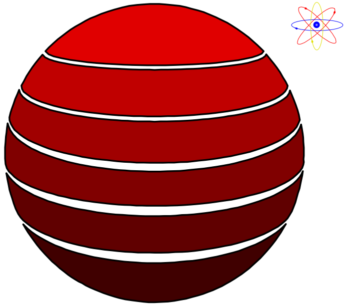

Modular Pebble Bed Reactor
High Temperature Gas Reactor

Andrew C Kadak
Massachusetts Institute of Technology

American Nuclear Society
Winter Meeting - Washington, D.C
November 2002

MACHINE DESIGN

SEPTEMBER 27, 2001
www.machinedesign.com

A PENTON PUBLICATION
Periodicals
USPS 481 Approved Poly

SPECIAL FOCUS
The Future of Energy
page 77

Kudos for best new designs, page 50

World's smartest appliances, page 71

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 ser-

THE WORLD'S LARGEST SCIENCE & TECHNOLOGY MAGAZINE

THE WHAT'S NEW MAGAZINE

Popular Science

New Life for Nuclear Power
Inside the Reactor That Won't Melt Down

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Mystery Skin Cells BEST HOPE FOR BURN VICTIMS

www.popsci.com

AVR: Jülich

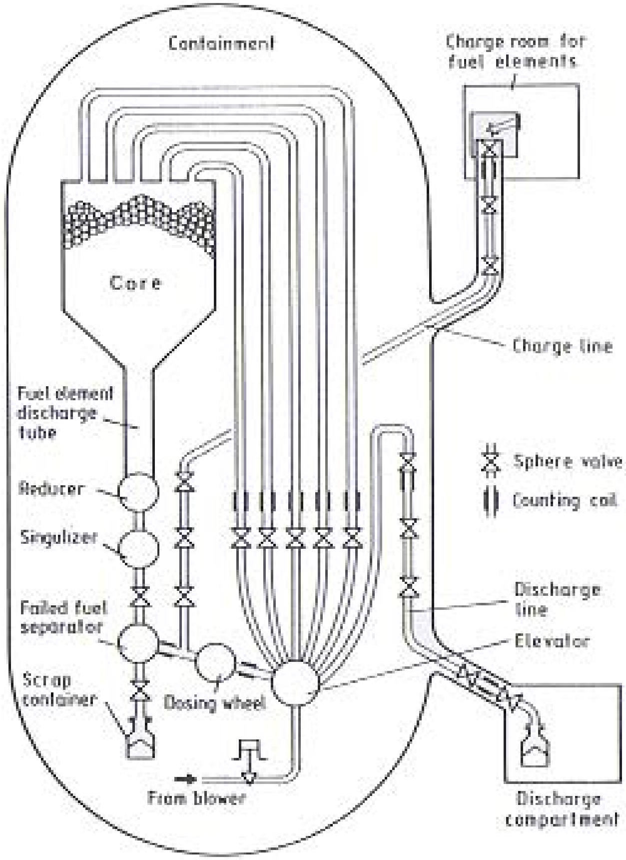
15 MWe Research Reactor

THTR: Hamm-Uentrop

300 Mwe Demonstration Reactor

HTR- 10 China
First Criticality Dec.1, 2000

What is a Pebble Bed Reactor ?



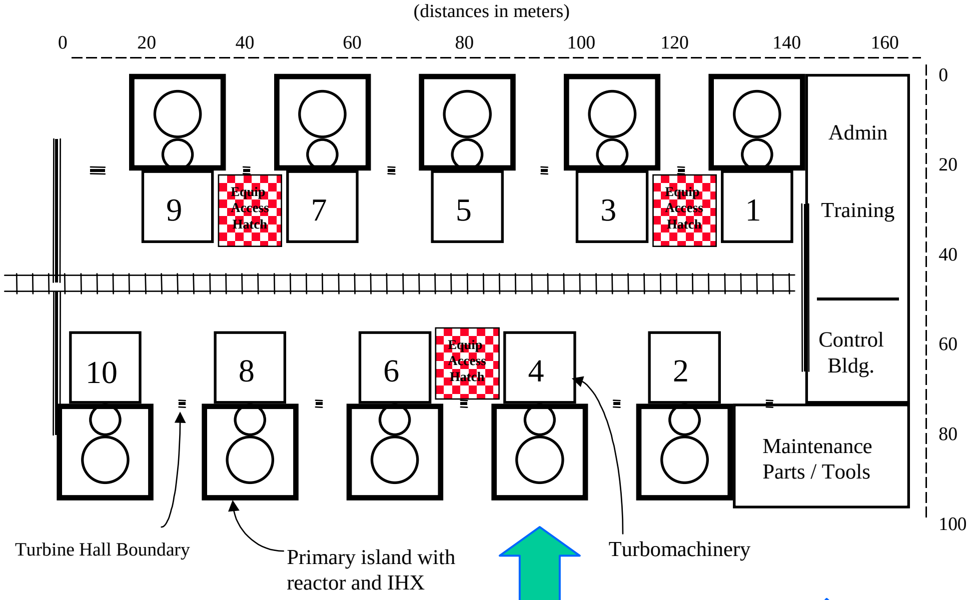
- **360,000 pebbles in core**
- **about 3,000 pebbles handled by FHS each day**
- **about 350 discarded daily**
- **one pebble discharged every 30 seconds**
- **average pebble cycles through core 10 times**
- **Fuel handling most maintenance-intensive part of plant**

Modular High Temperature Pebble Bed Reactor

- 110 MWe
- Helium Cooled
- 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
- Process Heat Applications - Hydrogen, water

For 1150 MW Combined Heat and Power Station

Ten-Unit VHTR Plant Layout (Top View)



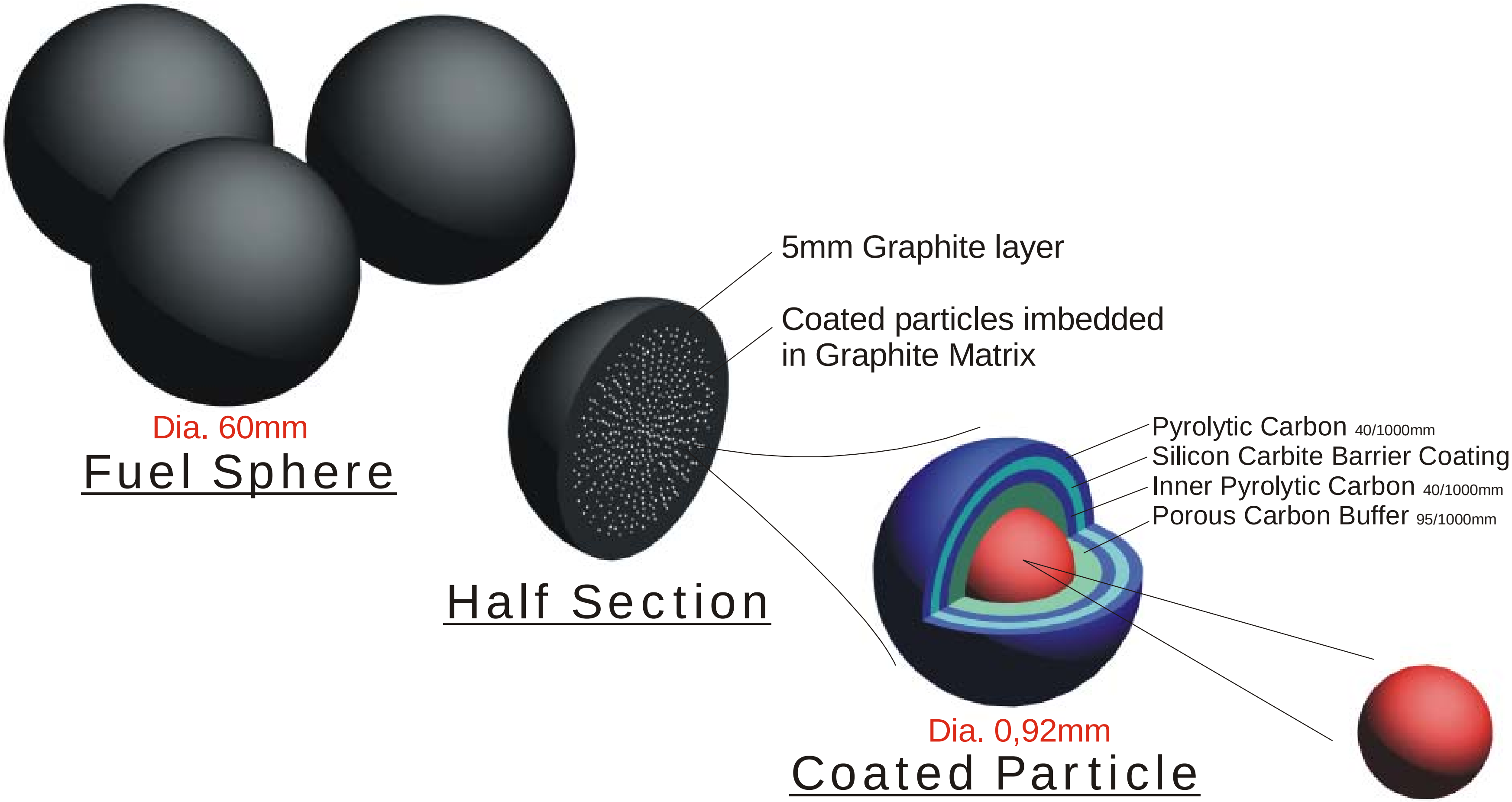
VHTR Characteristics
- Temperatures > 900 C
- Indirect Cycle
- Core Options Available
- Waste Minimization

Oil Refinery

Hydrogen Production

Desalinization Plant

FUEL ELEMENT DESIGN FOR PBMR



5mm Graphite layer

Coated particles imbedded
in Graphite Matrix

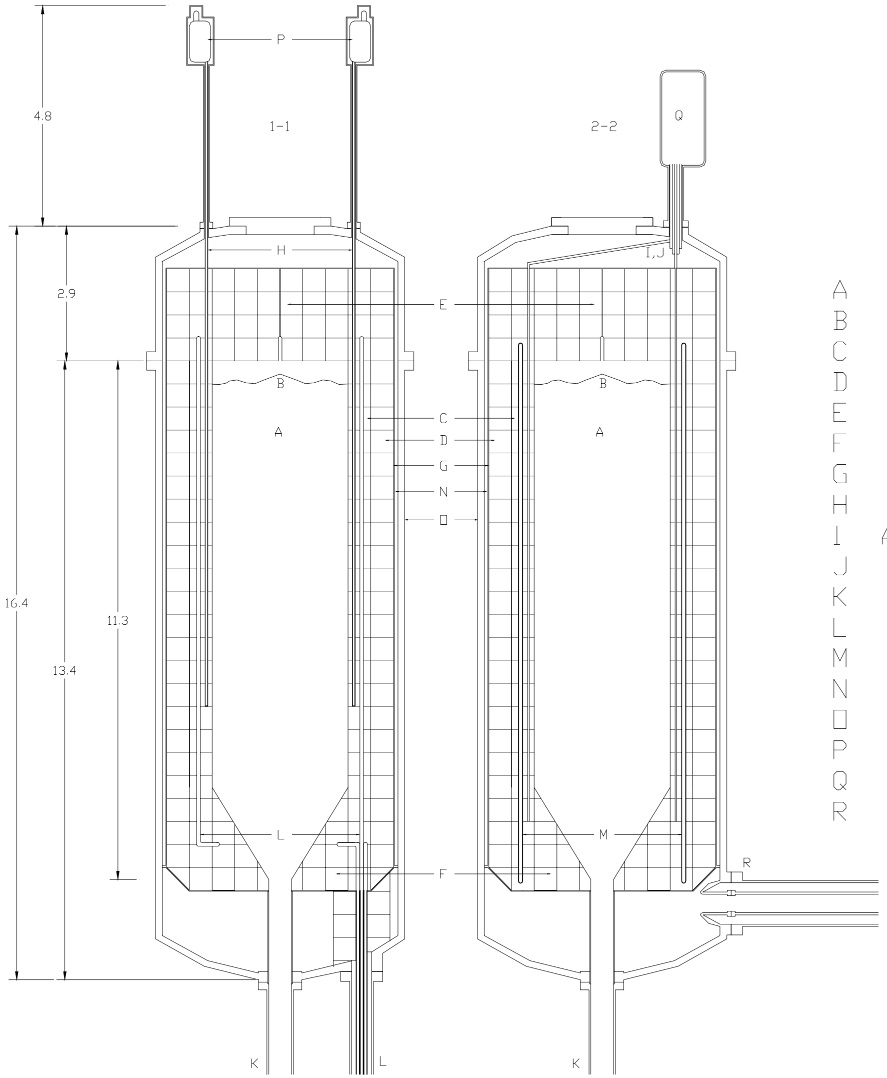
Pyrolytic Carbon 40/1000mm
Silicon Carbite Barrier Coating 35/1000
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm

Dia. 60mm
Fuel Sphere

Half Section

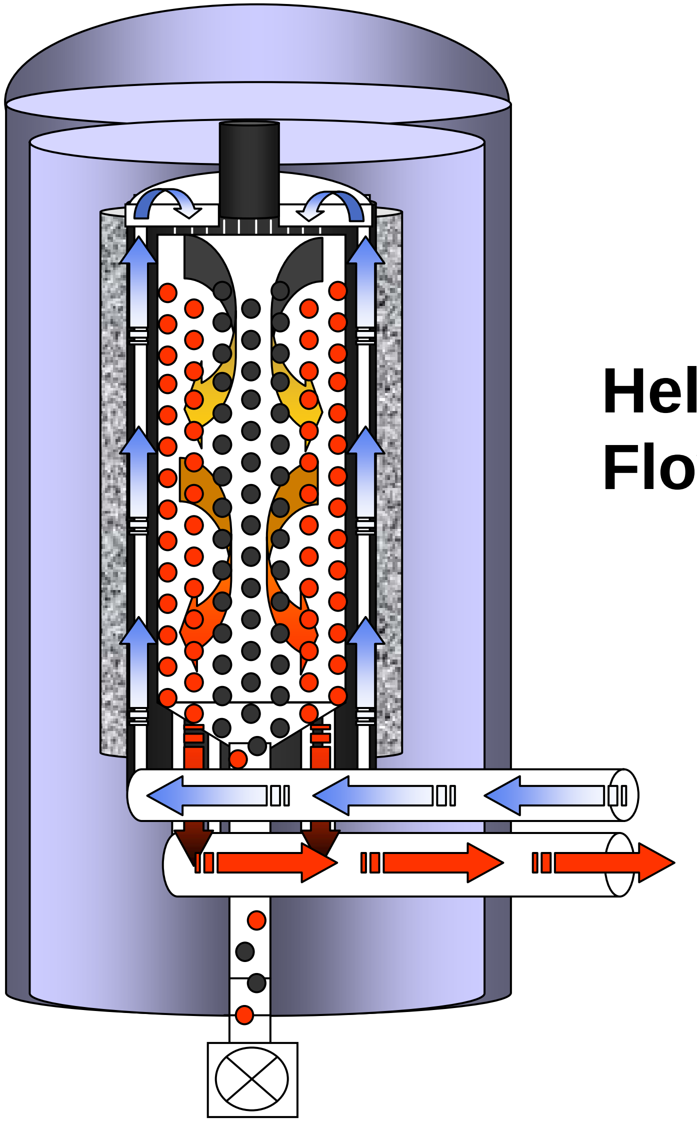
Dia. 0,92mm
Coated Particle

Dia.0,5mm
Uranium Dioxide
Fuel



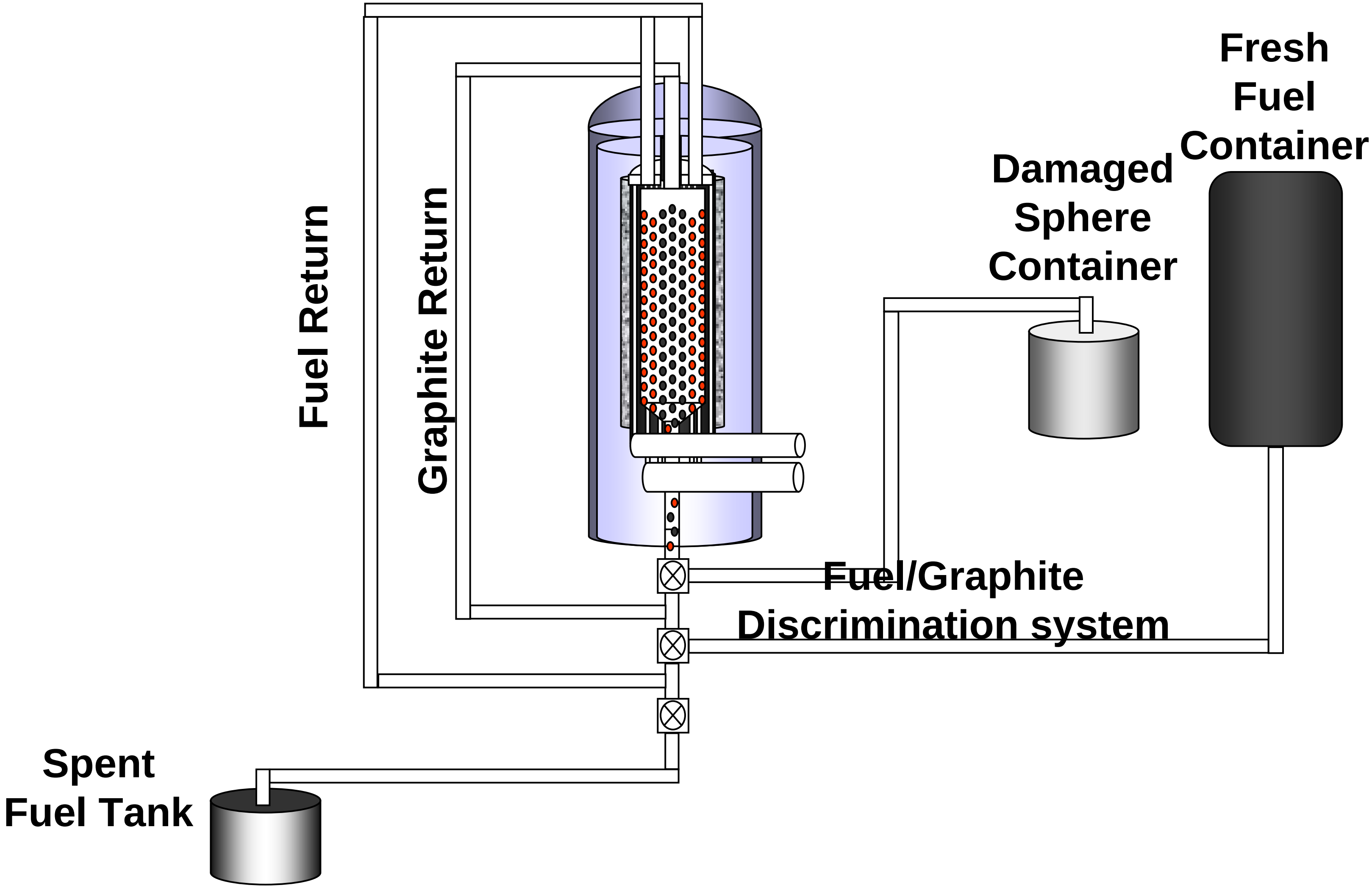
A	Pebble Bed Core
B	Fuel Drop Points (5)
C	Inner Reflector
D	Outer Reflector
E	Top Reflector
F	Bottom Reflector
G	Core Barrel
H	Control Rod Channels (6)
I	Absorber Ball Drop Channels (18)
J	Absorber Ball Lift Channel (1)
K	Fuel Discharge Tube
L	Pebble Fuel Lift Channels (5)
M	Coolant Flow Channels (6)
N	Stagnant Helium Gap
O	Pressure Vessel
P	Control Rod Drivers
Q	Absorber Ball Container
R	Coaxial Pipe to IHX Module

Reactor Unit

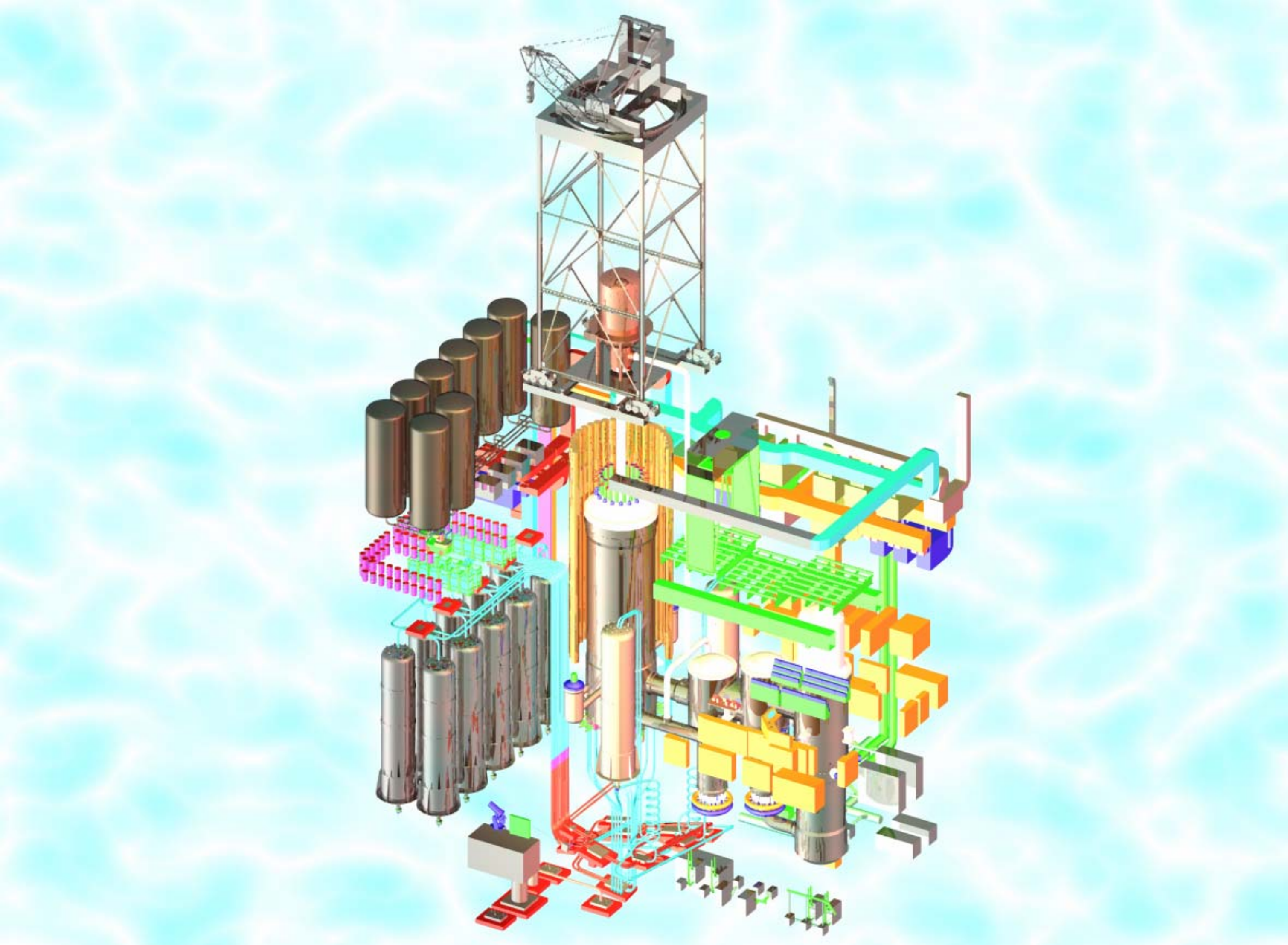


Helium Flowpath

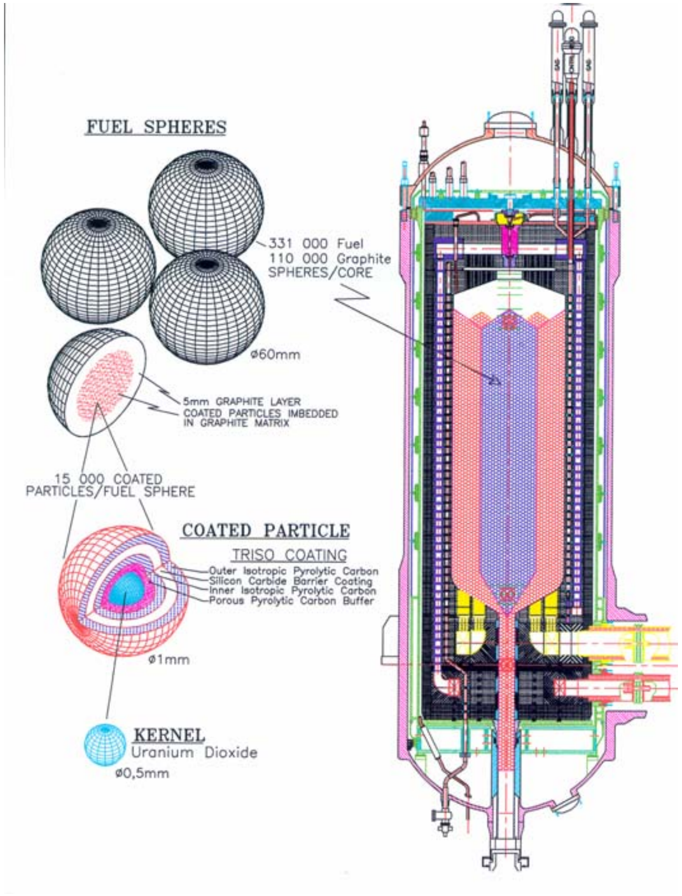
Fuel Handling & Storage System



Equipment Layout

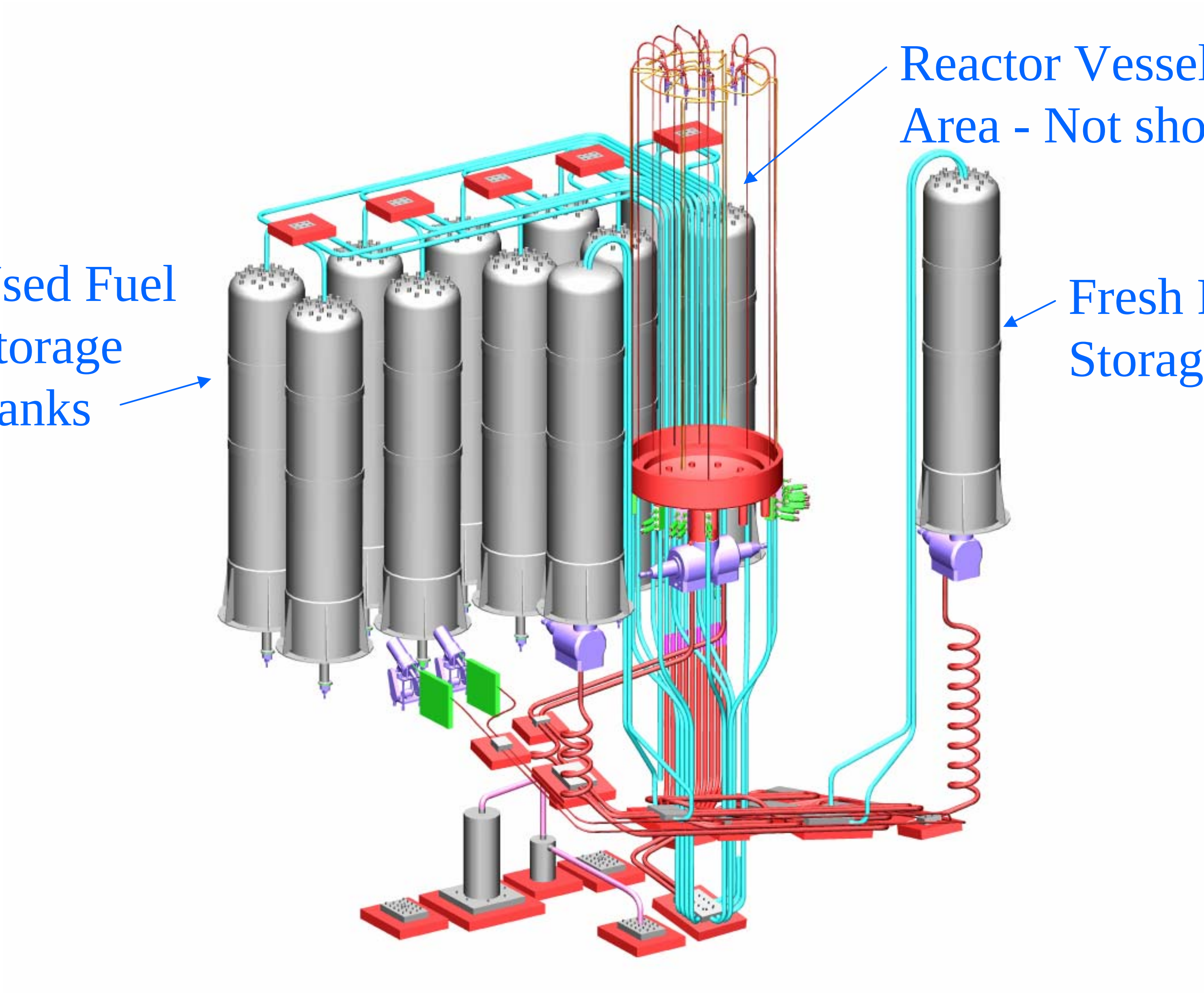


Modular Pebble Bed Reactor



Thermal Power	**250 MW**
Core Height	**10.0 m**
Core Diameter	**3.5 m**
Fuel	**UO_2**
Number of Fuel Pebbles	**360,000**
Microspheres/Fuel Pebble	**11,000**
Fuel Pebble Diameter	**60 mm**
Microsphere Diameter	**~ 1mm**
Coolant	**Helium**

Fuel Handling System

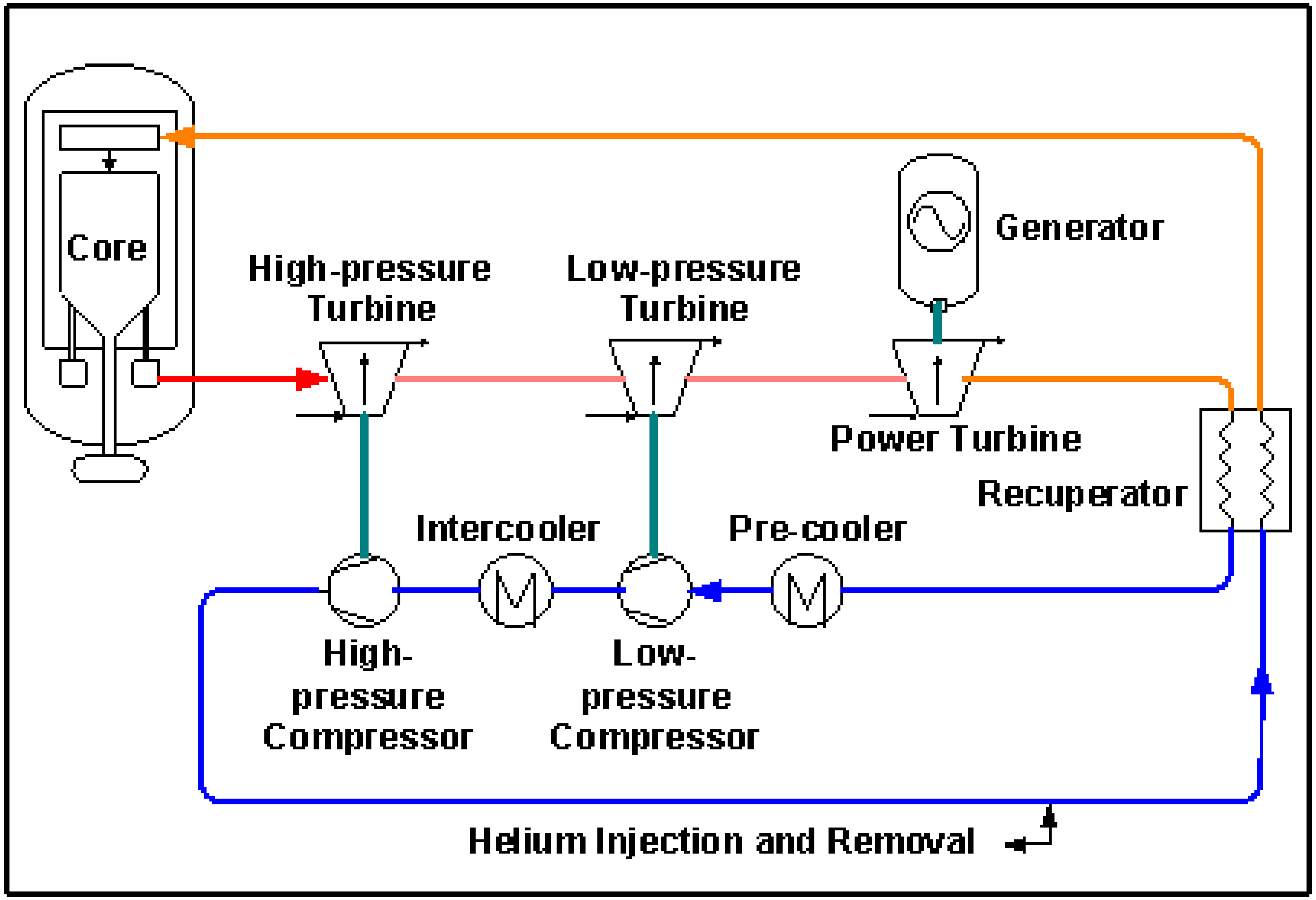


Reactor Vessel in this Area - Not shown

Used Fuel Storage Tanks

Fresh Fuel Storage

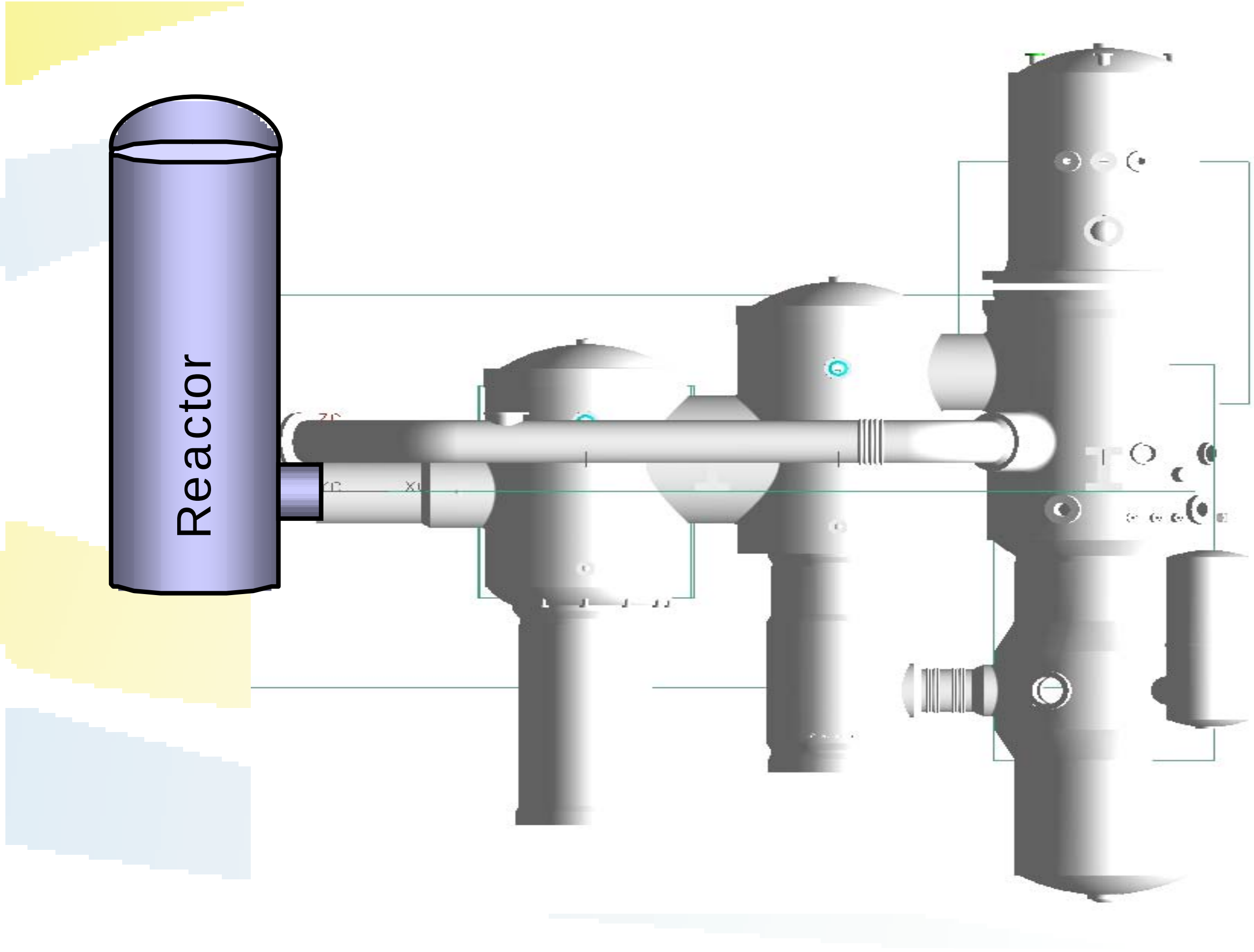
Power Cycle - Brayton



Pebble Bed Reactor Designs

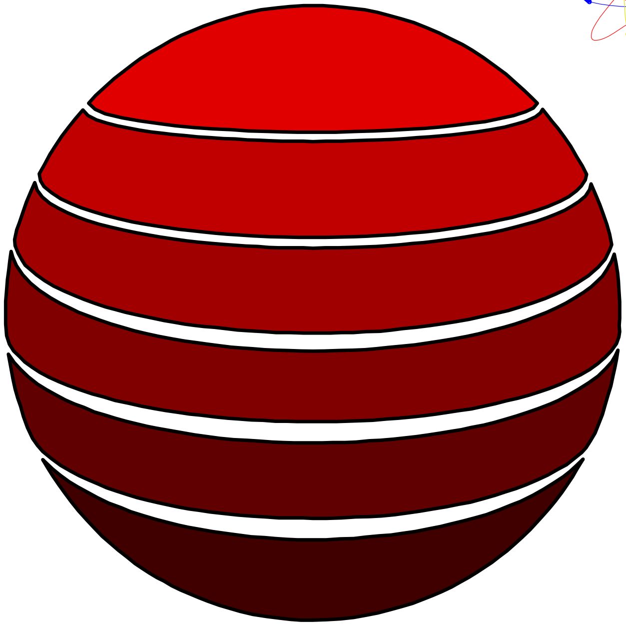
- PBMR (ESKOM) South African
  - Direct Cycle
  - Two Large Vessels plus two smaller ones
- MIT/INEEL Design
  - Indirect Cycle - Intermediate He/He HX
  - Modular Components - site assembly

PBMR Layout



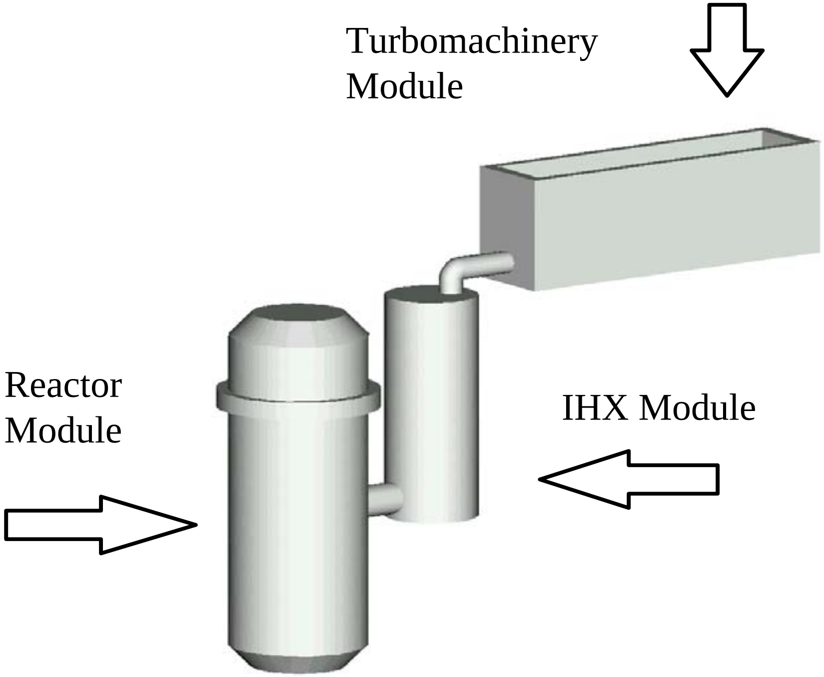
MIT's Pebble Bed Project

- Similar in Concept to ESKOM
- Developed Independently
- Indirect Gas Cycle
- Costs 3.3 c/kwhr
- High Automation
- License by Test



MIT Design for Pebble Bed

Conceptual Design Layout



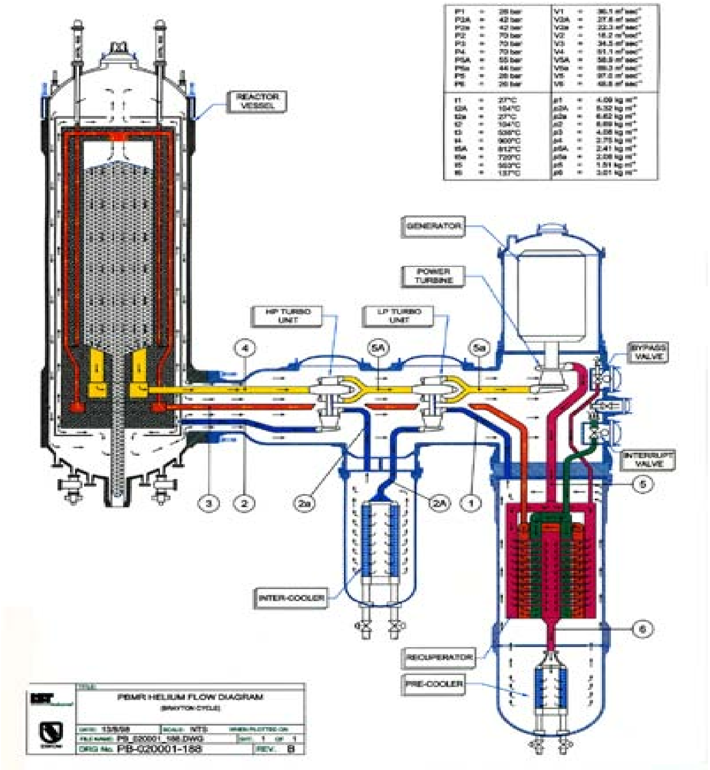
Project Overview

- **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

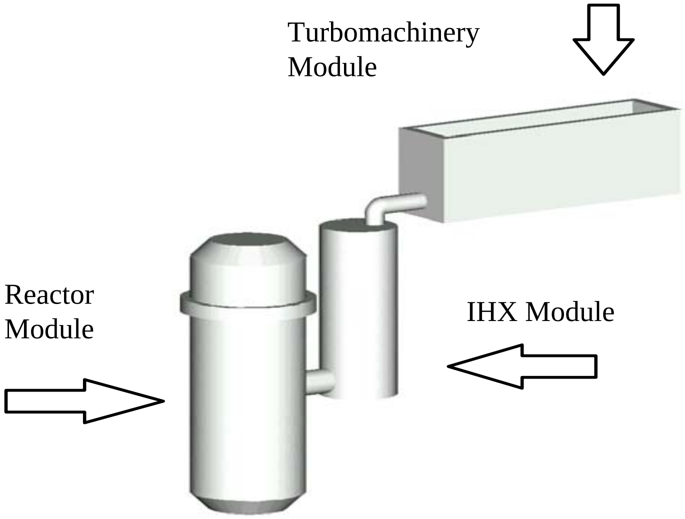
Thermal Power	250 MW - 115 Mwe
Target Thermal Efficiency	45 %
Core Height	10.0 m
Core Diameter	3.5 m
Pressure Vessel Height	16 m
Pressure Vessel Radius	5.6 m
Number of Fuel Pebbles	360,000
Microspheres/Fuel Pebble	11,000
Fuel	UO_2
Fuel Pebble Diameter	60 mm
Fuel Pebble enrichment	8%
Uranium Mass/Fuel Pebble	7 g
Coolant	Helium
Helium mass flow rate	120 kg/s (100% power)
Helium entry/exit temperatures	450ºC/850ºC
Helium pressure	80 bar
Mean Power Density	3.54 MW/m^3
Number of Control Rods	6

PBMR-Direct Cycle



MIT Indirect Cycle

Conceptual Design Layout



Turbomachinery Module

Reactor Module

IHX Module

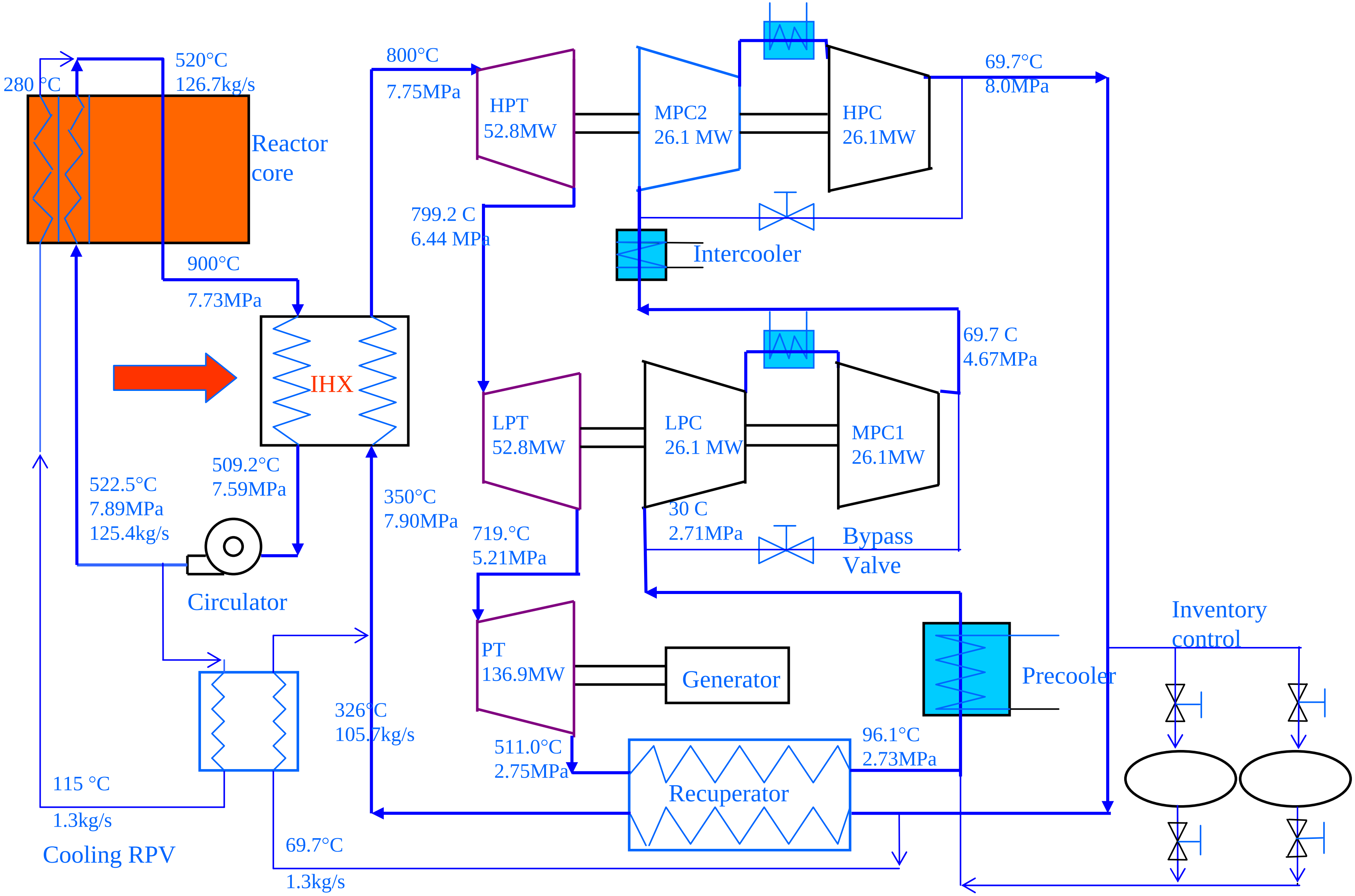
PBMR - MIT/INEEL Projects

PBMR	**MIT/INEEL**
Commercial	Private/Government
Direct Cycle	Indirect Cycle
German Technology	US advanced Technology
Not Modular	Truly modular
German Fuel	US fuel design (U/Th/Pu)
NRC site specific application (exemptions)	NRC Certification using License by Test
Repair Components	Replace Components

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

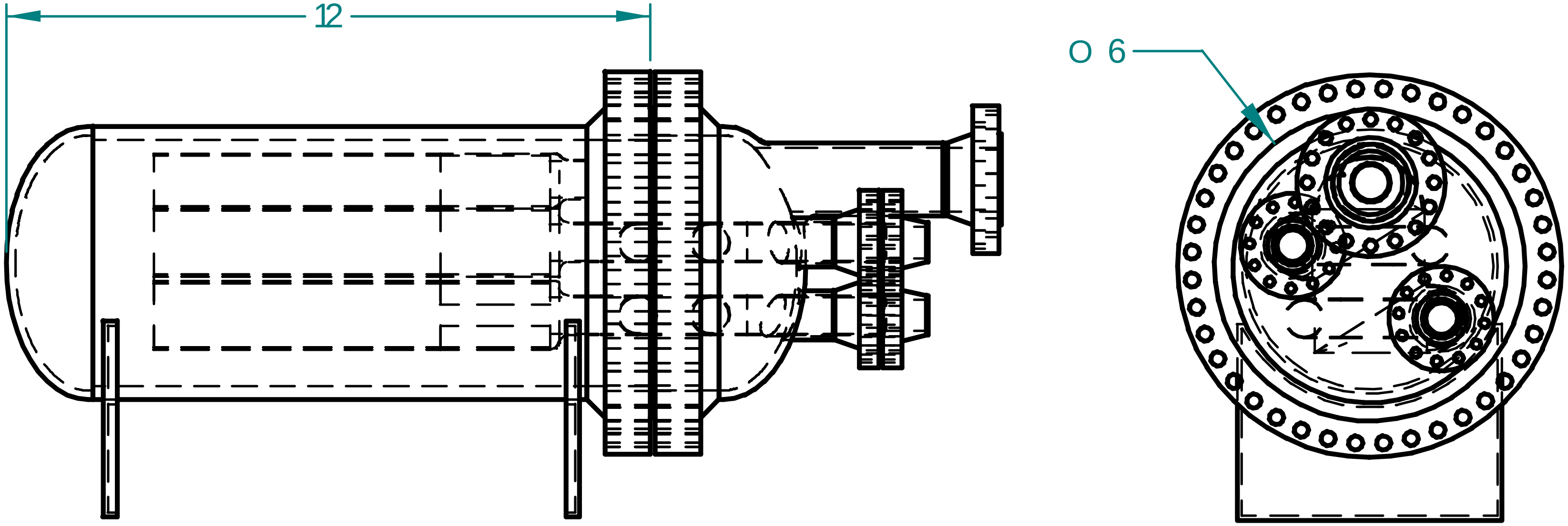


Mechanical Design Constraints

- Size/Modularity
  - Manufacturing off site
  - Transportation to construction site
  - Maintenance during operation

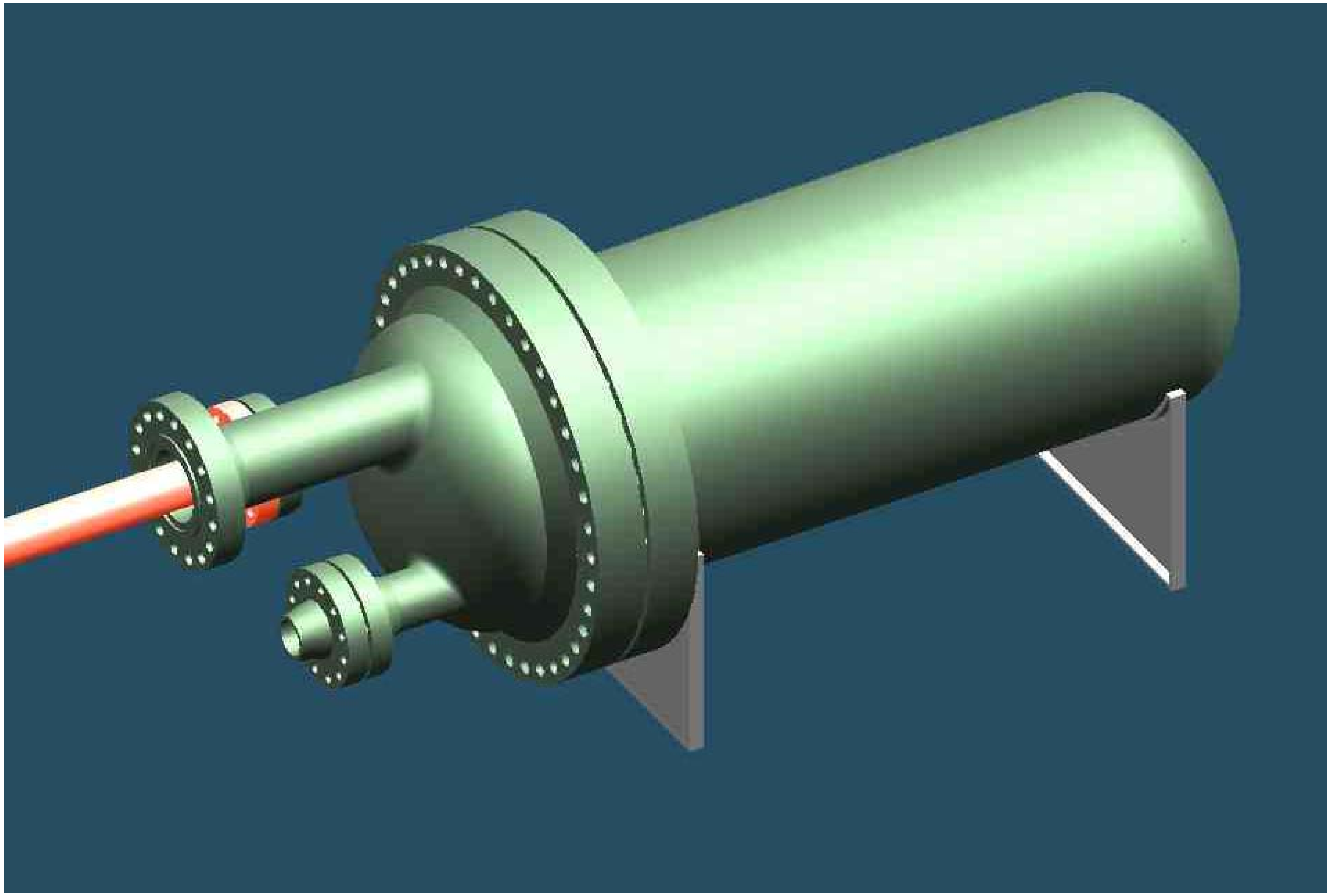
- ASME Boiler & Pressure Vessel Codes
  - Section III for Nuclear Components
  - Section VIII for Balance of Plant

IHX Outer Configuration

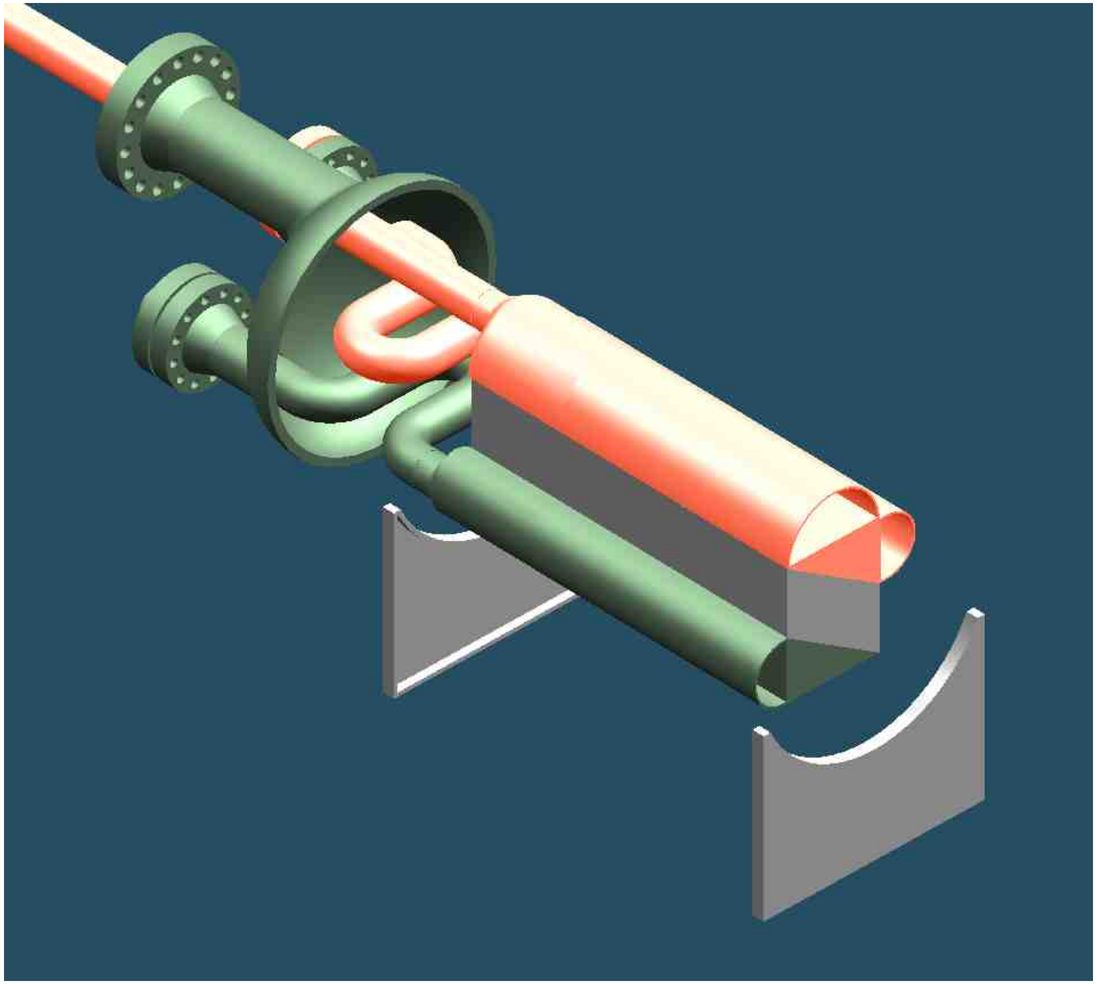


Units U.S. Customary

IHX Outer Pictorial



IHX Internal Pictorial



MPBR Modularity

Marc V Berte
Prof. Andrew Kadak

MIT Nuclear Engineering Department

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

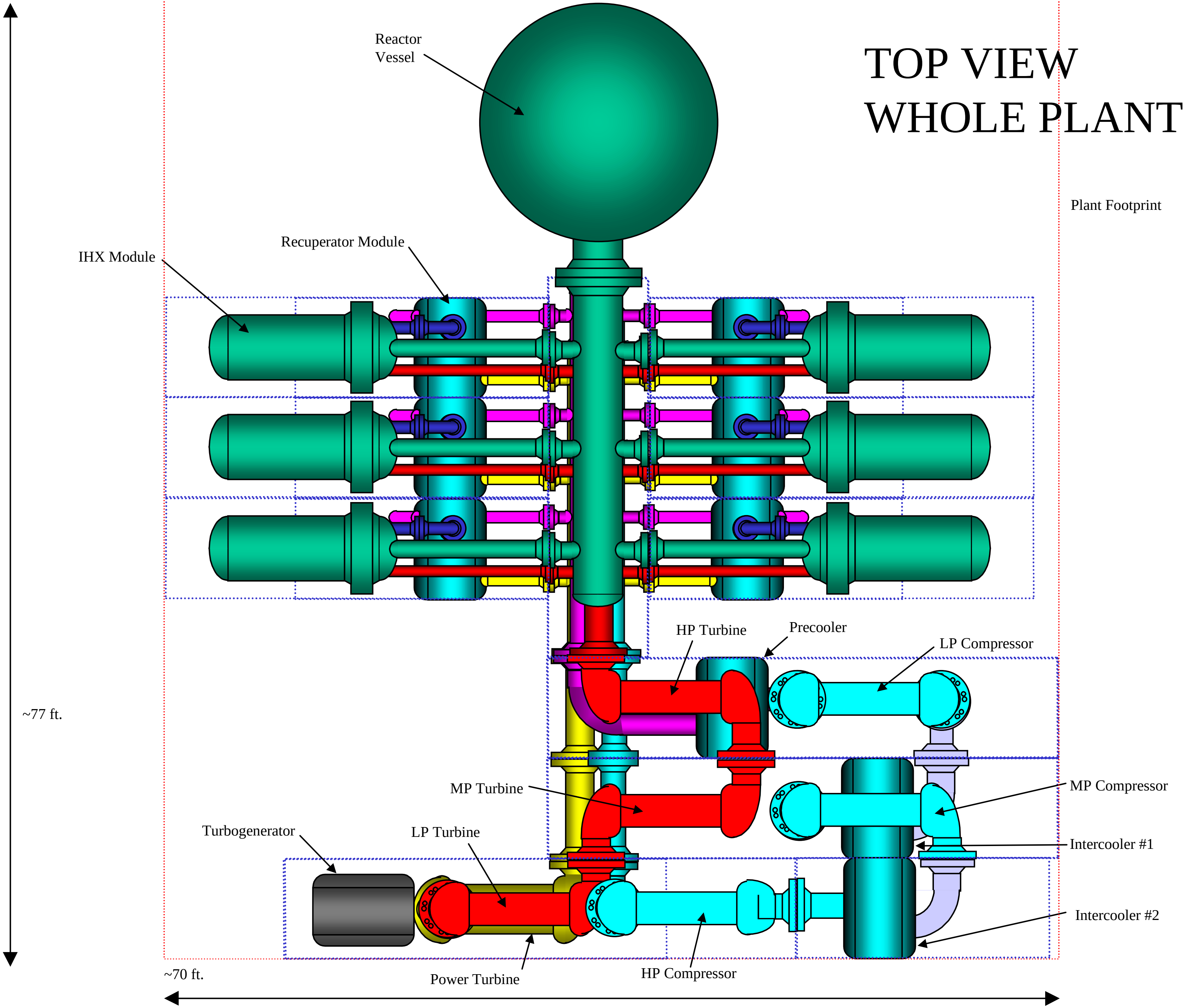
MPBR **Modularity** Plan

- 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

Design Elements

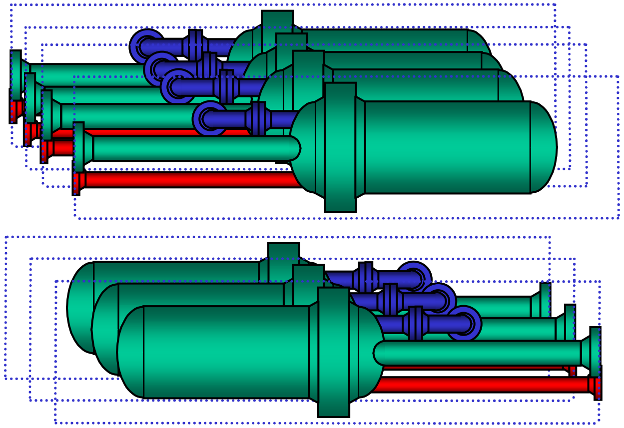
- Assembly
    - Self-locating Space-frame Contained Modules and Piping.
    - Bolt-together Flanges Join Module to Module
    - Space-frame Bears Facility Loads, No Additional Structure
- Transportation / Delivery
    - Road-mobile Transportation Option
        - Reduces Site Requirements (Rail Spur Not Required)
    - Module Placement on Site Requires Simple Equipment
- Footprint
    - Two Layer Module Layout Minimizes Plant Footprint
    - High Maintenance Modules Placed on Upper Layer

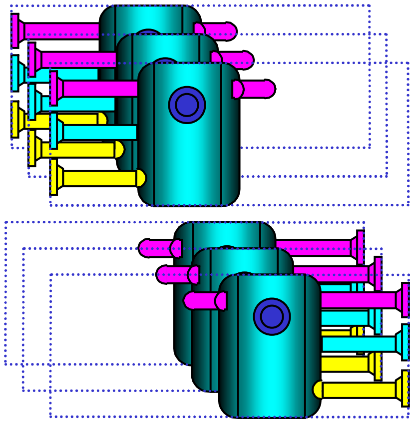
TOP VIEW
WHOLE PLANT

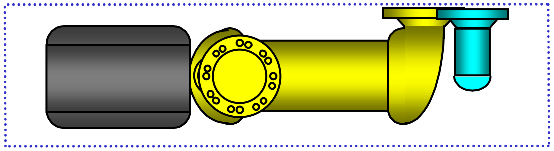


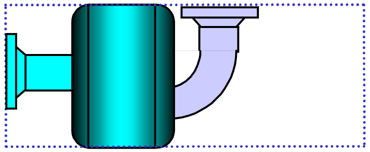
PLANT MODULE SHIPPING BREAKDOWN

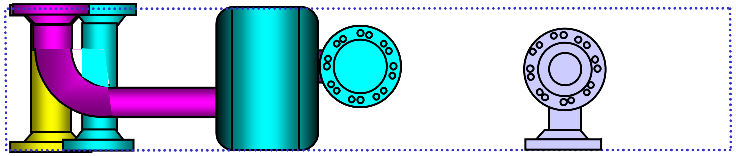
Total Modules Needed For Plant Assembly (21): Nine 8x30 Modules, Five 8x40 Modules, Seven 8x20 Modules

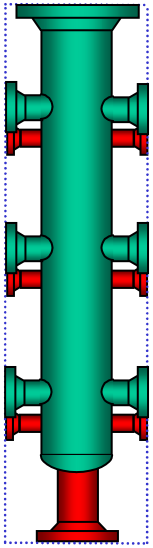

Six 8x30 IHX Modules

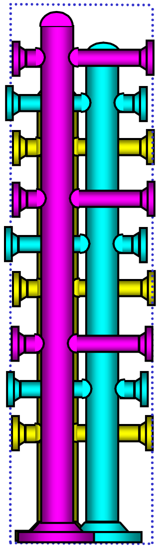

Six 8x20 Recuperator Modules

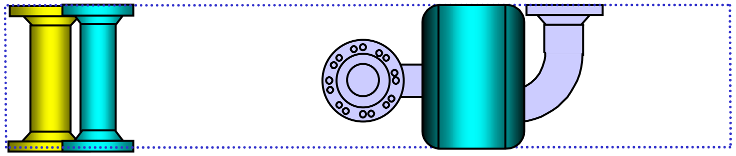

8x30 Power Turbine Module

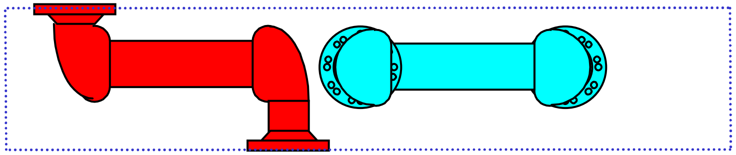

8x20 Intercooler #2 Module

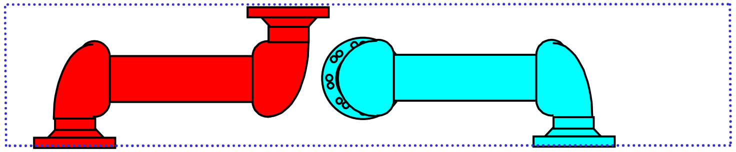

8x40 Piping and Precooler Module

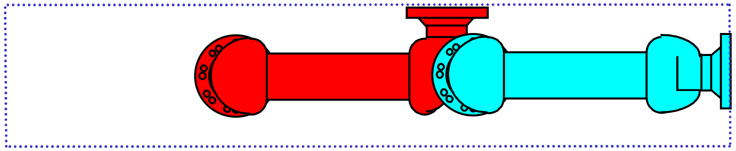

8x30 Upper Manifold Module


8x30 Lower Manifold Module

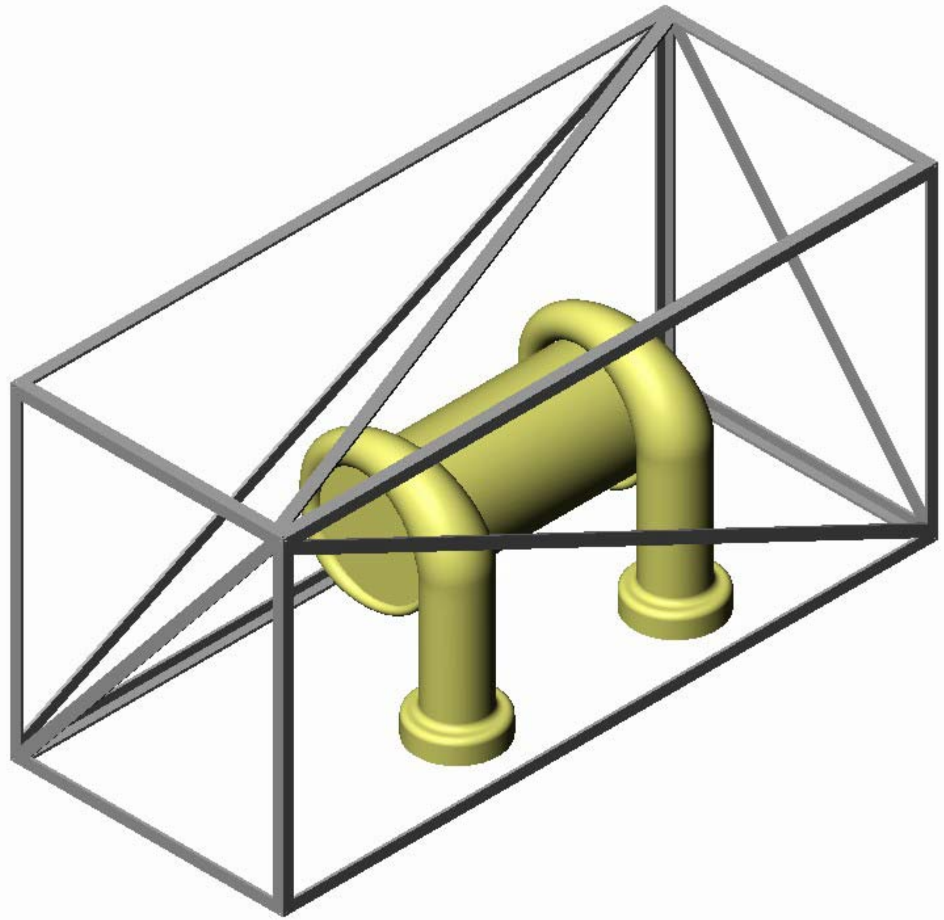

8x40 Piping & Intercooler #1 Module


8x40 HP Turbine, LP Compressor Module

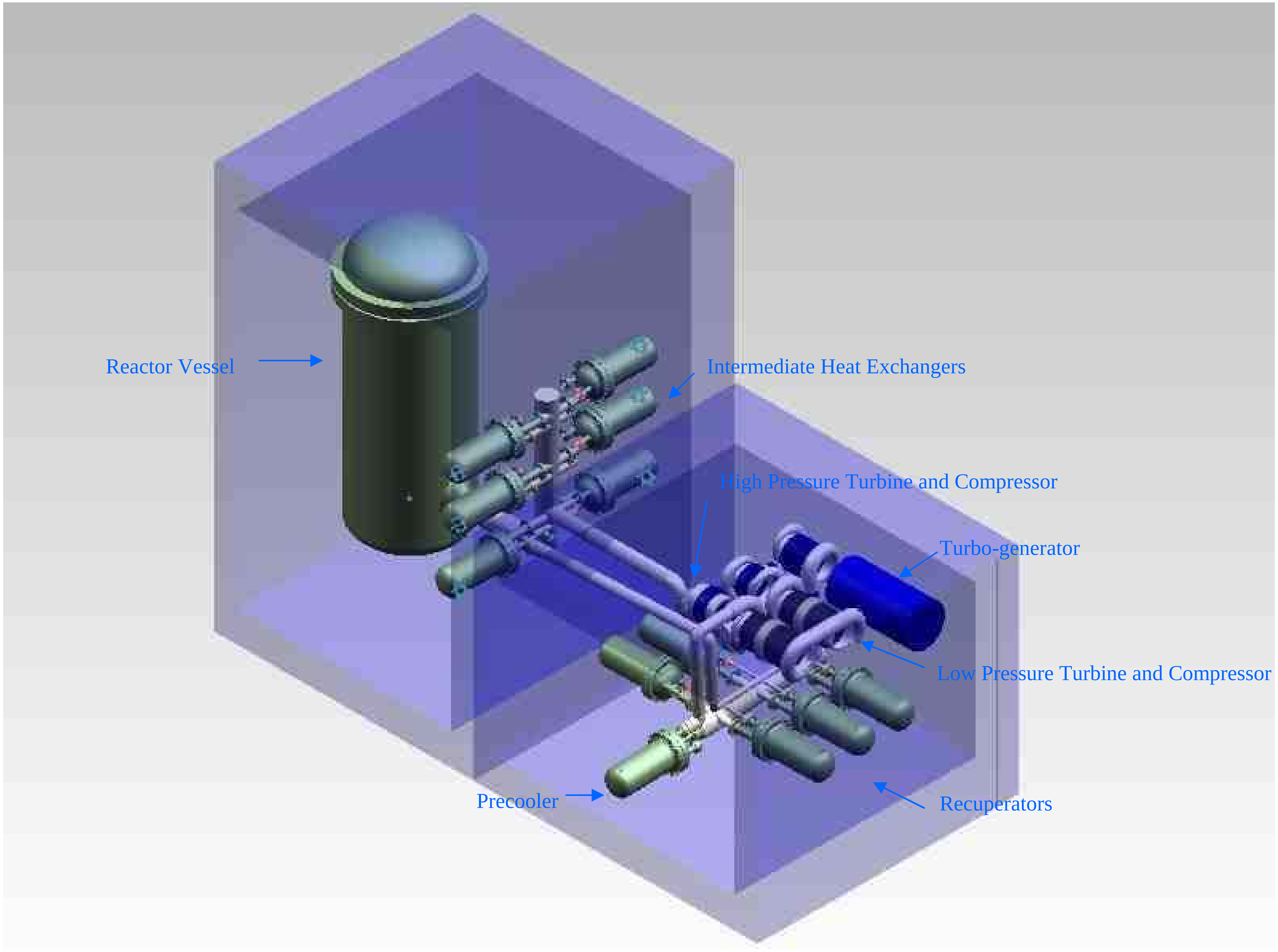

8x40 MP Turbine, MP Compressor Module

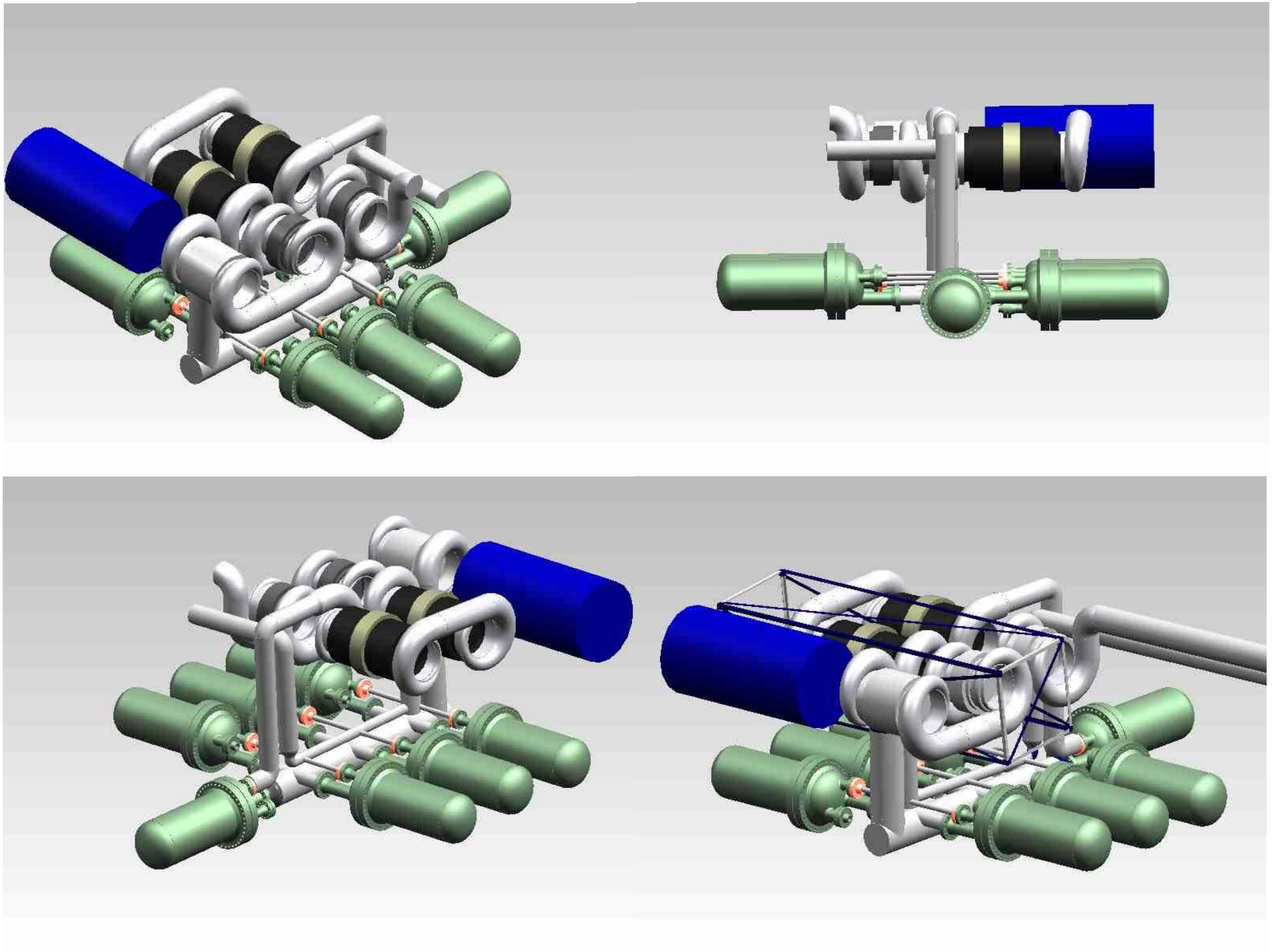

8x40 LP Turbine, HP Compressor Module

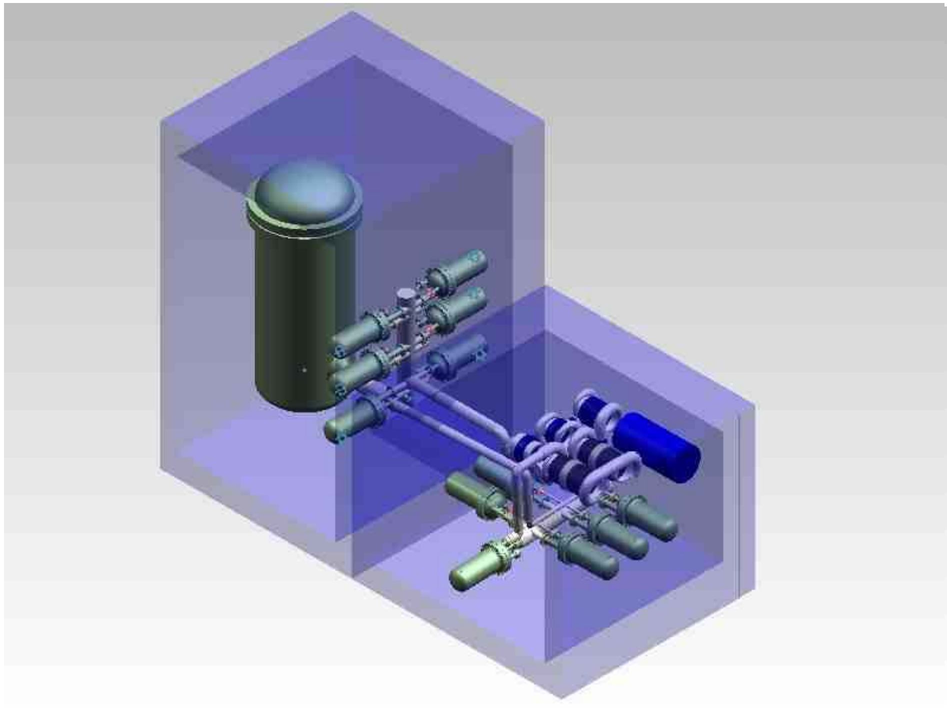
Space Frame Technology for Shipment and Assembly

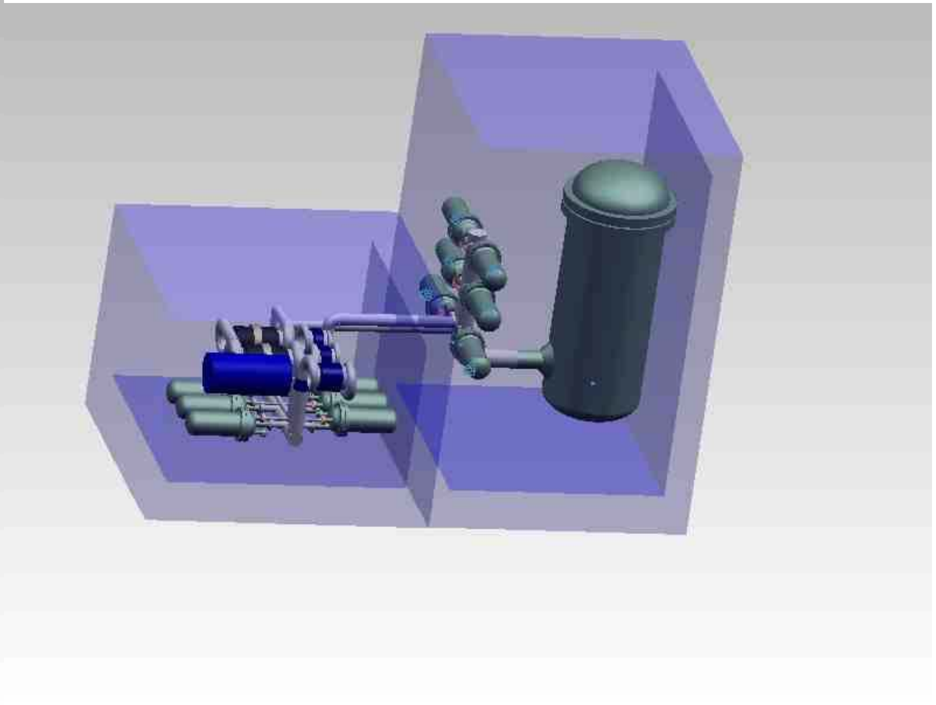


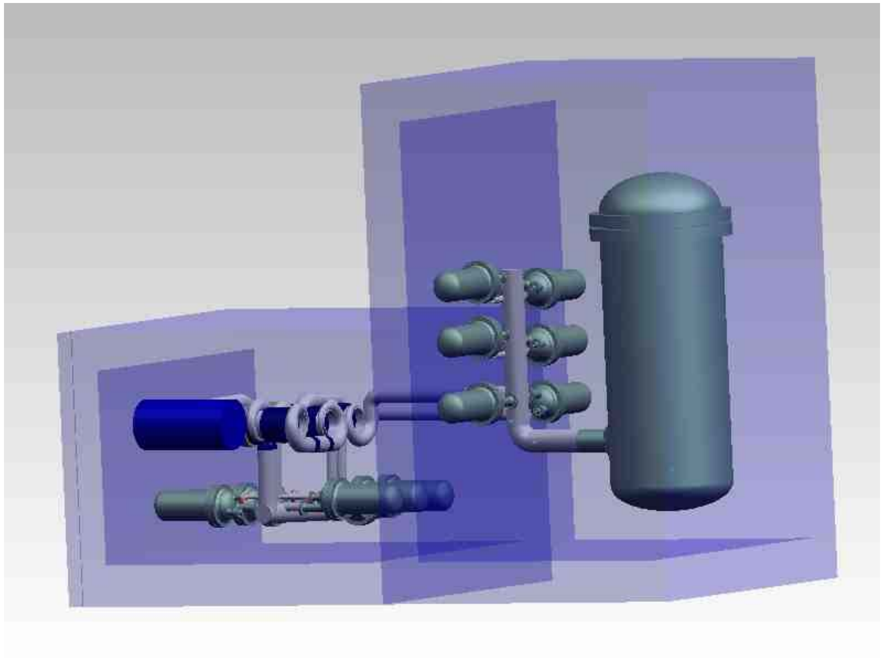
Current MIT/INEEL Design Layout



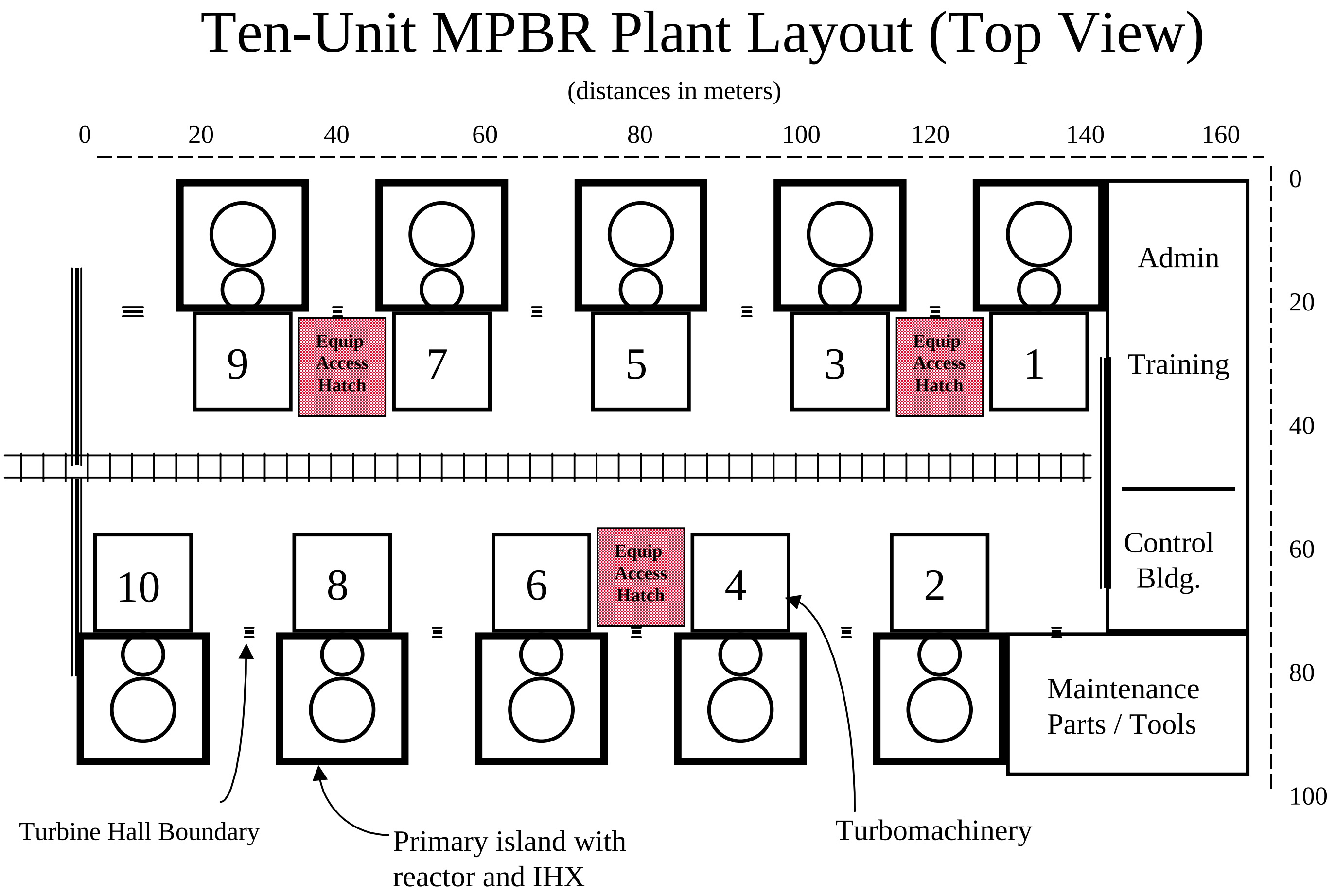




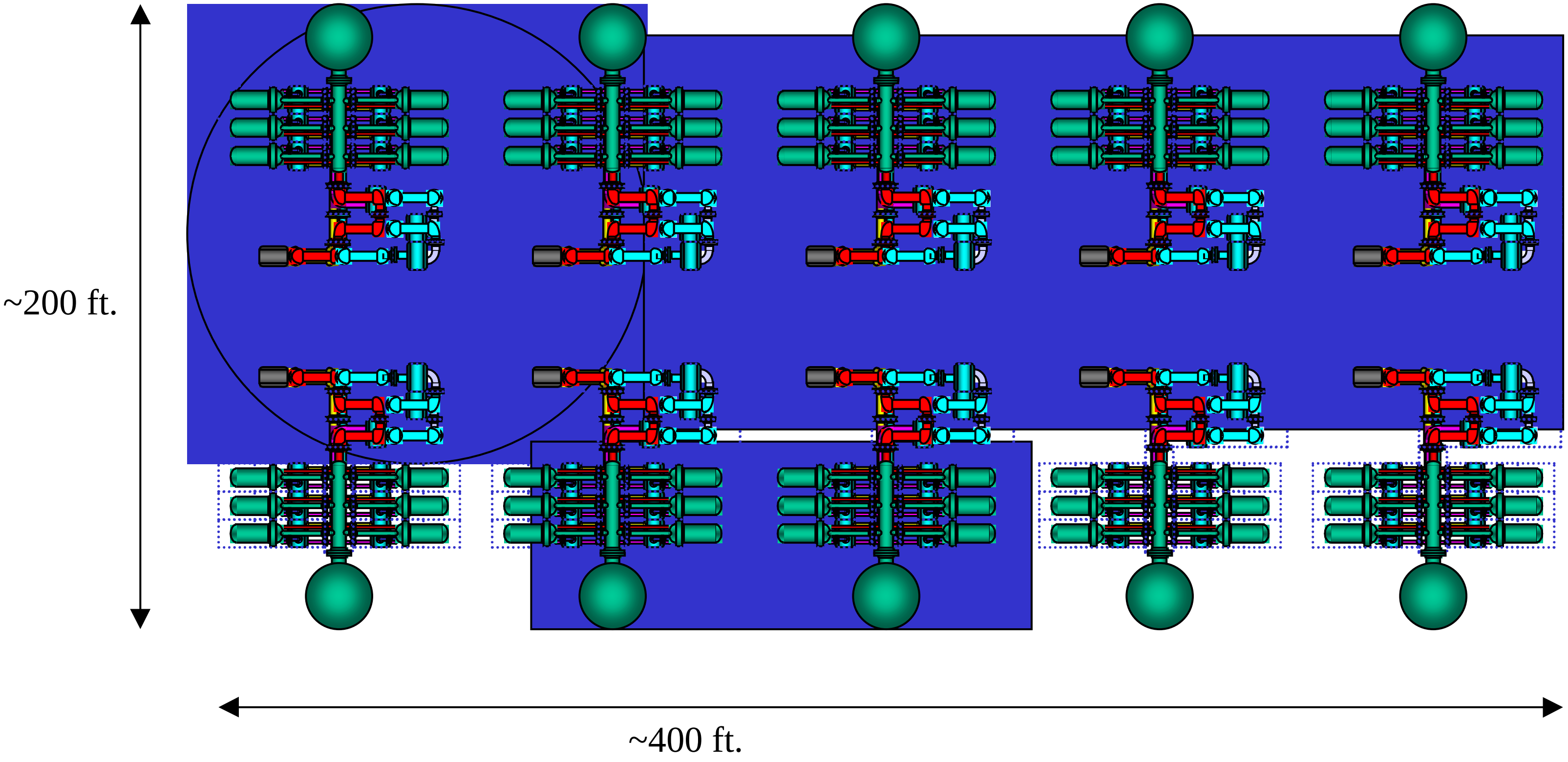




For 1150 MW Electric Power Station



AP1000 Footprint Vs. MPBR-1GW

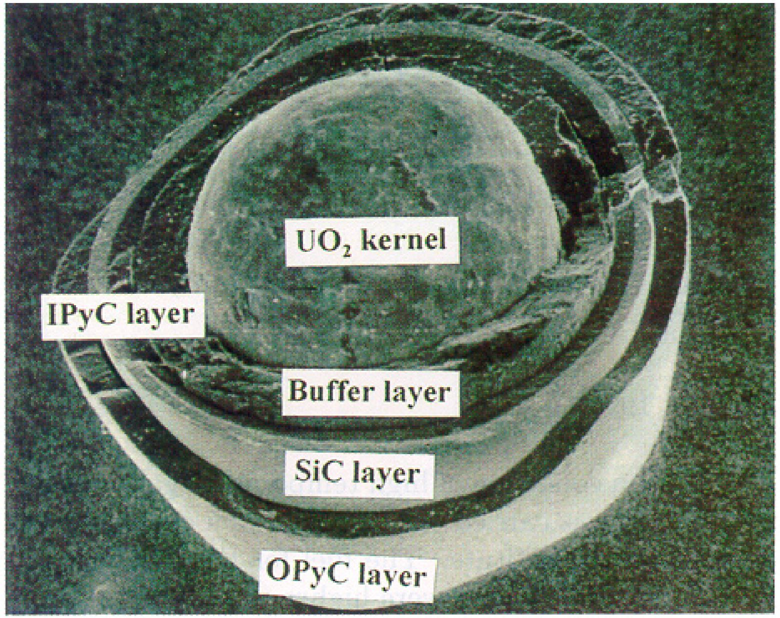


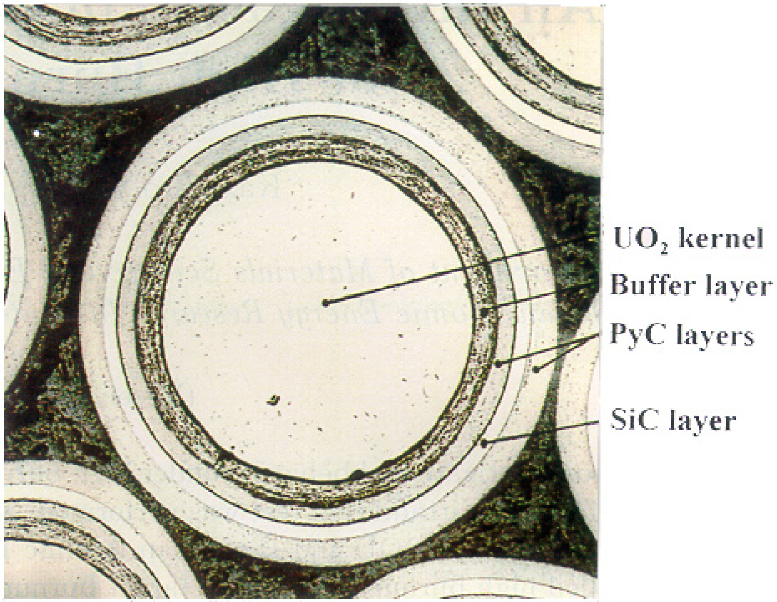
Fuel

The Key Safety System

- Develop Fuel Performance Model
- Identify Barriers to Diffusion of Silver
- Understand impact of Palladium on SiC
- Develop an optimized design for reliability
- Work with manufacturer to optimize
- Make fuel and test

Coated TRISO Fuel Particles





IPyC/SiC/OPyC: structural layers as pressure vessel and fission product barrier

Buffer PyC: accommodate fission gases and fuel swelling

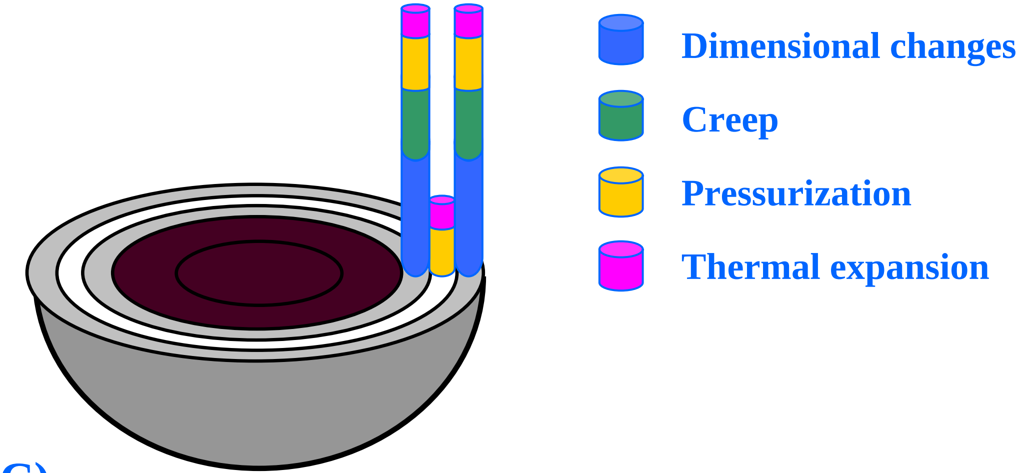
From Kazuhiro Sawa, et al., J. of Nucl. Sci. & Tech., 36, No. 9, pp. 782. September 1999

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.

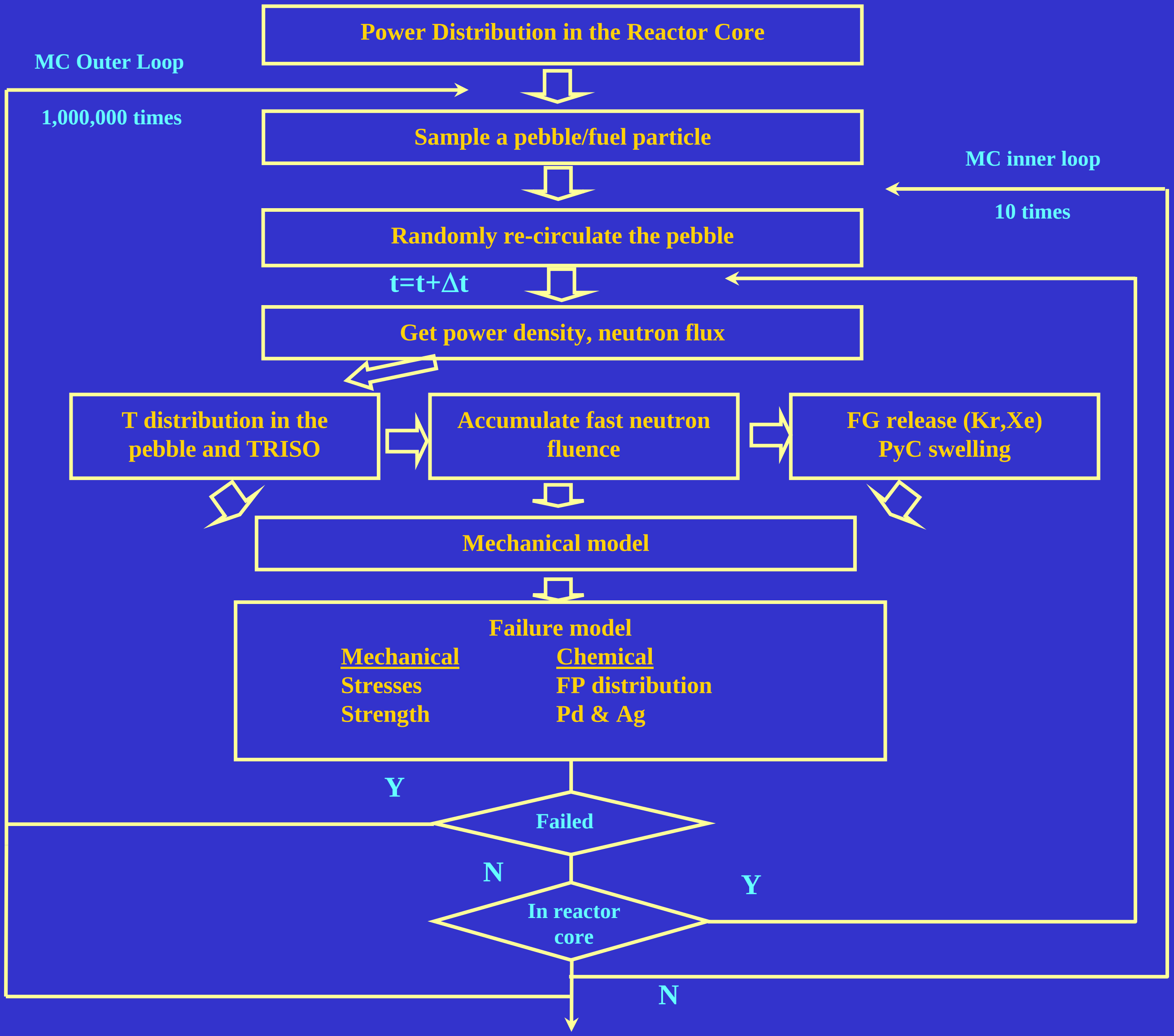
Mechanical Analysis

- **System: IPyC/SiC/OPyC**
- **Methods: Analytical or Finite Element**
- **Viscoelastic Model**
- **Mechanical behavior**
  - **irradiation-induced dimensional changes (PyC)**
  - **irradiation-induced creep (PyC)**
  - **pressurization from fission gases**
  - **thermal expansion**



Stress contributors to IPyC/SiC/OPyC

Integrated Fuel Performance Model



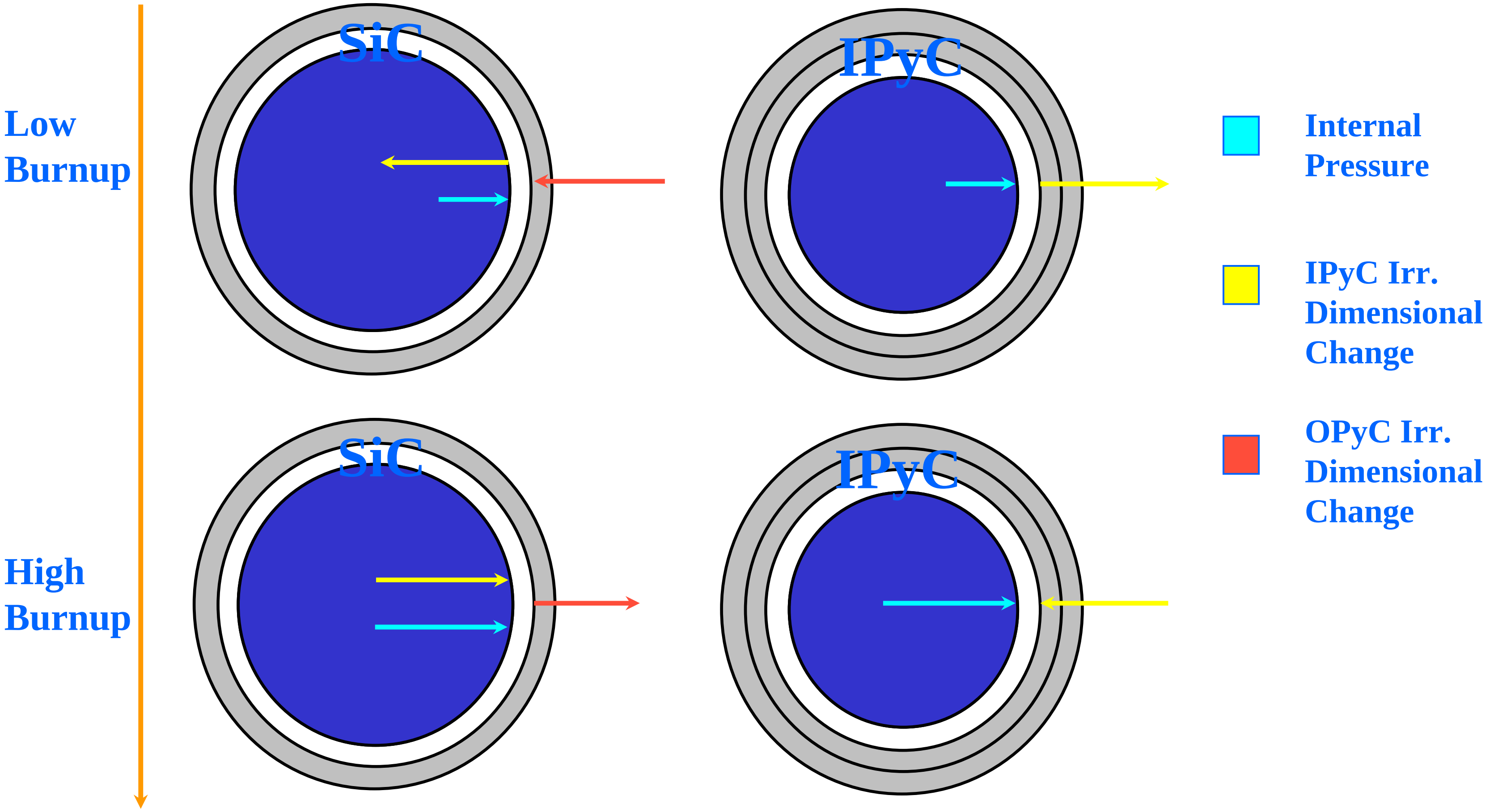
MC outer loop:

samples fuel particles of statistical characteristics

MC inner loop:

implements refueling scheme in reactor core

Stress Contributors



Barrier Integrity

- Silver Diffusion observed in tests @ temps
- Experiments Proceeding with Clear Objective - Understand phenomenon
- Palladium Attack Experiments Underway
- Zirconium Carbide being tested as a reference against SiC.
- Focus on Grain SiC Structure Effect
- Will update model with this information

Silver Diffusion Couples

Spherical Shells

- Graphite substrate 760 μm

  chemical conditioning

  ~15% porosity

- Fission product inside

  powder

- SiC or ZrC coating

  ~50 μm thick

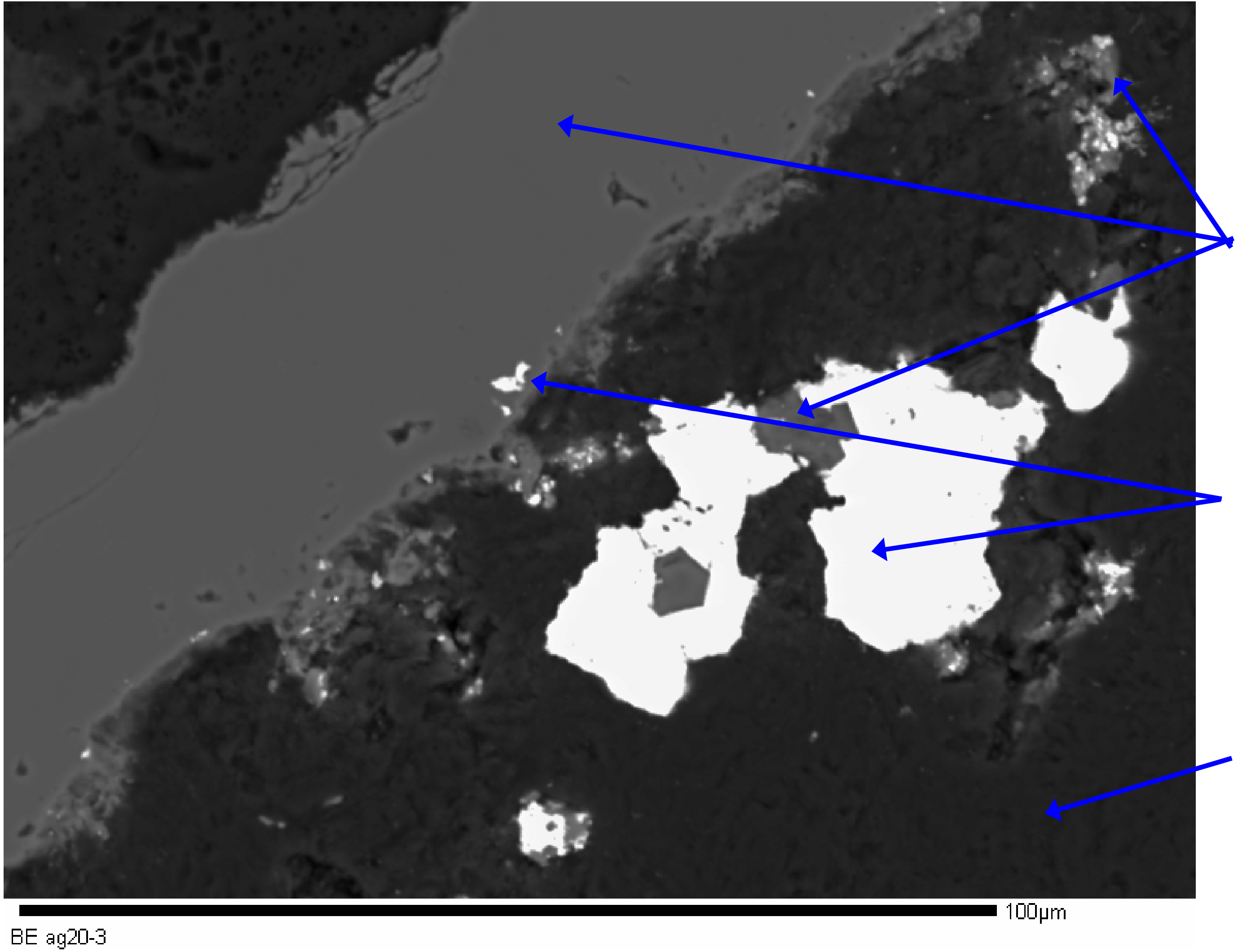
  silver can ONLY diffuse

  through graphite and barrier

3/4 inch OD **30 mil thick wall**

Silver Migration -- Ag20

Backscatter Electron Image



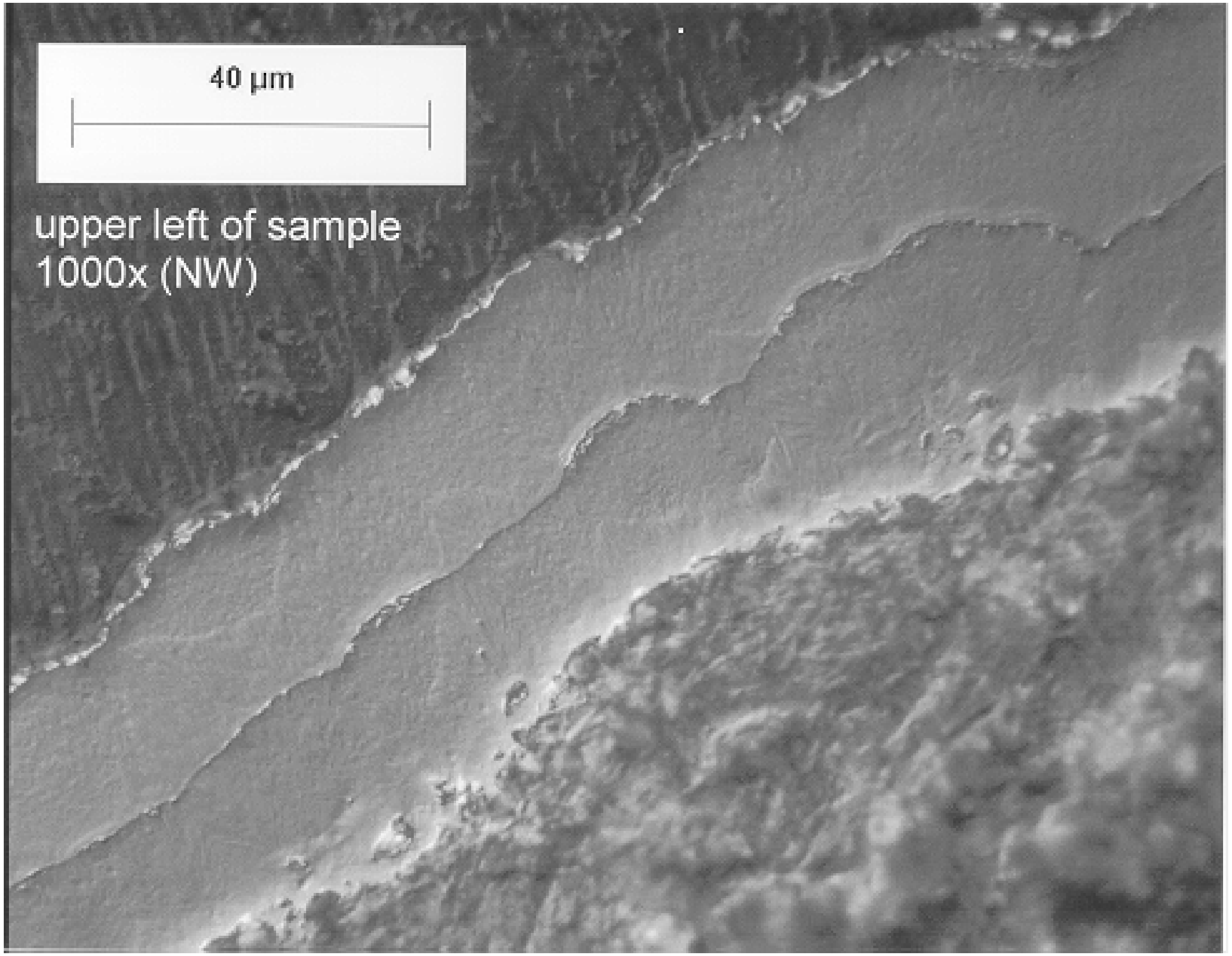
SiC
(light gray)

Silver
(bright white)

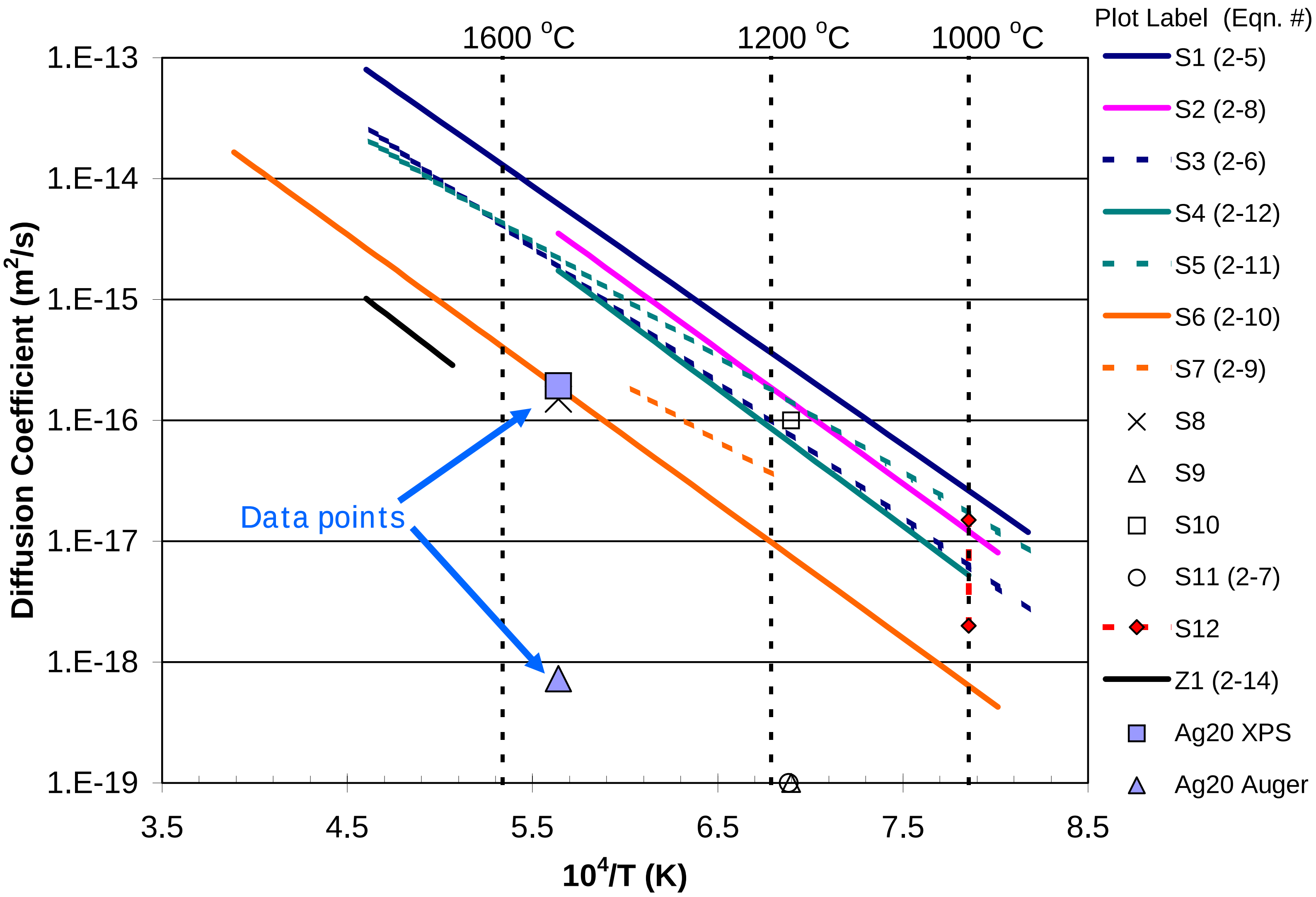
Graphite
(dark gray)

SiC Microstructure -- Ag29

Optical Microscopy (1000x)

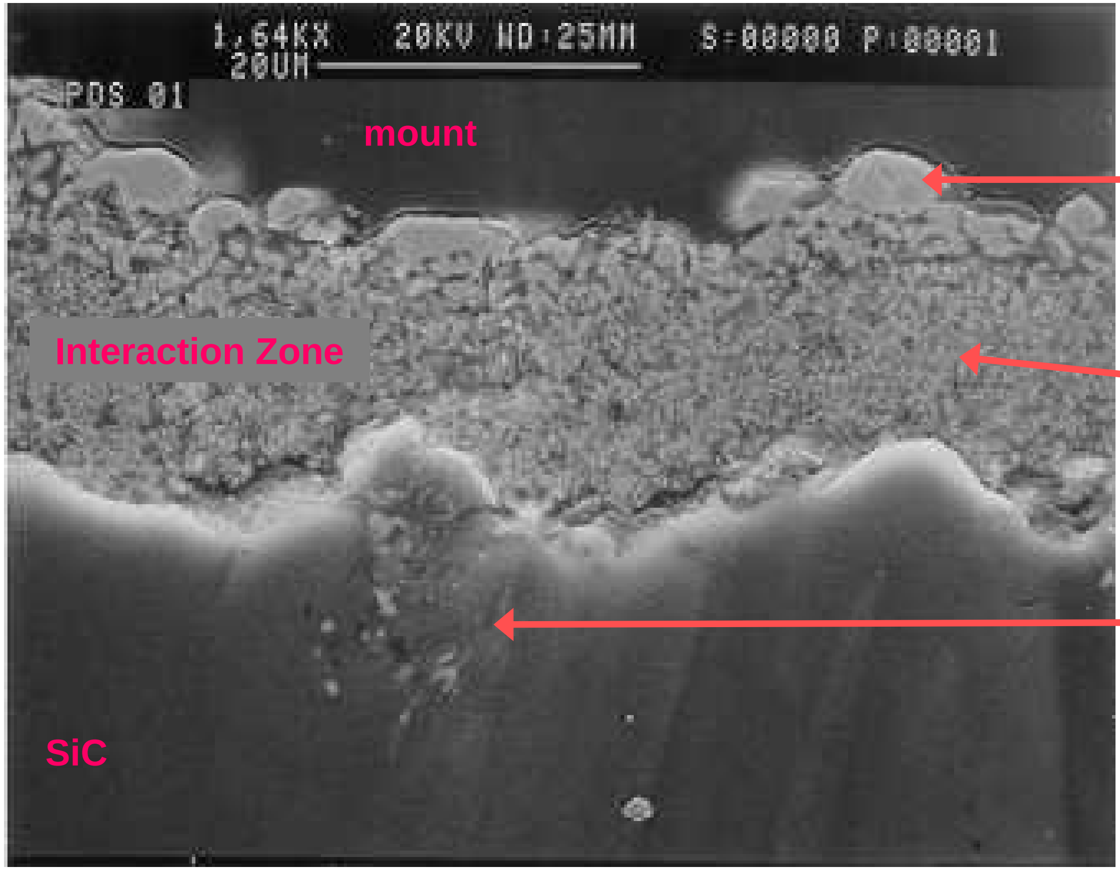


Calculated Diffusion Coefficients



Pd-SiC Interaction

Sample PdS01, Backscatter Electron Image



Atomic %

Pd : 32
Si : 14
C : 54

Pd : 22
Si : 10
C : 68

Pd : 9
Si : 26
C : 65

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
- VSOP Verification and Validation Effort Beginning
- Working on International Benchmark

MCNP4B Modeling of Pebble Bed Reactors

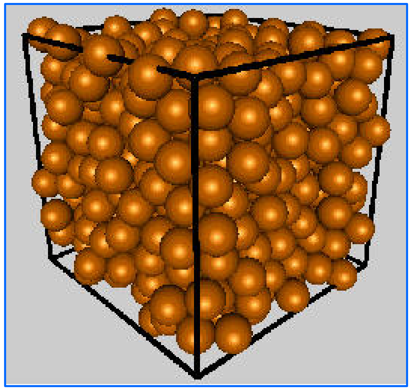
Steps in Method Development

PROTEUS critical experiments @ PSI	▪ simple cores ▪ stochastic packing
HTR-10 physics benchmark	▪ predict criticality ▪ *cf.* measurement
ASTRA critical experiments @ KI	▪ mockup of PBMR ▪ annular core
PBMR South Africa	▪ startup core ▪ MCNP *vs.* VSOP

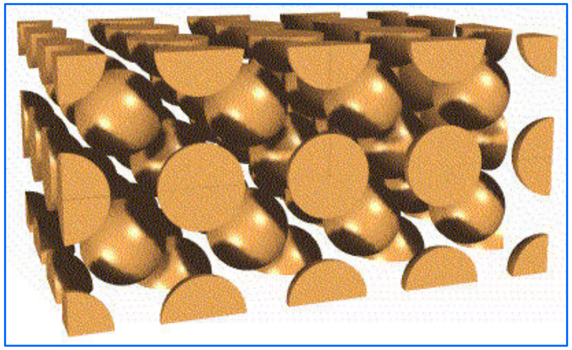
Modeling Considerations

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

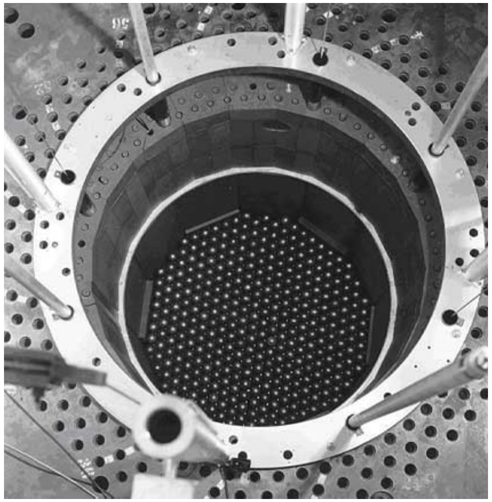


Body Centered Cubic

HTR-PROTEUS *(PSI)*

Zero-power critical facility:

- Graphite reflector
- Core: $R_c \approx 60$ cm, $H \approx 150$ cm
- Fuel/mod sphere: $R_s = 3$ cm
- TRISO fuel with 5.966 g U/FS
- 16.76% U235; F/M = 1



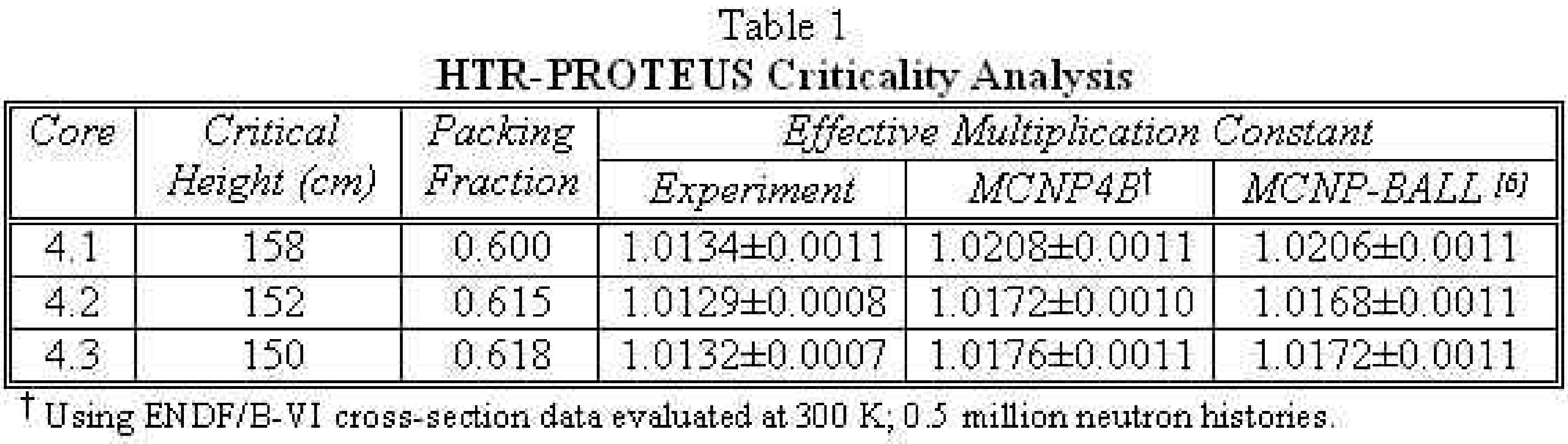


Table 1

HTR-PROTEUS Criticality Analysis

Core	Critical Height (cm)	Packing Fraction	Effective Multiplication Constant		
			Experiment	MCNP4B†	MCNP-BALL [6]
4.1	158	0.600	1.0134±0.0011	1.0208±0.0011	1.0206±0.0011
4.2	152	0.615	1.0129±0.0008	1.0172±0.0010	1.0168±0.0011
4.3	150	0.618	1.0132±0.0007	1.0176±0.0011	1.0172±0.0011

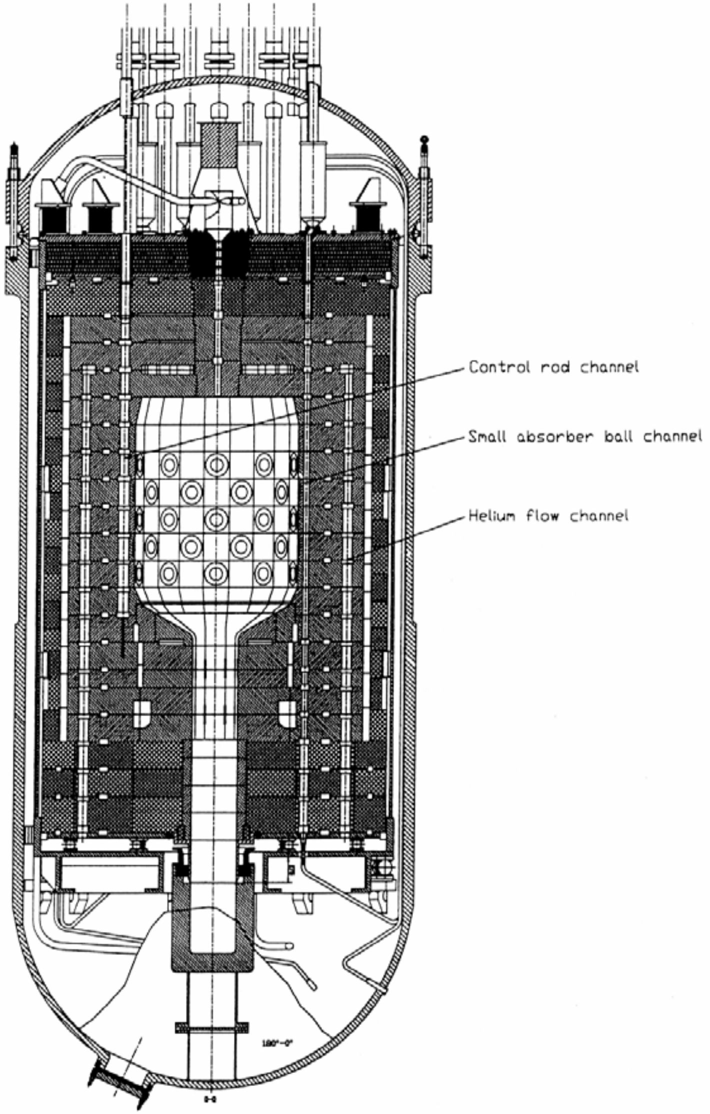
† Using ENDF/B-VI cross-section data evaluated at 300 K; 0.5 million neutron histories.

[6] JAERI calculation using version of MCNP with a stochastic geometry feature.

HTR-10 (*Beijing*)

10 MW Pebble Bed Reactor:

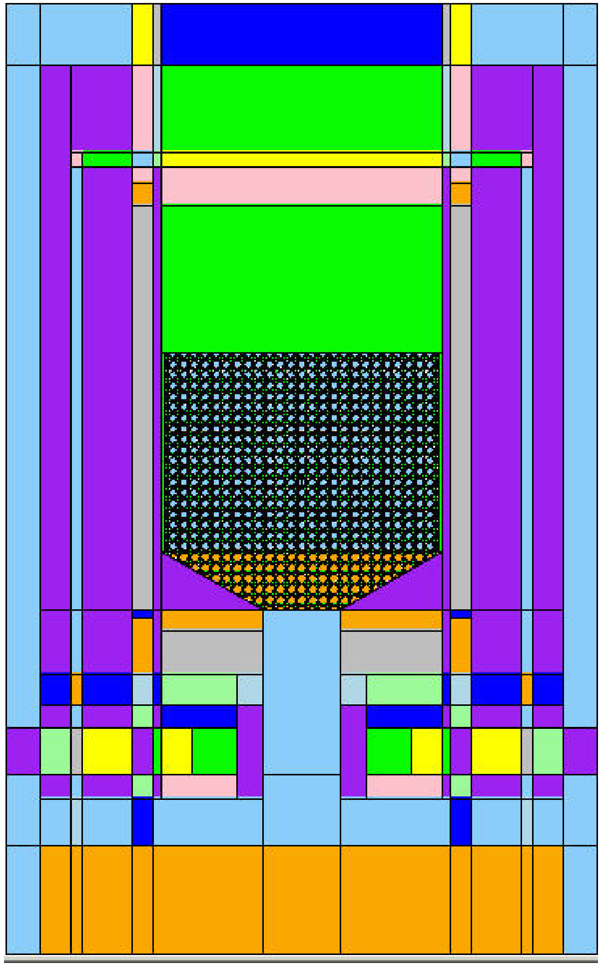
- Graphite reflector
- Core: R_c = 90 cm, H ≤ 197 cm
- TRISO fuel with 5 g U/Fuel Sphere
- 17% U235
- F/M *sphere* ratio = 57:43, modeled by reducing moderator sphere size
- Initial criticality December 2000



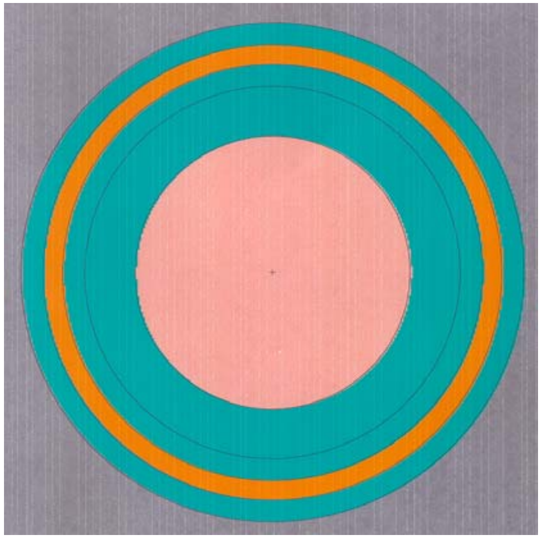
MCNP4B Results

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

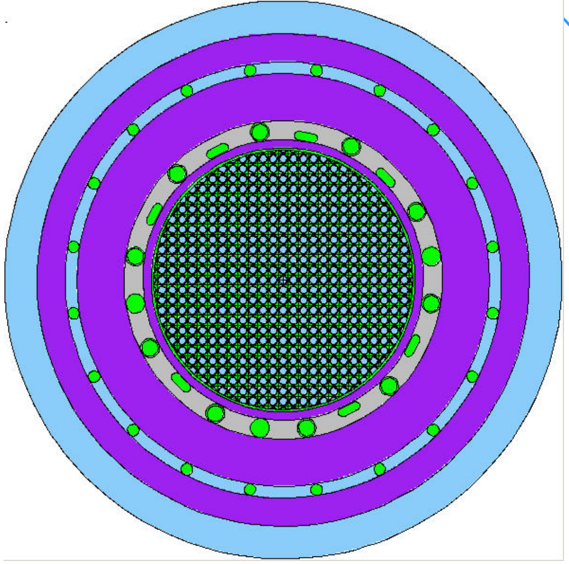
HTR-10
MCNP4B Model



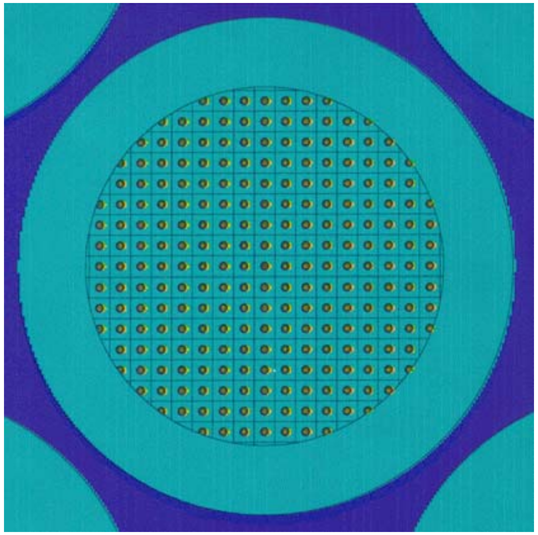
Reactor



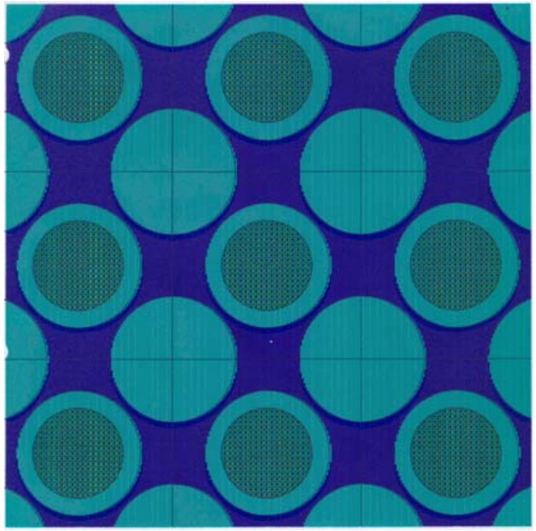
TRISO fuel particle



Core



Fuel sphere



Core lattice

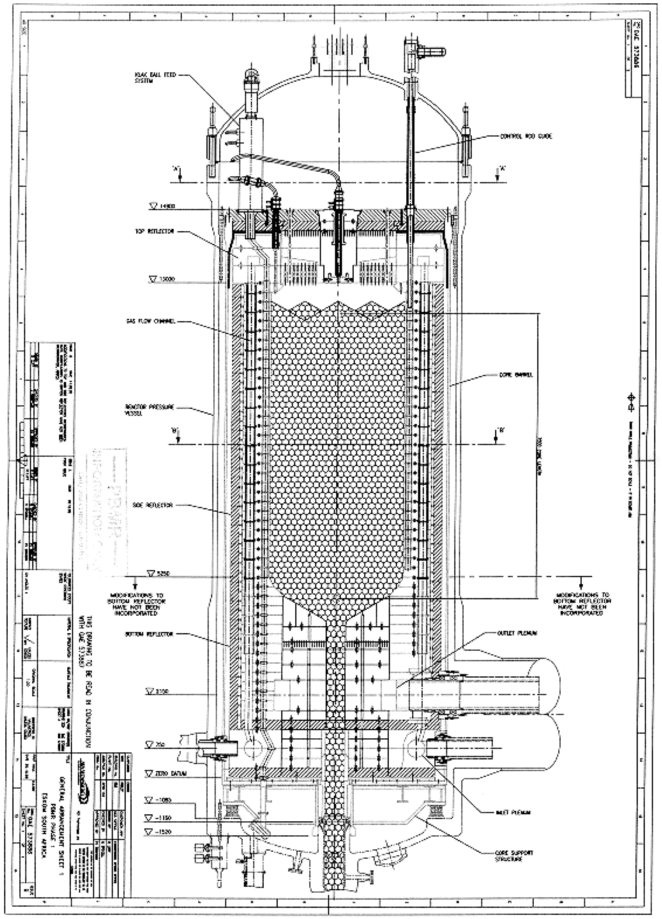
MCNP/VSOP Model of PBMR

Detailed MCNP4B model of ESKOM Pebble Bed Modular Reactor:

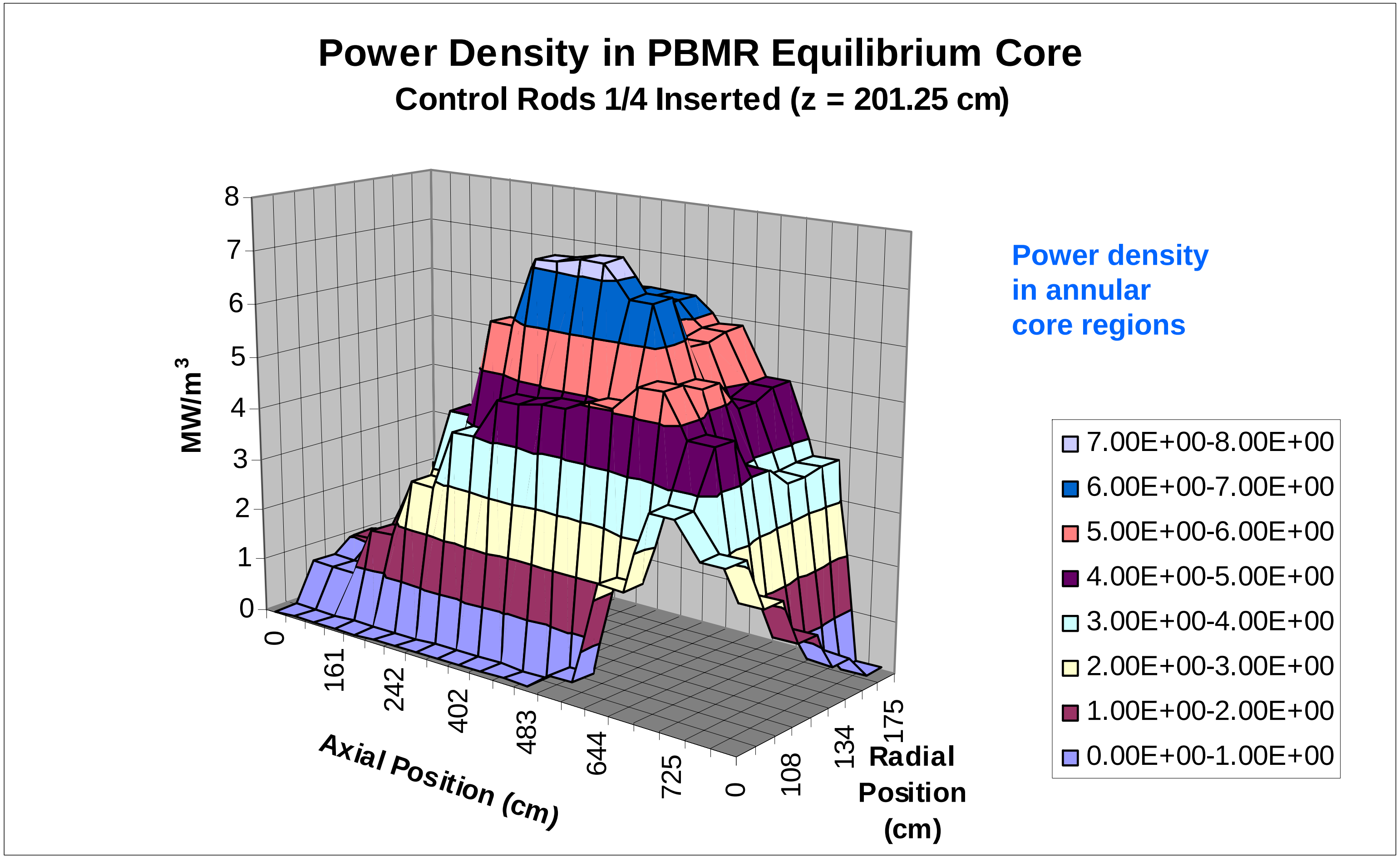
- reflector and pressure vessel
- 18 control rods (HTR-10)
- 17 shutdown sites (KLAK)
- 36 helium coolant channels

Core idealization based on VSOP model for equilibrium fuel cycle:

- 57 fuel burnup zones
- homogenized compositions



MCNP4B/VSOP Model Output



Power density in annular core regions

IAEA Physics Benchmark Problem

MCNP4B Results

B1	h = 128.5 cm	critical height (300 K)	
B20	k = 1.12780 ± 0.00079	300 K	UTX[†]
B21	k = 1.12801	293 K	| UTX, no expansion
B22	k = 1.12441	393 K	| (curve fit of k-eff @
B23	k = 1.12000	523 K	| 300 K, 450 K, 558 K)
B3	k = 0.95787 ± 0.00089	300 K	UTX
	$\Delta\rho \approx$ 157.3 mk	total control rod worth	
	($\Delta\rho \approx$ 152.4 mk	INET VSOP prediction)	

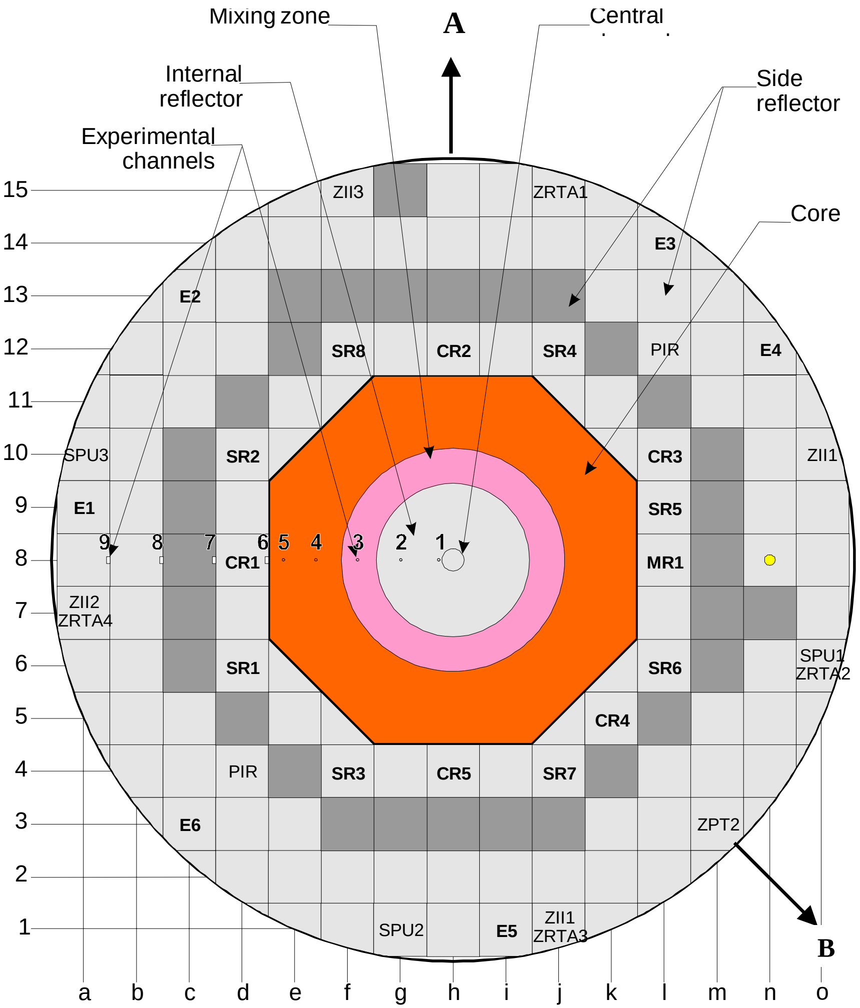
[†] Temperature dependent cross-section evaluation based on ENDF-B/VI nuclear data by U of Texas at Austin.

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:	50/47.5/2.5 105.5 cm OD	(M/F/A)
Fuel zone:	95/5 181 cm OD (equiv.)	(F/A)
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 (keff = .99977)
- Rod Worth Predictions off 10%
- Analysis Raises Issues of Coupling of Core

Safety Issues

- Fuel Performance - Key to safety case
- Air Ingress
- Water Ingress
- Loss of Coolant Accident
- Seismic reactivity insertion
- Reactor Cavity Heat Removal
- Redundant Shutdown System
- Silver and Cesium diffusion

Safety Advantages

- Low Power Density
- Naturally Safe
- No melt down
- No significant radiation release in accident
- Demonstrate with actual test of reactor

Safety

- LOCA Analysis Complete - *No Meltdown*
- Air Ingress now Beginning focusing on fundamentals of phenomenon
- Objectives
  - Conservative analysis show no “flame”
  - Address Chimney effect
  - Address Safety of Fuel < 1600 C
  - Use Fluent for detailed modeling of RV

Massachusetts Institute of Technology
Department of Nuclear Engineering

Advanced Reactor Technology Pebble Bed Project

Figure 1: The Figure of the Model

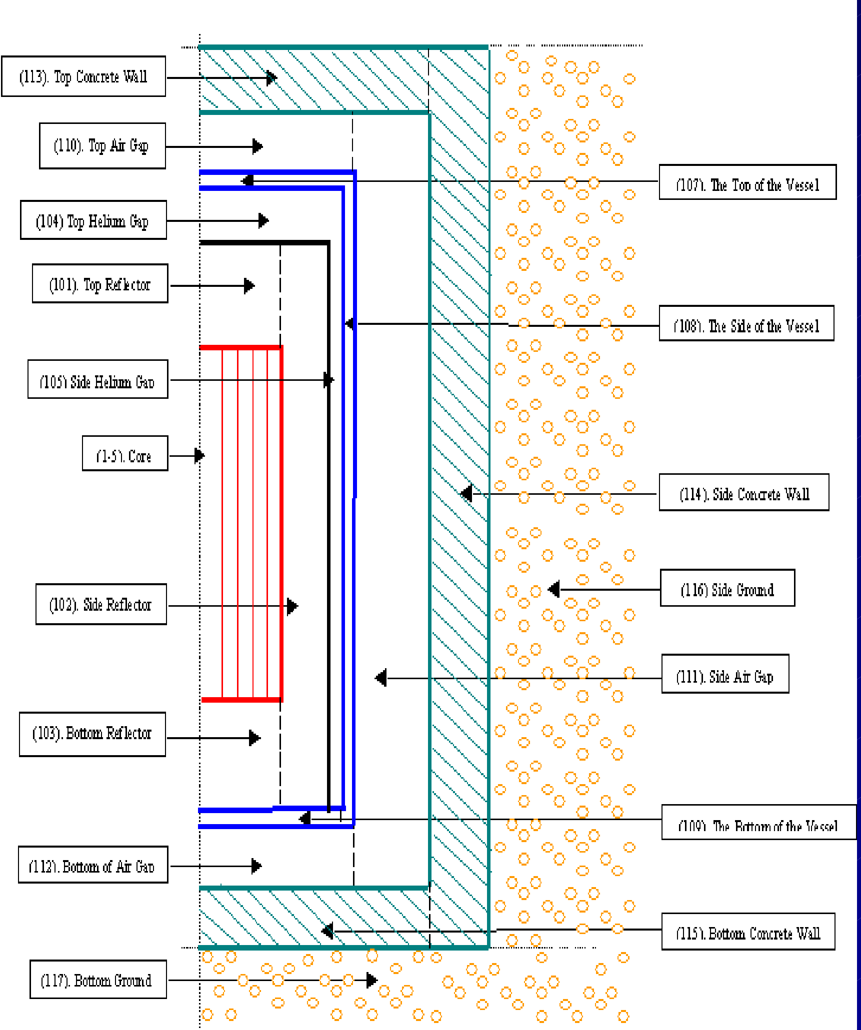
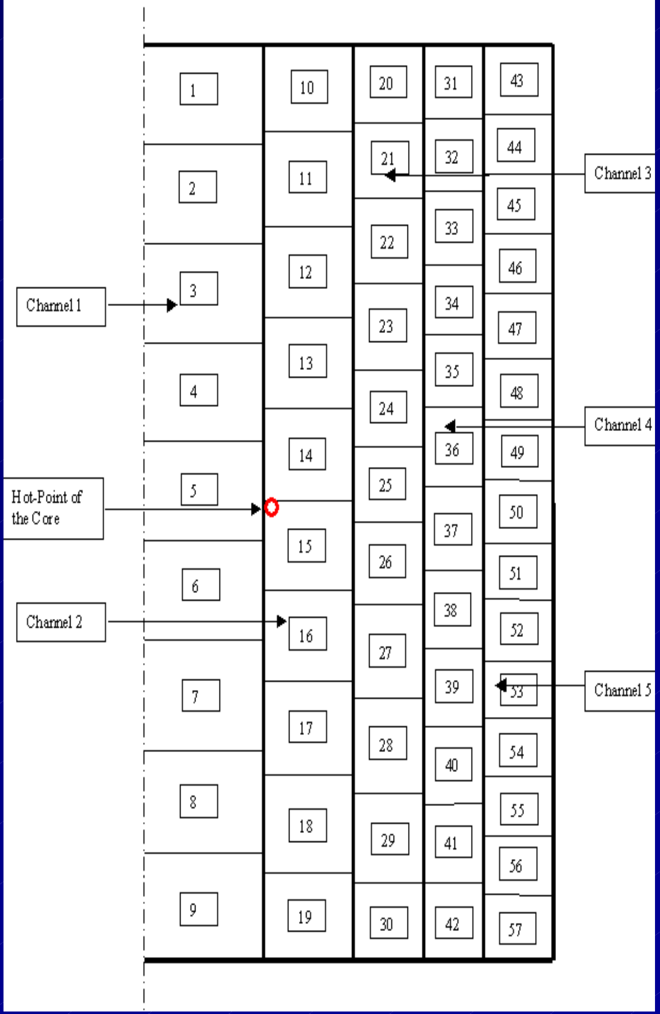
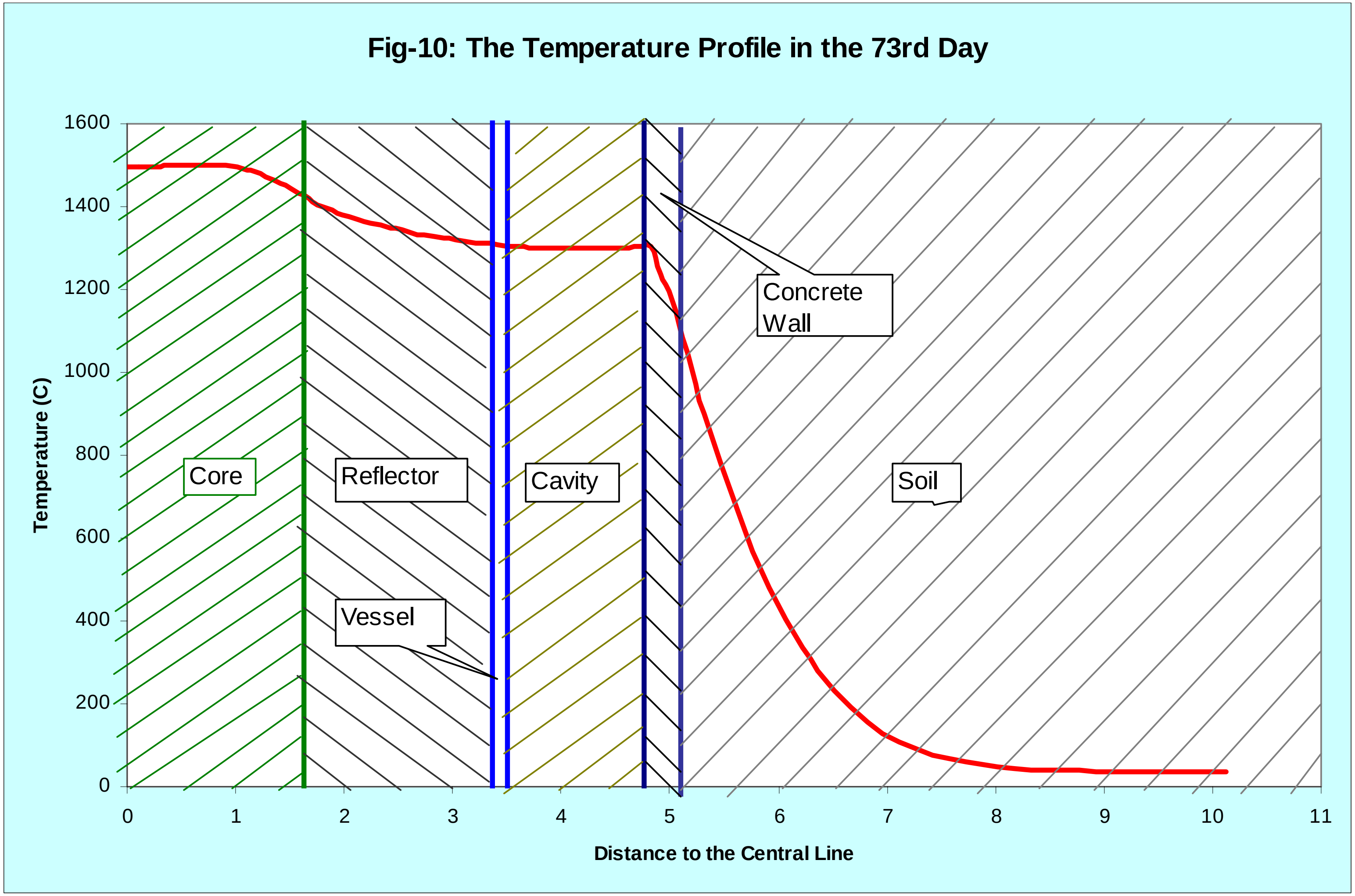


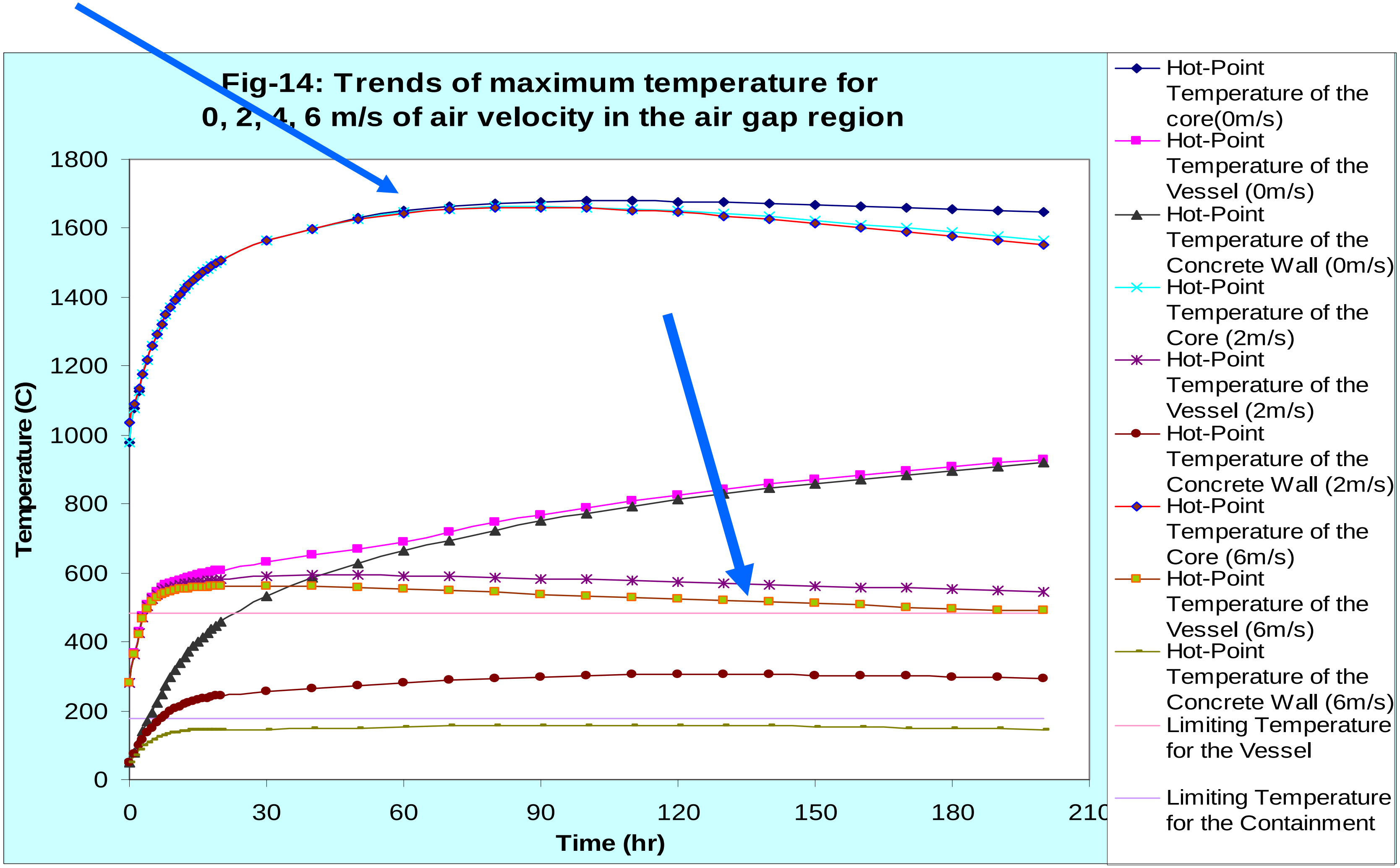
Fig-2: The Geometry of the Core



Temperature Profile

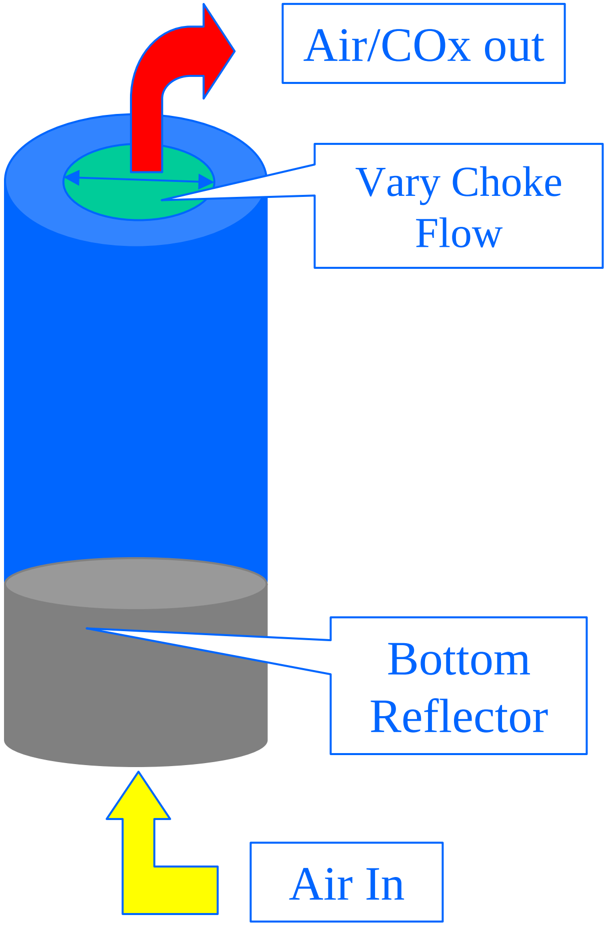


The Prediction of the Air Velocity
(By Dr. H. C. No)



Air Ingress

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



The Characteristics the Accident

- Important parameters governing these reactions
  - ❑Graphite temperature
  - ❑Partial pressures of the oxygen
  - ❑Velocity of the gases
- Three Stages:
  - ❑Depressurization (10 to 200 hours)
  - ❑Molecular diffusion.
  - ❑Natural circulation

Overall Strategy

- Theoretical Study (Aided by HEATING-7 and MathCad)
- Verification of Japan's Experiments (CFD)
- Verification of Germany's NACOK experiments(CFD)
- Model the real MPBR(CFD)
    - ❑Level 1: In-Vessel model
    - ❑Level 2: In-Cavity model
    - ❑Level 3: In-Containment model

Graphite Combustion

- Robust, self-sustaining oxidation in the gas phase involving vaporized material mixing with oxygen
- Usually produces a visible flame.
- True burning of graphite should not be expected below 3500 °C. (From ORNL experiments)

Critical Parameters for Air Ingress

- Temperature of reacting components
- The concentration of oxygen
- Gas flow rates
- Pressure (partial pressure and total pressure in the system)

The Assumptions for theoretical Study

- The gas temperature is assumed to follow the temperature of the solid structures.
- The reaction rate is proportional to the partial pressure of the oxygen
- There is enough fresh air supply.
- The inlet air temperature is 20 °C.

The Procedures for Theoretical Study

1. Calculate the resistance of the pebble bed

2. Calculate the chemical reaction rate

3. Add the heat by chemical reaction

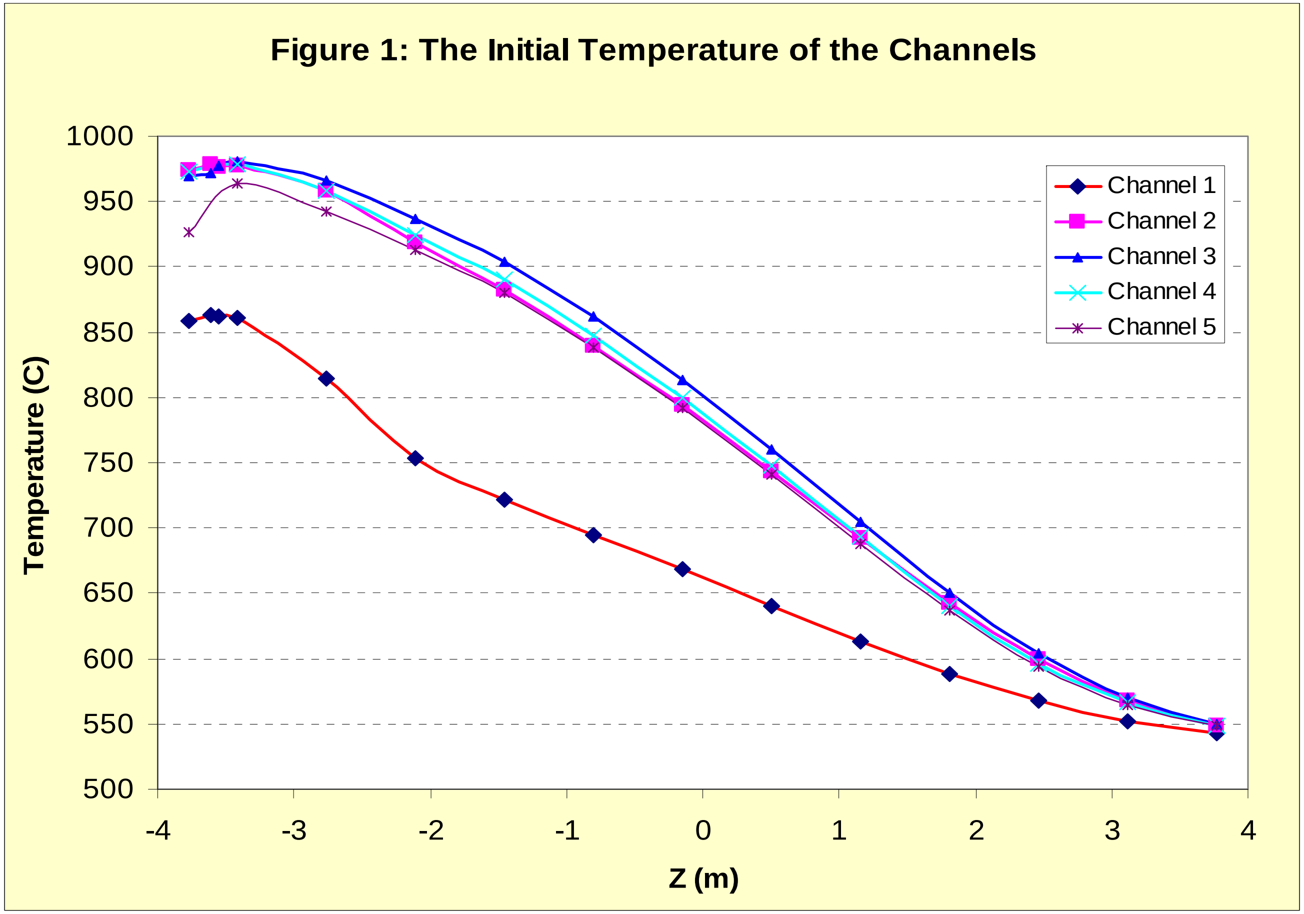
4. Run heating-7

5. Calculate the the air velocity and other

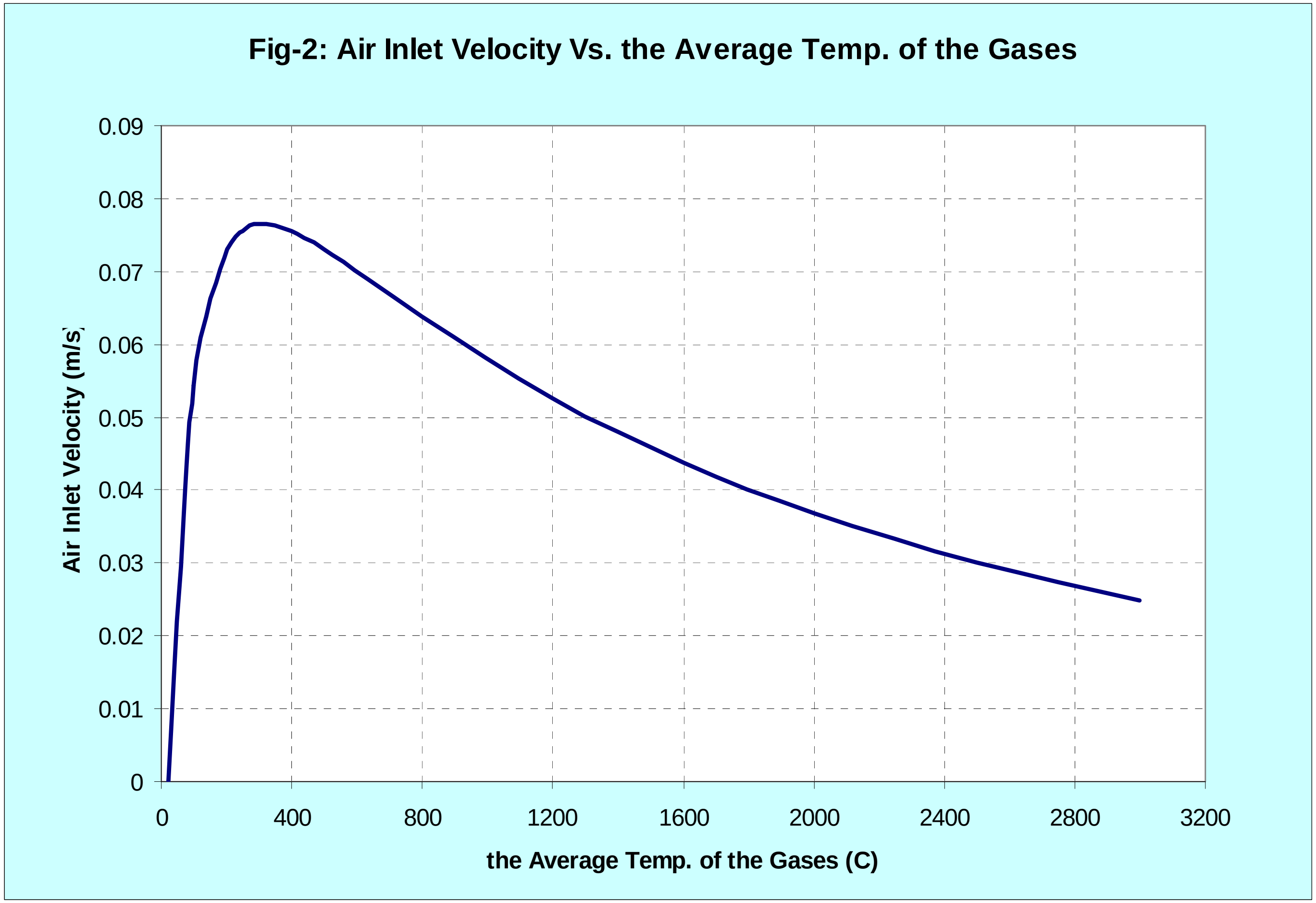
Key Functions

- $P_{\_buoyancy}=(\rho_{\_atm}-\rho_{\_outlet})*g*H$
- $P_{\_resistance}=\psi(H/d)*[(1-\varepsilon)/\varepsilon^{3}]\rho u^{2}/2$
  - $\psi=320/[Re/(1-\varepsilon)]+6/[(Re/(1-\varepsilon))^{0.1}]$
  - $Re=du\rho/\eta$
- $Q_{\_transfer}=hc*360000*(d/2)^{2}*(T_{\_graphite}-T_{\_gas})$
  - $hc=0.664(k/d)(Re/\varepsilon)^{1/2}Pr^{1/3}$

Initial Temperature Distribution



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.

The Chemical Reaction

- The Chemical Reaction Rate:(From Dave Petti's Paper)

  $Rate=K_1*exp(-E_1/T)(PO_2/20900)$

  When $T<1273K$: $K_1=0.2475$, $E_1=5710$;

  When $1273K<T<2073K$, $K_1=0.0156$, $E_1=2260$

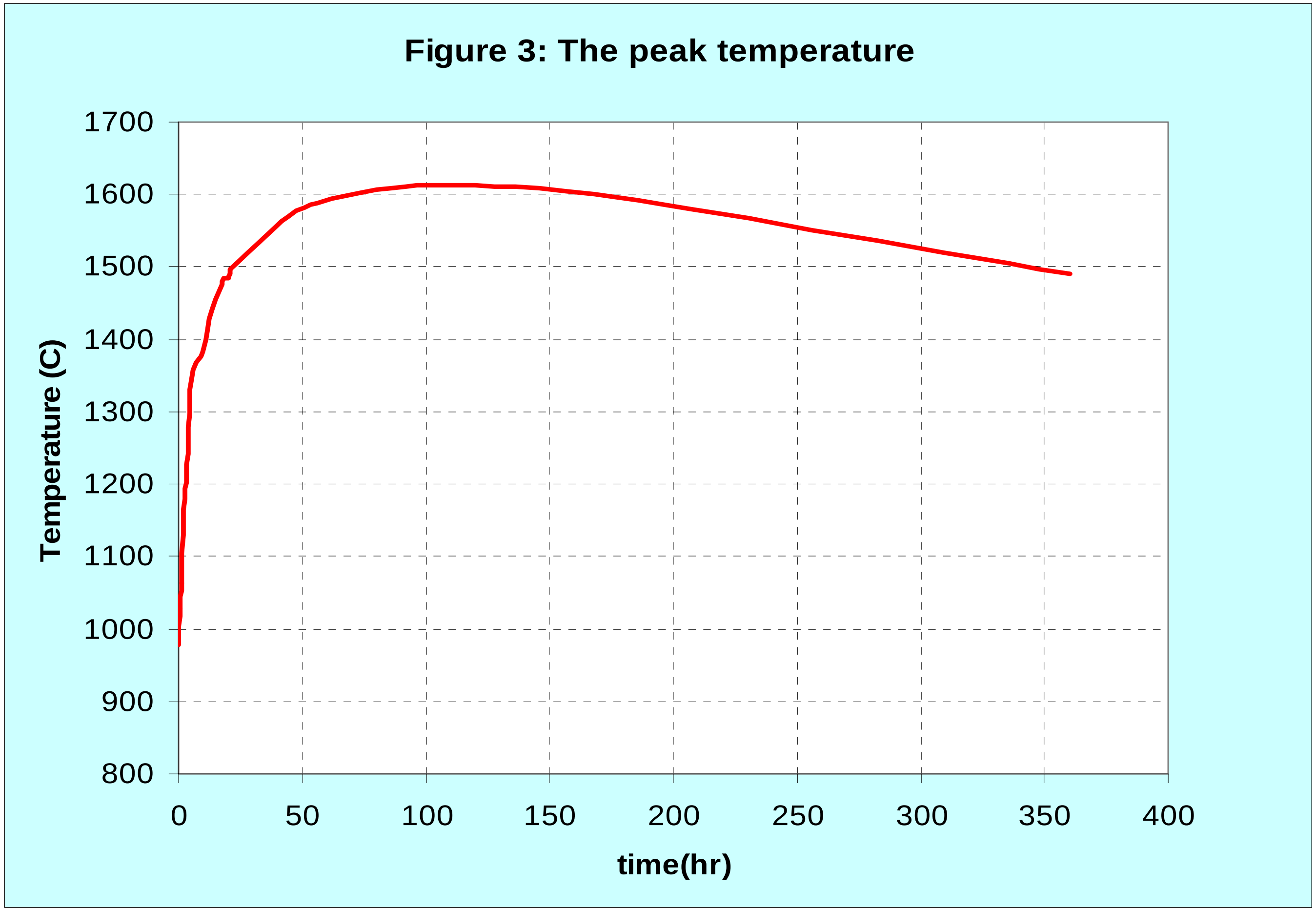
- The production ratio of CO to CO2(R):

  $R=7943exp(-9417.8/T)$

- For $C + zO2 = xCO + y\ CO2$

  $z=0.5(R+2)/(R+1)$, $x=R/(R+1)$, $y=1/(R+1)$

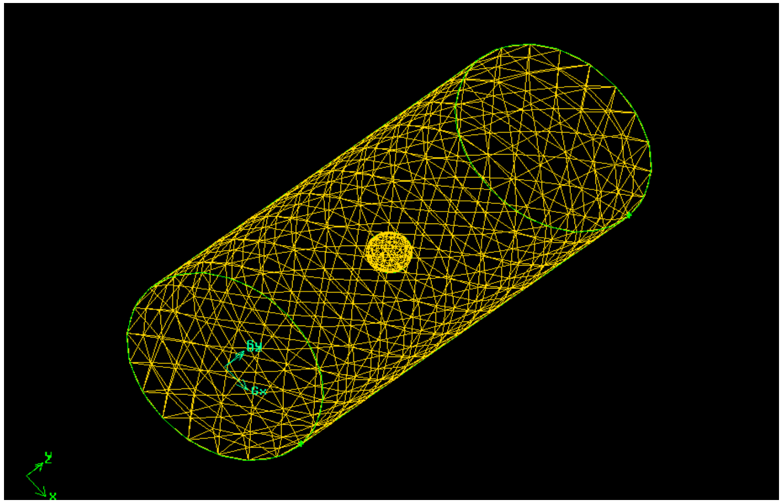
Simplified HEATING7 Open Cylinder Analysis Peak Temperature

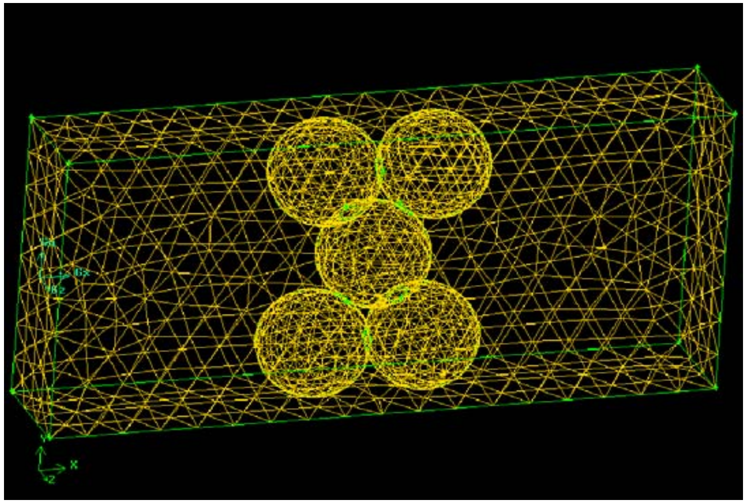


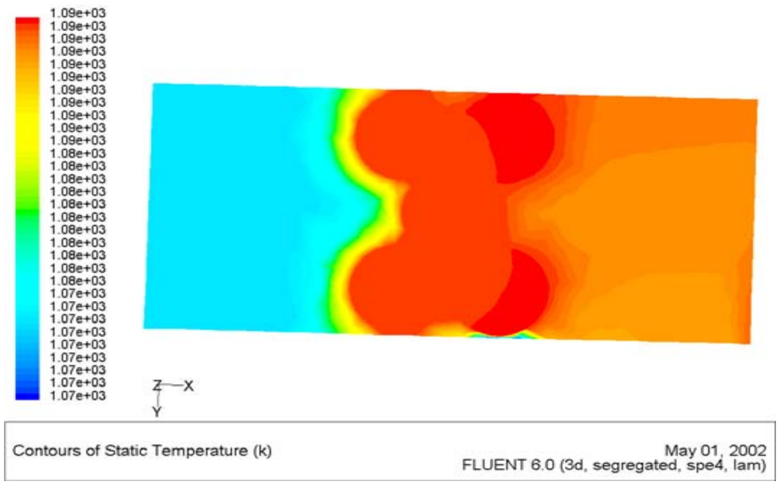
PBR_SIM Results with Chemical Reaction

- Considering only exothermic $C + O_2$ reactions
- Without chemical reaction - peak temperature 1560 C @ 80 hrs
- With chemical reaction - peak temperature 1617 C @ 92 hrs
- Most of the chemical reaction occurs in the lower reflector
- As temperatures increase chemical reactions change:
  - $C + O_2 > CO_2$ to
  - $2C + O_2 > 2C0$ to
  - $2CO + 0_2 > 2\,CO_2$
- As a function of height, chemical reactions change
- Surface diffusion of O is important in chemical reactions

Verify the Chemical Model (FLUENT 6.0)

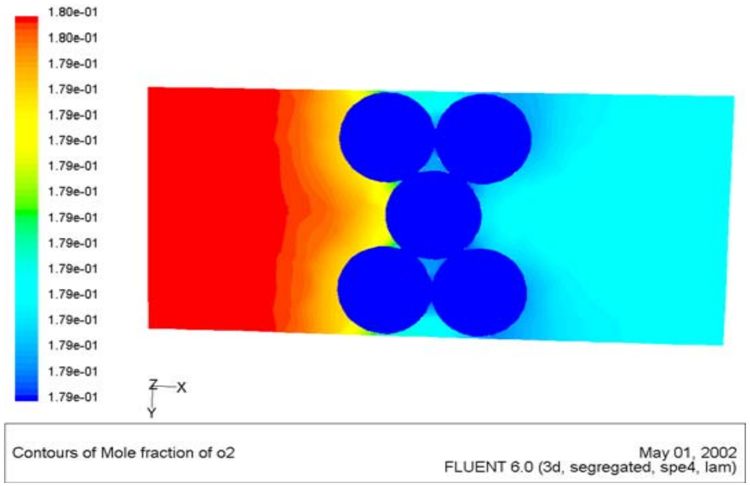






Contours of Static Temperature (k)

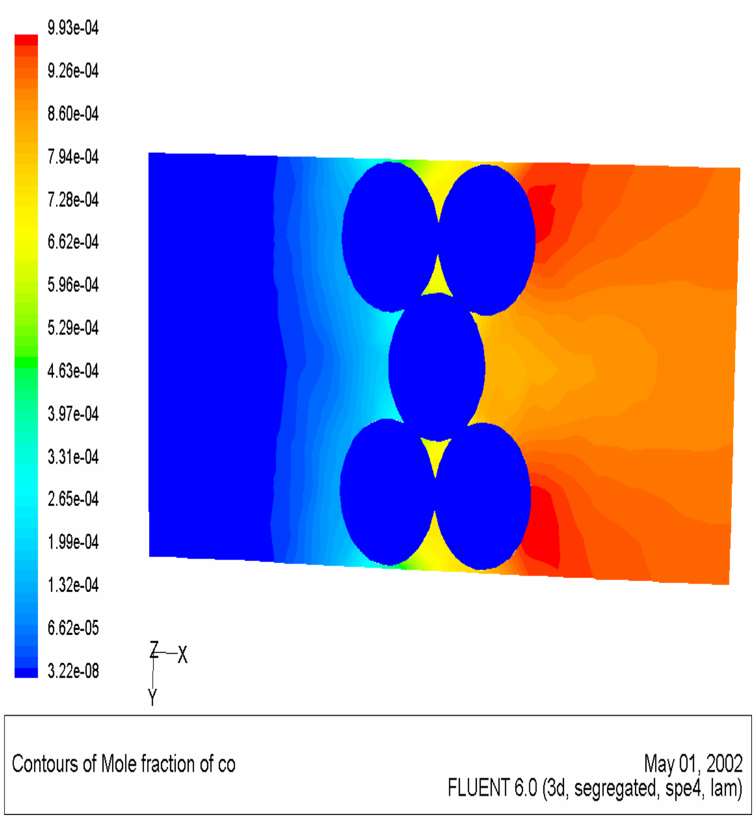
May 01, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)



Contours of Mole fraction of o2

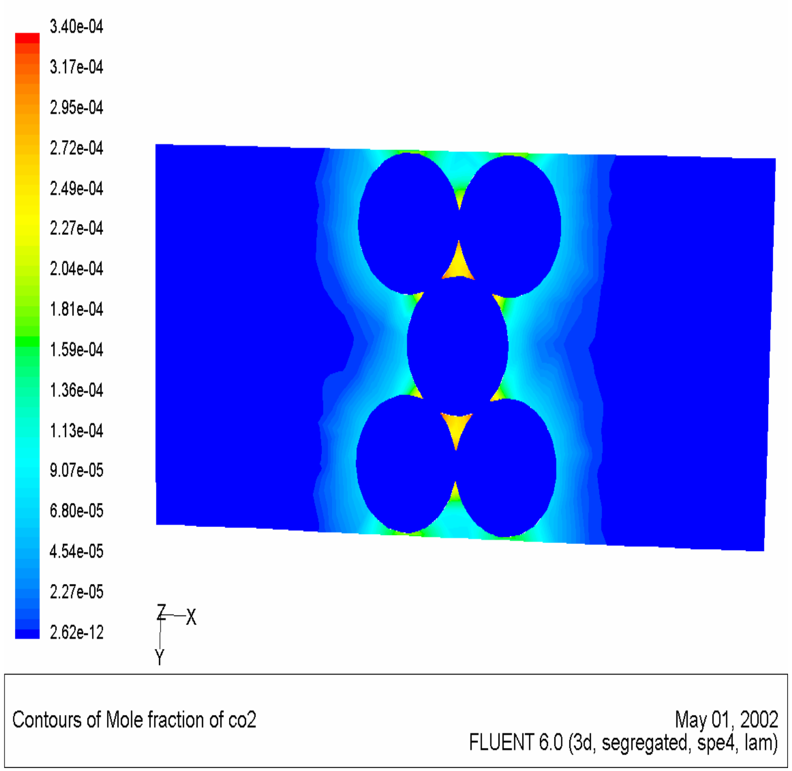
May 01, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)

Verify the Chemical Model



Contours of Mole fraction of co

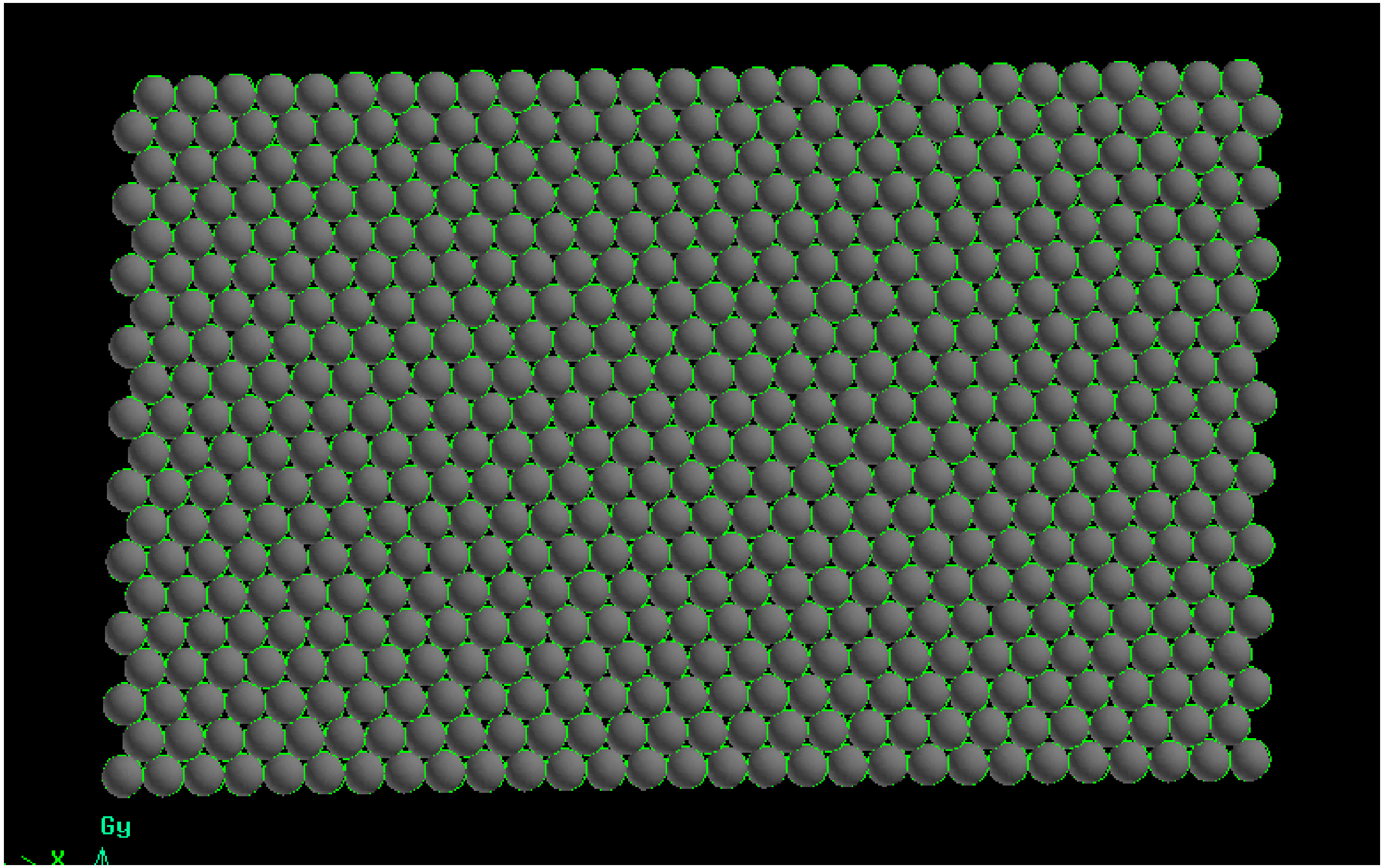
May 01, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)



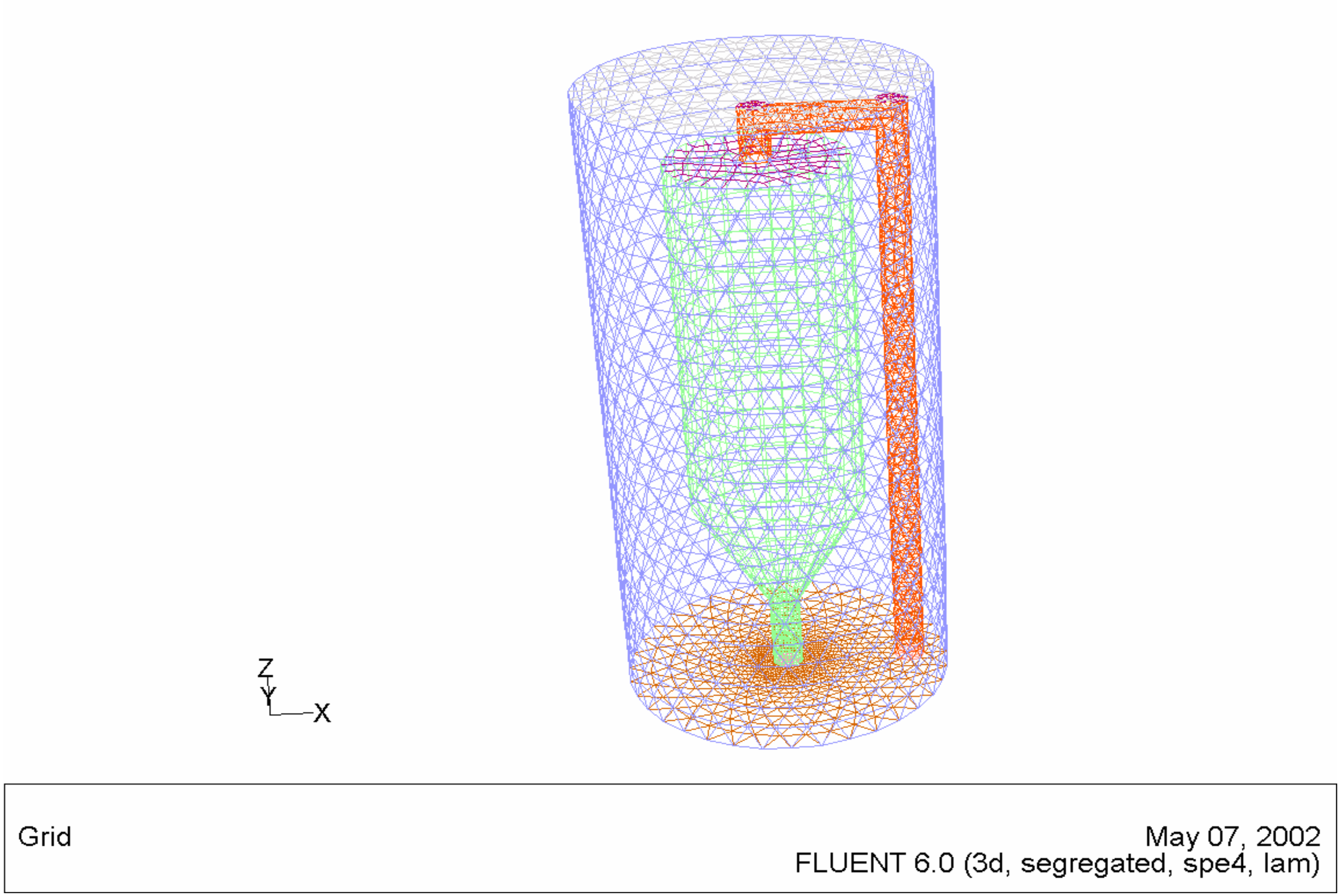
Contours of Mole fraction of co2

May 01, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)

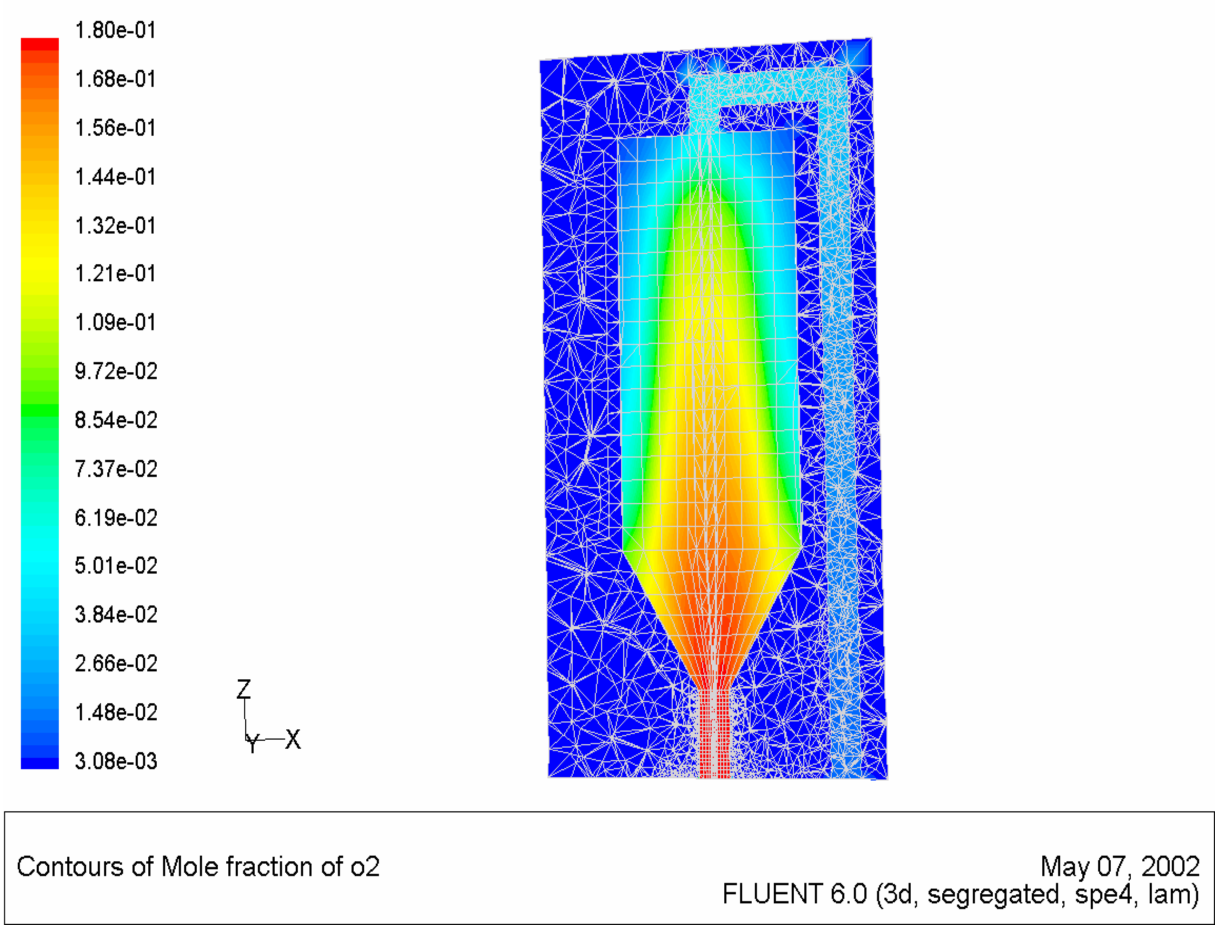
Model for Database Generation



Testing Model Using Simplified Geometrv



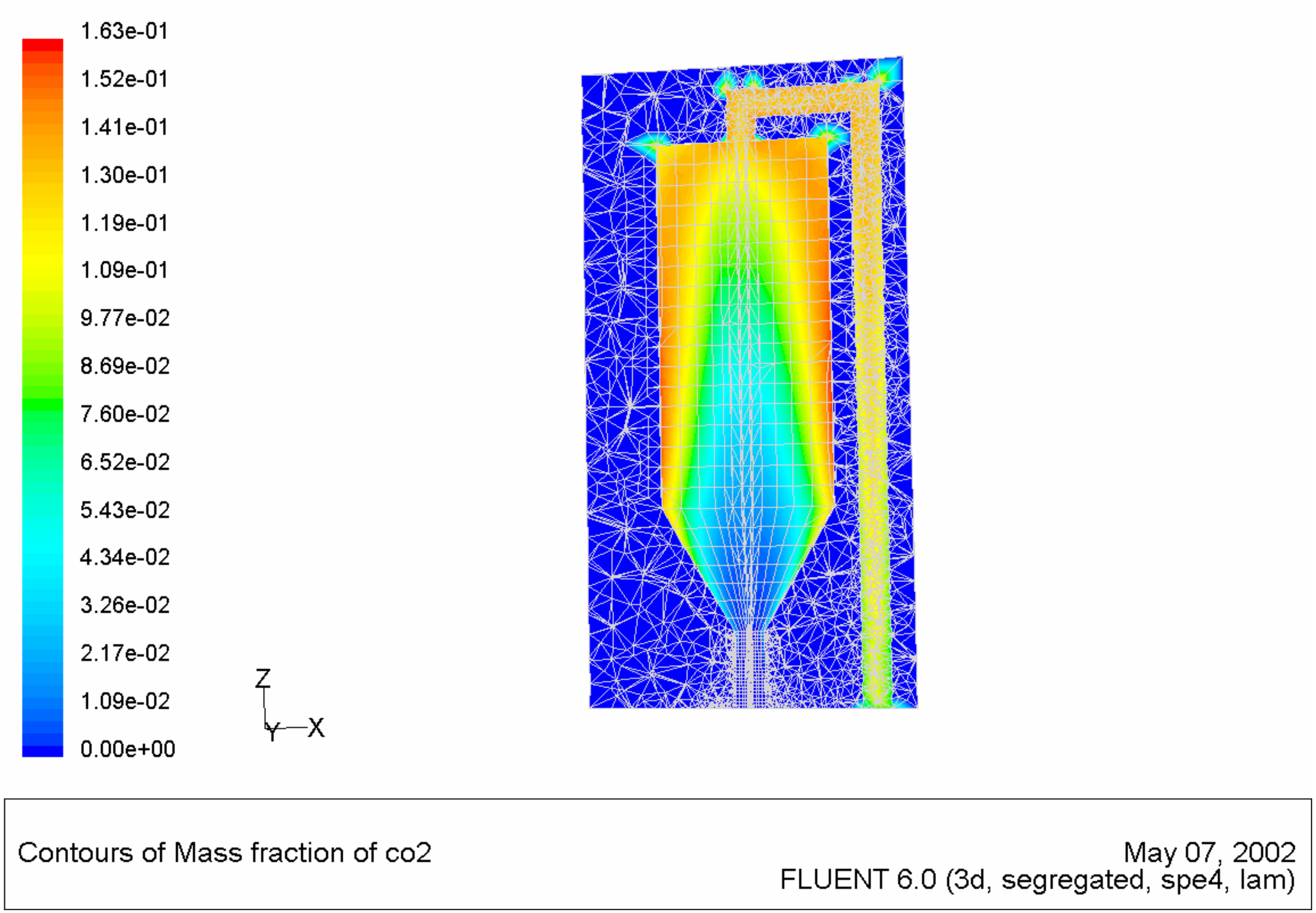
Testing Model Using Simplified Geometry (cont.)



Contours of Mole fraction of o2

May 07, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)

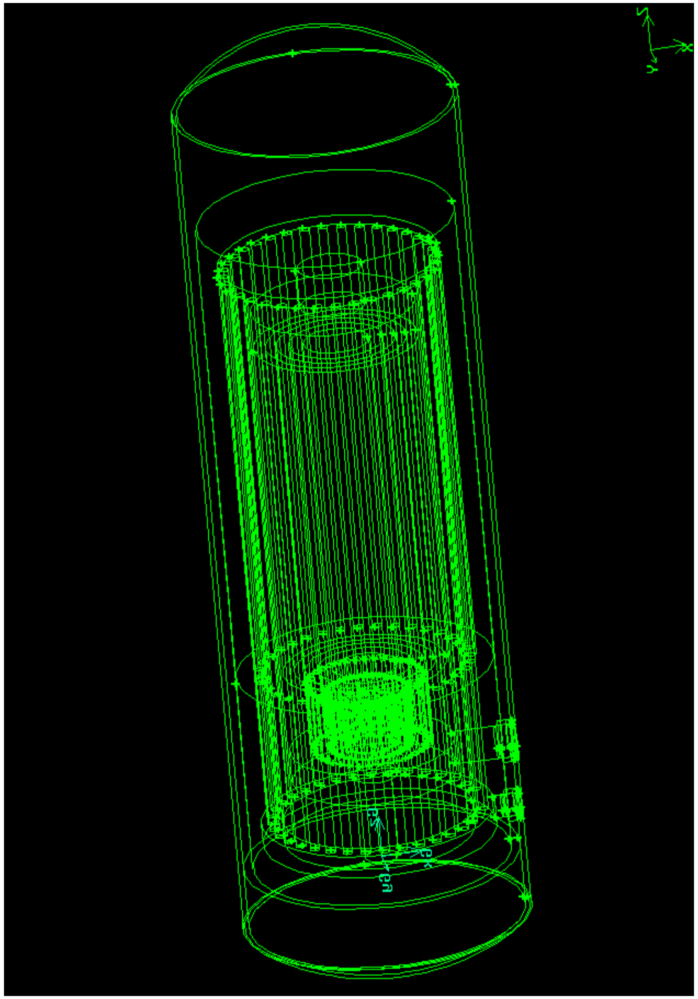
Testing Model Using Simplified Geometry (cont.)



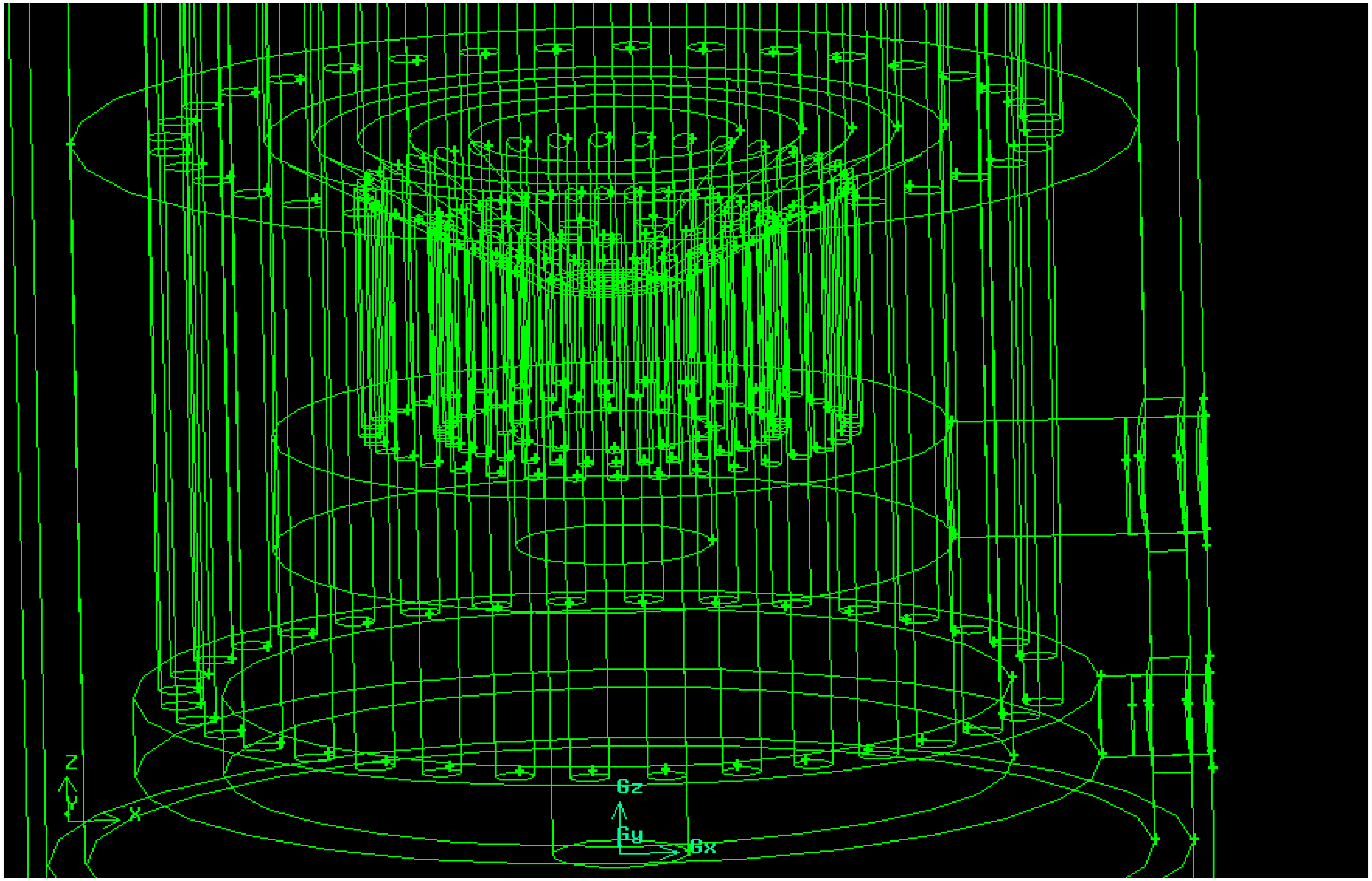
Contours of Mass fraction of co2

May 07, 2002
FLUENT 6.0 (3d, segregated, spe4, lam)

The Detailed Model in Progress



Detailed Bottom Reflector



Typical Treatment

- Assume that after blowdown (Large break) that the reactor cavity is closed limiting the amount of air available for ingress.
- Assume that all the air is reacted - mostly in the lower reflector - then chemical reaction stops consuming only several hundred kilograms of graphite.
- Need to cool down plant - fix break - stop air ingress path.

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.

Competitive With Gas ?

• Natural Gas	3.4 Cents/kwhr
• AP 600	3.6 Cents/kwhr
• ALWR	3.8 Cents/kwhr
• MPBR	3.3 Cents/kwhr

Relative Cost Comparison (assumes no increase in natural gas prices) based on 1992 study

ESKOM’s estimate is 1.6 to 1.8 cents/kwhr (bus bar)

MPBR PLANT CAPITAL COST ESTIMATE

(MILLIONS OF JAN. 1992 DOLLAR WITH CONTINGENCY)

Account No.	Account Description	Cost Estimate
20	LAND & LAND RIGHTS	2.5
21	STRUCTURES & IMPROVEMENTS	192
22	REACTOR PLANT EQUIPMENT	628
23	TURBINE PLANT EQUIPMENT	316
24	ELECTRIC PLANT EQUIPMENT	64
25	MISCELLANEOUS PLANT EQUIPMENT	48
26	HEAT REJECT. SYSTEM	25
	TOTAL DIRECT COSTS	1,275
91	CONSTRUCTION SERVICE	111
92	HOME OFFICE ENGR. & SERVICE	63
93	FIELD OFFICE SUPV. & SERVICE	54
94	OWNER’S COST	147
	TOTAL INDIRECT COST	375
TOTAL BASE CONSTRUCTION COST		1,650
CONTINGENCY (M$)		396
TOTAL OVERNIGHT COST		2,046
UNIT CAPITAL COST ($/KWe)		1,860
AFUDC (M$)		250
TOTAL CAPITAL COST		**2296**
FIXED CHARGE RATE		9.47%
LEVELIZED CAPITAL COST (M$/YEAR)		217

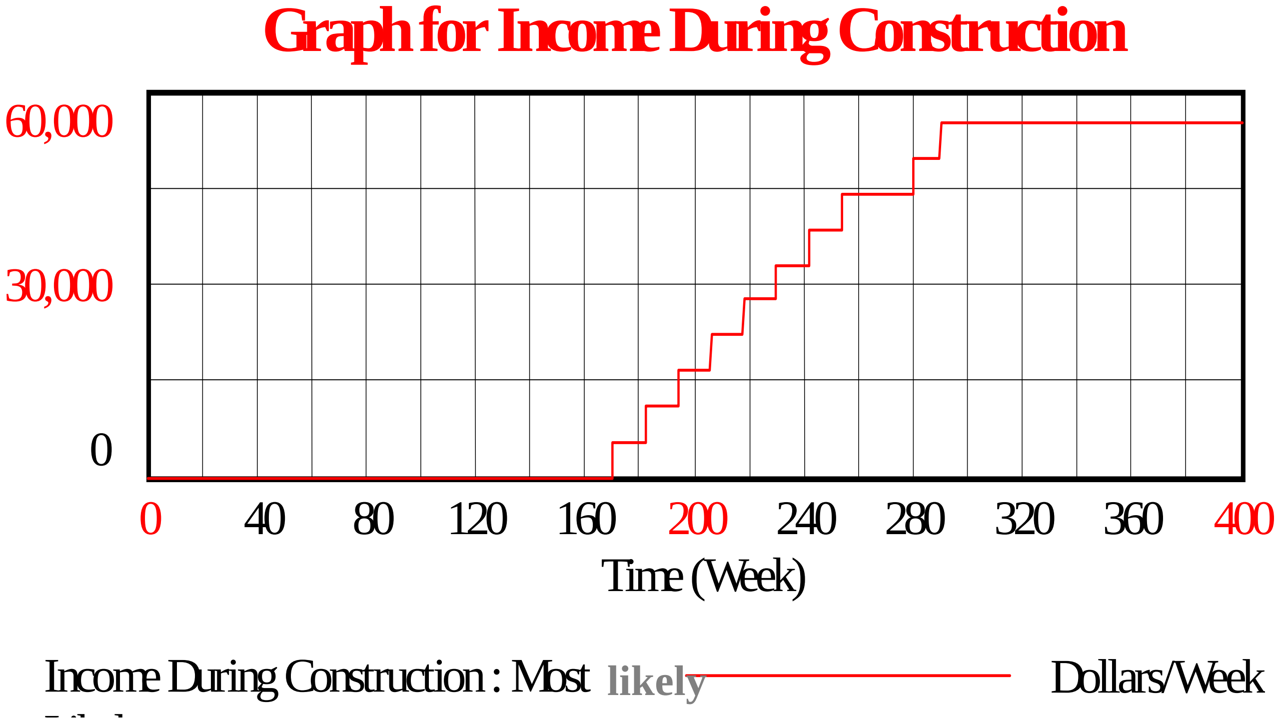
MPBR BUSBAR GENERATION COSTS (‘92$)

Reactor Thermal Power (MWt)	10 x 250
Net Efficiency (%)	45.3%
Net Electrical Rating (MWe)	1100
Capacity Factor (%)	90
Total Overnight Cost (M$)	2,046
Levelized Capital Cost ($/kWe)	1,860
Total Capital Cost (M$)	2,296
Fixed Charge Rate (%)	9.47
30 year level cost (M$/YR):	
Levelized Capital Cost	217
Annual O&M Cost	31.5
Level Fuel Cycle Cost	32.7
Level Decommissioning Cost	5.4
Revenue Requirement	286.6
Busbar Cost (mill/kWh):	
Capital	25.0
O&M	3.6
FUEL	3.8
DECOMM	0.6
TOTAL	33.0 mills/kwhr

O&M Cost

- Simpler design and more compact
- Least number of systems and components
- Small staff size: 150 personnel
- $31.5 million per year
- Maintenance strategy - Replace not Repair
- Utilize Process Heat Applications for Off-peak - Hydrogen/Water

INCOME DURING CONSTRUCTION ?



Generating Cost

PBMR vs. AP600, AP1000, CCGT and Coal

(Comparison at 11% IRR for Nuclear Options, 9% for Coal and CCGT[1])

(All in ¢/kWh)		AP1000 @			Coal[2]		CCGT @ Nat. Gas = [3]		
	AP600	3000Th	3400Th	PBMR	'Clean'	'Normal'	$3.00	$3.50	$4.00
Fuel	0.5	0.5	0.5	0.48	0.6	0.6	2.1	2.45	2.8
O&M	0.8	0.52	0.46	0.23	0.8	0.6	0.25	0.25	0.25
Decommissioning	0.1	0.1	0.1	0.08	-	-	-	-	-
Fuel Cycle	0.1	0.1	0.1	0.1	-	-	-	-	-
Total Op Costs	1.5	1.22	1.16	0.89	1.4	1.2	2.35	2.70	3.05
Capital Recovery	3.4	2.5	2.1	2.2	2.0	1.5	1.0	1.0	1.0
Total	4.9	3.72	3.26	3.09	3.4	2.7	3.35	3.70	4.05

---

[1] All options exclude property taxes

[2] Preliminary best case coal options: "mine mouth" location with $20/ton coal, 90% capacity factor & 10,000 BTU/kWh heat rate

[3] Natural gas price in $/million Btu

Nuclear Nonproliferation

Pebble-bed reactors are highly proliferation resistant:

- small amount of uranium (9 g/ball)
- high discharge burnup (80 MWd/kg)
- TRISO fuel is difficult to reprocess
- small amount of excess reactivity limits
- number of special production balls

Diversion of 6 kg Pu239 requires:

- 157,000 spent fuel balls – 1.2 yrs
- 258,000 first-pass fuel balls – 2+
- ~20,000 'special' balls – 1.5 +

Spent Fuel

Pu238	1.9%
Pu239	36.8
Pu240	27.5
Pu241	18.1
Pu242	15.7

First Pass

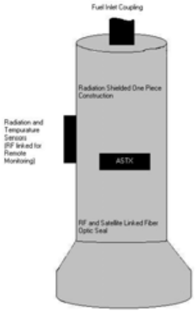
Pu238	~0 %
Pu239	82.8
Pu240	15.2
Pu241	1.9
Pu242	0.1

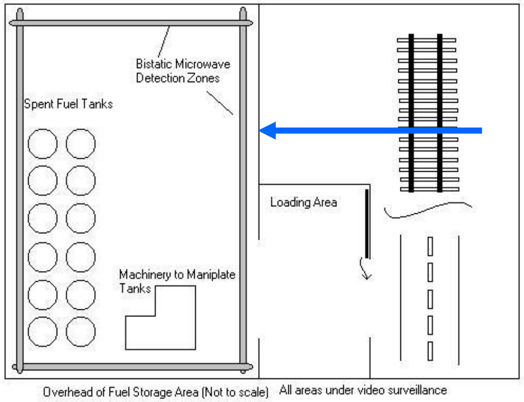
Extrinsic Safeguards Protection System for Pebble Bed Reactors

Proposed Concept

Extrinsic Safeguards System for Pebble Bed Reactors

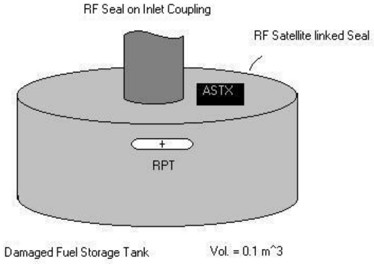
Waste Package

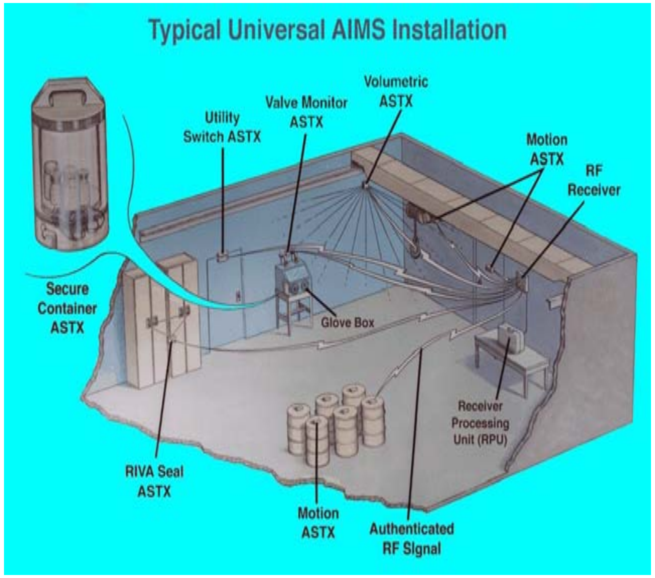




Fresh Fuel Room

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.

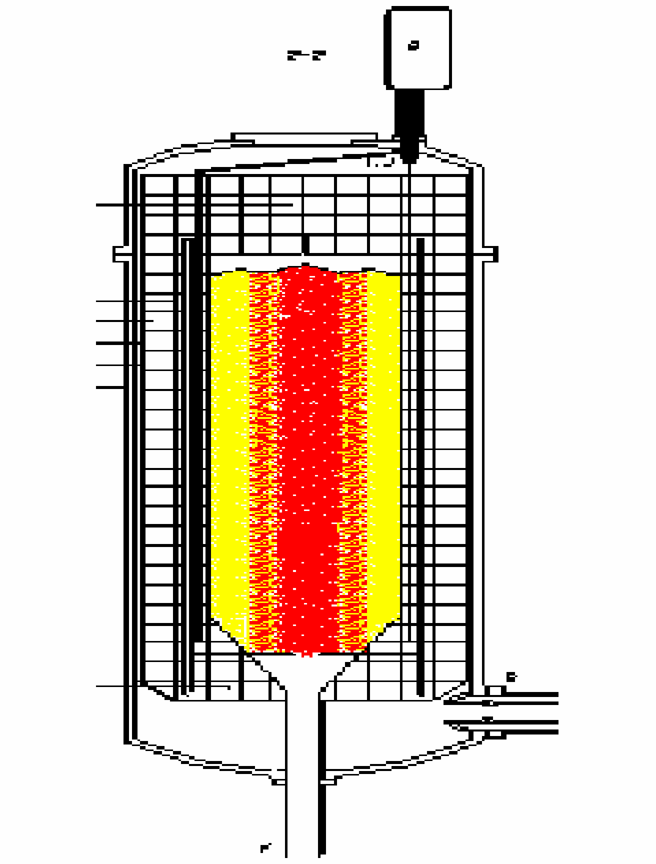
Pebble Flow

- 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

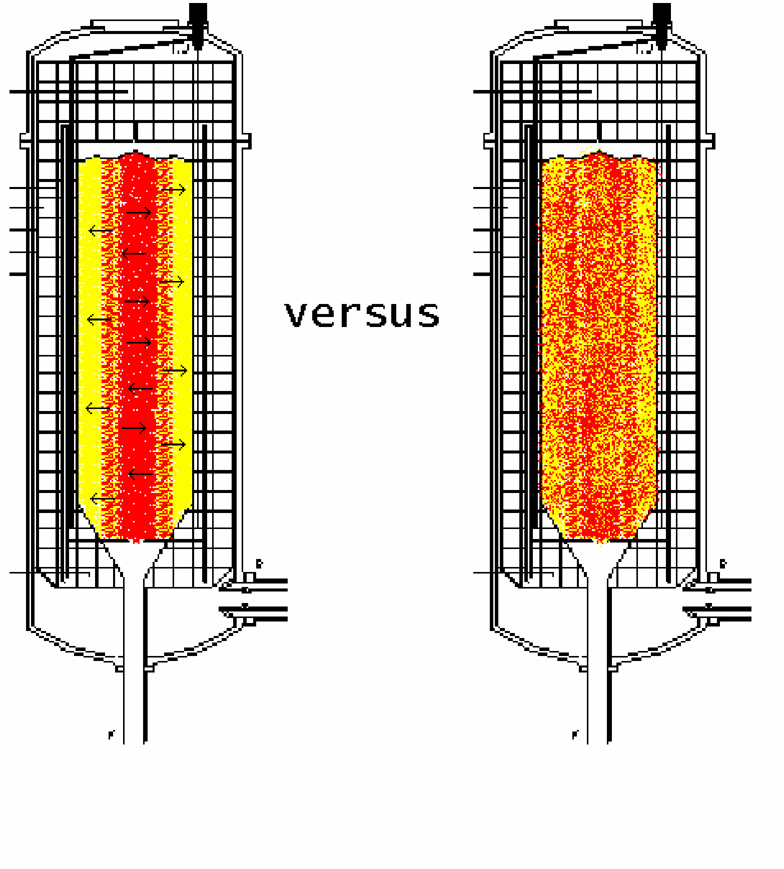
Radial Fuel Distribution

- 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.



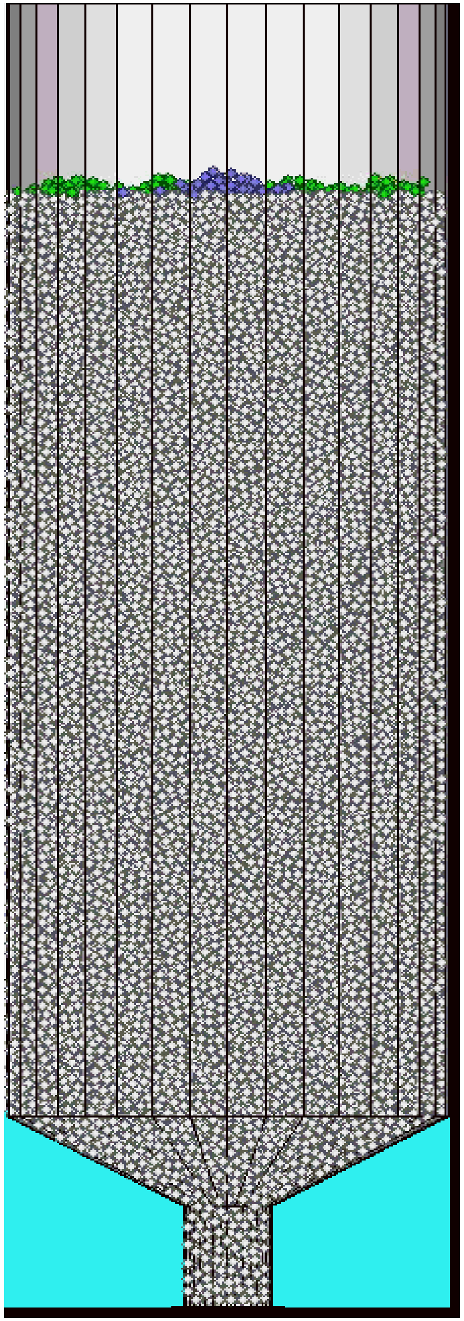
Flow Diffusion

- Several mathematical models for granular flow exist, with different amounts of diffusion and different velocity profiles.
- The neutron physics of the core relies on the assumption of laminar flow and low diffusion levels during flow down.



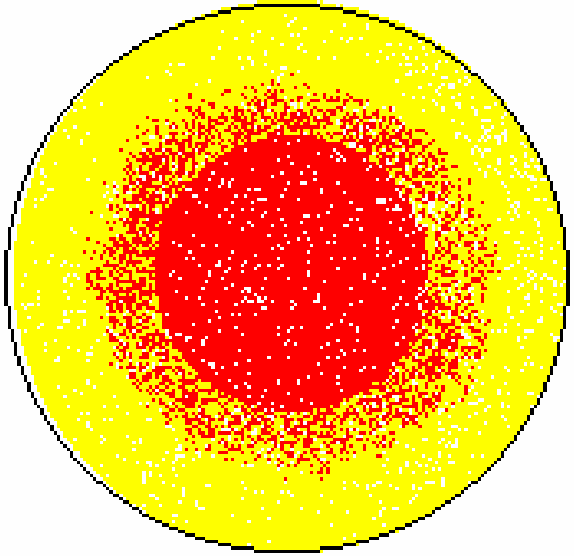
Molecular Dynamic Simulation of Pebble Flow in Reactor

PBMR Analysis



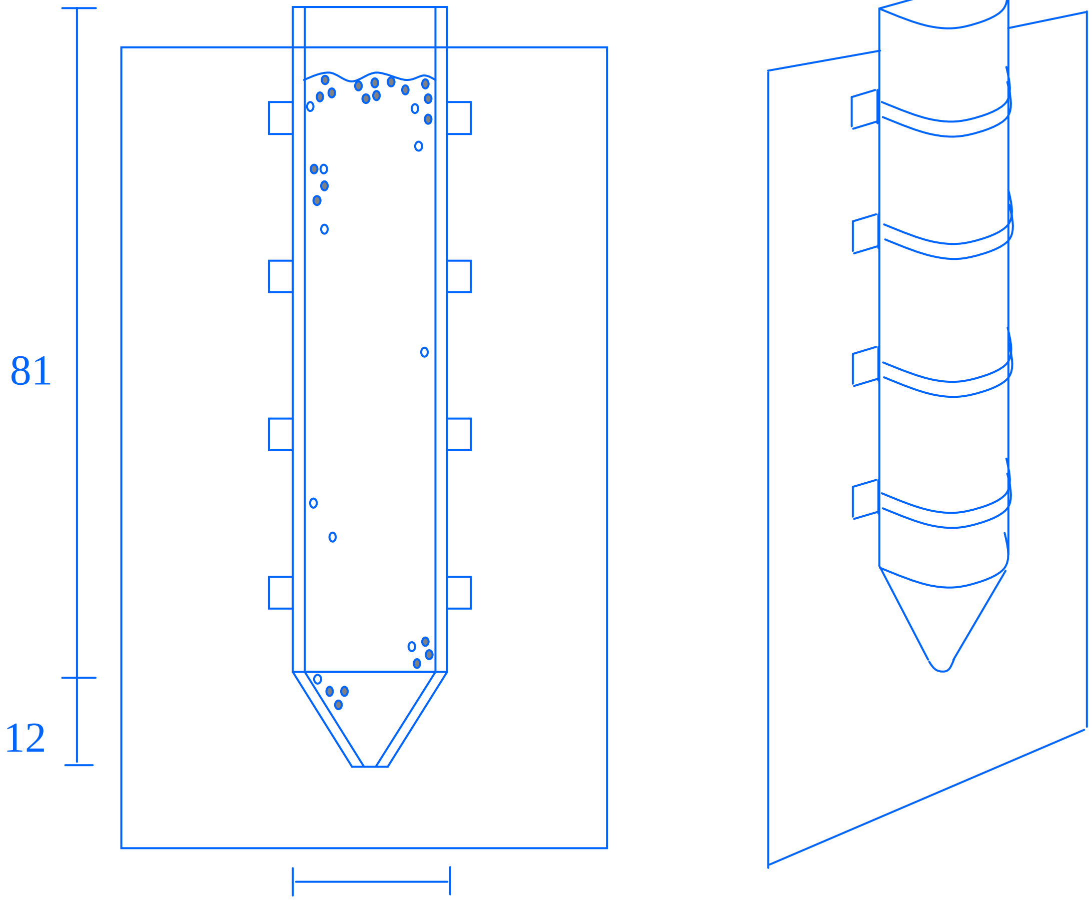
Dropping Diffusion

- The radial spread of pebbles dropped into the core is also an important factor in keeping the fixed radial distribution of the pebbles, as refueling is on-line during reactor operation.



Aerial View of Core

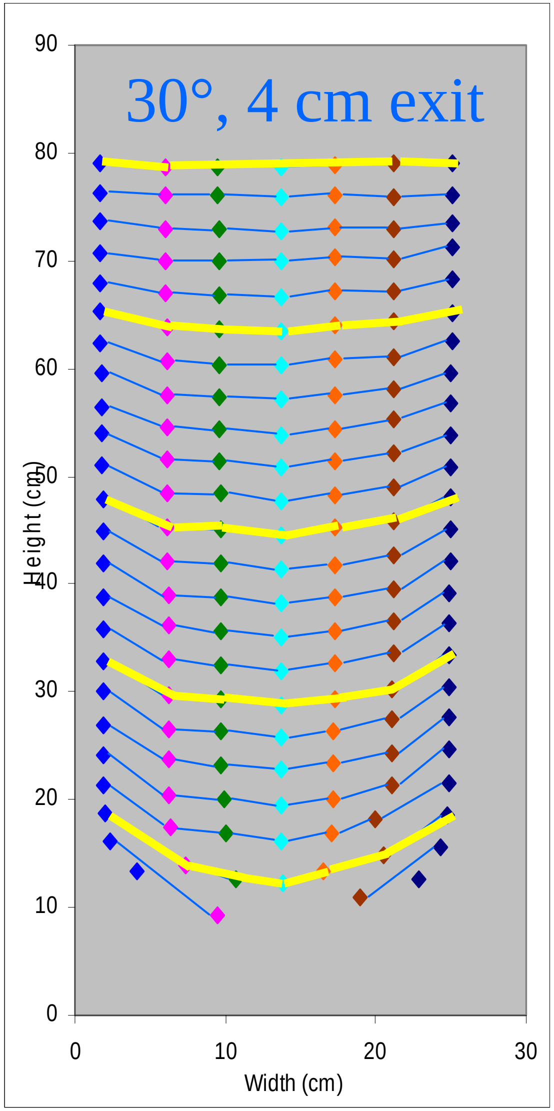
Half Model Design

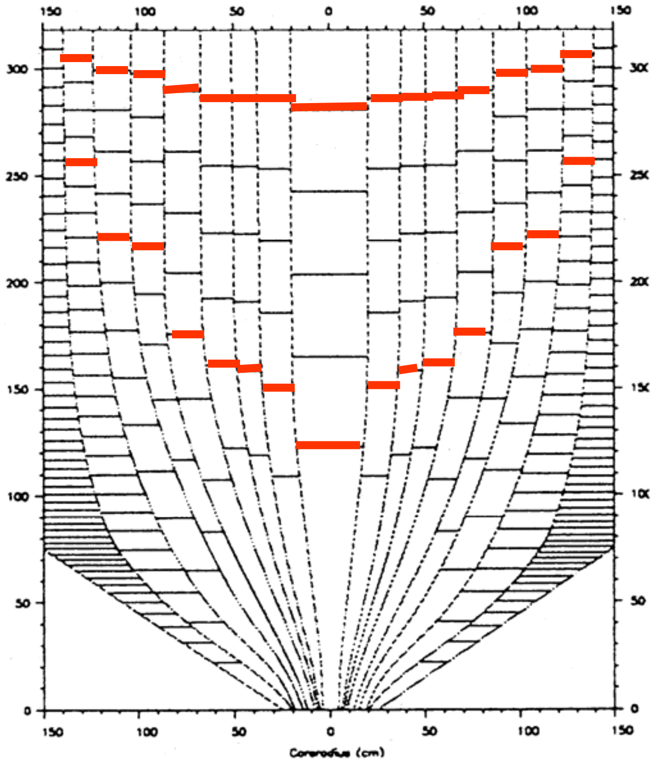


Measurements in centimeters

Half Model Data Collection

Comparison to Design Profile



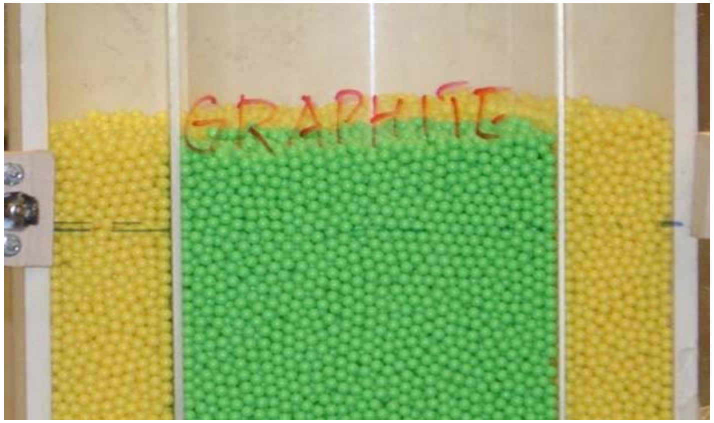


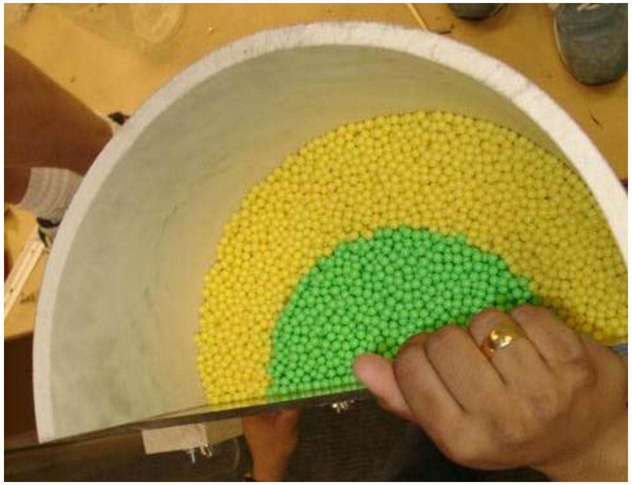
07.mpg

09.mpg

Movie Clips

Trial with Central Column





Video Demo

19.mpg

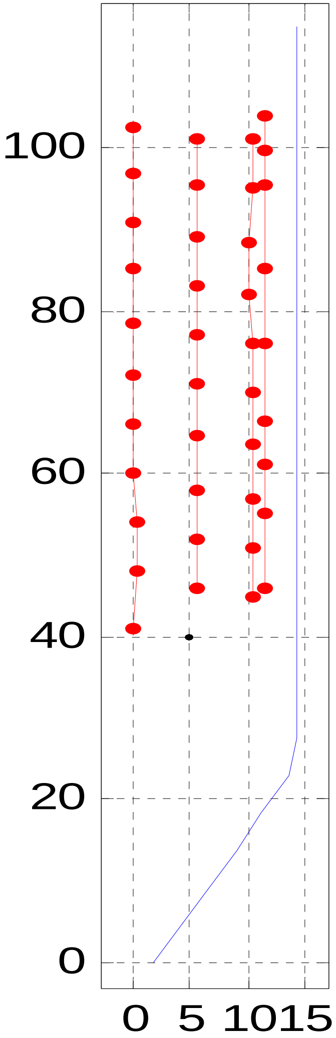
20.mpg

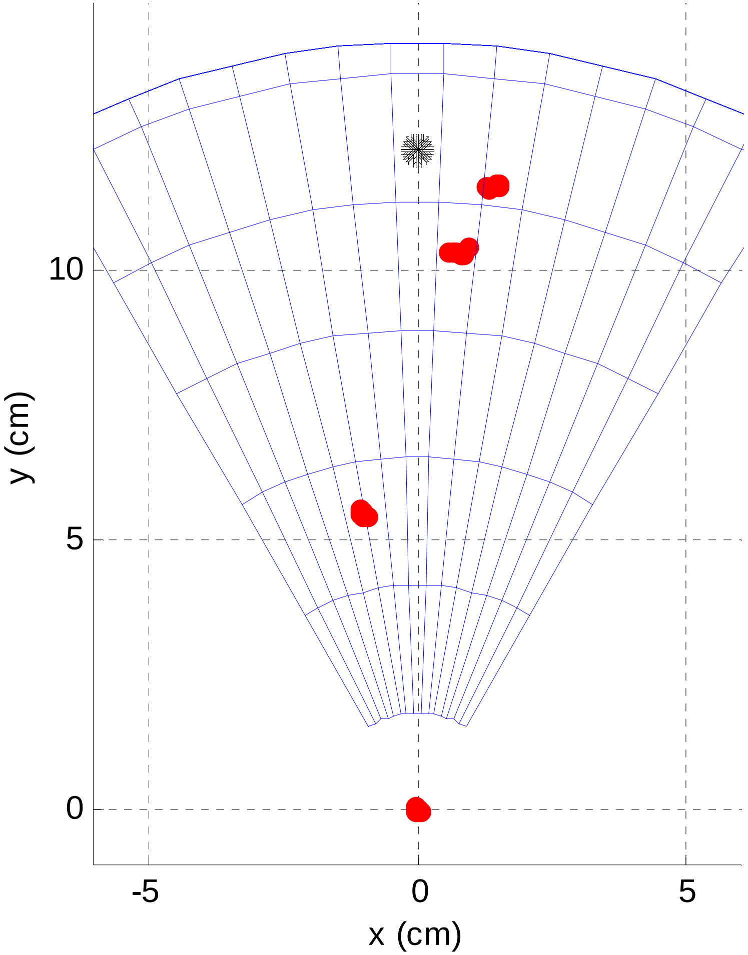
21.mpg

22.mpg

23.mpg

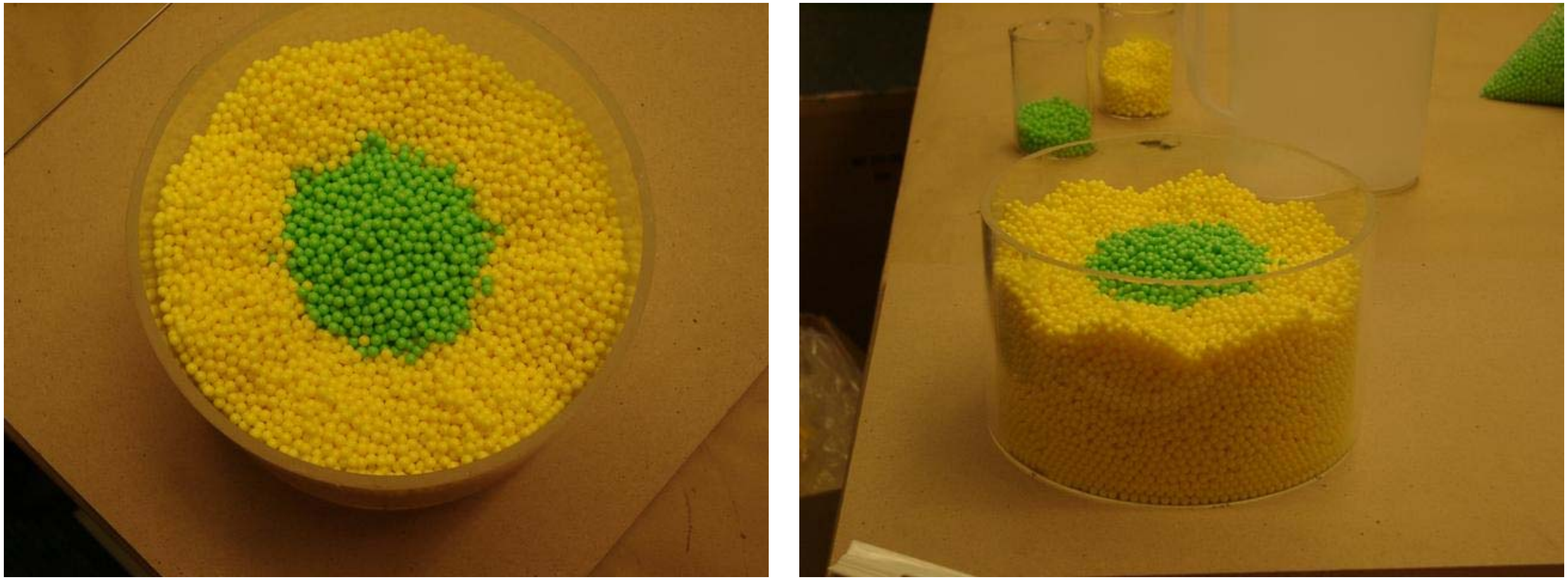
Streamlines
Confirmed by 3D Experiment





Radial Dispersion of Fuel and Graphite Pebbles During Refueling in the Pebble Bed Modular Reactor

Full 9-location drop



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

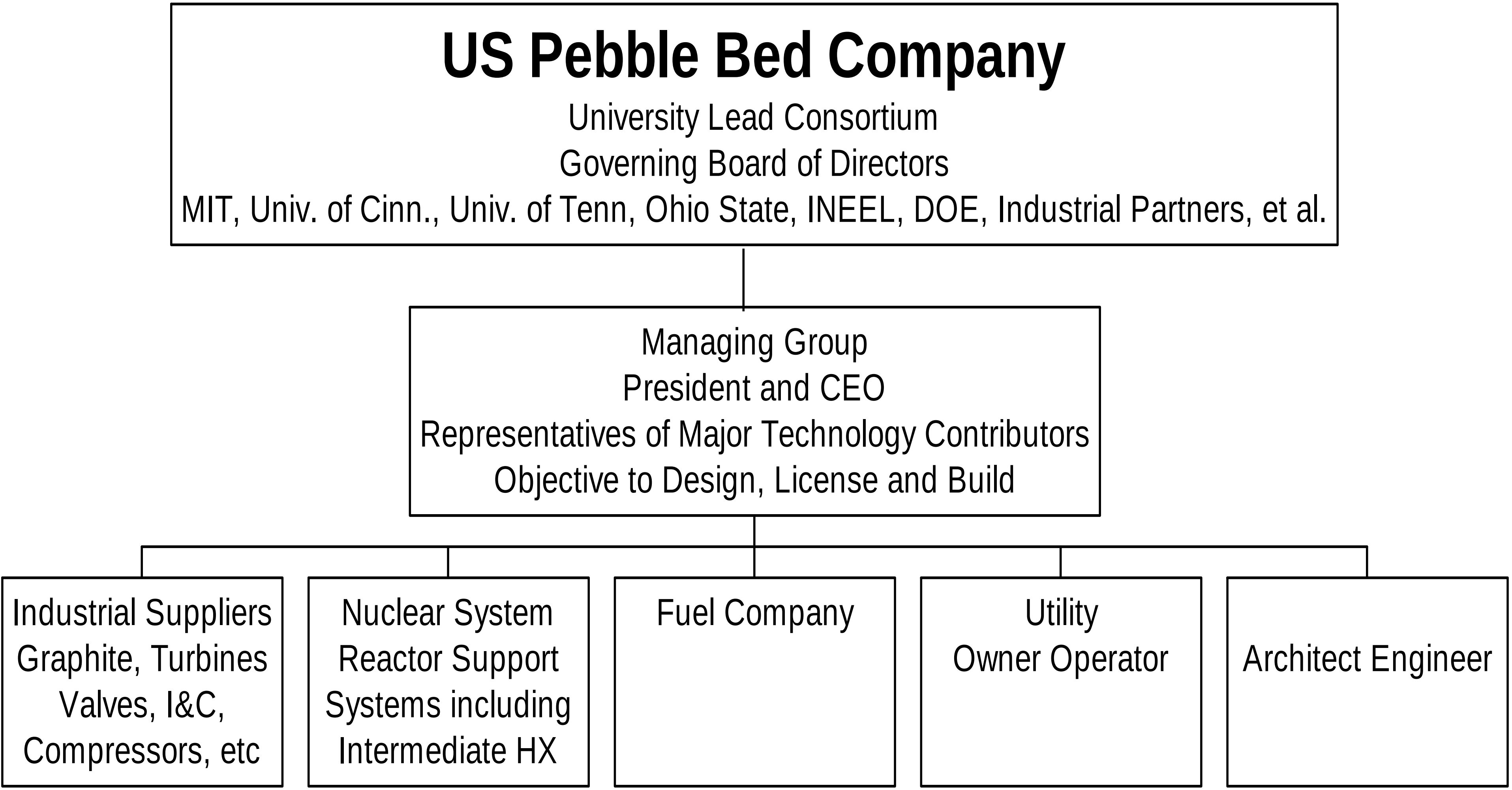
Sequence of Pebble Bed Demonstration

- China HTR 10 - December 2000
- ESKOM PBMR - Start Construction 2002
- MIT/INEEL - Congressional Approval to Build 2003 Reactor Research Facility
- 2007 ESKOM plant starts up.
- 2010 MIT/INEEL Plant Starts Up.

Highlights of Plan to Build

- Site - Idaho National Engineering Lab (maybe)
- “Reactor Research Facility”
- University Lead Consortium
- Need Serious Conceptual Design and Economic Analysis
- Congressional Champions
- Get Funding to Start from Congress this Year

Modular Pebble Bed Reactor Organization Chart



US Pebble Bed Company

University Lead Consortium
Governing Board of Directors
MIT, Univ. of Cinn., Univ. of Tenn, Ohio State, INEEL, DOE, Industrial Partners, et al.

Managing Group
President and CEO
Representatives of Major Technology Contributors
Objective to Design, License and Build

Industrial Suppliers
Graphite, Turbines
Valves, I&C,
Compressors, etc

Nuclear System
Reactor Support
Systems including
Intermediate HX

Fuel Company

Utility
Owner Operator

Architect Engineer

Reactor Research Facility

Full Scale

- **“License by Test” as DOE facility**
- **Work With NRC to develop risk informed licensing basis in design - South Africa**
- **Once tested, design is “certified” for construction and operation.**
- **Use to test - process heat applications, fuels, and components**

Why a Reactor Research Facility ?

- To “Demonstrate” Safety
- To improve on current designs
- To develop improved fuels (thorium, Pu, etc)
- Component Design Enhancements
- Answer remaining questions
- To Allow for Quicker NRC Certification

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.

Cost and Schedule

- Cost to design, license & build ~ $ 400 M over 7 Years.
- Will have Containment for Research and tests to prove one is NOT needed.
- 50/50 Private/Government Support
- Need US Congress to Agree.

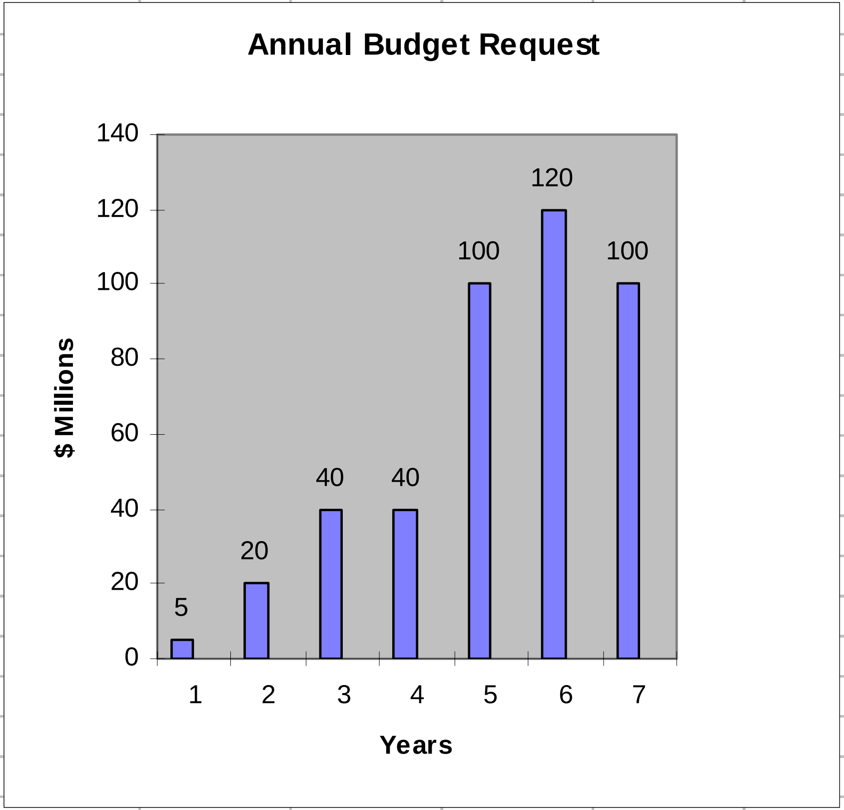
Cost Estimate for First MPBR Plant

Adjustments Made to MIT Cost Estimate for 10 Units

Estimate Category	Original Estimate	Scaled to 2500 MWTH	New Estimate	For single unit
21 Structures & Improvements	129.5	180.01	24.53	
22 Reactor Plant Equipment	448	622.72	88.75	
23 Turbine Plant Equipment	231.3	321.51	41.53	
24 Electrical Plant Equipment	43.3	60.19	7.74	
25 Misc. Plant Equipment	32.7	45.45	5.66	
26 Heat Rejection System	18.1	25.16	3.04	
Total Direct Costs	**902.9**	**1255.03**	**171.25**	
91 Construction Services	113.7	113.70	20.64	
92 Engineering & Home office	106	106.00	24.92	
93 Field Services	49.3	49.30	9.3	
94 Owner's Cost	160.8	160.80	27.45	
Total Indirect Costs	**429.8**	**429.80**	**82.31**	
Total Direct and Indirect Costs	**1332.7**	**1684.83**	**253.56**	
Contingency (25%)	**333.2**	**421.2**	**63.4**	
Total Capital Cost	**1665.9**	**2106.0**	**317.0**	
Engineering & Licensing Development Costs			**100**	
Total Costs to Build the MPBR			**417.0**	

Annual Budget Cost Estimates
For Modular Pebble Bed Reactor
Generation IV

Year	Budget Request
1	5
2	20
3	40
4	40
5	100
6	120
7	100
Total	**425**



Key Technical Challenges

- Materials (metals and graphite)
- Code Compliance
- Helium Turbine and Compressor Designs
- Demonstration of Fuel Performance
- US Infrastructure Knowledge Base
- Regulatory System

Technology Bottlenecks

- Fuel Performance
- Balance of Plant Design - Components
- Graphite
- Containment vs. Confinement
- Air Ingress/Water Ingress
- Regulatory Infrastructure

Regulatory Bottlenecks

- 10 CFR Part 50 Written for Light Water Reactors not high temperature gas plants
- Little knowledge of pebble bed reactors or HTGRs - codes, safety standards, etc.
- Fuel testing
- Resolution of Containment issue
- Independent Safety Analysis Capability

International Application

- Design Certified & Inspected by IAEA
- International “License”
- Build to Standard
- International Training
- Fuel Support
- No Special Skills Required to Operate

Collaborative Research Areas

- Air Ingress
- Accident Performance of TRISO Fuel
- Water Ingress
- Burnup Measurements
- Power Distribution Measurements
- Graphite Lifetime
- Defueling Systems
- Verification of Computer Codes - VSOP, Tinte
- Xenon Effects
- Modeling of Pebble Flow
- Mixing in Lower Reflector

Research Areas Continued

- Containments
- Terrorist Impacts
- Burning Potential
- Advanced I&C - Computer Control
- Safeguards
- International Standards
- Materials - ASME
- Blowdown Impacts
- Release Models
- Break Spectrum
- Water Ingress
- Seismic Impacts
- Post Accident Recovery
- “License By Test”

A “New” Question

- Can Nuclear Plants withstand a direct hit of a 767 jet with a plane load of people and fuel ?
- Can it deal with other Terrorist Threats?
  - Insider
  - Outsider
  - General Plant Security

Pebble Advantages

- Low excess reactivity - on line refueling
- Homogeneous core (less power peaking)
- Simple fuel management
- Potential for higher capacity factors - no annual refueling outages
- Modularity - smaller unit
- Faster construction time - modularity
- Indirect cycle - hydrogen generation
- Simpler Maintenance strategy - replace vs repair

Generation IV

- Very High Temperature Gas Reactors (VHTR)
  - Pebble or Prismatic
  - > 1100 C
  - Large Materials Challenges
- Fast Gas Reactors
  - Fast Spectrum - need to manage reactivity coefficients
  - Pressurized Containment - decay heat removal
  - Need new fuel type (pebble or prismatic)
  - Need to develop full fuel cycle (reprocessing)

Very High Temperature Reactor Pebble or Prismatic

- Reactor power 600 MWth
- Coolant inlet/outlet temperature 640/1000°C
- Core inlet/outlet pressure Dependent on process
- Helium mass flow rate 320 kg/s
- Average power density 6–10 MWth/m 3
- Reference fuel compound ZrC-coated particles in blocks, pins or pebbles
- Net plant efficiency >50%

Fast Gas Reactor

- Advantage of Sustainability
- Disadvantage - post shutdown decay heat removal
- Need new fuel development - for either pebble or prismatic - cermet or composite metal fuels

Design Features of the GFR Concept

Reactor Design Parameter	Conceptual Data
wer plant	600 MWth
t efficiency (direct cycle helium)	48 %
olant pressure	90 bar
tlet coolant temperature	850 °C (Helium, direct cycle)
et coolant temperature	490 °C (Helium, direct cycle)
minal flow & velocity	330 kg/s & 40 m/s
re Volume	10.9 m^3 (H/D ~1.7/2.9 m)
re pressure drop	~ 0.4 bar
lume fraction (%) Fuel/Gas/SiC	50/40/10 %
erage power density	55 MW/m^3
ference fuel compound	UPuC/SiC (50/50 %)
	17 % Pu
eeding/Burning performances	Self-Breeder
aximum fuel temperature	1174 °C (normal operation)
	< 1650 °C (depressurization)
core heavy nuclei inventory	30 tons
sion rate (at %); Damage	~ 5 at%; 60 dpa
el management	multi-recycling
el residence time	3 x 829 efpd
ppler effect (180°C-1200°C)	$-1540\ 10^{-5}$
layed neutron fraction	$356\ 10^{-5}$
tal He voidage effect	$+230\ 10^{-5}$
erage Burn up rate at EOL	~ 5 % FIMA
imary vessel diameter	< 7 m

Schematic of a Fast Gas Reactor

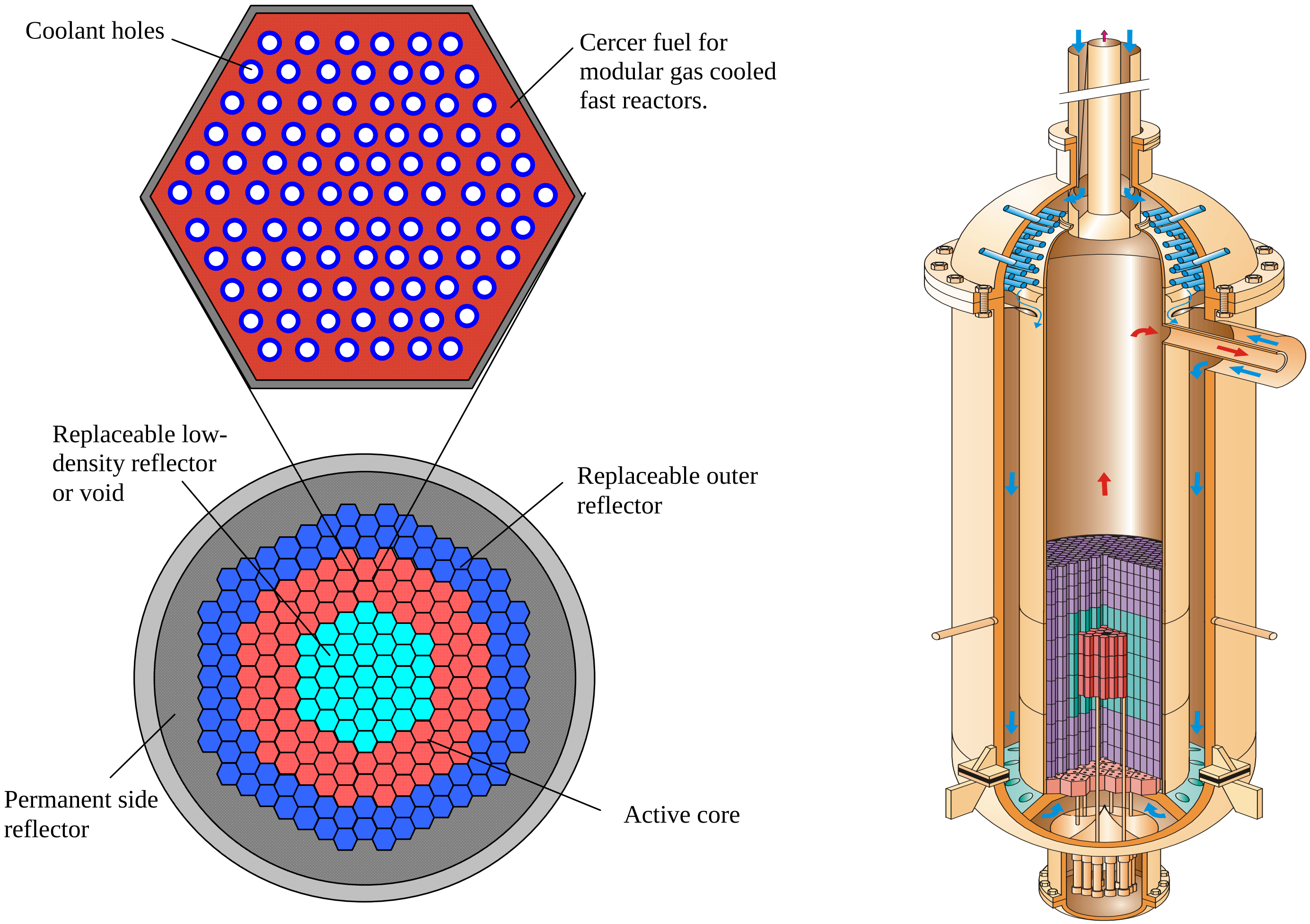


Figure 5. Schematic diagram of possible core layout with inner reflector for a modular, helium-cooled fast nuclear energy system with ceramics fuel (cercer), or ceramics/metal (cermet) or composite metal (metmet) as back-up solutions. Could also be a smaller pebble bed .

Summary

- **Pebble Power** Appears to Meet Economic, Safety and Electricity Needs for Next Generation of Nuclear Energy Plants
- Eskom to decide in December whether to build protoype plant in South Africa.
- **MIT Project aimed at longer term 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.**