Supercritical CO_2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept

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Outline

- Goals
- Advantages and Disadvantages
- Fast Gas, CO_2, and S-CO_2 Reactor Concepts
- Super Critical Cycle
- Reference Core and Plant Layout
- Heat Transfer and Thermal Hydraulics
- Keff, Burnup, and Void coefficient
- Natural Circulation Flow and Decay Heat Removal
- Economics

Goals
Advantages and Disadvantages

Goal of CO2 Reactor Design Study

Goal – Determine if a direct cycle, supercritical CO_2 cooled, fast reactor could be designed to be cost effective, maintain natural circulation decay heat removal, and last 20 years at 200 MWth (100 MWe)

- **Direct Cycle**
  No primary heat exchanger. CO_2 coolant in the reactor is the same as in the power conversion system.
- **Cost Effective**
  plant + power conversion system + pressure vessel + fuel < $5000/kWe
  $500M at 100MWe
  $1,000M at 200MWe
- **Natural Circulation Decay Heat Removal**
  Remove 1% of the steady-state operating power level though the power conversion system or auxiliary system with an acceptable ΔT through the reactor with no mechanical pump operating.
- **20 Years at 200 MWth**
  Burnup in fuel/clad limited to an acceptable level (72,000 MWD/MT ?).
  Reactivity change over core lifetime minimized.

Advantages and Disadvantages

Major Advantages -

- Natural circulation flow can allow for decay heat removal for loss of flow condition.
- Fast spectrum allows for effective breeding (conversion) and with the right geometry, a small reactivity swing over the core lifetime.
- Small void coefficient of reactivity (<$1.00).
- Proven coolant (CO_2), fuel (oxide), and cladding (Cr-Ni-Fe-Nb) steels.
- Can use simple fuel rod design and core design.
- Coolant is inexpensive, relatively chemically inert, and is not flammable.
- Long blow down times for postulated leaks and large breaks.
- Pressure vessel can be made small (~2 - 2.5 m diameter) to allow for replacement of core and PV as a single unit, if desired.
- Minimal infrastructure development.
- Supercritical cycle allows for high efficiency at 650°C core outlet temperature.
- Lower balance of plant costs due to direct cycle and small size of balance of plant.
- Brayton cycle allows for high-efficiency load following.
- High heat rejection temperature allows for efficient use of cooling water.

Major Disadvantages -

- High pressure required, ~20 MPa (3000 psi) – (could potentially be lowered)
- Engineered safety feature required for decay heat removal for loss of coolant accident due to large or small pipe break.
- Fission product isolation and buildup on cold components.
- Stainless-steel components required for corrosion minimization for CO_2 at high temperature.

Fast Gas, CO2 and S-CO2 Reactor Concepts

Commercial CO2 Reactors

CO_2 Cooled Reactors (not supercritical, not direct cycle, thermal)
52 operated – 41 UK, 8 France, 1 Italy, 1 Japan, 1 Spain
14 AGRs, 4 Magnox still in operation

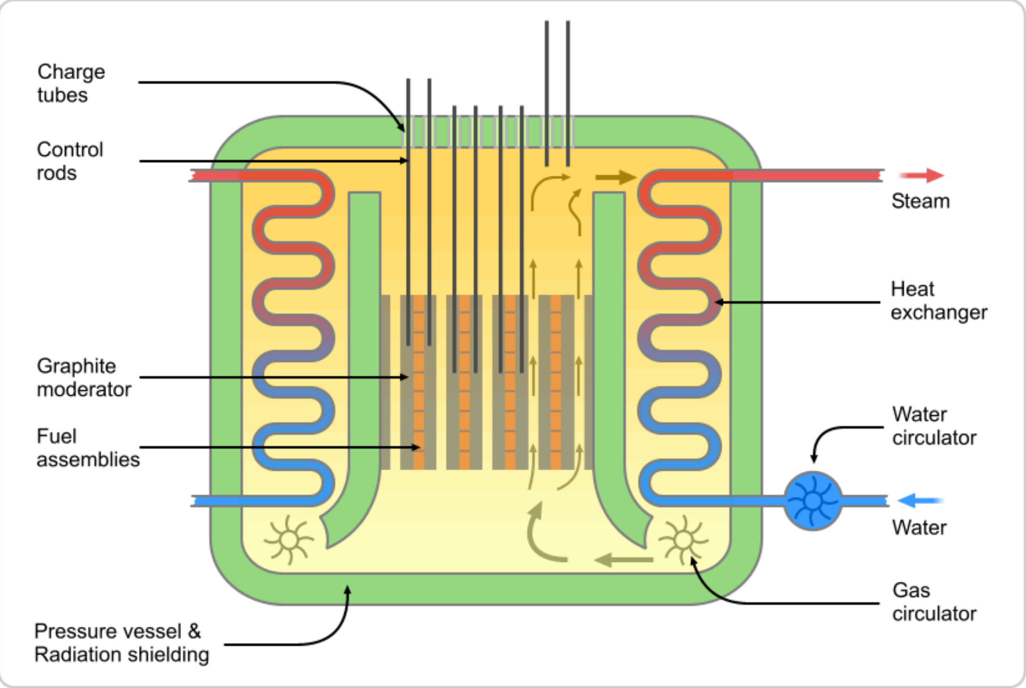
Magnox – UK and France (UNGG-independent and parallel), 1956

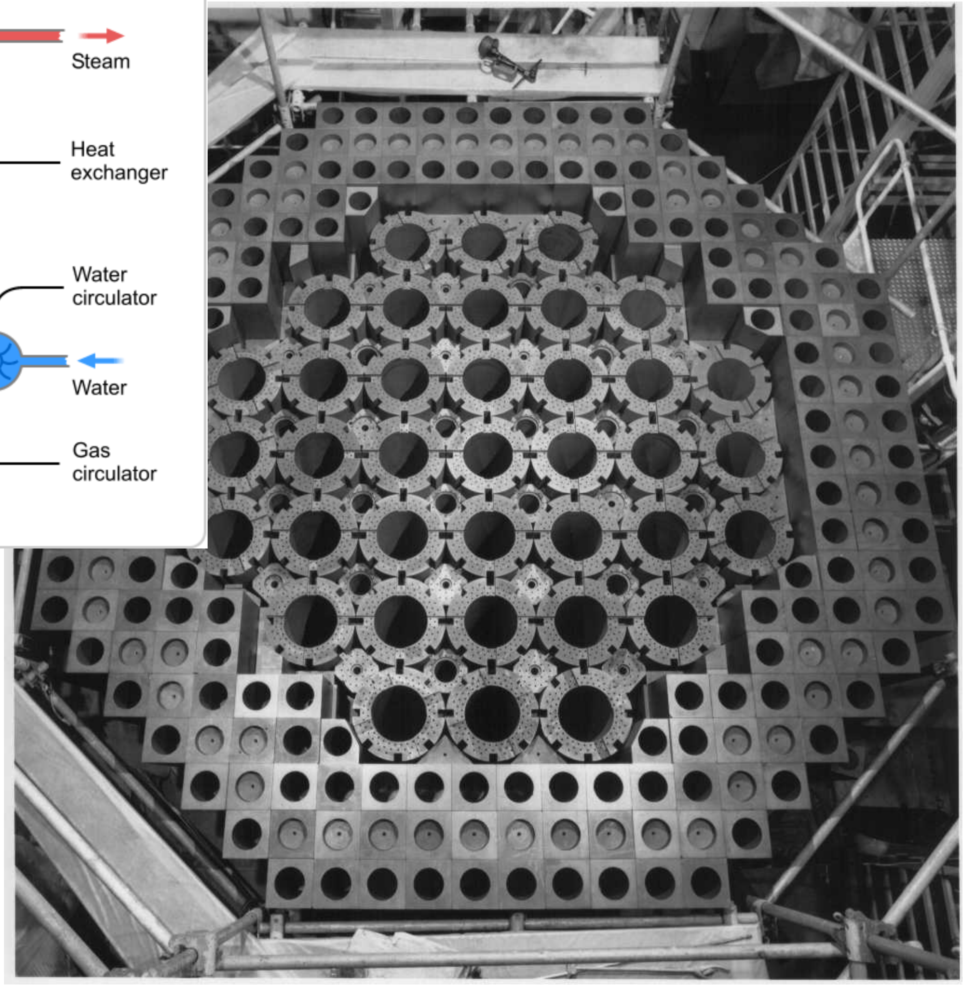
- Graphite moderated, U metal natural enriched
- Clad pin bundles in graphite matrix – online refueling
- Magnox from magnesium alloy cladding
- Secondary steam Rankine cycle
- Tout = 414°C, 1 W/cc, 5,500 MWD/MT, 200-500 MWe, 30% eff
- Pre-stressed concrete pressure Vessel with steel liner
- Pressure = 0.59 MPa (100 psia)

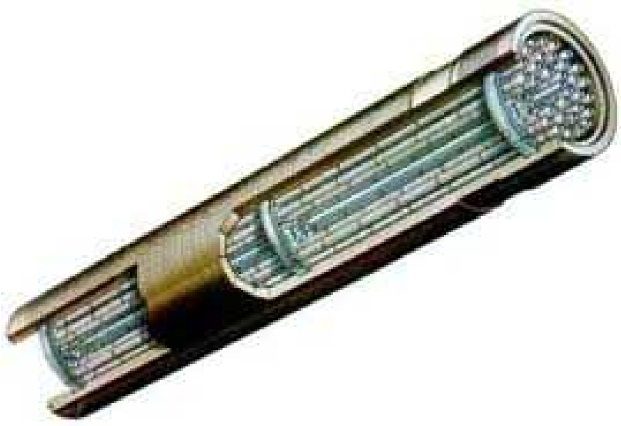
AGR – UK 1963

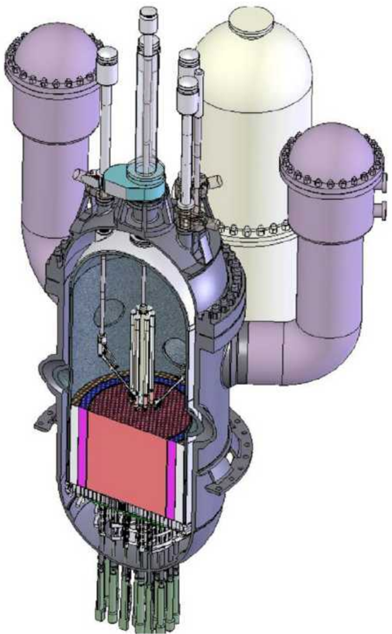
- Graphite moderated, UO_2 slightly enriched
- Clad pin bundles in graphite matrix – online refueling
- Stainless-steel cladding
- Secondary steam Rankine cycle
- Tout = 650°C, 2 W/cc, 24,000 MWD/MT, 555-625 MWe, 40% eff
- Pre-stressed concrete pressure Vessel with steel liner
- Pressure = 4.33 MPa (640 psia)

AGR Design

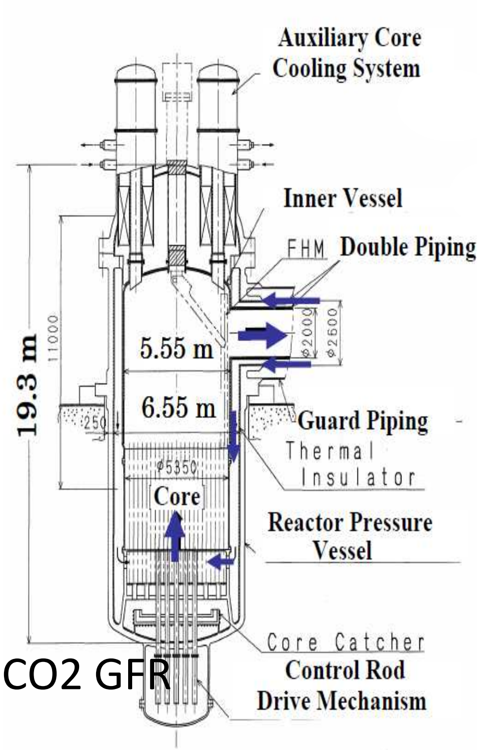

Charge tubes
Control rods
Graphite moderator
Fuel assemblies
Pressure vessel & Radiation shielding
Steam
Heat exchanger
Water circulator
Water
Gas circulator





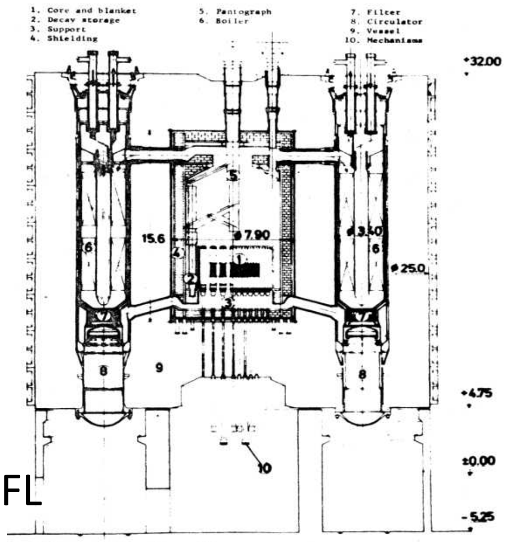


CEA



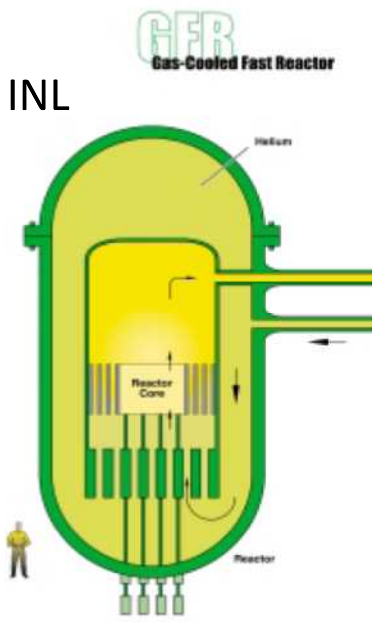
Japan CO2 GFR

CO2/He GFR Pre-stressed Concrete PV

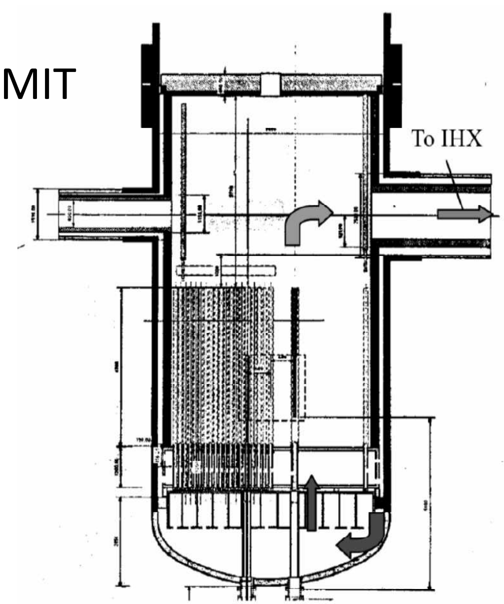


BNFL

INL



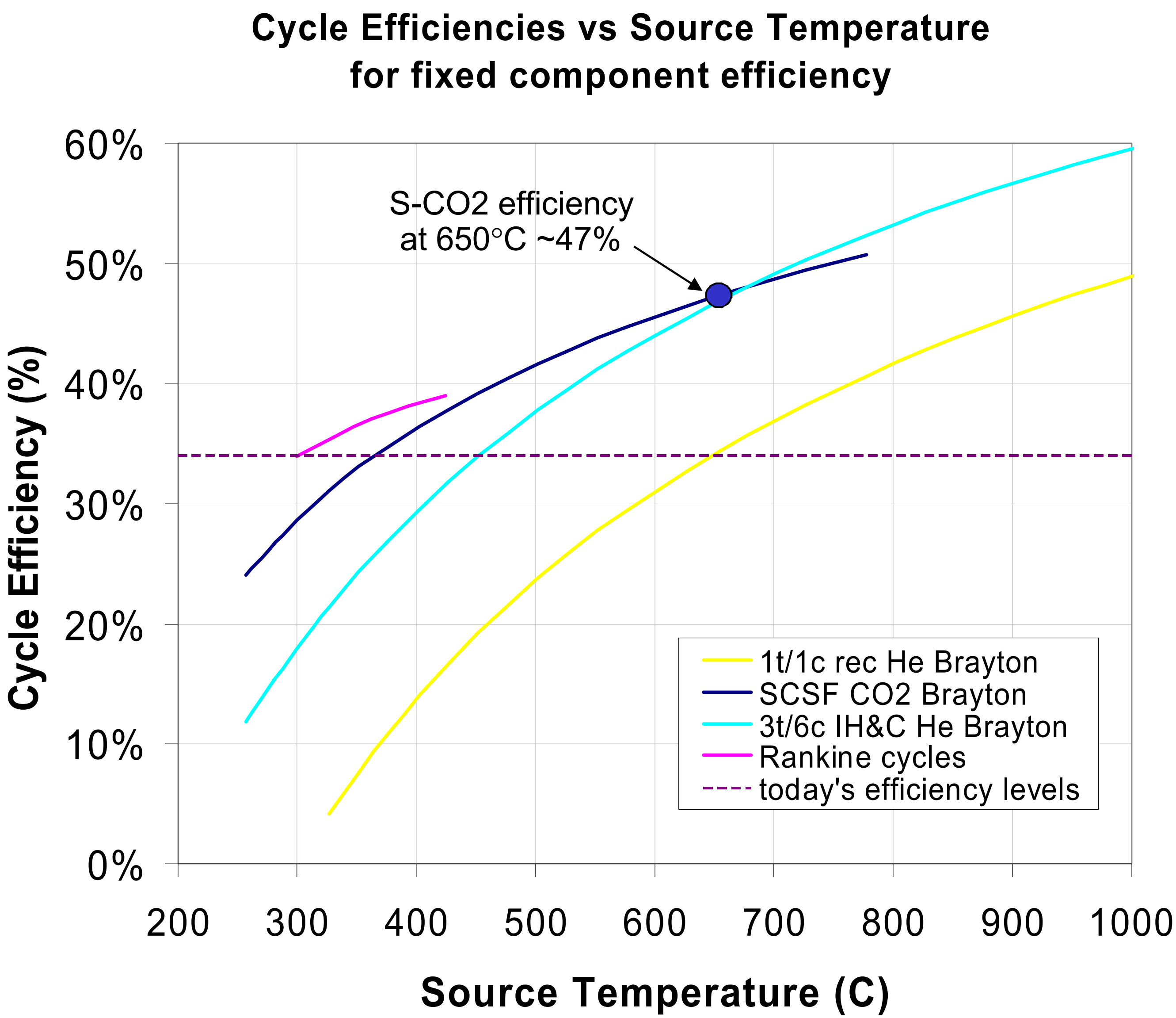
MIT



Super Critical Cycle

Cycle Efficiencies

Today's technology provides significant potential for improvement in cycle efficiency



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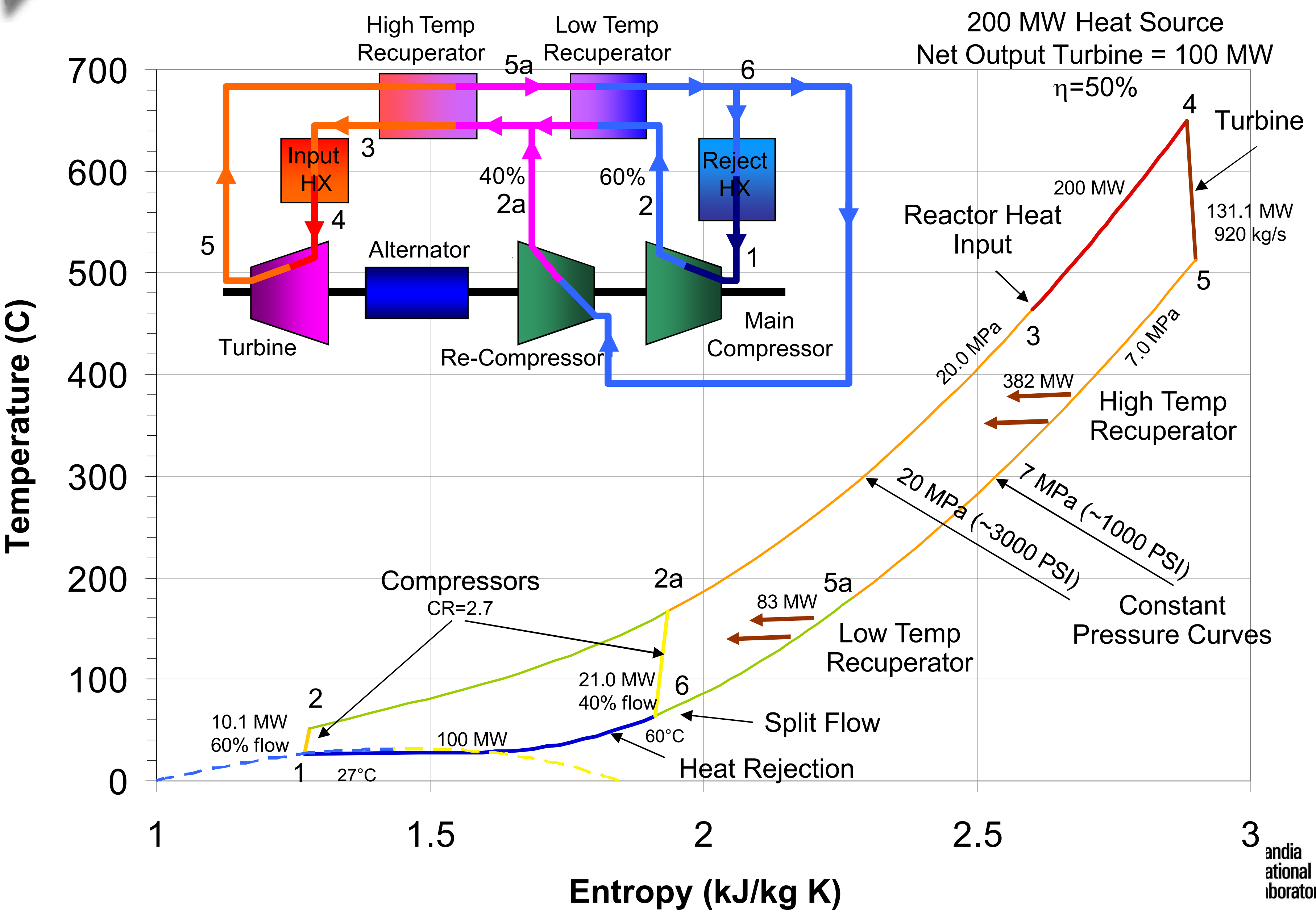
S-CO2 Brayton Cycle With Split Flow



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Reference Core and Conceptual Plant Layout

Baseline Reactor Concept

Baseline reactor and assumptions

200 MWth and 400 MWth with 20 year core lifetime.

0.75 cm OD fuel pin, cf = 0.2 (PWR ~ 1 cm OD, cf = 0.5)
and
1.20 cm OD fuel pin, cf = 0.3

UO_2 fuel, clad thickness = 0.0056 cm SS, gap = 0.008 cm
Initial fuel loading is 12% U-235

Reactor inlet temperature = 450°C
Reactor outlet temperature = 650°C

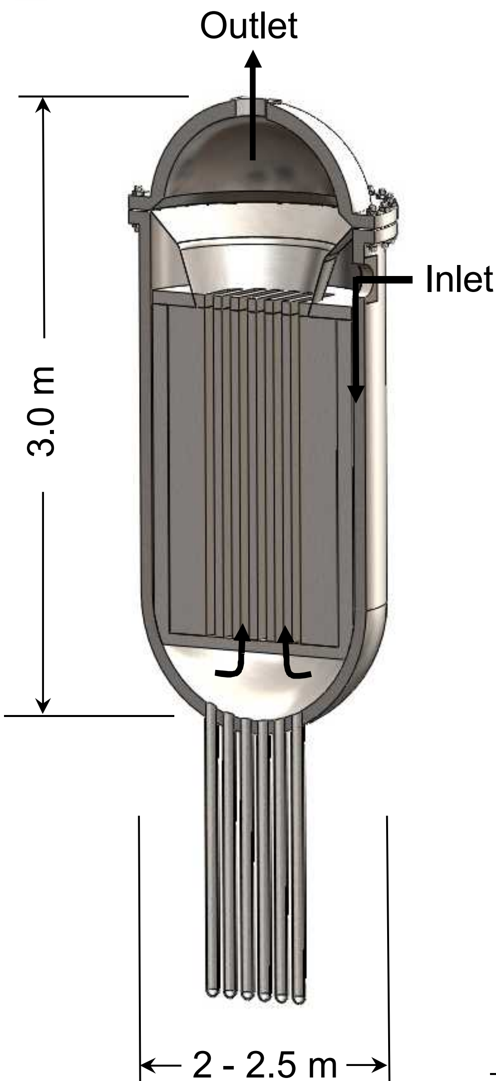
Reactor pressure (CO_2) = 20 MPa = 3000 psi

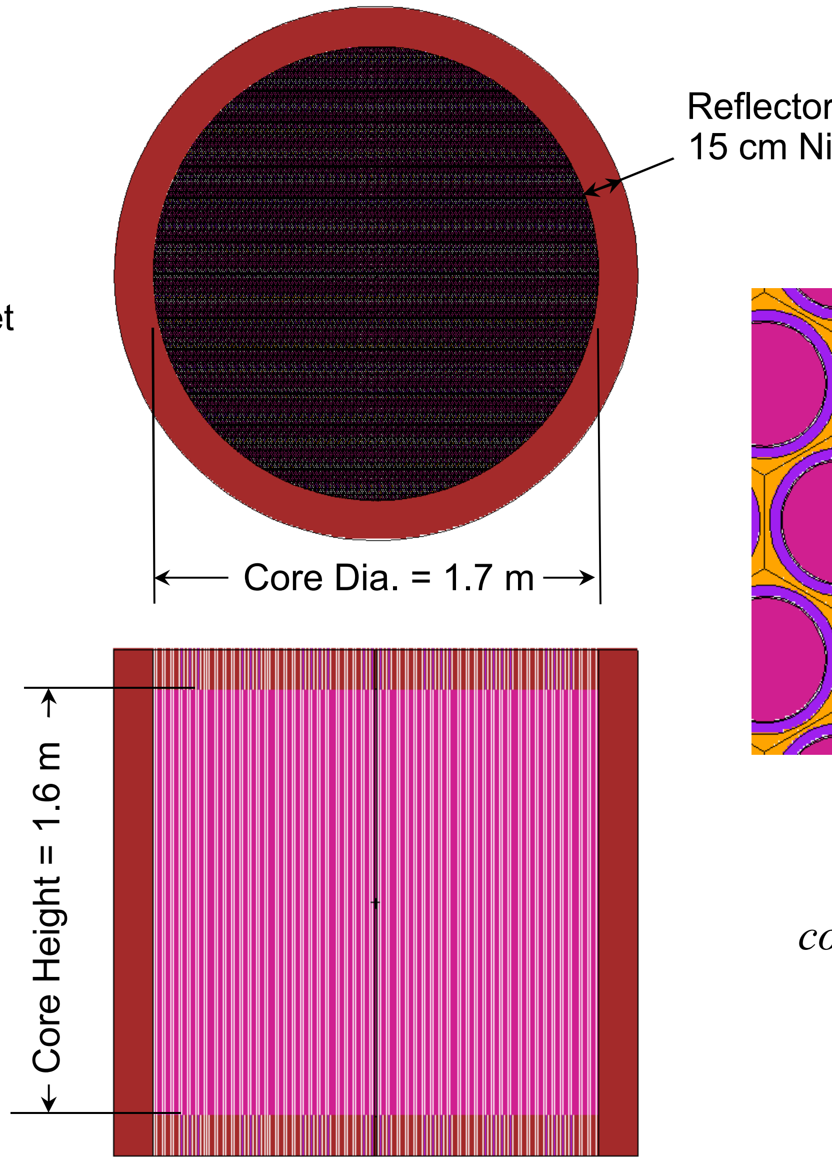
Core 1.7 m Dia. x 1.6 m H with 15 cm Ni reflector
Power density = 55 W/cc core at 200 MW

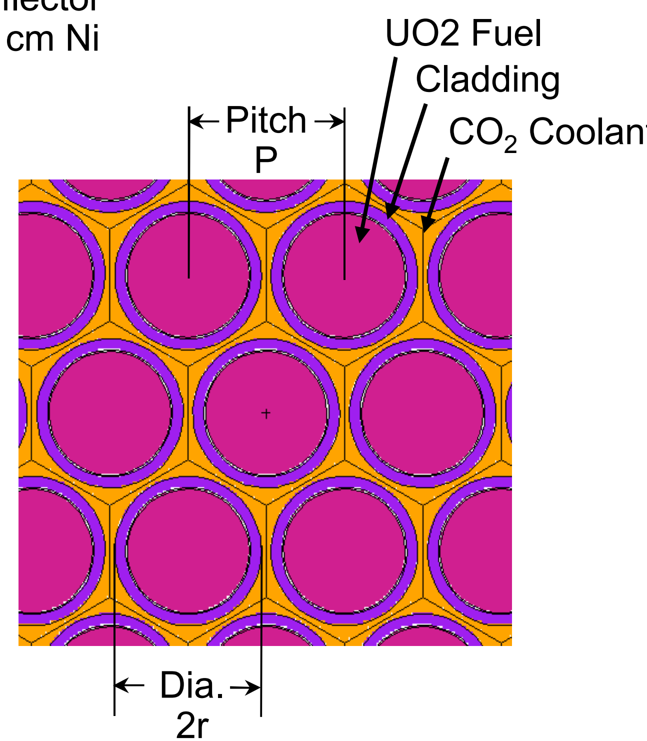
Desired Objectives

Minimal reactivity swing over core lifetime
Core pressure drop less than 1% total power
Small reactivity void coefficient
Acceptable clad and fuel peak temperature

MCNP Model of Core

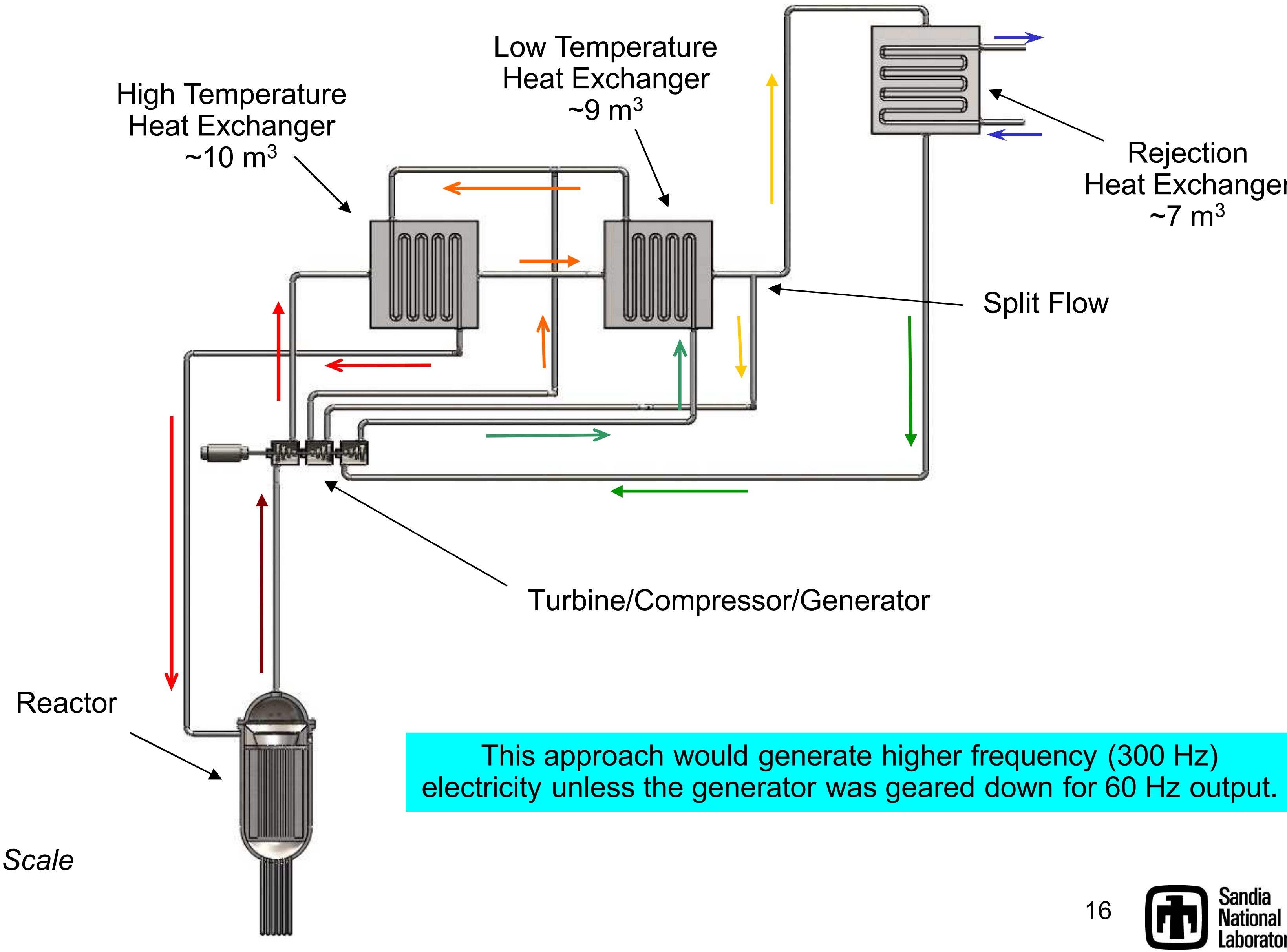






$$coolant\ fraction = 1 - \frac{2\pi r^2}{\sqrt{3}\,P^2}$$

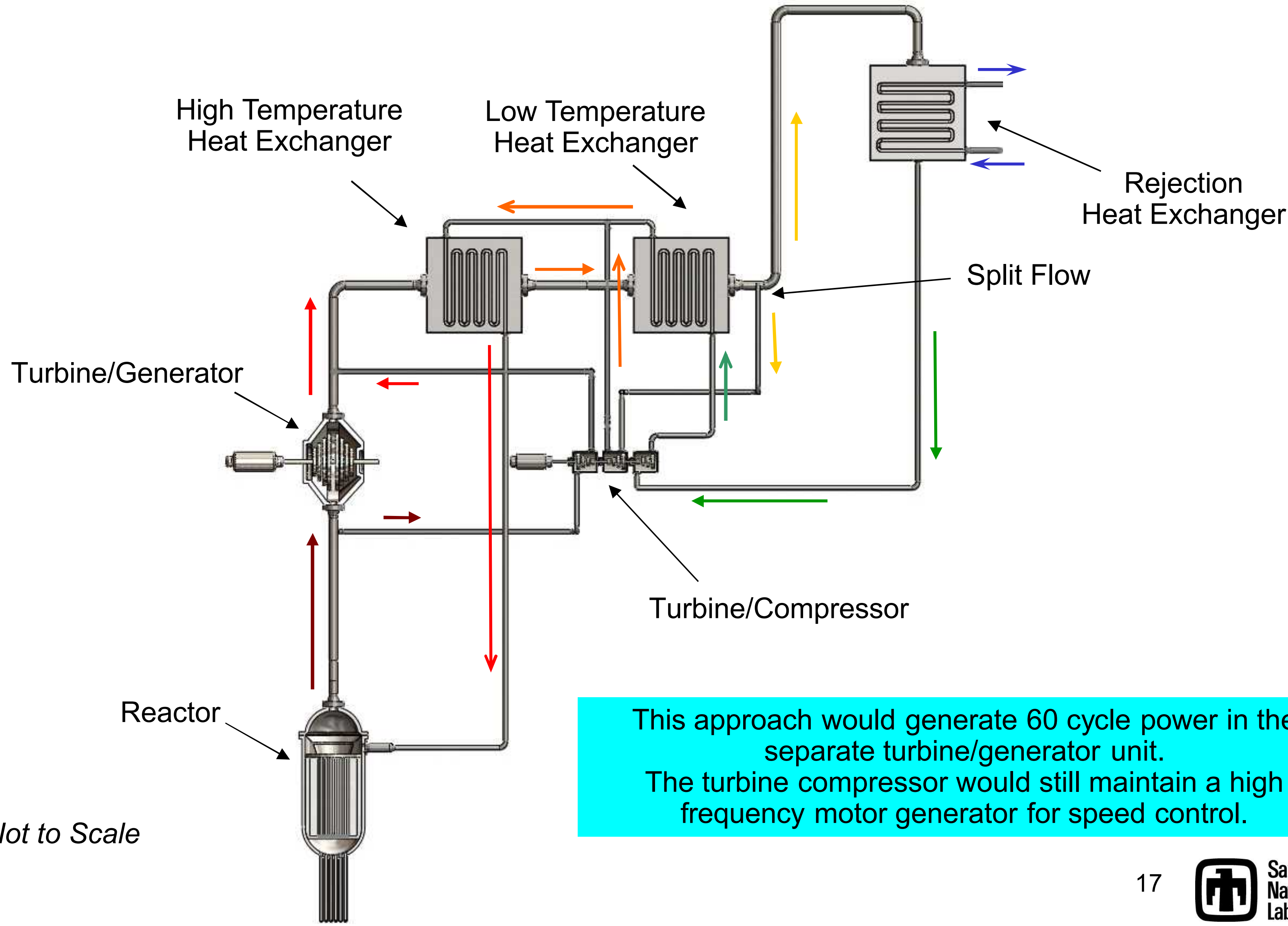
Split Flow With Combined Turbine/Generator/Compressor



This approach would generate higher frequency (300 Hz) electricity unless the generator was geared down for 60 Hz output.

Not to Scale

Split Flow With Separate Turbine/Generator and Turbine/Compressor



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This approach would generate 60 cycle power in the separate turbine/generator unit.
The turbine compressor would still maintain a high frequency motor generator for speed control.

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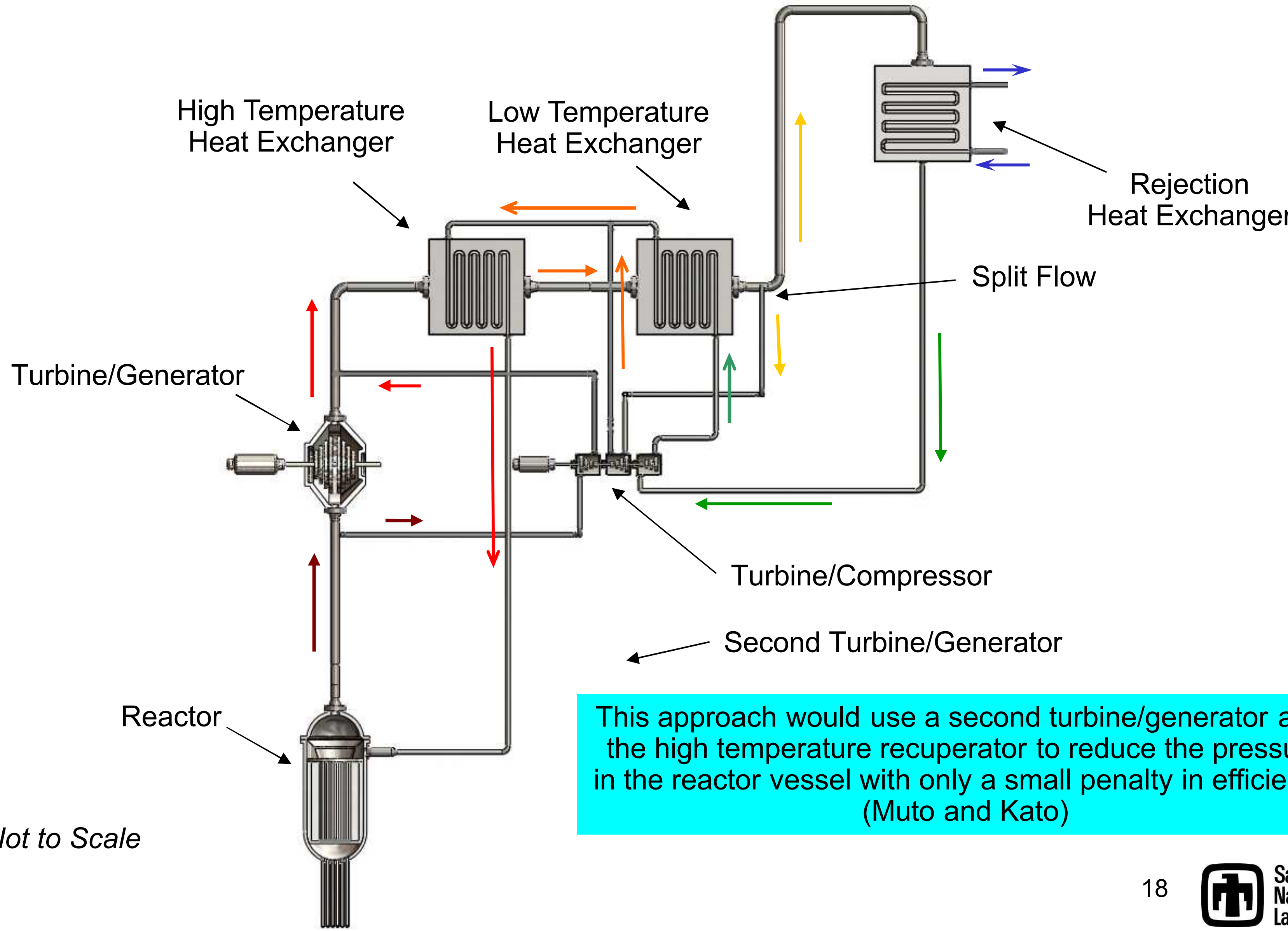
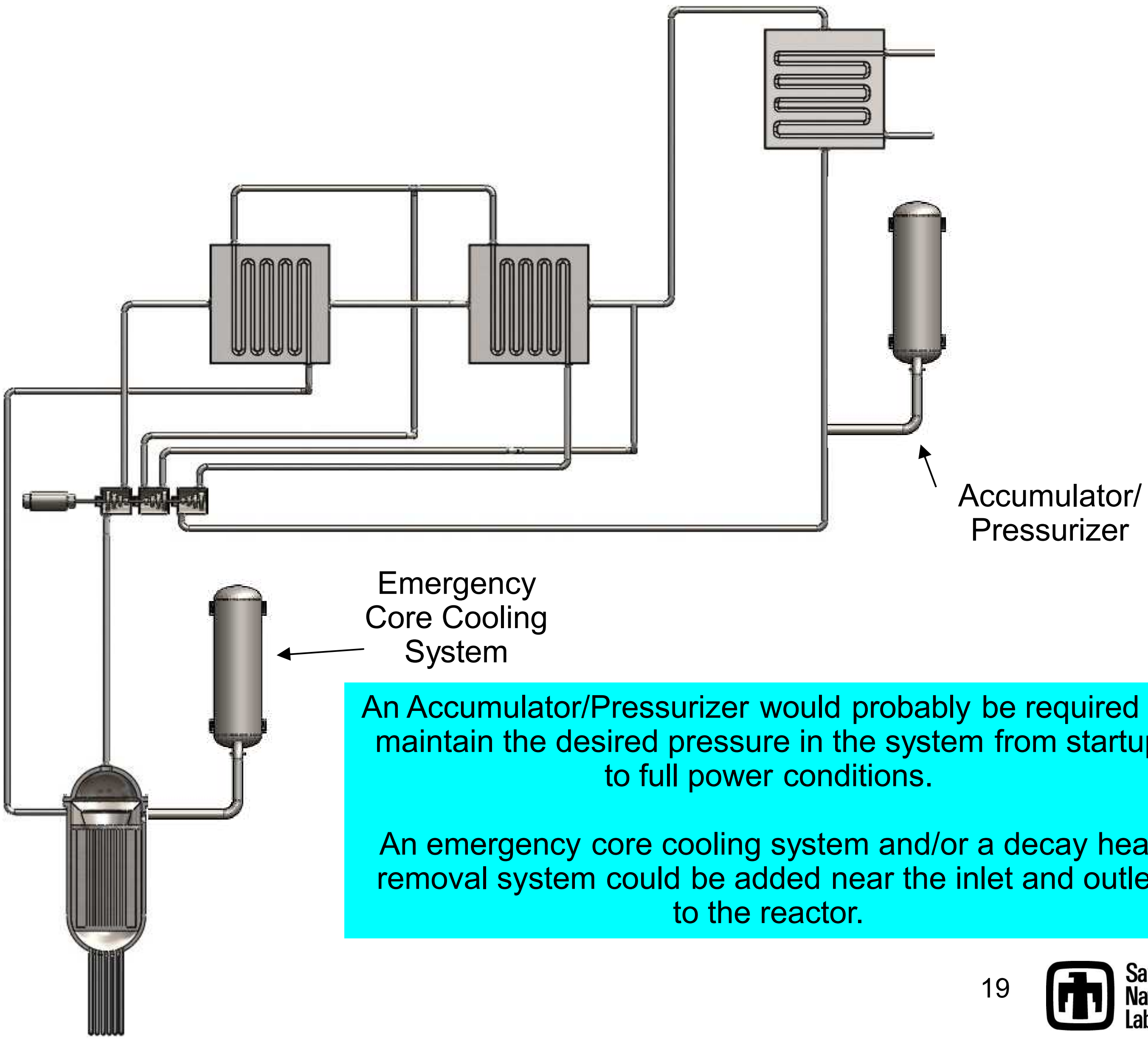
Split Flow With Two Turbine/Generators and Turbine/Compressor



Not to Scale

This approach would use a second turbine/generator after the high temperature recuperator to reduce the pressure in the reactor vessel with only a small penalty in efficiency. (Muto and Kato)

Layout Showing Possible Locations for Pressurizer/Accumulator



An Accumulator/Pressurizer would probably be required to maintain the desired pressure in the system from startup to full power conditions.

An emergency core cooling system and/or a decay heat removal system could be added near the inlet and outlet to the reactor.

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Heat Transfer and Thermal Hydraulics

Thermal Hydraulics Parametric Analysis

Parametric Analysis Assumptions

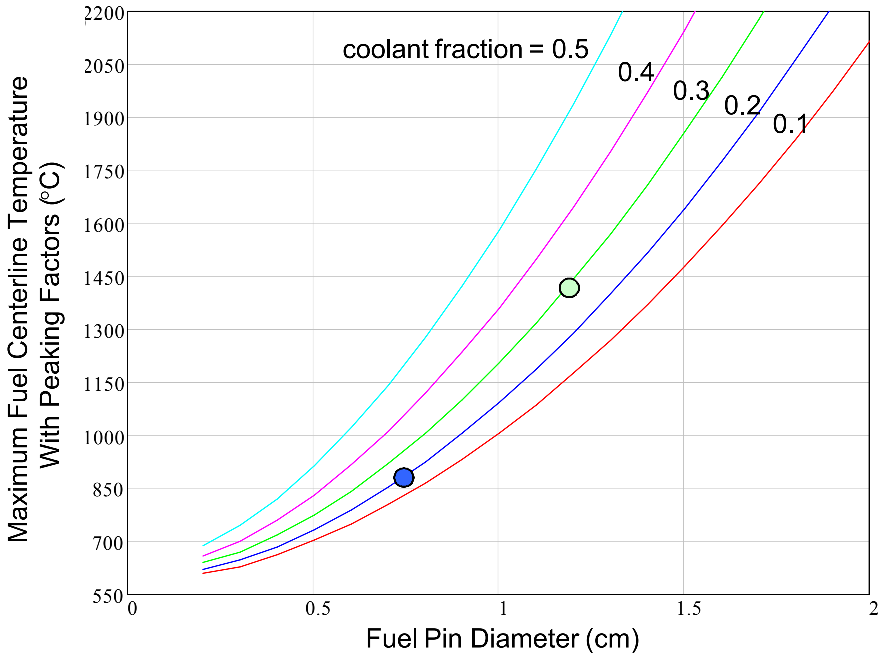
200 MW and 400 MW
Reactor inlet temperature = 450°C
Reactor outlet temperature = 650°C
Reactor average coolant temperature = 550°C
Reactor pressure = 20 MPa = 3000 psi
clad thickness = 0.0056 cm HT9, gap = 0.008 cm He
Core 1.7 m Dia. x 1.6 m H – additional height for plenum

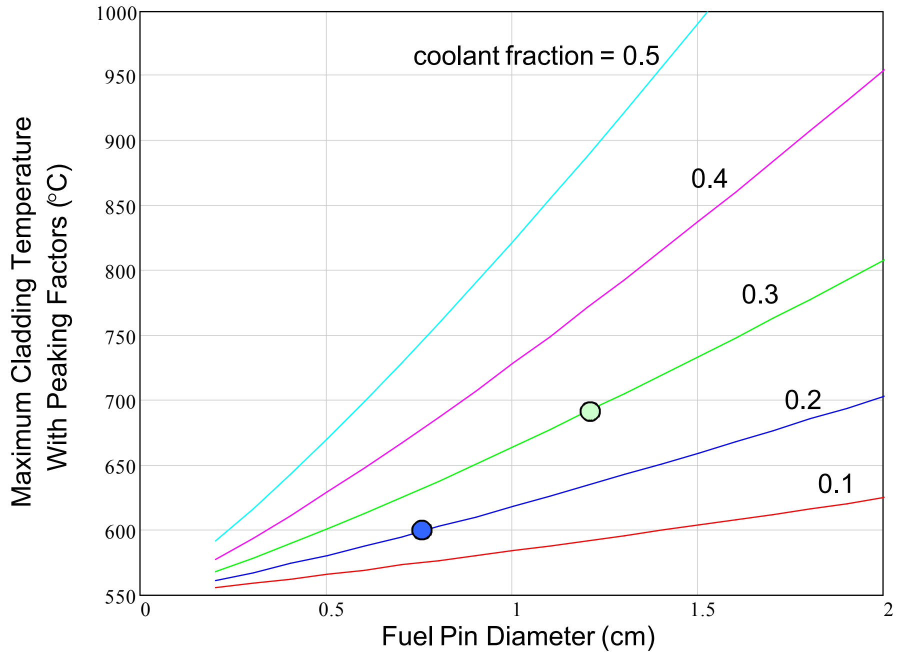
MATHCAD SS-T-P Results

Parametric analysis for maximum fuel temperature and pressure drop performed as a function of coolant fraction and pin diameter.

0.75 cm dia 0.2 cf and 1.2 cm dia 0.3 cf
Both have about same fuel/core ratio of 0.55
At 200 MW both work
At 400 MW pp is much higher for 0.2, temps much higher for 0.3
Flow rate (200 MW) = 900 kg/s = 5,600 Liters/s
Density in reactor = 0.146 g/cc

200 MWth Temperature Analysis





- (blue dot) 0.75 cm dia 0.2 cf - Tmax = 880°C, Tclad = 600°C
- (green dot) 1.20 cm dia 0.3 cf - Tmax = 1440°C, Tclad = 690°C

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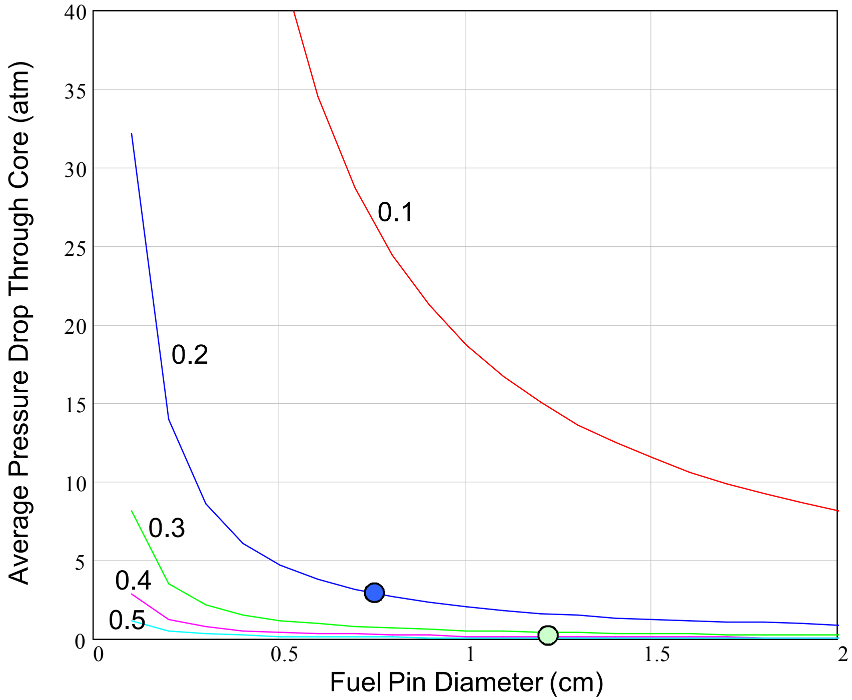
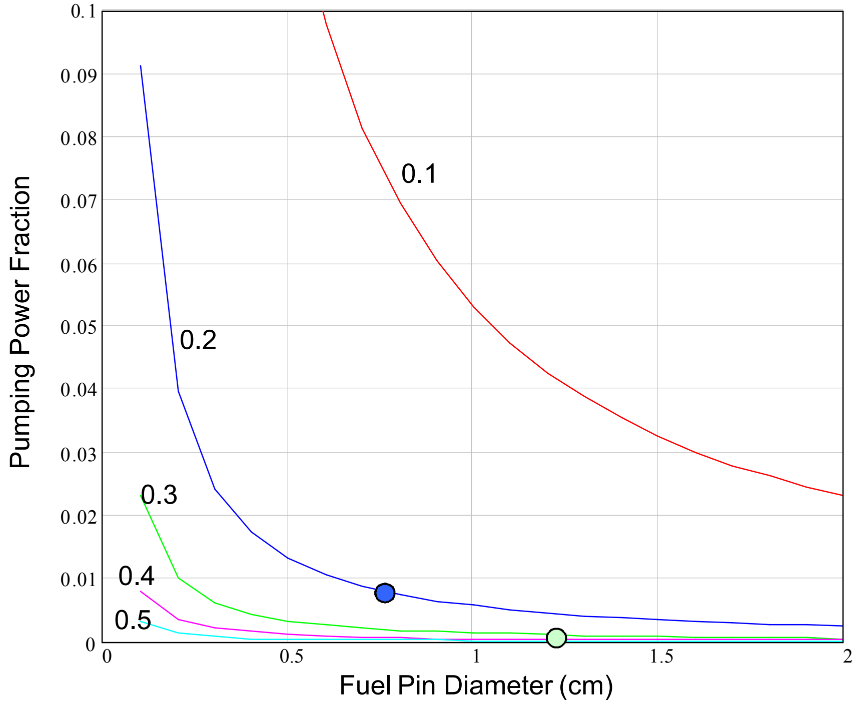
200 MWth Flow Analysis





- 0.75 cm dia 0.2 cf - ΔPcore = 2.9 atm, PPfraction = 0.008 = 1.6 MW
- 1.20 cm dia 0.3 cf - ΔPcore = 0.4 atm, PPfraction = 0.001 = 0.23 MW

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Keff, Burnup, and Void Coefficient

Reactor Burnup Calculations

Keff, Burnup, and Void Coefficients calculated using MCNP
Burnup using BURNCAL (MCNP and Tallies)
Simple calculations performed to-date using one zone
Trade off reactor size, coolant fraction, and enrichment to maintain a constant Keff over the operating history.

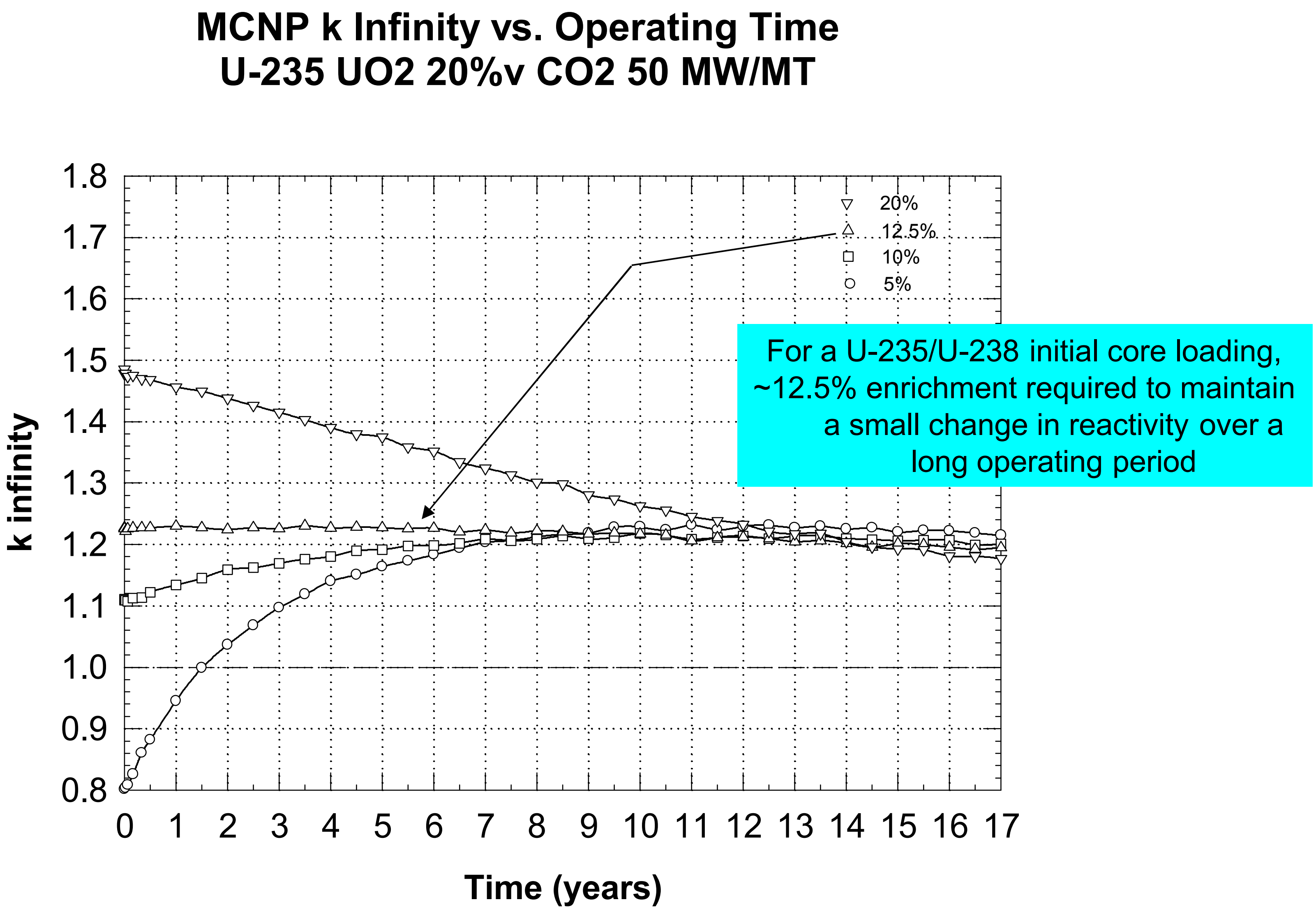
UO_2 fuel, 12% en, clad thickness = 0.0056 cm HT9, gap = 0.008 cm
1.7 m dia x 1.6 m H, 15 cm Ni Reflector

<u>Core Size</u>

Case 1 - 0.75 cm OD, cf = 0.2
Core Vol = 3.63e6 cm3
f/c=0.550
Fuel vol = 2e6 cm3 ~20 MT
55W/cc core = 200 MW

Case 2 - 1.20 cm OD, cf = 0.3
Core Vol = 3.63e6 cm3
f/c=0.5586
Fuel vol = 2e6 cm3 ~20 MT
55W/cc core = 200 MW

K infinity Burnup Calculation



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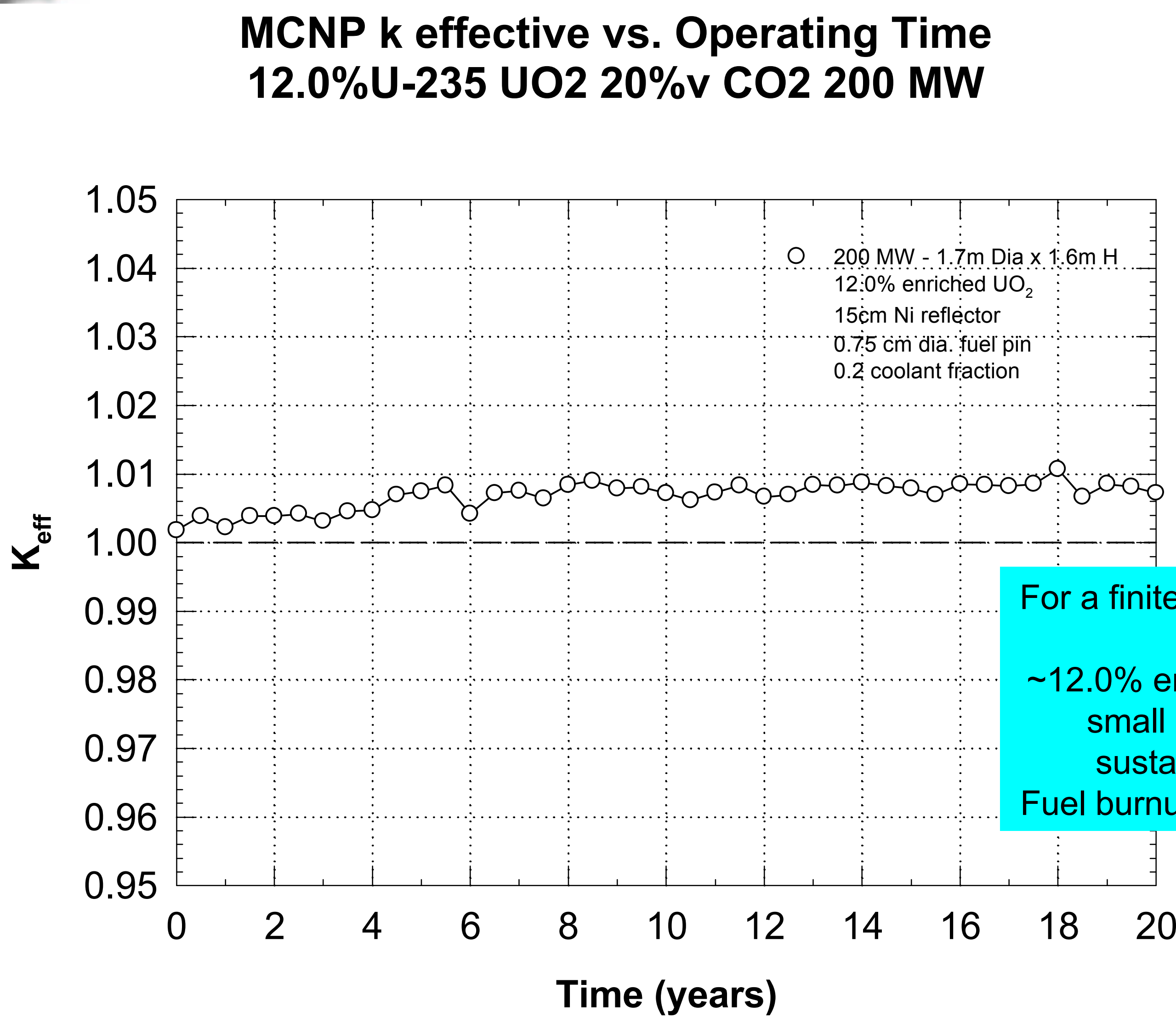
200 MW Burnup for 12.0% Core – Case 1



For a finite core with 0.2 cf and 0.75 cm diameter fuel pin, ~12.0% enrichment works. A relatively small reactivity change over time is sustainable (Δk=0.01) at 200 MW. Fuel burnup would be 72,000 MWD/MT

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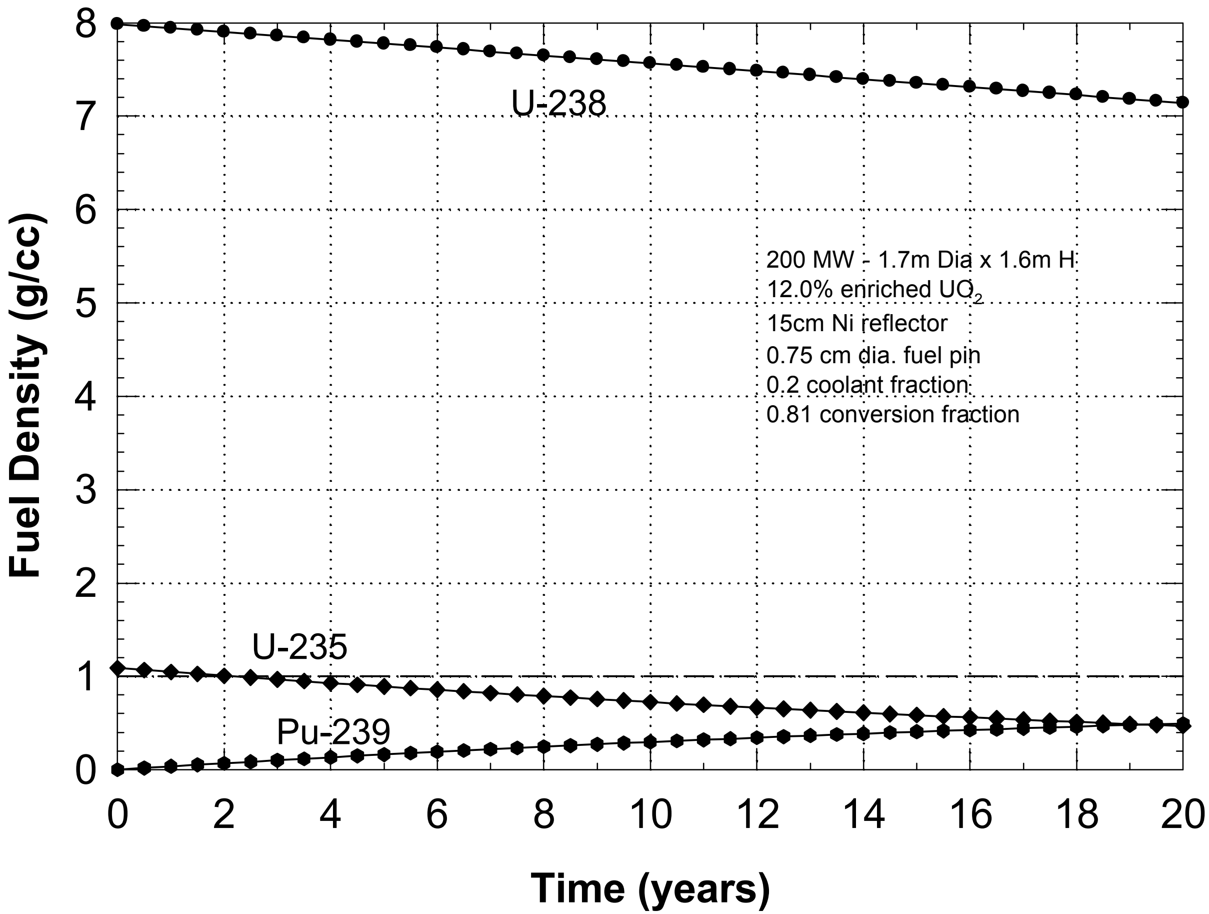
Fuel Constituent Density

MCNP Fuel Density vs. Operating Time
12.0%U-235 UO2 20%v CO_2 200 MW



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Reactivity Void Coefficient

Void Coefficients calculated using MCNP at 20 MPa (3000 psi) and 0.1 MPa (14.7 psi) pressure and 550°C temperature gas.

From Lewins – Fast Fission - β(U-235) = 0.0066
β(U-238) = 0.0161
β(Pu-239) = 0.00212

Estimates for the delayed neutron fraction β
β BOL = 0.0080
β EOL (200 MW @ 20 yrs) = 0.0062
β EOL (400 MW @ 20 yrs) = 0.0052

Case 1 - 0.75 cm OD, cf = 0.2

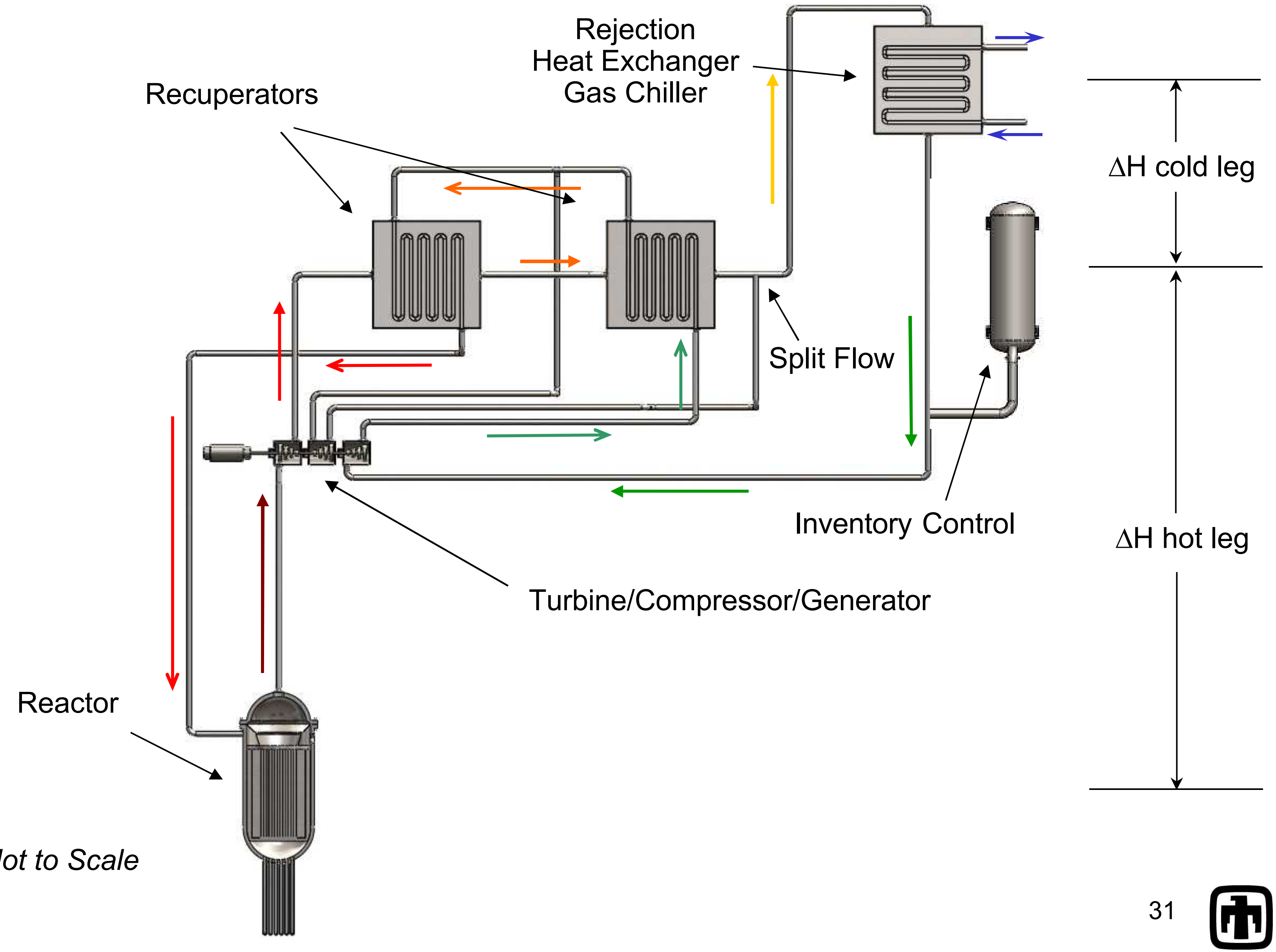
Δk/k (BOL) = 0.00185 ± 0.0016	ρ = +$0.23 ± $0.20
Δk/k (200MW@20yrs) = 0.0020 ± 0.0015	ρ = +$0.32 ± $0.24
Δk/k (400MW@20yrs) = 0.0015 ± 0.0013	ρ = +$0.29 ± $0.25

Case 2 - 1.20 cm OD, cf = 0.3

Δk/k (BOL) = 0.00056 ± 0.0015	ρ = +$0.07 ± $0.19
Δk/k (200MW@20yrs) = 0.0057 ± 0.0015	ρ = +$0.92 ± $0.24
Δk/k (400MW@20yrs) = 0.0040 ± 0.0014	ρ = +$0.76 ± $0.27

Natural Circulation Flow And Decay Heat Removal

Natural Convection Flow



Not to Scale

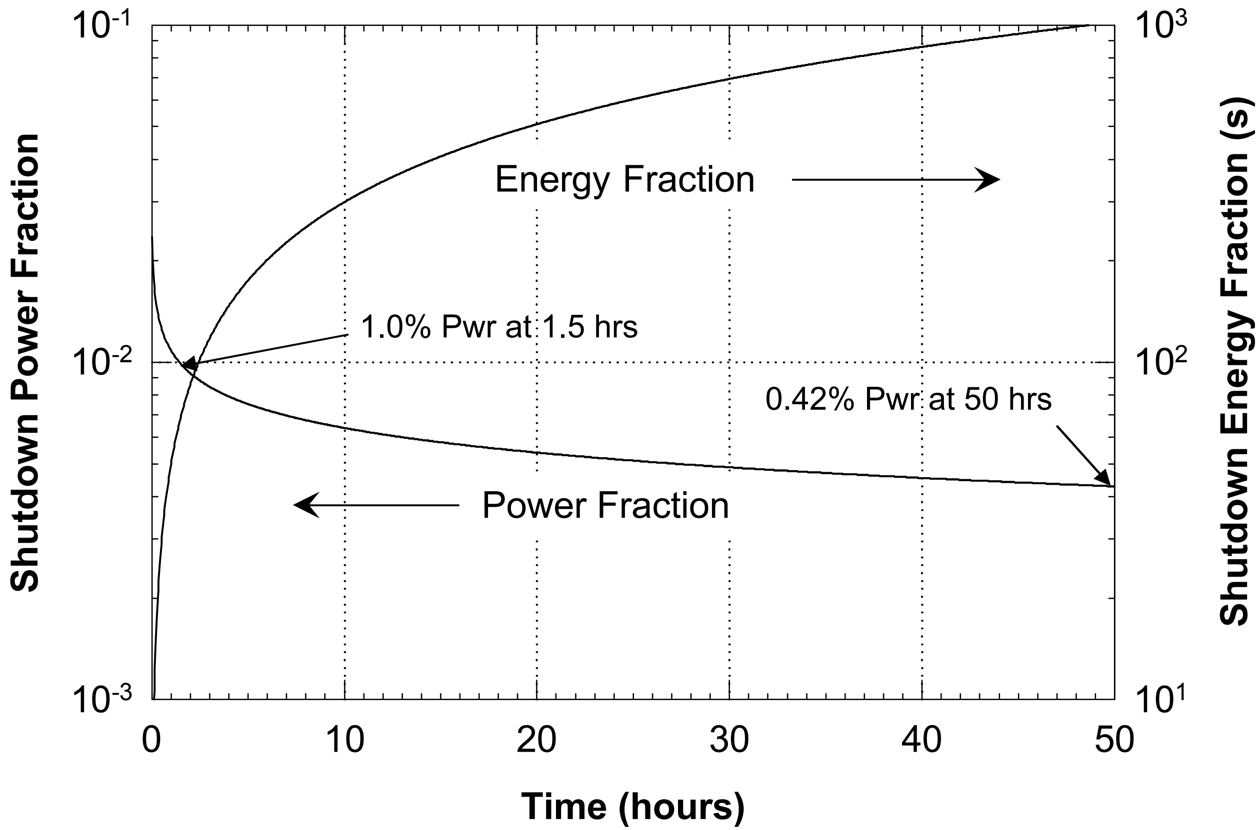
Natural Circulation Summary

- Developed Simple Scoping Calculation Models in Excel
  - Based on theory described by D. Milone
  - Validated against experiments in a ½" OD Loop 72" Tall
- Modified Scoping Model to Apply it to
  - Reactors, Heat Exchangers, Gas-Chiller
  - Evaluated Proposed SNL Experiment
- Developed a 3 D CFD model by modifying a fire code C3D
  - Implement Nist Calls
  - Modified Energy Equation to use Enthalpy
  - Verified against D. Milone Report
  - Explored Natural Circ in Rx, with HXs and with Gas Chiller

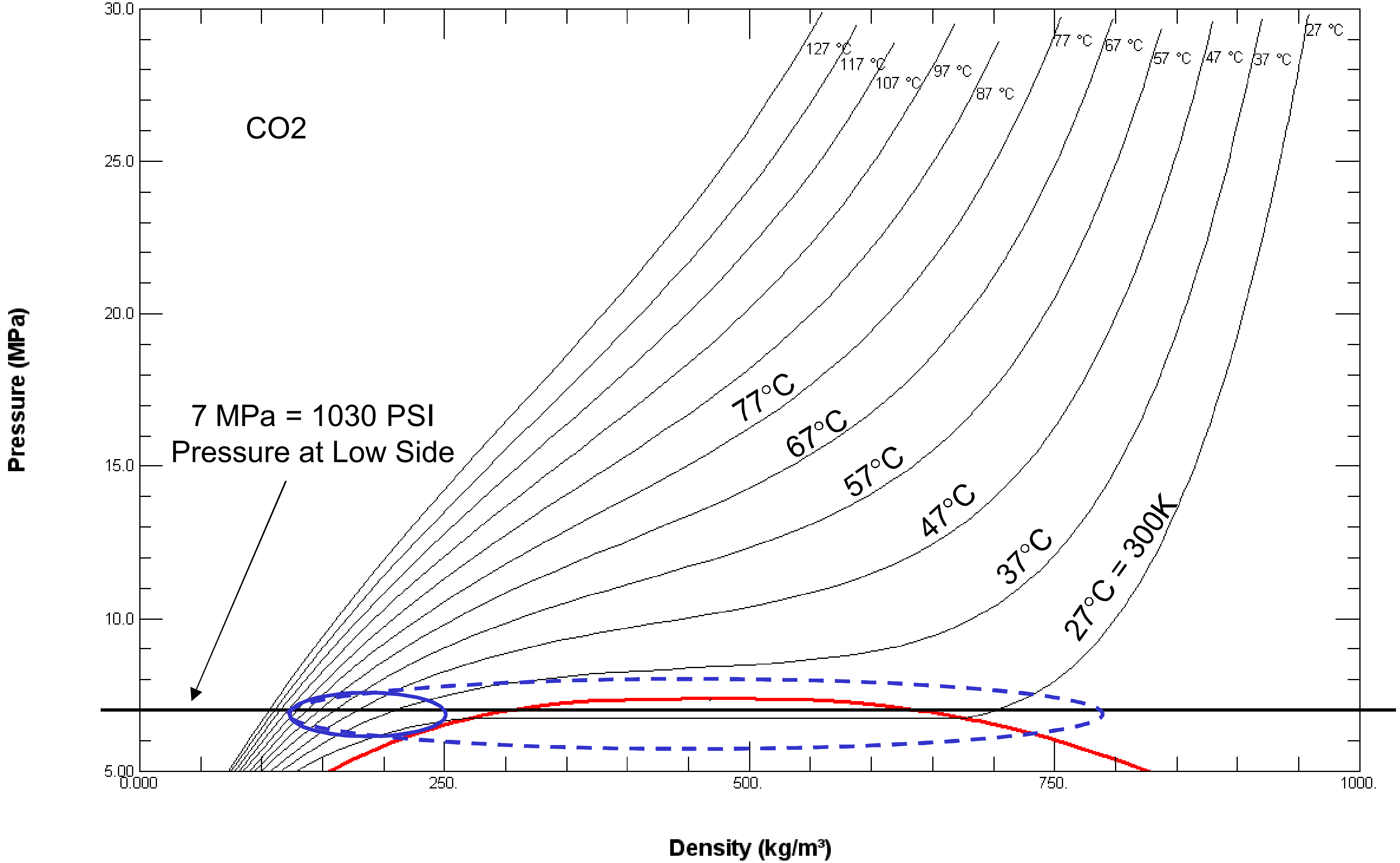
Background

Wigner-Way Formulation for Decay Power

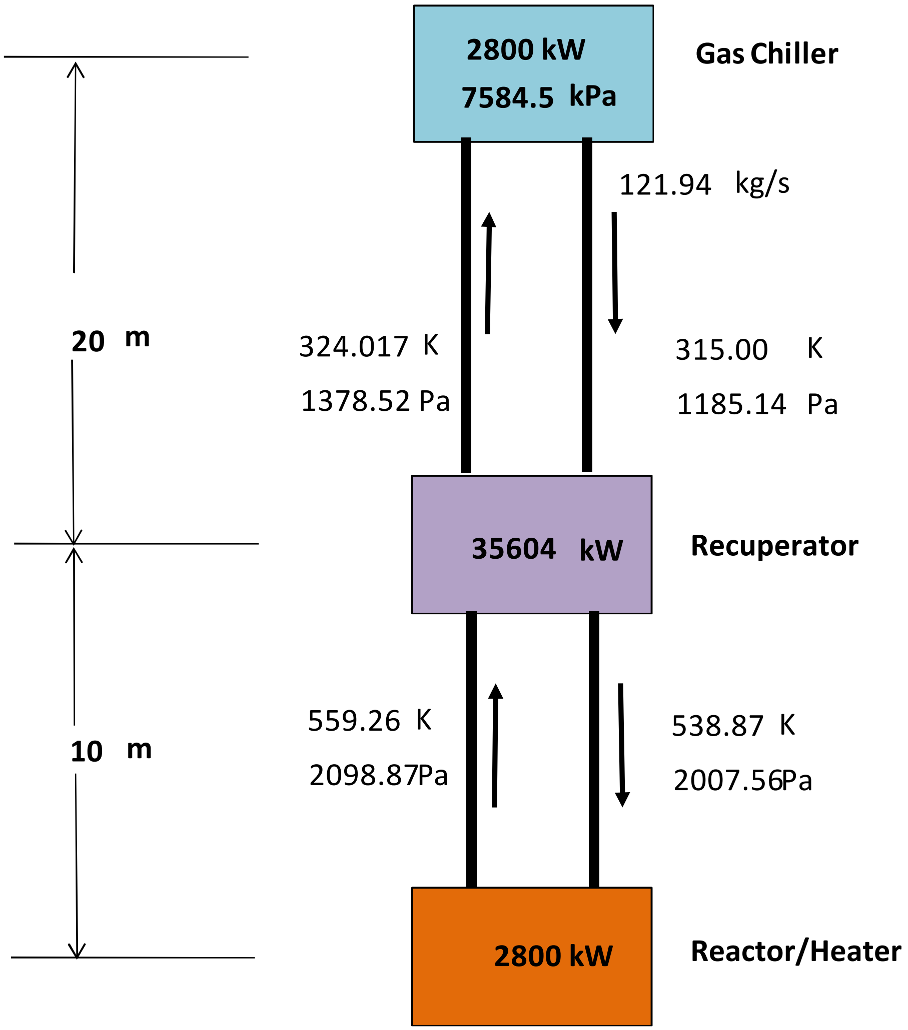
$$P_d(t)/P_0 = 0.0622\left[\ t^{-0.2} - \left(t_0 + t\right)^{-0.2}\ \right]$$



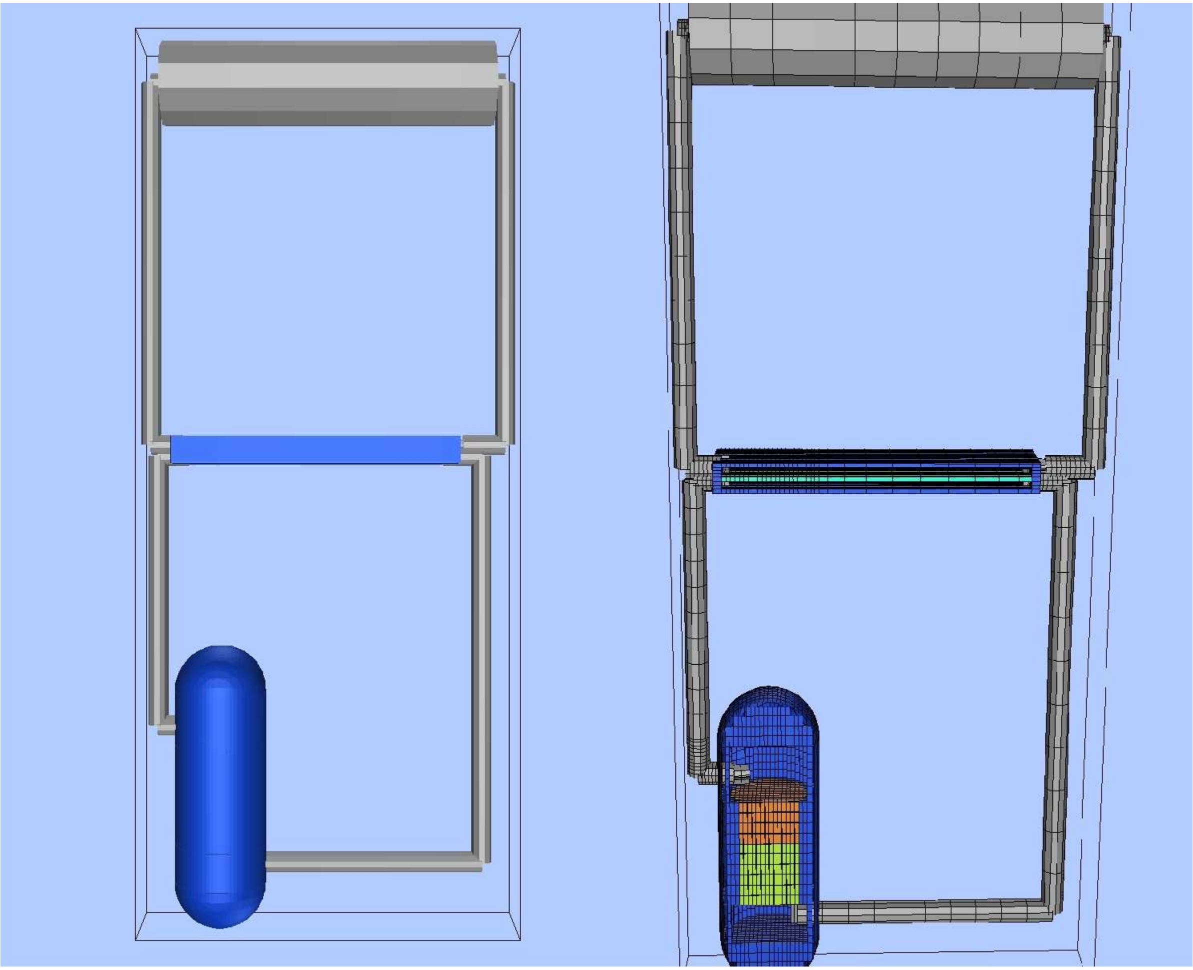
Conditions for Natural Circulation



Lumped Parameter Analysis (2.8 MW decay heat source)



CD3-SC Natural Convection Flow



Natural Circulation Conculsions

- Large amounts of natural circulation occur in S-CO2
  - Need a sufficiently large elevation difference between the gas chiller and the heat sourcs (10 m)
  - Pressures need to be kept near the critical pressure
    - (5-12 MPa)
  - HXs/Recuperators do not destroy the ability for natural circulation
  - Pressure drop is important large dPs must be avoided
    - e. g. turbine and compressor
    - If large dP's exit they can be bypassed
  - There is sufficient flow to remove decay heat given proper design
  - SNL now has tools to evaluate S-CO2 Natural Circulation
    - Both scoping and CFD codes
    - So effect on reactor can be modeled

Economics

Cost Estimates

Initial Core Loading Fuel Cost (20 MT, 12% enriched = 7,500$/kg) = **$150M**

- future cores with Pu recycle would be expected to be much less

HX cost (2 recuperators and 1 heat rejection = **20** to **$50M**

Pressure Vessel and Piping = **$50M**

Total = **$250M**

At $5,000/kW a 100 MWe system would cost **$500M**

Summary

- From the analyses that we have preformed so far, we believe that the direct cycle, S-CO2 cooled, fast reactor concept is worth further study.
- The concept is simple and relatively straight forward. We have shown that a reactor power of 200 to 400 MWth is achievable with a reactivity burnup lifetime of potentially up to 20 years.
- The concept has many advantages over other advanced reactor concepts. The reactor can be cooled by natural circulation flow in the event of a loss of flow condition.
- The major disadvantages are the high pressure of the reactor coolant and the corrosion at high temperatures. The pressure can be lowered significantly without a large penalty in efficiency using a slightly different cycle configuration, and will be studied in future work. Corrosion issues requires further experimental work.