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Advanced Reactor Technology Pebble Bed Project

Modular High Temperature Pebble Bed Reactor

Faculty Advisors

Andrew C. Kadak
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Sidney Yip
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Student Researchers

- **Fuel Performance**
  - Heather MacLean
  - Jing Wang
- **Thermal Hydraulics**
  - Chunyun Wang
  - Tamara Galen
- **Core Physics**
  - Julian Lebenhaft
- **Safety**
  - Tieliang Zhai

Project Objective

Develop a sufficient technical and economic basis for this type of reactor plant to determine whether it can compete with natural gas and still meet safety, proliferation resistance and waste disposal concerns.

Generation IV Reactor

- Competitive with Natural Gas
- Demonstrated Safety
- Improved Proliferation Resistance
- Readily Disposable Waste Form

Modular High Temperature Pebble Bed Reactor

- 110 MWe
- Helium Cooled
- "Indirect" Cycle
- 8 % Enriched Fuel
- Built in 2 Years
- Factory Built
- Site Assembled
- On-line Refueling
- Modules added to meet demand.
- No Reprocessing
- High Burnup >90,000 Mwd/MT
- Direct Disposal of HLW

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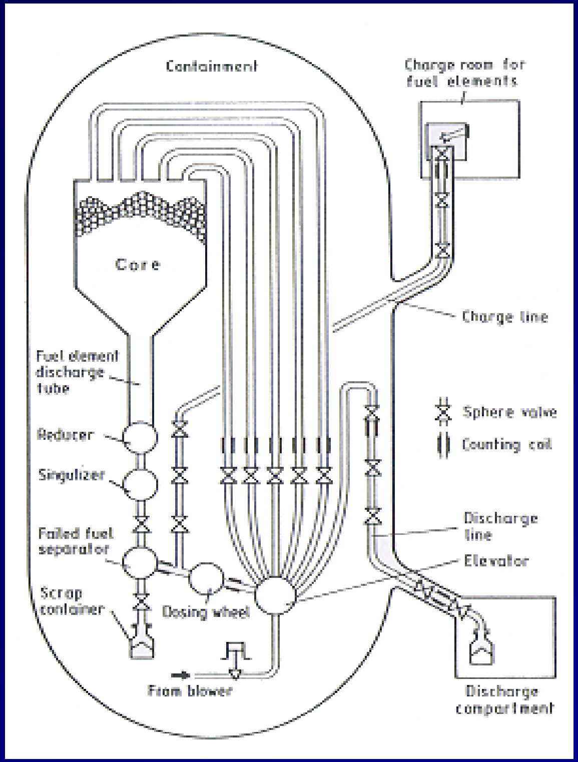
What is a Pebble Bed Reactor ?

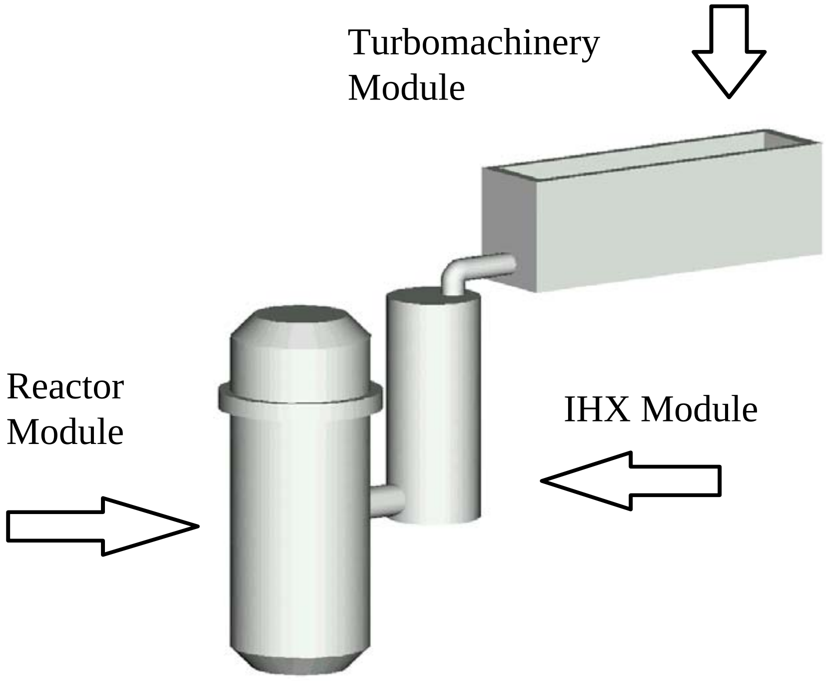


- 360,000 pebbles in core
- about 3,000 pebbles handled by FHS each day
- about 350 discarded daily
- one pebble discharged every 30 seconds
- average pebble cycles through core 15 times
- Fuel handling most maintenance-intensive part of plant

MPBR Specifications

Thermal Power	**250 MW**
Core Height	**10.0 m**
Core Diameter	**3.0 m**
Pressure Vessel Height	**16 m**
Pressure Vessel Radius	**5.6 m**
Number of Fuel Pebbles	**360,000**
Microspheres/Fuel Pebble	**11,000**
Fuel	**UO_2**
Fuel Pebble Diameter	**60 mm**
Fuel Pebble enrichment	**8%**
Uranium Mass/Fuel Pebble	**7 g**
Coolant	**Helium**
Helium mass flow rate	**120 kg/s (100% power)**
Helium entry/exit temperatures	**450ºC/850ºC**
Helium pressure	**80 bar**
Mean Power Density	**3.54 MW/m^3**
Number of Control Rods	**6**
Number of Absorber Ball Systems	**18**

Conceptual Design Layout



Competitive With Gas ?

• Natural Gas	3.4 Cents/kwhr
• AP 600	3.62 Cents/kwhr
• ALWR	3.8 Cents/kwhr
• MPBR	3.3 Cents/kwhr

Levelized Costs (1992 $ Based on NEI Study)

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Improved Fuel Particle Performance Modeling: Chemical Modeling

Student: Heather MacLean
Advisor: R. Ballinger

Objective

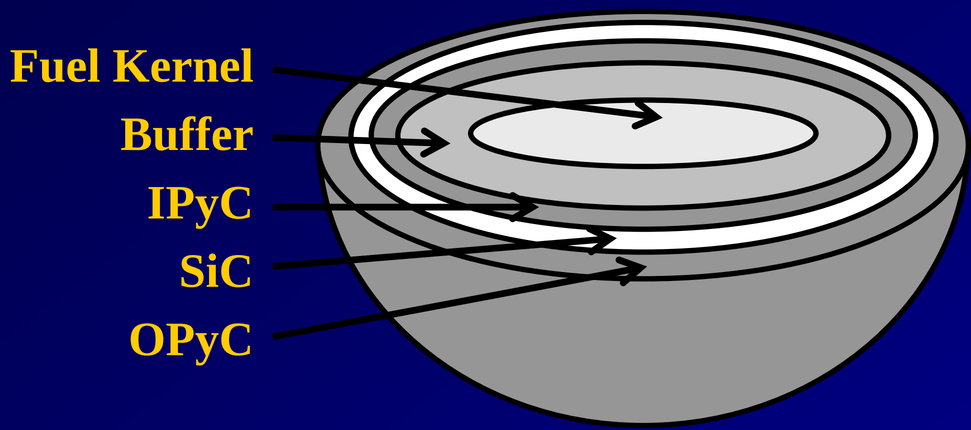
- **Model fuel particle chemical environment**
  - particle temperature distributions
  - internal particle pressure

- **Model chemical interactions with coatings (SiC)**
  - migration of fission products (Ag) through coatings (SiC)
  - chemical attack (Pd) of SiC

Accomplishments

- Analyzed likely temperatures in fuel particles in different core locations
  - ΔT across any particle < 20 °C
  - peak kernel temperature range: 500-1100 °C
- Diffusion experiment in progress
  - 2 diffusion couples heated, continuing
  - characterization in progress

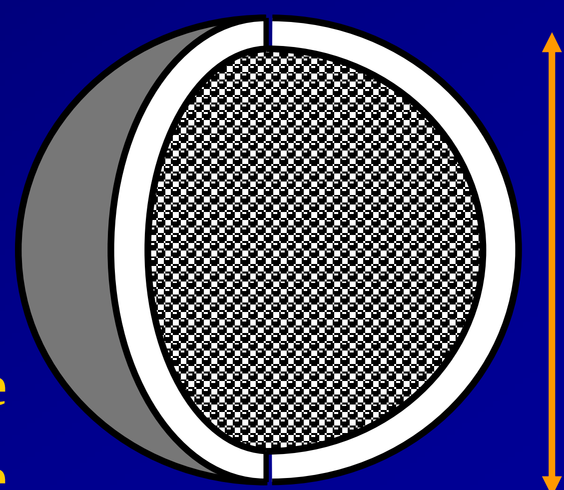
Coated Particle Fuel System



Individual Microsphere

780 μm nominal diameter

Fuel Pebble



60 mm diameter

~11,000 microspheres per fuel pebble

~350,000 pebbles per core

Thermal Model

Calculate temperatures in a pebble:

- Linear axial bulk He temperature rise (450-850 °C)
- Packed-bed He heat transfer correlation
  (ΔT across He film surrounding a pebble)

$\Rightarrow$ Pebble surface temperature for any core location

- Homogenized (volumetric averages) pebble thermal conduction model based on core average power
- Thermal conductivity depends on temperature

$\Rightarrow$ Temperature distribution inside a pebble

$\Rightarrow$ Fuel particle thermal model

Fuel Particle Thermal Model

Calculate temperatures in a particle:

- Particle surface temperature determined by radial location in a pebble
- Fuel kernel fission product swelling data
  1% volume swelling per 10 GWd/T
- Buffer densification to accommodate kernel swelling
- Kernel thermal expansion -- 10^{-6} K^{-1}

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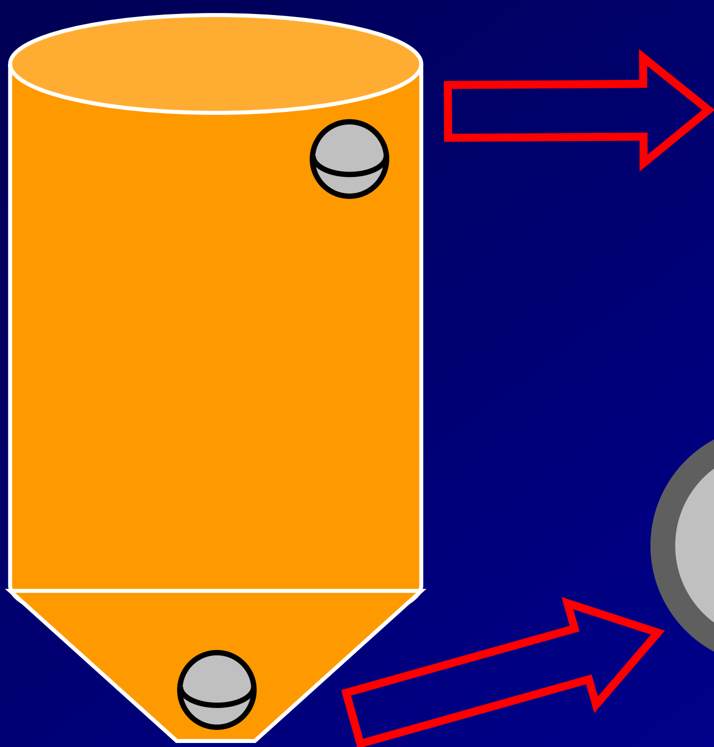
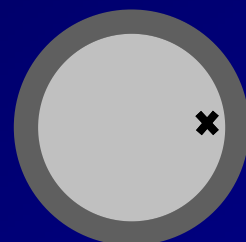
Bounding Thermal Examples

T_{He}(inlet) = 450 °C



T_{He}(outlet) = 850 °C

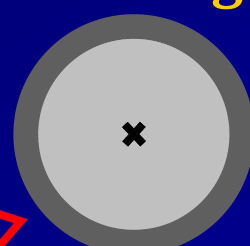
Low Temperature Case



core inlet

power: average
peak T: 513 °C
ΔT: 16 °C

High Temperature Case



core outlet

power:	average	2x average
peak T:	968 °C	1074 °C
ΔT:	17 °C	19 °C

Typical Particle Temperatures

Pebble Power Axial Location Loc. In Pebble	Average Core Inlet Outer Edge	Average Core Outlet Center	2x Average Core Outlet Center
Bulk He Temp.(°K)	723	1123	1123
Temperatures			
Kernel Center	786	1241	1347
Kernel Outer Edge	779	1234	1340
Buffer Outer Edge	771	1225	1329
IPyC Outer Edge	770	1224	1329
SiC Outer Edge	770	1224	1329
OPyC Outer Edge	770	1224	1328
Particle ΔT	16	17	19

Significance of Temperatures

- **Small ΔT across all particles**
  - $\Rightarrow$ can use average temperature in a particle for chemical analyses
- **Variation in particle peak temperature**
  - $\Rightarrow$ chemistry phenomena (diffusion) vary exponentially with temperature
- **Gradient across particle**
  - $\Rightarrow$ significant impact on mechanical phenomena

Chemical Interactions

- **Palladium**
  - very destructive, local attack
  - can open a pathway for fission product release
  - limited data
- **Silver**
  - diffuses through intact SiC
  - activity / maintenance concern
  - limited data in MPBR proposed temperature range

SiC Diffusion Experiments

- **Limited data for specific fission products and temperatures of interest**
- **Develop experimental foundation for future study of advanced fission product barrier materials**

3/4 inch OD   30 mil thick wall

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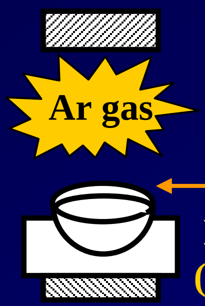
Experimental Procedure

1. Sputter Coating

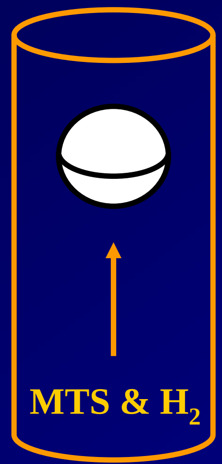
Ag or Pd target



Graphite Hemisphere (hollow shell)

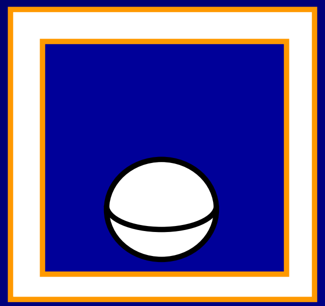
Metal Coating Deposited on Inside of Shell

2. SiC Overcoating



3. Heat Treatment

1000-1600 °C
10-1000 hours

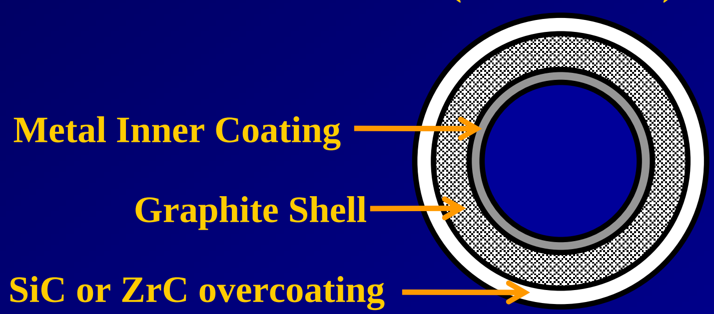


4. Characterization

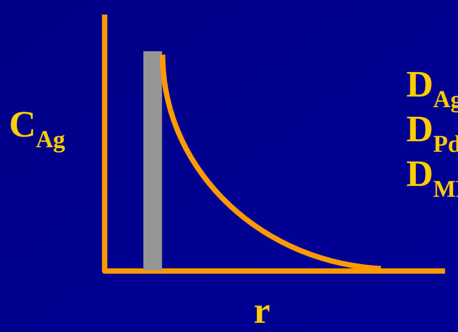
Microscopy
SIMS
ESCA
XRD

Diffusion Couple

(cross section)



5. Data Analysis



$D_{Ag}(T)$
$D_{Pd}(T)$
$D_{MFP}(T)$

Status of Experiments

- Experimental procedure defined
- System operational
- 2 diffusion heat treatments completed
  - 1500 °C, 24 hours, Ag-SiC
  - 1400 °C, 44 hours, Ag-SiC
  - other temperatures in progress
- Characterization in progress

Future Work

- Continue diffusion couple heat treatments
- Collect and analyze diffusion experiment data
- Update thermal and pressure models
  - include UCO data
  - include radial and axial power peaking

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Fuel Performance Modeling — Mechanical Analysis

Student: Jing Wang

Advisors: Prof. Ballinger & Prof. Yip

Objective

- Develop a mechanical model to predict the mechanical behavior of TRISO fuel particles, including failure, that can be used as a tool in understanding past behavior and in developing advanced particles

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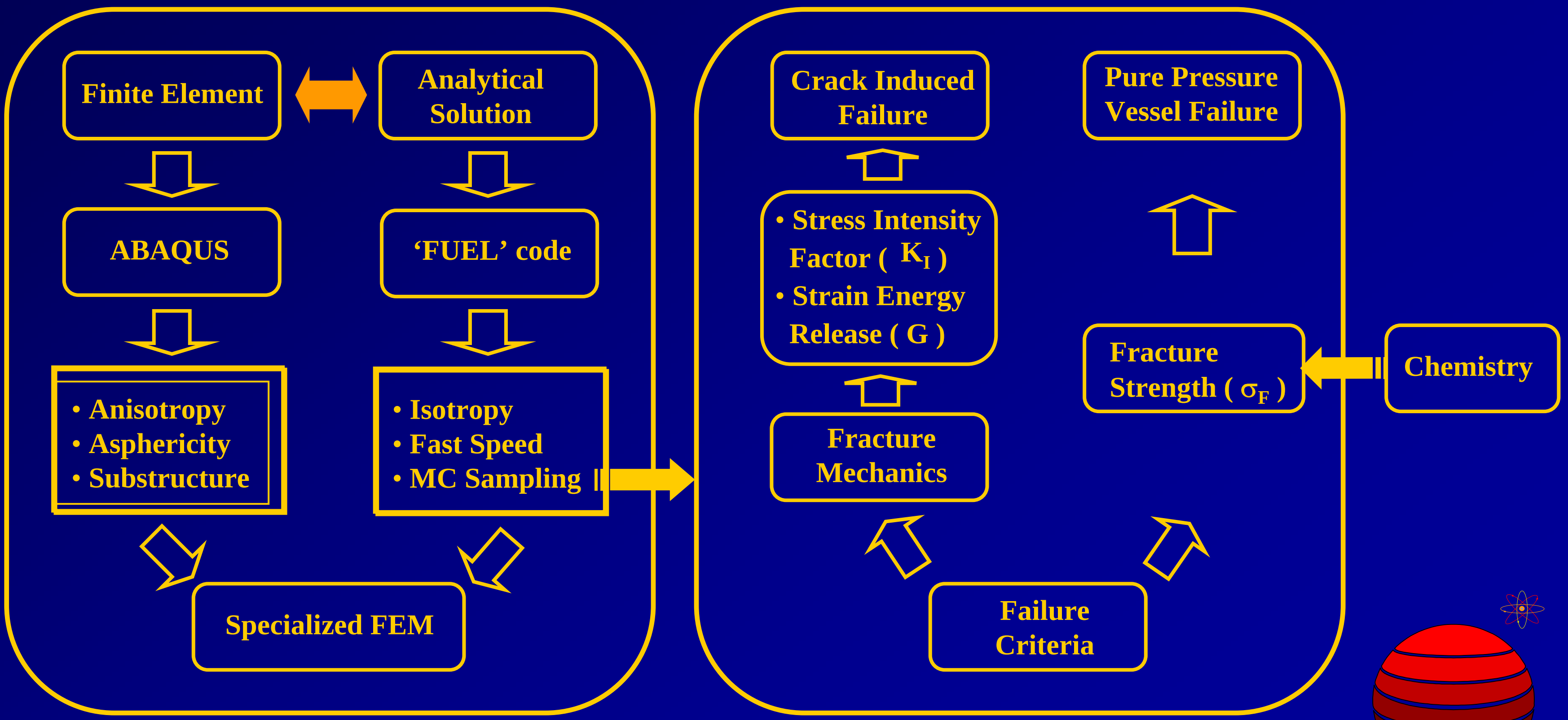
Mechanical Model

Stress Analysis

Failure Model

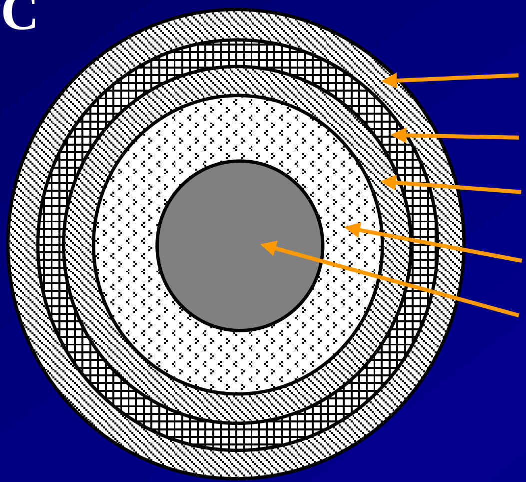


Conclusion

- **Currently with closed form solutions, the fracture mechanics based failure model, developed as part of this task, yields a good prediction of the failure probability of TRISO fuel particles**

Closed Form Solutions

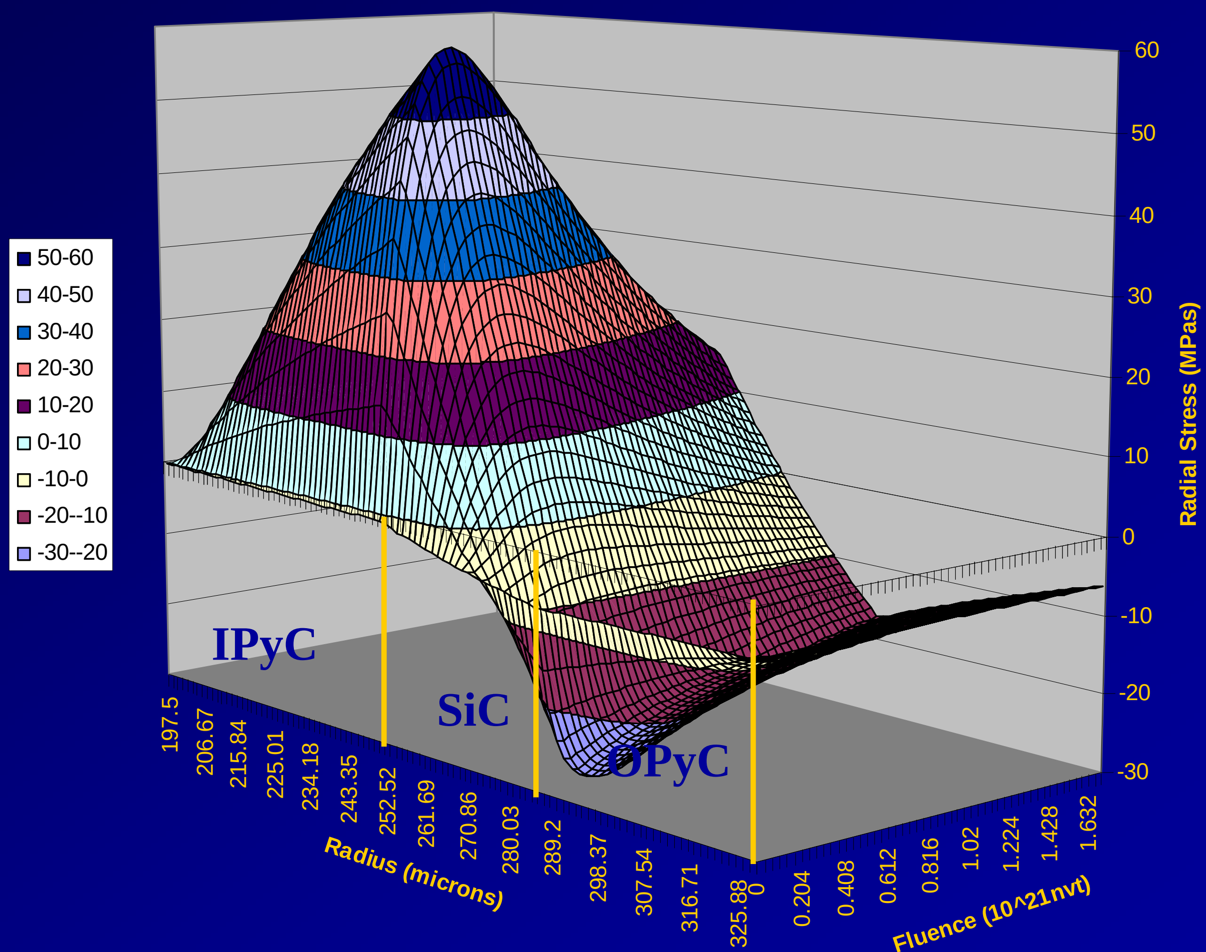
- **System: IPyC/SiC/OPyC**
- **Assumptions**
  - Spherical layers
  - Elastically isotropic
  - Creep and swelling are treated for IPyC/OPyC
  - SiC is just elastic shell
  - Three layers are tightly bonded



Layer	Thickness (μm)
Outer PyC	43
SiC	35
Inner PyC	53
Buffer PyC	100
UCO	195 (diameter)
Total Diameter	0.66 mm

TRISO Fuel Particle

Time Evolution of Radial Stress Distribution in TRISO Fuel Particles



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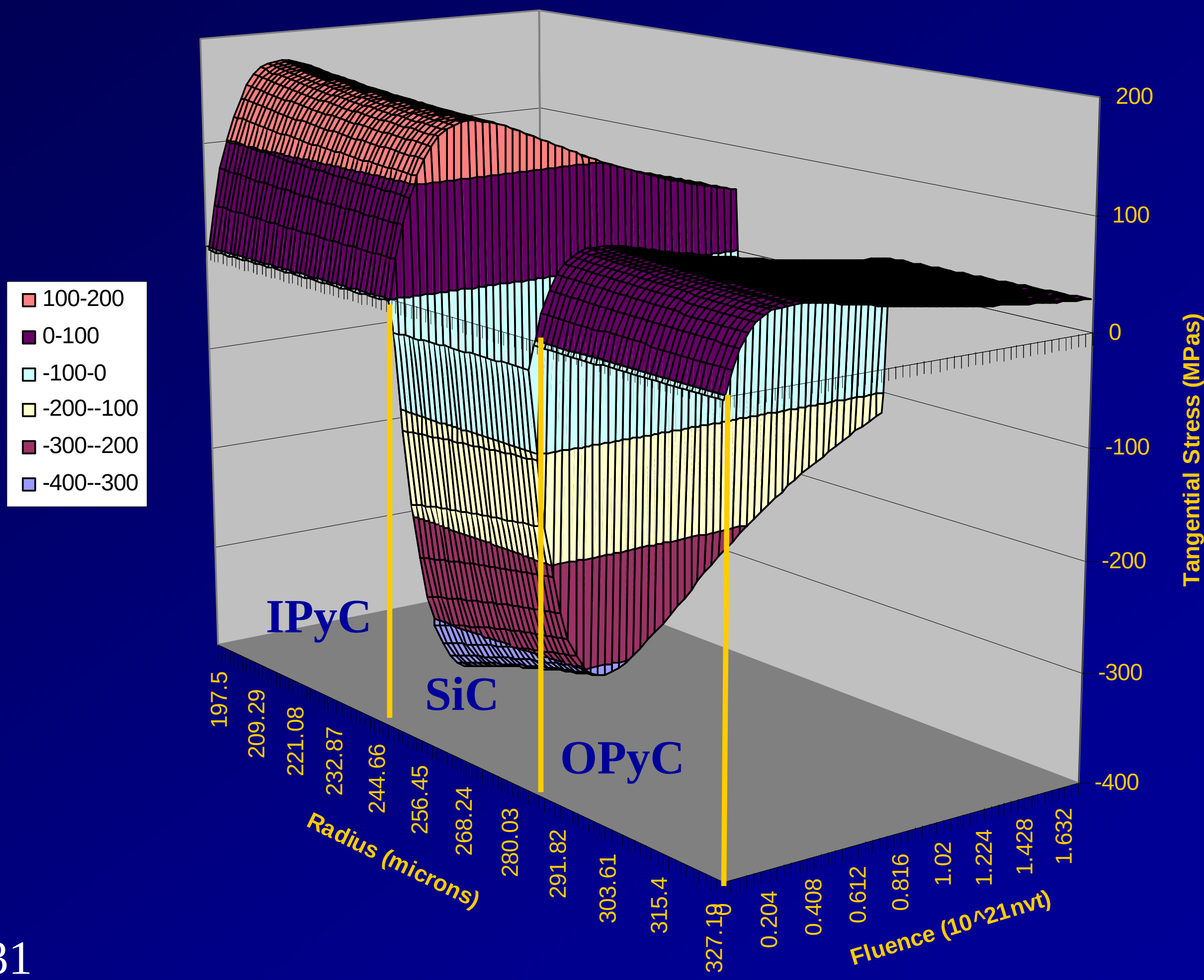
Time Evolution of Tangential Stress Distribution in TRISO Fuel Particles



Finite Element Method

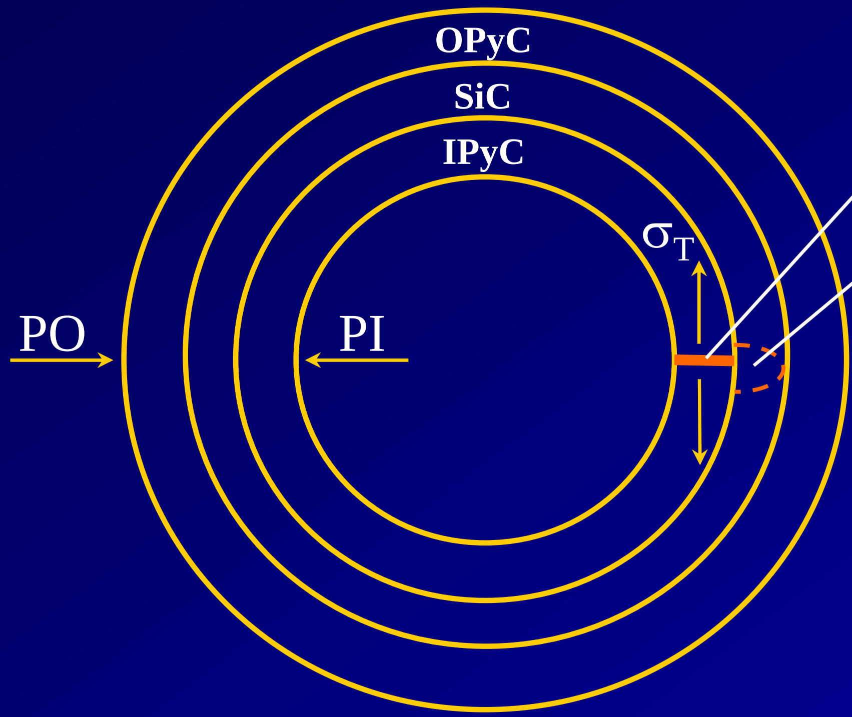
- **Check with analytical solutions and other calculations**
- **Study the non-ideal particles**
  - anisotropy of material
  - anisotropy of geometry
- **Evaluate the effects of crack and debonding**
- **Combine with analytical solutions to predict failure**

Fracture Mechanics based Failure Model

- **Consider the impact of the cracking of IPyC to SiC**
- **Stress distributions come from closed form solutions**
- **Currently use stress intensity factor to evaluate local stresses**
- **Predict failure probability with MC sampling process**

(Gaussian Distribution : Layer thickness, kernel & buffer densities
Weibull Distribution : Fracture strength of IPyC, SiC and OPyC
Triangular Distribution : Critical stress intensity factor of SiC)

The Sketch for FM based Failure Model



$$K_I(IPyC) = \sigma_T \sqrt{\pi a}$$

$$K_{IC}(SiC)$$

Material Property

Prediction by FM based Failure Model

- **Inputs**

SiC layer — (Sampled with triangular distribution)

K_{IC}(SiC) (mean) = 3300MPa·$\mu m^{1/2}$ [1]   Standard Deviation = 530MPa·$\mu m^{1/2}$

IPyC layer — (Sampled with Weibull distribution)

σ_F(IPyC) (mean) = 384MPa [2]   Weibull modulus = 8.6 [2]

End-of-life Burnup — 75% FIMA

Particles Sampled — N=1,000,000

- **Outputs**

Cases with IPyC Failure: 595   Failure Probability: 5.95×10^{-4}

Cases with SiC Failure: 17   Failure Probability: 1.70×10^{-5}

[1] Material Specification No. SC-001, Morton Advanced Materials, 185 New Boston Street, Woburn, MA 01801
[2] J. L. Kaae, et al., Nucl. Tech., 35, 1977, p368

Conclusions

- The previous mechanical model, based on a pressure vessel failure by overpressure, from INEEL predicts zero fuel failure
- New fracture mechanics based failure model gives reasonable prediction of the failure probability of TRISO fuel particles

Future Work

- Use finite element method (ABAQUS) to incorporate non-ideal particles
- Improve the fracture mechanics based failure model
- Build a more realistic pyrocarbon model
- Use specialized finite element method

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Dynamic Modeling for MPBR

Chunyun Wang
Advisors: Prof. R. G. Ballinger
Dr. H. C. No

(Draft) Presentation for INEEL Review   Aug. 01, 00

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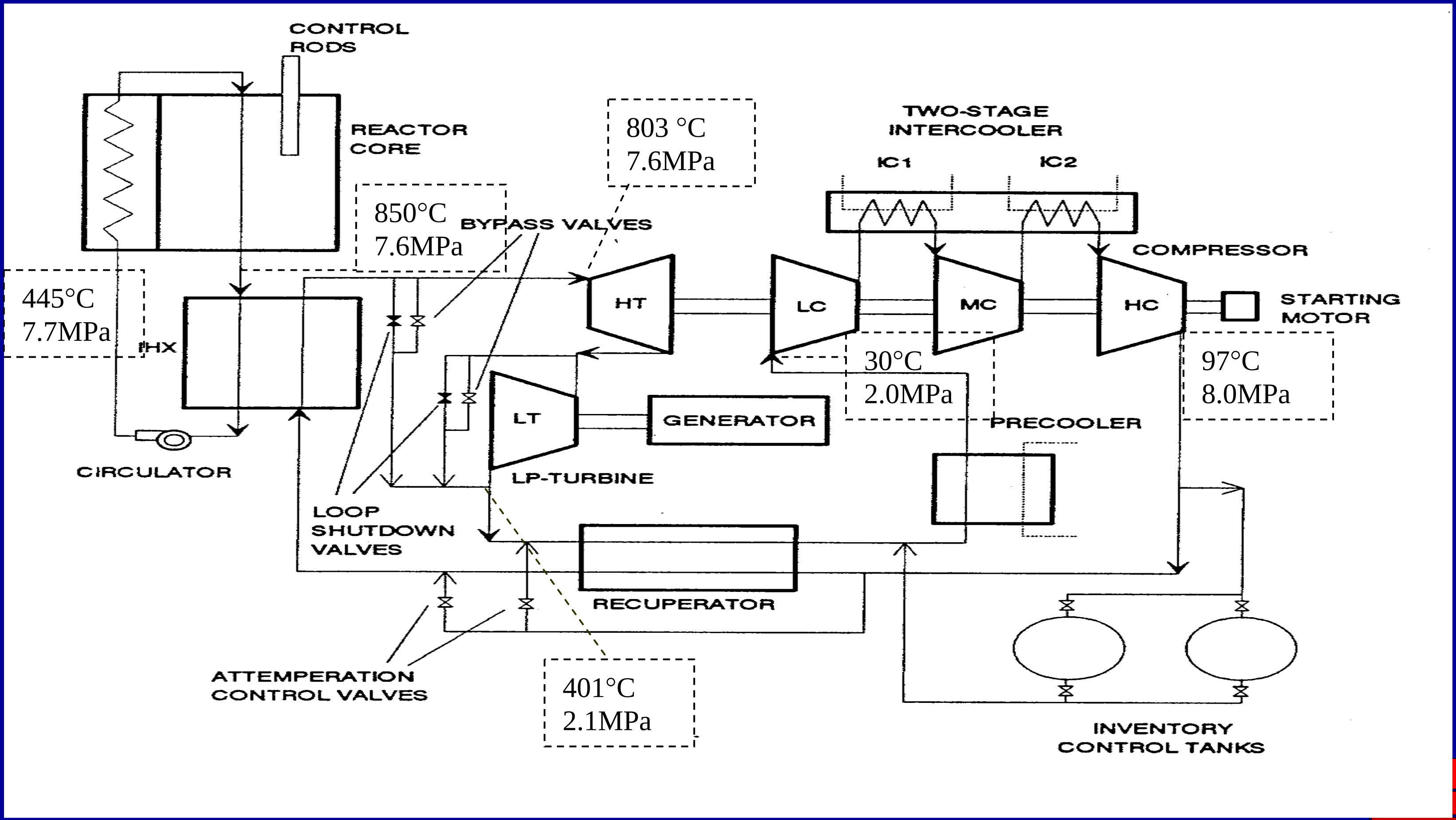
Current Design Schematic



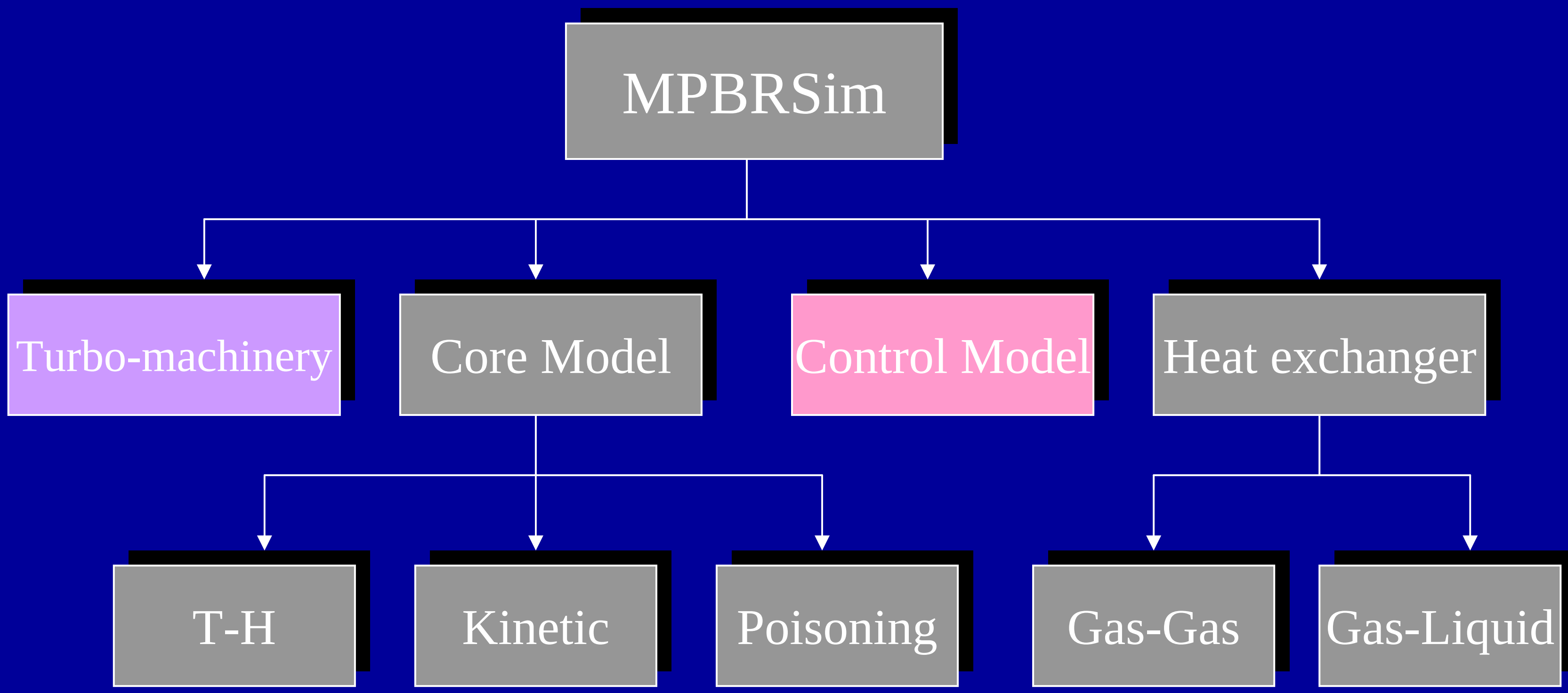
Objective

- **Develop a dynamic model as the primary tool for**
  - developing the control system
  - performing transient analysis
  - optimizing power conversion system

Summary

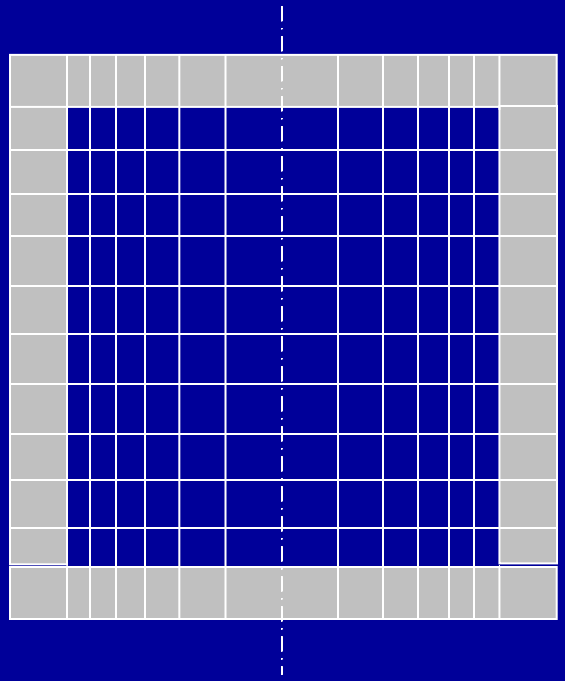
- Have developed dynamic models for core , heat exchanger. A simple steady state turbo-machinery model is used.
- Verification of core kinetic model
- Verification heat exchanger model
- Provide control methods and use PID controller to implement them

Model Structure



Core Thermal-Hydraulic Model

- **Nodalization**
- **Assumptions**
  - Fuel region is treated as a homogeneous region
  - Helium heat conduction is negligible
  - The heat loss from the reactor vessel is negligible
- **Pebble bed effective thermal conductivity (GE correlation, taking into account both conduction and radiation).**
- **Helium convection:KFA correlation**



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Core neutronics, product poisoning and verification

- One effective group point kinetics equation (Fig. 1)
- Fission product poisoning (Fig.2)
- Temperature coefficient of reactivity(Doppler effect)

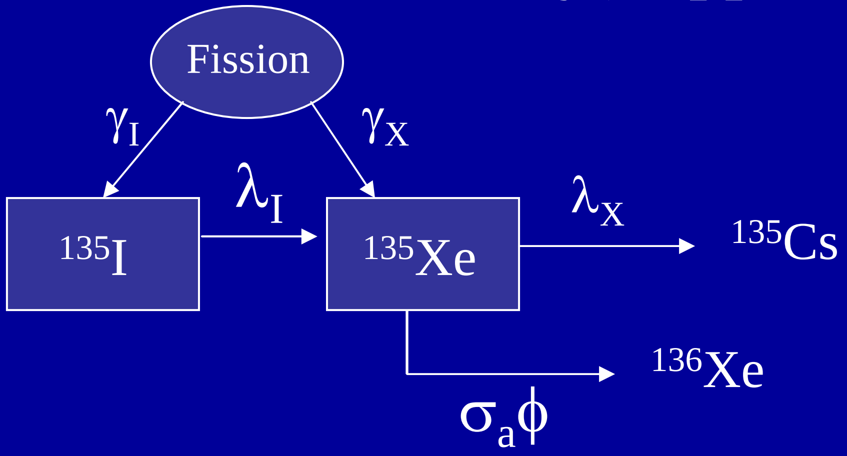

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Fig. 1 Numerical result versus analytical result for one effective group kinetics equation

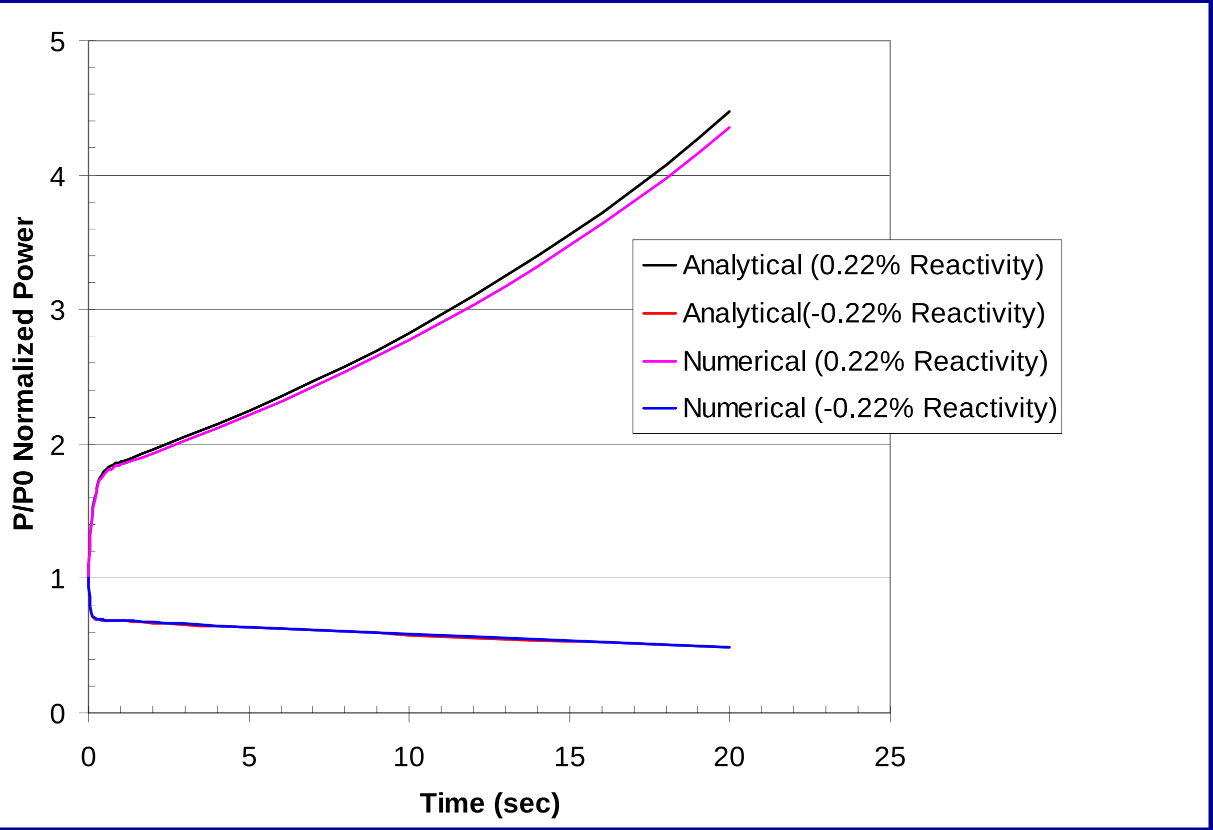
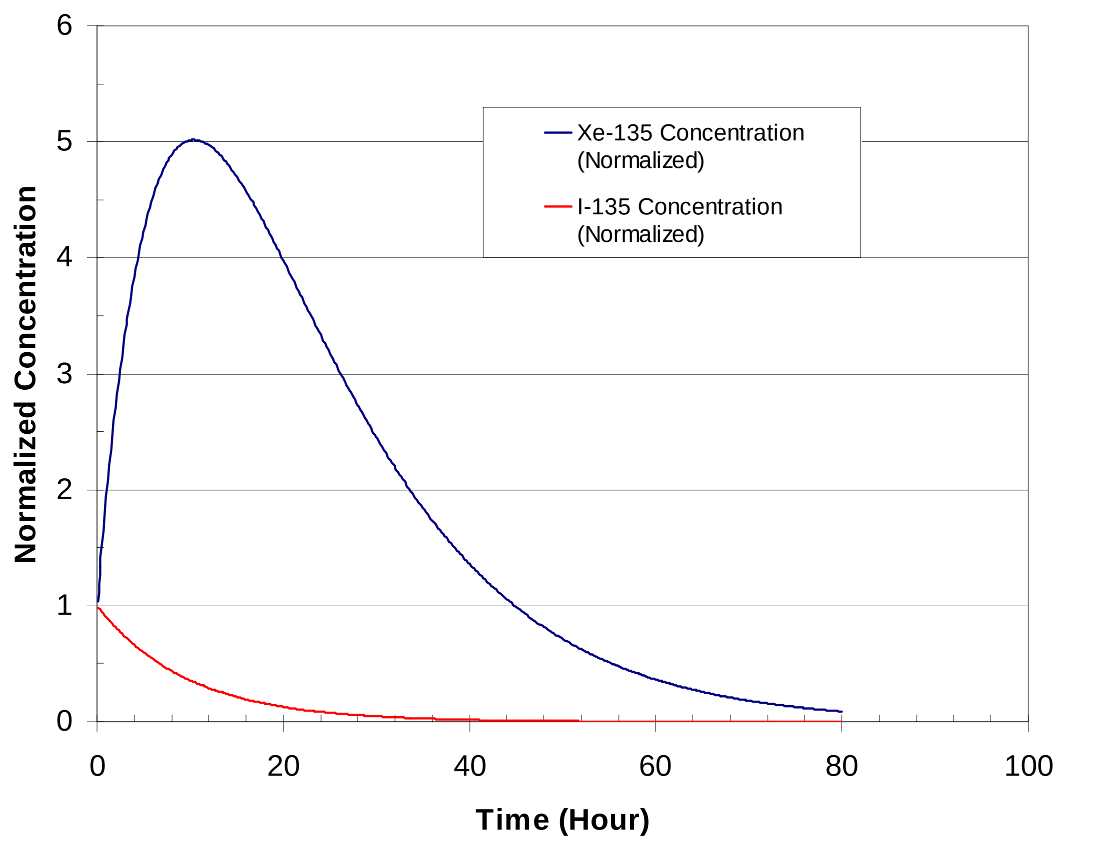


Fig.2 ^{135}Xe buildup following the core shutdown



Heat Exchanger Model

- **Heat exchanger model**
  - For counter flow heat exchanger
  - Divide it into many equally length sections
  - In each section, for gas side, ignore the gas mass, therefore ignore the gas stored energy

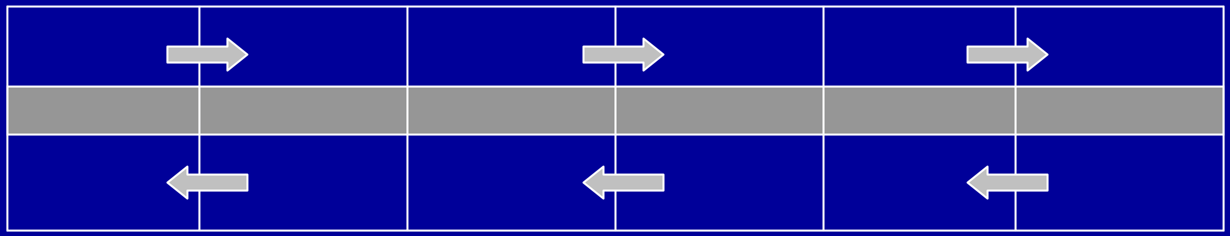


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Fig. 3 Recuperator steady state temperature distribution

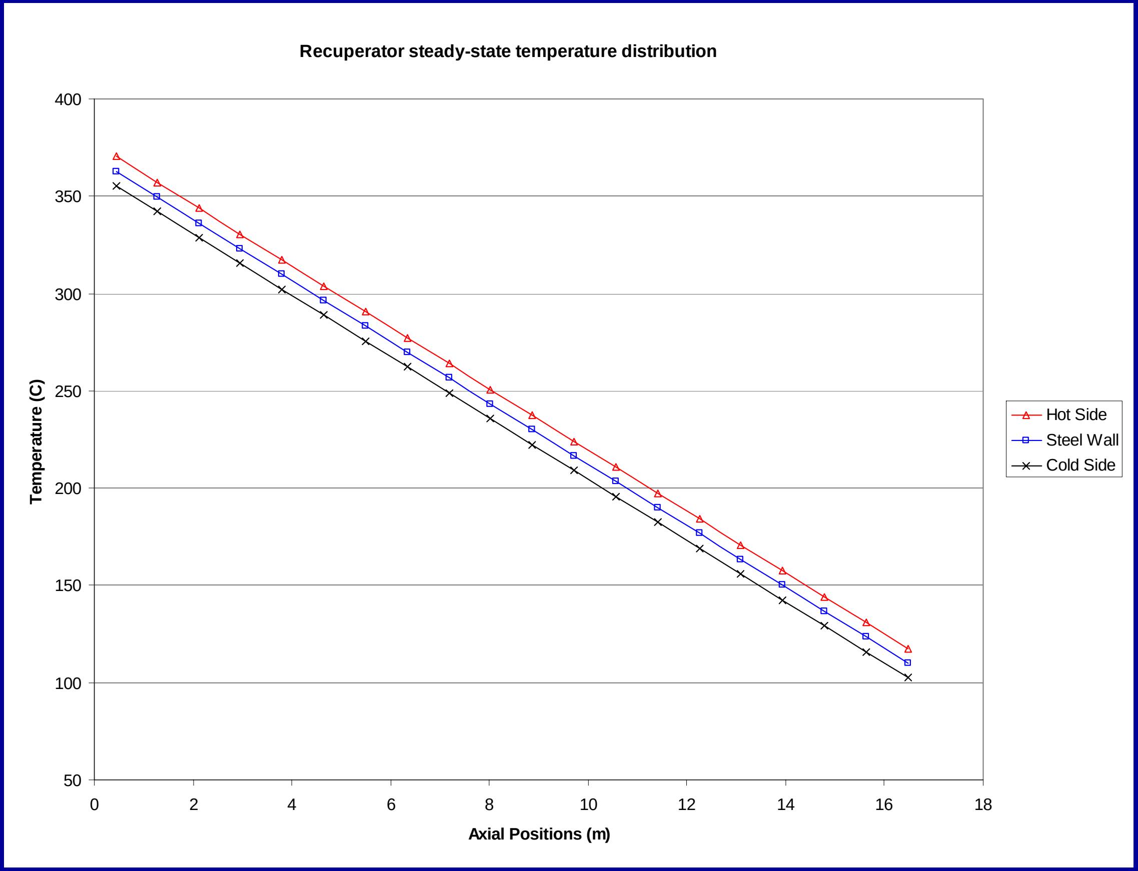


Fig. 4 Recuperator transient response to a step temperature increase of 200 C at hot helium inlet side

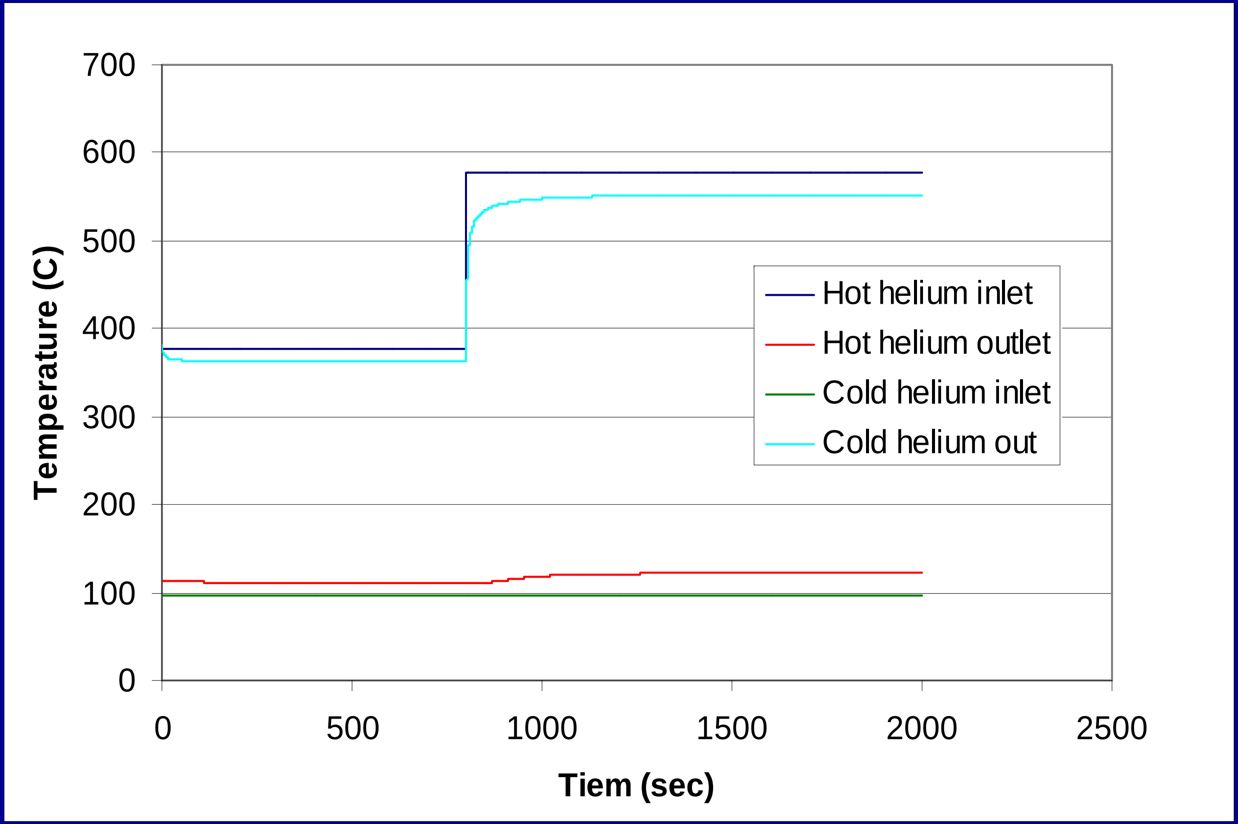
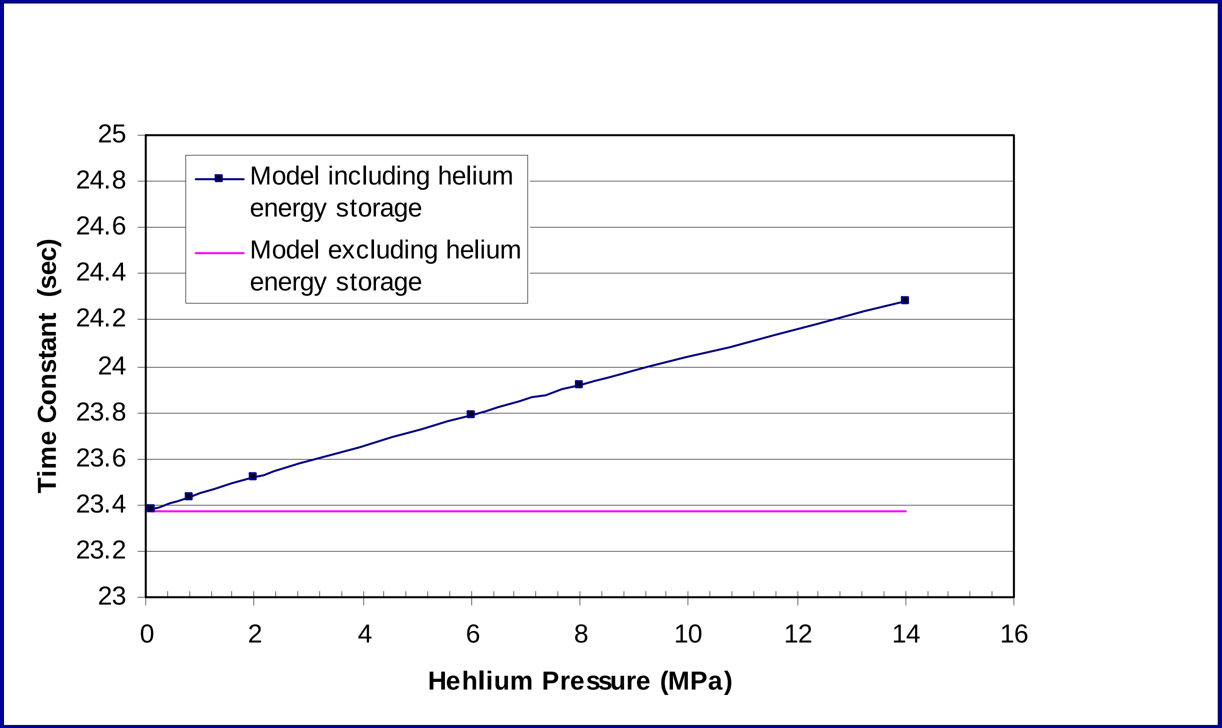


Fig. 5 Helium energy storage's effect on the recuperator performance



Control Model

- **Control methods**
  - Control rod motion
  - Primary circulator speed
  - Bypass control in the power conversion system
  - Inventory control in the power conversion system
- **Controller: PID**

Summary

- Have developed dynamic models for core , heat exchanger. A simple steady state turbo-machinery model is used
- Verification of core kinetic model
- Verification of heat exchanger model
- Provide control methods and use PID controller to implement them

Future Work

- Use programmed turbo-machinery characteristic maps (Cooperate with NREC) in the model
- Develop valve model
- Simulate electric load ramp

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Comparison Between Air and Helium for Use as Working Fluids in the Energy-Conversion Cycle of the MPBR

Student: Tammy Galen
Faculty: D. G. Wilson

Objective:

To assess the relative advantages of using air and helium for the working fluid in the MPBR energy-conversion cycle.

Comparisons:

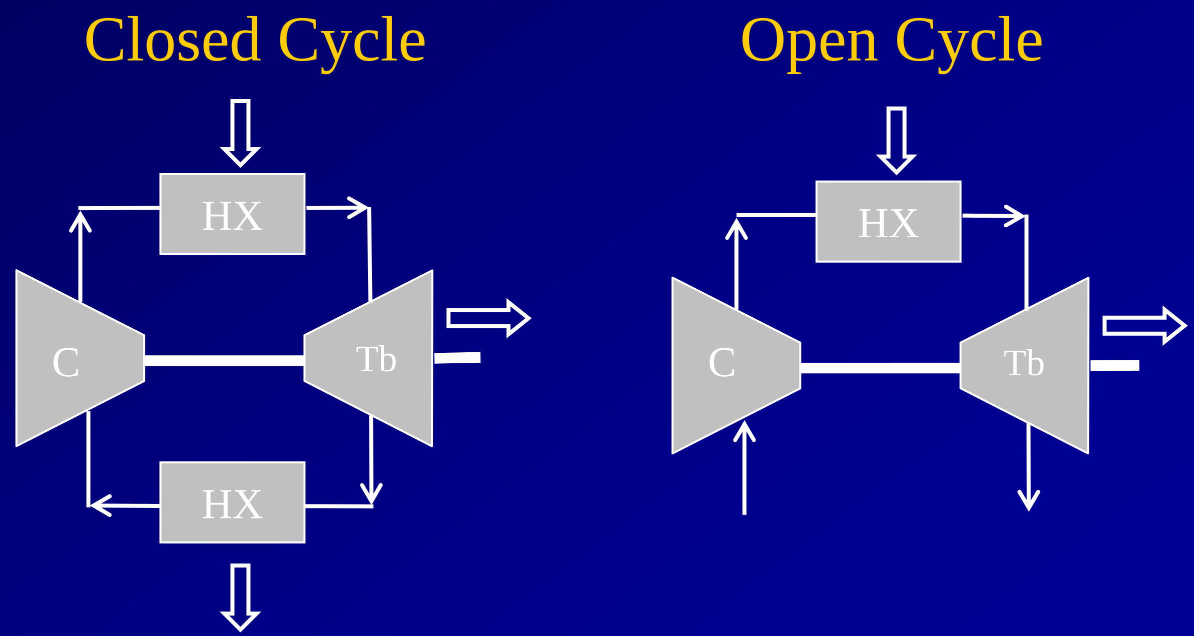
- Cycle efficiency
- Component design
  - Size
  - Efficiency
  - Possible development work required

Conclusion

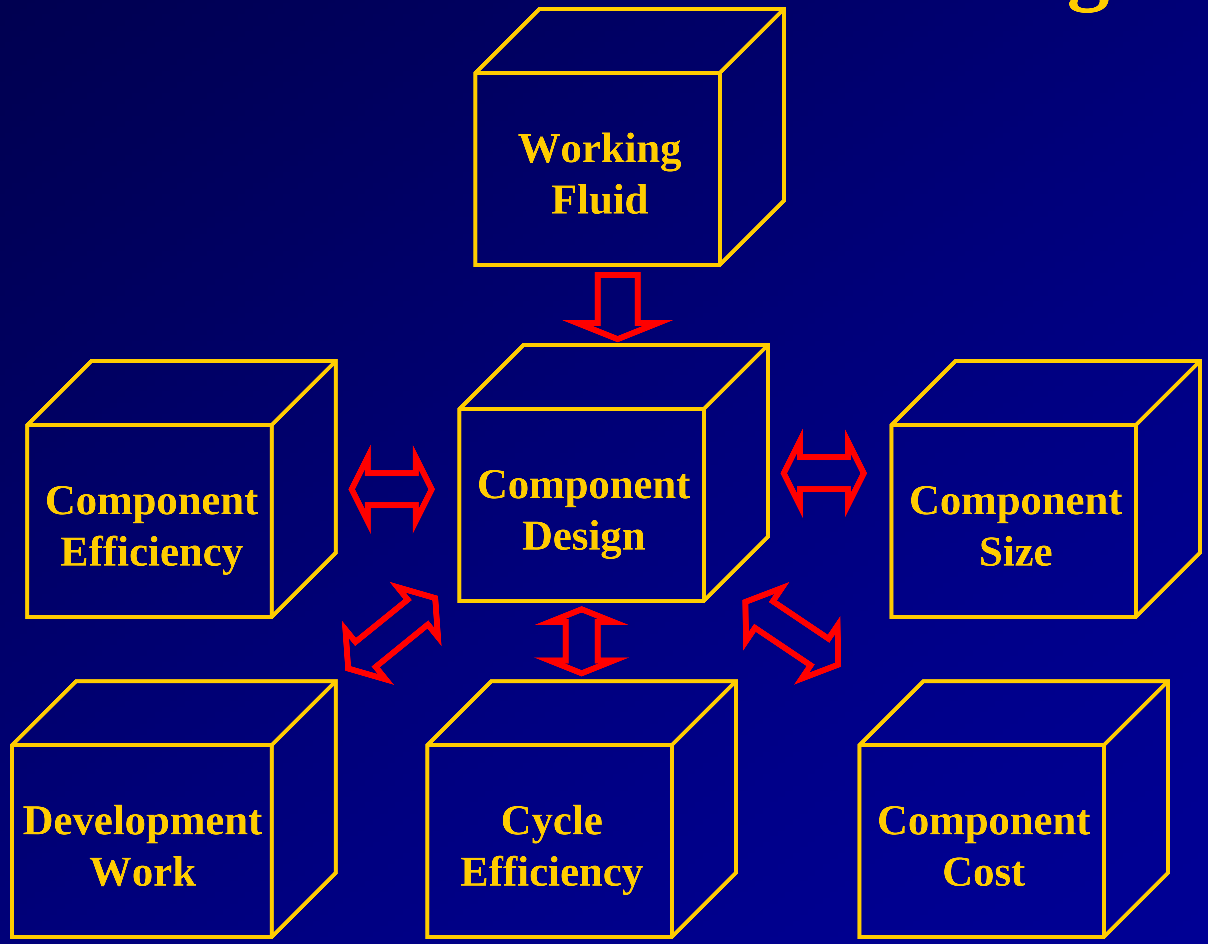
Use of helium in a closed-cycle configuration is best suited to the modularity requirement of the MPBR. It results in the smallest sized components, high efficiency, and implements well established turbomachinery technology.

Three cycles investigated

- Air open cycle
- Air closed cycle
- Helium closed cycle



Influence of choice of working fluid



Thermophysical Properties of Helium and Air at 700K and 2MPa

Turbines and Compressors

- ↑ Specific heat
- ↑ Number of stages

- ↓ Viscosity, ↑Re #
- ↑ Efficiency

- ↑ Sonic velocity,
- ↑ Compressor blade speed
- ↓ Mean diameter

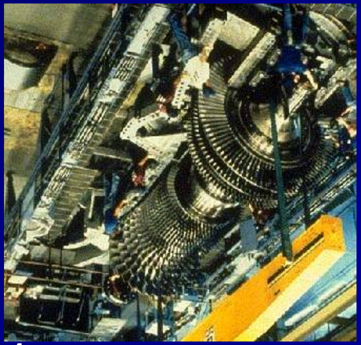
- ↑ Density
- ↓ Mean diameter

Heat Exchangers

- ↑ Thermal conductivity
- ↓ Size

	Air	Helium
Molecular weight	28.97	4.003
Specific heat (J/kgK)	1074	5193
Sonic velocity (m/s)	590	1500
Thermal conductivity (W/mK)	.056	.273
Viscosity (10^{-5})	3.33	3.56
Density (kg/m^3)	9.96	1.42

Turbomachinery industrial experience



- Air open-cycle experience
  - Majority of gas-turbomachinery experience
  - Combustion-gas turbines: power and aircraft industries
- Air closed-cycle experience
  - Less popular demand and less industrial experience to date
  - First built in 1939 by Escher Wyss in Switzerland
  - 20 plants built in Europe following WW2 ranging in power under 20MWe

- Helium experience:
  - 2 facilities part of HHT international high tempera[...] reactor project
    - Oberhausen II (50MWe, 2MPa), HHV(90MWe, 5MPa)
  - Circulators from previous gas reactors

Industrial experience conclusions

- Open-cycle air plant
  - Least amount of development work required for MPBR deployment

- Closed-cycle helium and closed-cycle air plants
  - Comparable amount of development work required
  - Technology has been tested and judged successful*
  - Open-cycle turbomachinery design methodology and operating experience is directly applicable

*IAEA Summary report on technical experiences from high-temperature helium turbomachinery testing in Germany, 1995

Busbar Efficiency

- **Deducts**
  - Primary circulator work, 7.7 MW
  - 3.5 MW station load
  - 98% electric generator efficiency

Baseline Thermodynamic Comparison

	Helium	Air closed	Air open
Pressure ratio	3.0	4.7	4.6
Busbar efficiency	45.2%	46.9%	47.7%
Reactor T_{in} (K)	767	792	797
Turbine T_{in} (K)	1101	1101	1101

Reactor inlet temperature constrained to 718K*

	Helium	Air closed	Air open
Pressure ratio	3.7	7.4	7.3
Busbar efficiency	44.8%	46.0%	46.8%
Turbine T_{in} (K)	1101	1101	1101

*Permissible using 9Cr-1-Mo-V as the vessel material according to ASME Class 2 &3 pressure-vessel in Codes Case N-47

Turbine Design Choices

Maximum blade speed at tip (m/s)	550
Work Coefficient (Ψ)	1 and 2
Flow coefficient (ϕ)	0.5
Reaction (%)	50
Hub shroud ratio at turbine outlet	0.6

Component volumes (m^3)

	Helium	Air-closed	Air-open
IHX	17	86	260
HP turbine	0.27	0.06	2.2
LP turbine	0.58	0.22	13
LP compressor	0.35	0.13	2.7
Recuperator	13	61	180
Precooler	50	97	---
Intercooler 1	41	80	180
Intercooler 2	41	80	180
Sum	160	400	820

Final Cycle Conclusions

	Helium	Air-closed	Air-open
Pressure ratio	3.7	7.1	7.1
Busbar efficiency	45.3%	47.1%	47.3%
Turbine T_{in} (K)	1101	1101	1101
Component volume (m^3)	160	400	820
Number of flatbed trucks*	1	2	N/A

*Based on volume analysis, carries all components except IHX and ducting

Conclusion

Use of helium in a closed-cycle configuration is best suited to the modularity requirement of the MPBR. It results in the smallest sized components, high efficiency, and implements well established turbomachinery technology.

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Advanced Reactor Technology Pebble Bed Project

Pebble-Bed Reactor Physics Research at MIT

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Professor Michael Driscoll

Overview

- Statement of progress
- Program goals
- Neutronic design methodology
  - MCNP/VSOP model of PBMR
  - Preliminary results
- Proliferation resistance of PBMR
- Path forward

Progress

- MCNP4B benchmark of HTR-10 completed
- VSOP94 fuel management code implemented
- Procedure established for linking MCNP and VSOP for core neutronic calculations
- MCNP/VSOP model of PBMR developed and preliminary analysis performed
- Proliferation resistance of PBMR investigated

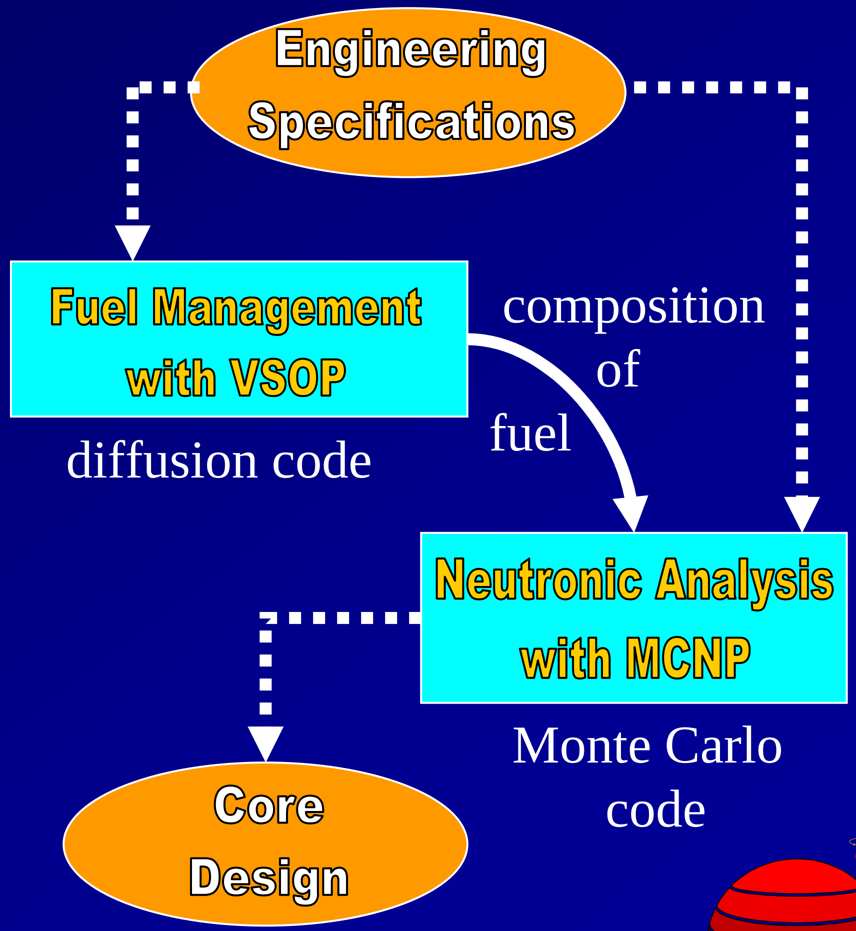
Program Goals

- Establish a Monte-Carlo based methodology for modeling neutron and photon transport in PBRs
- Ability to model cores with fuel burnup
- Integrated computer-aided design tools
- Perform preliminary design calculations
- Investigate fuel cycles and assess their proliferation resistance
- Validation of codes and methods

Neutronic Design Methodology

- Monte Carlo method for accurate analysis of:
  - **control rod worth**
  - **void effects**
  - **geometry changes**
  - **shielding**
  - **heat deposition**
- Diffusion-theory code for burnup calculation

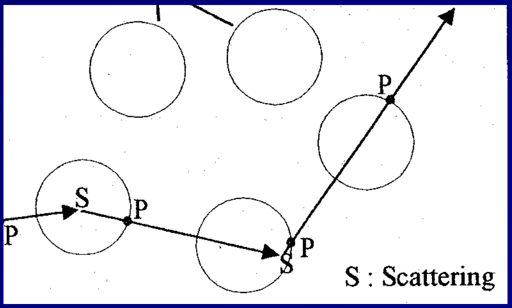
A versatile design tool!

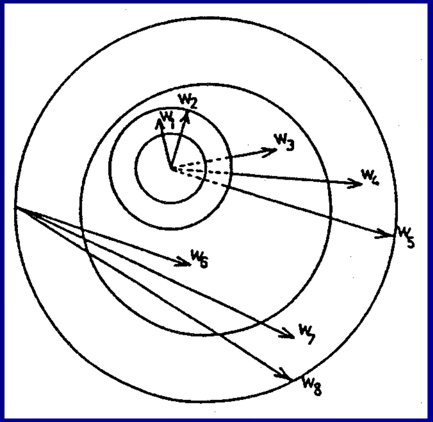


Why MCNP?

- Solves the Boltzmann equation by the Monte-Carlo method
- Exact representation of neutron and photon transport
- Continuous-energy cross sections
- Detailed geometry specification
- Millions of n-histories used to generate ensemble averages

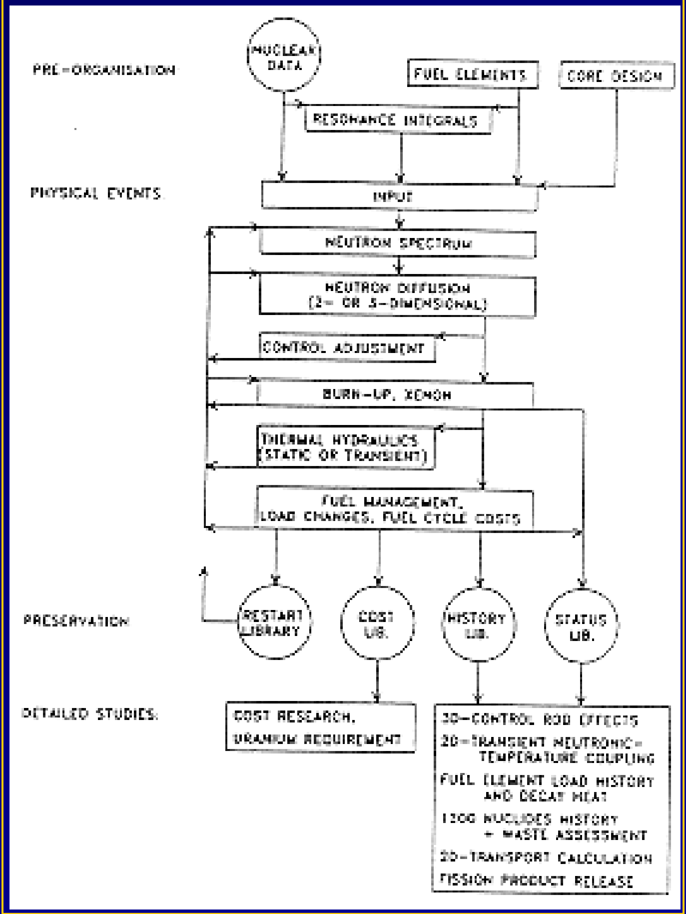
accurate calculations





VSOP

- Very Superior Old Programs
- Widely used for PBRs
- Diffusion theory
- Comprehensive code suite:
  - Neutronics
  - Thermal hydraulics
  - Fuel cycles
  - Economics
- Installed at MIT
- Verification in progress



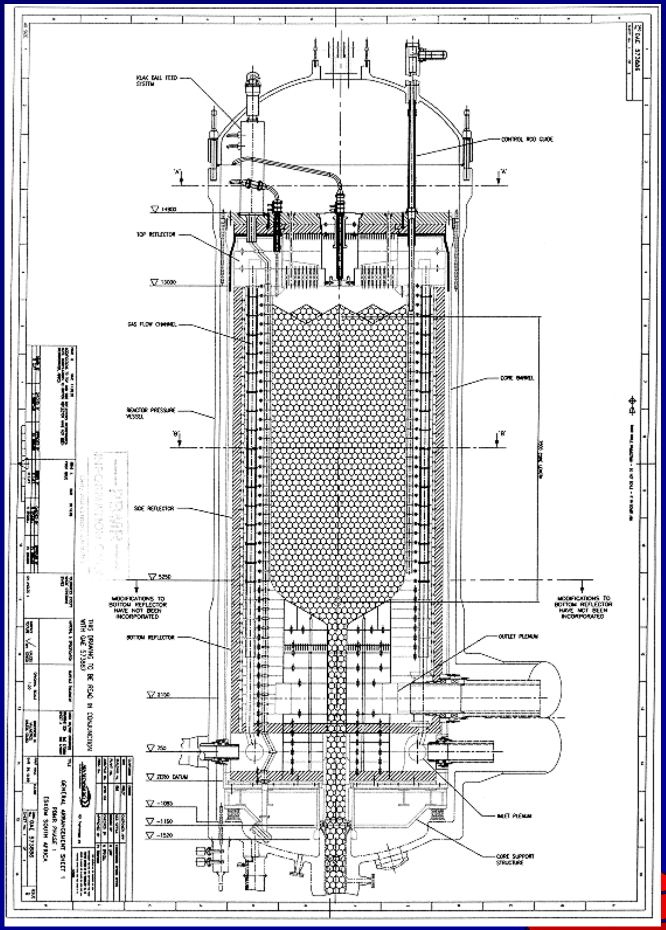
MCNP / VSOP Model of PBMR

Detailed MCNP4B model of ESKOM Pebble Bed Modular Reactor:

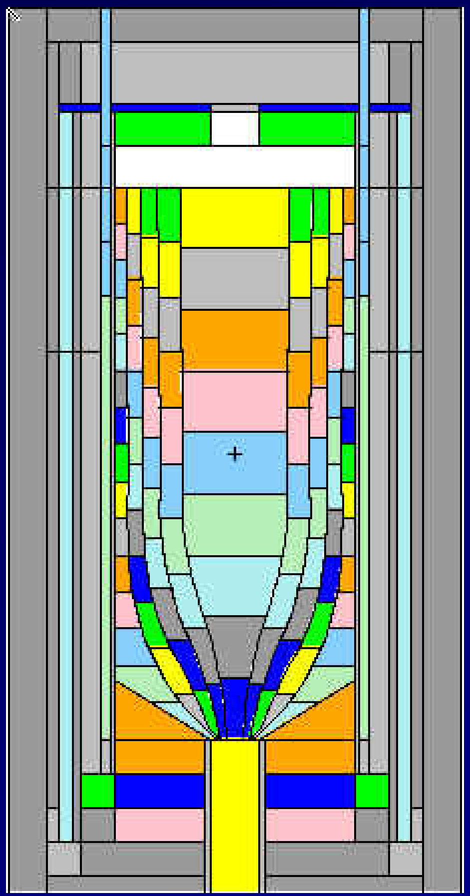
- reflector and pressure vessel
- 18 control rods (HTR-10)
- 17 shutdown sites (KLAK)
- 36 helium coolant channels

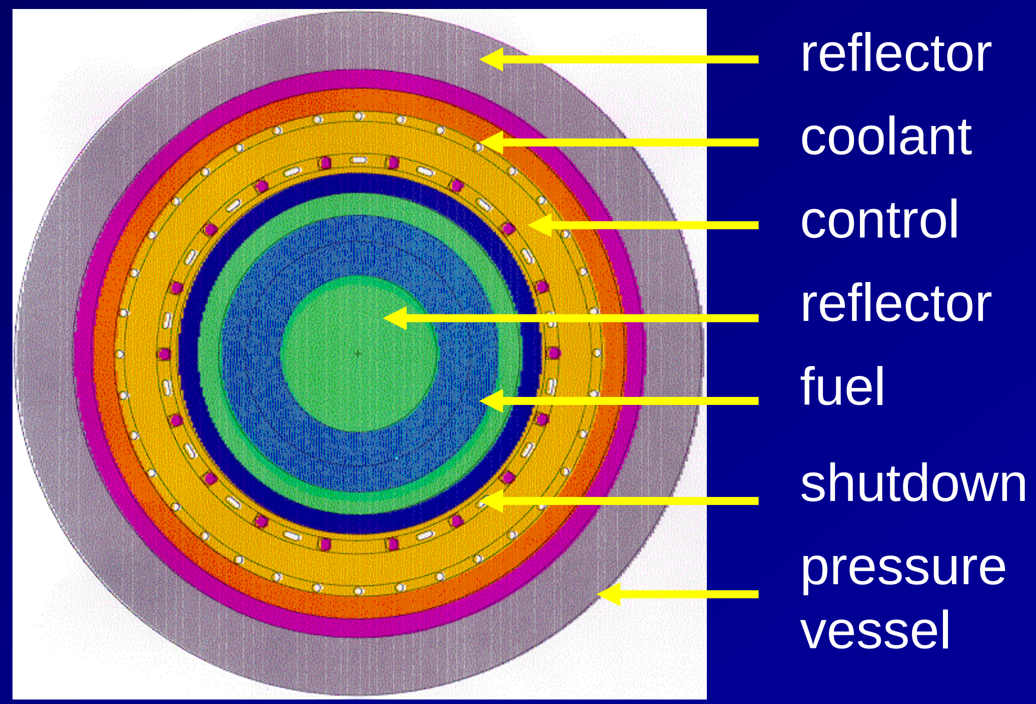
Core idealization based on VSOP model for equilibrium fuel cycle:

- 57 fuel burnup zones
- homogenized compositions



MCNP4B Model of Core





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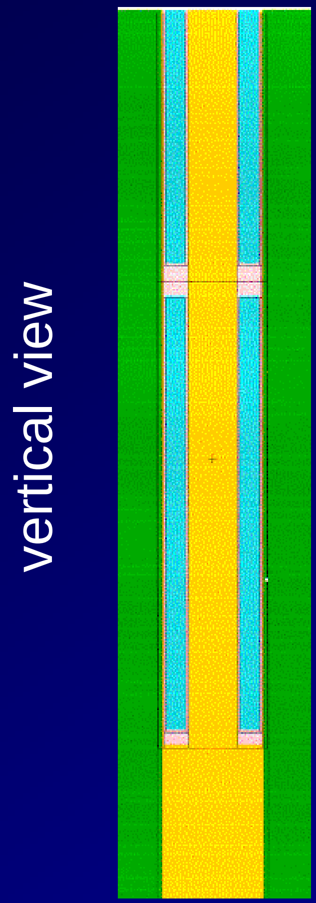
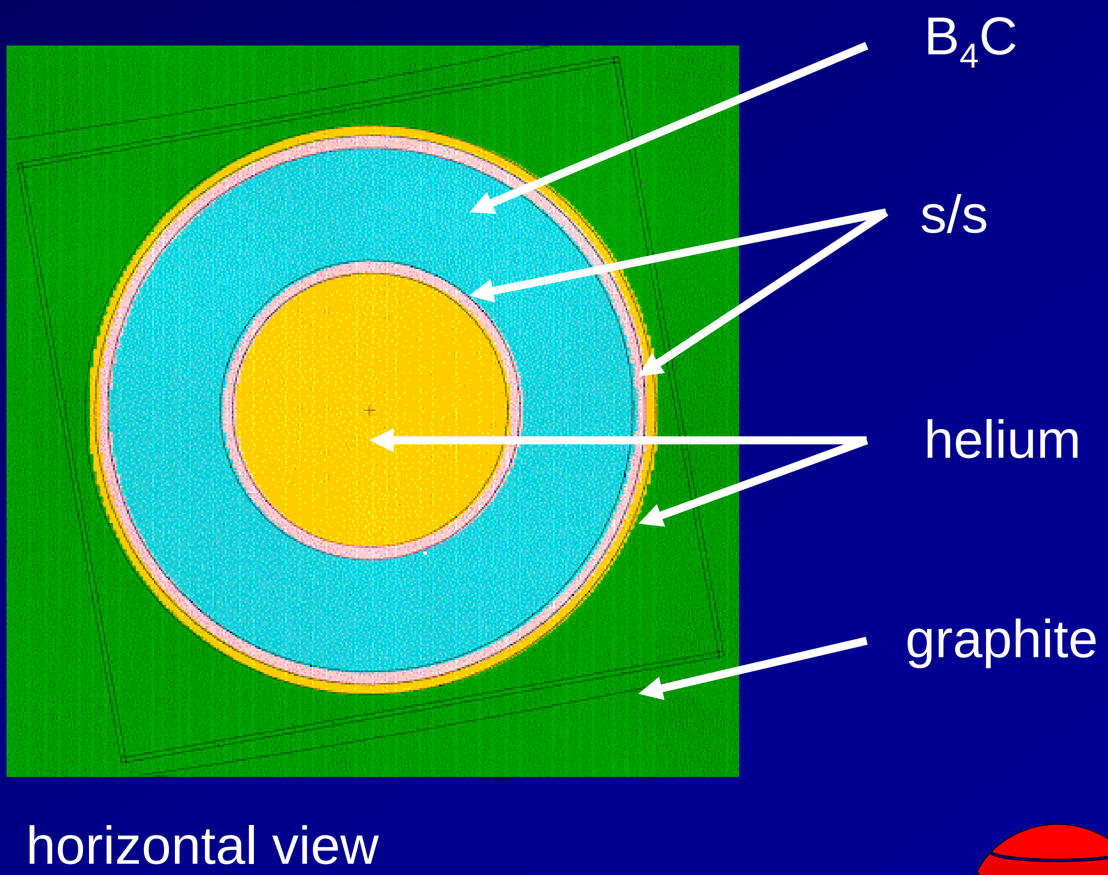
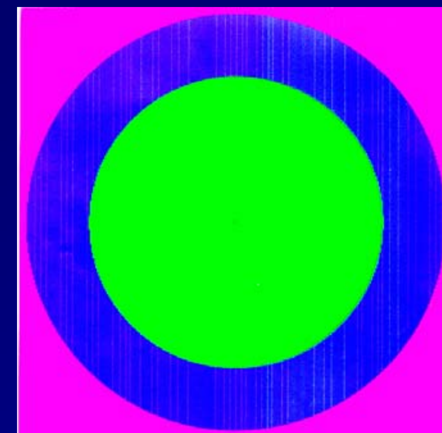
MCNP4B Model of Control Rod





MCNP4B Model of Shutdown Site

1



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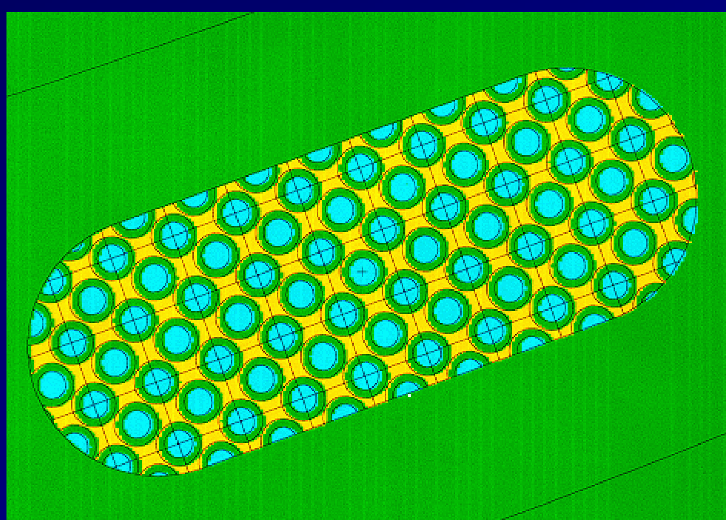

2

1) empty channel
2) channel filled with absorber balls
3) 0.25 in. absorber ball with graphite coating

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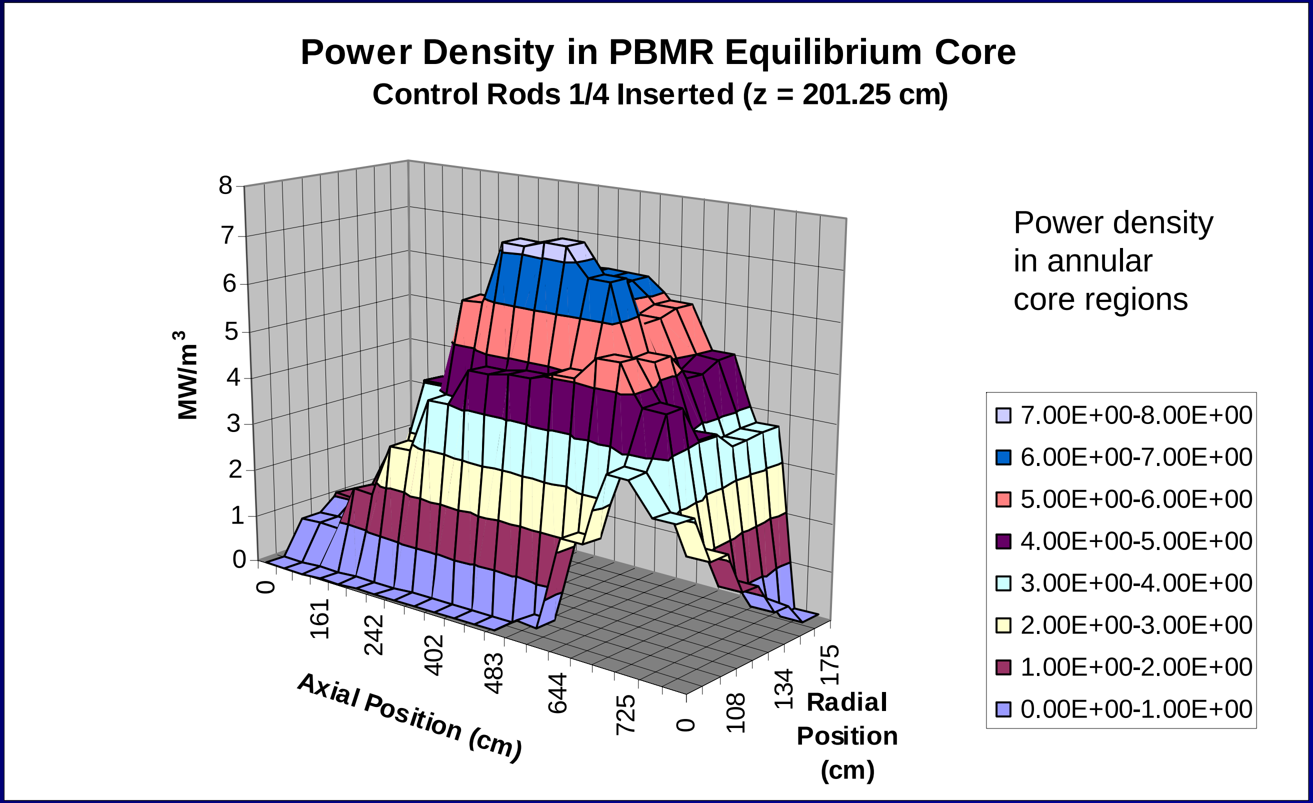
MCNP4B / VSOP Model Output



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Bottom
of core

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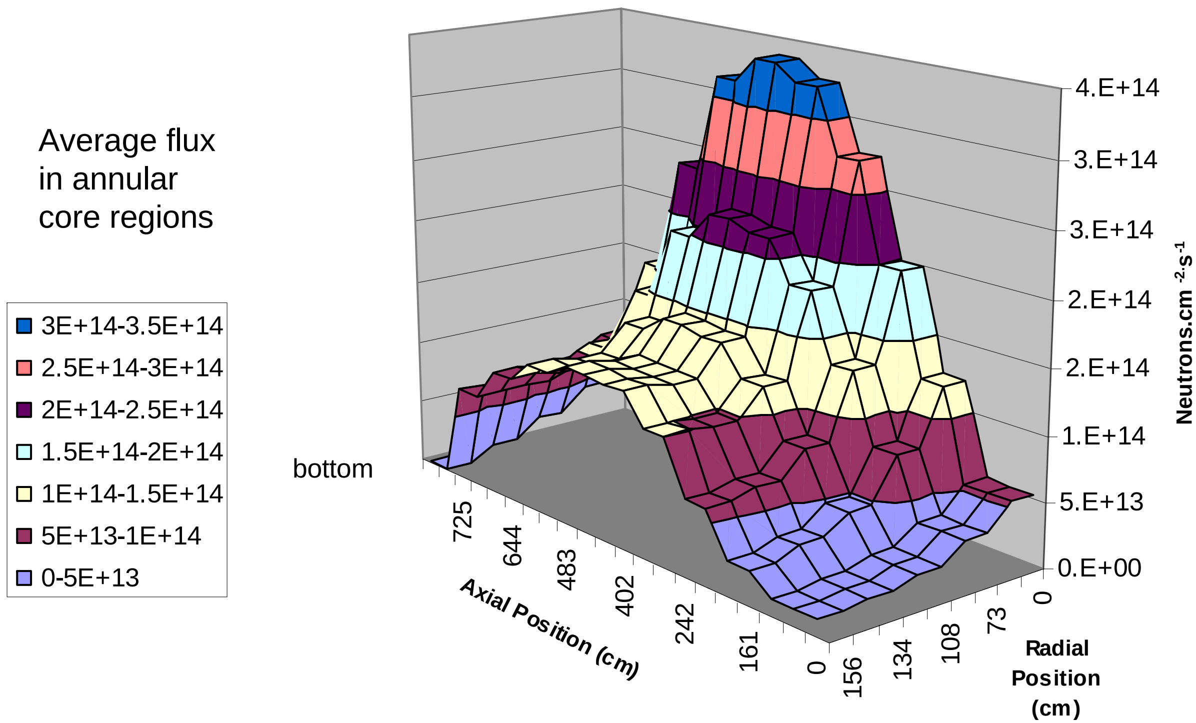
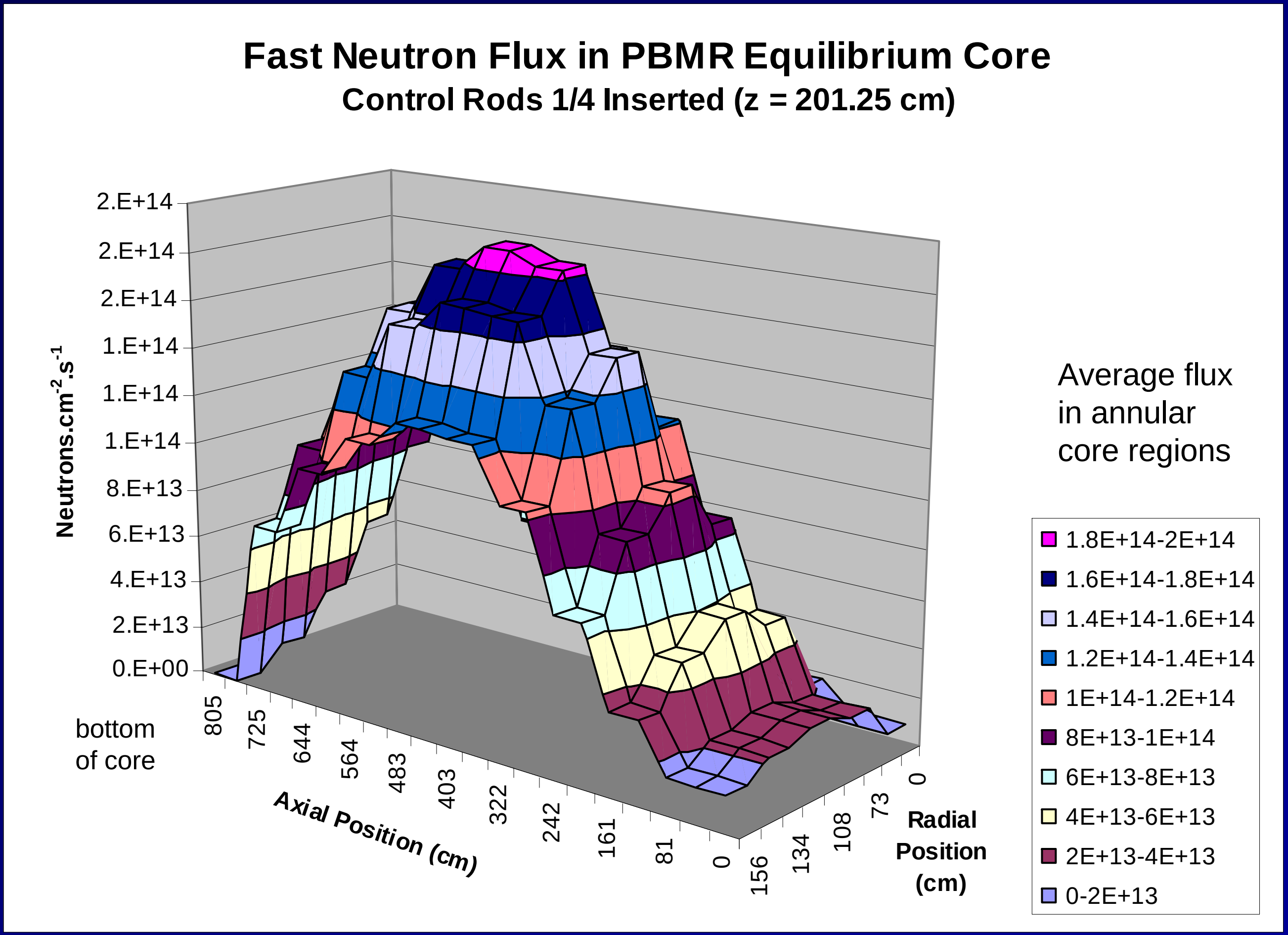
MCNP4B / VSOP Model Output .. 2

Thermal Neutron Flux in PBMR Equilibrium Core
Control Rods 1/4 Inserted (z = 201.25 cm)

Average flux
in annular
core regions



MCNP4B / VSOP Model Output .. 3



Nonproliferation

Pebble-bed reactors are highly proliferation resistant:

- small amount of uranium (9 g/ball)
- high discharge burnup (100 MWd/kg)
- TRISO fuel is difficult to reprocess
- small amount of excess reactivity limits number of special production balls

Diversion of 8 kg Pu requires:

- 260,000 spent fuel balls – 2.6 yrs
- 790,000 first-pass fuel balls – 7.5
- ~50,000 ‘special’ balls – 3

Spent Fuel	
Pu238	5.5%
Pu239	24.1
Pu240	25.8
Pu241	12.6
Pu242	32.0

First Pass	
Pu238	~0 %
Pu239	64.3
Pu240	29.3
Pu241	5.6
Pu242	0.8

MCNP4B Analysis of Heavy Balls

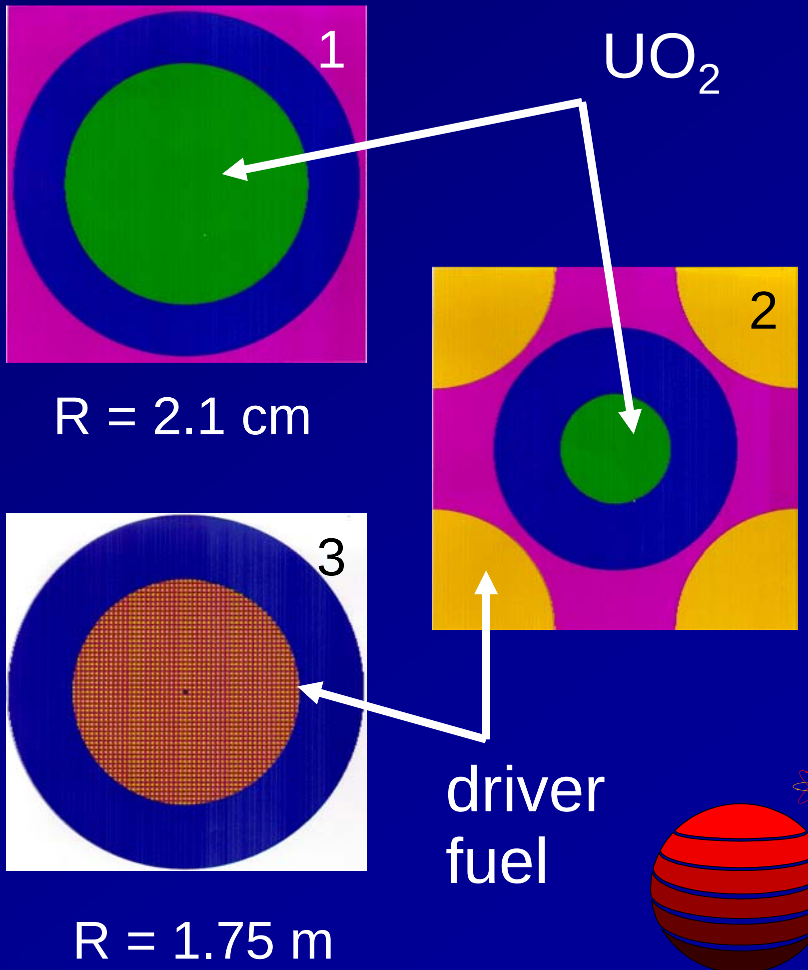
Supercell Model

1 Ball with depleted U

2 Surrounded by BCC lattice of driver balls

3 Spherical driver core with fuel composition from VSOP model

- Critical core (k_{eff} = 1)
- $^{238}U(n,\gamma)^{239}U$



Path Forward

- Complete implementation of MCNP/VSOP link
- Improve model of PBMR $\Rightarrow$ ESKOM input
- Validate MCNP4B using PROTEUS criticals & VSOP predictions of PBMR startup core
- Investigate proliferation resistance of PBR fuel cycles using VSOP (Th/LEU, OTTO-PAP2)
- Assess applicability of Monteburns to modeling burnup in PBRs using MCNP4B and ORIGEN2

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The Safety Analysis of PBMR

Student: Tieliang Zhai
Advisors: Prof. A. Kadak
Dr. W.Y. Kato

Objectives

- Identification of the Safety Issues for MHTGR
- Analysis of a Major Accident
- The Temperature Distribution Calculation After the Depressurization With the Failure of RCCS

The Identification of the Safety Issues

- Review of Safety Literature on HTGR
- Based on a Specific Design Concept, Identified the Critical Safety Issues:

A. Fuel Performance

B. Completely Passive System for Ultimate Heat Sink

C. Air Ingress

D. Lack of Containment

E. Calculation of Source Term

Air Ingress Accident

- **Important parameters governing these reactions:**

  Gas flow rates

  Temperature

  Pressure

- **3 steps**
- **Mainly Depends on Possibility of Enough and continuous air supply**

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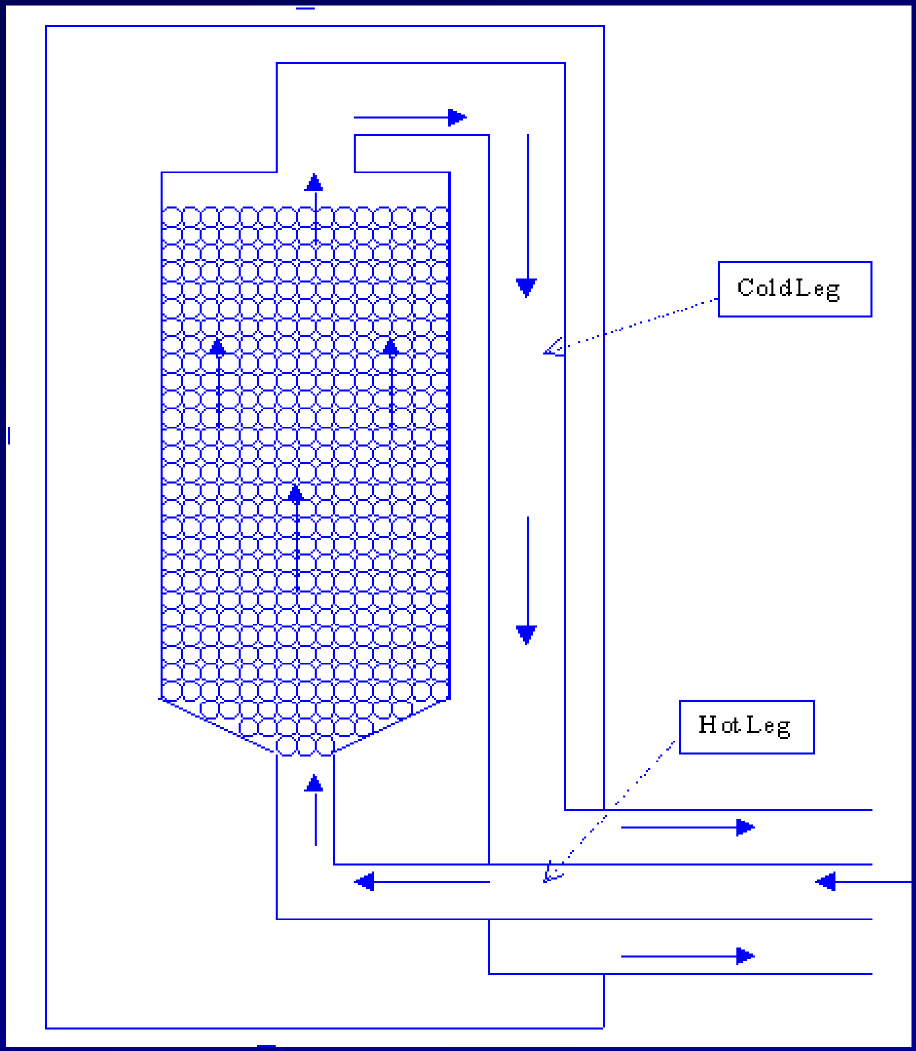

Specific areas for additional research:

- Chimney effect
- Airflow rate
- The extent that a below-grade confinement building could limit the supply of air

The Temperature Distribution Calculation After the Depressurization With the Failure of RCCS

- The Code "Heating-7"

Heating-7 is a general-purpose 3-D conduction heat transfer program written in Fortran 77. It can solve steady-state and/or transient heat conduction problems

The Model Established

- 20-Region 3-Dimensional model. The core void is filled with stagnant helium at atm.
- The air in the confinement is steady and heat transfer only through conductivity and radiation.
- The outer radius of this model is 28.4m, i.e. all the heat transfer happen only in this huge volume.
- The Materials and their thermal properties (Conductivity, Density and Specific Heat): In the case that the thermal properties could not been fully determined, the conservative values would be selected

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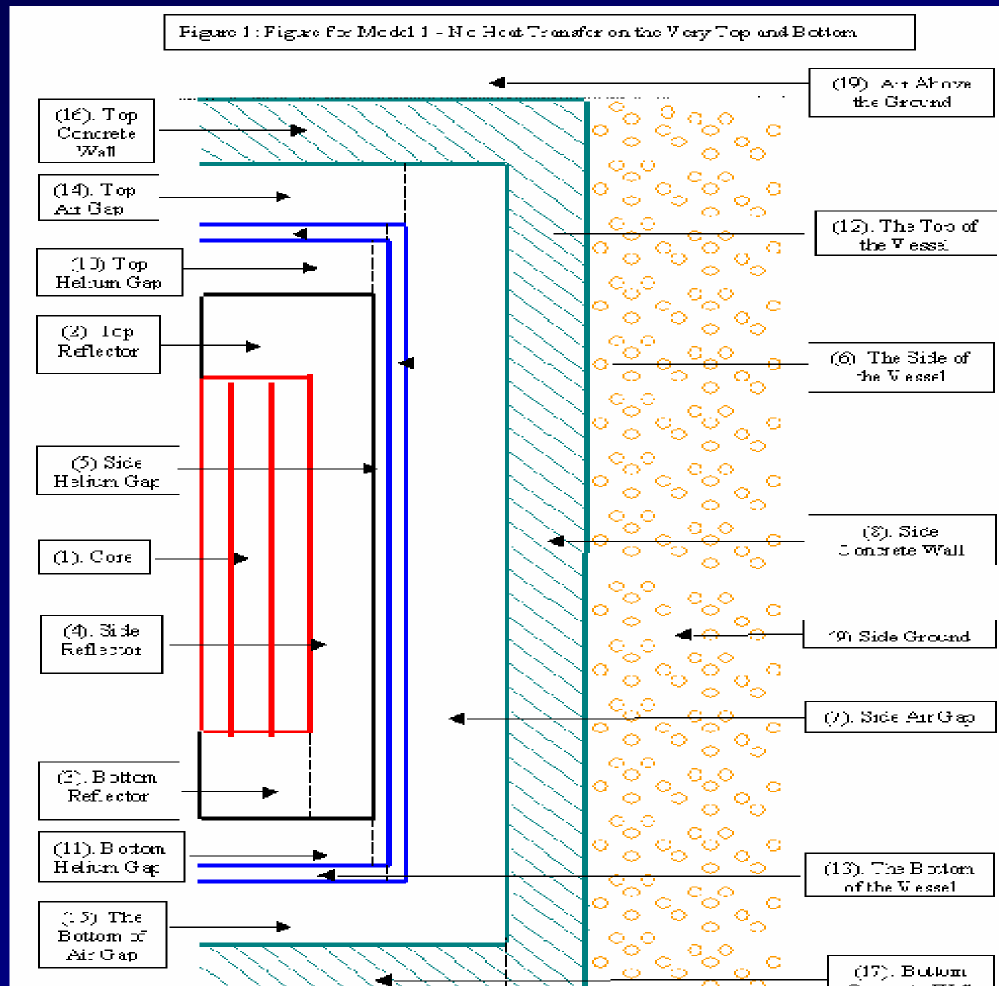

Figure 1: Figure for Model 1 - No Heat Transfer on the Very Top and Bottom

The Conclusion

- The core peak temperature is 1557^{0}C. This is below the 1600 C SiC fuel temperature target and No Core Melt is predicted assuming only conduction.

- 192 hours (8 days) later, the peak temperatures of the pressure vessel and the Concrete Wall will be 1348 °C and 1322°C , respectively. The temperatures of the vessel and the concrete wall are out of the design capability range

- The sensitivity analyses of the initial temperature of the core, the conductivity of the air, the initial temperature of the air gap, the conductivity of the concrete wall and the soil indicate that: The key factors that determine the temperatures of the pressure vessel and concrete wall are the conductivity and heat capacity of the concrete and soil.

- Some convection cooling will be required to keep the temperature of the vessel and concrete within acceptable ranges - conduction alone is not sufficient.

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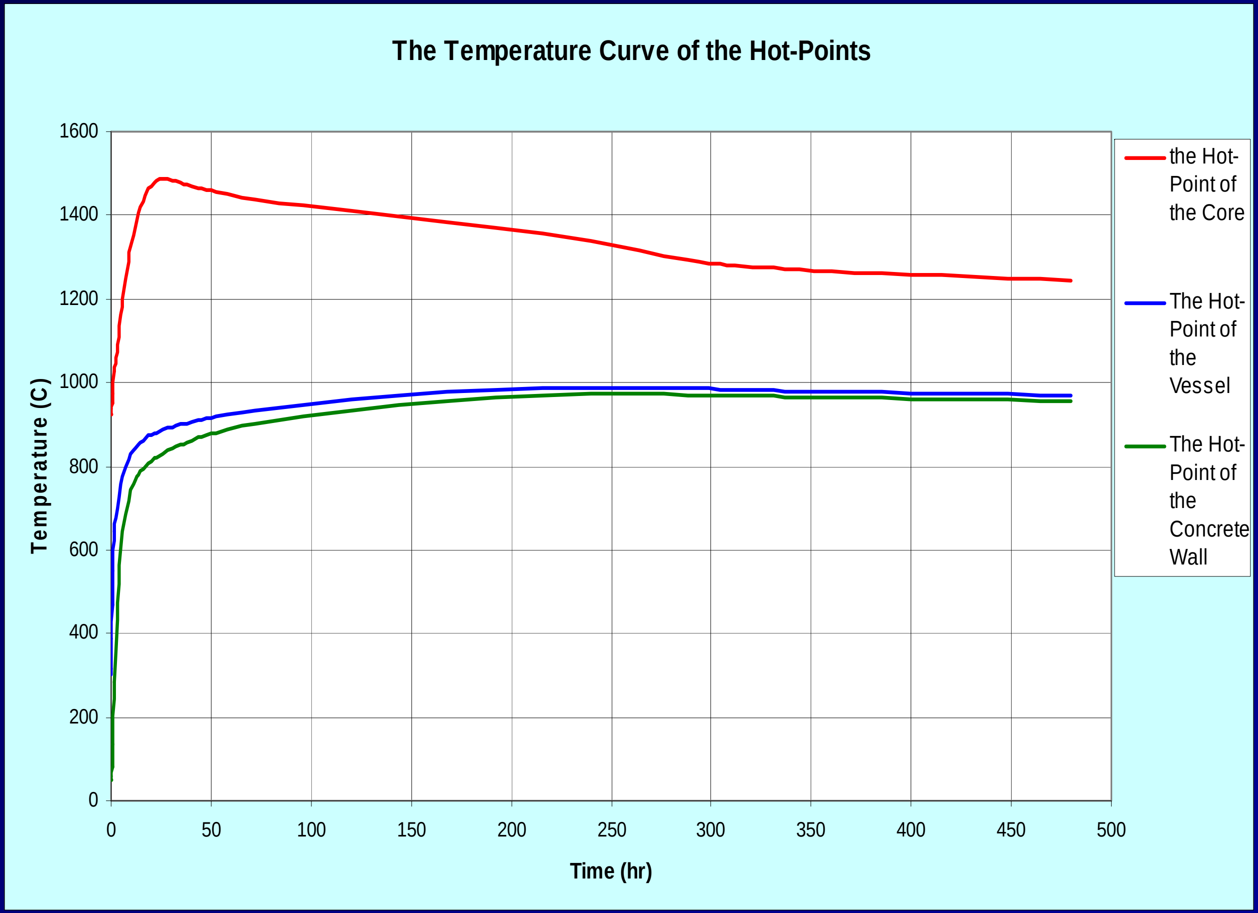

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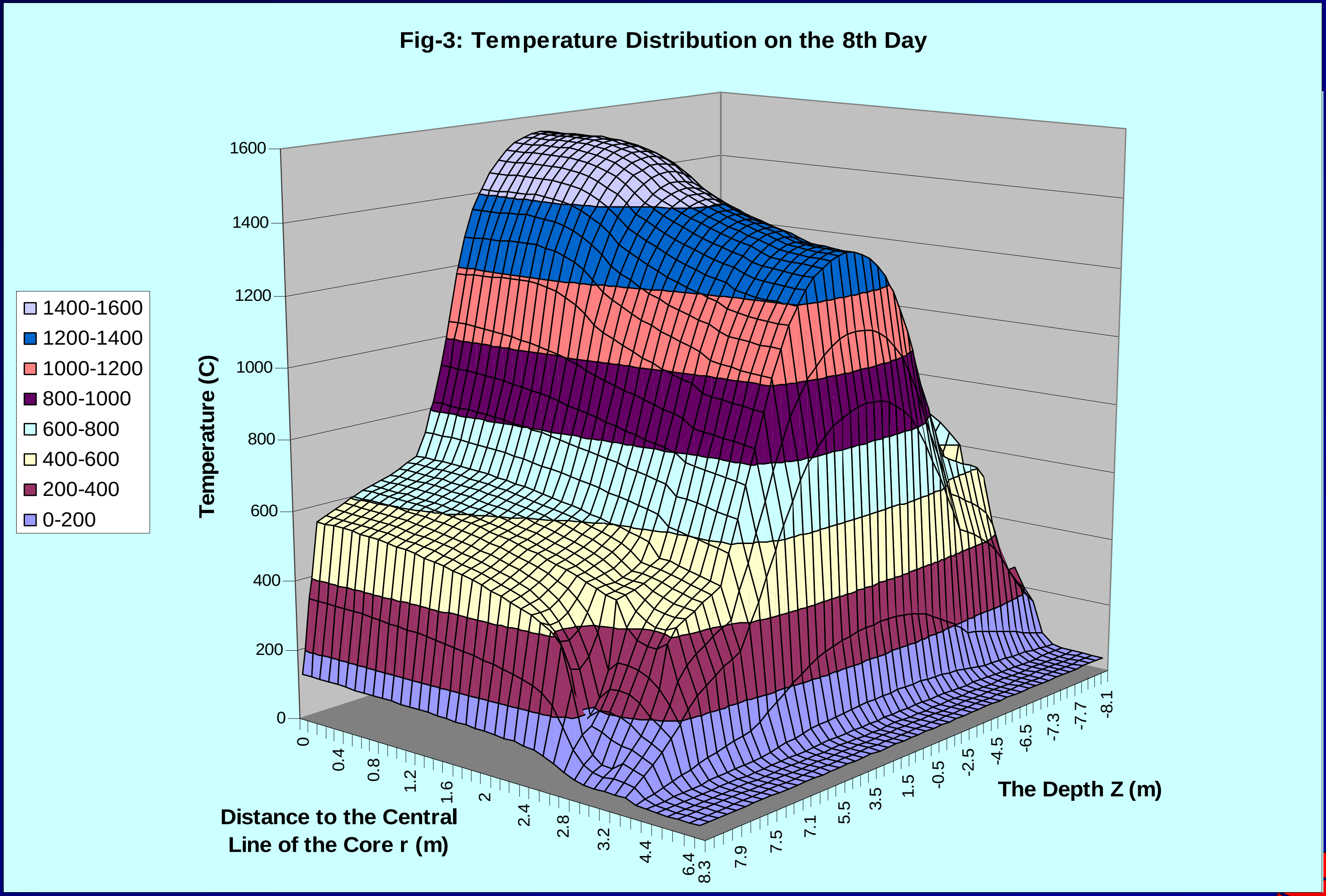

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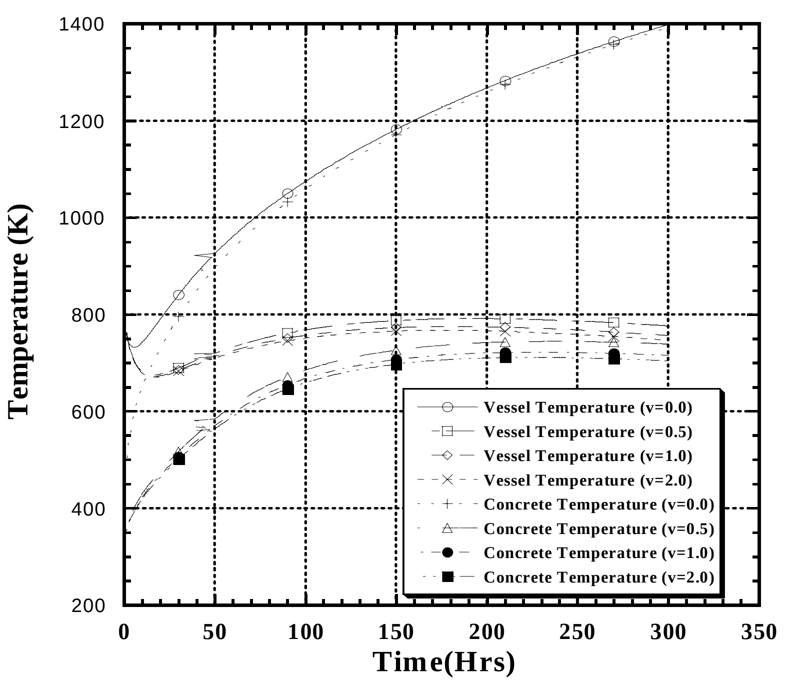
Temperatures with Convection



Future Work

- The perfection of the model, especially how to model the core of the reactor and the heat transfer through convection and how to obtain the accurate initial condition of the accident.
- Air ingress accident simulation.