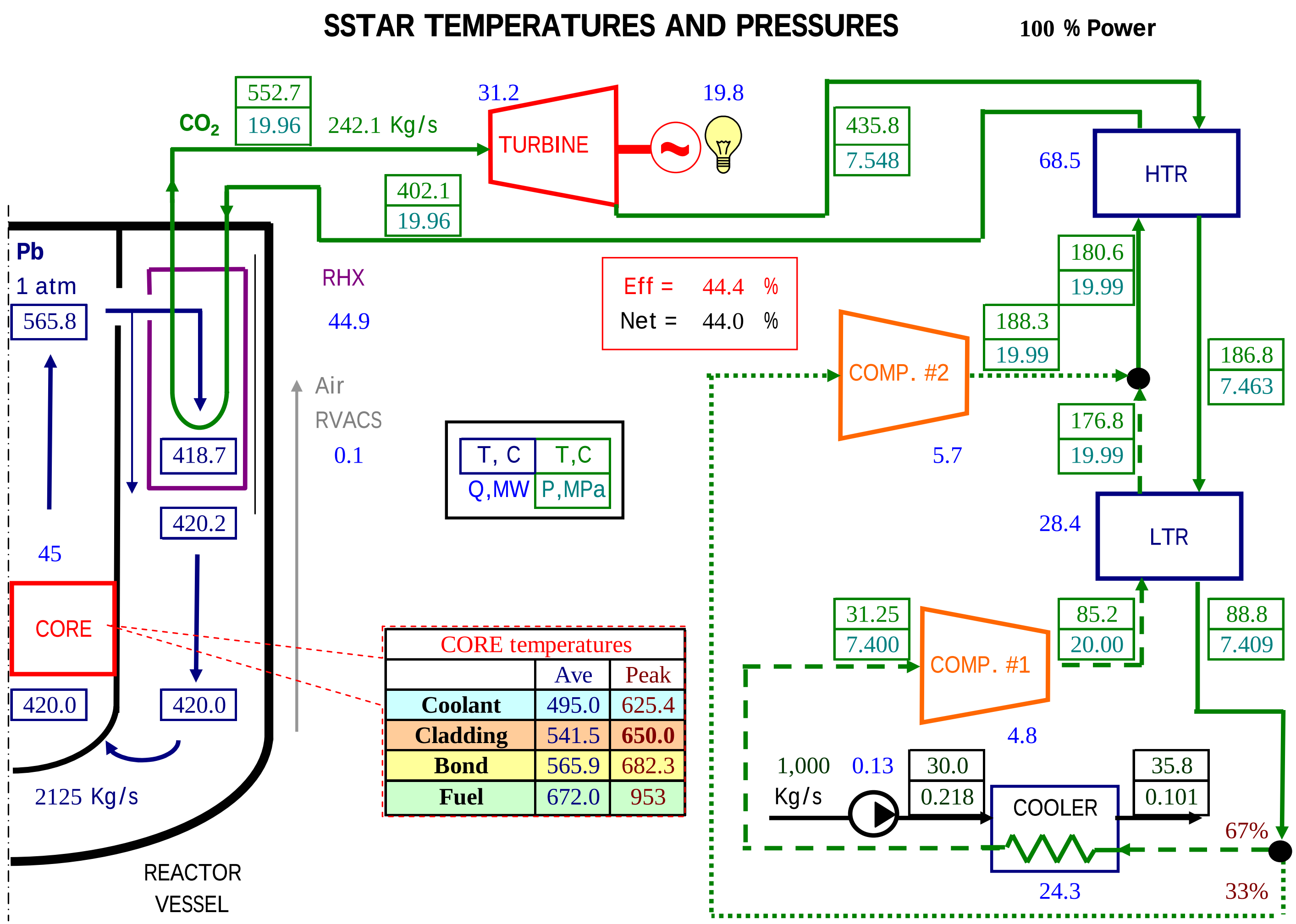


Peak Nitride Fuel Centerline Temperature

- **Peak fuel temperature = 953 °C**



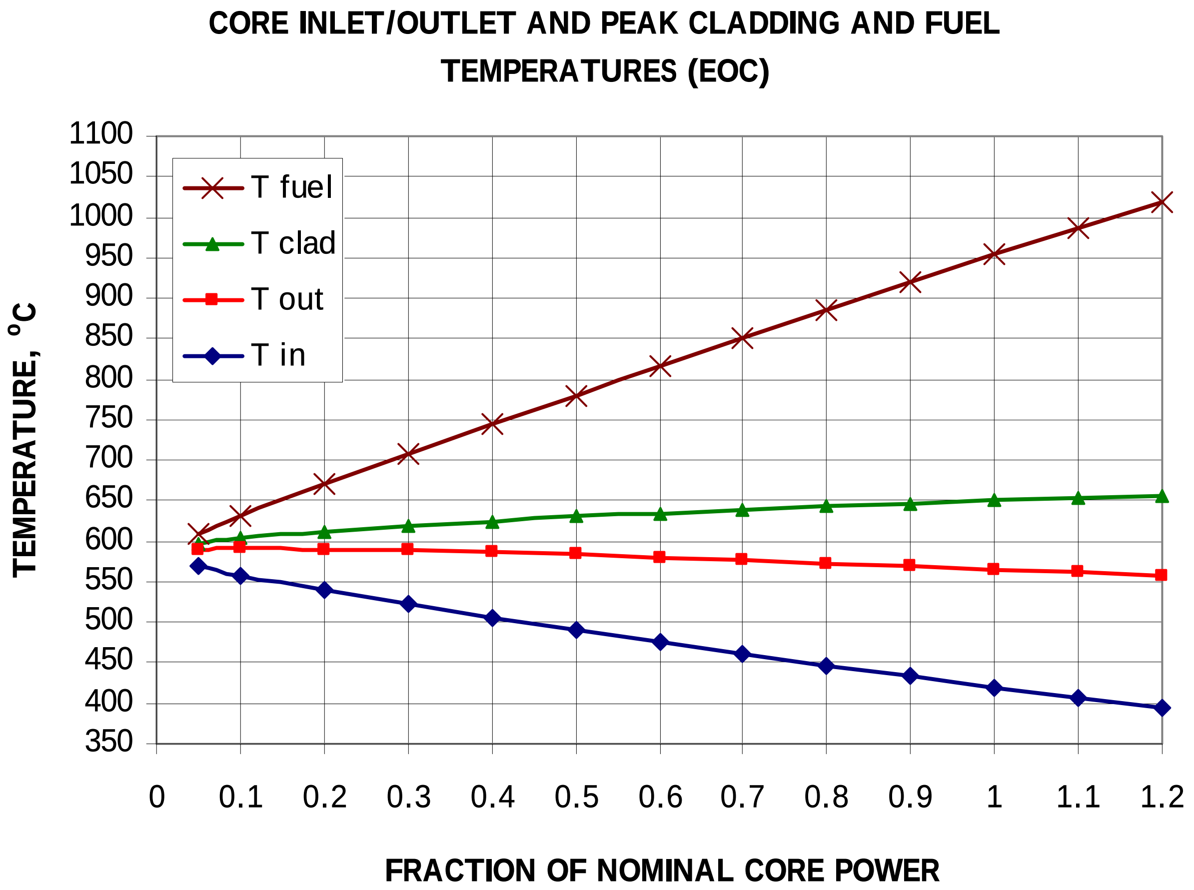
Schematic of SSTAR Coupled to S-CO_2 Brayton Cycle Showing Nominal Conditions



CORE temperatures		
	Ave	Peak
Coolant	495.0	625.4
Cladding	541.5	**650.0**
Bond	565.9	682.3
Fuel	672.0	953

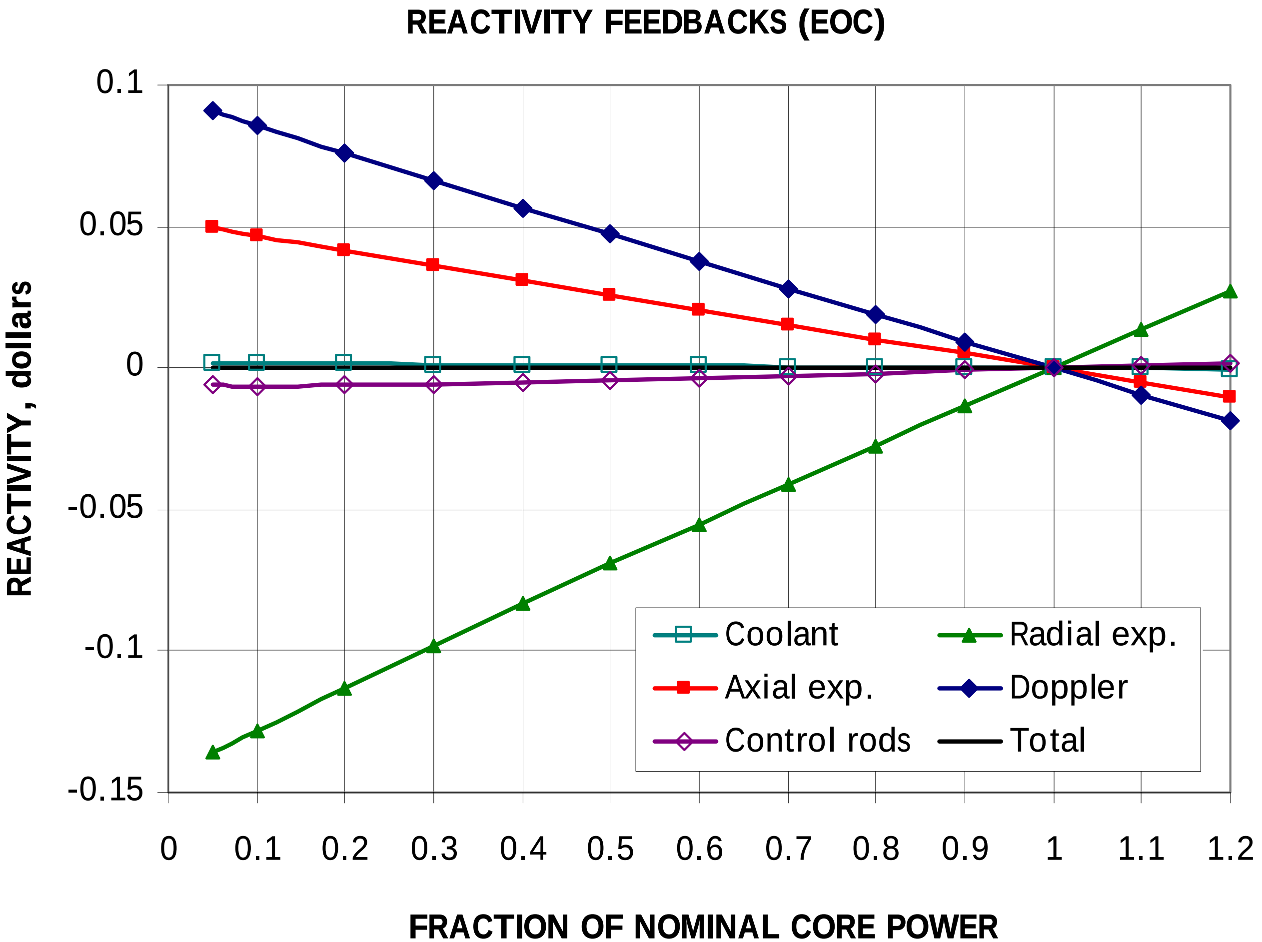
Autonomous Load Following Behavior

- **System temperatures following an autonomous power change from nominal power to a new steady state at End-of-Life (EOC)**



Autonomous Load Following Behavior

- **Comparison of contributions from individual reactivity feedbacks**



20 MWe (45 MWt) SSTAR Operating Conditions

• Power	19.8 MWe (45 MWt)
• Reactor vessel height	18.3 m (60.0 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 smeared density	90 %
• Fuel pin outer diameter	2.5 cm
• Fuel pin pitch-to-diameter ratio	1.121
• Core hydraulic diameter	0.964 cm
• Fuel pin cladding material	HT9
• Cladding thickness	1.0 mm
• Fission gas plenum height	2.8 m

20 MWe (45 MWt) SSTAR Operating Conditions

• HX tube height	6.0 m
• HX tube outer diameter	1.4 cm
• HX tube inner diameter	1.0 cm
• HX tube pitch-to-diameter ratio	1.242
• HX hydraulic diameter for Pb flow	0.983 cm
• HX-core thermal centers separation height	12.2 m
• Peak cladding temperature	650 ☜C
• Core outlet temperature	566 ☜C
• Maximum S-CO_2 temperature	553 ☜C
• Core inlet temperature	420 ☜C
• Core coolant velocity	0.896 m/s
• Pb coolant flowrate	2125 Kg/s
• CO_2 flowrate	242 Kg/s
• Brayton cycle efficiency	44.4 %
• Net plant efficiency	44.0 %

Summary of SSTAR

- **Results of preconceptual core neutronics, fuel pin cladding mechanical, 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 44 % may be viable at an electrical power level of 20 MWe (45 MWt)**
  - 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 146 ☜C while the peak cladding structural temperature is limited to 650 ☜C

Summary of SSTAR

- **Key contributors to achievement of SSTAR goals are features of transuranic nitride fuel**
  - High atom density
  - Low swelling enabling 90 % smeared density
  - Low fission gas release reducing fission gas plenum pressurization
  - High melting and thermal decomposition temperatures enabling high system temperatures including 650 ☜C peak cladding temperature
  - Compatibility with F/M stainless steel cladding and Pb bond
  - High thermal conductivity and Pb bond limiting peak fuel centerline temperature to 953 ☜C

Summary of SSTAR

- **F/M stainless steel fuel pin cladding similar to HT9 has insufficient strength above ~ 600 ☜C**
- **For F/M SSt with HT9 properties and 650 ☜C peak cladding temperature, the total thermal creep strain can be limited to less than 1.0 % but this requires significant enlargement of the fission gas plenum height or thicker cladding wall to accommodate thermal creep over 20 years resulting from internal fission gas pressurization**
- **High HT9 creep rates at end of core life are undesirable**
- **Development of fuel pin cladding materials and structural materials having greater strength and resistance to Pb attack at high temperatures is indicated**

Summary of SSTAR

- **One path forward may be oxide dispersion strengthened (ODS) Si-enhanced F/M SSt –Will require development, compatibility testing with flowing Pb, and code cases**
- **Steady state and transient irradiations of nitride fuel with selected cladding and Pb bonding including high burnups will be required**