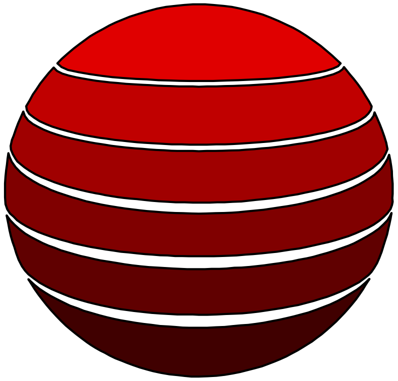
MIT Modular Pebble Bed Reactor (MPBR)



A Summary of Research Activities and Accomplishments

Andrew C. Kadak
Ronald Ballinger

2nd International Topical Meeting on
High Temperature Reactor Technology
Beijing, China
September 22-24, 2004

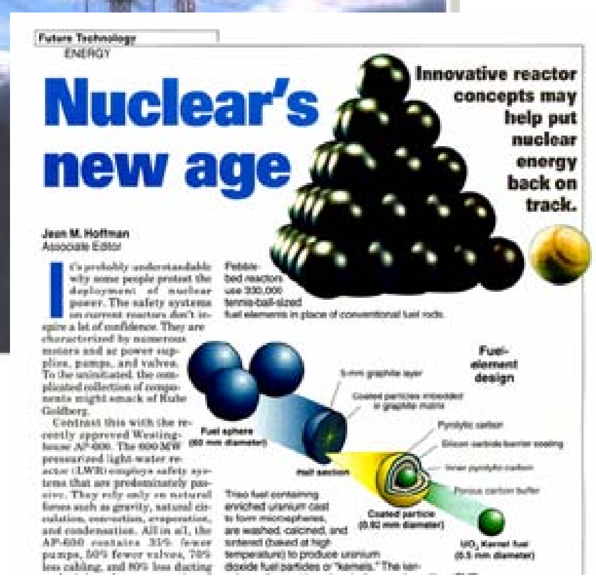
Students Who Have Worked on the Project

- Heather MacLean
- Jing Wang
- Julian Lebenhaft
- Marc Berte
- Chunyun Wang
- Tieliang Zhai
- Tamara Galen
- Jeremy Johnson
- Elton Dean
- Jennifer Anderson
- Paul Owen
- Nate Carstens
- Daniel Walker
- Andreea Chisca
- Ryan Kabir
- Michael Stawicki
- Richard Watkins
- Ian Parrish
- Victoria Anderson
- Paige Hopewell
- Ishna Trivedi
- Mark Laughter

- Dean Wang
- Jacob Eapen
- Tanya Burka
- Lars Gronning
- Nicholas Hernandez
- Mathew Aichele
- Jaehyuk Choi
- Rhett Creighton
- Dandong Feng
- Catherine Goff
- Jeff Hung
- William Kennedy
- Ashley Finan
- Scott Mahar
- Marina Savkina
- Timothy Alvey
- Chang W. Kang
- Allan Smith
- Mark Wright
- Frank Yao
- Jamie Warburton

Faculty:

- David Gordon Wilson (ME)
- Sidney Yip
- Michael Driscoll
- Richard Lanza
- Martin Bazant (Math)


Future Technology
ENERGY

Nuclear's new age

Innovative reactor concepts may help put nuclear energy back on track.

Jean M. Hoffman
Associate Editor

It's probably understandable why some people protest the deployment of nuclear power. The safety systems on current reactors don't inspire a lot of confidence. They are characterized by numerous motors and ac power supplies, pumps, and valves. To the uninitiated, the complicated collection of components might smack of Rube Goldberg.

Contrast this with the recently approved Westinghouse AP-600. The 600-MW pressurized light-water reactor (LWR) employs safety systems that are predominately passive. They rely only on natural forces such as gravity, natural circulation, convection, evaporation, and condensation. All in all, the AP-600 contains 35% fewer pumps, 50% fewer valves, 70% less cabling, and 80% less ducting

Pebble-bed reactors use 330,000 tennis-ball-sized fuel elements in place of conventional fuel rods.

Triso fuel containing enriched uranium cast to form microspheres, are washed, calcined, and sintered (baked at high temperature) to produce uranium dioxide fuel particles or "kernels." The ker-


ARUNDHATI ROY ► "NOT BEHAVING" • DONELLA MEADOWS ► "DANCING WITH SYSTEMS"
CHRIS ALEXANDER ► "ALIVENESS" • PERMACULTURE • ONLINE HEALTH • EVEREST • EVE ENSLER
Whole Earth
Access to Tools, Ideas, and Practices Winter 2001
THE UNHOLY TRIUMVIRATE
Energy, Water, Cash
LOCAL MICROPOWER
Solar, Wind, Hydrogen, Biomass, Geothermal, Tidal, Wave
WHOLE EARTHling
Gift List
14>
0 74851 64582 6
$6.95/$8.50 CDN

LET A THOUSAND REACTORS BLOOM

Explosive growth has made the People's Republic of China the most power-hungry nation on earth. Get ready for the mass-produced, meltdown-proof future of nuclear energy.

by SPENCER REISS

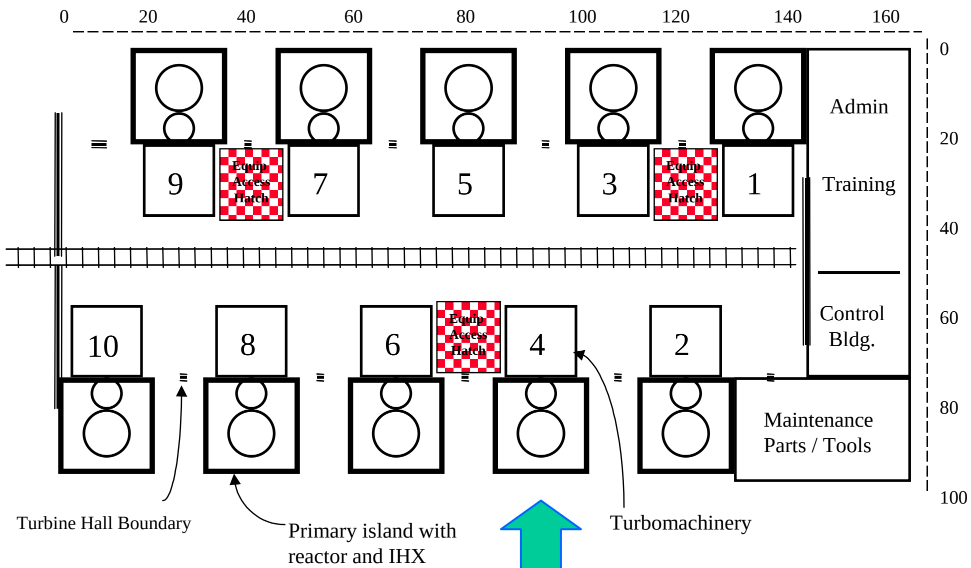
illustration by KENN BROWN and CHRIS WREN

Our Vision for
1150 MW Combined Heat and Power Station

VHTR Characteristics
- Temperatures > 900 C
- Indirect Cycle
- Core Options Available
- Waste Minimization

Ten-Unit VHTR Plant Layout (Top View)

(distances in meters)



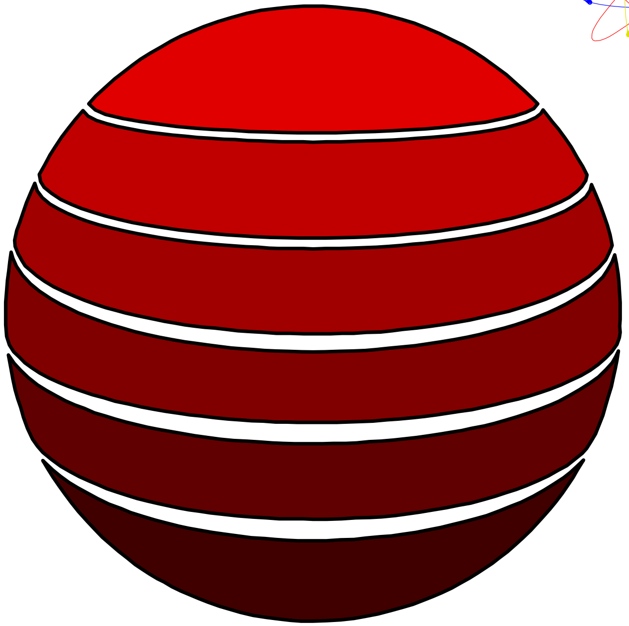
Oil Refinery

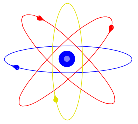
Hydrogen Production

Desalinization Plant

MIT's Pebble Bed Project

- Developed Independently
- Indirect Gas Cycle
- Real Modularity
- High Automation
- License by Test





Project Overview

- **Fuel Performance**
- **Fission Product Barrier (silver migration)**
- **Core Physics**
- **Safety**
  - **Loss of Coolant**
  - **Air Ingress**
- **Balance of Plant Design**
- **Modularity Design**
- **Intermediate Heat Exchanger Design**
- **Core Power Distribution Monitoring**
- **Pebble Flow Experiments**
- **Non-Proliferation**
- **Safeguards**
- **Waste Disposal**
- **Reactor Research/ Demonstration Facility**
- **License by Test**
- **Expert I&C System - Hands free operation**

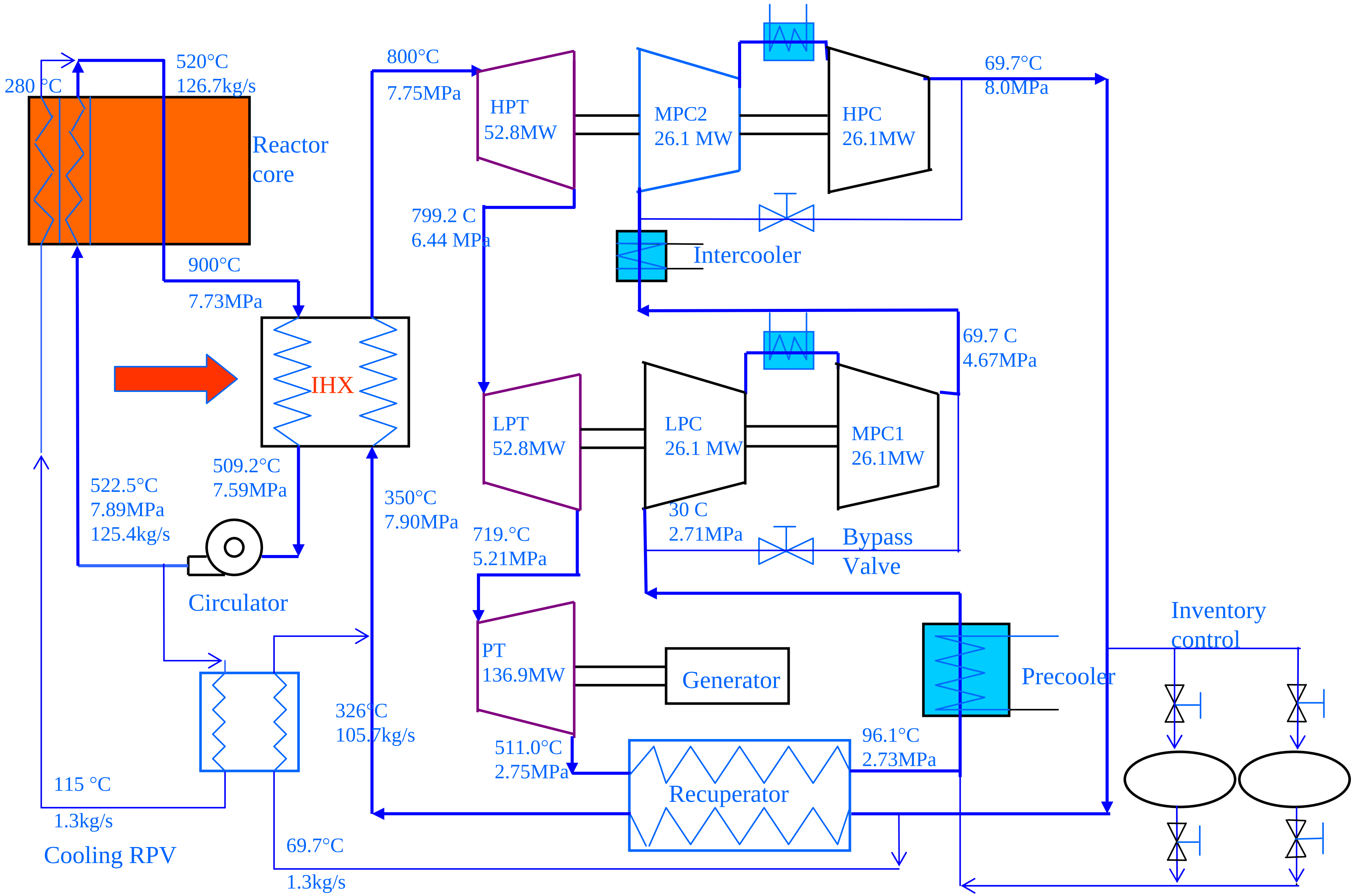
MIT MPBR Specifications

Thermal Power	250 MW - 120 Mwe
Target Thermal Efficiency	45 %
Core Height	10.0 m
Core Diameter	3.5 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	520°C/900°C
Helium pressure	80 bar
Mean Power Density	3.54 MW/m^3
Number of Control Rods	6

Features of Current Design

Thermal Power	250 MW
Gross Electrical Power	132.5 MW
Net Electrical Power	120.3 MW
Plant Net Efficiency	48.1% (Not take into account cooling IHX and HPT. if considering, it is believed > 45%)
Helium Mass flowrate	126.7 kg/s
Core Outlet/Inlet T	900°C/520°C
Cycle pressure ratio	2.96
Power conversion unit	Three-shaft Arrangement

Current Design Schematic



BOP System Analysis and Dynamic Simulation Model Development

Student: Chunyun Wang

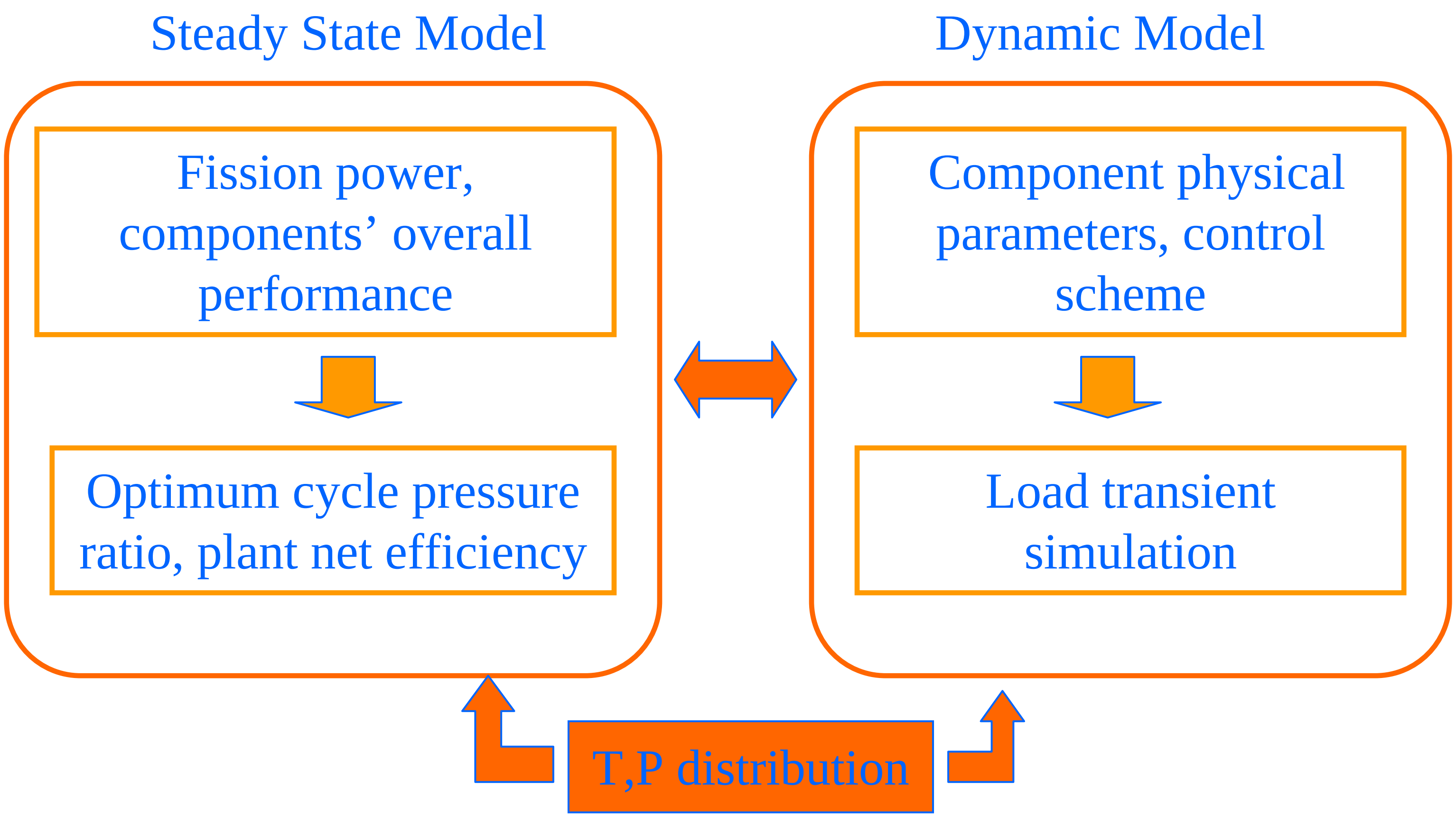
Advisor: Prof. Ronald G. Ballinger

Objectives

- Develop an advanced design for a pebble bed reactor power plant system with high efficiency and minimum capital cost
  - Net efficiency > 45%
  - Must be achievable with current technology or minimal extension of technology
- Develop a dynamic simulation model to determine the control structure, investigate the control schemes and simulate the transients

Model Development

T/H Steady State & Dynamic Model Development



Design Constraints

- Compliance with ASME code
  - Section III, Class 1 Pressure Boundary (Nuclear side)
  - Section VIII (where applicable)
- Build with achievable extension of Technology
- Using “ESKOM-Like” reactor as heat source
- Components must be commercially feasible

Consequences of Indirect Cycle

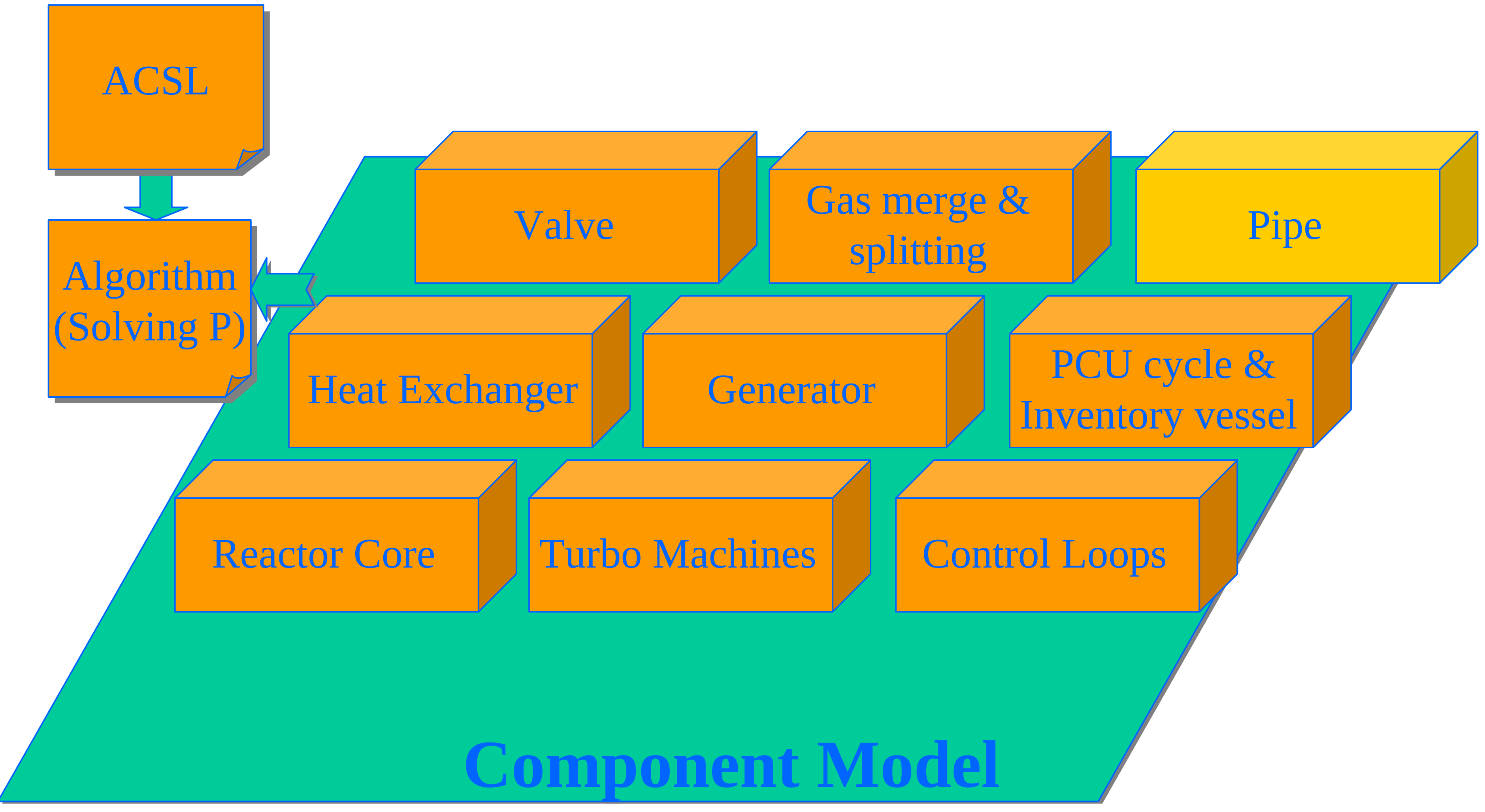
- Advantages
  - Section VIII used for BOP (Exclusive IHX)
  - Non-radioactive maintenance
  - Air/Water ingress to primary less likely
  - Less of a “loose parts” problem
- Disadvantages
  - Efficiency penalty
  - System complexity
  - IHX “operating curve” required
  - Vessel cooling system
  - Primary system volume control

IHX & Recuperator Design Data (Printed Circuit HX configuration)—By Concepts-NREC

		IHX		Recuperator		
Effectiveness(%)	90	92.5	95	95	95	95
Hot side pres. loss(%)	1.60	1.68	1.77	0.8	1.4	2.0
Cold side pres. Loss(%)	2.00	2.00	2.00	0.13	0.23	0.33
Number of Modules	6	6	6	30	30	30
Module Width (mm)	600	600	600	600	600	600
Module Length(mm)	885	1013	1255	648	694	727
Module Height (mm)	2773	3014	3454	2745	2042	1693
Est. Weight (kg)	38,854	50,669	76,233	155,585	126,260	110,821
Cost (million $)	4.53	5.91	8.88	2.59	2.10	1.84

Dynamic Model Development

Dynamic Model Structure



Component Models

- Reactor core
  - Thermal-hydraulic model: two-dimensional
  - Core neutronics: Point kinetics equations
  - Fission product poisoning
  - Temperature coefficient of reactivity (Doppler effect)
- Heat Exchanger
  - Lumped parameter modeling approach

    (Has been verified with the HX model of Flownet)
- Turbomachines
  - Use normalized non-dimensional characteristic maps of turbine and compressor (By combination of the nondimentional parameters, the Correct mass flowrate W_c, Correct speed N_c, the axial turbine map collapses into one line for different speed line)
- PI controller algorithm

Control Methods and Control Objective

- “Primary” system:
  - Control rod position: Combined with the negative temperature coefficient of reactivity to control the reactivity and core outlet temperature
  - Circulator rotational speed: Adjusting the coolant mass flow rate in the “primary” loop allows the mass flow rates of two loops are identical
- “Secondary” system
  - (1) Bypass valve: For rapid load decreases

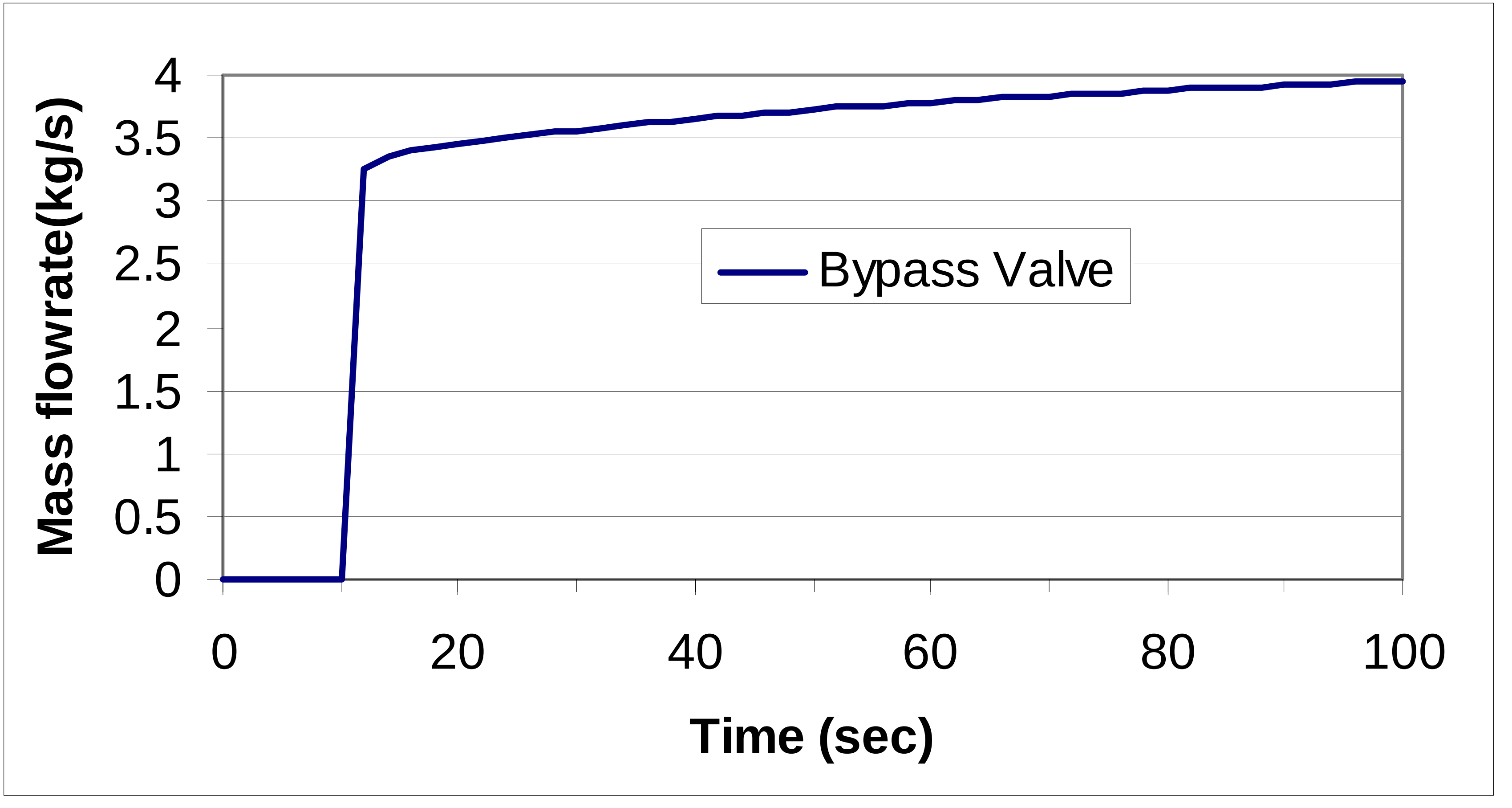
    (2) Inventory control: For less rapid load reductions and load increases

  To maintain the power turbine’s shaft speed constant

Control Scheme

- 100% power (Normal Steady State)
  - Full primary and secondary mass flowrate
- 100% --> 50% ramp
  - Fast response: Bypass control
  - Slow response: Inventory control
  - Inventory in the secondary system is decreased gradually. After reaching new steady state, bypass valve is closed or “feathered”.
- 50% --> 100% ramp
  - Inventory control
- 50% <--> 0% ramp
  - Bypass control (Automatic or manual)

10% Load Step Reduction—Bypass valve mass flowrate



Summary

- Analyses of balance of plant have been performed for cycle optimization
- Plant cycle design has been defined and the MBPR net efficiency can reach 45% with achievable technology
- A dynamic model has been developed for plant dynamic simulation and HX sub-model has been verified
- The preliminary control scheme has been designed
- 10% load rejection, both for centrifugal compressors and axial compressors, has been simulated, and its results agree, in general, with the results of a model for a similar system developed using FlowNet

MPBR Modularity

Marc V Berte

Prof. Andrew Kadak

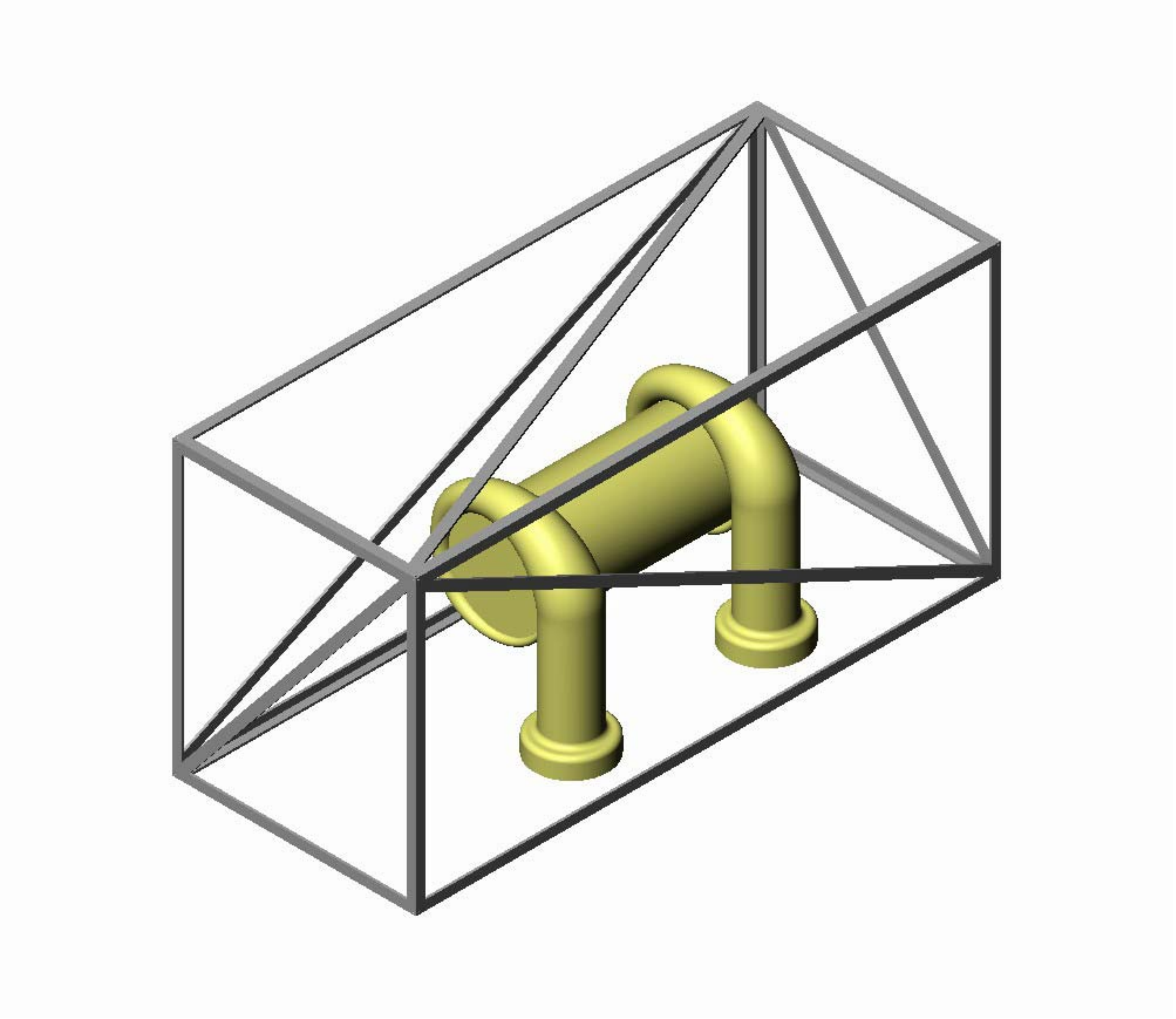
Modularity Progression

- Conventional Nuclear Power Systems
  - Assembled on site
  - Component-level transportation
  - Extensive Site Preparation
- Advanced Systems
  - Mass Produced / “Off the Shelf” Designs
  - Construction / Assembly Still Primarily on Site
- MPBR
  - Mass Produced Components
  - Remote Assembly / Simple Transportation & Construction

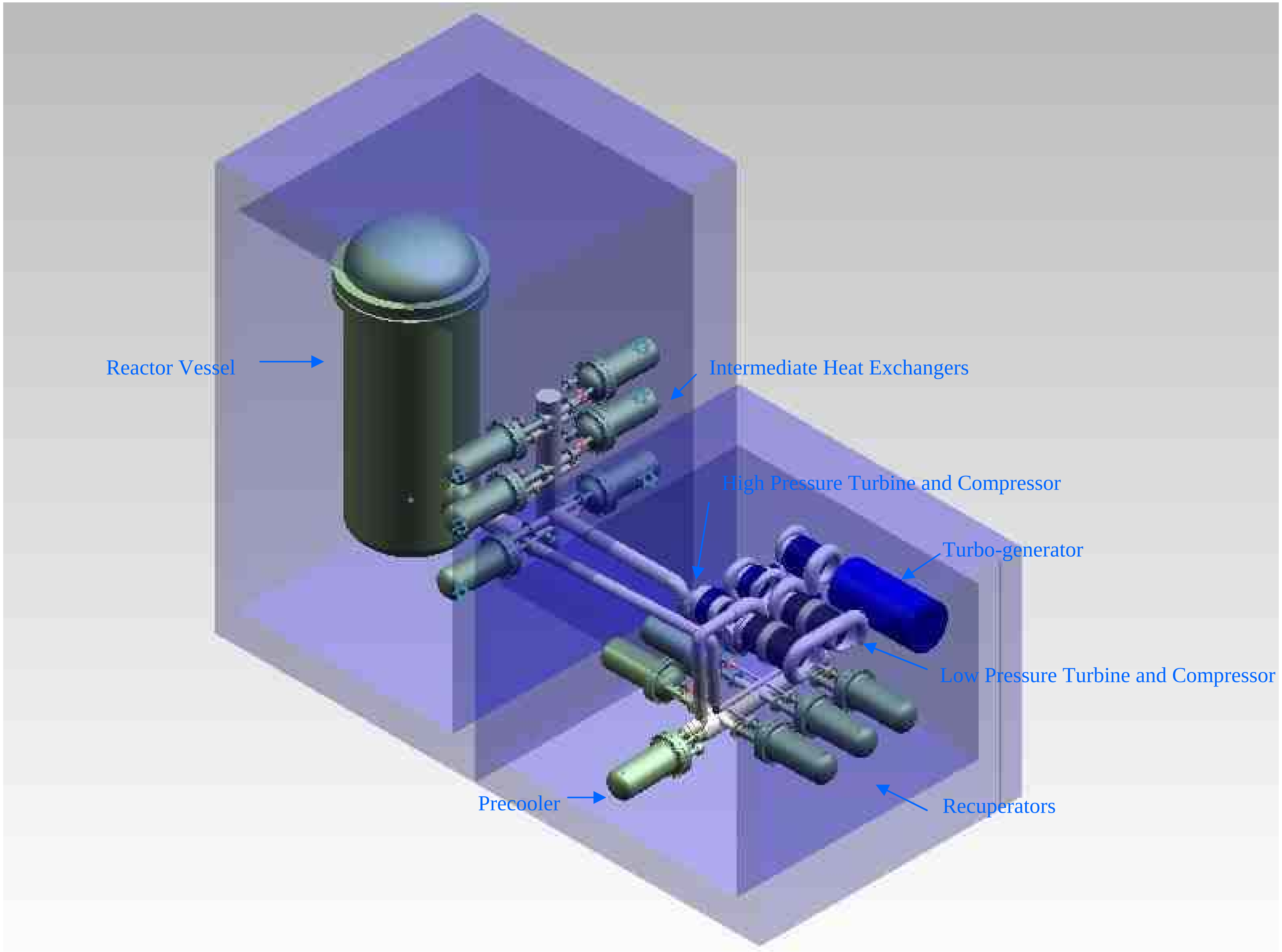
MPBR Modularity Plan

- Road- Truck / Standard-Rail Transportable
  - 8 x 10 x 60 ft. 100,000 kg Limits
- Bolt-together Assembly
  - Minimum labor / time on site required
  - Minimum assembly tools
  - Goal: Zero Welding
- Minimum Site Preparation
  - BOP Facilities designed as “Plug-and-Play” Modules
  - Single Level Foundation
  - System Enclosure integrated into modules
- ASME Code compliant
  - Thermal expansion limitations
  - Code material limitations

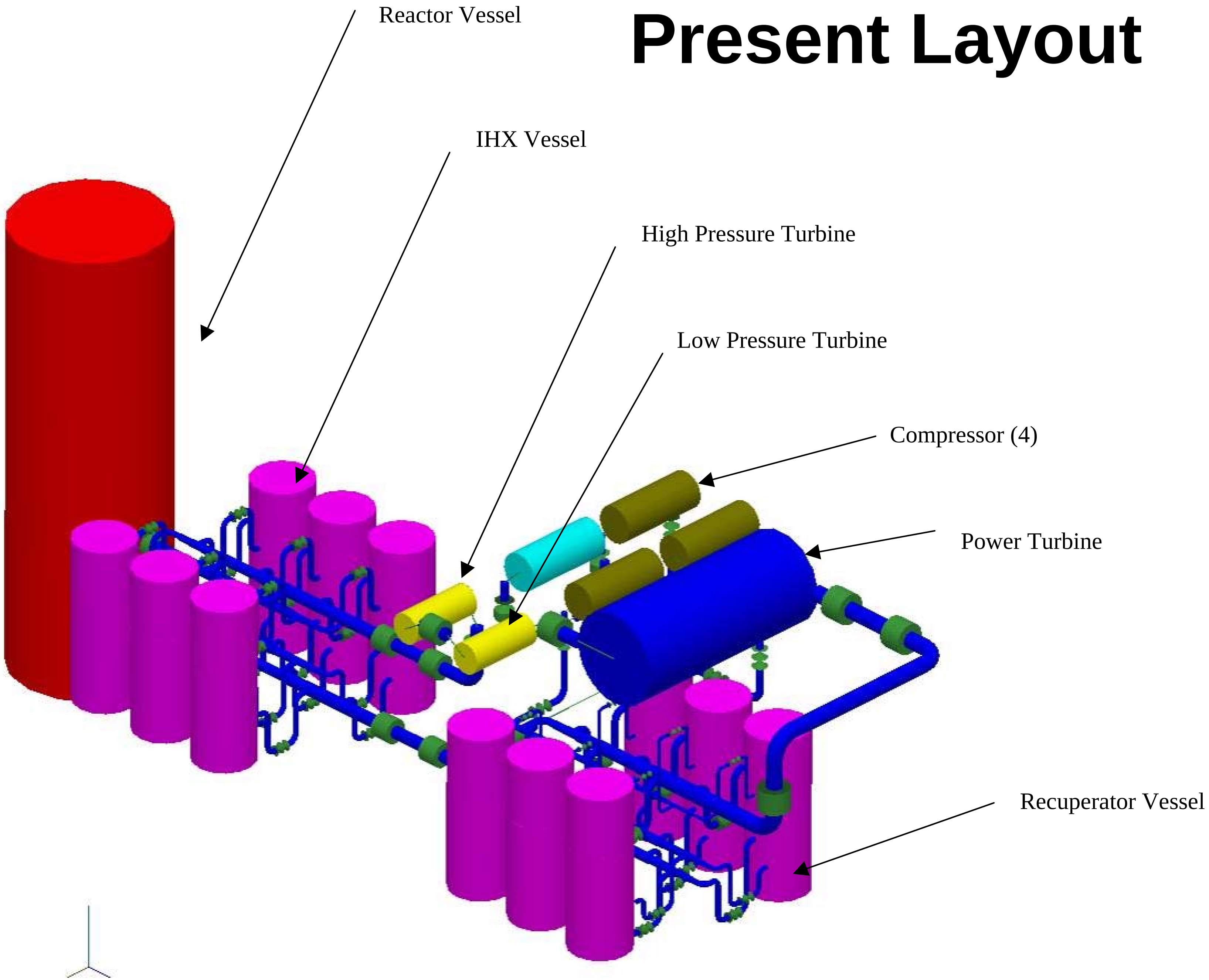
Space Frame Technology for Shipment and Assembly



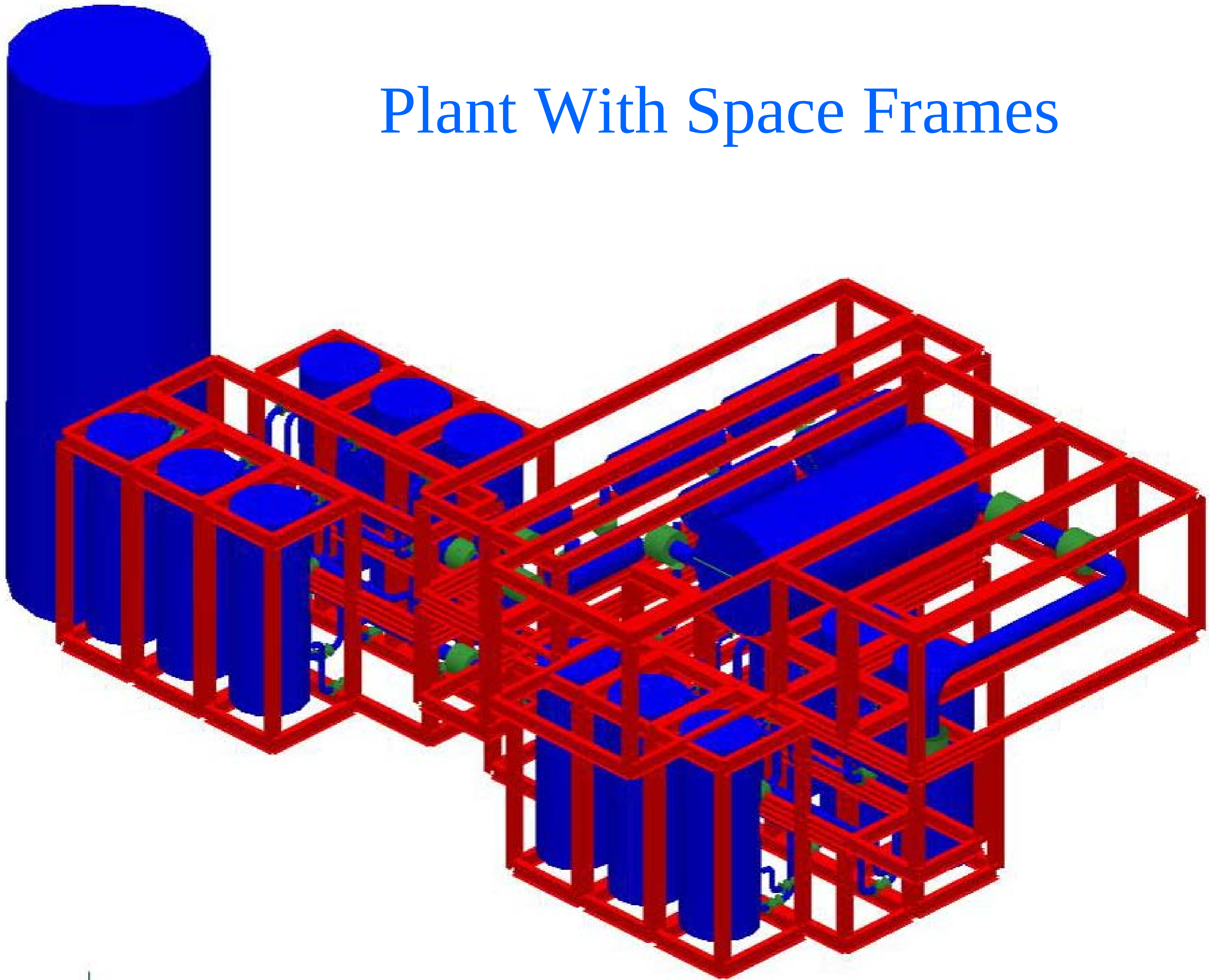
Current MIT/INEEL Design Layout

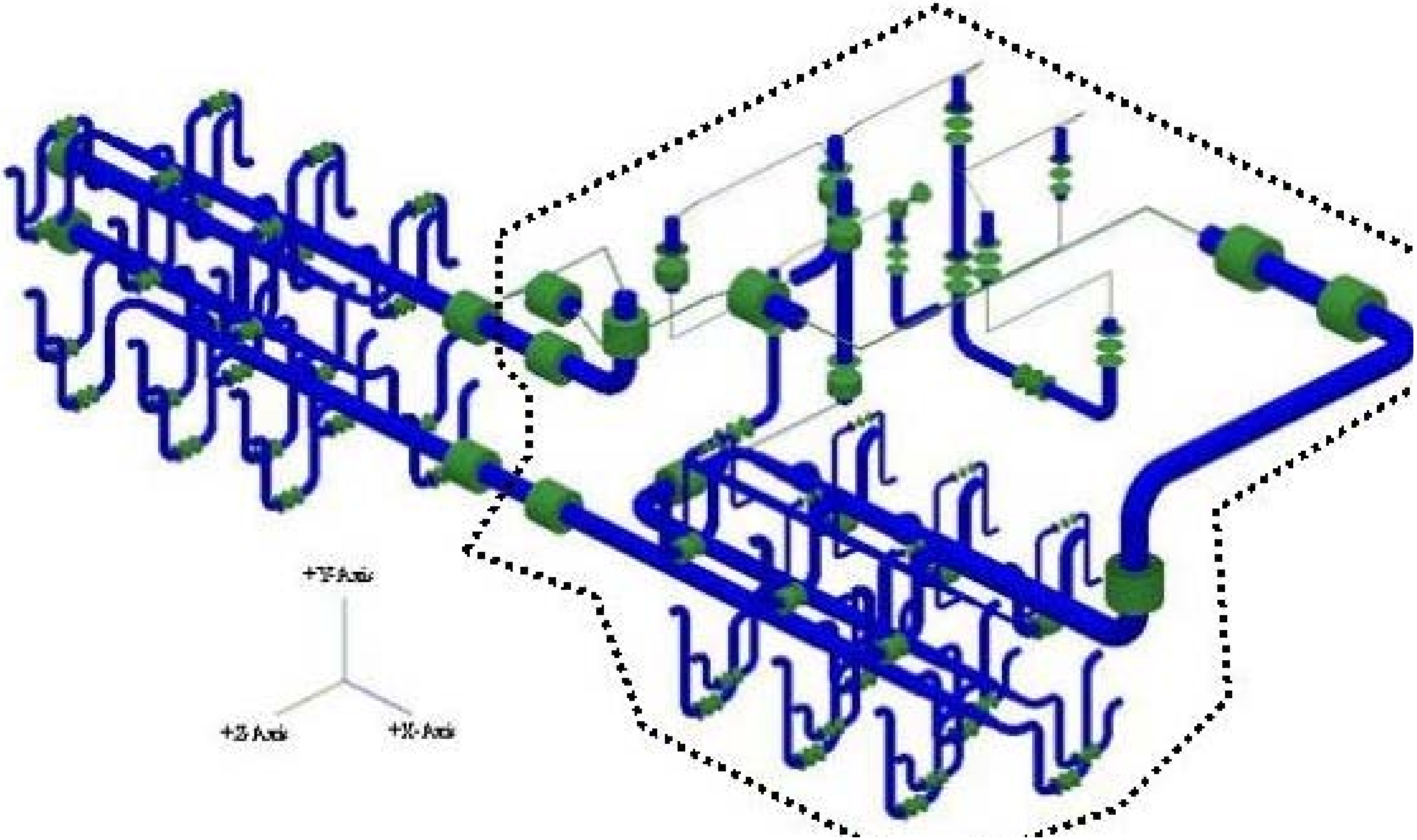


Present Layout



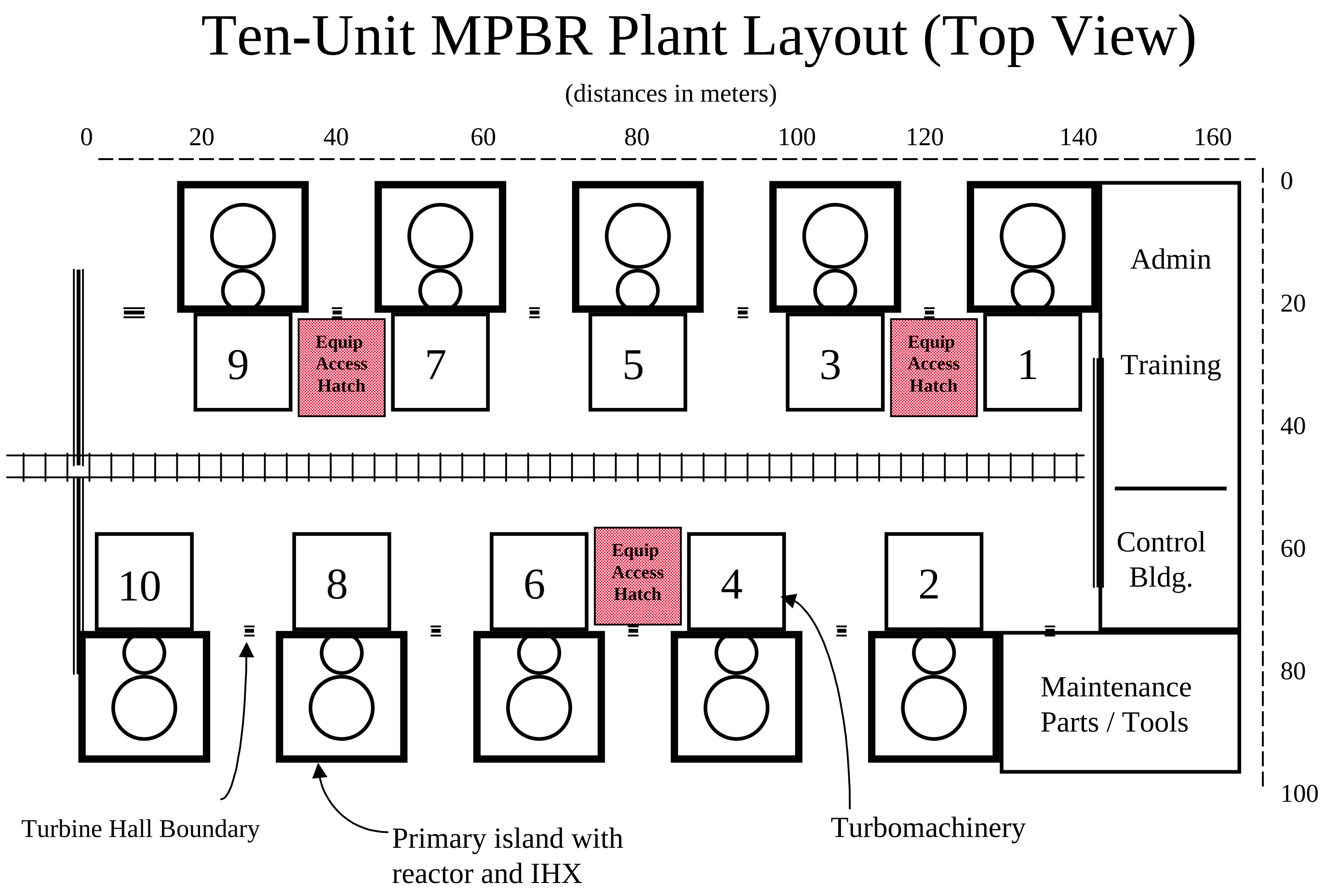
Plant With Space Frames



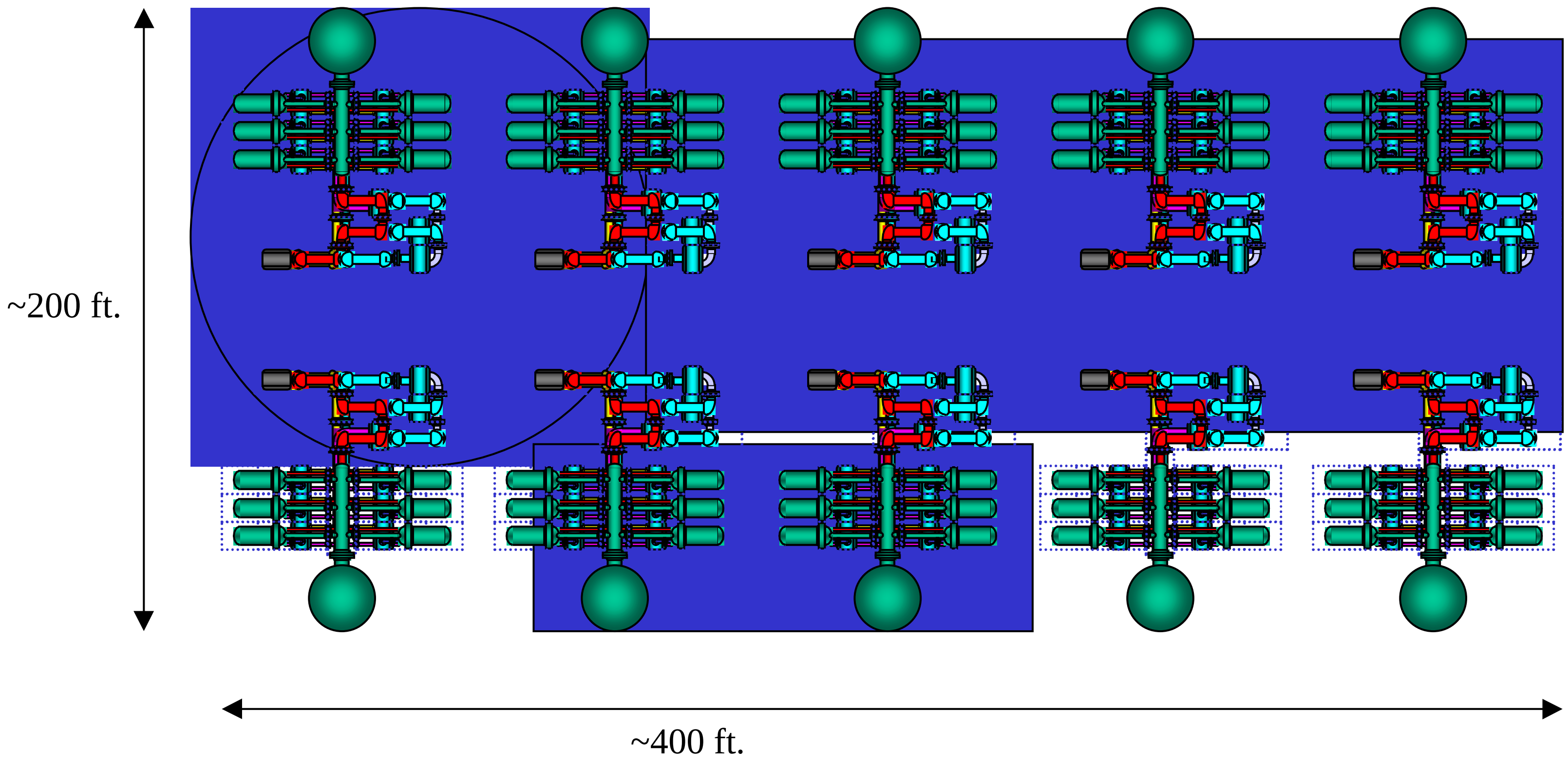


+Y-Axis
+Z-Axis
+X-Axis

For 1150 MW Electric Power Station



AP1000 Footprint Vs. MPBR-1GW



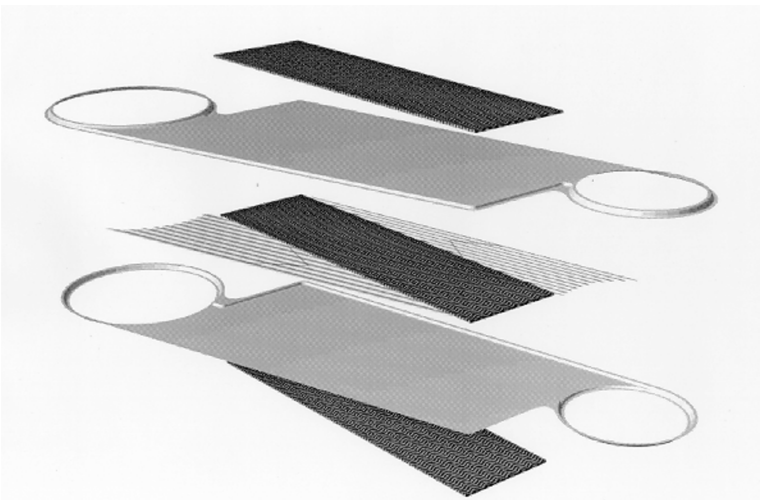
Intermediate Heat Exchanger Design

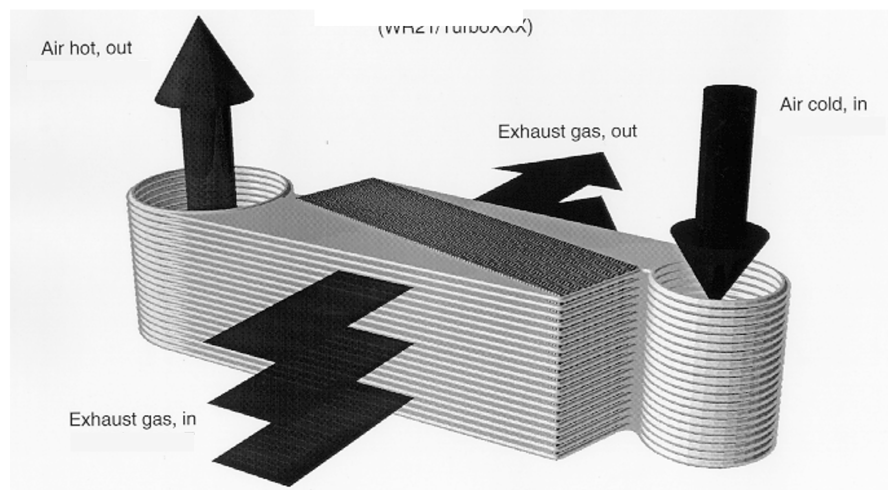
Prof. R. Ballinger, P. Stahle
Jim Kesseli - Brayton Energy

Heat Exchanger Design

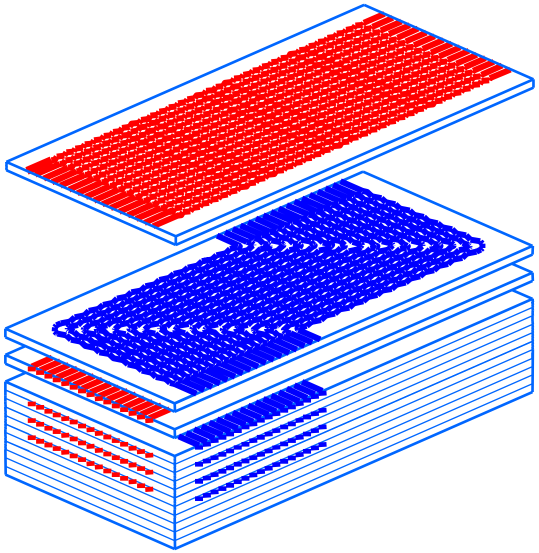
- Two Concepts Identified
  - Compact Plate-Fin (NREC)
  - PCHE Design (Heatric)
- Base Designs Established
- Model Developed for System Analysis
- Limitations Identified

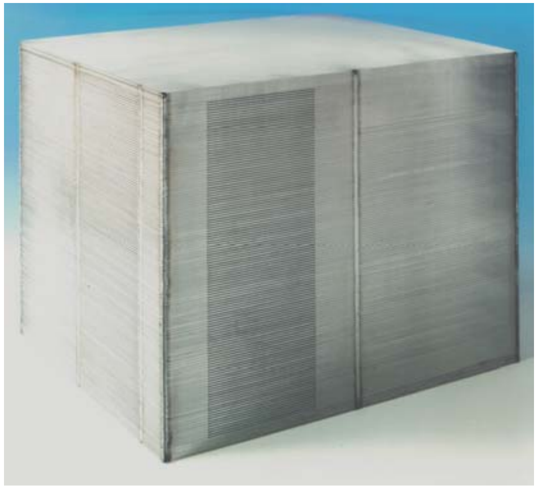
Compact Plate-Fin
Old Design (NREC)

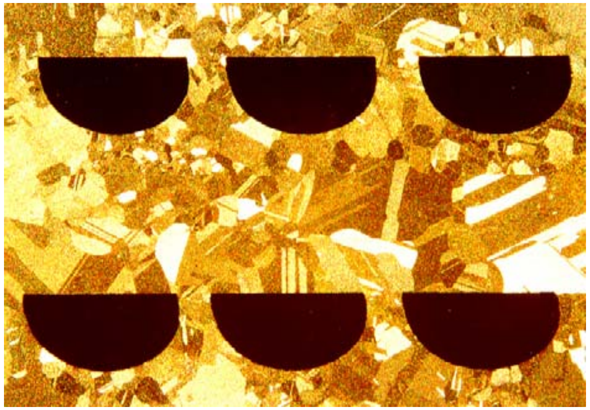




Printed Circuit Design (Heatric)







IHX Primary Conditions

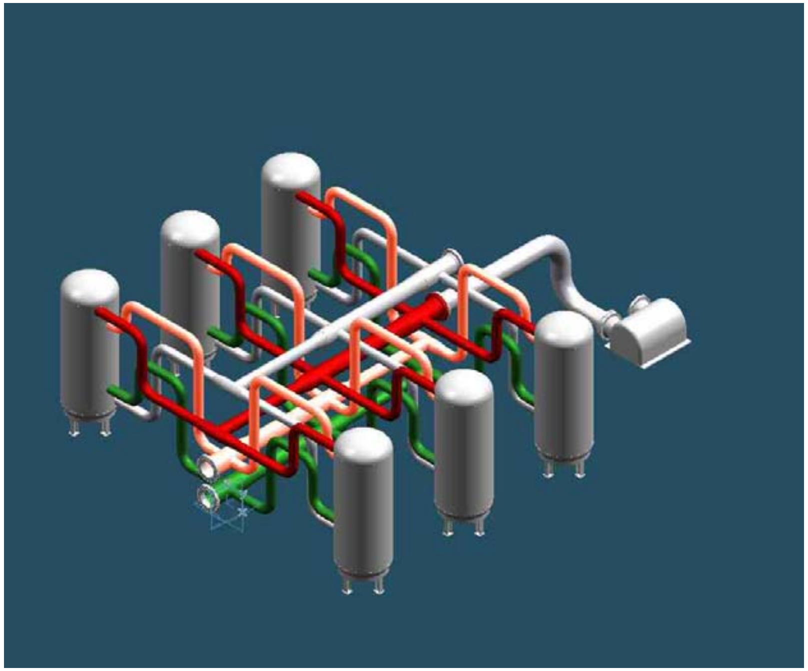
- Inlet
  - Temperature 900^{o}C
  - Pressure 7.73 Mpa
- Outlet
  - Temperature 509^{o}C
  - Pressure 7.49 Mpa
- Flow ~130 Kg/s

IHX Secondary Conditions

- Inlet
  - Temperature 488^{o}C
  - Pressure 7.99 Mpa
- Outlet
  - Temperature 879^{o}C
  - Pressure 7.83 Mpa
- Flow ~130 Kg/s

IHX Modular Assembly Isometric View

- Six units per assy.
- Interconnection piping between units
- Pipe loops relieve expansion stress
- Small units for ease of fabrication and maintenance.



IHX Design Data (Concepts-NREC)

Effectiveness (%)	90	92.5	95
Hot Side Pres. Loss (%)	1.60	1.68	1.77
Cold Side Pres. Loss (%)	2.00	2.00	2.00
Number of Modules	6	6	6
Module Width (mm)	600	600	600
Module Length (mm)	885	1013	1255
Module Height (mm)	2773	3014	3454
Est. Wt. PC Config. (kg)	38,854	50,669	76,233
Est. Wt. PF Config. (kg)	10,335	13,478	20,278
Cost (M$)	4.53	5.91	8.88

Heat Exchanger Core Modules

- Plate Fin 92% Eff
  - Wt 30,000 lb.
  - Ht 118”
  - Wd 24”
  - Dp 40”
- 18 Req’d for IHX

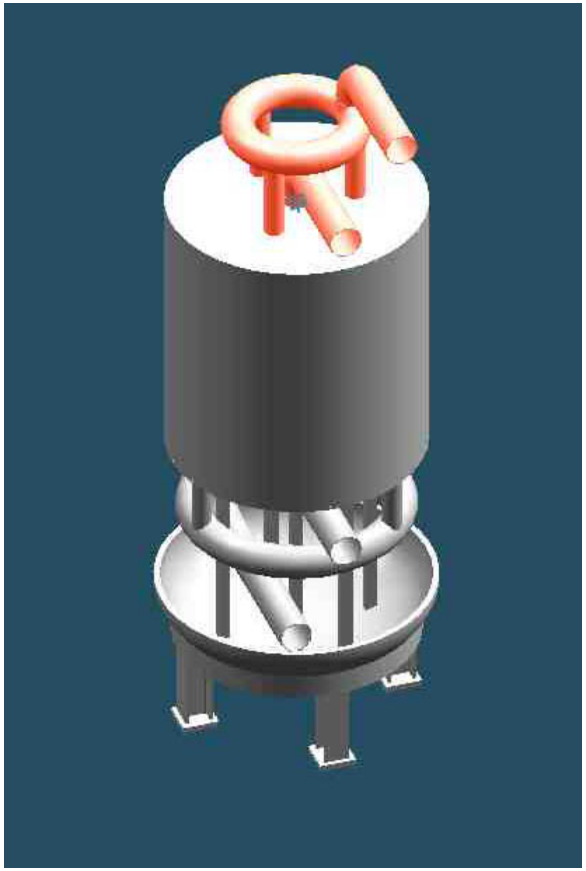
- Printed Circuit 92%
  - Wt 111,700 lb.
  - Ht Same as PF
  - Wd Same as PF
  - Dp Same as PF
- 18 Req’d for IHX

IHX Unit Pressure Vessel

- Dia. 90.5”
- Thk. 2”
- Ht. 240”
- Wt. 90,000 lb
  - (inc. Plate Fin xch.)

Cooled Internal Volume

- Temp. 288^{o}C
- Press. ~8 Mpa
- ASME Sec III Bndry
- Piping grouped by temperature
- Internal legs for flexibility



Primary Internals

- (3) Plate Fin Core Modules
- Core Modules Suspended to accommodate expansion

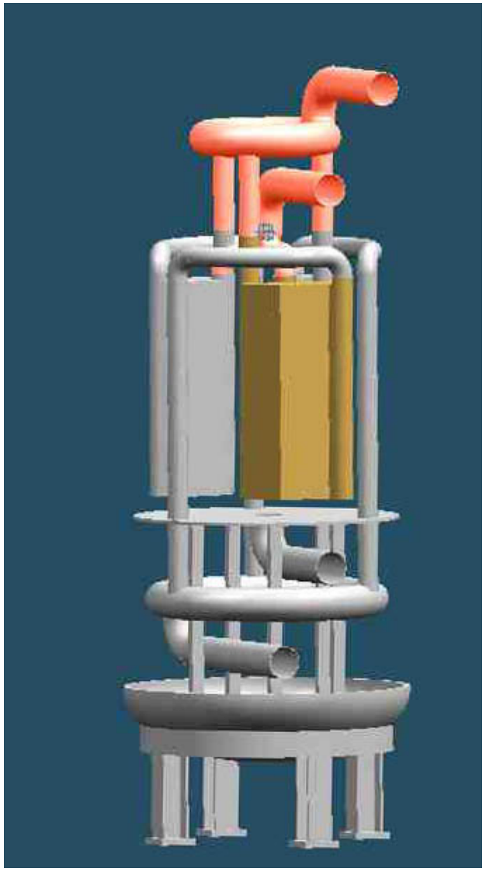
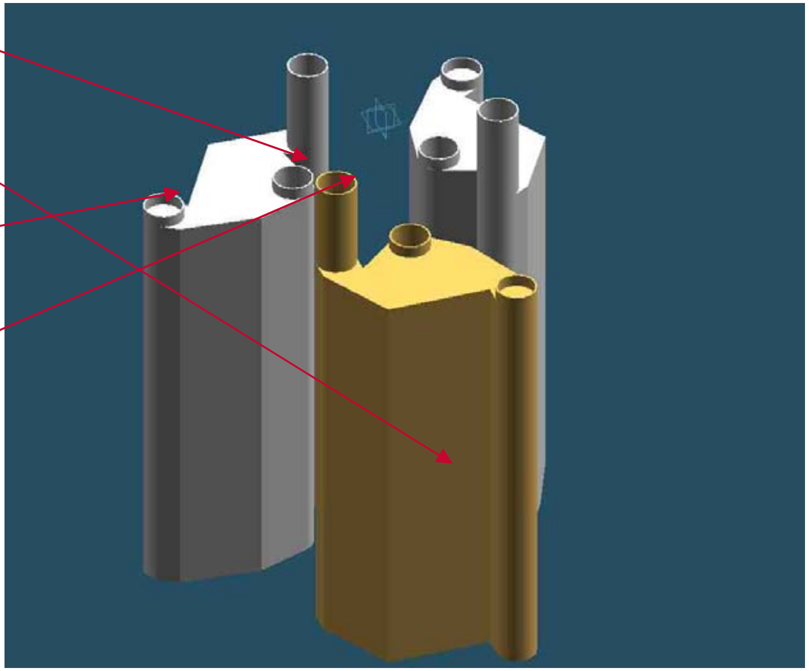


Plate Fin Grouping

- Primary Inlet
- Primary Outlet

- Secondary Inlet
- Secondary Outlet

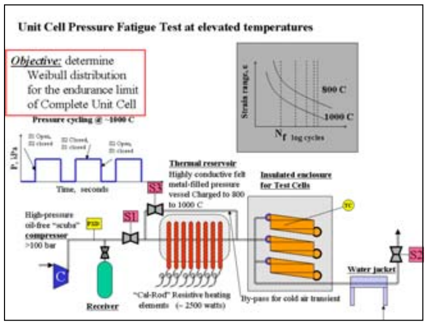


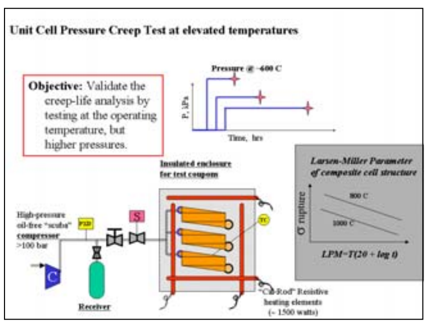
Future Plans

- Join with industrial partner(s) to develop highest temperature IHX (900-950 C) possible using current material knowledge for Hydrogen demonstration plant.
- Identify key design issues for higher temperatures including transients.
- Work on materials challenges for higher temperature operation.
- Modular approach allows for testing.

Proposed Test Program

for Advanced High Temperature Plate Fin HX (800 - 1000 C)





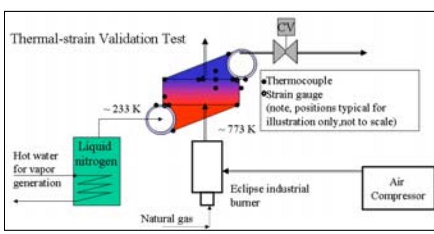


Figure 6 Unit Cell Pressure Fatigue Test at Elevated Temperature.
This test conducts numerous pressure cycles on three cells at elevated temperature (800 and 1000 C). At each selected pressure, the cycling will continue to failure (ie gas leakage is out of spec). The test will be performed at three to five pressures of increasing magnitude. The data will be formulated into an endurance plot. The results will be used to calibrate and validate the analytical models. The MIT high-temperature furnace is capable of heating three or more cells to 1000 C.

Figure 7 Unit cell Creep Test and Elevated Temperatures.
This test will use a modified version of the rig MIT high temp furnace. The tests are performed at steady pressure and temperature conditions. An empirical Larsen-Miller map of the cell is created by operating the cell to failure at two elevated temperatures, 800 and 1000 C. The pressures imposed on the cell will be selected to induce failure at intervals ranging from one hour to 1000 hours. Failure is indicated by the cells inability to maintain the leak specification. After completing the mapping, three cells will be subjected to the design pressure and temperature and left to operate indefinitely. Inspection will be made at regular intervals.

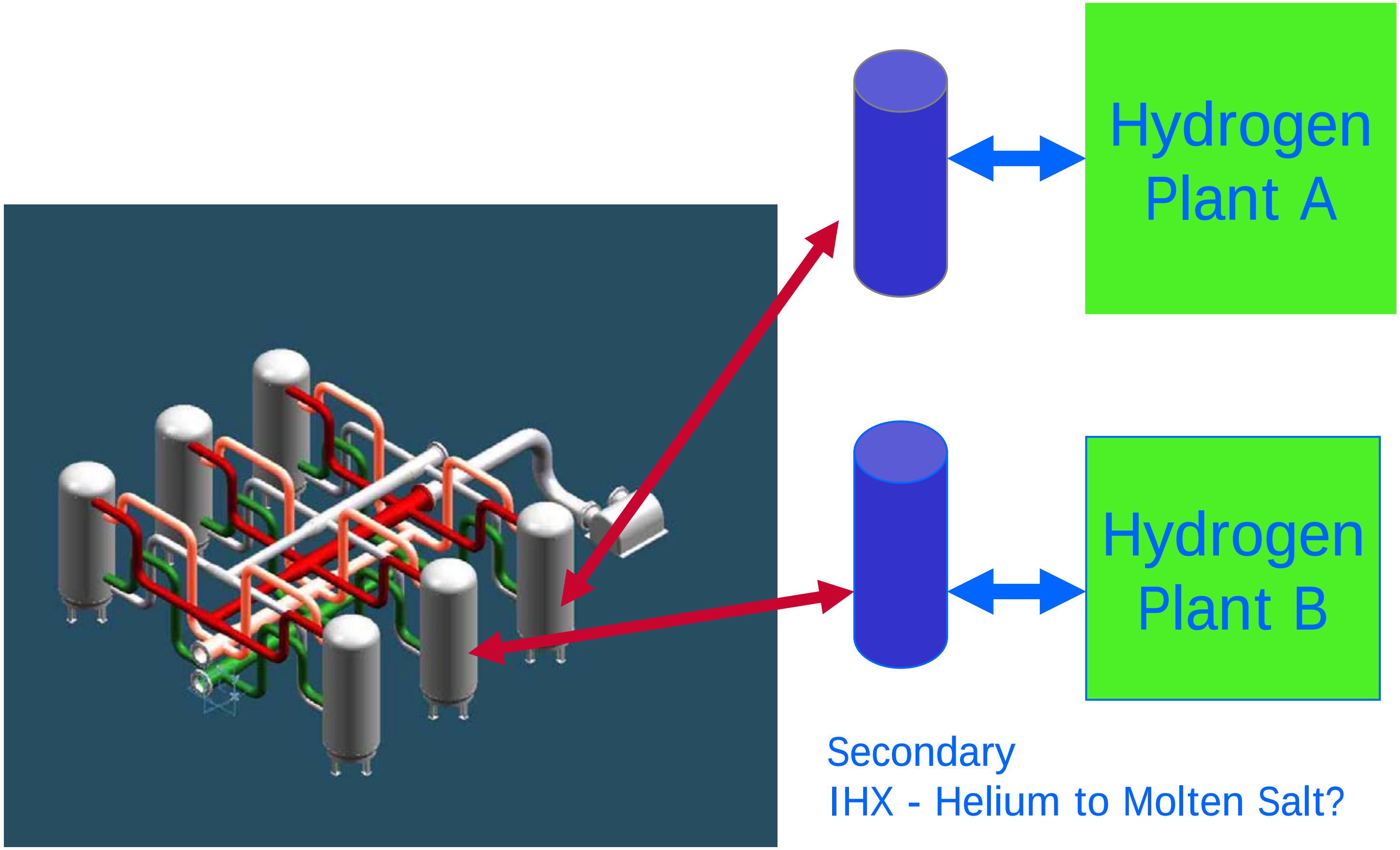
Figure 8 Thermal Strain Measurement for model Validation.
This test rig will heat a sub-core (5 or more cells) to an elevated temperature, but not so high as to compromise the accuracy of piezoresistive strain gauges. Transient temperature and strain measurements will be recorded while flowing very cold gas generated from a liquid nitrogen bath on one side and combustion products from a commercial burner on the other side.

~~Proof of manufacturability, demonstration of mechanical integrity, and validation of analytical life prediction models are critical steps towards the qualification of the proposed high temperature heat exchanger. This program will address a these three steps by fabricating and instrument roughly 30 IHX cells for a series of rigorous endurance tests and characterizing.~~

MIT/Brayton Energy

1. **Unit Cell Pressure Fatigue Test**
2. **Unit cell Creep Test**
3. **Thermal Strain Measurement for model Validation.**

Hydrogen Mission
Modularity Flexibility



May use one or more IHX's from base electric plant for H_2

An Integrated Fuel Performance Model for Modular Pebble Bed Reactor

Jing Wang

Professor R. G. Ballinger

Fuel Performance Model

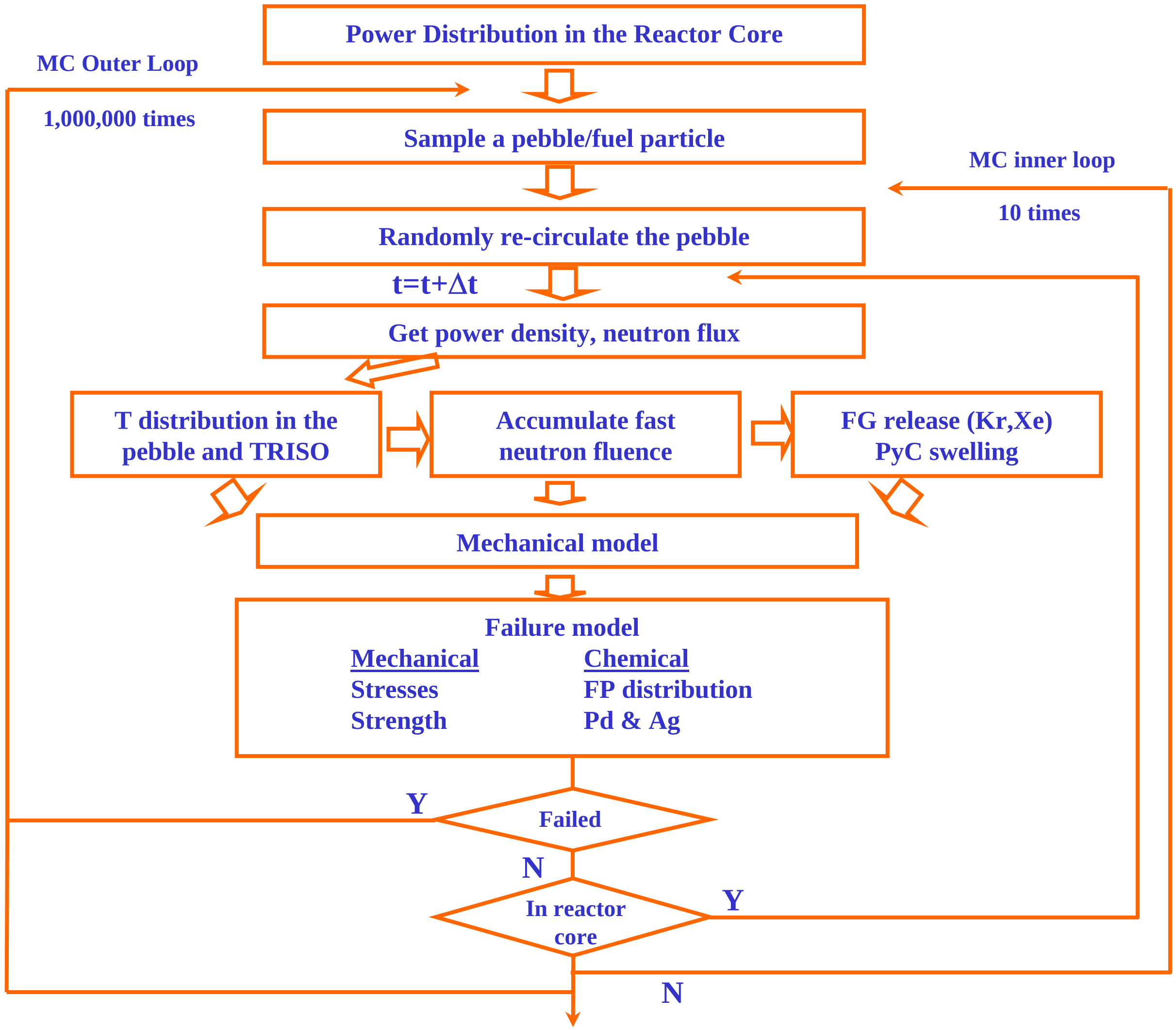
- Detailed modeling of fuel kernel
- Microsphere
- Monte Carlo Sampling of Properties
- Use of Real Reactor Power Histories
- Fracture Mechanics Based
- Considers Creep, stress, strains, fission product gases, irradiation and temperature dependent properties.

Fuel Performance

The Key Safety System

- Develop Fuel Performance Model
- Develop an optimized design for reliability
- Work with manufacturer to optimize
- Make fuel and test

Integrated Fuel Performance Model



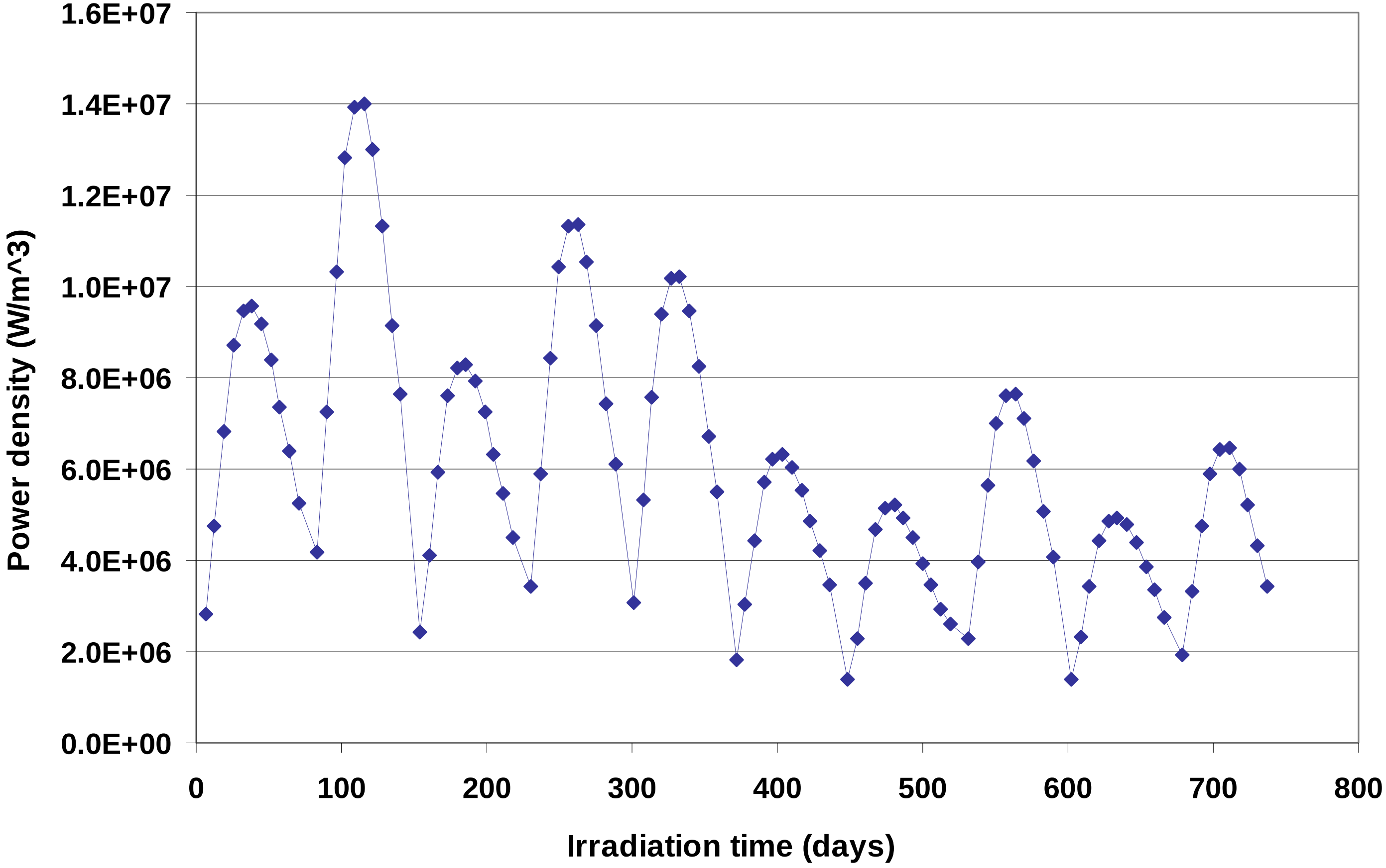
Monte Carlo outer loop:

Samples fuel particle statistical characteristics

MC inner loop:

Implements refueling scheme in reactor core

Simulation of Refueling - cont'd



A typical power history of a pebble in MPBR core

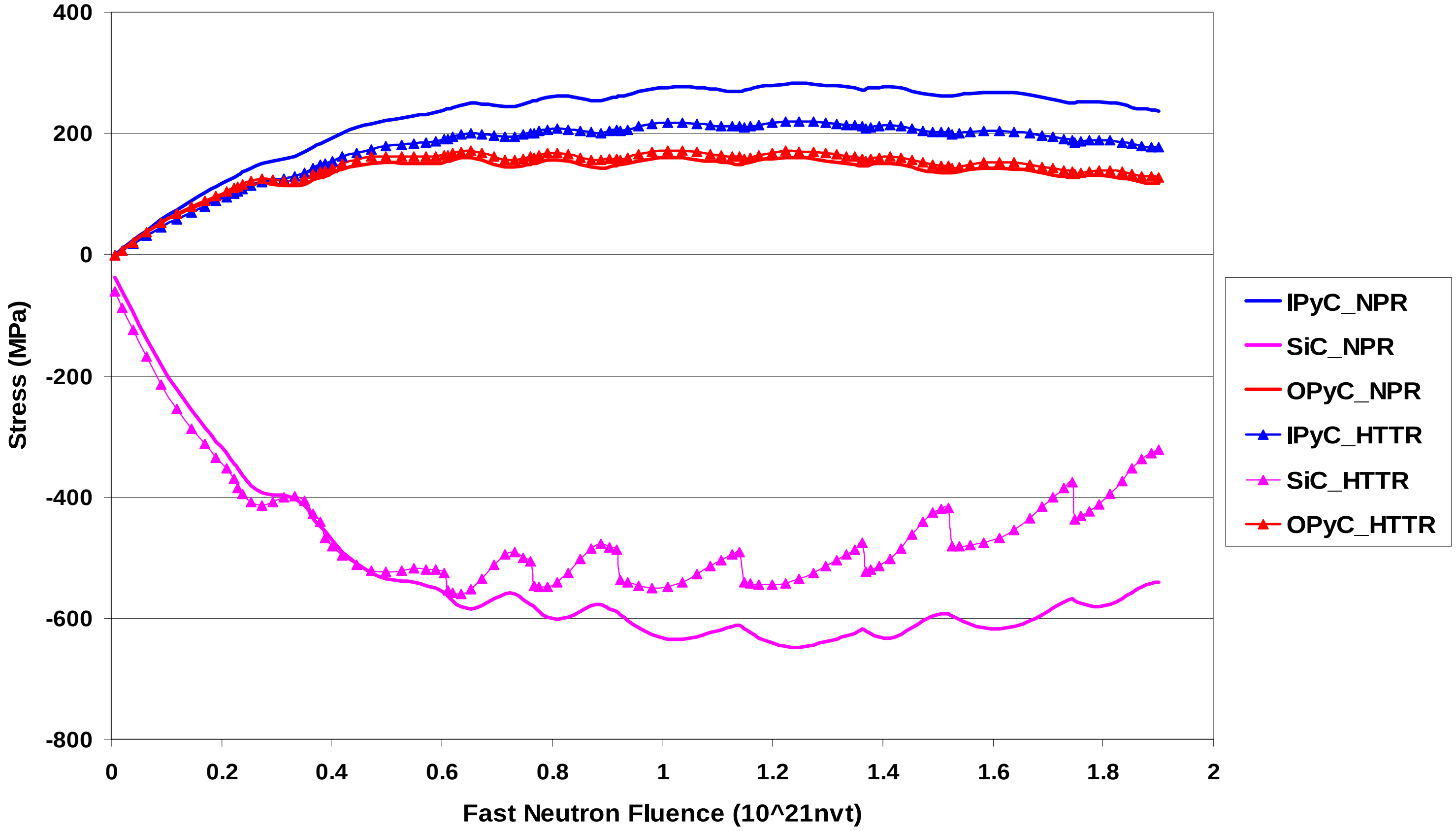
Simulations

	Fuel Type	Kernel Density (g/cm^3)	Kernel Diameter (μm)	Buffer Thickness (μm)	IPyC Thickness (μm)	SiC Thickness (μm)	OPyC Thickness (μm)
NPR	UCO	10.70	195	100	53	35	43
HTTR	UO_2	10.96	600	60	30	25	45

NPR — New Production Reactor (USA)

HTTR — High Temperature Test Reactor (Japan)

Circumferential Stresses in NPR & HTTR Type Fuel



NPR & HTTR Type Fuel Reliability in MPBR Environments

	Cases Sampled	IPyC Failure Probability	OPyC Failure Probability	SiC Failure Probability	Particle Failure Probability
NPR type fuel	1,000,000	27.79%	17.07%	13.30%	13.30%
HTTR type fuel	1,000,000	5.660%	16.22%	0.1017%	0.1017%

All particle failures observed were induced by IPyC cracking

Fuel Design Parameters

Parameter	Design Value	Uncertainty	As-Fabricated Value	Uncertainty
Uranium Enrichment (%)	**96**	**0.1**	**96**	**0.1**
Kernel Density (gm/cm^3)	**10.4**	**0.01**	**10.4**	**0.01**
Kernel Theoretical Density (gm/cm^3)	**10.95**	**-**	**10.95**	**-**
Kernel Diameter (μm)	**500**	**20**	**497**	**14.1**
Buffer Density (g/cm^3)	**1.05**	**0.05**	**1.05**	**0.05**
Buffer Theoretical Density (g/cm^3)	**2.25**	**-**	**2.25**	**-**
Buffer Thickness (μm)	**90**	**18**	**94**	**10.3**
IPyC Initial BAF	**1.05788**	**0.00543**	**1.05788**	**0.00543**
IPyC Density (g/cm^3)	**1.9**	**-**	**1.9**	**-**
IPyC Characteristic Strength (MPa.m^3/Modulus)	**24**	**-**	**24**	**-**
IPyC Weibull Modulus	**9.5**	**-**	**9.5**	**-**
IPyC Thickness (μm)	**40**	**10**	**41**	**4**
OPyC Initial BAF	**1.05788**	**0.00543**	**1.05788**	**0.00543**
OPyC Density (g/cm^3)	**1.9**	**-**	**1.9**	**-**
OPyC Characteristic Strength (MPa.m^3/Modulus)	**24**	**-**	**24**	**-**
OPyC Weibull Modulus	**9.5**	**-**	**9.5**	**-**
OPyC Thickness (μm)	**40**	**10**	**40**	**2.2**
SiC Thickness (μm)	**35**	**4**	**36**	**1.7**
SiC Characteristic Strength (MPa.m^3/Modulus)	**9**	**-**	**9**	**-**
SiC Fracture Toughness (MPa.μm$^{1/2}$)	**3300**	**530.7**	**3300**	**530.7**
SiC Weibull Modulus	**6**	**-**	**6**	**-**

Fuel Performance Model Development Path

Steady State

Initial Steady State Model
- Initial Probabilistic Fracture Mechanics Model
- Simple Chemistry Model

Advanced Steady State Model
- Advanced Fracture Mechanics Model
- Ag Migration & Release Model

Complete Steady State Model
- Detailed Chemical Model
- Detailed Layer Degradation Model

Transient & Accident

Current Development Status

Initial Transient & Accident Model

Complete Transient & Accident Model

Conclusions

- A fuel performance model has been developed which can simulate fuel behavior in Pebble Bed Reactor cores
- Monte Carlo simulations can be performed to account for particle-to-particle variability in fabrication parameters as well as variability in fueling during operation
- Results have been compared with other models and with actual fuel performance.
- Model can be used to optimize fuel particle design

Silver Transport in Silicon Carbide for High-Temperature Gas Reactors

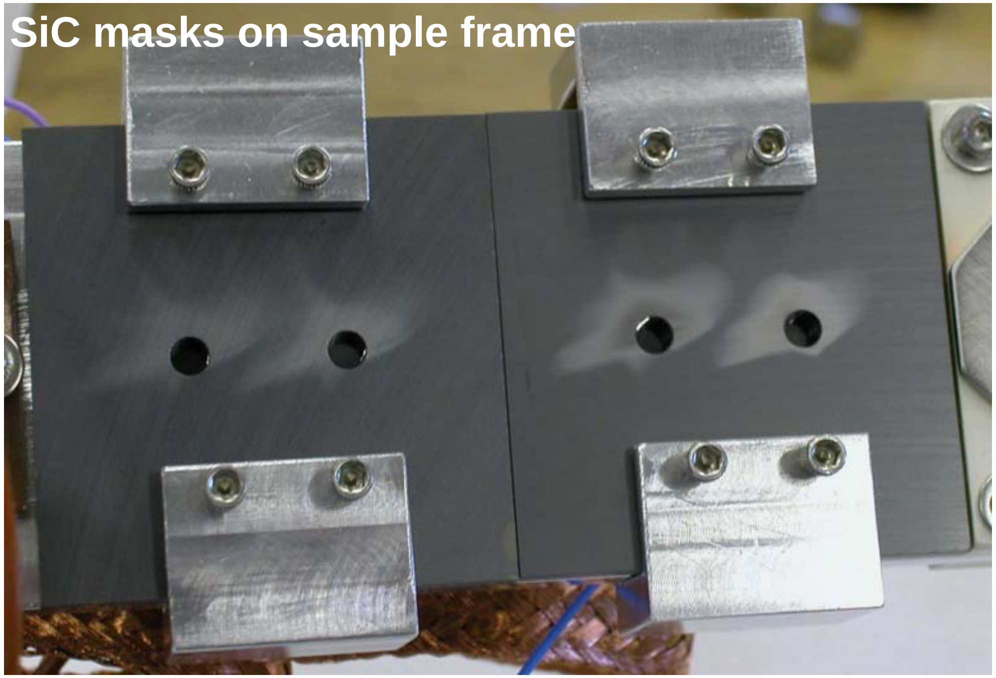
Heather J. MacLean

Professor Ronald Ballinger

Barrier Integrity

- Silver Diffusion observed in tests @ temps
- Experiments Proceeding with Clear Objective - Understand phenomenon
- Focus on Grain SiC Structure Effect

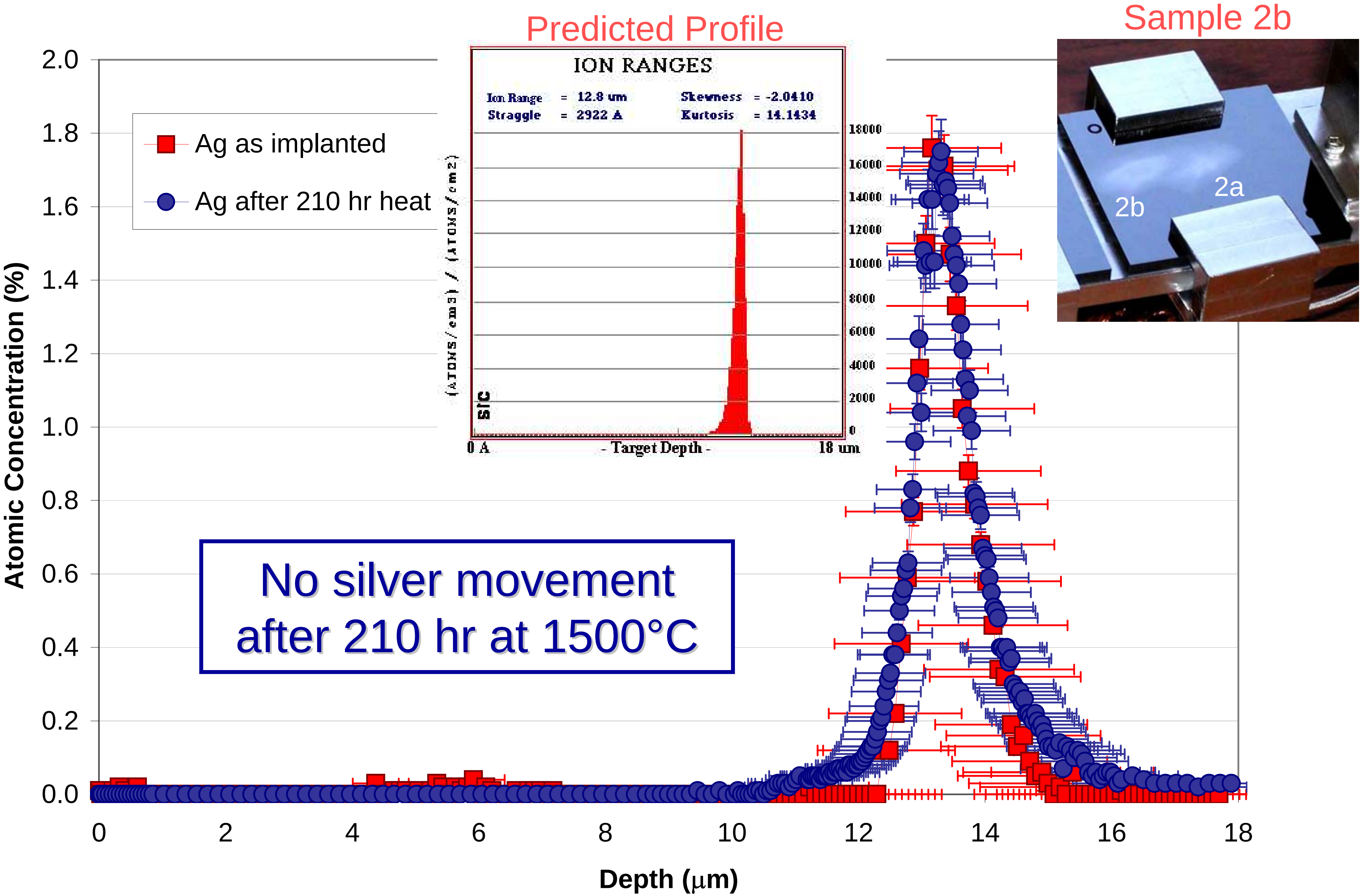
Silver Ion Implantation



- 161 MeV silver beam, peak at 13 µm
- 93 MeV silver beam, peak at 9 µm
- implanted ~10^{17} ions = ~2 atomic % silver
- measure silver concentration profiles
- examine SiC damage

Light transmission through SiC mask and sample

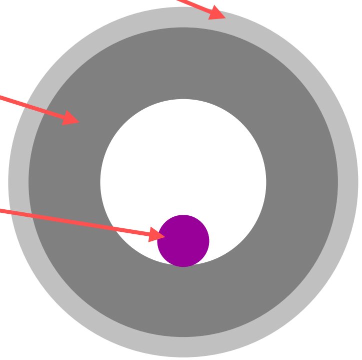
Ion Implantation Silver Depth Profile



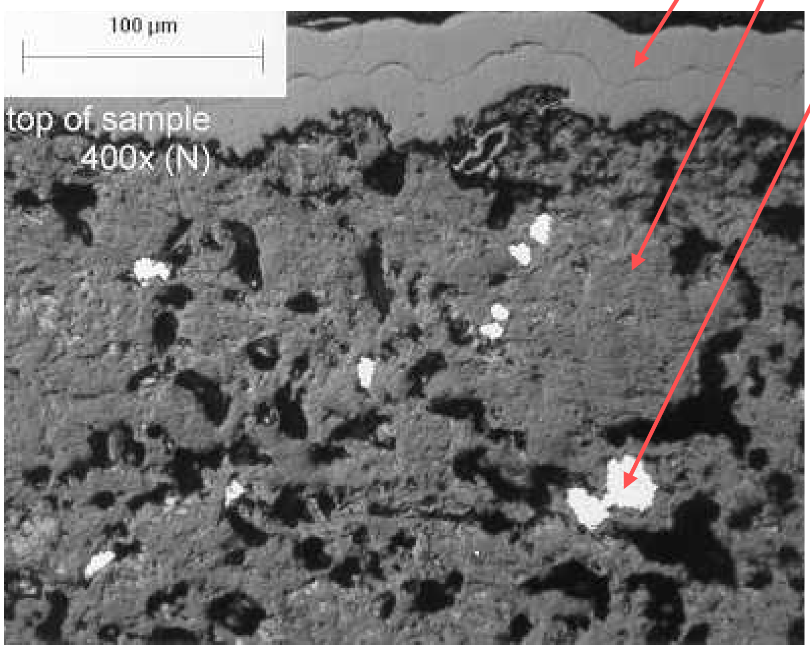
Spherical Diffusion Couple Experiments

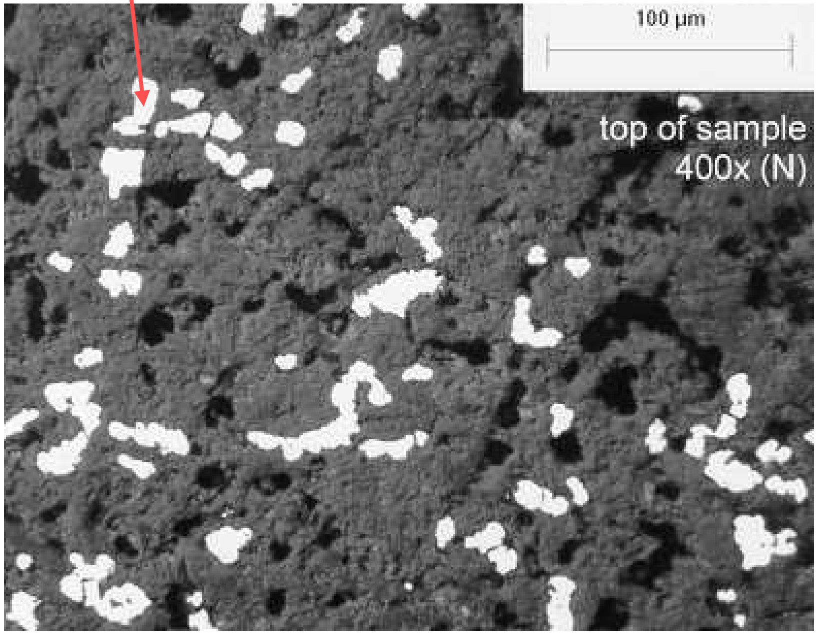
RESULTS

- No silver in SiC depth profiles
- Mass loss after heating
- Leak rates increased after heating



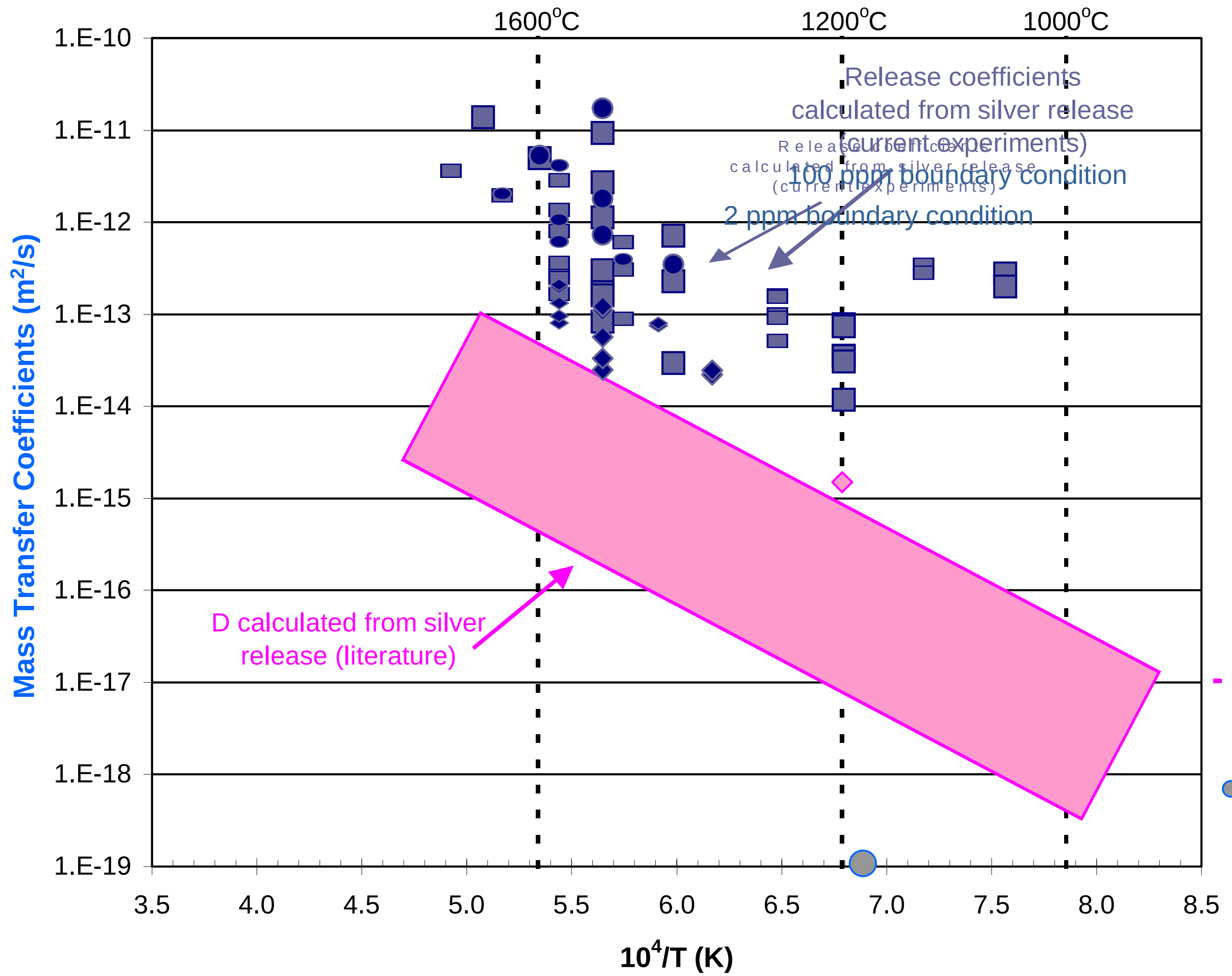
Diffusion couple
(cross-section)

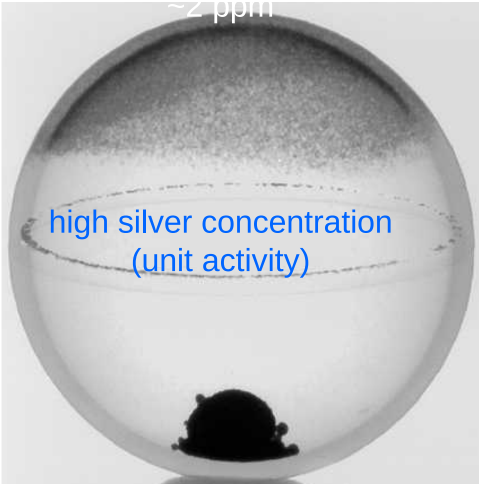




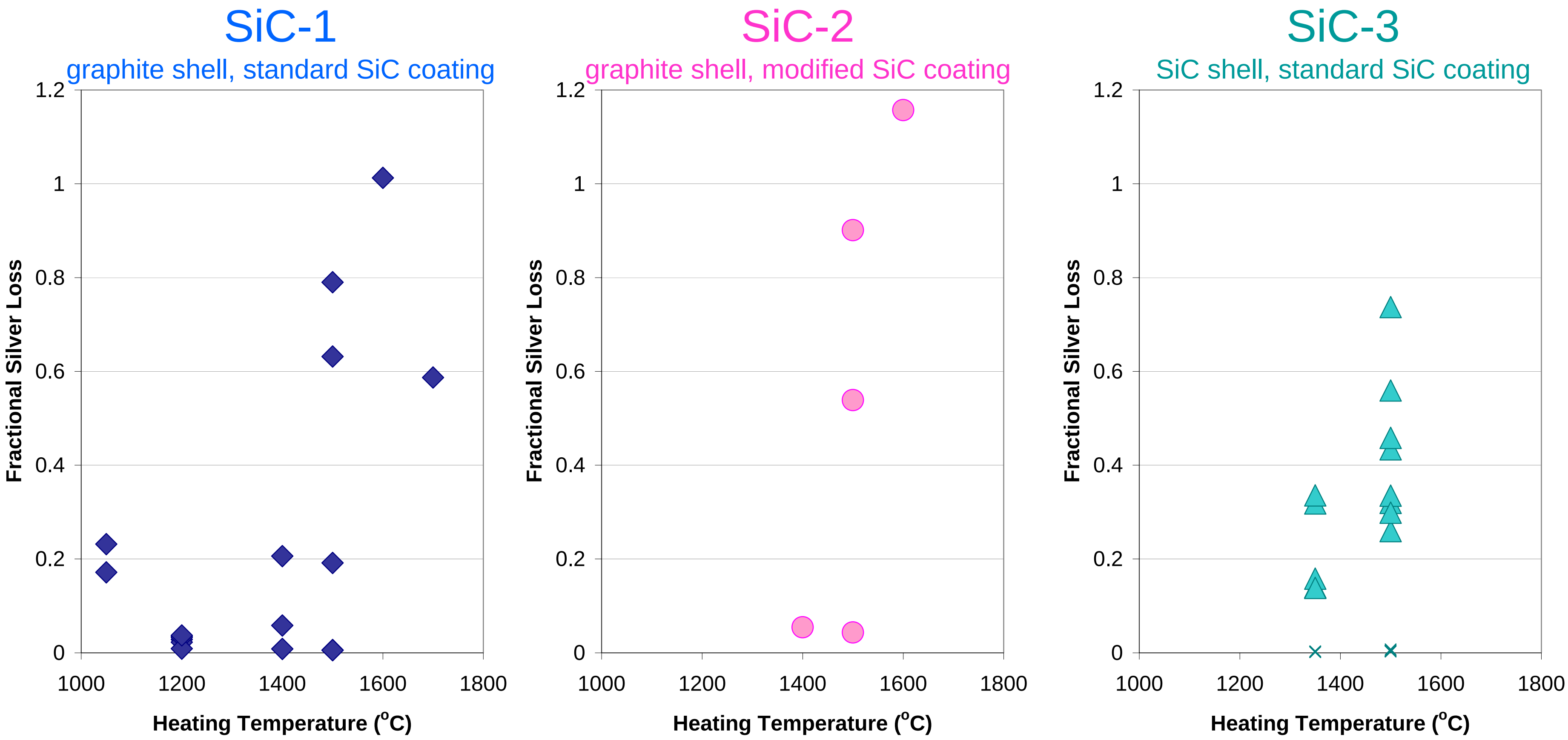
optical microscopy from top of graphite-SiC diffusion couple

Calculated Silver Diffusion (from release)





Silver Mass Loss



(normalized to seam area)

Possible Nano-Cracking

- Nanometer-sized features (cracks) observed in experimental SiC coating in AFM (atomic force microscopy)
- Mechanical pathway
- Origin not yet known
- Stresses from differential thermal expansion between individual SiC grains may cause nano-scale cracks
- May be aggravated by thermal cycling
- Consistent with fuel performance discussions at ORNL

Conclusions

- Silver does not diffuse through intact, fine-grained SiC
  - no change in silver concentration profiles
  - no silver movement despite increased grain boundary area
- Vapor migration governs silver release from CVD SiC coatings
  - mass release observed, but silver profiles not found
  - increased leak rates indicate mechanical cracks
- Transport model will compare proposed mechanisms with literature data
- Continued SiC development needs to focus on identifying and eliminating crack path

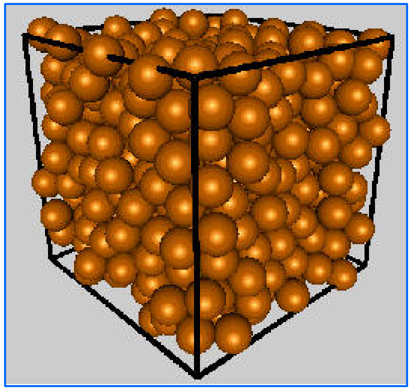
Core Physics

- Basic tool Very Special Old Programs (VSOP)
- Developing MNCP Modeling Process
- Tested Against HTR-10 Benchmark
- Tested Against ASTRA Tests with South African Fuel and Annular Core

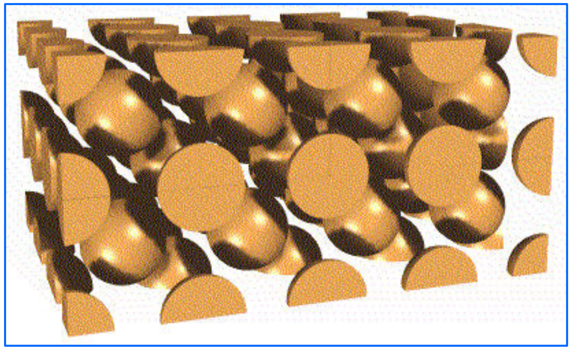
Modeling Considerations

Packing of Spheres

- Spheres dropped into a cylinder pack randomly
- Packing fraction ~ 0.61
- Repeated-geometry feature in MCNP4B requires use of a regular lattice
- SC, BCC, FCC or HCP?
- BCC/BCT works well for loose sphere packing

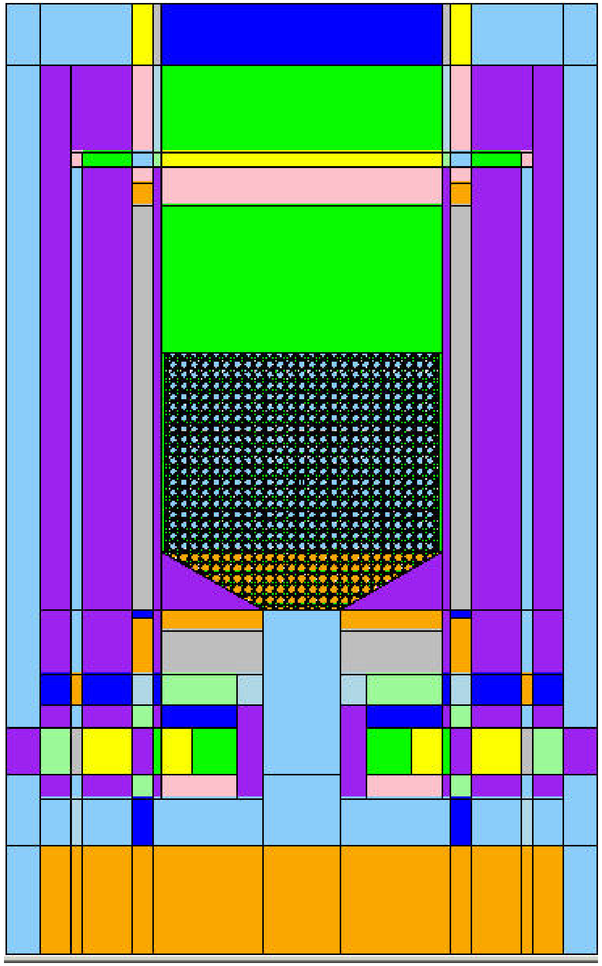


Random Close Packed

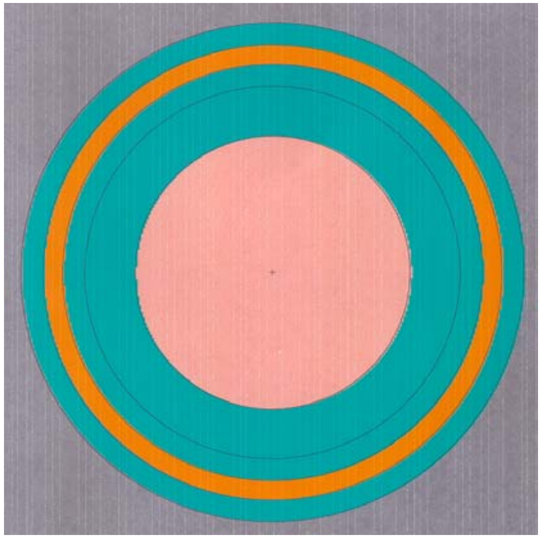


Body Centered Cubic

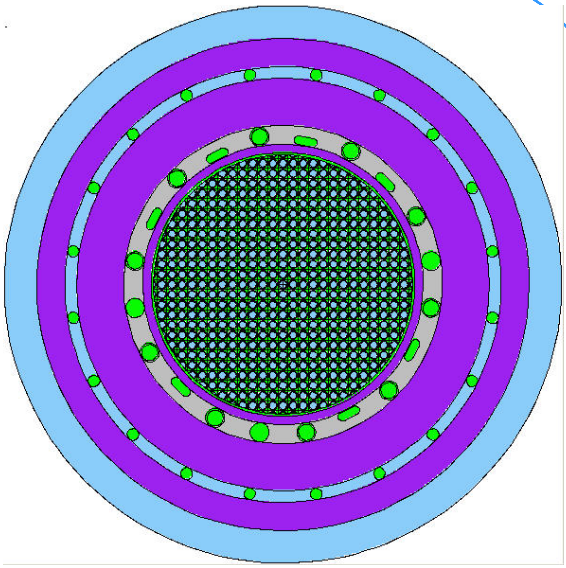
HTR-10
MCNP4B Model



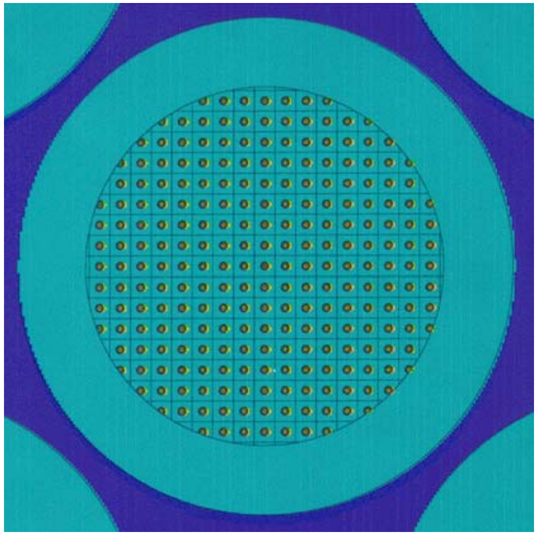
Reactor



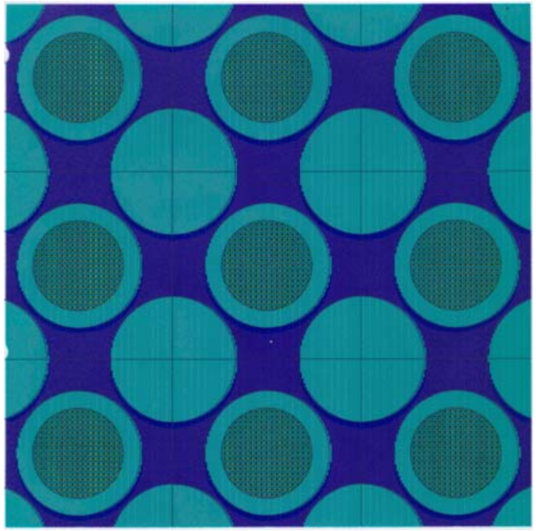
TRISO fuel particle



Core

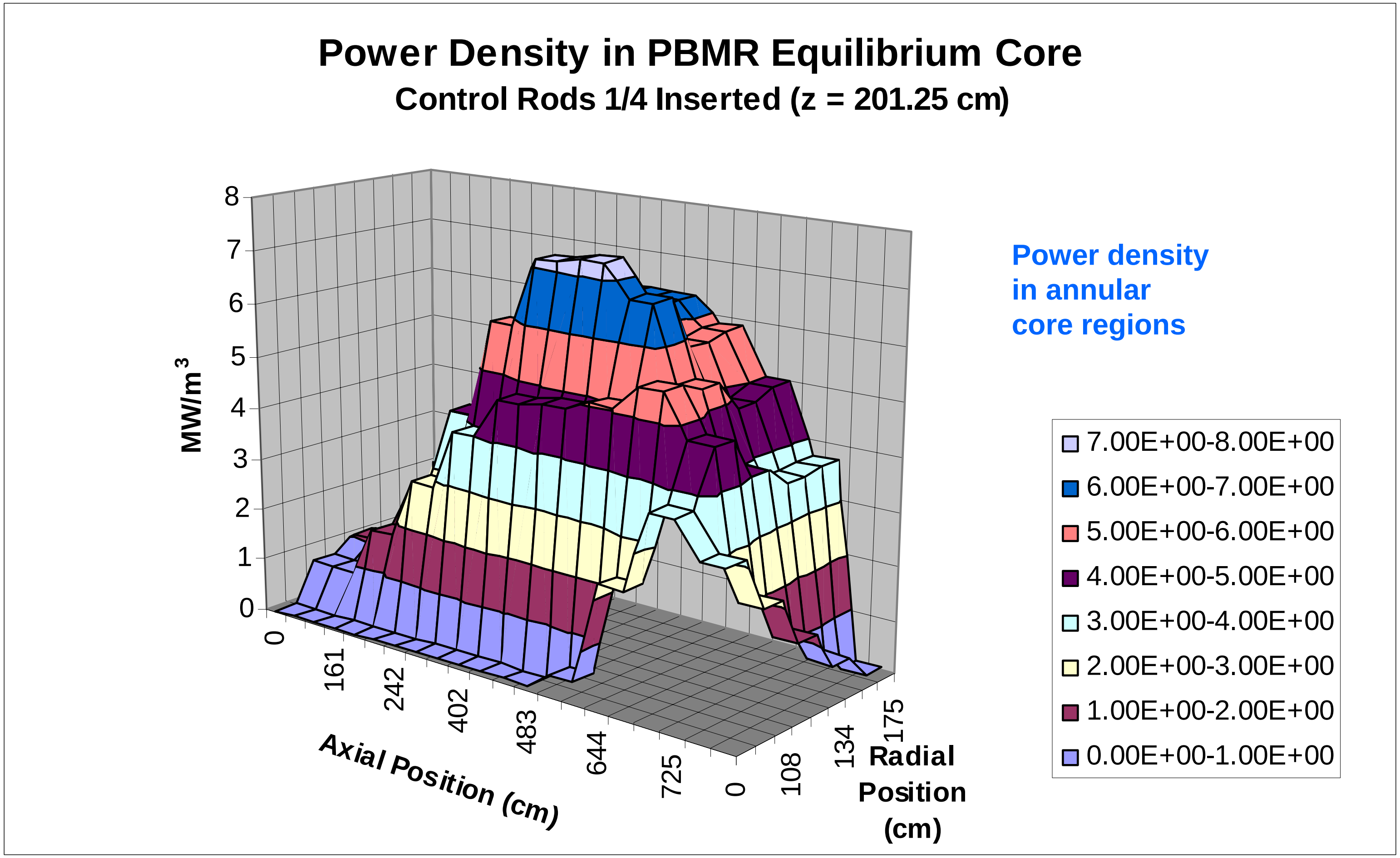


Fuel sphere



Core lattice

MCNP4B/VSOP Model Output



ASTRA Critical Experiments

- Kurchatov Institute, Moscow
- Mockup of PBMR annular core

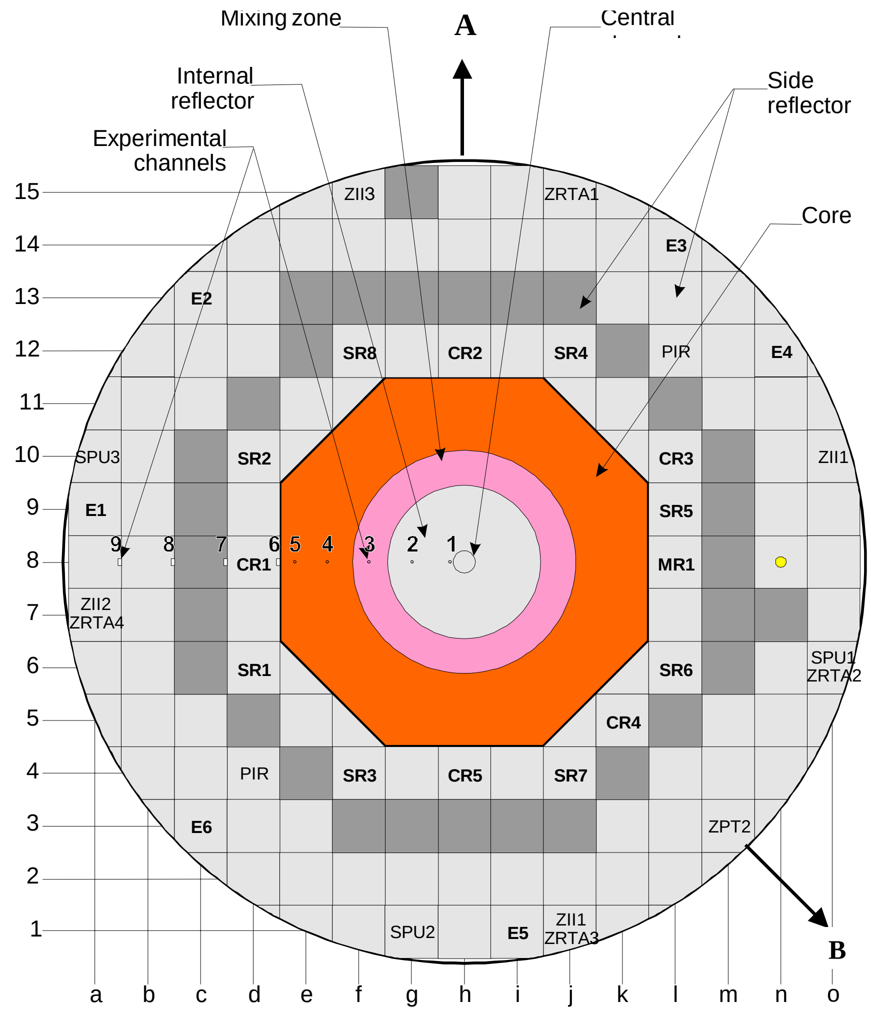
Inner reflector: graphite spheres (M)
10.5 cm ID
72.5 cm OD

Mixed zone: 50/47.5/2.5 (M/F/A)
105.5 cm OD

Fuel zone: 95/5 (F/A)
181 cm OD (equiv.)

Core height: 268.9 cm

- packing fraction = 0.64
- 2.44 g U/FS, 21% U235, 0.1 g B/AS
- 5 CRs, 8 SRs, 1 MR
- CR = 15 s/s tubes with B4C powder
- 6 in-core experimental tubes



CR - Control
MR1 - Manual control
SR - Safety
E1-E6 - Experimental chambers
1-9 - Experimental channels for
PIR,ZPT,ZII,ZRTA - Ionization chambers and neutron
Neutron source channel

ASTRA Conclusions

- Criticality Predictions fairly close (k_{eff} = .99977)
- Rod Worth Predictions off 10%
- Analysis Raises Issues of Coupling of Core

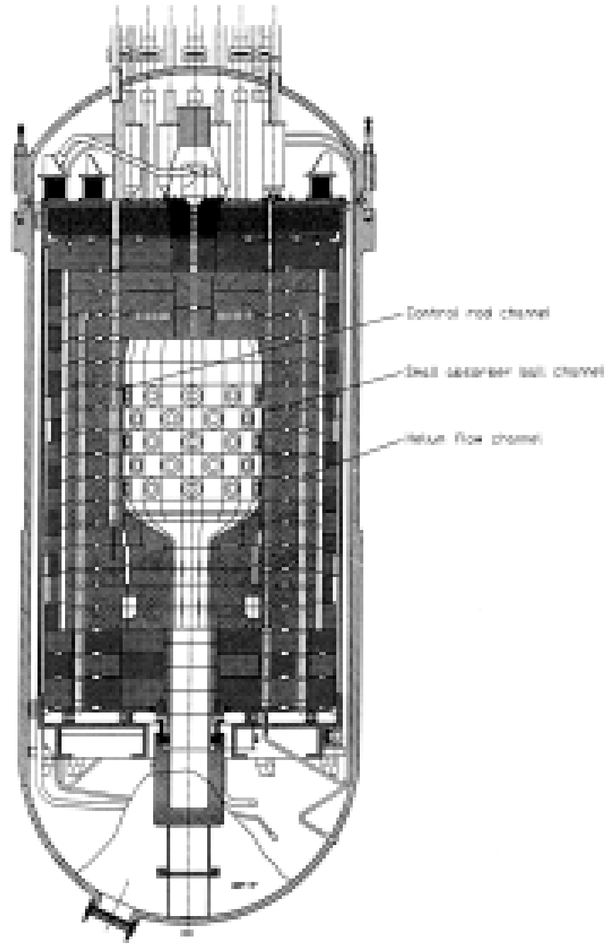
HTR-10 (*Beijing*)

10 MW Pebble Bed Reactor:

- Graphite reflector
- Core: R_c = 90 cm, H ≤ 197 cm
- TRISO fuel with 5 g U/Fuel Sphere
- 17% U235
- F/M *sphere* ratio = 57:43, modeled by reducing moderator sphere size
- Initial criticality December 2000

MCNP4B Results

K-eff	1.00081±0.00086
Critical Height	128.5 cm
Calculated Loading	16,830
Actual Loading	16,890



Safety

Tieliang Zhai
Prof. Hee Cheon No (Korea)
Professor Andrew Kadak

Safety Issues

- Loss of Coolant Accident
- Air Ingress
- Reactor Cavity Heat Removal

Safety

- LOCA Analysis Complete - *No Meltdown*
- Air Ingress to study fundamental processes and benchmark Computational Fluid Dynamics Codes

  - Conservative analysis show no “flame”

  - Address Chimney effect

  - Address Safety of Fuel < 1600 C

  - Use Fluent for detailed modeling of RV

Advanced Reactor Technology Pebble Bed Project

Figure 1: The Figure of the Model

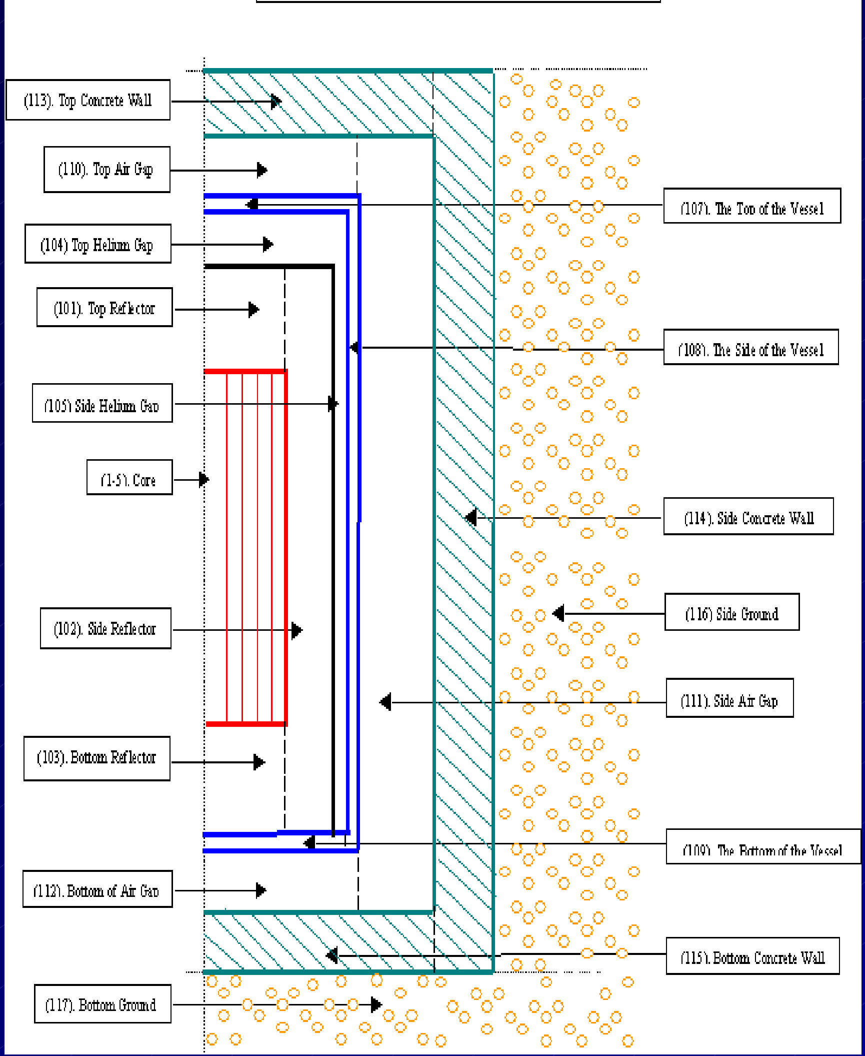
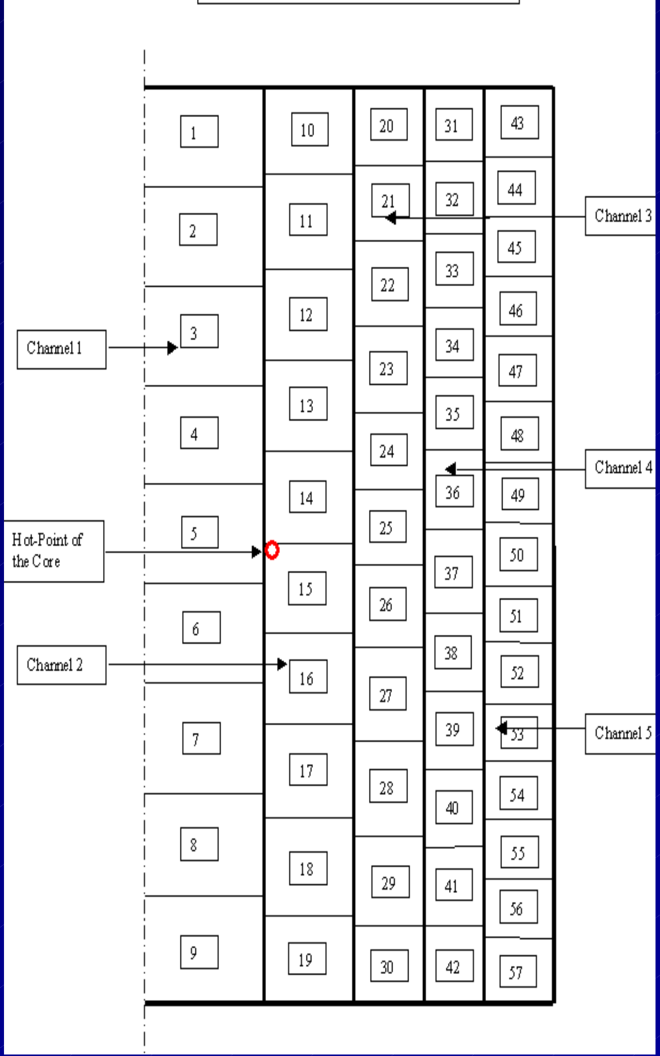
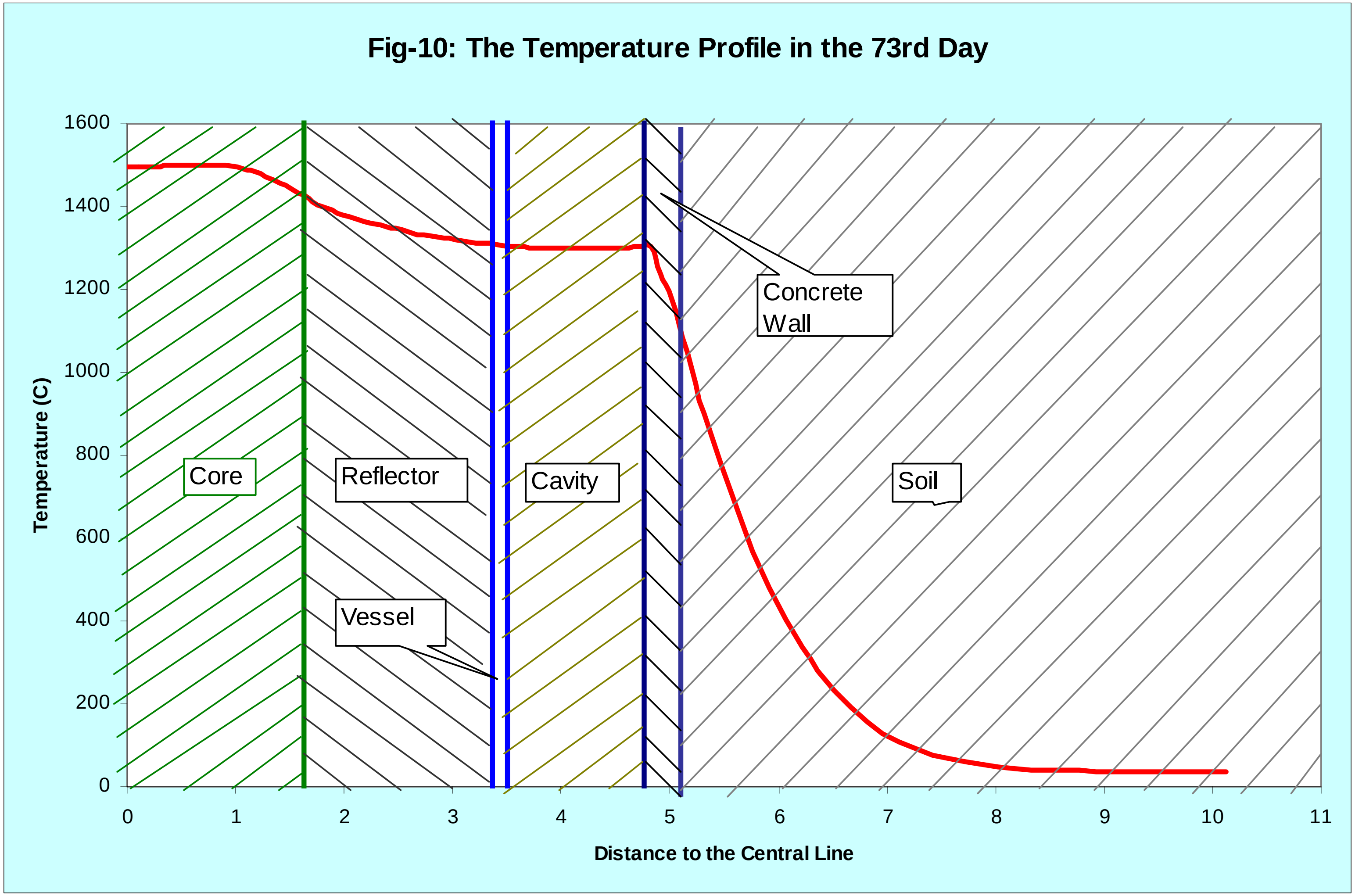


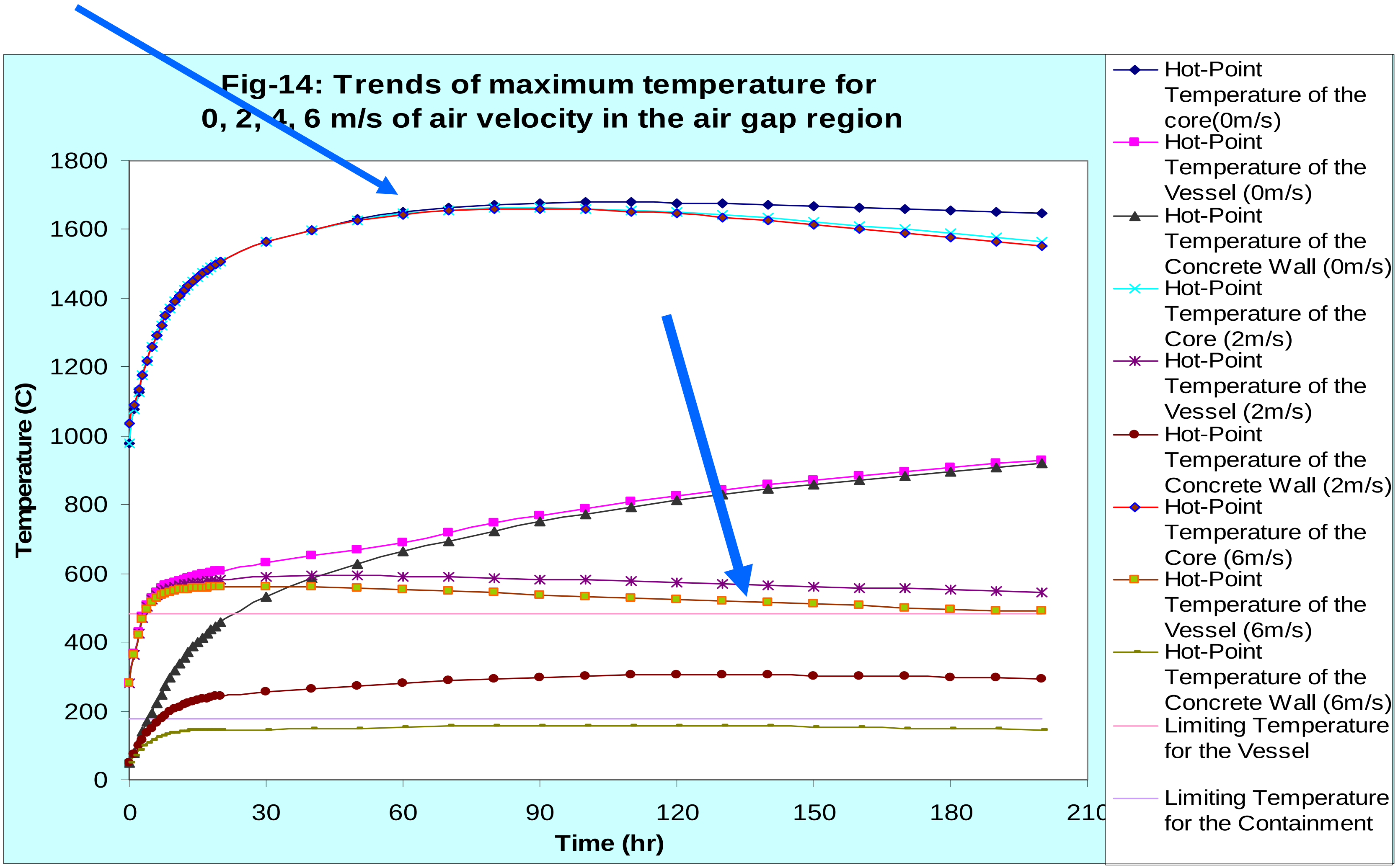
Fig-2: The Geometry of the Core



Temperature Profile

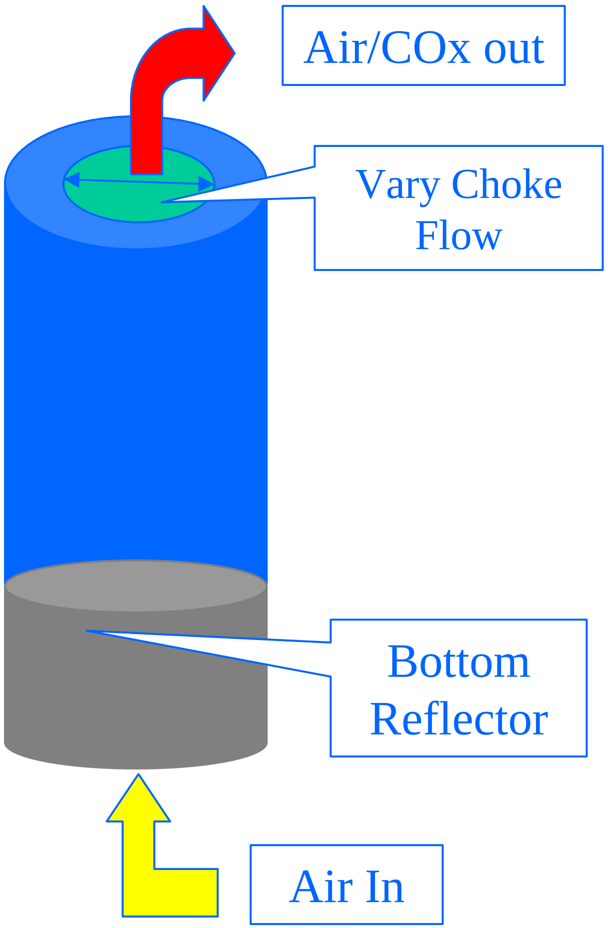


The Prediction of the Air Velocity
(By Dr. H. C. No)

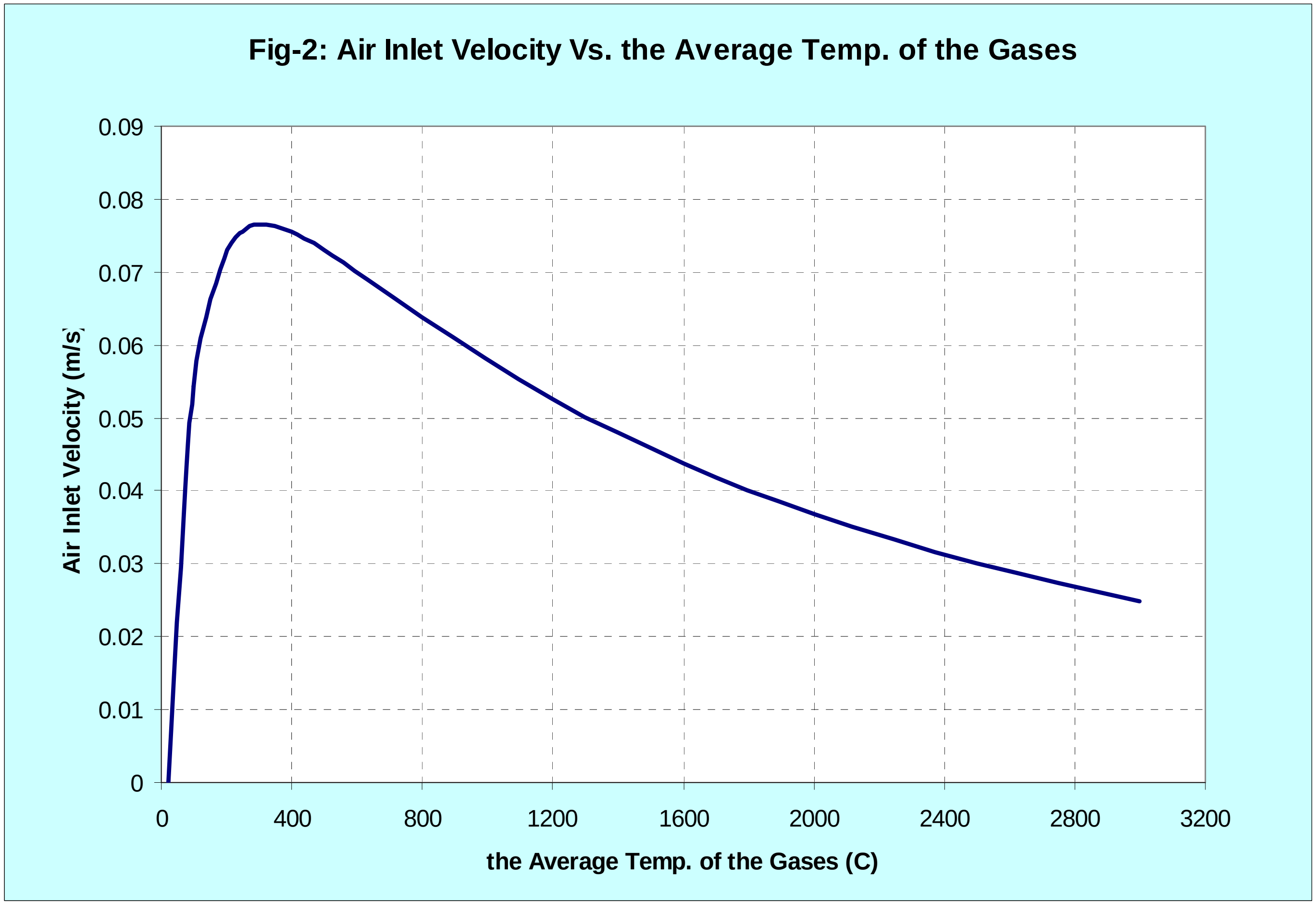


Air Ingress

- **Most severe accidents among PBMR's conceivable accidents with a low occurrence frequency.**
- **Challenges: Complex geometry, Natural Convection, Diffusion, Chemical Reactions**



Air Ingress Velocity f(temperature)

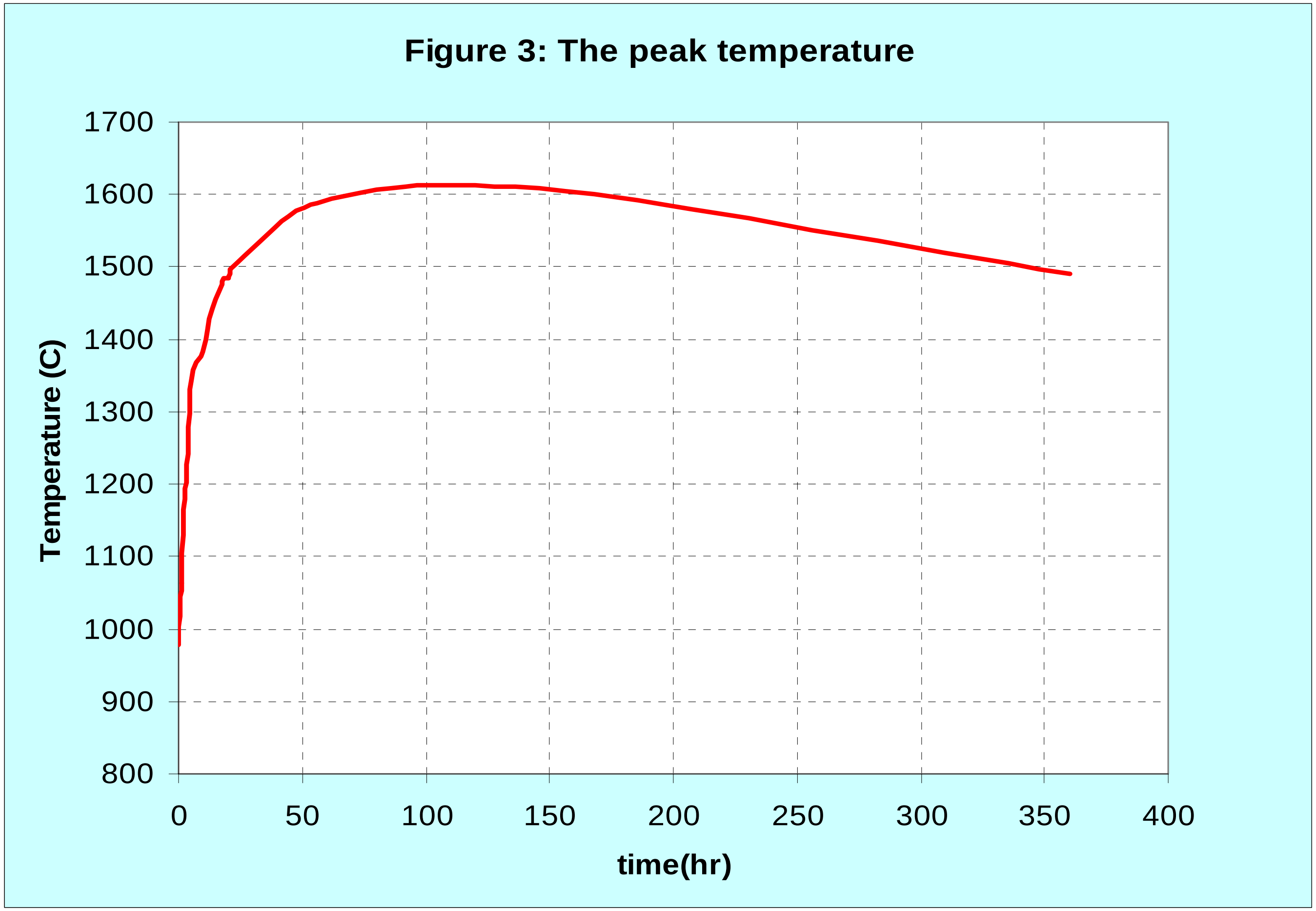


Preliminary Conclusions
Air Ingress

For an open cylinder of pebbles:

- Due to the very high resistance through the pebble bed, the inlet air velocity will not exceed 0.08 m/s.
- The negative feedback: the Air inlet velocity is not always increase when the core is heated up. It reaches its peak value at 300 °C.
- Preliminary combined chemical and chimney effect analysis completed - peak temperatures about 1670 C.

Simplified HEATING7 Open Cylinder Analysis Peak Temperature



Analysis Results

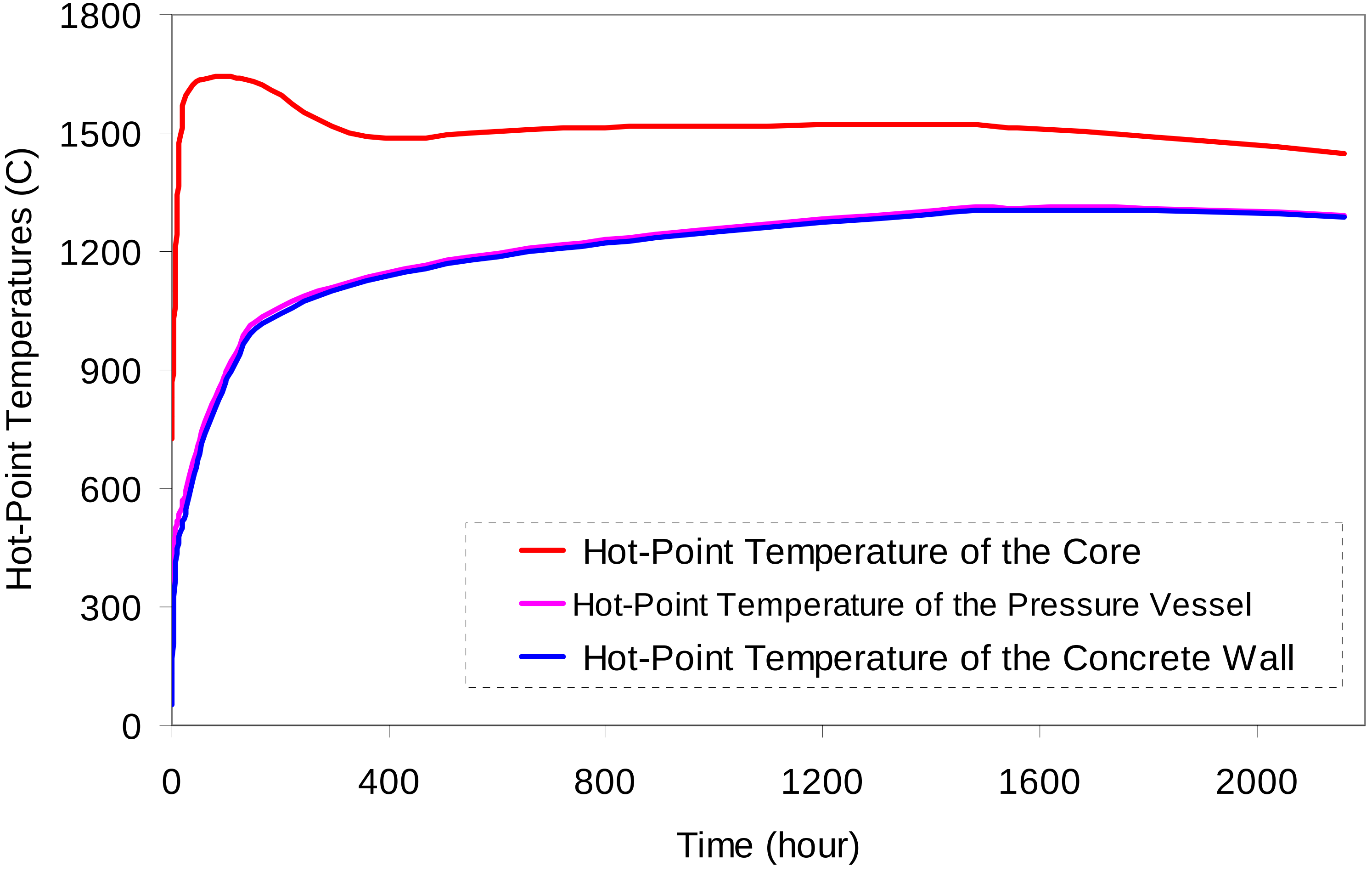


Figure 9: Hot-Point Temperatures

Sensitivity Analysis - Emissivity

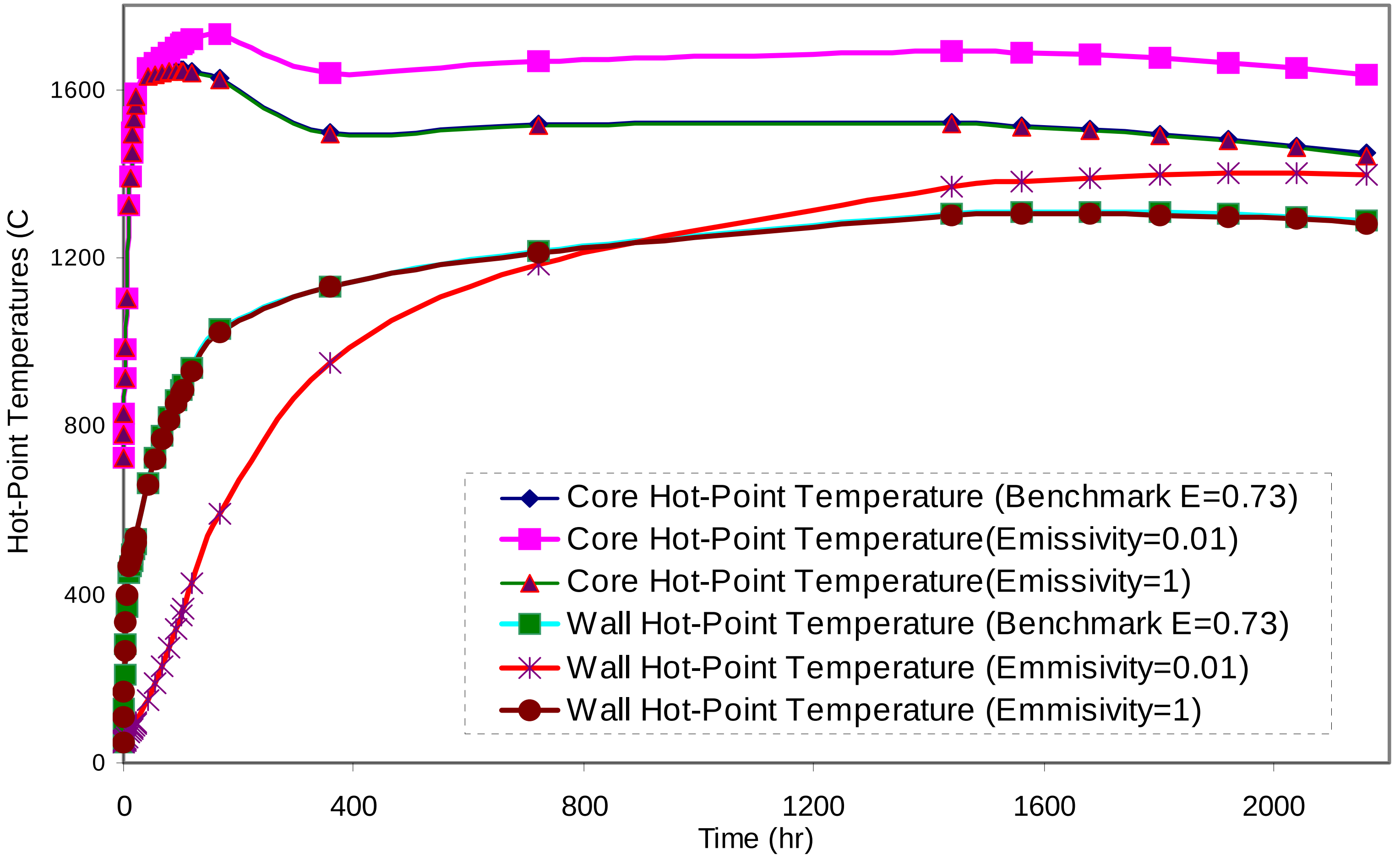


Figure 11: Hot-Point Temperature Sensitivity to Emissivities of Vessel and Concrete Wall in the LOCA Analysis

Sensitivity Analysis-Conductivity

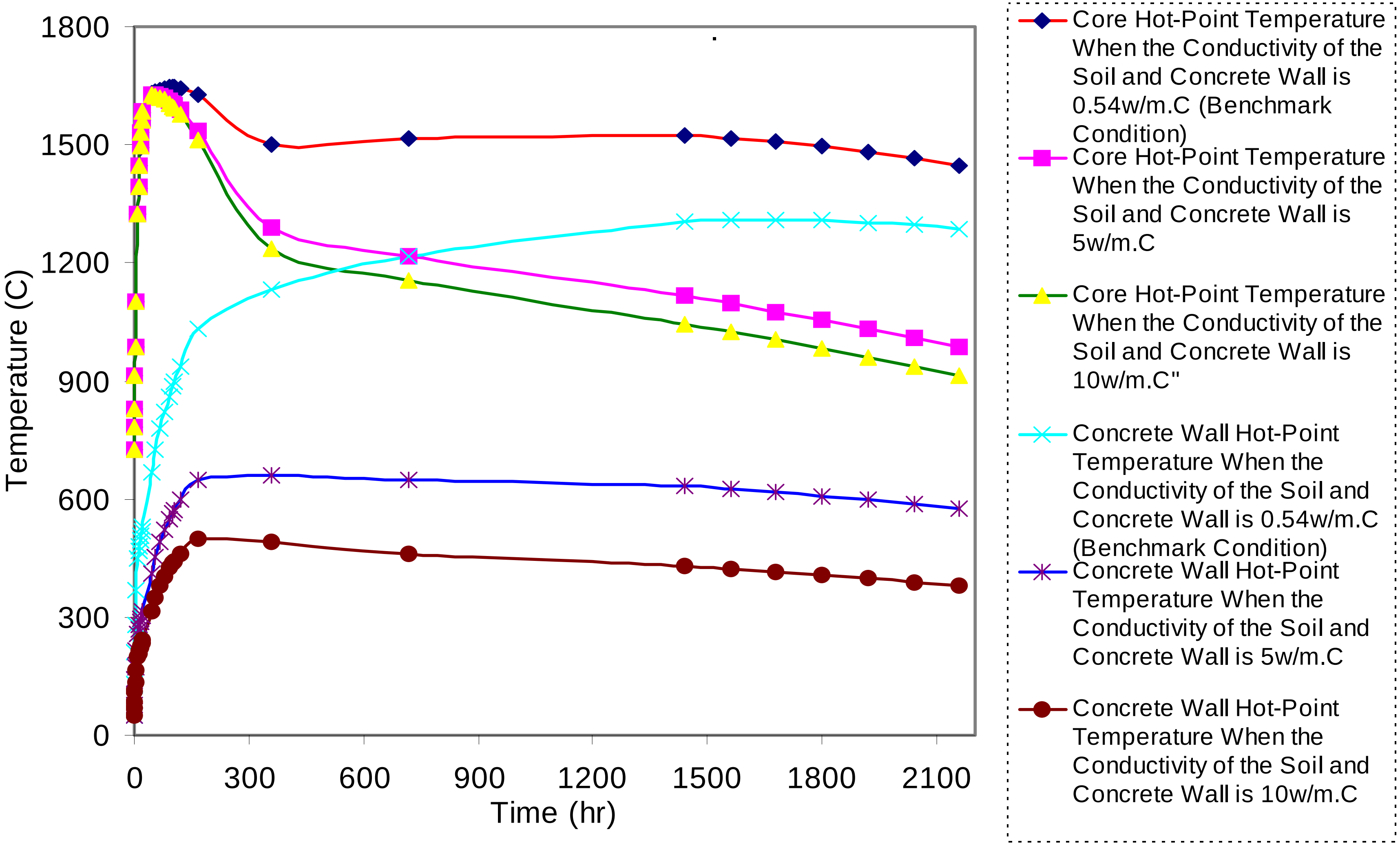


Figure 12: Hot-Point Temperature Sensitivity to the Conductivity of Soil and Concrete Wall in the LOCA Analysis

Conclusions for LOCA Analysis

- No meltdown occurs
- The temperatures of the concrete wall and the steel pressure vessel are above their safety limit

Explain this somewhere

- The safety objectives can not been satisfied by the improvement of the thermal properties
- A convective term, natural or forced, is needed to cool the concrete wall and the pressure vessel

Air Ingress Analysis
Computational Fluid Dynamics

- Benchmark to Japanese Diffusion, Thermal and Multi-Component Tests
- Benchmark to NACOK air ingress tests
- Use FLUENT CFD code to develop methodology

Experimental Apparatus - Japanese

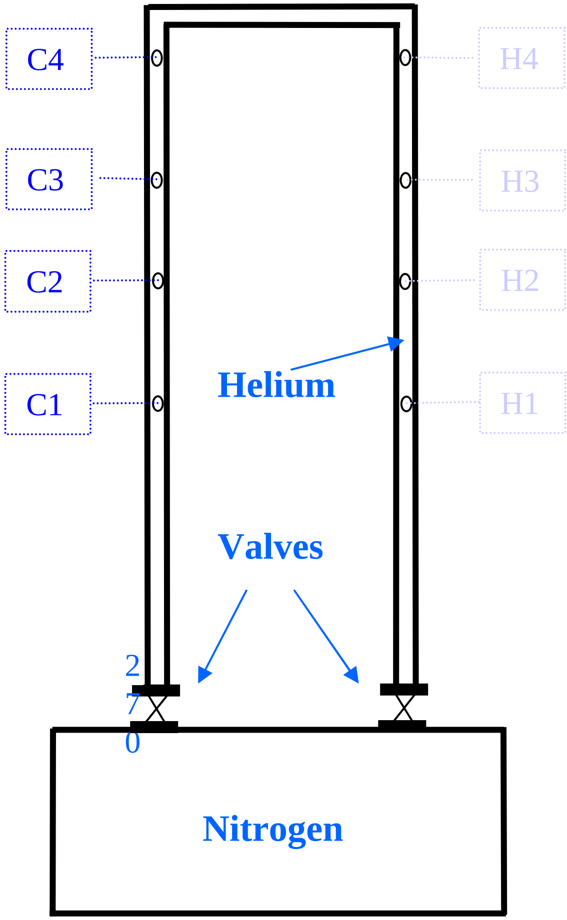


Figure 16: Apparatus for Isothermal and Non-Isothermal experiments

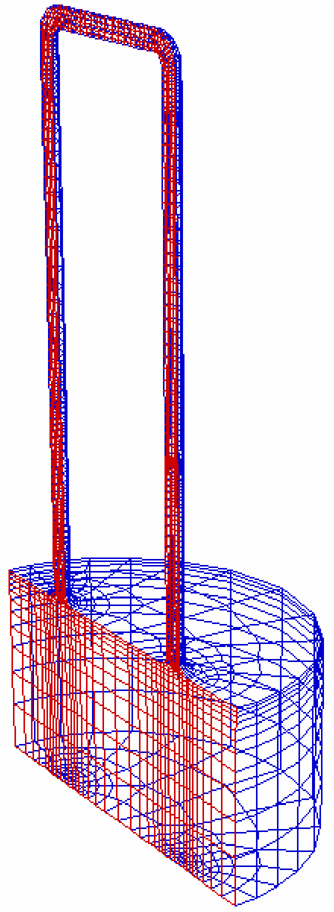


Figure 17: Structured mesh

Isothermal Experiment

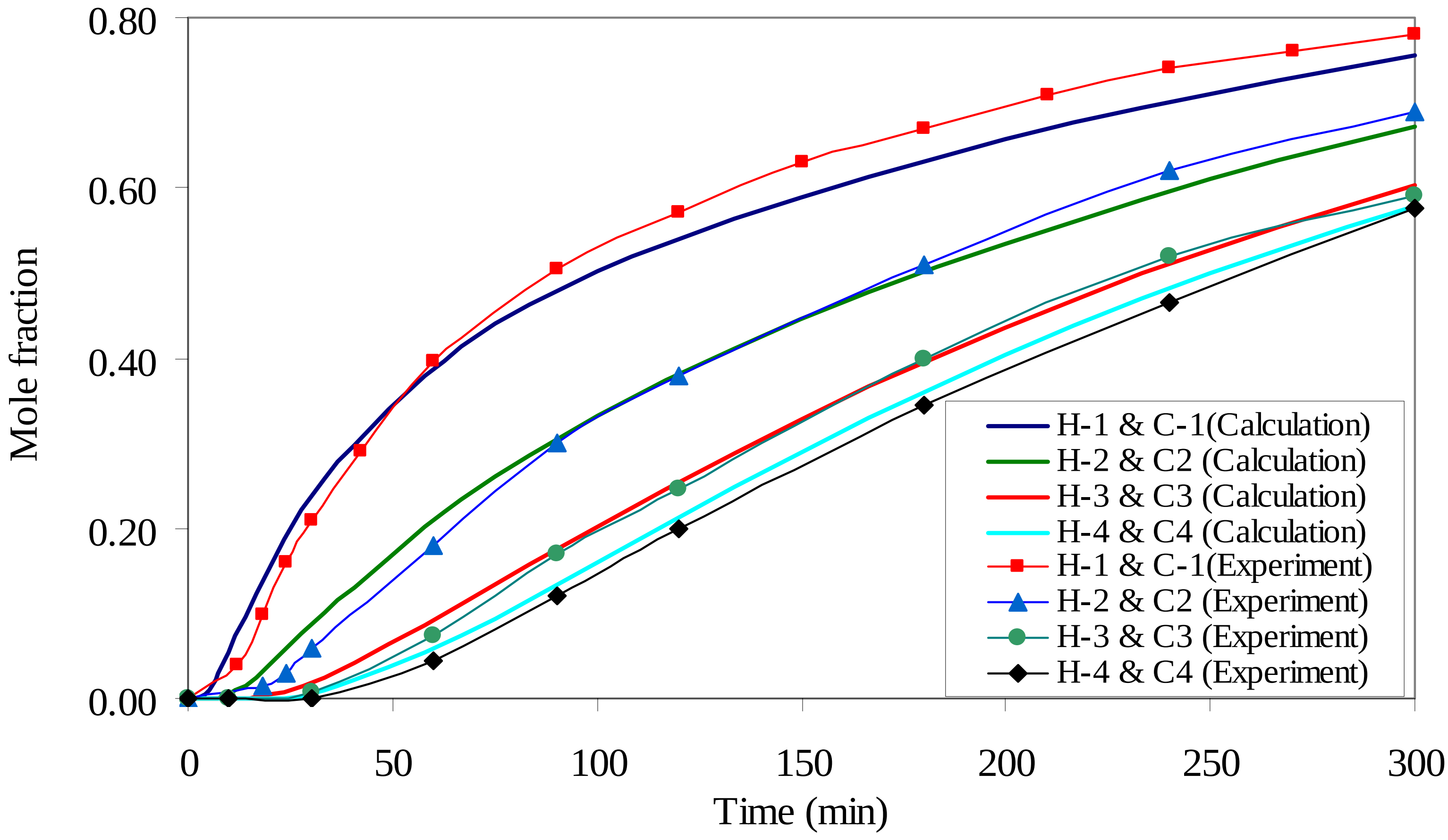


Figure 18: Mole fraction of N_2 for the isothermal experiment

Thermal Experiment

- Pure Helium in top pipe, pure Nitrogen in the bottom tank
- N_2 Mole fractions are monitored in 8 points
- Hot leg heated
- Diffusion Coefficients as a function of temperature

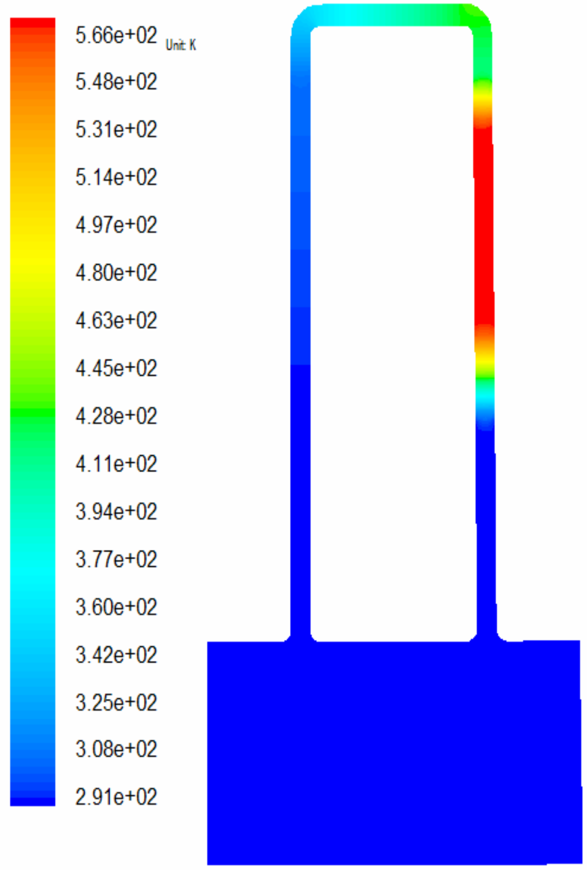


Figure 19: The contour of the temperature bound4ary condition

Thermal Experiment

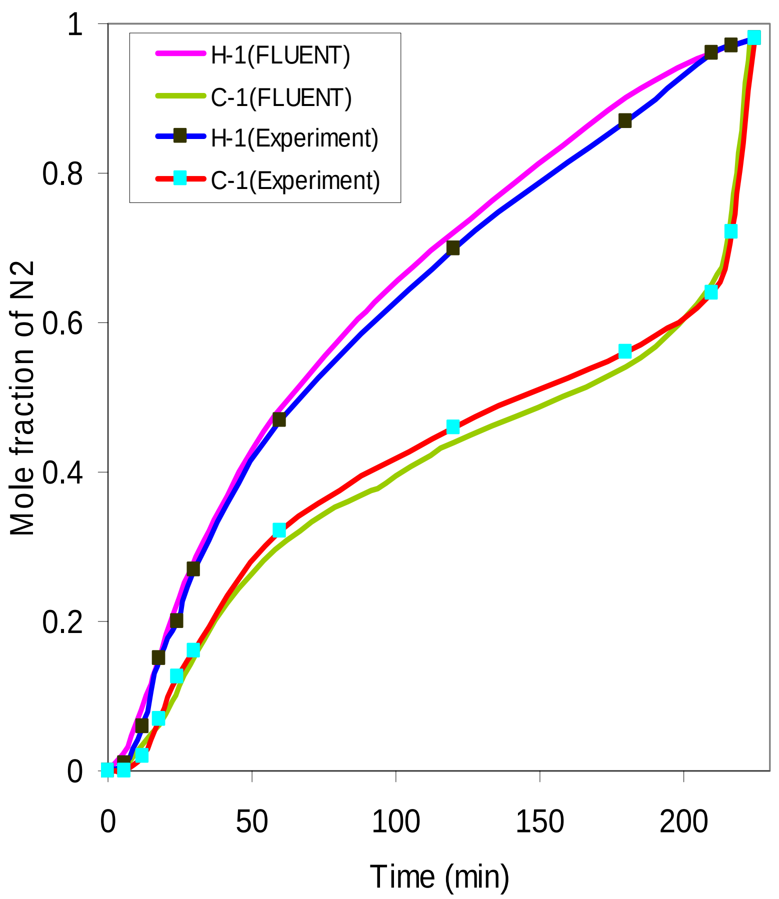


Figure 20: Comparison of mole fraction of N_2 at Positions H-1 and C-1

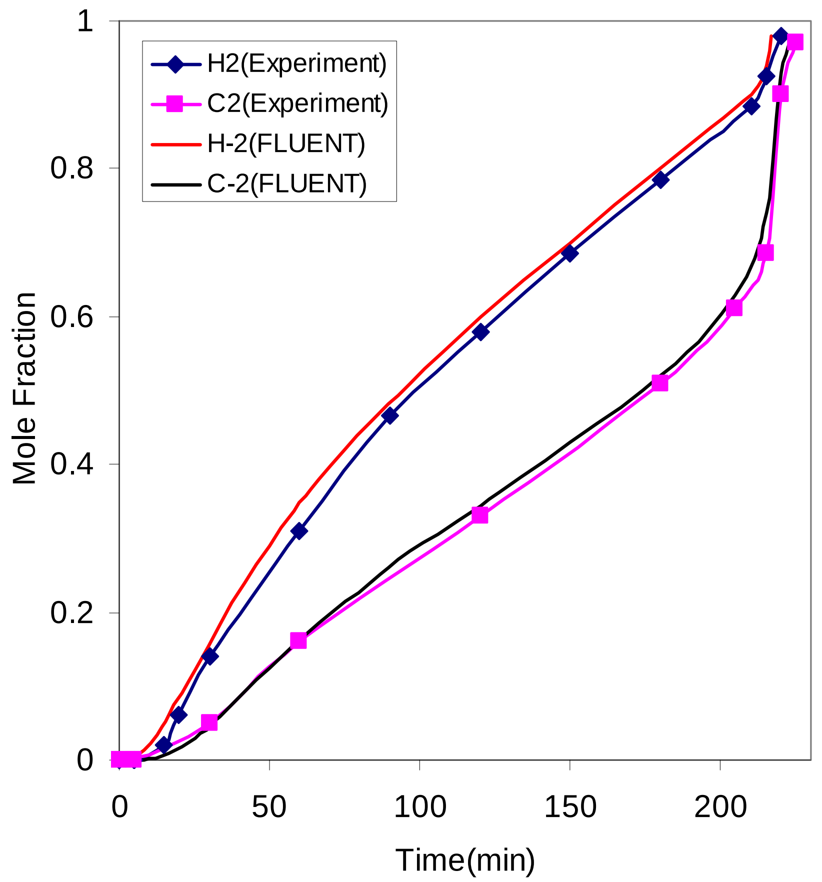


Figure 21: Comparison of mole fraction of N_2 at Positions H-2 and C-2

Thermal Experiment (Cont.)

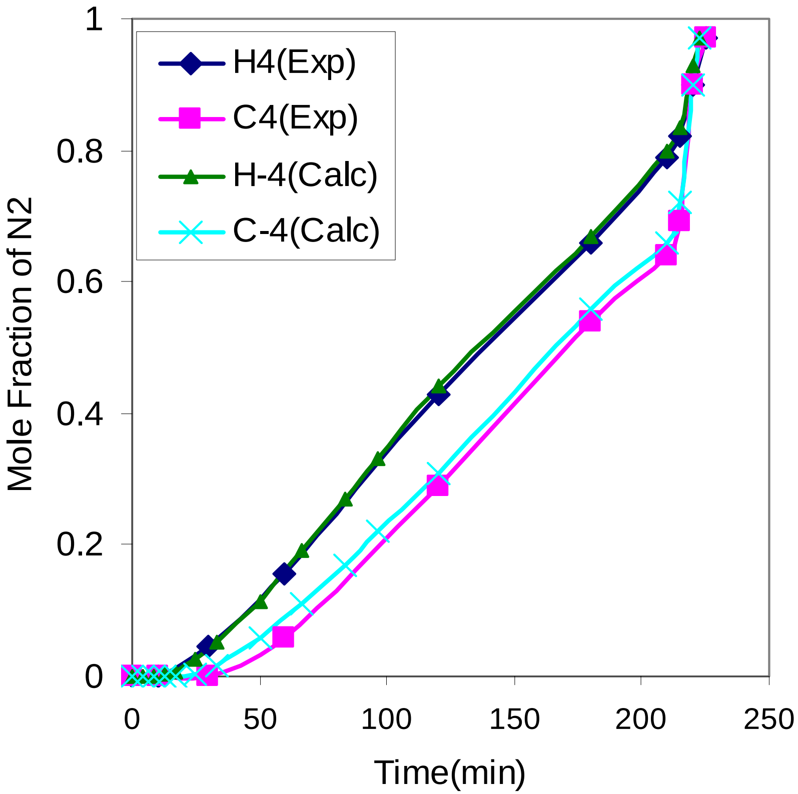


Figure 22: Comparison of mole fraction of N_2 at Positions H-1 and C-1

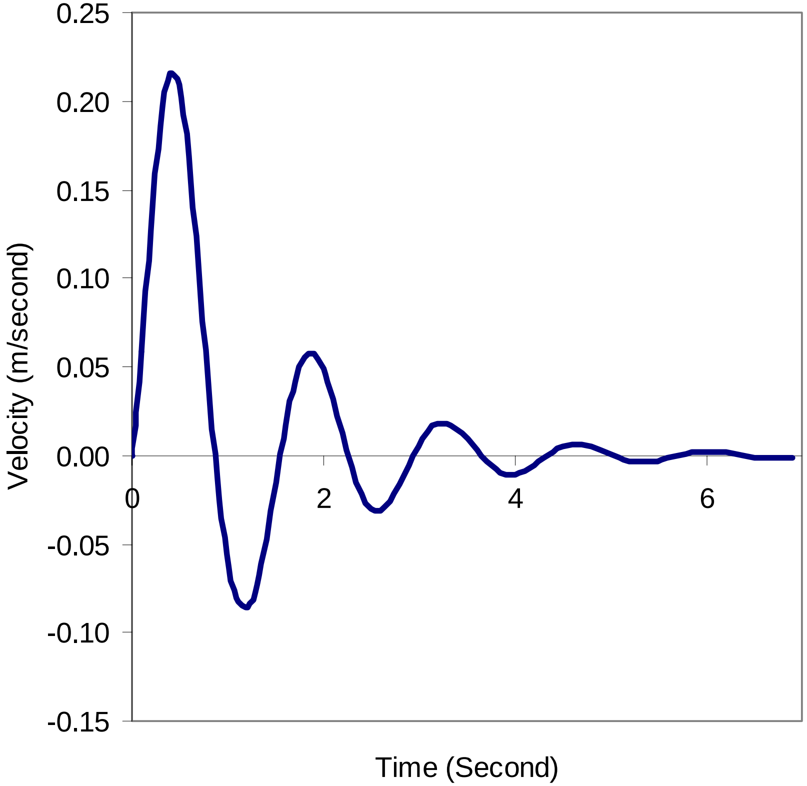


Figure 23: The vibration after the opening of the valves.

Multi-Component Experiment(Cont.)

- Chemical Reactions
  - 1 surface reaction:

    $C + O_2 = x\,CO + y\,CO_2$ (+ Heat)

$$r_{c-o} = K_0 \exp(-\frac{E_0}{RT})\, p_{o_2}^n$$

  - 2 volume Reactions:

    $2\,CO + O_2 = 2CO_2$ (+ Heat)

    $2\,CO_2 = 2\,CO + O_2$ (- Heat)

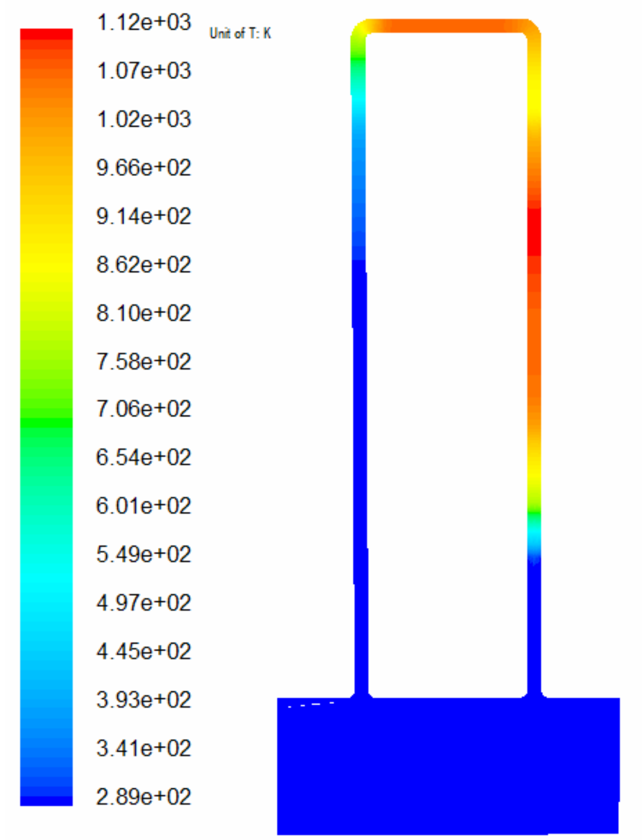


Figure 35: The temperature boundary conditions for the multi-component experiment

Multi-Component Experiment(Cont.)

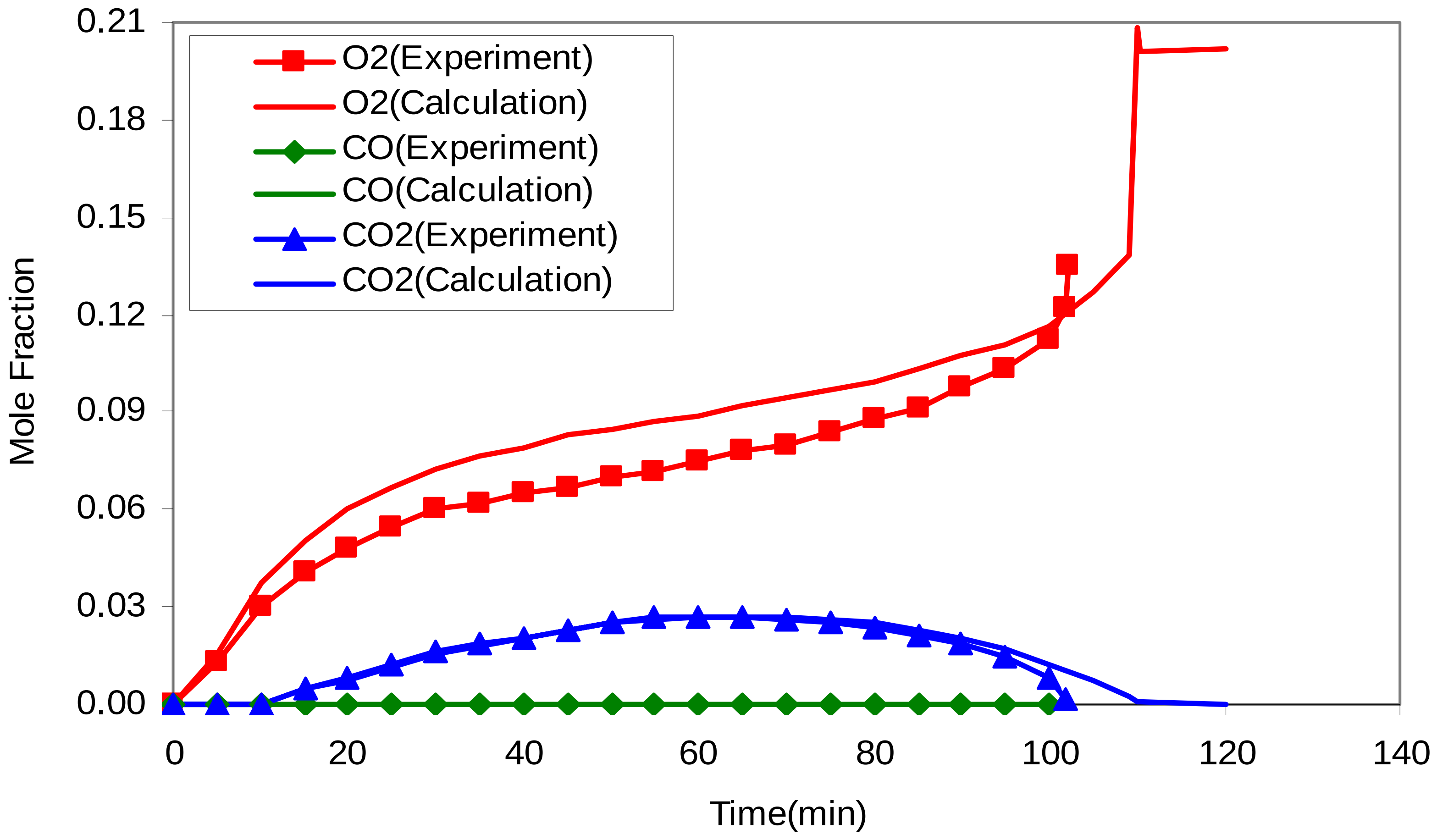


Figure 36: Mole Fraction at Point-1 (80% Diffusion Coff.)

Multi-Component Experiment(Cont.)

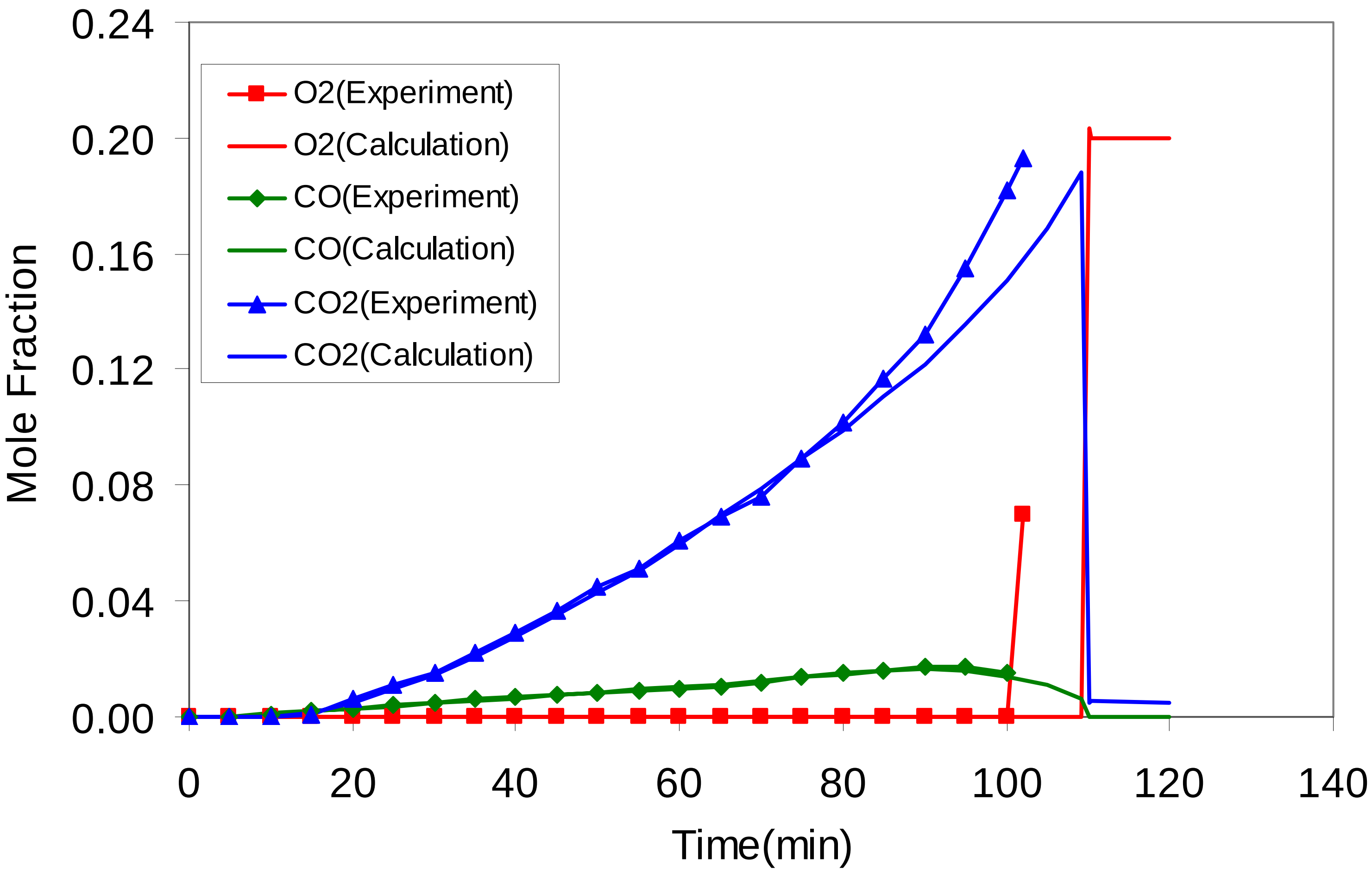


Figure 37: Mole Fraction at Point-3

Multi-Component

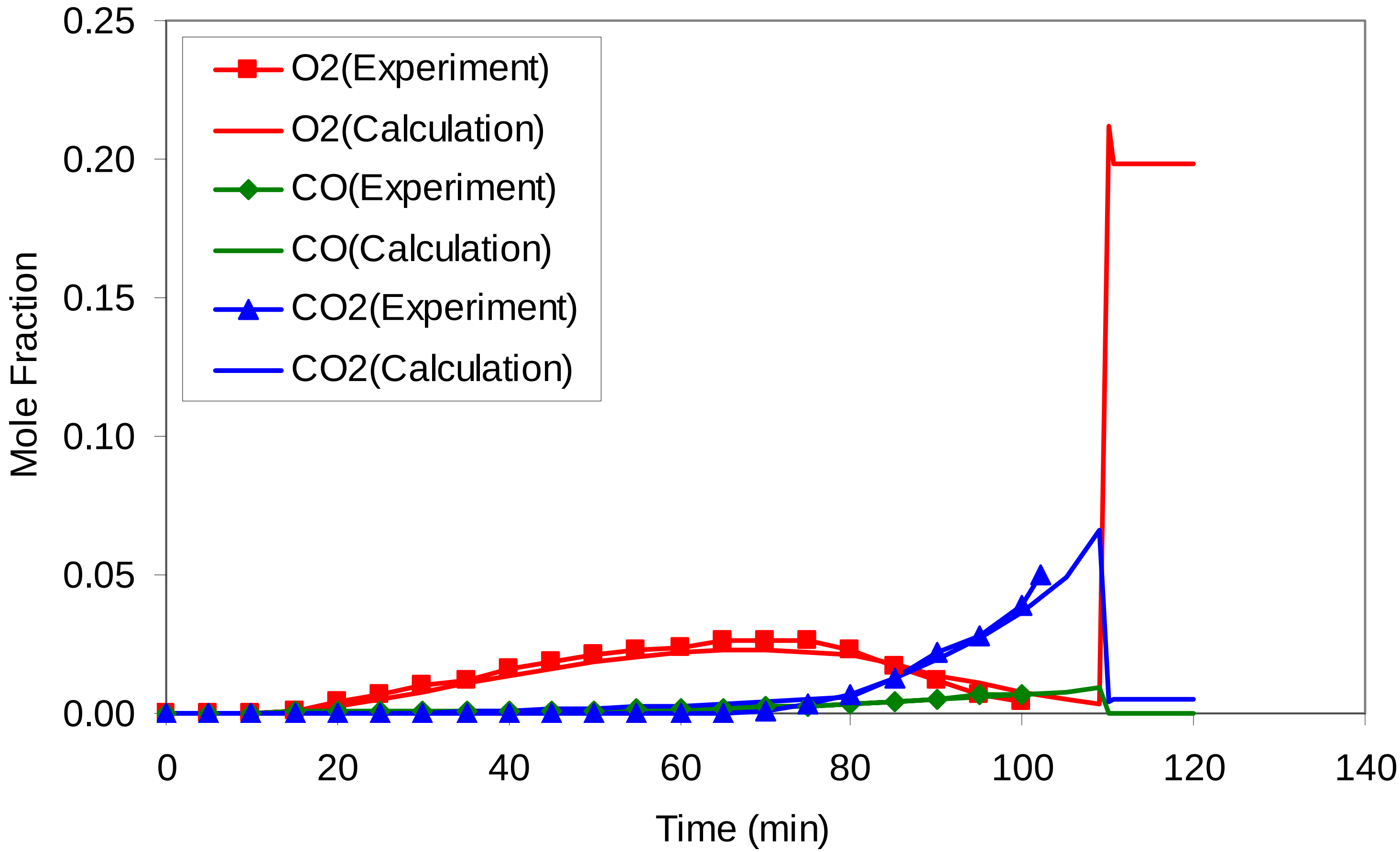


Figure 38: Mole Fraction at Point-4

NACOK Natural Convection Experiments no cont.

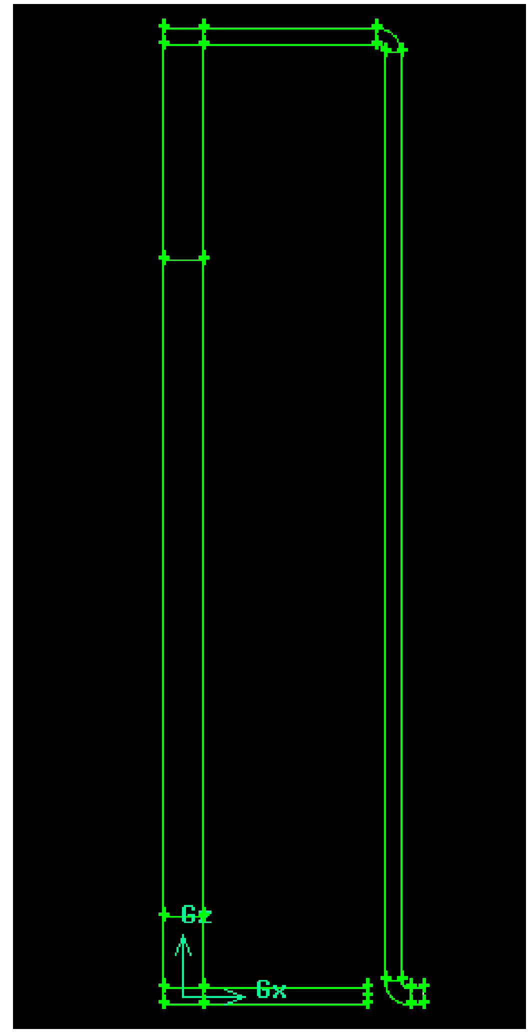


Figure 39: NACOK Experiment

Boundary Conditions

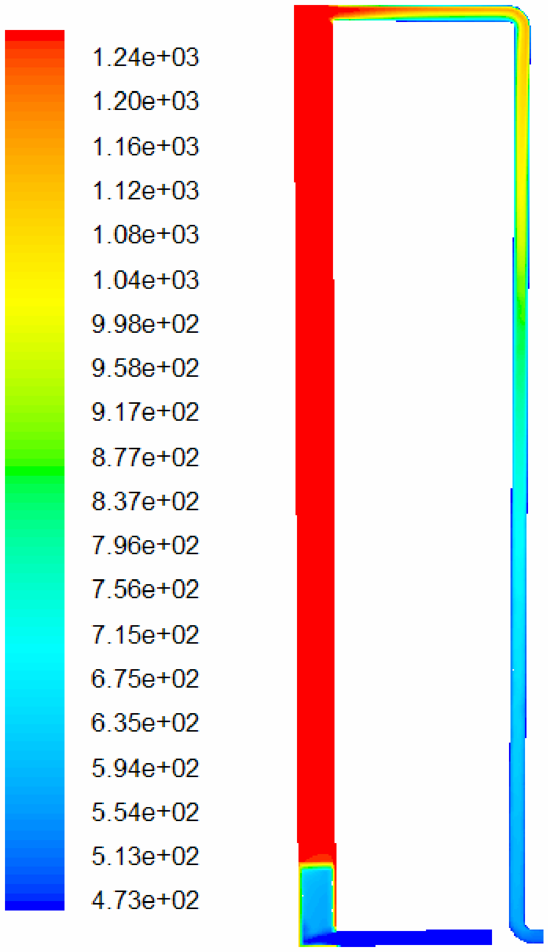


Figure 41: Temperature Profile for one experiment

The Mass Flow Rates

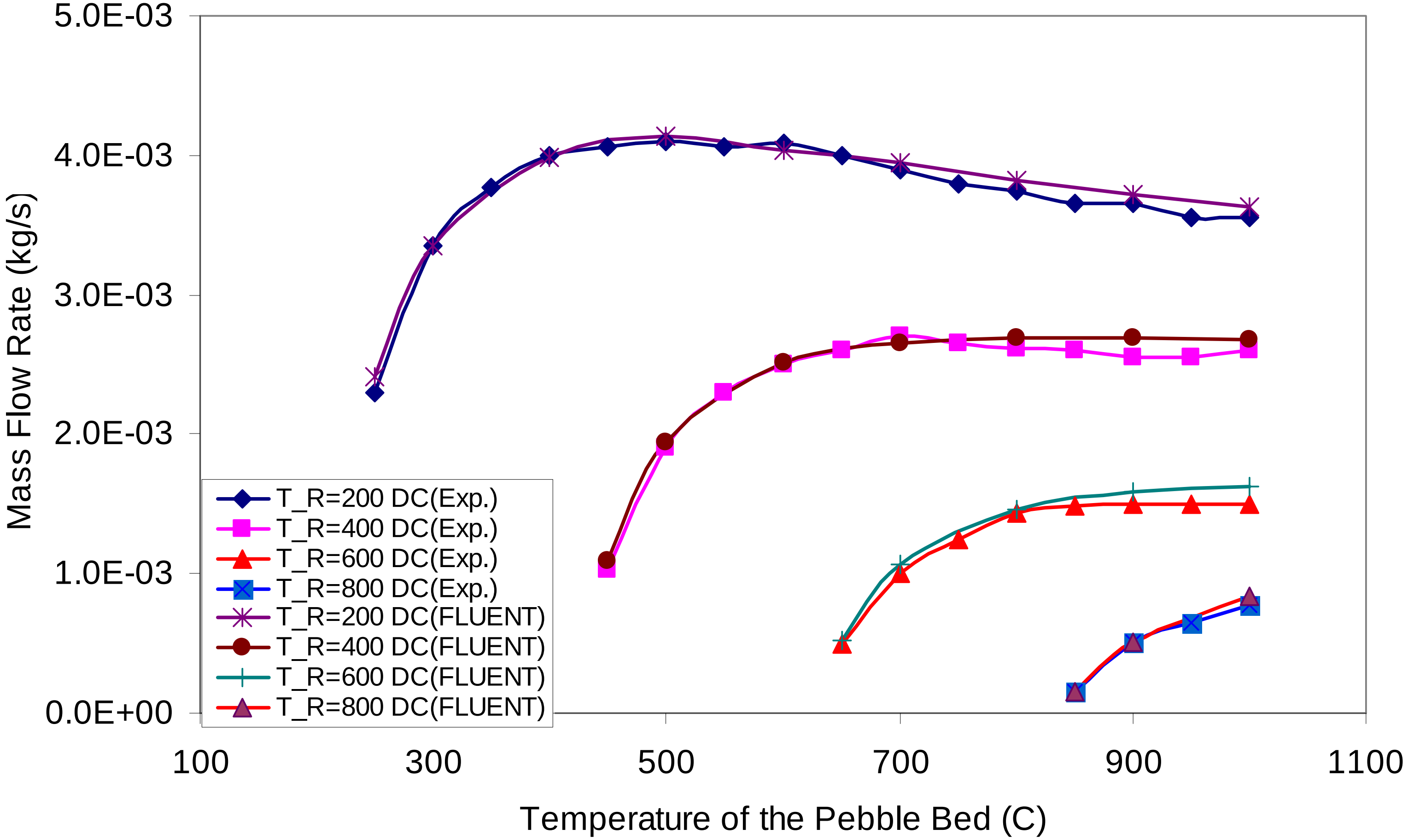
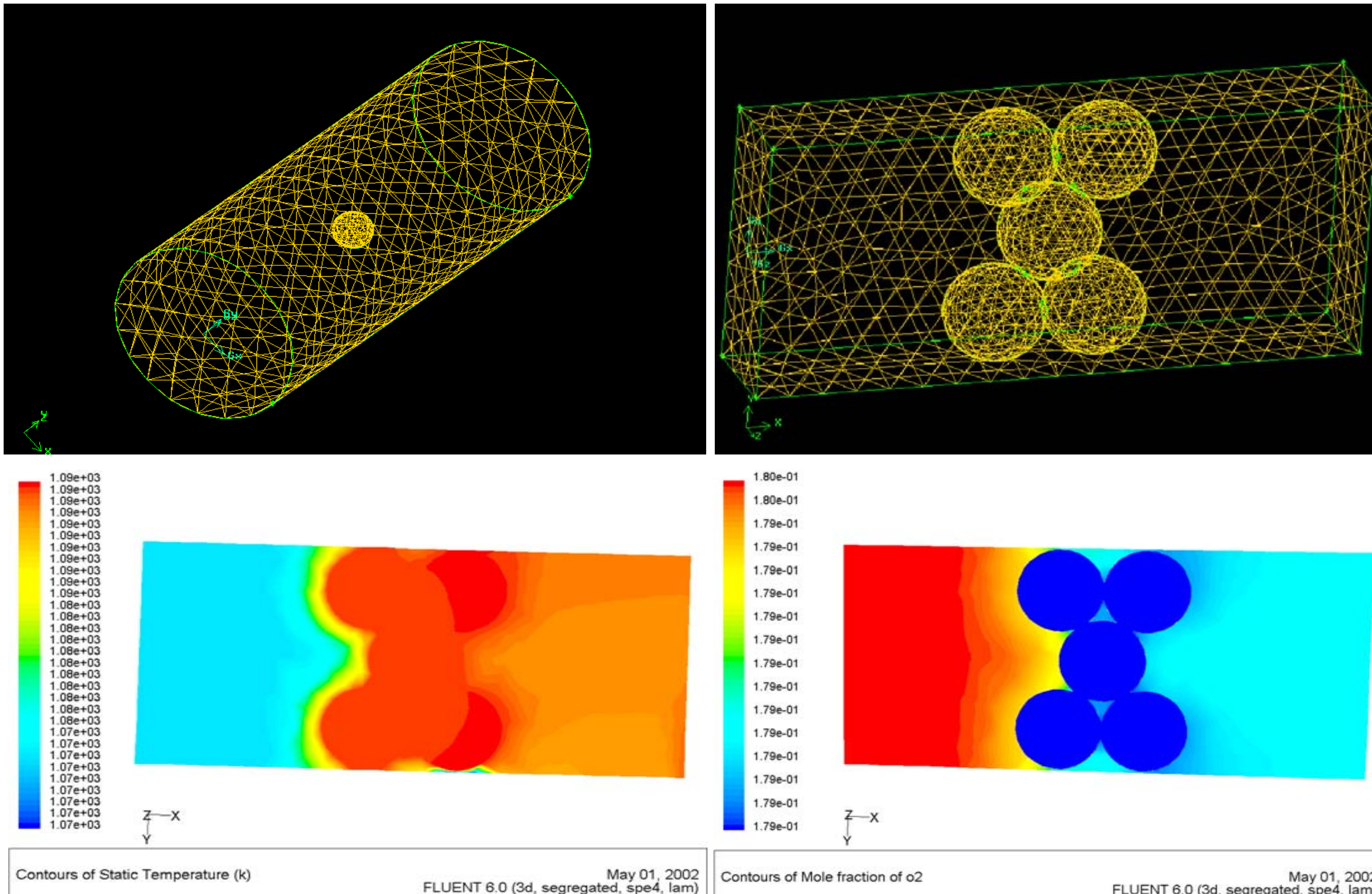
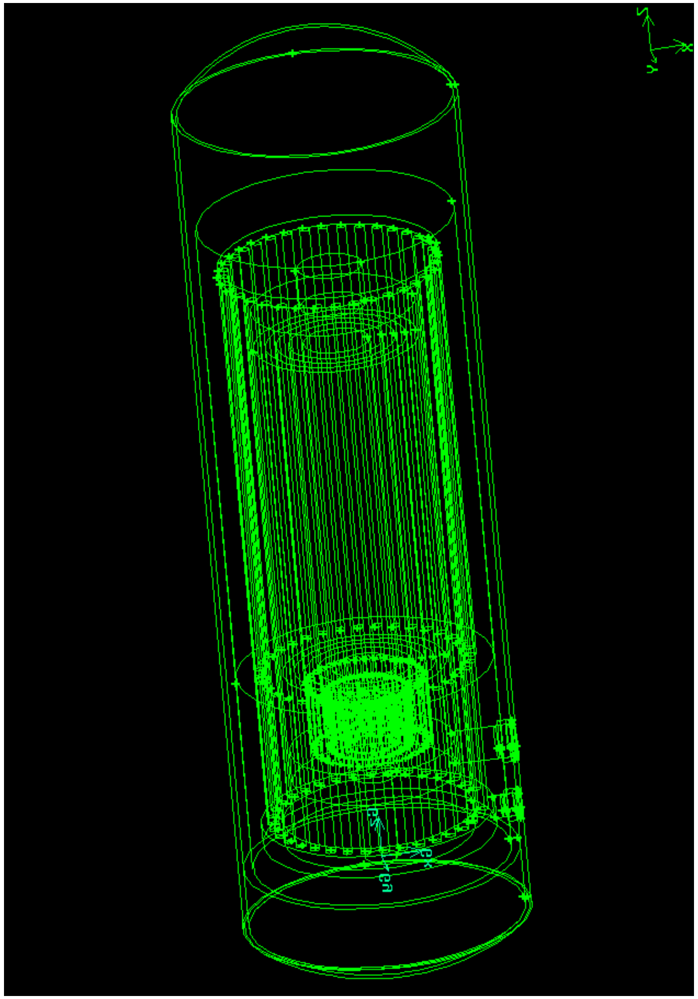


Figure 42: Mass Flow Rates for the NACOK Experiment

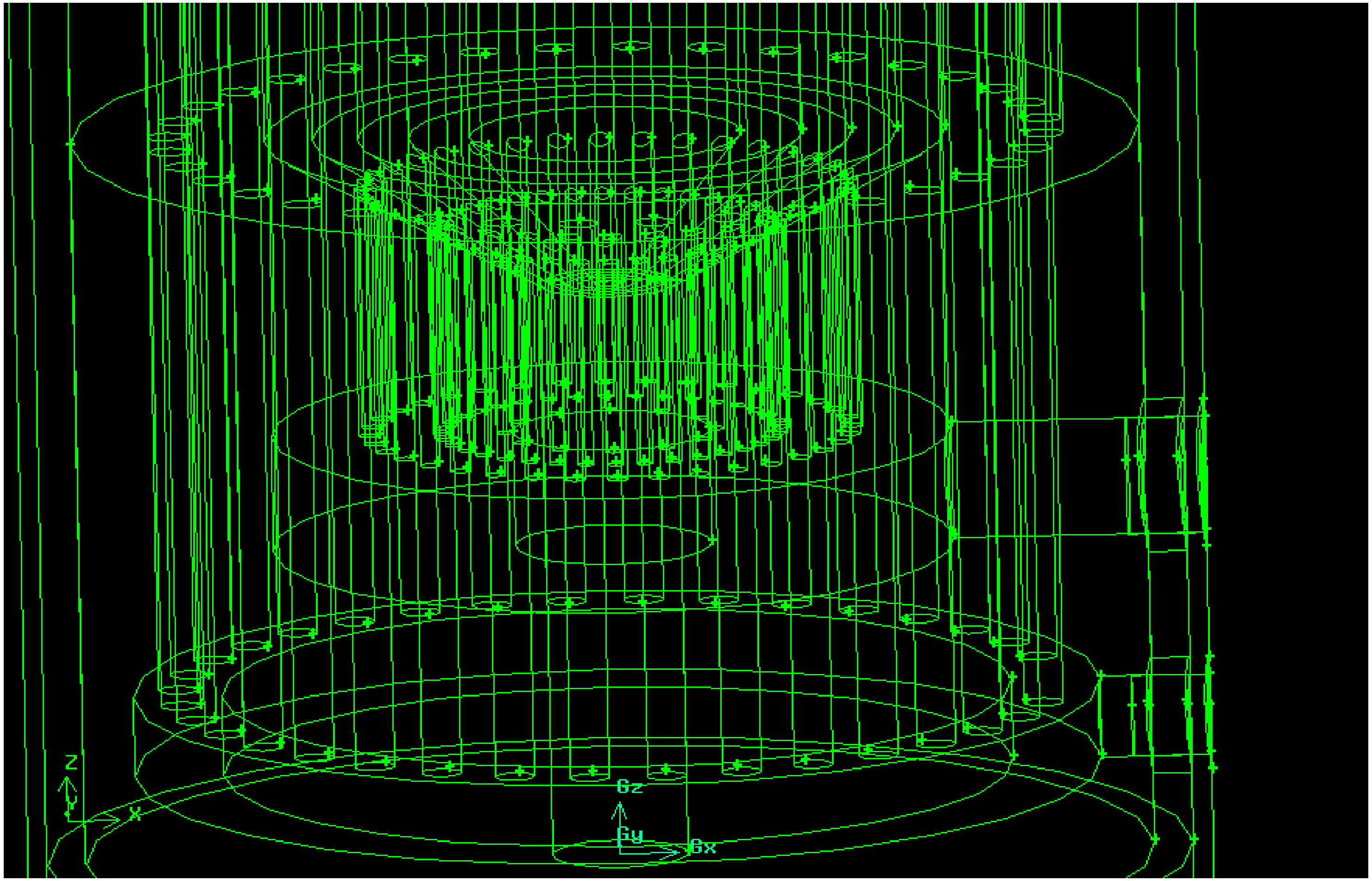
Verify the Chemical Model (FLUENT 6.0)



The Detailed Model in Progress



Detailed Bottom Reflector



Summary

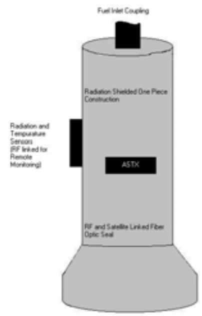
- Air Ingress is a potentially serious event for high temperature graphite reflected and moderated reactors (prismatic and pebble).
- Realistic analyses are necessary to understand actual behavior
- Based on realistic analyses, mitigation strategies are required.
- Good news is that long time frames are involved at allow for corrective actions (70 to 200 hours).
- MIT working on detailed analysis of the event with baseline modeling and testing with German Julich NACOK upcoming tests on air ingress.

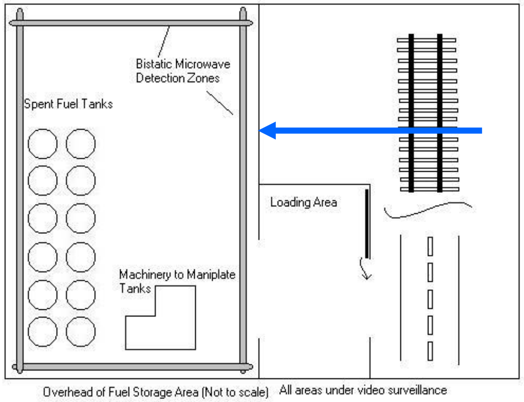
Extrinsic Safeguards Protection System for Pebble Bed Reactors

Proposed Concept

Extrinsic Safeguards System for Pebble Bed Reactors

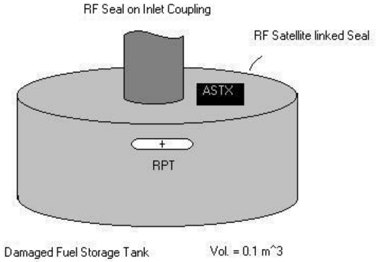
Waste Package

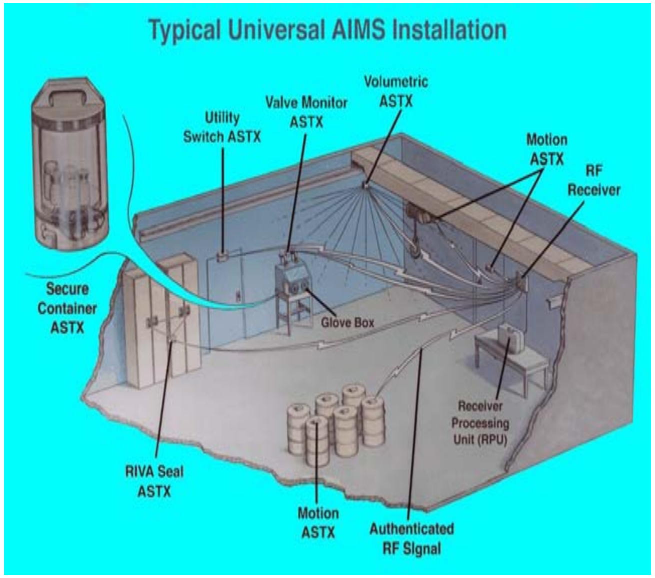




Fresh Fuel Room

Scrap Waste Can





Typical Waste Storage Room

Waste Disposal Conclusions

- Per kilowatt hour generated, the space taken in a repository is less than spent fuel from light water reactors.
- Number of shipments to waste disposal site 10 times higher using standard containers.
- Graphite spent fuel waste form ideal for direct disposal without costly overpack to prevent dissolution or corrosion.
- Silicon Carbide may be an reffective retardant to migration of fission products and actinides.

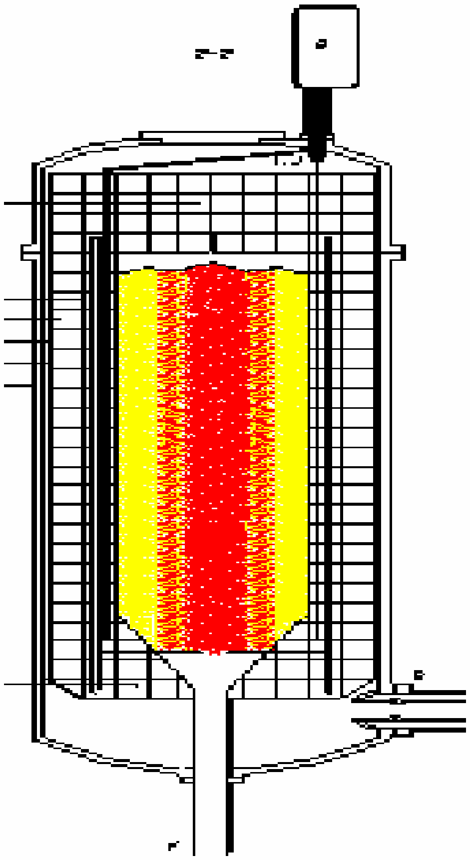
Pebble Flow

- Issue is the central graphite column and its integrity
- Don’t want fuel pebble in graphite or graphite pebble in fuel
- How to assess flow to assure high power peaks do not occur that could lead to fuel failure

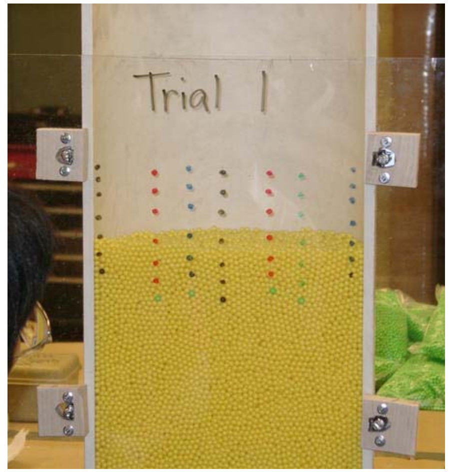
→ Conducted Experiment to determine flow

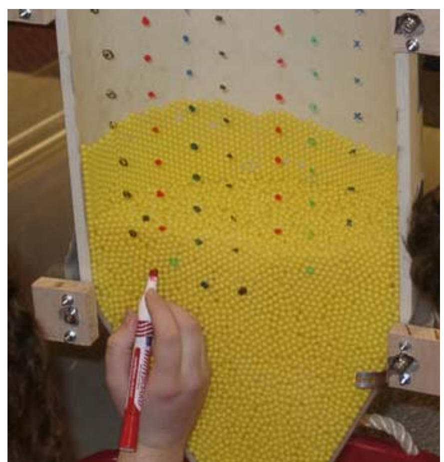
Radial Fuel Distribution

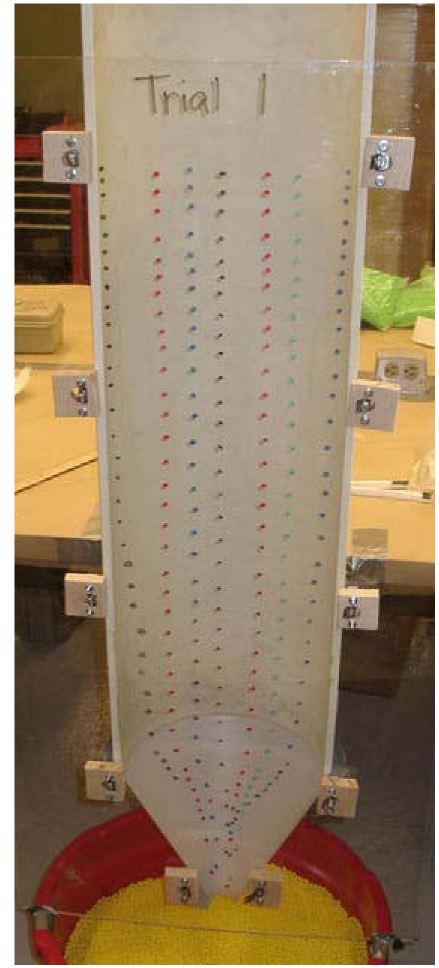
- A central core of pure graphite reflector pebbles is surrounded by an annulus of a 50/50 fuel-and-reflector mix, and a larger annulus of pure fuel pebbles.



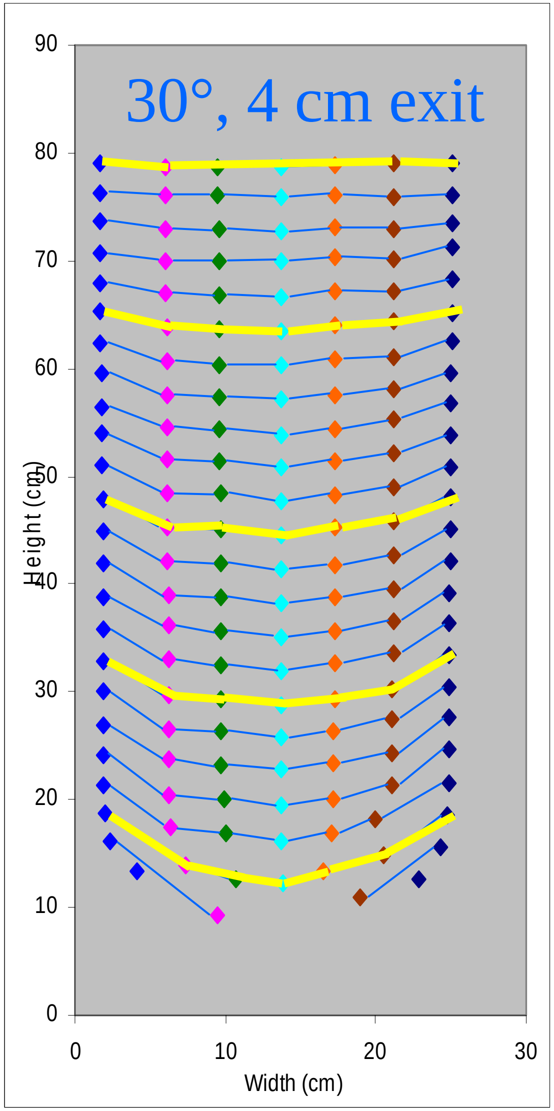
Half Model Data Collection

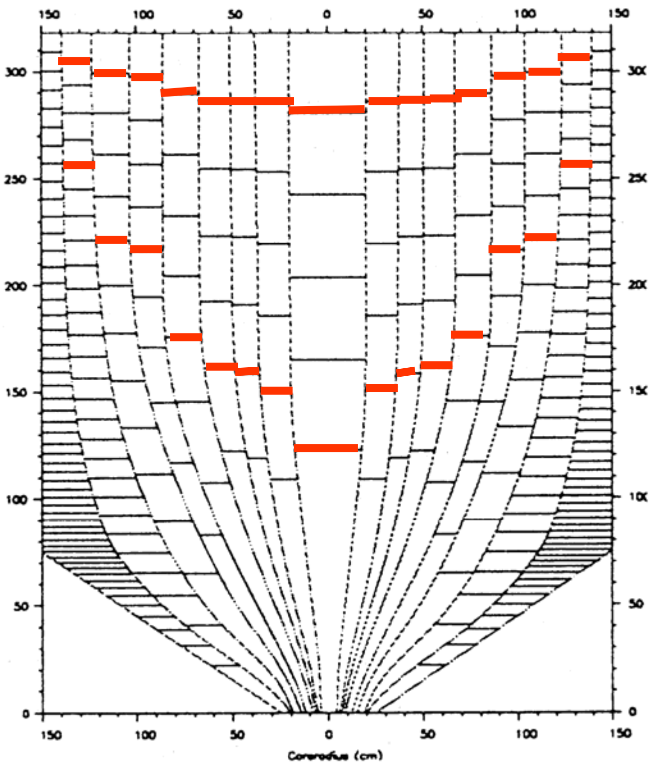


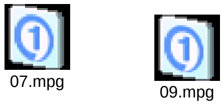




Comparison to Design Profile

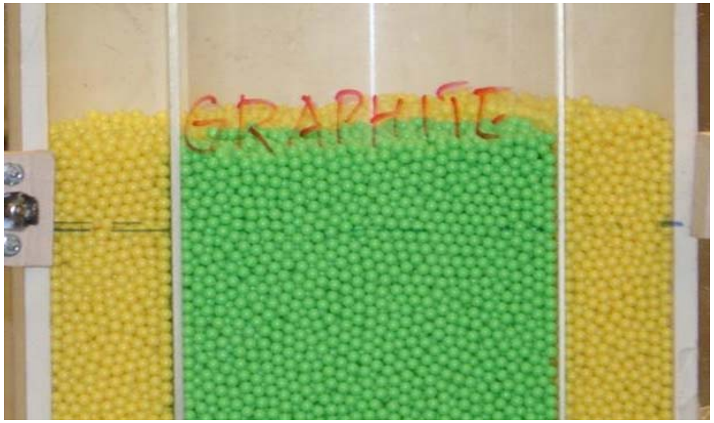


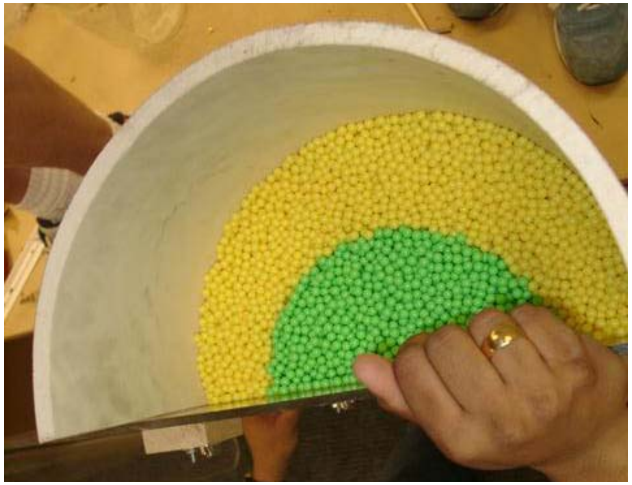




Movie Clips

Trial with Central Column





Video Demo

19.mpg

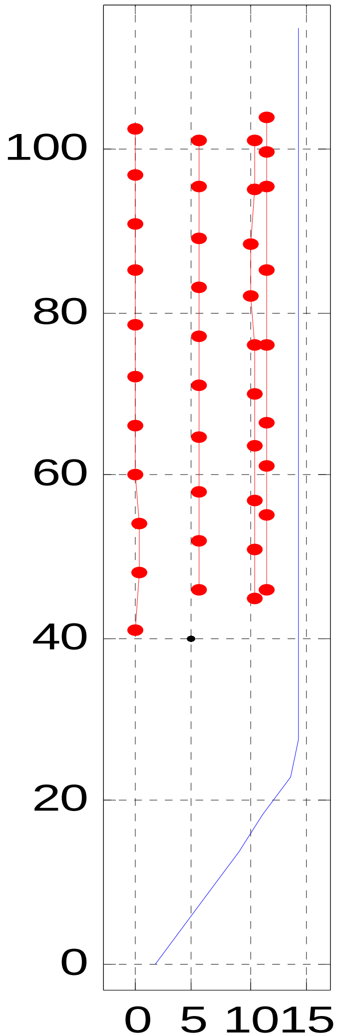
20.mpg

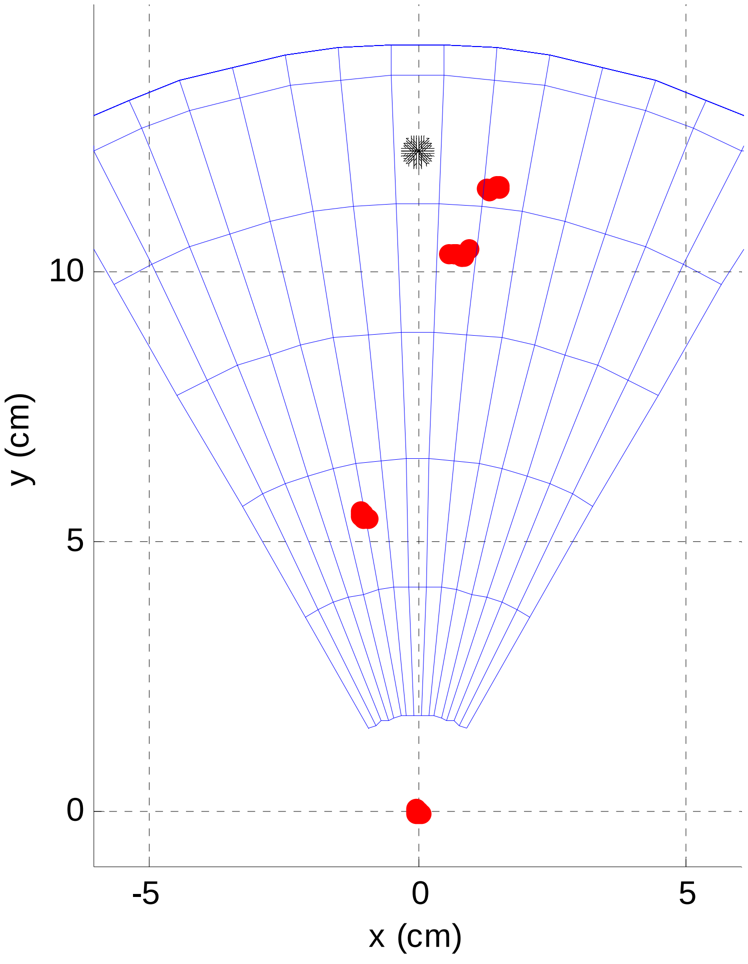
21.mpg

22.mpg

23.mpg

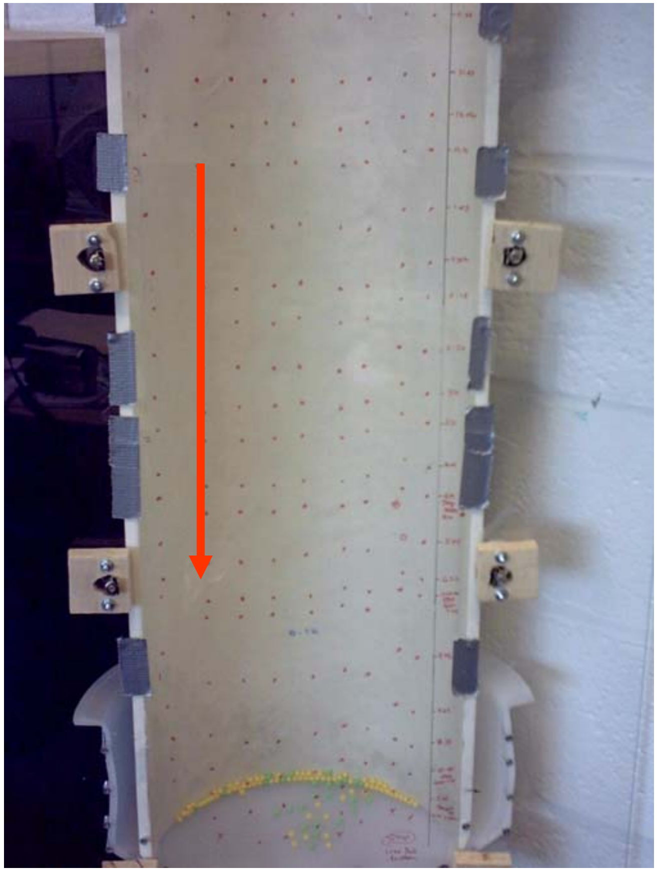
Streamlines
Confirmed by 3D Experiment





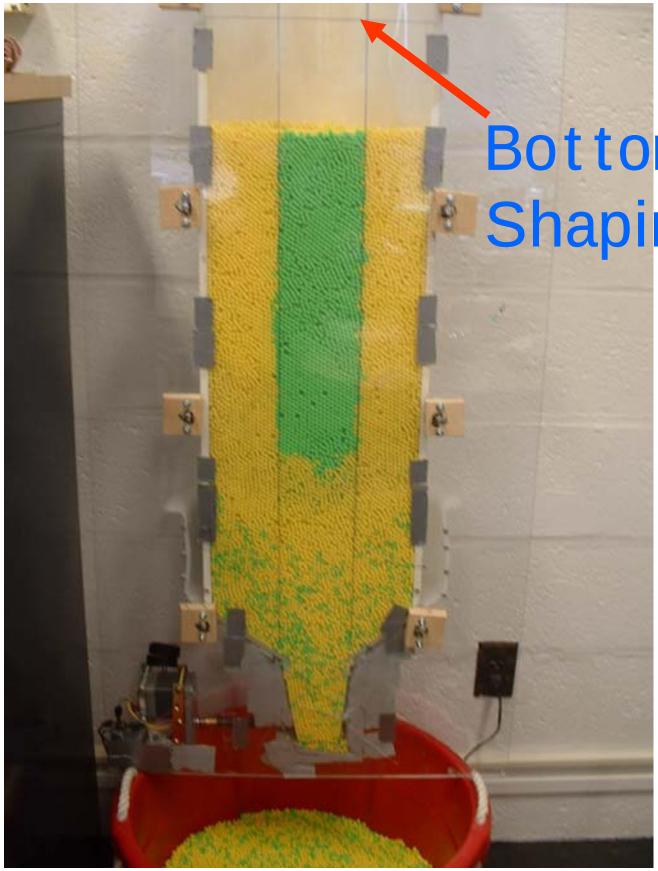
Slow Flow Results

- Used drill to remove pebbles at 120 /min.
- Flow lines still linear



Shaping Ring for Central Column Formation

- Shaping ring used to form central column at top 3 inches
- Rest open - no ring
- Column maintained during slow drain down.

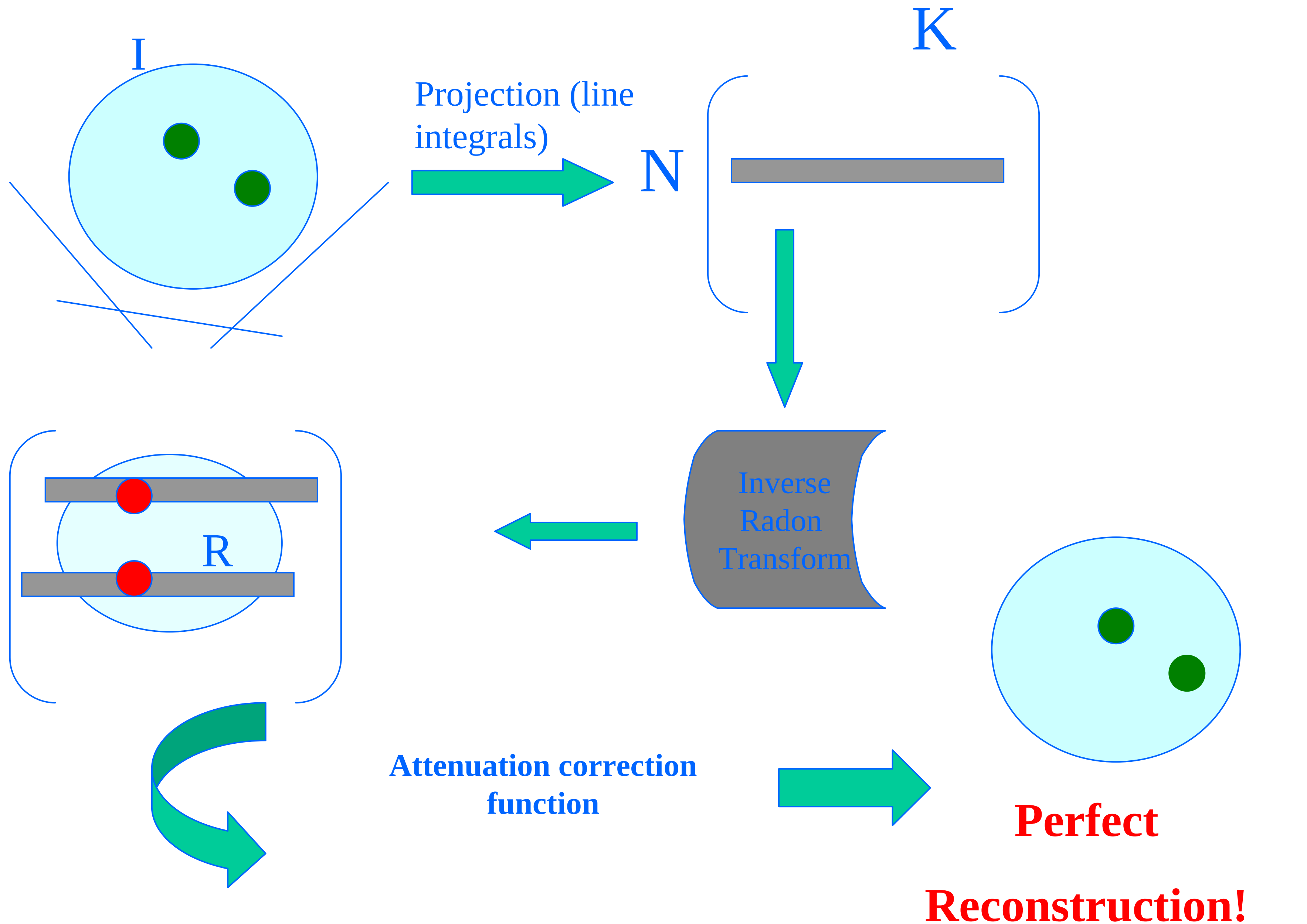


Core Monitoring System

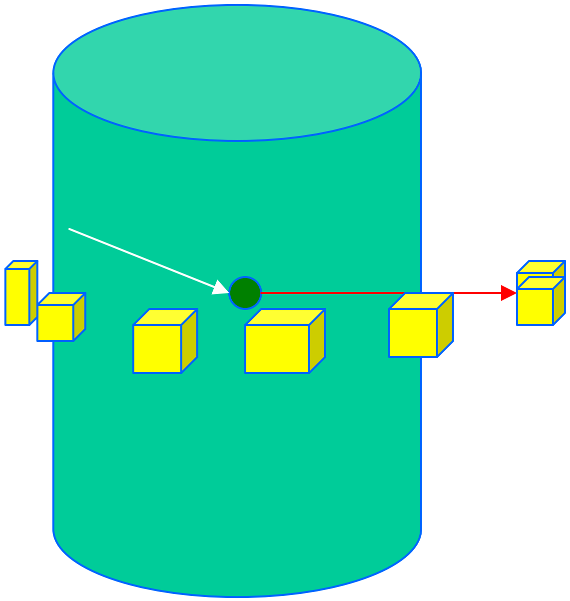
Imaging of Core

Tracer Ball Method

Visually speaking…



Summary



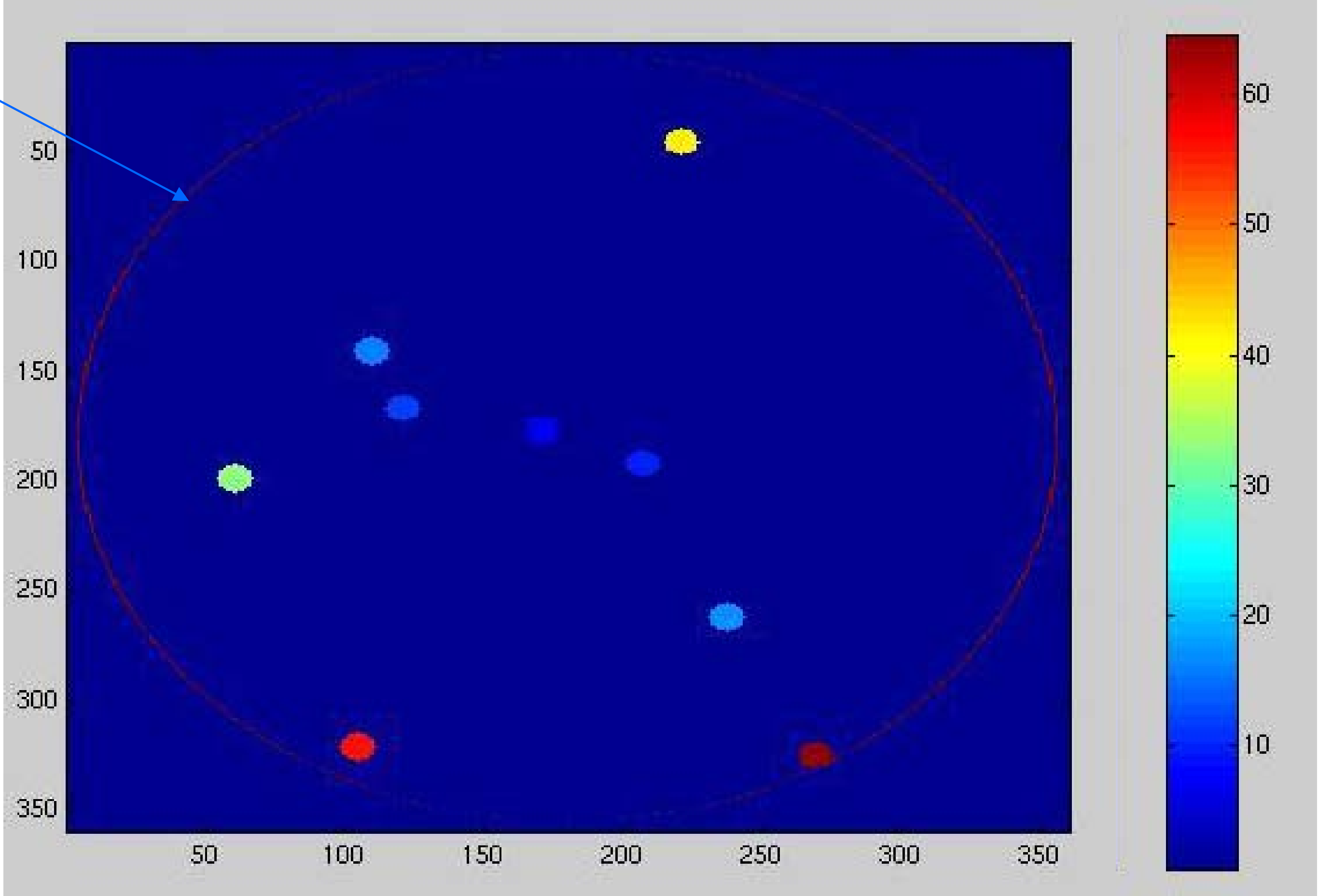
•Nitrogen tracer produces 10.8 MeV gamma ray

•Gamma ray detected by detector ring

•Core is imaged by Tomography

Image of Core

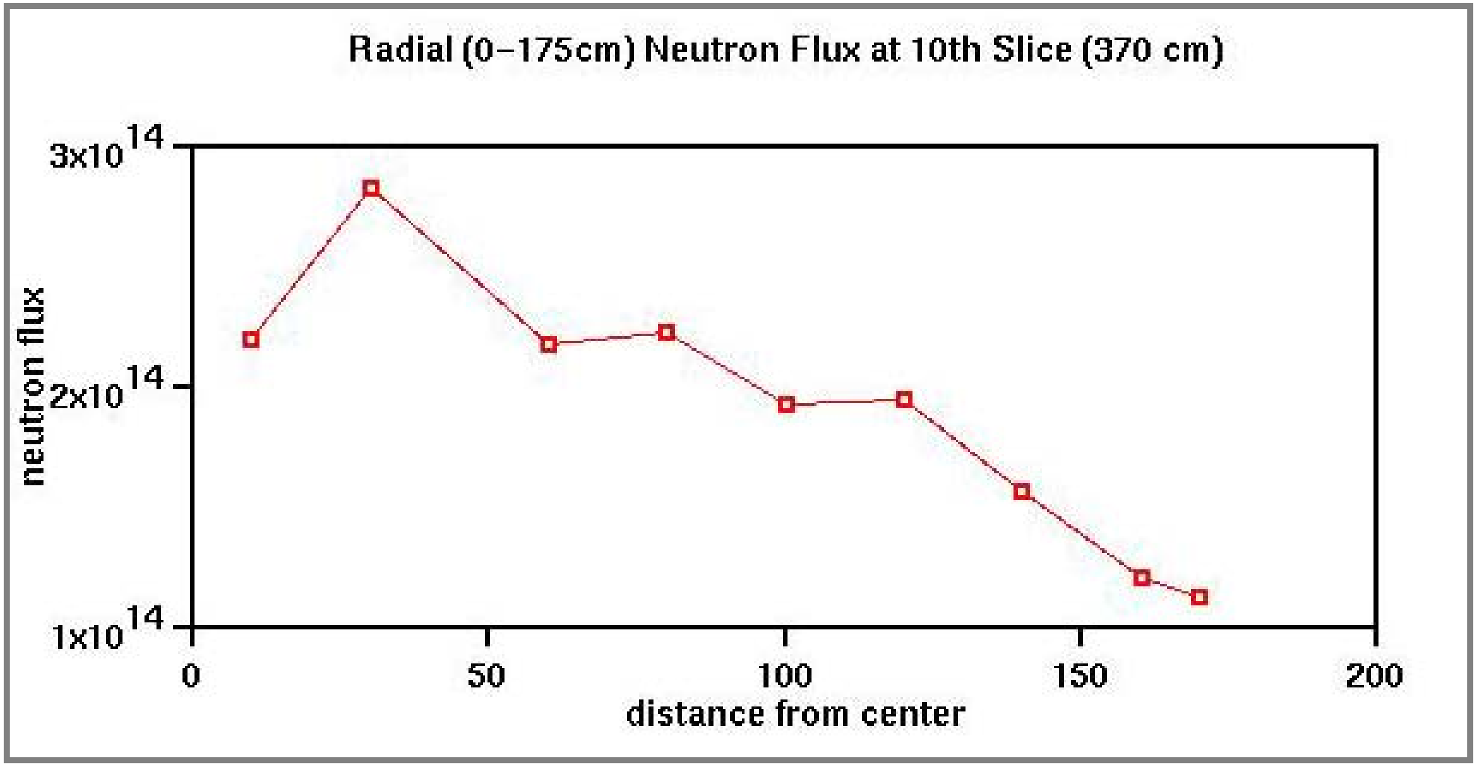
Core Boundary



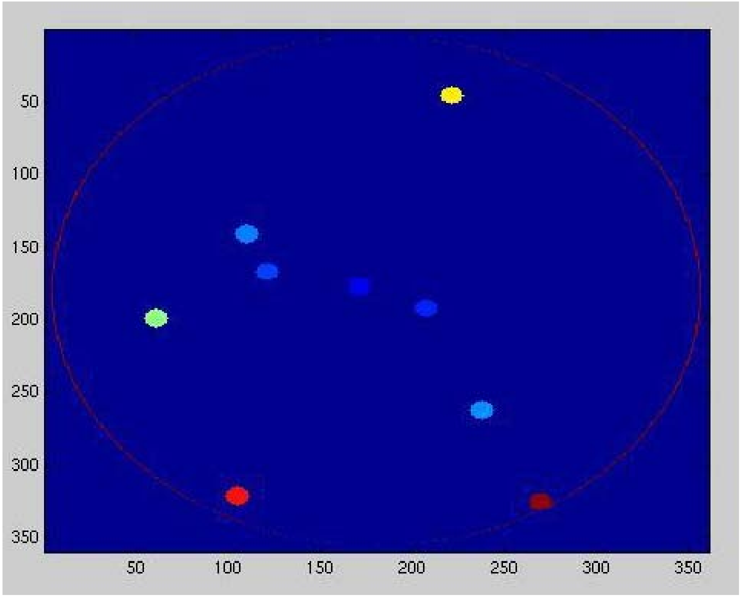
•Color intensity proportional to gamma flux measured by detector

Radial Neutron Flux (0-175cm) Profile of PBMR Core

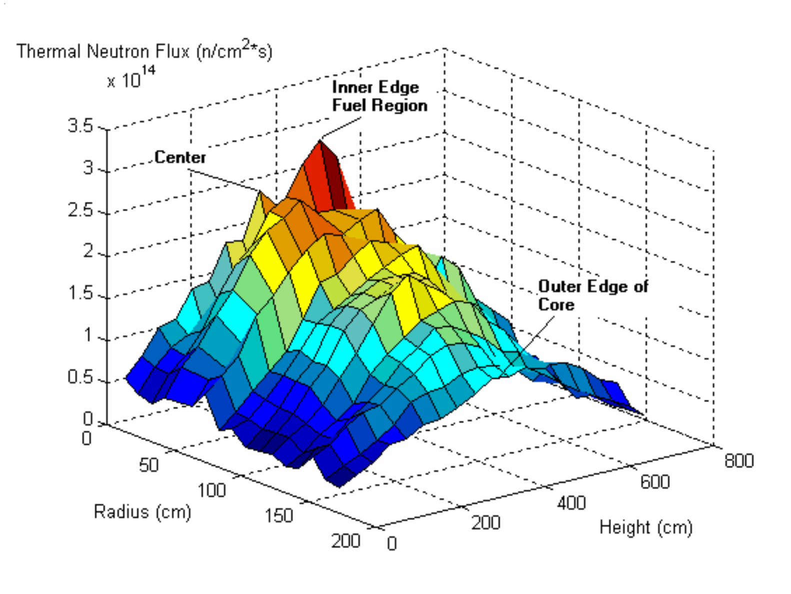
10^{th} slice (370 cm)



Summary



Result of tomography



Neutron flux is reconstructed

License By Test

- Build a research/demonstration plant
    - -reactor research facility
- Perform identified critical tests
- If successful, certify design for construction.

Risk Informed Approach

- Establish Public Health and Safety Goal
- Demonstrate by a combination of deterministic and probabilistic techniques that safety goal is met.
- Using risk based techniques identify accident scenarios, critical systems and components that need to be tested as a functional system.

MIT's Project Innovations

- Advanced Fuels
- Totally modular - build in a factory and assemble at the site
- Replace components instead of repair
- Indirect Cycle for Hydrogen Generation for fuel cells & transportation
- Advanced computer automation
- Demonstration of safety tests

Future Research Activities

- Build and Test Advanced Plate Fin IHX Design
- Benchmark new series of NACOK Air Ingress Tests with CFD.
- Perform Pebble Flow Experiments to Reduce Central Column By-pass Flow
- Expand Fuel Performance Model to handle rapid transients (rod ejection)
- Make and Test Advanced Fuel Particles with Tsinghua University

Summary

- MIT Project aimed at advanced pebble bed reactor development with focus on innovation in design, modularity, license by test, using a full scale reactor research facility to explore different fuel cycles, process heat applications, and advanced control system design, helium gas turbines and other components.

- Desire Collaborations to develop international confidence in the technology, safety,economics and practicality.

- We have a unique opportunity to develop pebble bed reactors but it is time critical