High Temperature Gas Reactors

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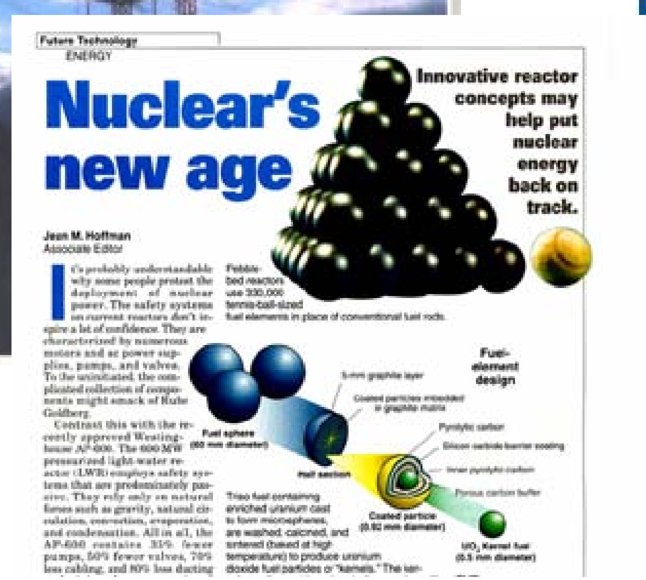
Massachusetts Institute of Technology



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.

Fuel-element design

Fuel sphere (60 mm diameter)
Half section
Coated particle (0.92 mm diameter)
UO_2 Kernel fuel (0.5 mm diameter)

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-

The Politically Correct NUKE

MIT Students help design a nuclear power plant that they hope will revive the industry.

by Charles Wardell

Above right: A "pebble" (about eight-ball size) containing 10,000 uranium dioxide particles the size of a pencil point, each coated with several layers of graphite and a silicon carbide outer shell (inset). Though the pebbles heat to more than 1,000°C, the coatings trap the radiation inside. The particles decay within 250,000 years, but the graphite ball maintains its integrity for more than one million years.

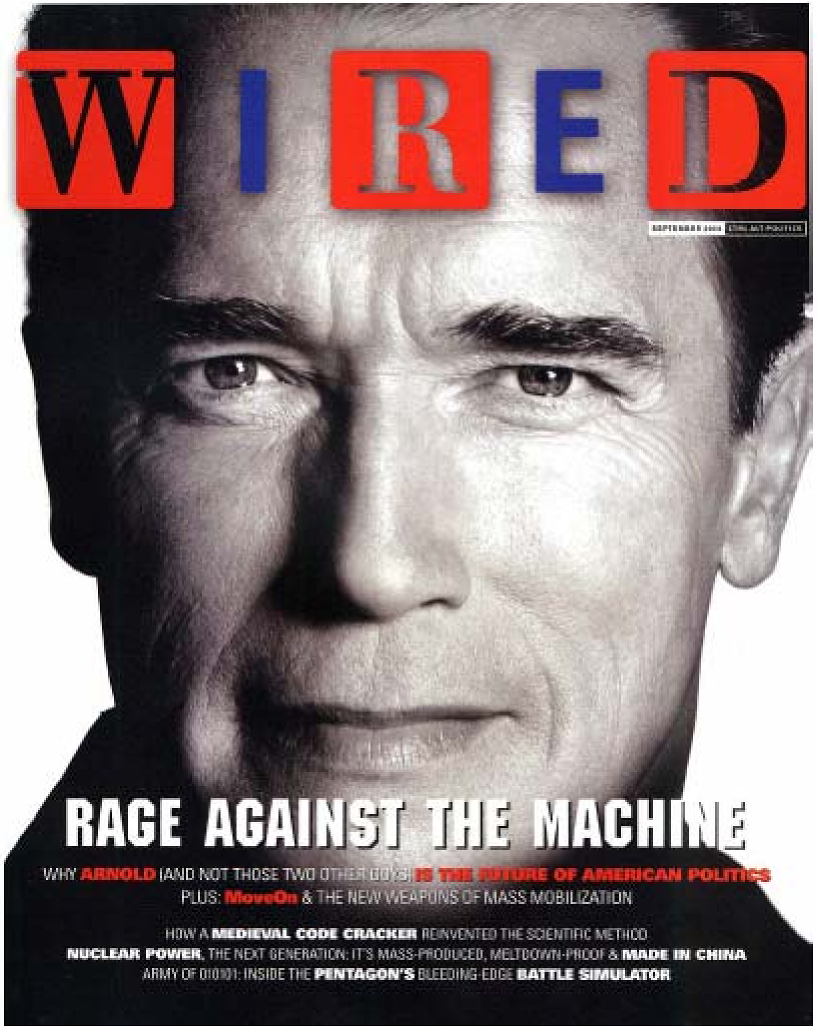
To truly understand the renewed buzz for nuclear, you have to travel to the Massachusetts Institute of Technology in Cambridge. Here, Andrew Kadak, professor of nuclear engineering, holds two billiard-size balls that many believe represent the future of nuclear energy. The balls are the "pebbles" in something called a pebble bed reactor, a new type of plant that proponents say is safer and more efficient than current plants. It could even crank out electricity for less than a gas-fired plant, savings that would presumably be passed on to you. More important, considering our anxiety toward nuclear energy, it's immune to meltdowns. The technology could be implemented, possibly at Three Mile Island, within five years.

When Kadak, formerly vice president of the American Nuclear Society, came to MIT in 1997, nuclear power seemed doomed. So in January 1998, he challenged eleven students to design "a politically correct reactor" that would win acceptance from regulators and the public while giving gas a run for its energy-generating money.

All existing US commercial reactors are "light water" reactors. They're powered by half-inch cylindrical pellets of uranium—like cutoffs from a 1/2-inch dowel—stacked up in 14-foot-long metal rods. Hundreds of rods are lowered into a water-filled reactor core. The uranium atoms give off neutrons, some of which crash into other uranium atoms, splitting them, generating heat, and knocking free more atom-splitting neutrons—the process known as fission. The water in the core carries the heat away to drive an electric turbine.

Kadak's students rejected light-water technology for this reason: If the coolant leaks away, the core heats up enough to melt. Instead, they found something they considered safer: a pebble bed research reactor that had run for twenty-two years in Germany ("until Chernobyl came along and Germany got out of nuclear," Kadak says). It relied on fission too, but was fueled by eight-ball-sized pebbles, and rather than water coolant, it used helium gas.

The main safety feature is the fuel itself. Each pebble consists of roughly 10,000 "microspheres" of uranium dioxide the size of a pencil point. Each is in turn coated with several layers of graphite, and a silicon carbide outer shell. While fission heats the pebbles to as much as 1,100°C, the coatings trap all radioactivity inside. Once the


WIRED
RAGE AGAINST THE MACHINE
WHY ARNOLD (AND NOT THOSE TWO OTHER GUYS) IS THE FUTURE OF AMERICAN POLITICS
PLUS: MoveOn & THE NEW WEAPONS OF MASS MOBILIZATION
HOW A MEDIEVAL CODE CRACKER REINVENTED THE SCIENTIFIC METHOD
NUCLEAR POWER, THE NEXT GENERATION: IT'S MASS-PRODUCED, MELTDOWN-PROOF & MADE IN CHINA
ARMY OF 010101: INSIDE THE PENTAGON'S BLEEDING-EDGE BATTLE SIMULATOR


LET A THOUSAND REACTORS BLOOM
CHINA
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
拼裝式反應爐
Joy-Joy Snap-together Reactor
Meltdown-proof! Safe for all ages.
不會熔毀！

Presentation Overview

- Introduction to Gas Reactors
- Pebble Bed Reactor
- Players
- International Status
- Research Needs

Fundamentals of Technology

- Use of Brayton vs. Rankine Cycle
- High Temperature Helium Gas (900 C)
- Direct or Indirect Cycle
- Originally Used Steam Generators
- Advanced Designs Use Helium w/wo HXs
- High Efficiency (45% - 50%)
- Microsphere Coated Particle Fuel

History of Gas Reactors in US

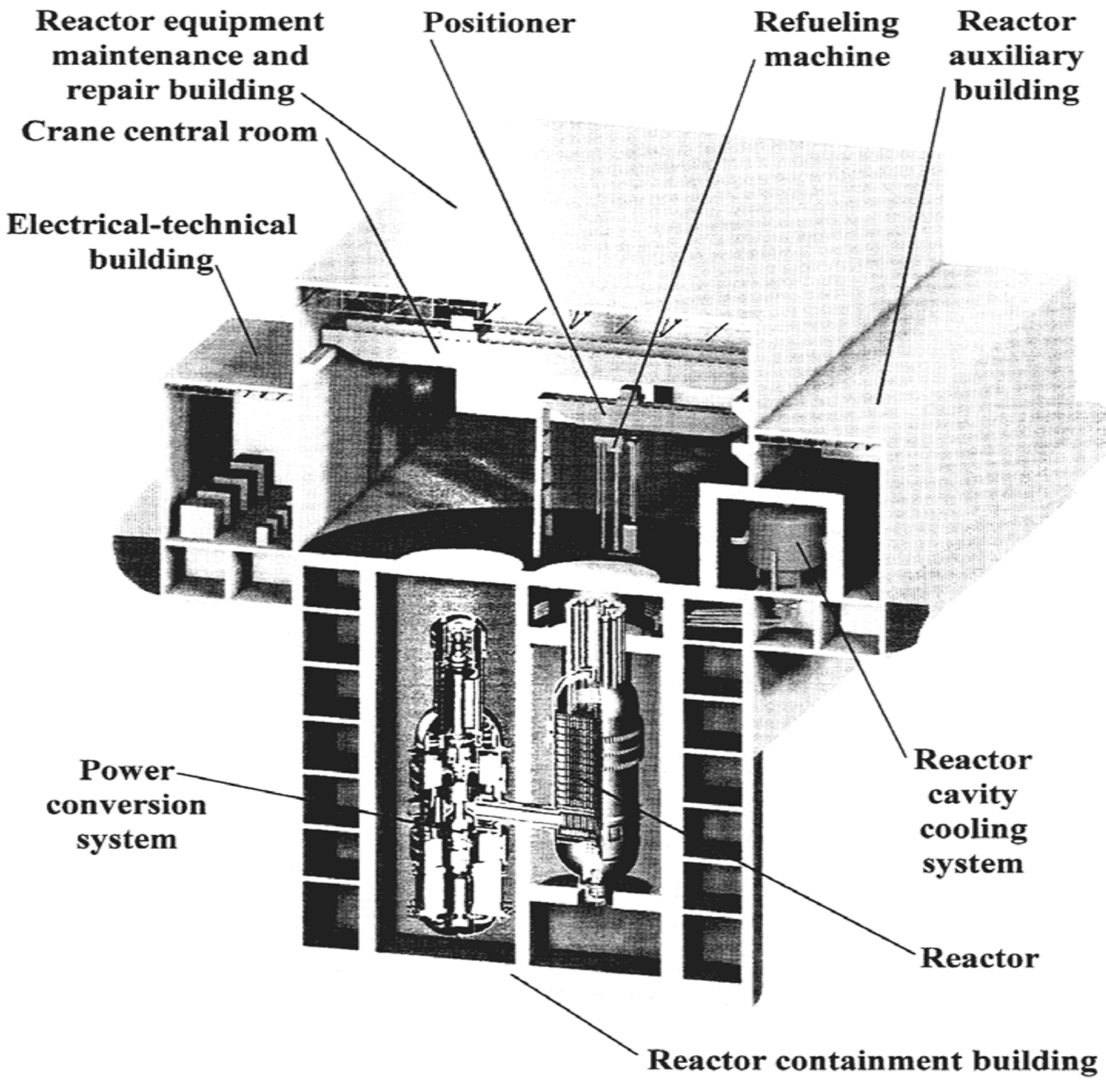
- Peach Bottom (40 MWe) 1967-1974
  - First Commercial (U/Thorium Cycle)
  - Generally Good Performance (75% CF)
- Fort St. Vrain (330 MWe) 1979-1989 (U/Th)
  - Poor Performance
  - Mechanical Problems
  - Decommissioned

Fort St. Vrain

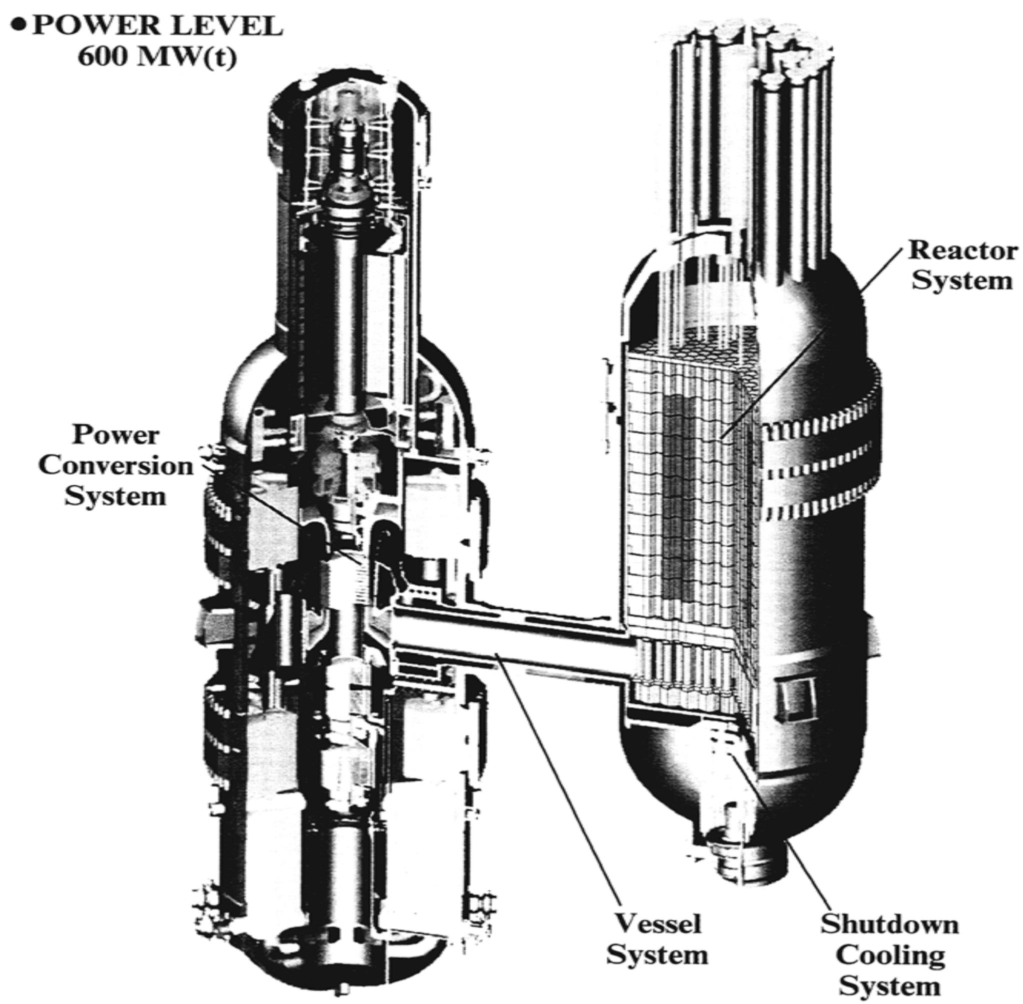
Different Types of Gas Reactors

- Prismatic (Block) - General Atomics
  - Fuel Compacts in Graphite Blocks
- Pebble Bed - German Technology
  - Fuel in Billiard Ball sized spheres
- Direct Cycle
- Indirect Cycle
- Small Modular vs. Large Reactors

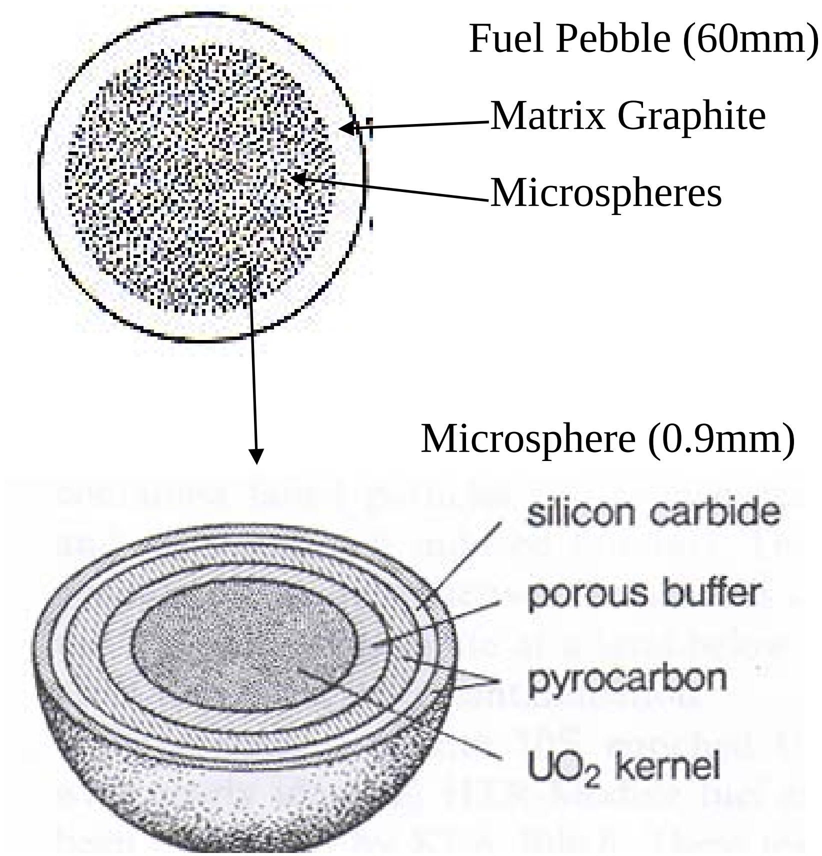
GT-MHR Module General Arrangement



GT-MHR Combines Meltdown-Proof Advanced Reactor and Gas Turbine

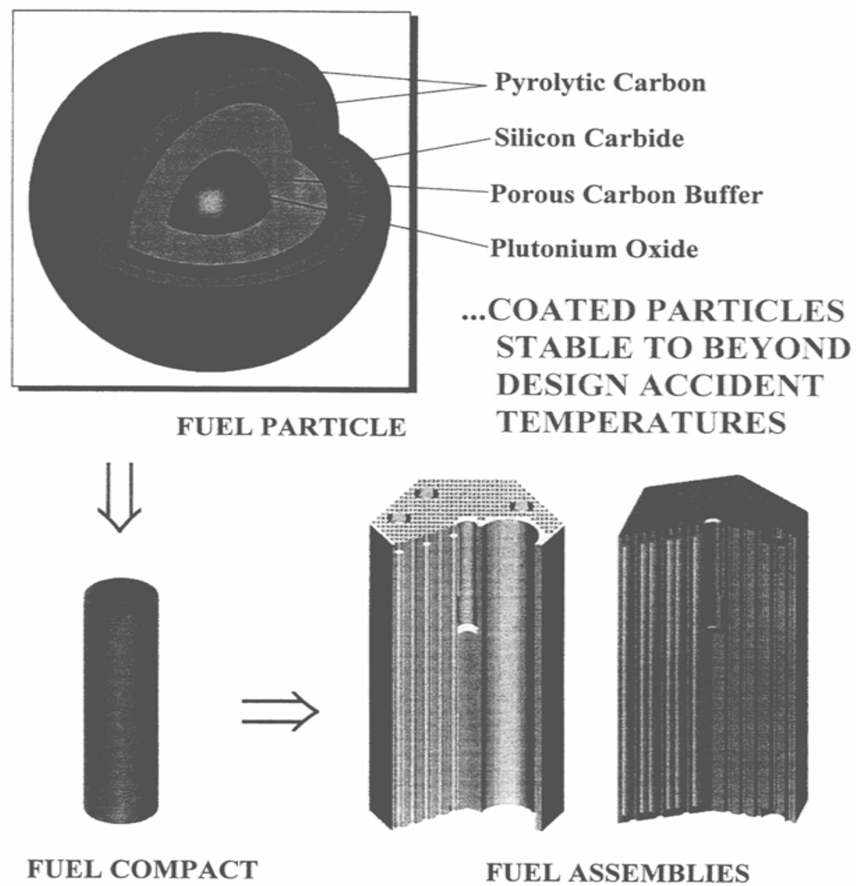


TRISO Fuel Particle -- “Microsphere”



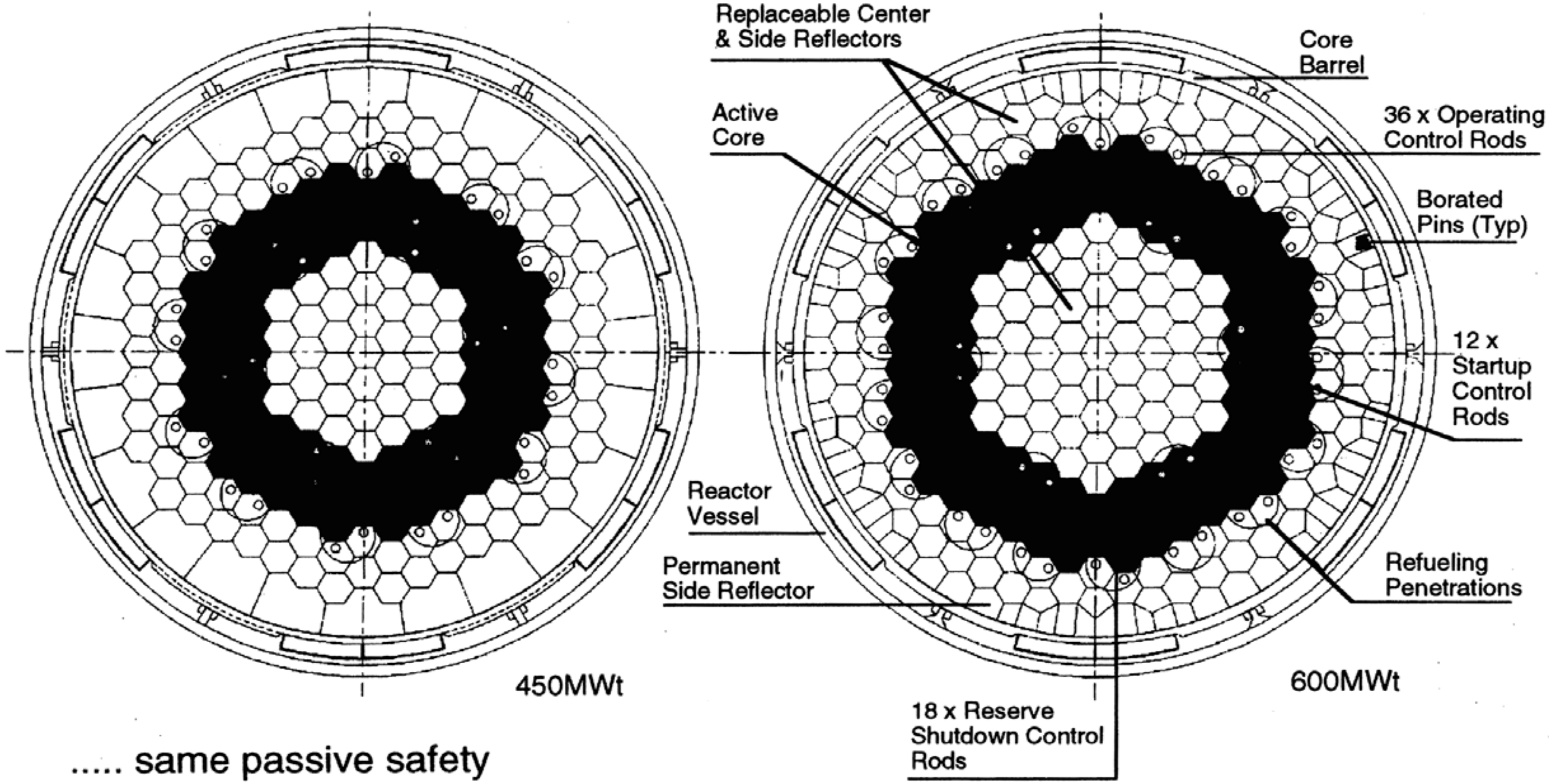
- 0.9mm diameter
- ~ 11,000 in every pebble
- 10^9 microspheres in core
- Fission products retained inside microsphere
- TRISO acts as a pressure vessel
- Reliability
  - Defective coatings during manufacture
  - ~ 1 defect in every fuel pebble

Fuel Components with Plutonium Load



- Fuel Normal Peak Temperature 1200 °C
- Fuel Maximum Design Basis Event Temperature 1600 °C

Comparison of 450 MWt and 600 MWt Cores

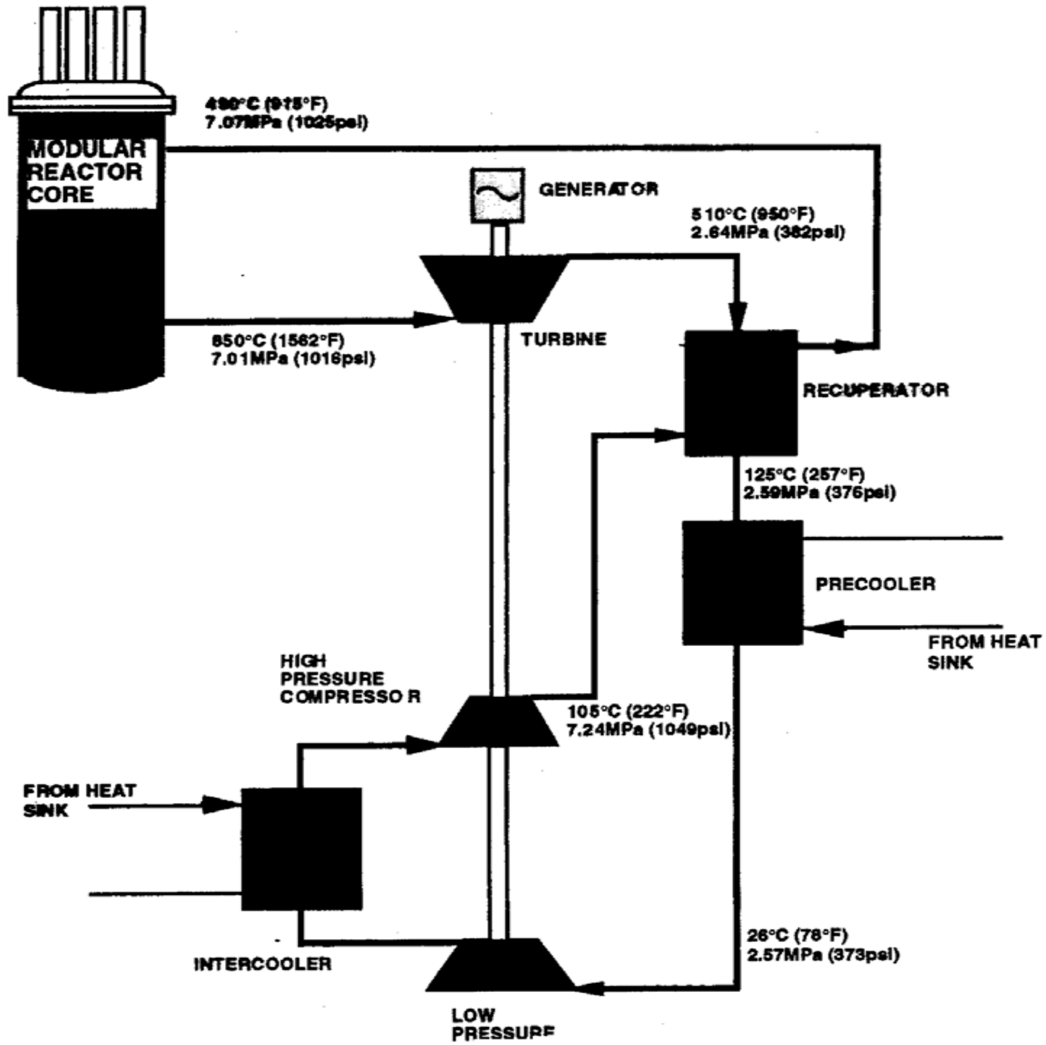


..... same passive safety

..... annular core using existing technology

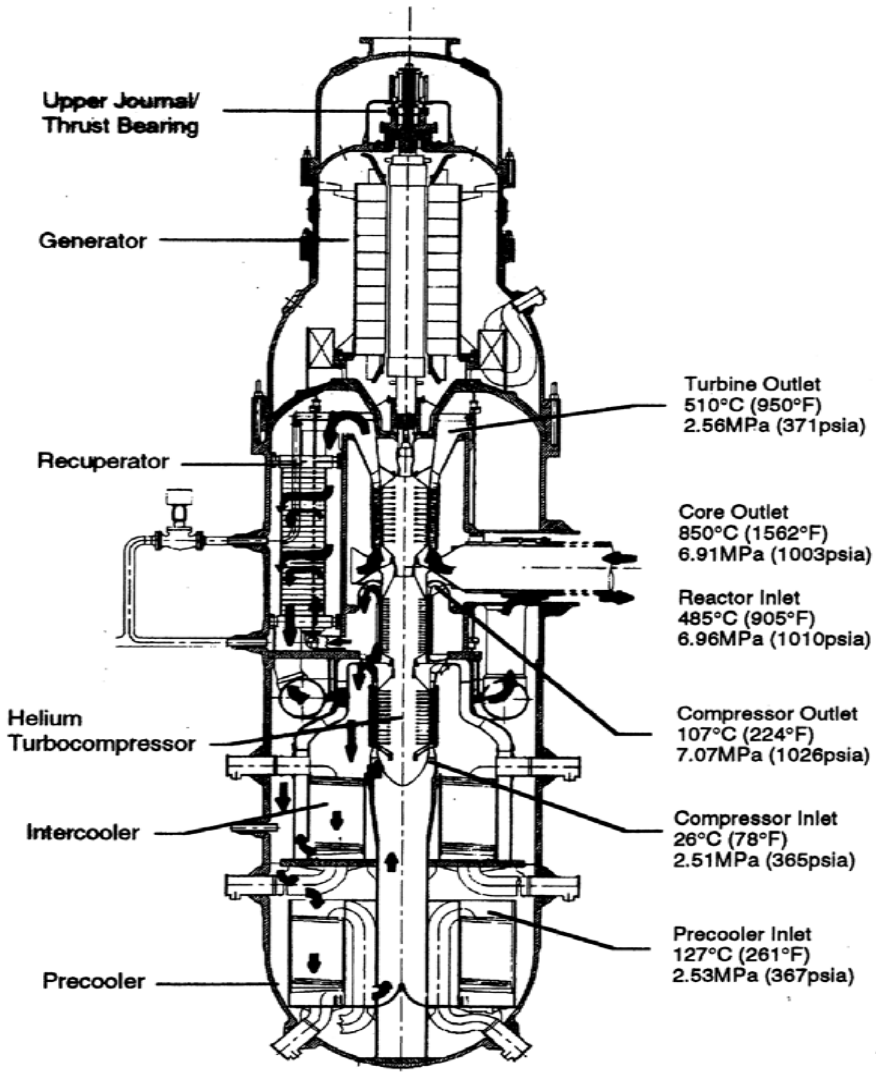
GENERAL ATOMICS

GT-MHR Flow Schematic



GENERAL ATOMICS

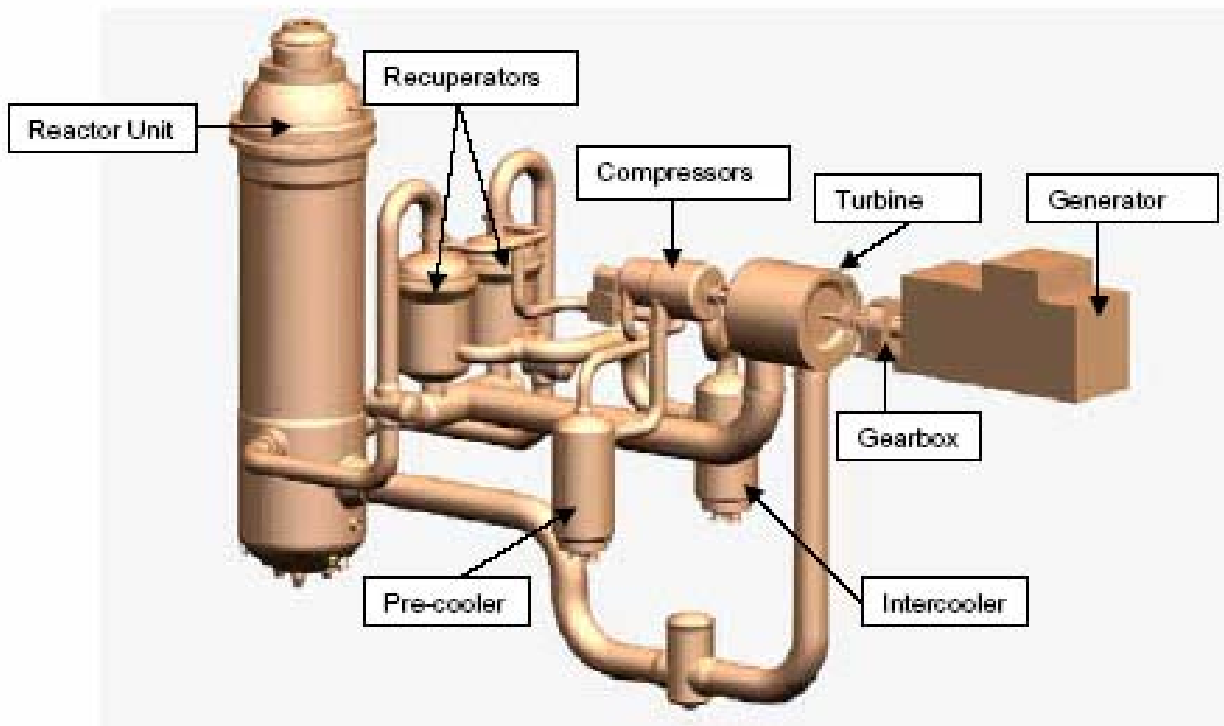
Flow through Power Conversion Vessel



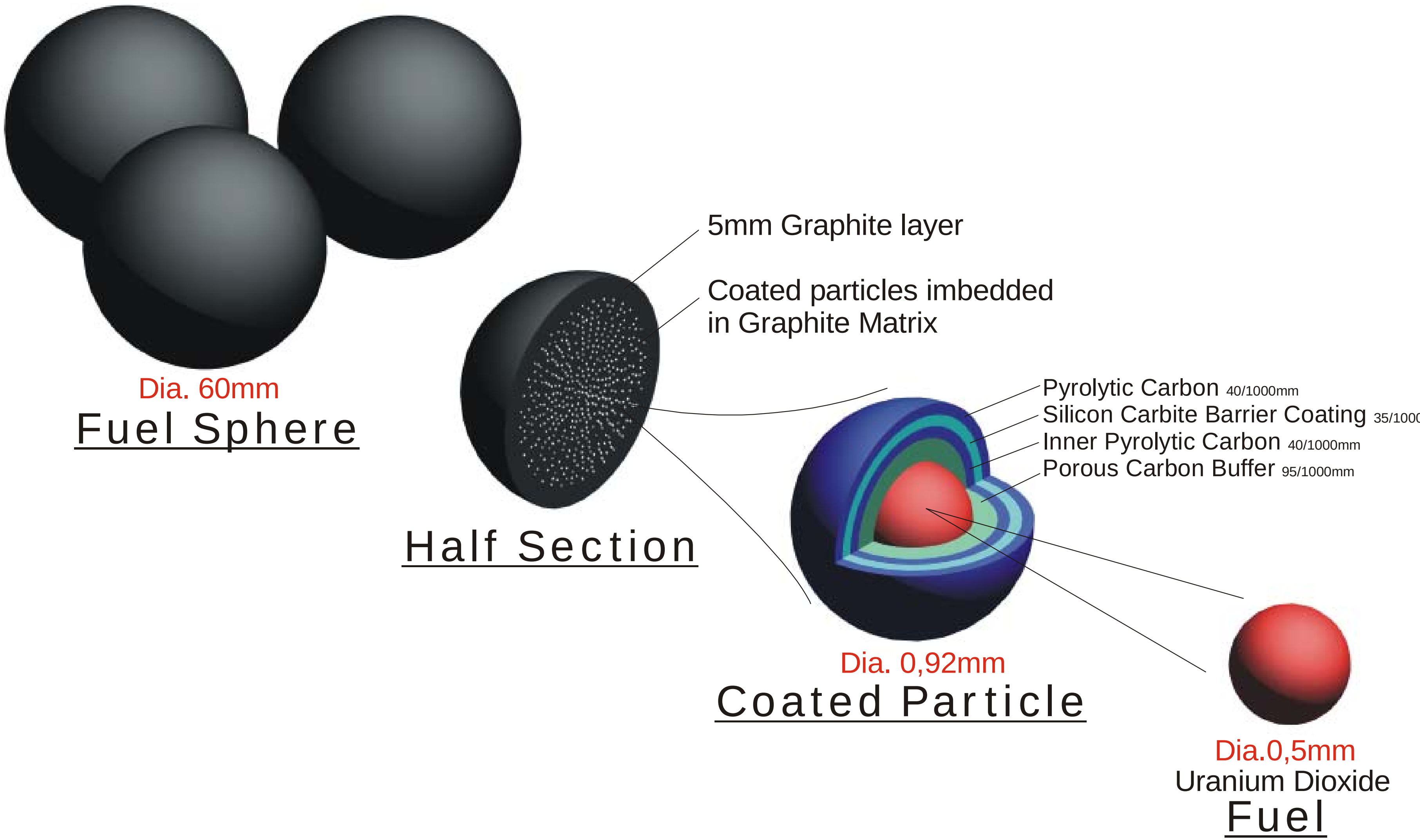
GENERAL ATOMICS

FIGURE 9. The 400 MWt single shaft main power system in the building.

Modular Pebble Bed Reactor South Africa - ESKOM



FUEL ELEMENT DESIGN FOR PBMR



Differences Between LWRS

- Higher Thermal Efficiencies Possible
- Helium inert gas
- Minimizes use of water in cycle - corrosion
- Single Phase coolant – fewer problems in accident
- Utilizes gas turbine technology
- Lower Power Density – no meltdown potential
- Less Complicated Design (No ECCS)

Advantages & Disadvantages

Advantages

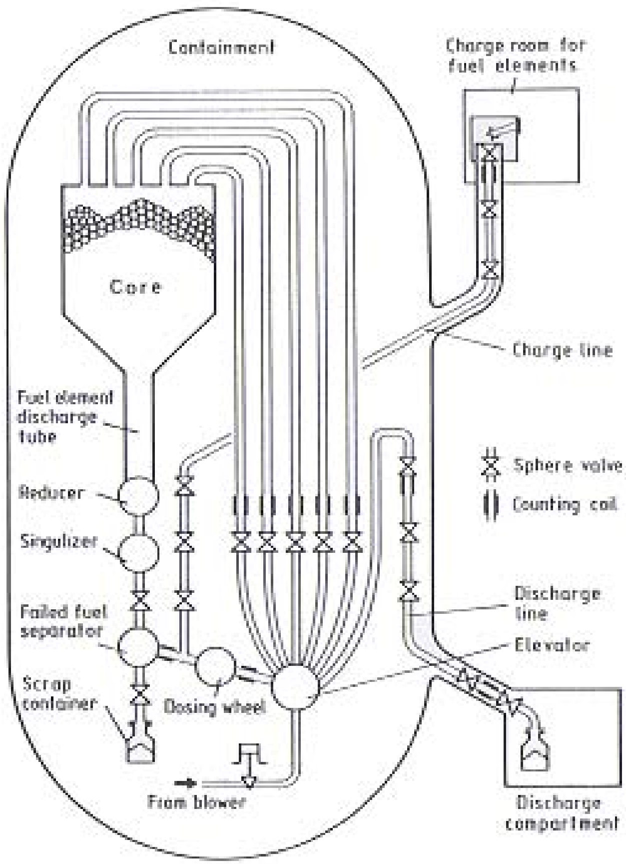
- Higher Efficiency
- Lower operating waste
- Higher Safety Margins
- High Burnup

  - 100 MWD/kg

Disadvantages

- Poor History in US
- Little Helium Turbine Experience
- US Technology Water Based
- Licensing Hurdles due to different designs

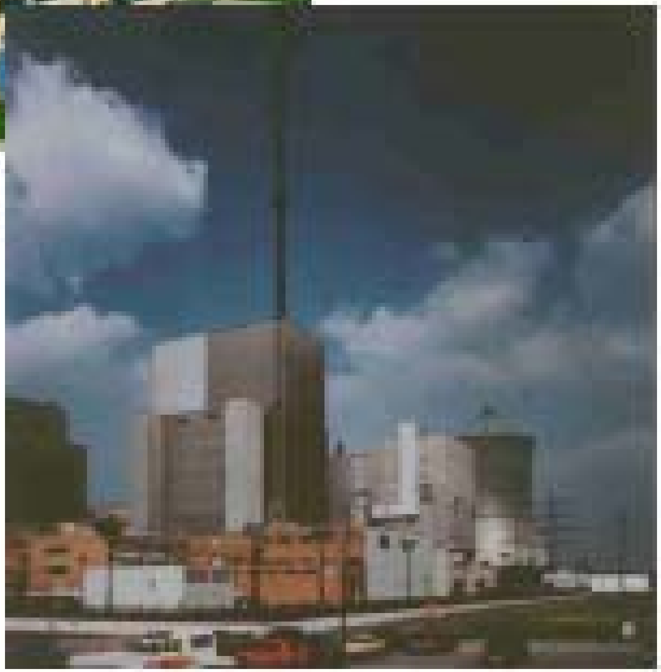
What is a Pebble Bed Reactor ?



- **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**

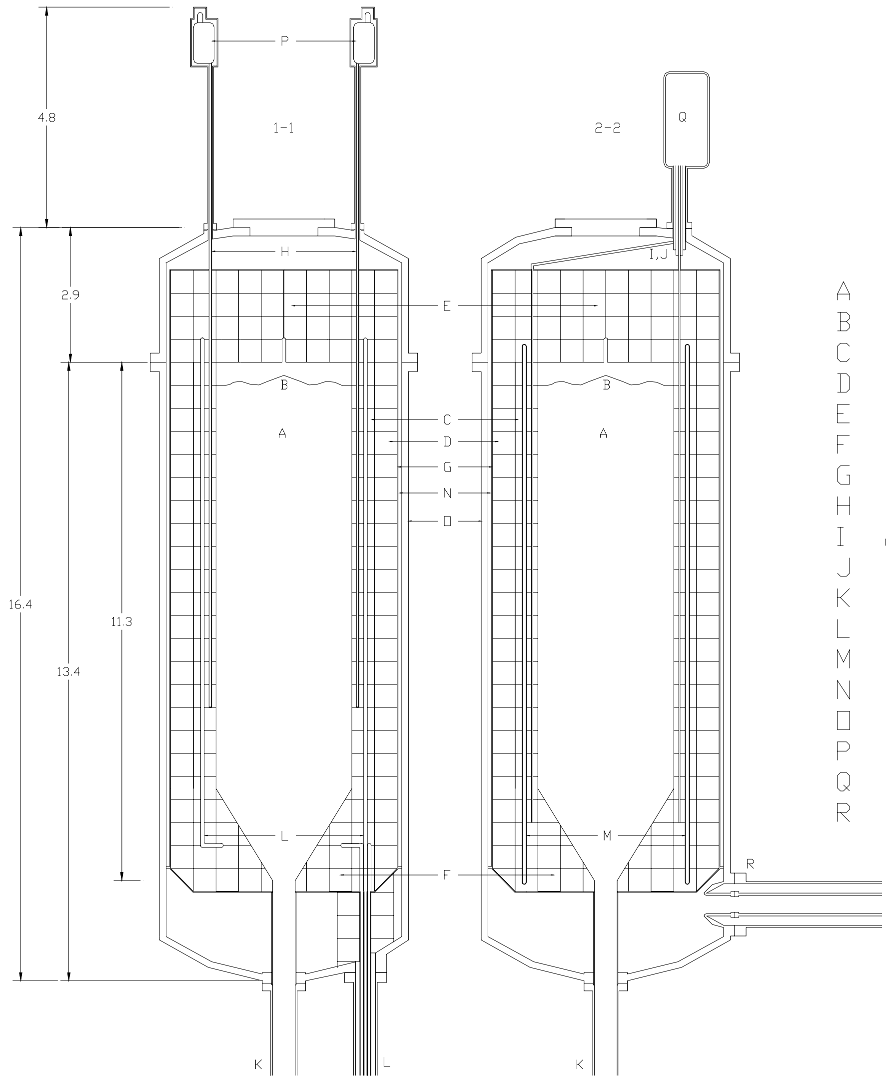
Germany

AVR (1967-88)
15 MWe



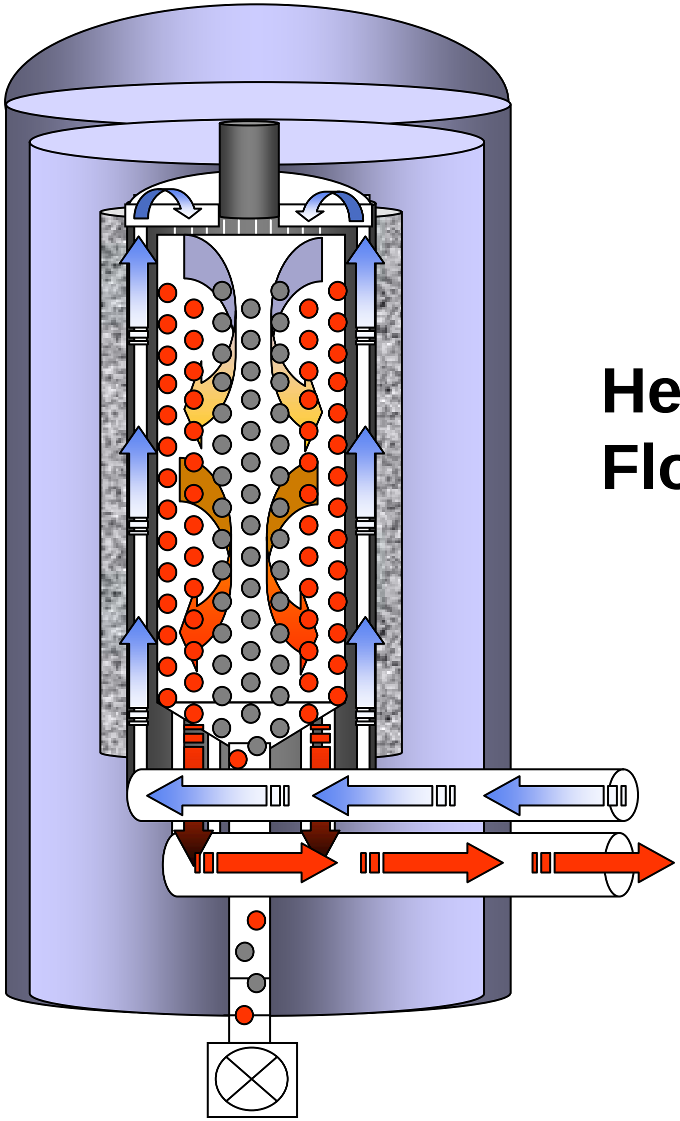
THTR (1985-89)
300 MWe

HTR- 10 China
First Criticality Dec.1, 2000



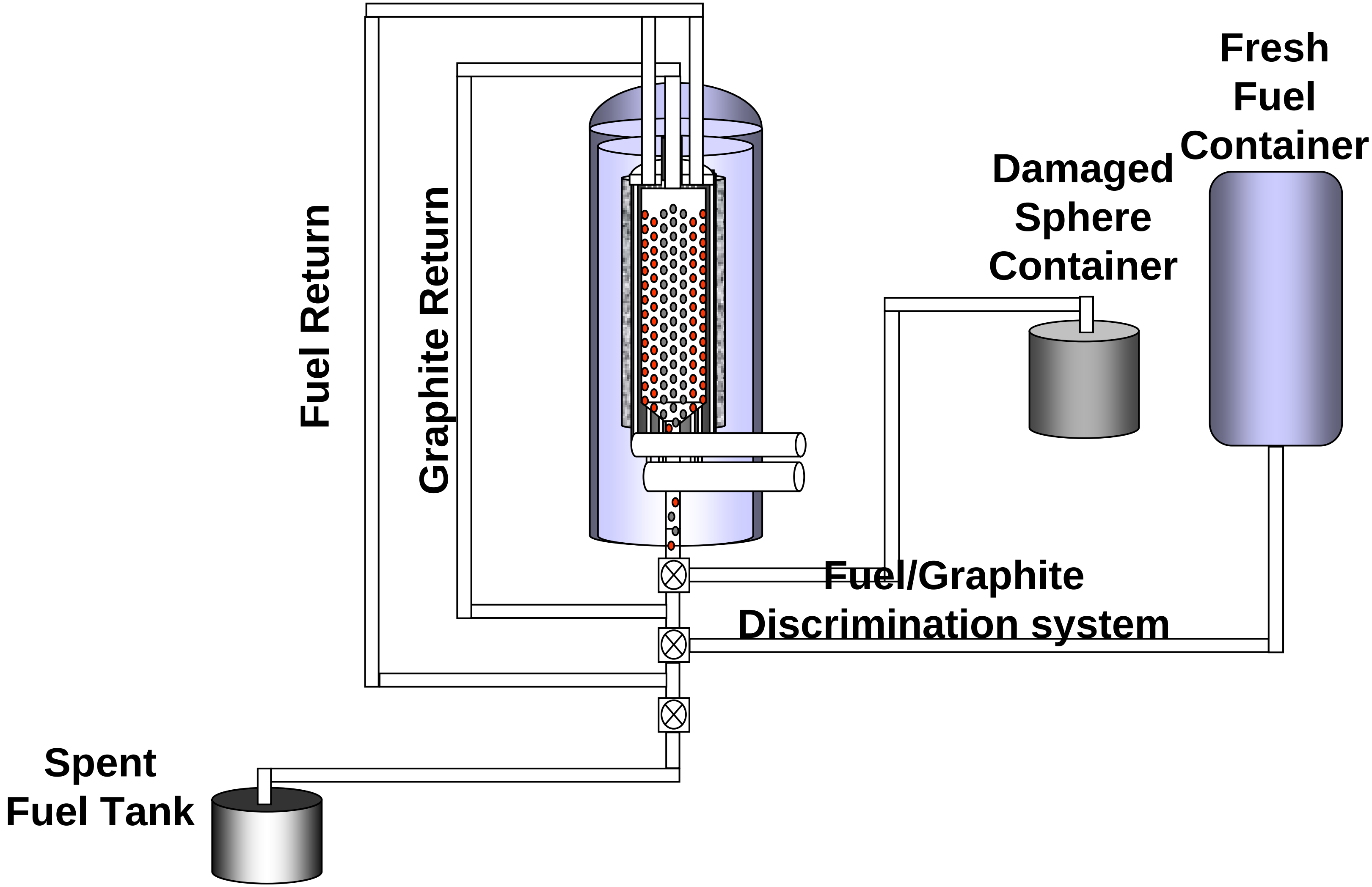
A Pebble Bed Core
B Fuel Drop Points (5)
C Inner Reflector
D Outer Reflector
E Top Reflector
F Bottom Reflector
G Core Barrel
H Control Rod Channels (6)
I Absorber Ball Drop Channels (18)
J Absorber Ball Lift Channel (1)
K Fuel Discharge Tube
L Pebble Fuel Lift Channels (5)
M Coolant Flow Channels (6)
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



Pebble Bed Reactor Designs

- PBMR (ESKOM) South African
  - Direct Cycle
- China – Indirect He/Steam Cycle
- MIT Design
  - Indirect Cycle - Intermediate He/He HX
  - Modular Components - site assembly

MIT 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**

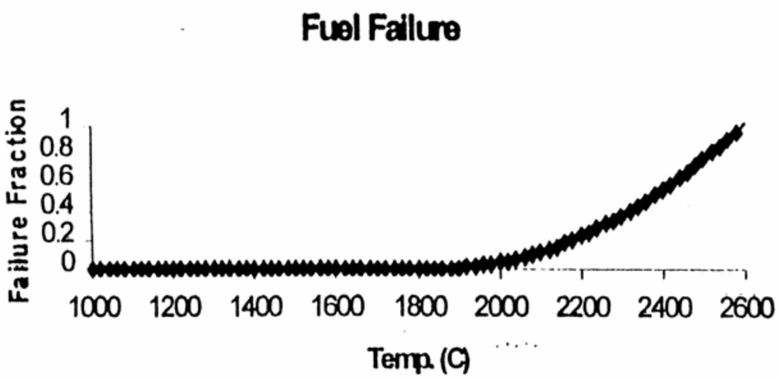
Safety Issues

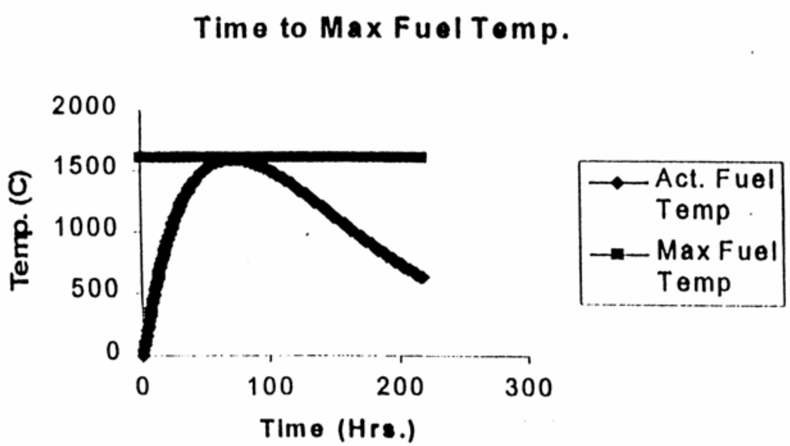
- Fuel Performance - Key to safety case
- Air Ingress
- Water Ingress
- Loss of Coolant Accident
- Seismic reactivity insertion
- Reactor Cavity Heat Removal
- Redundant Shutdown System
- Silver and Cesium diffusion

Safety Advantages

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

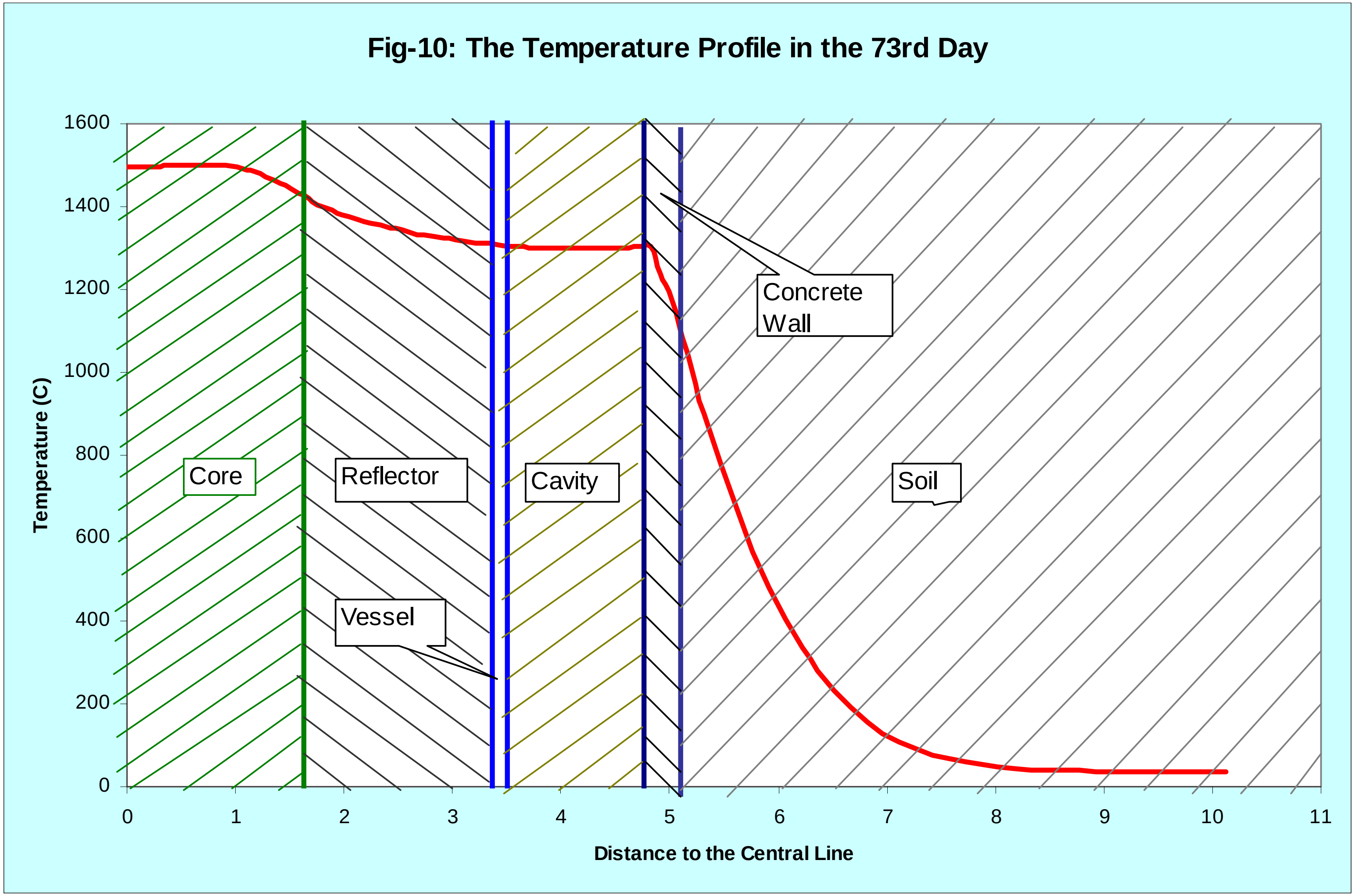
“Naturally” Safe Fuel



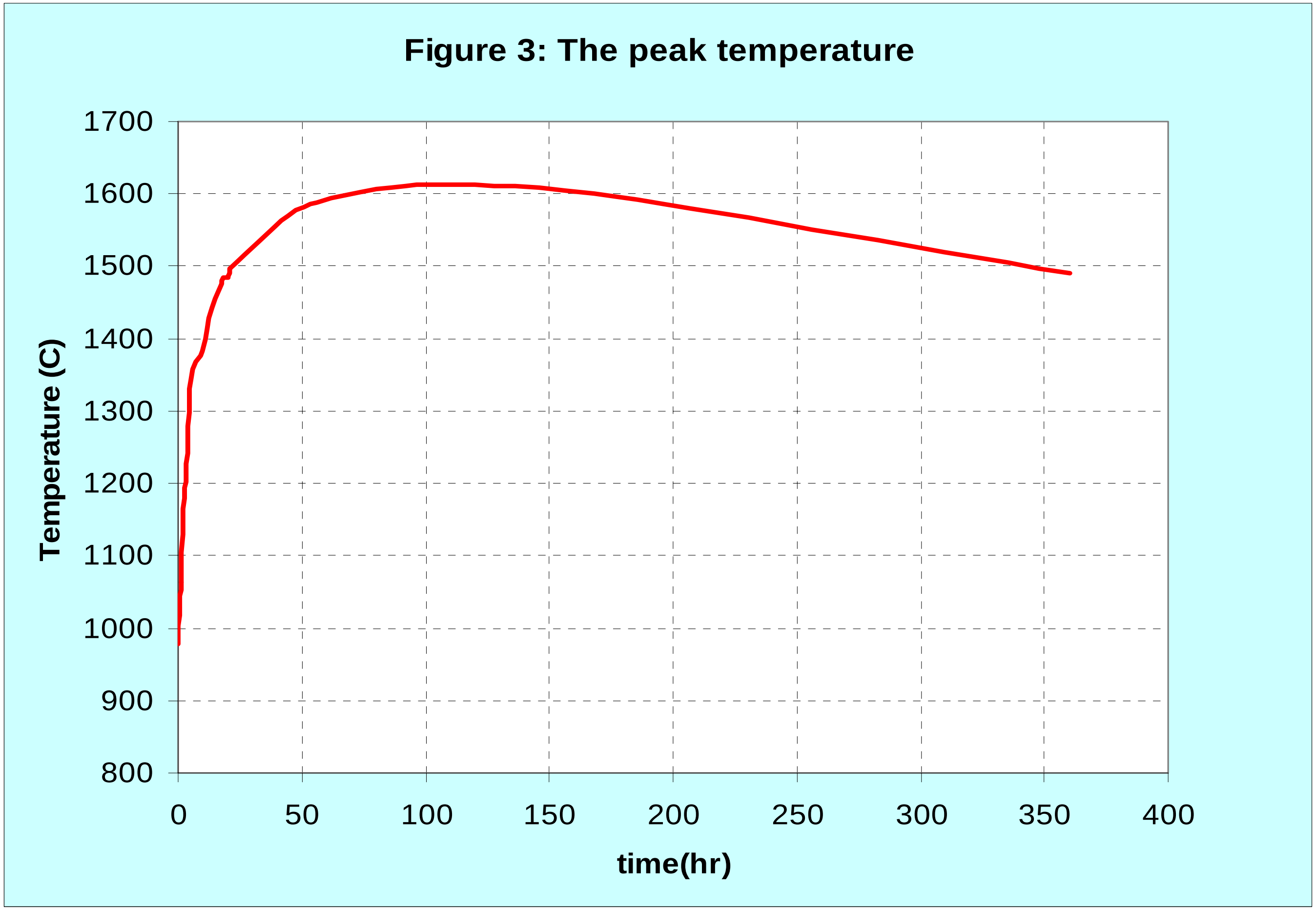


- Shut Off All Cooling
- Withdraw All Control Rods
- No Emergency Cooling
- No Operator Action

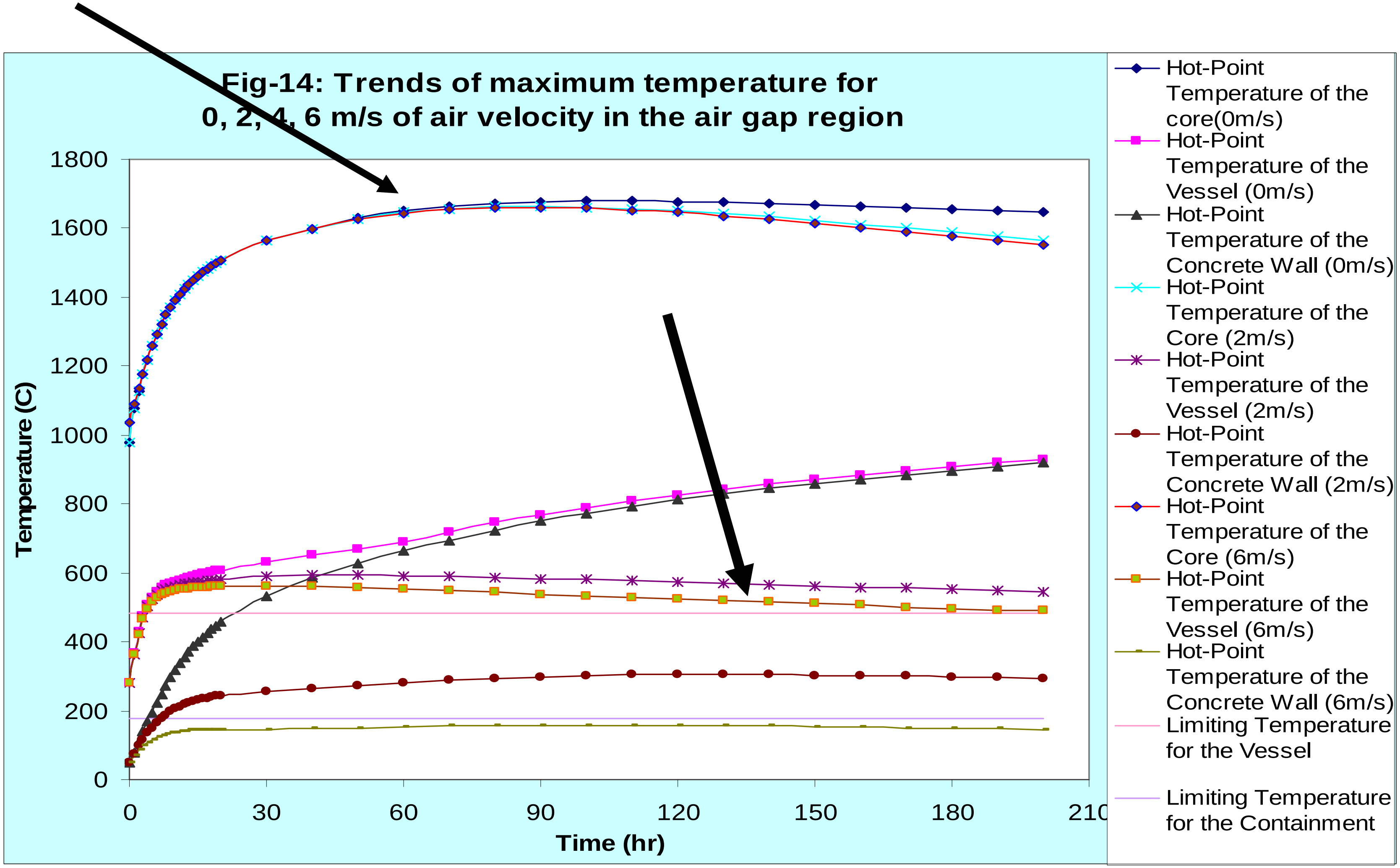
Temperature Profile



Simplified HEATING7 Open Cylinder Analysis Peak Temperature



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



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.

TIM Code Model
Fuel Performance Code

- Deals Explicitly With Statistical Nature of Fuel Characteristics, Materials Properties Uncertainty, and Power History Uncertainty (Fueling Scheme in PBMR) Using Monte Carlo Techniques.
- Advanced Fracture Mechanics Model for PyC and SiC Failure.
- Able to Model Prismatic as well as Pebble Bed Cores
- Results Compare Well With Irradiation Experiments
- Chemical Model-In Progress

Fuel Optimization Criteria

Considered Fuel Failure Mechanisms

- Over-pressurization failure by tensile stress
- Crack-in-pyrocarbon induced failure by stress concentration

↓

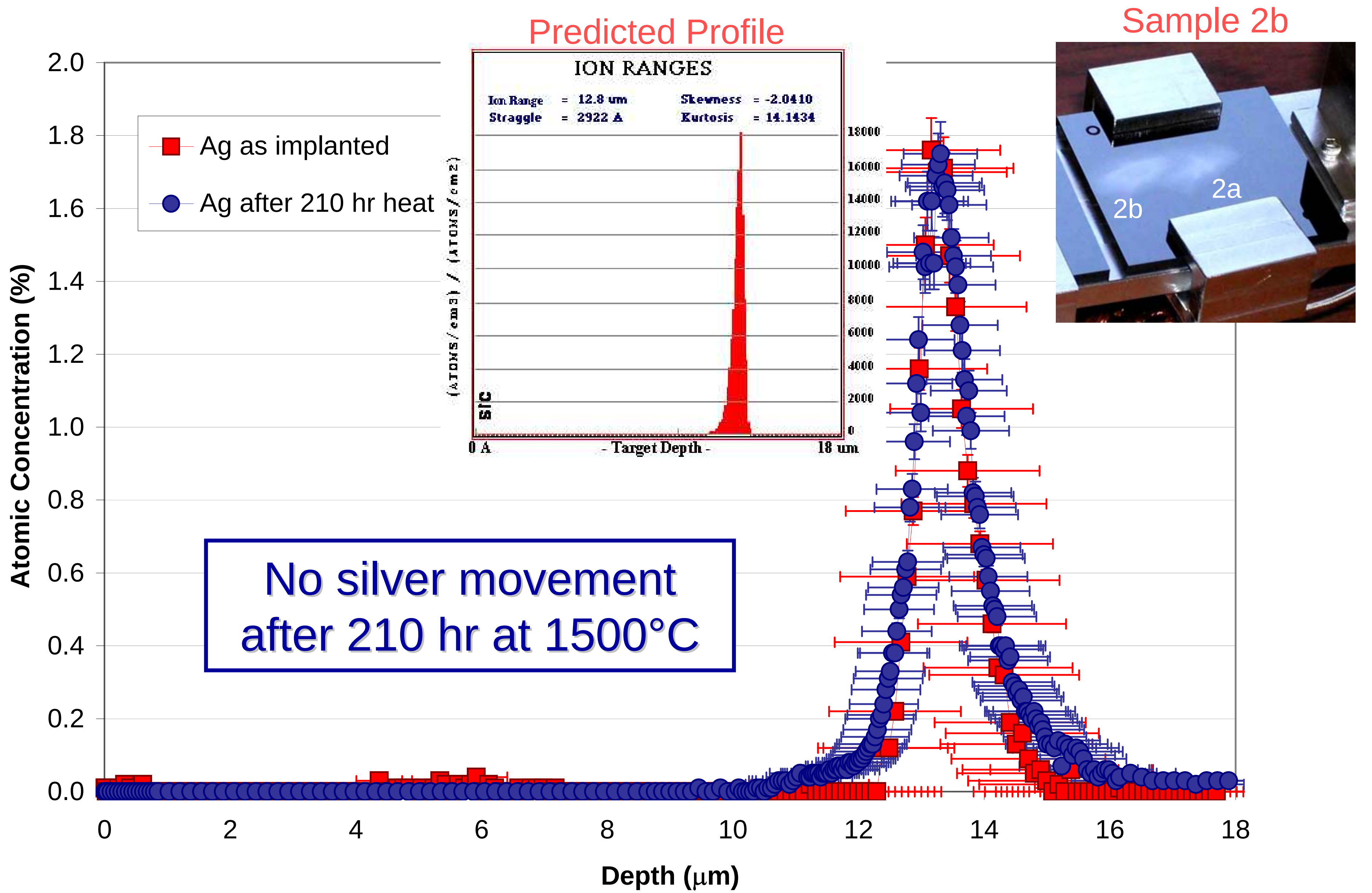
Fuel Optimization Criteria

- ❑ Minimize the maximum stresses in IPyC and OPyC layers
- ❑ Maximize the gap between Weibull strength and maximum stress for IPyC and OPyC layers
- ❑ Keep the maximum stress in SiC layer non-positive

Barrier Integrity

- Silver leakage 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

Ion Implantation Silver Depth Profile



Core Physics

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

MCNP4B Modeling of Pebble Bed Reactors

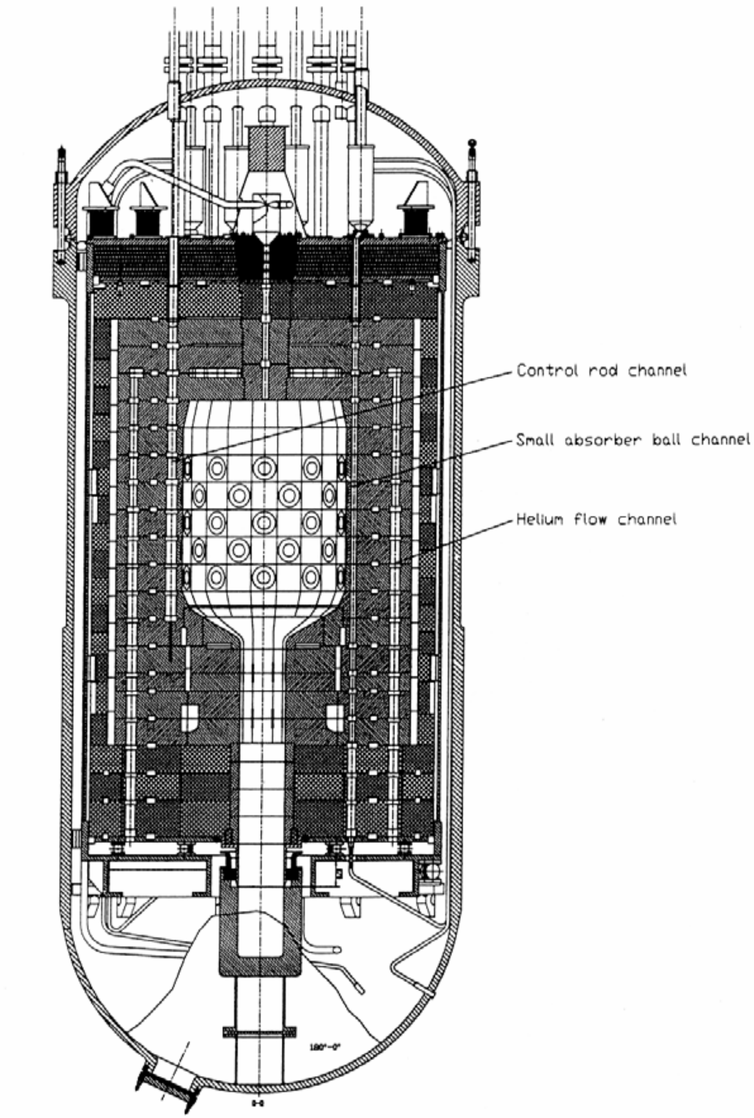
Steps in Method Development

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

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

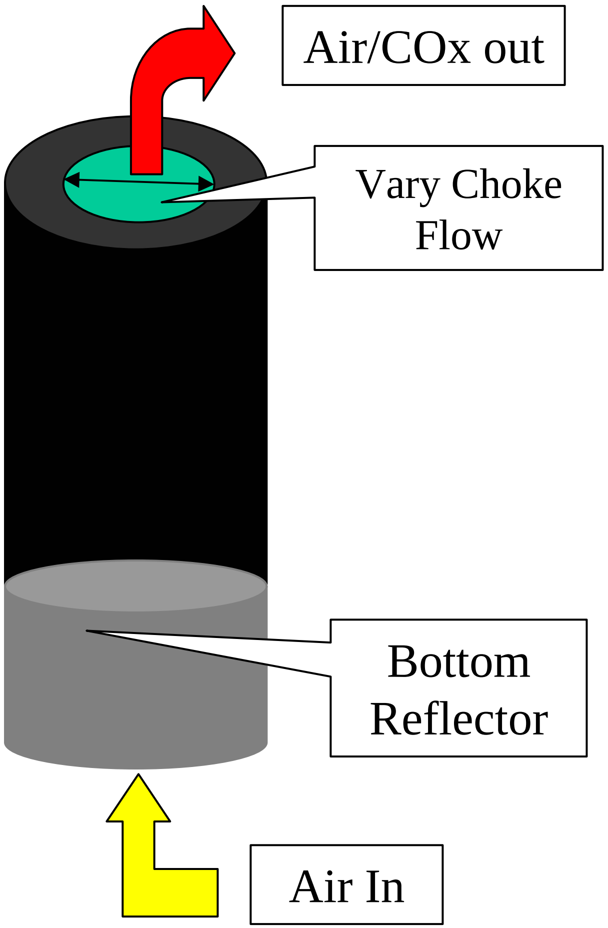


MCNP4B Results

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

Air Ingress

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



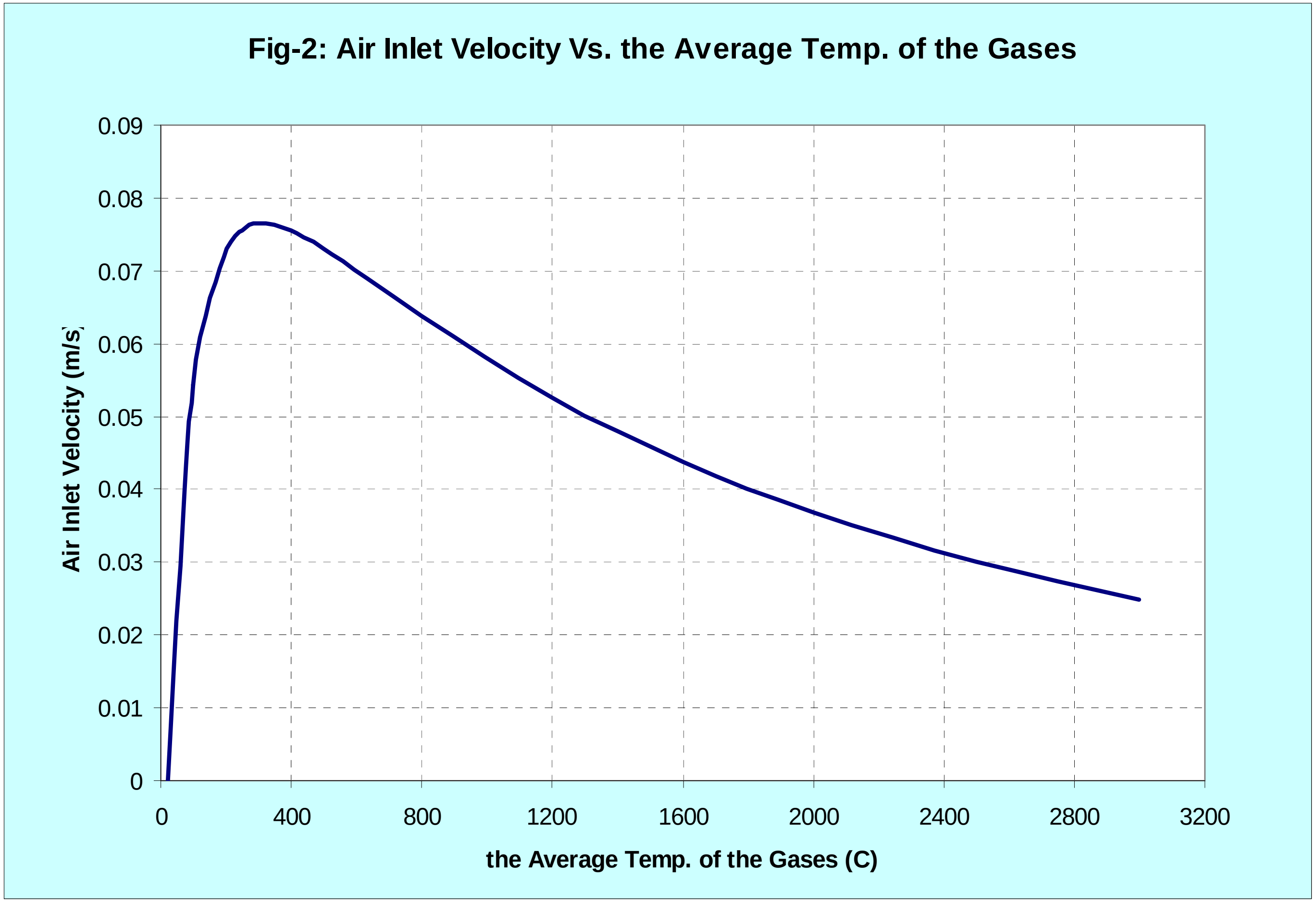
The Characteristics the Accident

- **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**

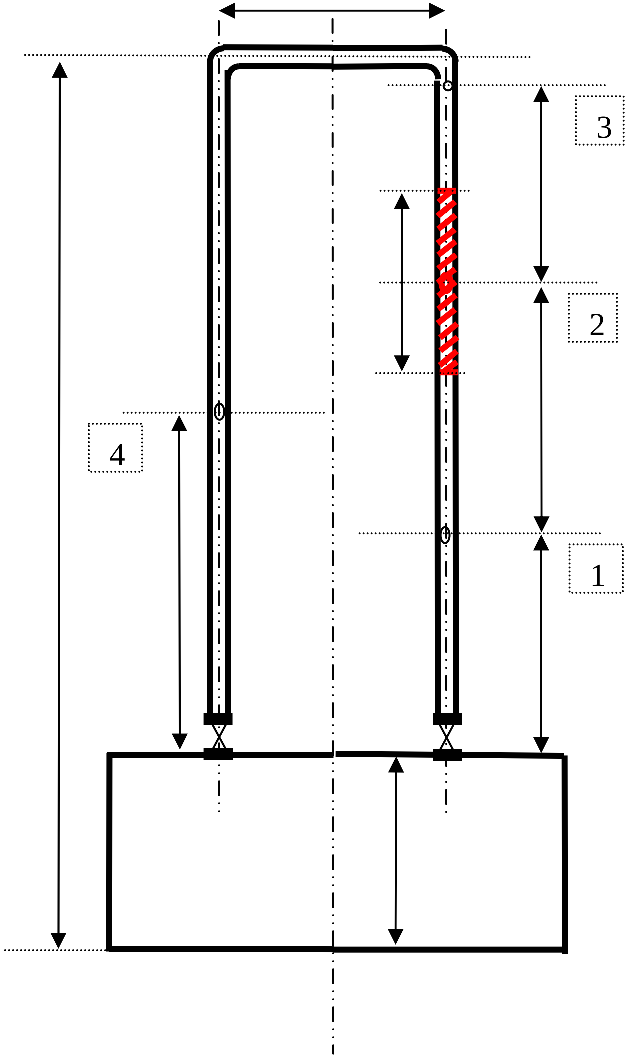
Critical Parameters for Air Ingress

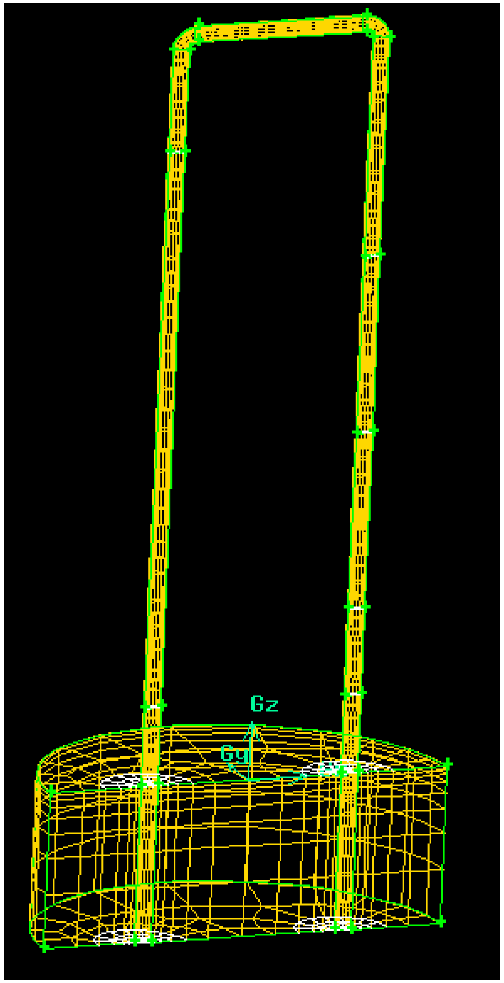
- Temperature of reacting components
- The concentration of oxygen
- Gas flow rates
- Pressure (partial pressure and total pressure in the system)

Air Ingress Velocity f(temperature)



Multi-Component experiment
Japanese Air Ingress Tests





Multi-Component Experiment

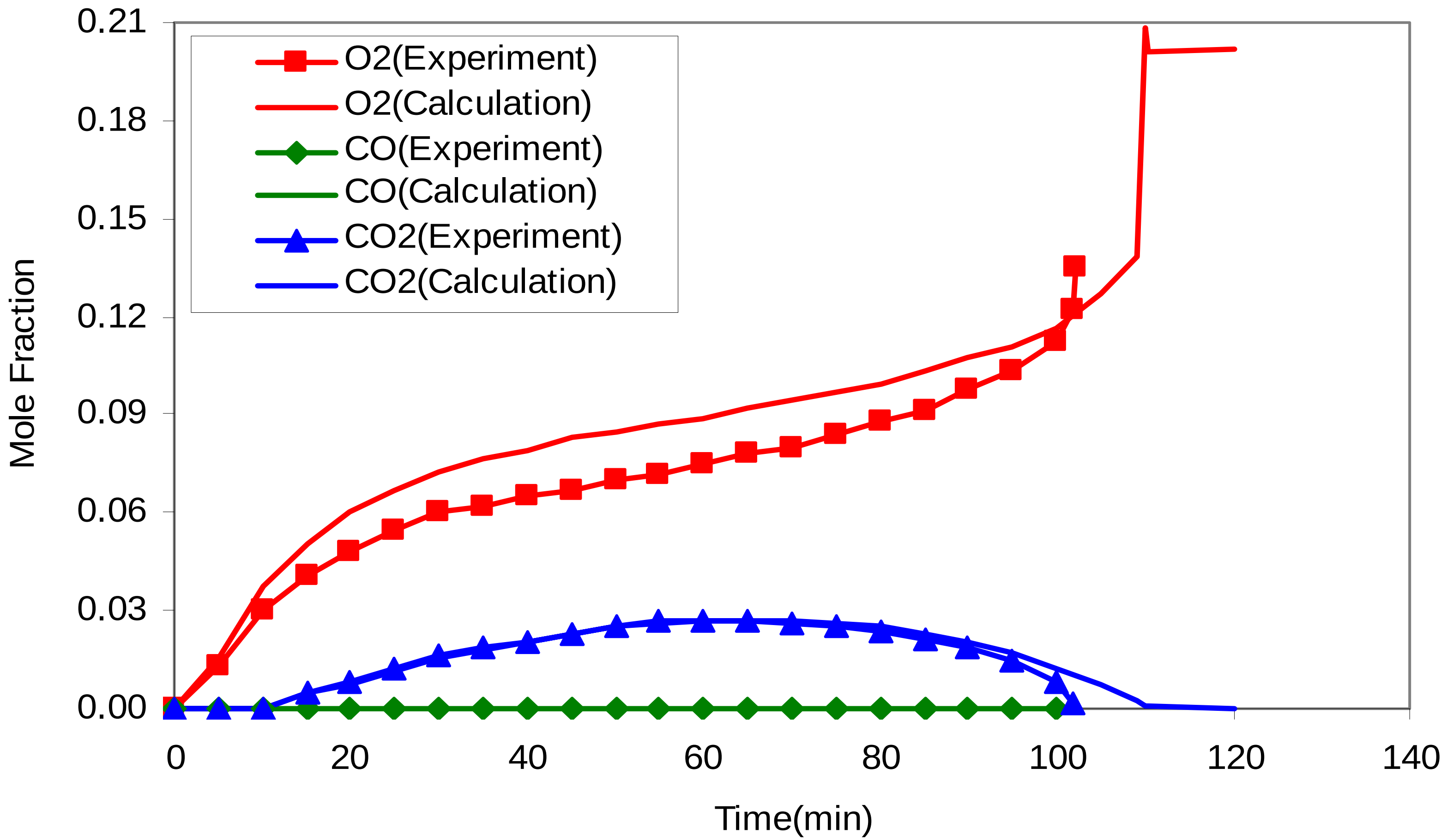


Figure 36: Mole Fraction at Point-1 (80% Diffusion Coff.)

Multi-Component Experiment(Cont.)

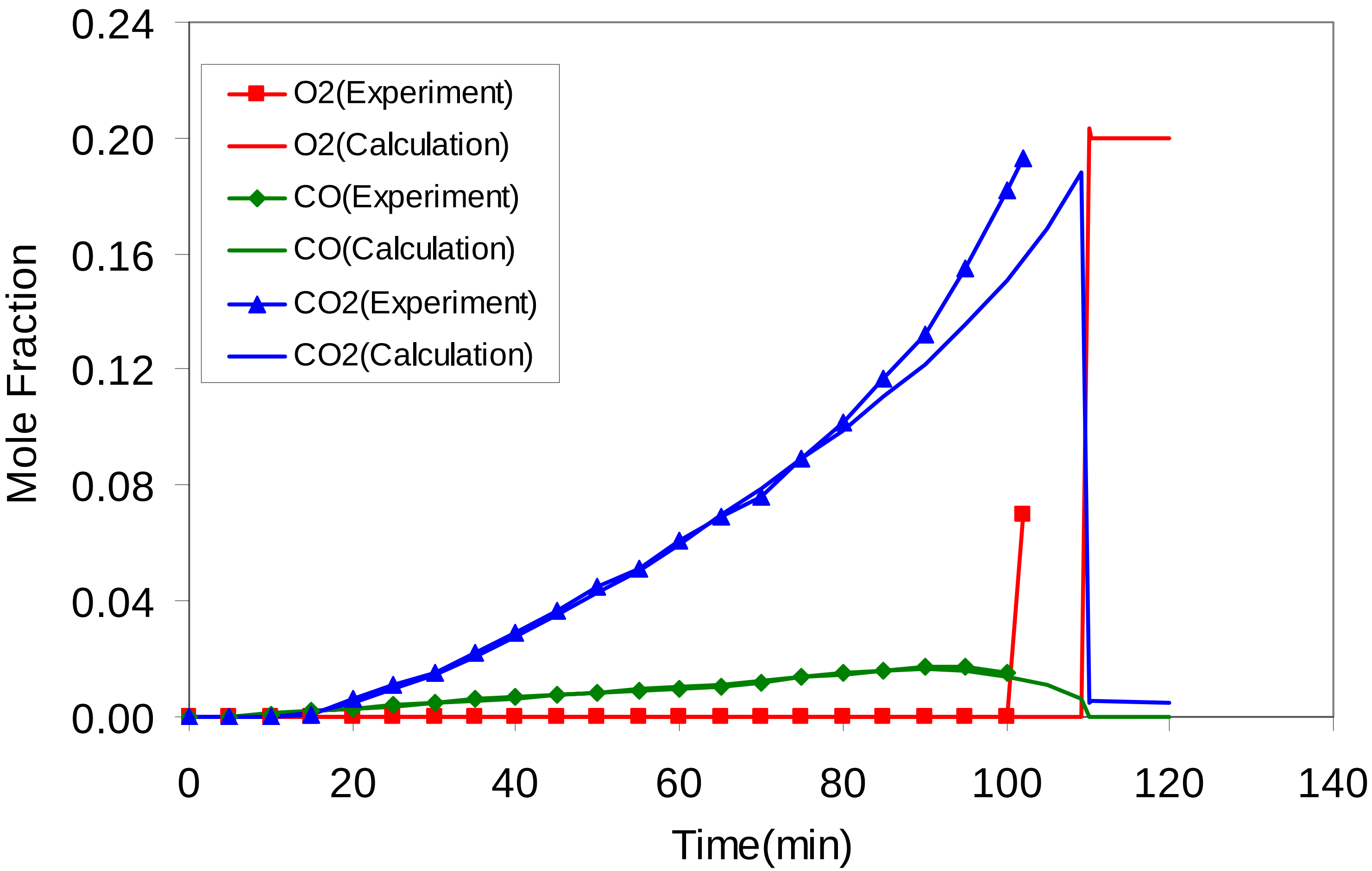


Figure 37: Mole Fraction at Point-3

Multi-Component

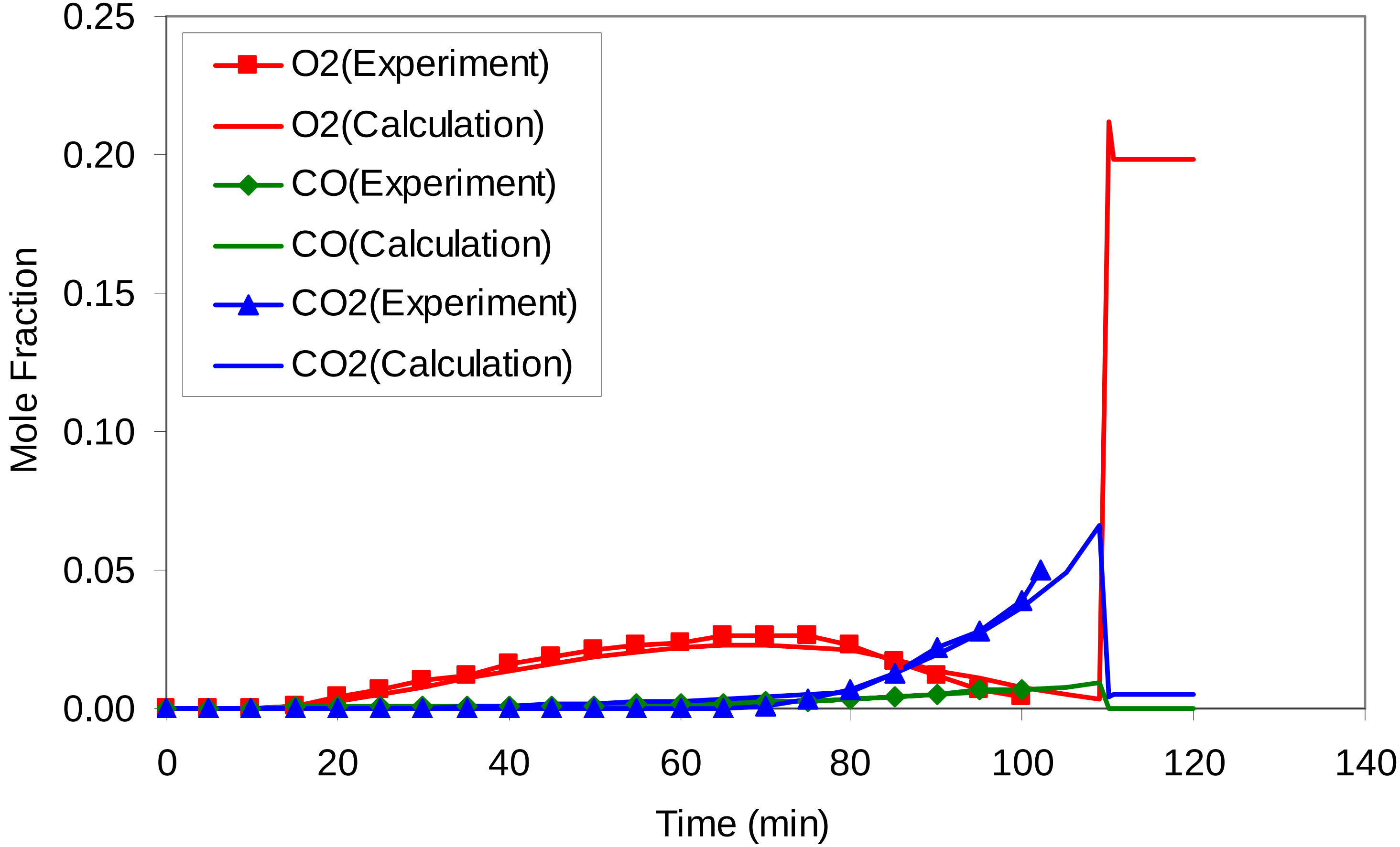


Figure 38: Mole Fraction at Point-4

NACOK Natural Convection Experiments

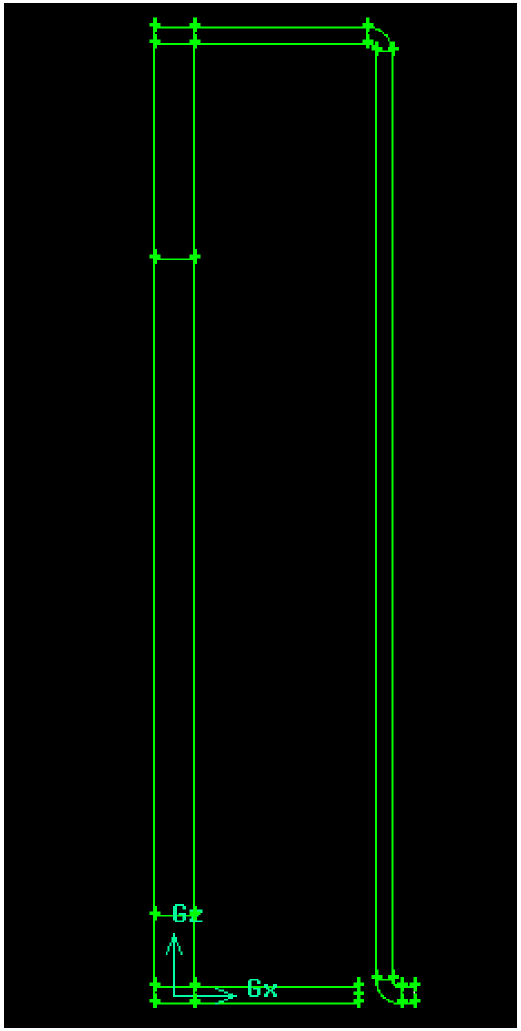


Figure 39: NACOK Experiment

Boundary Conditions

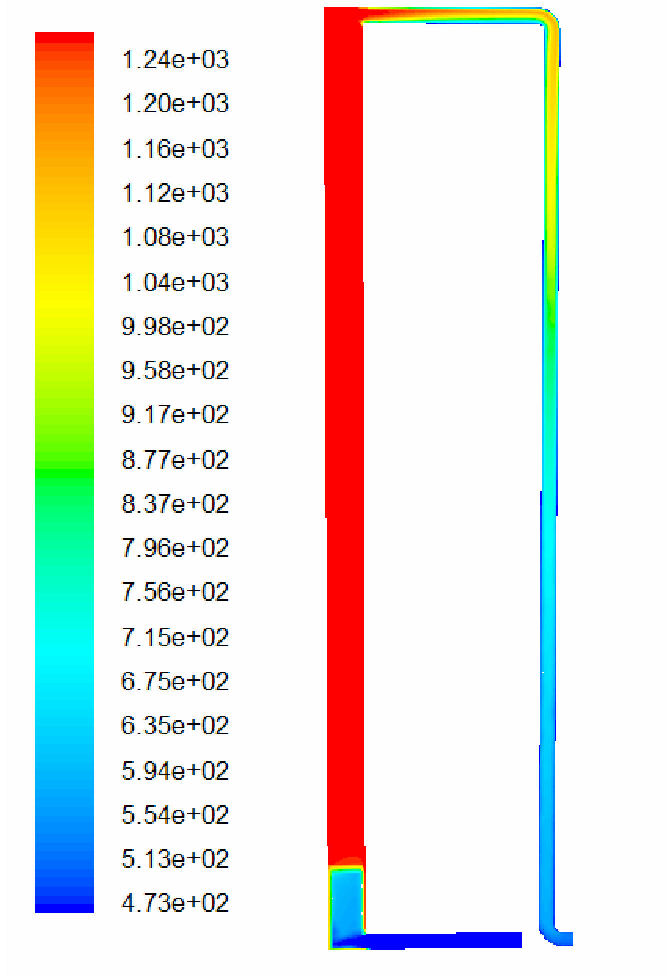


Figure 41: Temperature Profile for one experiment

The Mass Flow Rates

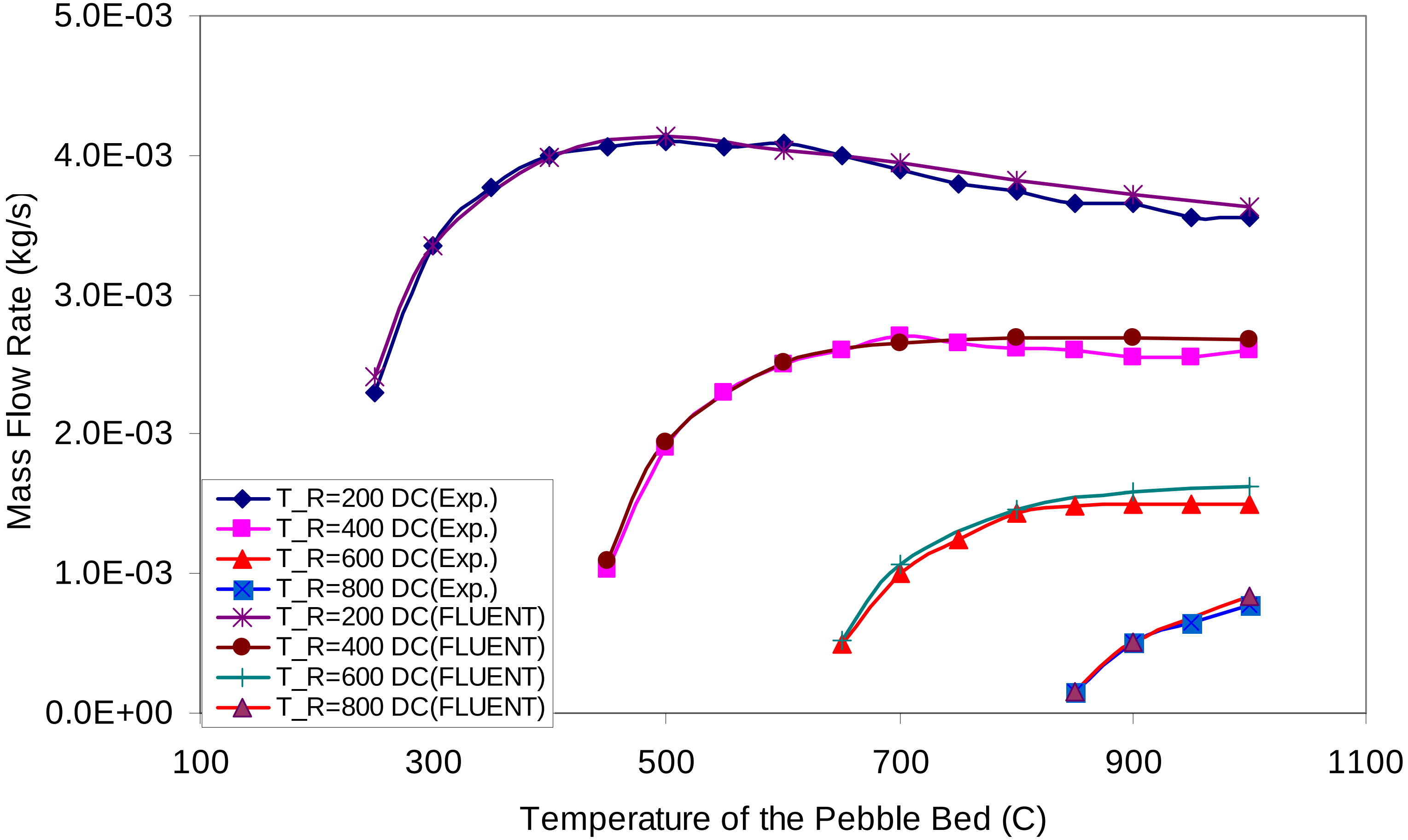


Figure 42: Mass Flow Rates for the NACOK Experiment

Future NACOK Tests

- Blind Benchmark using MIT methodology to reproduce recent tests.
- Update models
- Expectation to have a validated model to be used with system codes such as RELAP and INL Melcor.

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.

Overall Safety Performance Demonstration and Validation

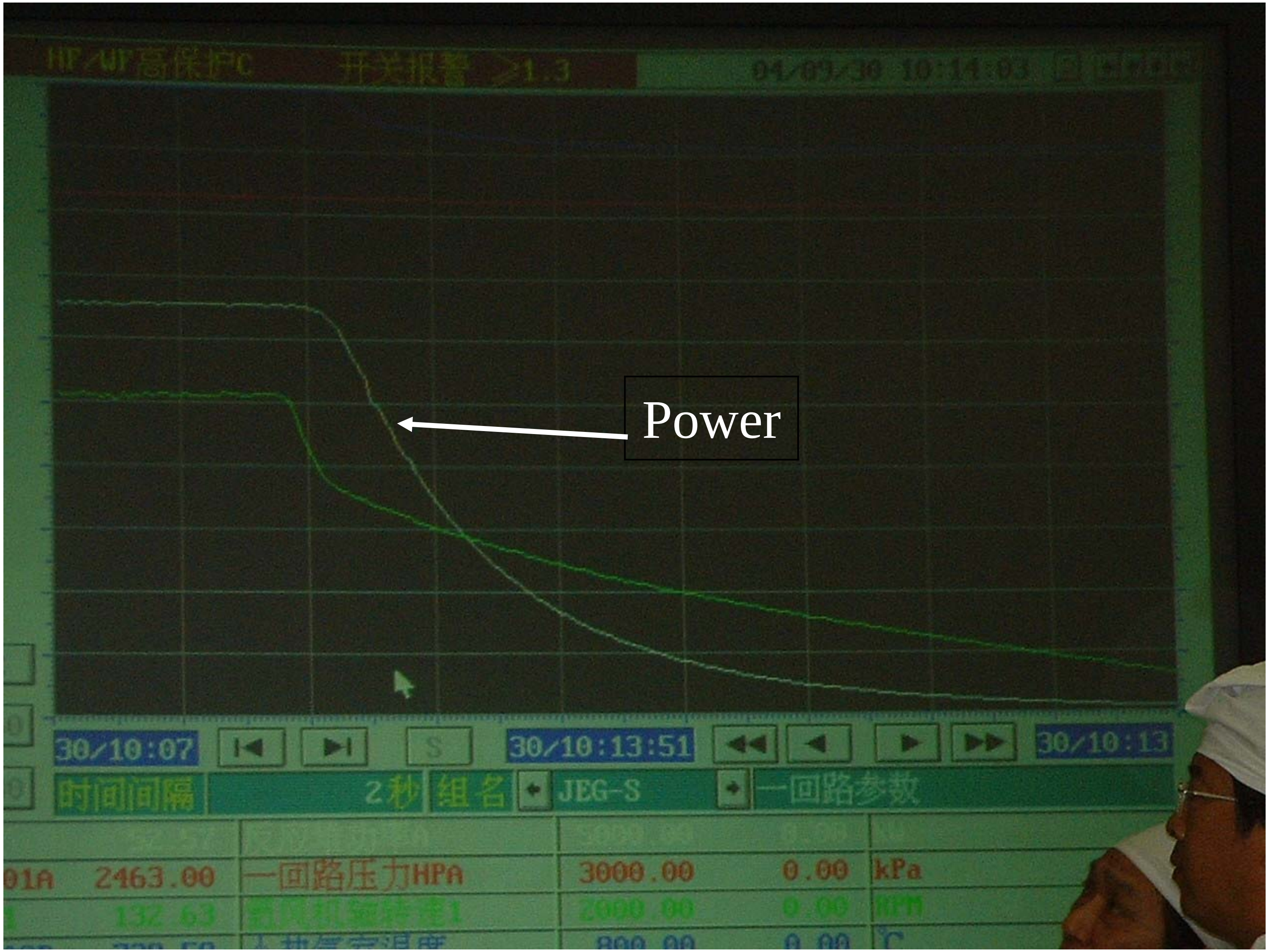
- China’s HTR-10 provides an excellent test bed for validation of fundamentals of reactor performance and safety.
- Japan’s HTTR provides a similar platform for block reactors.
- Germany’s NACOK facility vital for understanding of air ingress events for both types.
- PBMR’s Helium Test Facility, Heat Transfer Test Facility, Fuel Irradiation Tests, PCU Test Model.
- Needed - open sharing of important technical details to allow for validation and common understanding.

Chinese HTR-10 Safety Demonstration

- Loss of flow test
  - Shut off circulator
  - Restrict Control Rods from Shutting down reactor
  - Isolate Steam Generator - no direct core heat removal only but vessel conduction to reactor cavity

Video of Similar Test

Loss of Cooling Test



Loss of Cooling Test

International Activities
Countries with Active HTGR Programs

- China - 10 MWth Pebble Bed - 2000 critical
- Japan - 40 MWth Prismatic
- South Africa - 400 MWth Pebble - 2012
- Russia - 290 MWe - Pu Burner Prismatic 2007 (GA, Framatome, DOE, etc)
- Netherlands - small industrial Pebble
- Germany (past) - 300 MWe Pebble Operated
- MIT - 250 MWth - Intermediate Heat Exch.

Pebble Bed Modular Reactor
South Africa

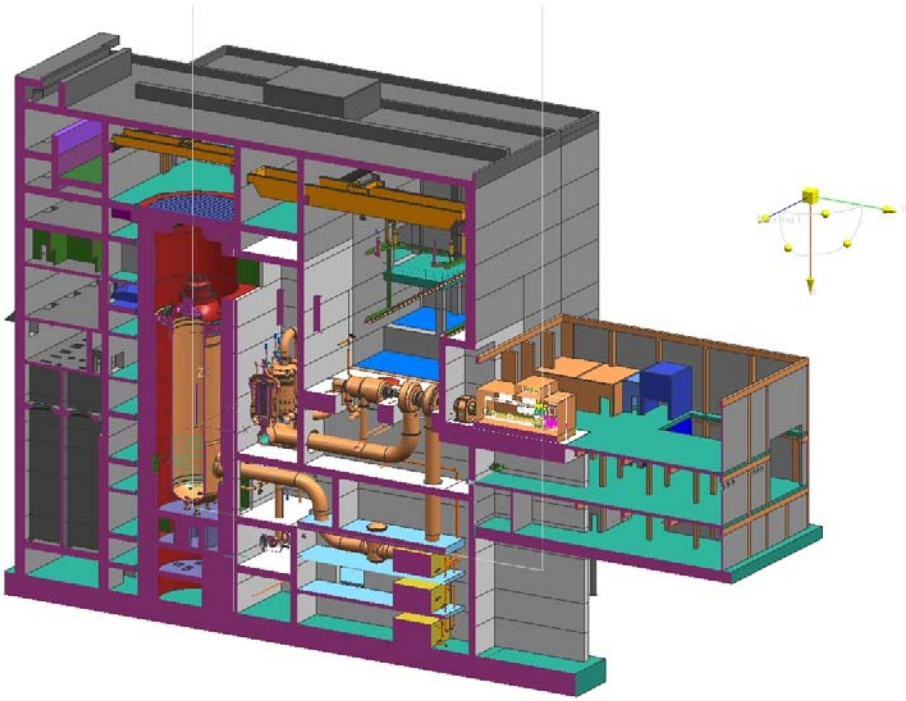
- 165 MWe Pebble Bed Plant - ESKOM
- Direct Helium High Temperature Cycle
- In Licensing Process
- Schedule for construction start 2007
- Operation Date 2011/12
- Commercial Reference Plant

South Africa Demonstration Plant Status

- **Koeberg site on Western Cape selected**
- **Designated national strategic project in May 2003**
- **Environmental Impact Assessment (EIA) completed with positive record of decision; appeals to be dispositioned by December 2004**
- **Revised Safety Analysis Report in preparation; to be submitted to National Nuclear Regulator in January 2006**
- **Construction scheduled to start April 2007 with initial operation in 2010**
- **Project restructuring ongoing with new investors and new governance**

Commercial Plant Target Specifications

- **Rated Power per Module 165-175 MW(e) depending on injection temperature**
- **Eight-pack Plant 1320 MW(e)**
- **Module Construction (1st) 24 months Schedule**
- **Planned Outages 30 days per 6 years**
- **Fuel Costs & O&M Costs < 9 mills/kWh**
- **Availability >95%**



Modular High Temperature Gas Reactor
Russia

- General Atomics Design
- 290 MWe - Prismatic Core
- Excess Weapons Plutonium Burner
- In Design Phase in Russia
- Direct Cycle
- Start of Construction – Depends on US Gov Funding – maybe never

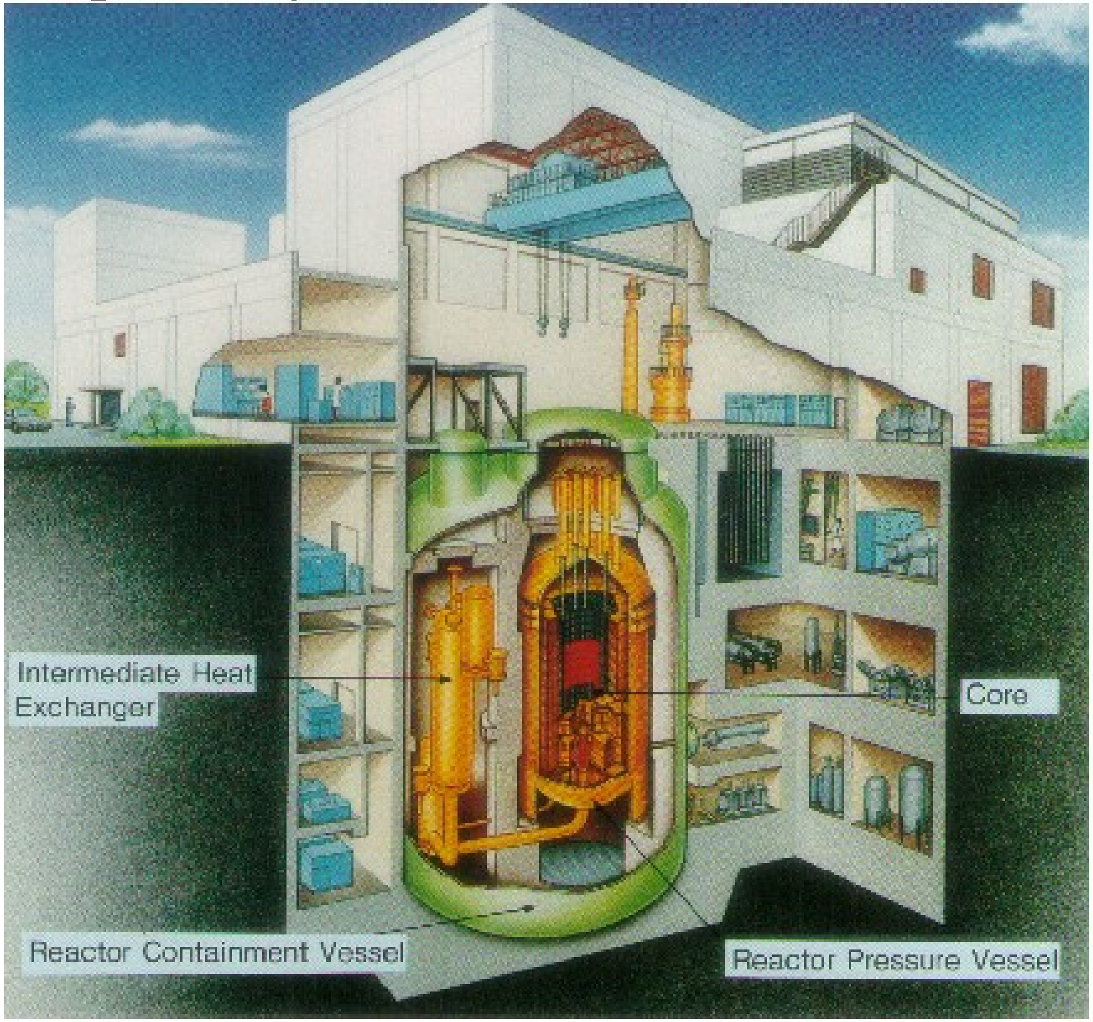
High Temperature Test Reactor

Japan

- 40 MWth Test Reactor
- First Critical 1999
- Prismatic Core
- Intermediate Heat Exchangers
- Reached full power and 950 C for short time

High Temperature Test Reactor

High Temperature Test Reactor (HTTR)

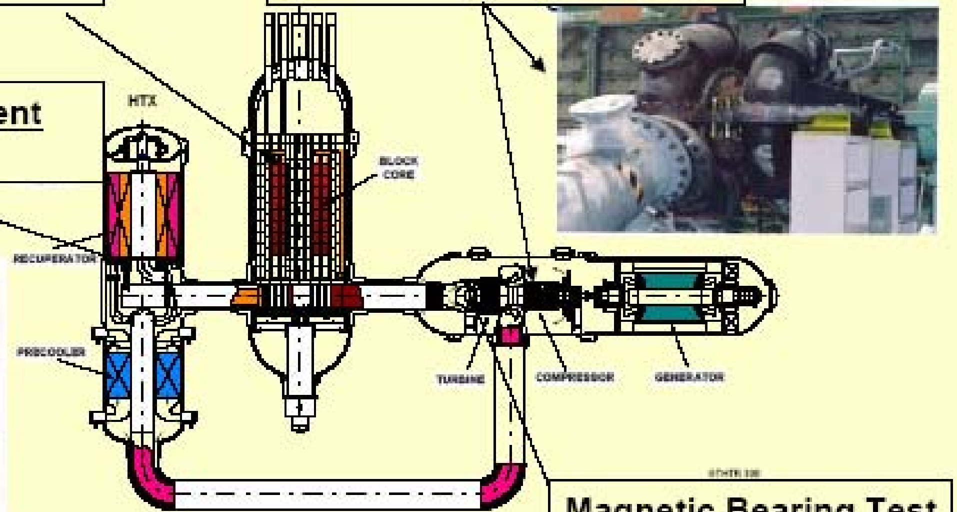


R&D Programs on Gas Turbine Power Conversion System

Gas Turbine System Test
Operation & Control
(2003-2010)

Compressor Model Test
Aerodynamic performance
(2001-2004)

Recuperator development
(-2003)



Magnetic Bearing Test
Rotor dynamics
(2002-2007)

Design study on the GTHTR300
Reactor design, PCU design,Safety design
(2001-2007)

High Temperature Reactor
China

- 10 MWth - 4 MWe Electric Pebble Bed
- Initial Criticality Dec 2000
- Intermediate Heat Exchanger - Steam Cycle
- Using to as test reactor for full scale demonstration plant – HTR-PM

HTR- 10 China
First Criticality Dec.1, 2000

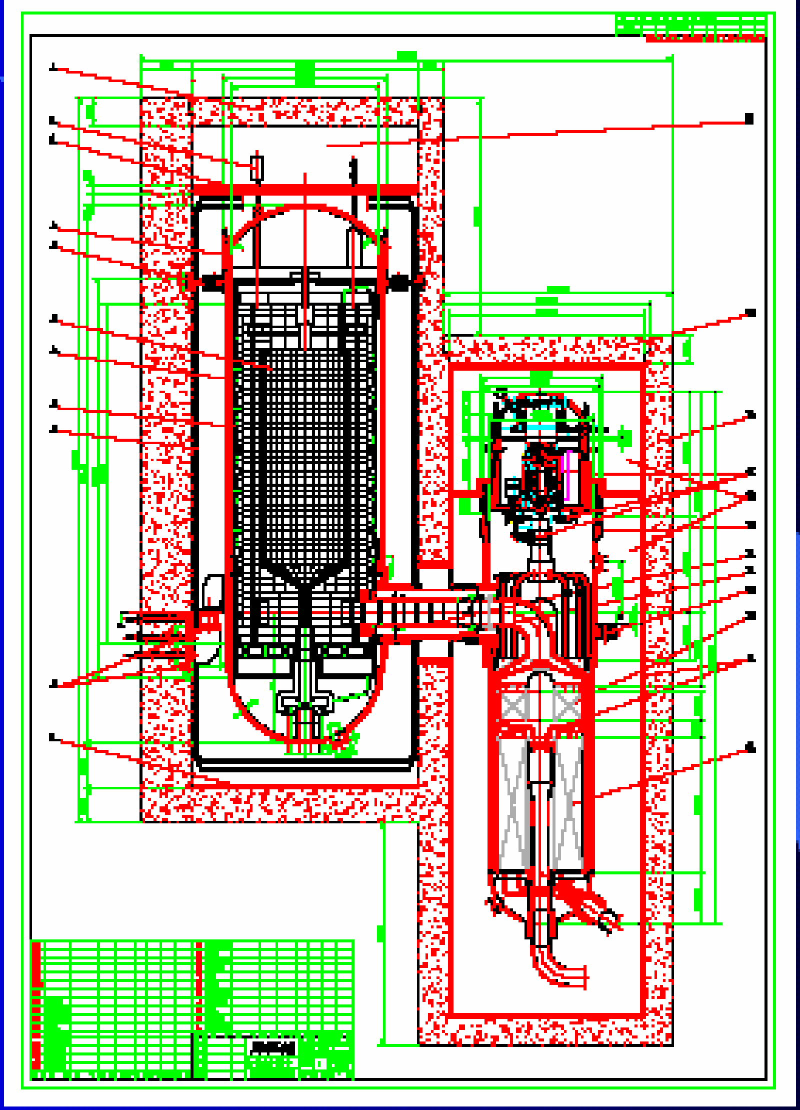
Main parameters of HTR-PM

Reactor thermal power	MW	371
Active core diameter/height	m	2.00-4.00/9.43
Average power density	MW/m^3	4.28
Primary helium pressure	MPa	7.0
Helium inlet temperature	°C	250
Helium outlet temperature	°C	750
Helium mass flow rate	Kg/s	145
Fuel		UO_2
U-235 enrichment of fresh fuel elements	%	8.77
Diameter of spherical fuel elements	mm	60
Number of spherical fuel elements	ball	479358
Number of graphite balls	ball	159786
Average discharge burnup	MWd/tU	80,000

Roles of HTGRs in China

- Supplement of nuclear power generation for densely and sparsely populated regions
- Providing process steam for heavy oil recovery and petrochemical industry
- As process heat resource for coal gasification and liquefactionas well as hydrogen producution

HTR-PM
with the steam
turbine cycle



China is Focused

- Formed company – Chinergy
  - Owned by Institute of Nuclear Energy Technology of Tsinghua University and China Nuclear Engineering Company (50/50)
  - Customer – Huaneng Group – largest utility
- Two Sites selected – evaluating now
- Target commercial operation 2010/2011

France – AREVA - Framatome

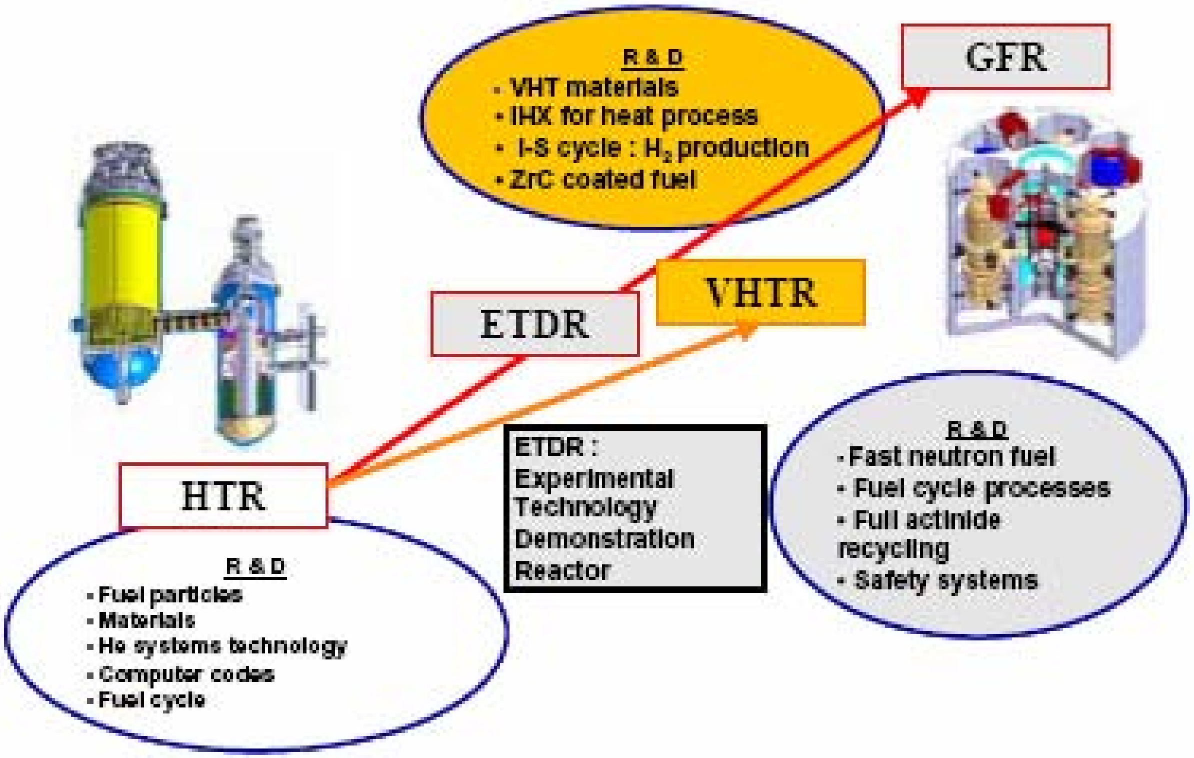
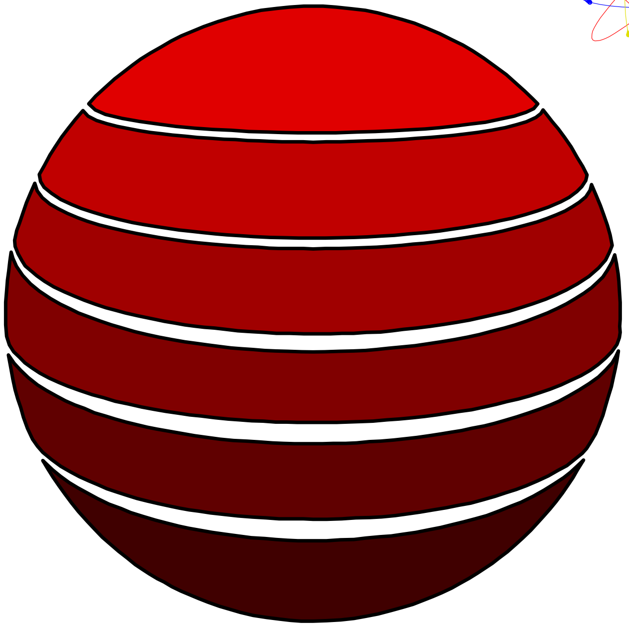
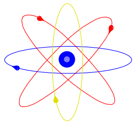


FIGURE 1: "Gas Technology Path" for a sequenced development of high temperature gas cooled reactors.

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





Modular High Temperature Pebble Bed Reactor

- 120 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

MIT MPBR Specifications

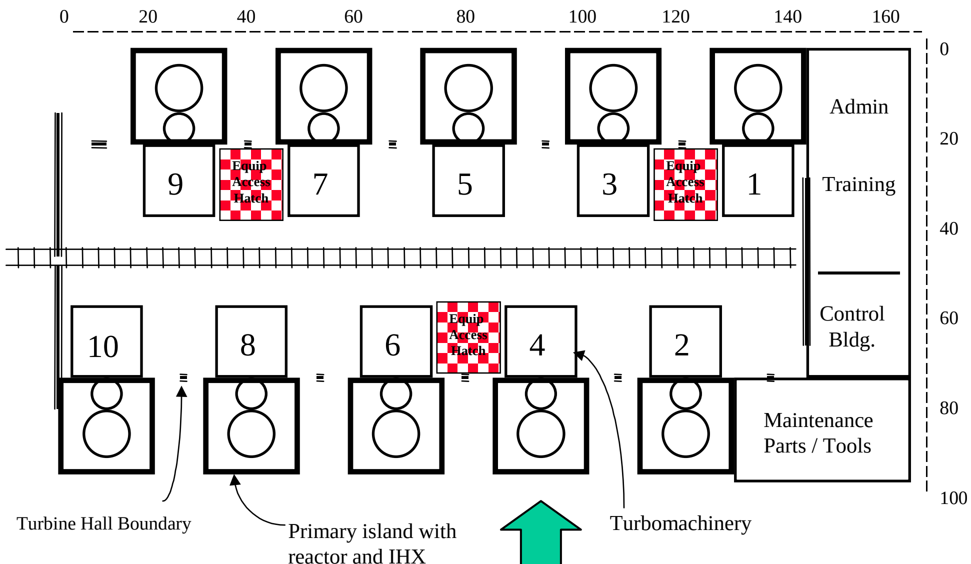
Thermal Power	250 MW - 115 Mwe
Target Thermal Efficiency	45 %
Core Height	10.0 m
Core Diameter	3.5 m
Pressure Vessel Height	16 m
Pressure Vessel Radius	5.6 m
Number of Fuel Pebbles	360,000
Microspheres/Fuel Pebble	11,000
Fuel	UO_2
Fuel Pebble Diameter	60 mm
Fuel Pebble enrichment	8%
Uranium Mass/Fuel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

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)



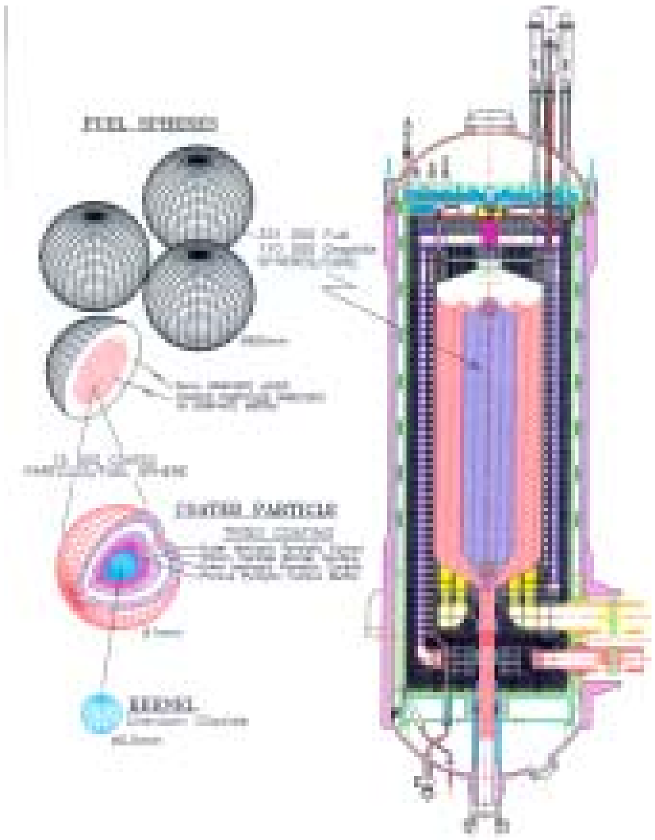
Oil Refinery

Desalinization Plant

Hydrogen Production

Reference Plant

Modular Pebble Bed Reactor



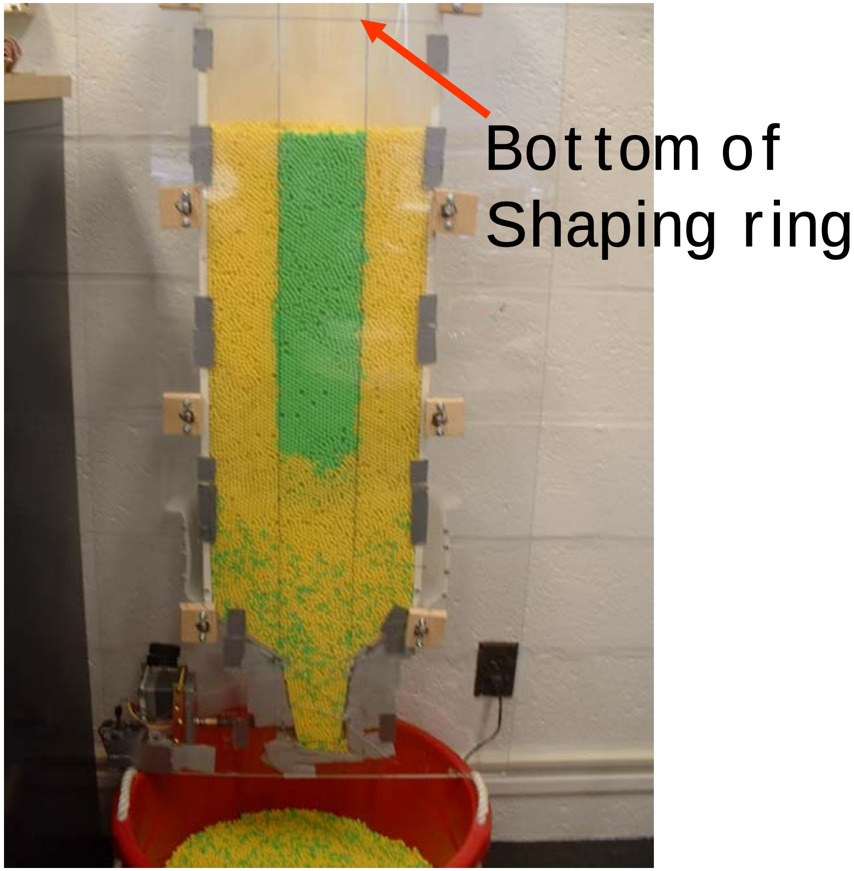
Thermal Power	**250 MW**
Core Height	**10.0 m**
Core Diameter	**3.5 m**
Fuel	**UO_2**
Number of Fuel Pebbles	**360,000**
Microspheres/Fuel Pebble	**11,000**
Fuel Pebble Diameter	**60 mm**
Microsphere Diameter	**~ 1mm**
Coolant	**Helium**

Video Demo

19.mpg
20.mpg
21.mpg
22.mpg
23.mpg

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.

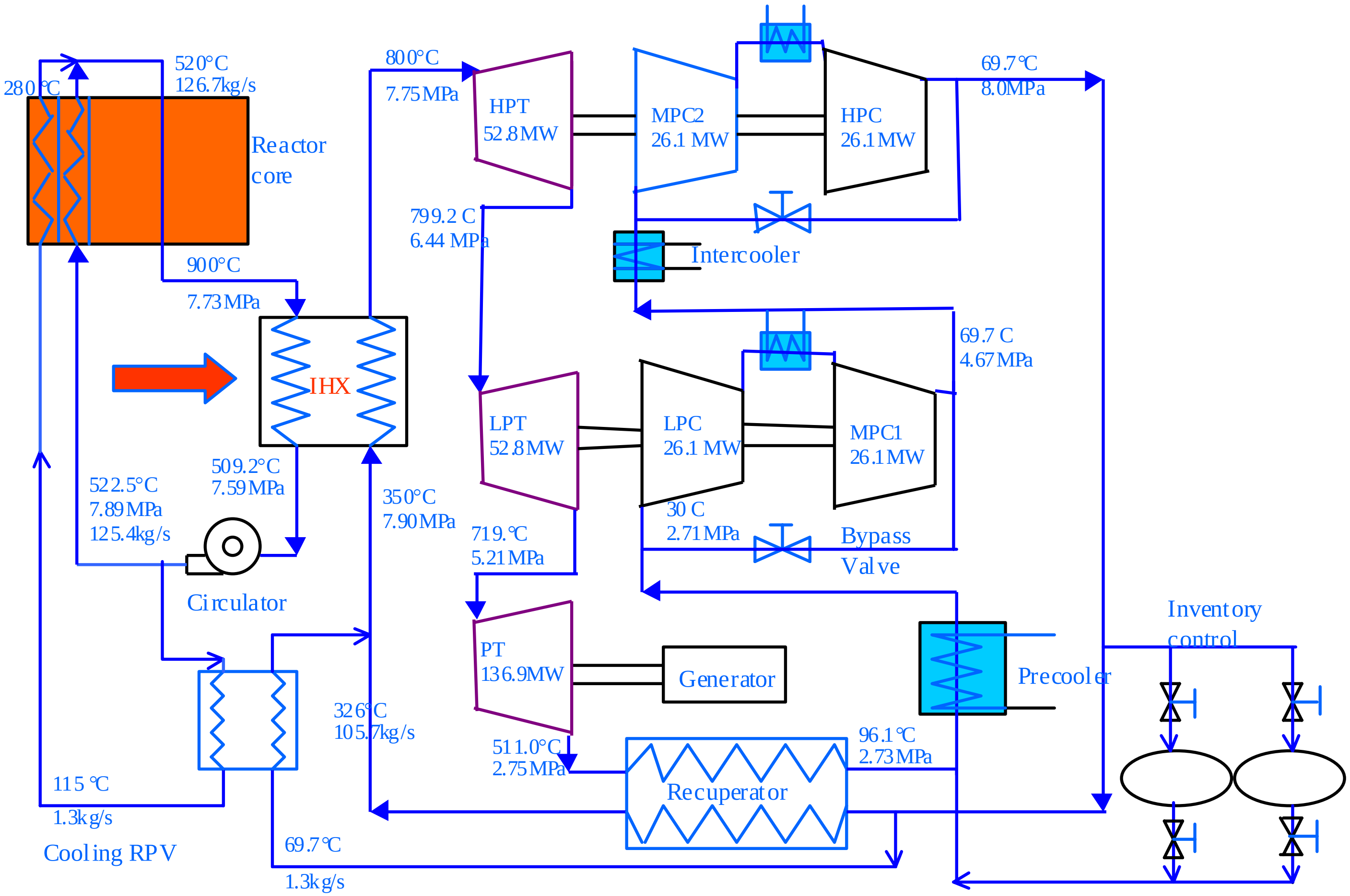


Features of Current Design

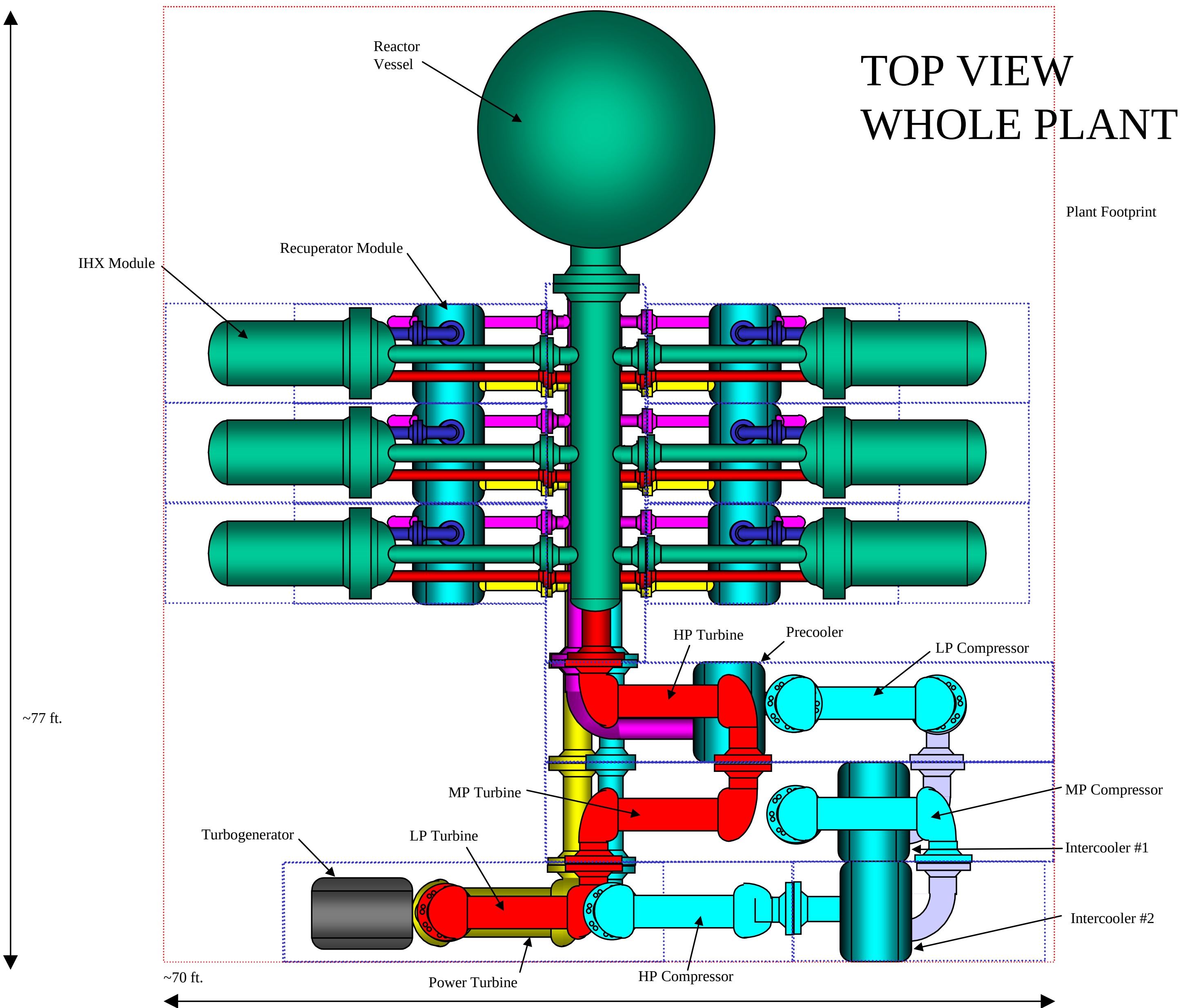
Thermal Power	250 MW
Gross Electrical Power	132.5 MW
Net Electrical Power	120.3 MW
Plant Net Efficiency	48.1% (Not take into account cooling IHX and HPT. if considering, it is believed > 45%)
Helium Mass flowrate	126.7 kg/s
Core Outlet/Inlet T	900°C/520°C
Cycle pressure ratio	2.96
Power conversion unit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

Indirect Cycle with Intermediate Helium to Helium Heat Exchanger

Current Design Schematic

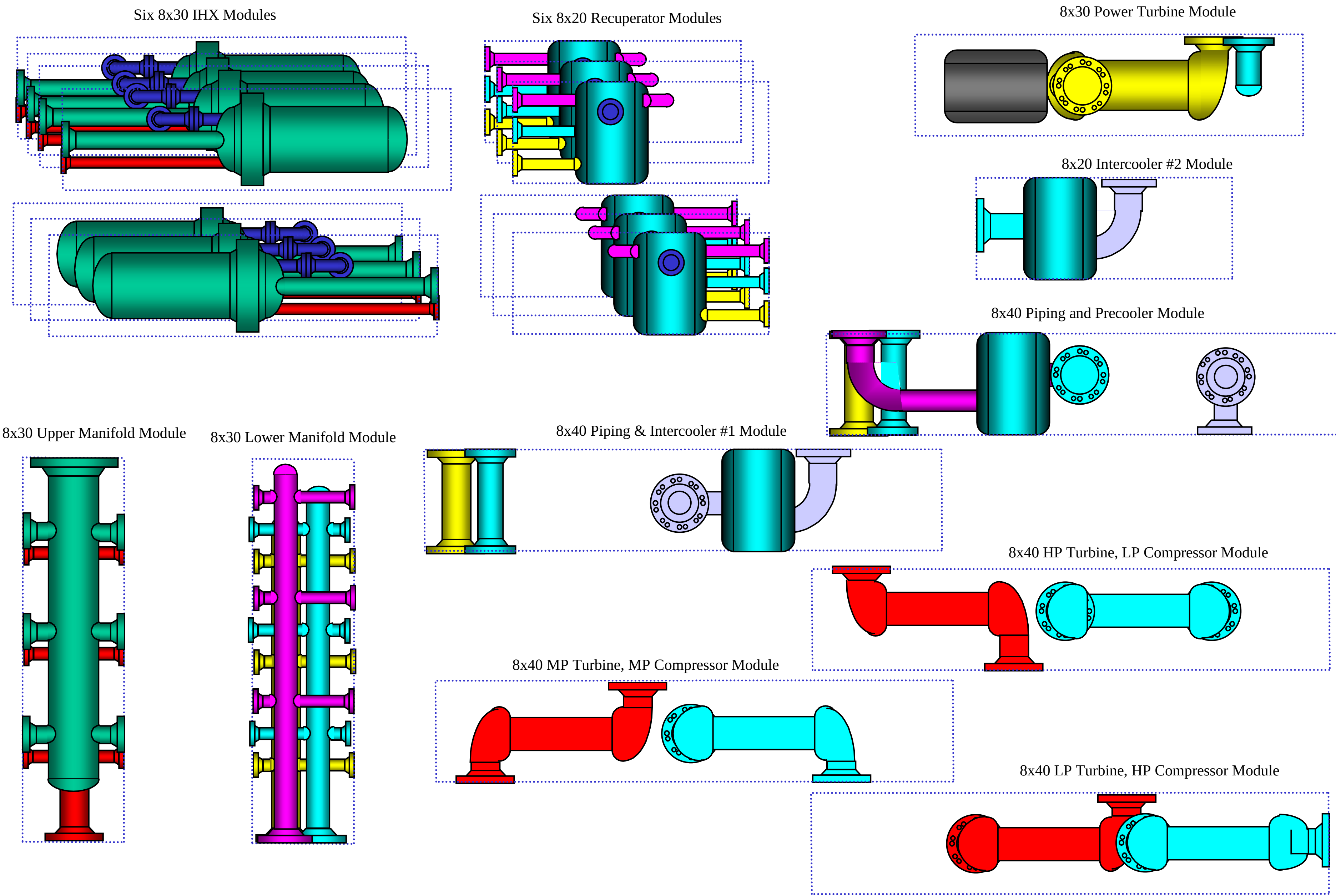


Top Down View of Pebble Bed Reactor Plant

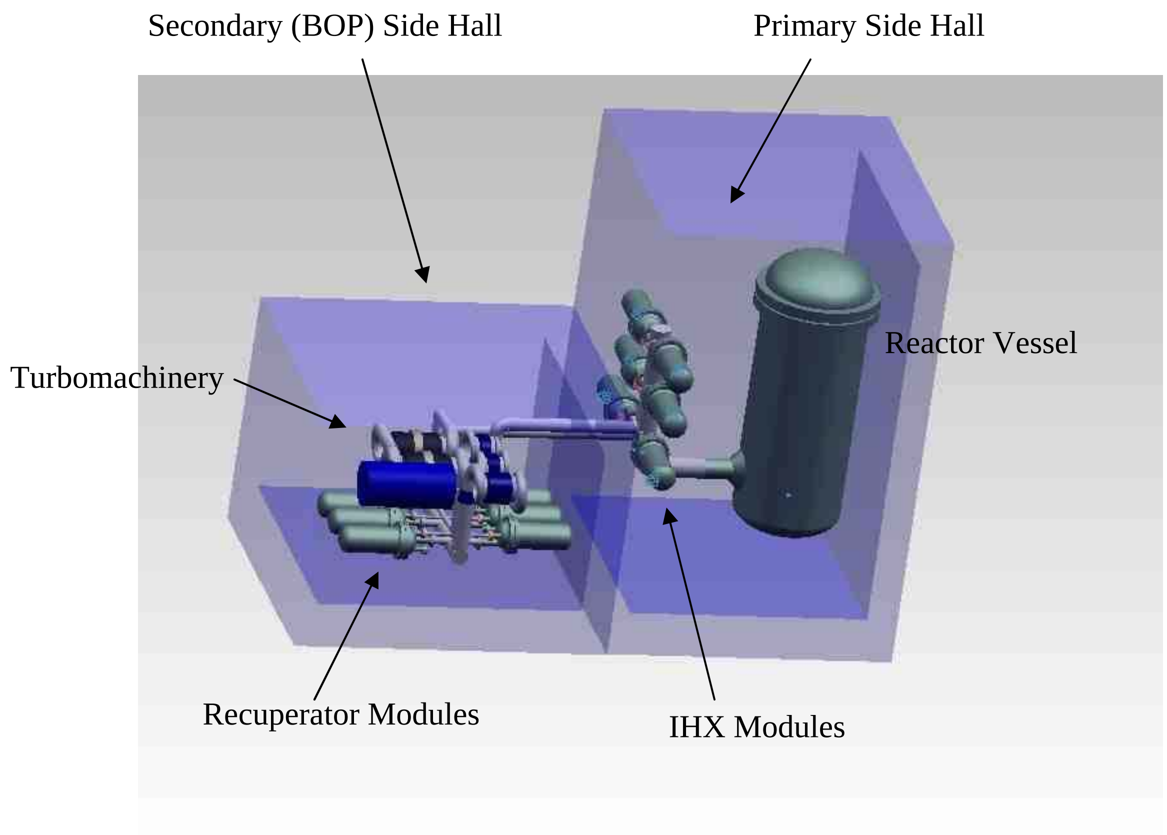


PLANT MODULE SHIPPING BREAKDOWN

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



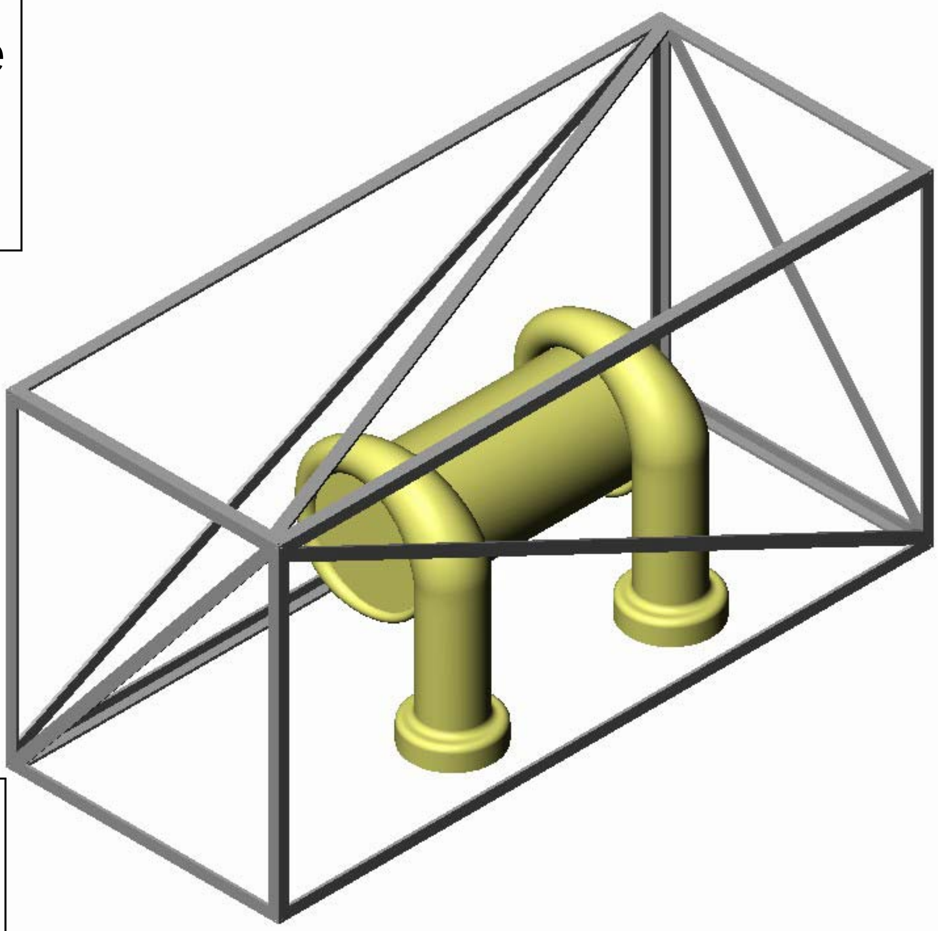
Example Plant Layout



NOTE: Space-frames and ancillary components not shown for clarity

Space Frame Technology for Shipment and Assembly

Everything is installed in the volume occupied by the space frame - controls, wiring, instrumentation, pumps, etc.



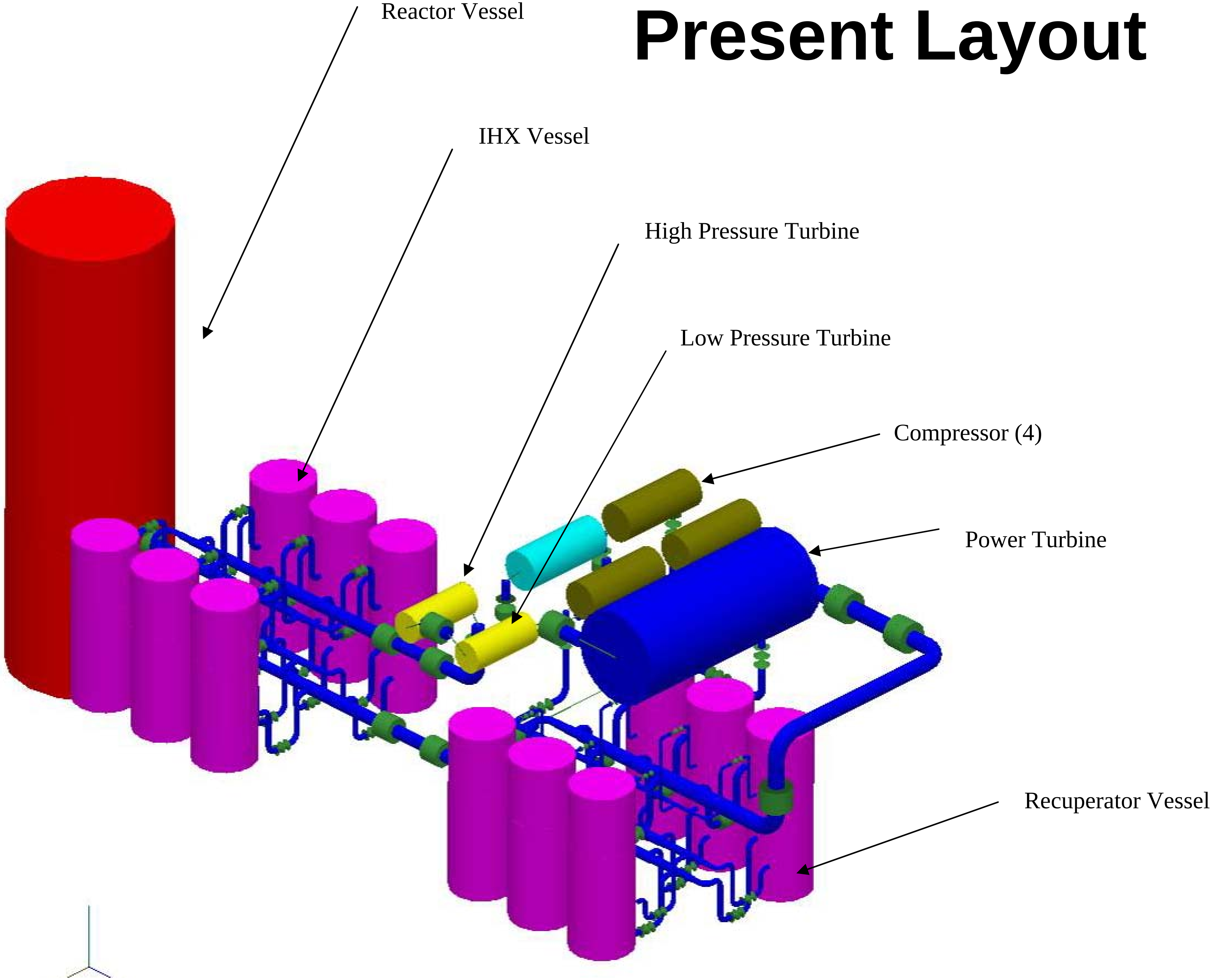
Each space frame will be "plugged" into the adjacent space frame.

“Lego” Style Assembly in the Field

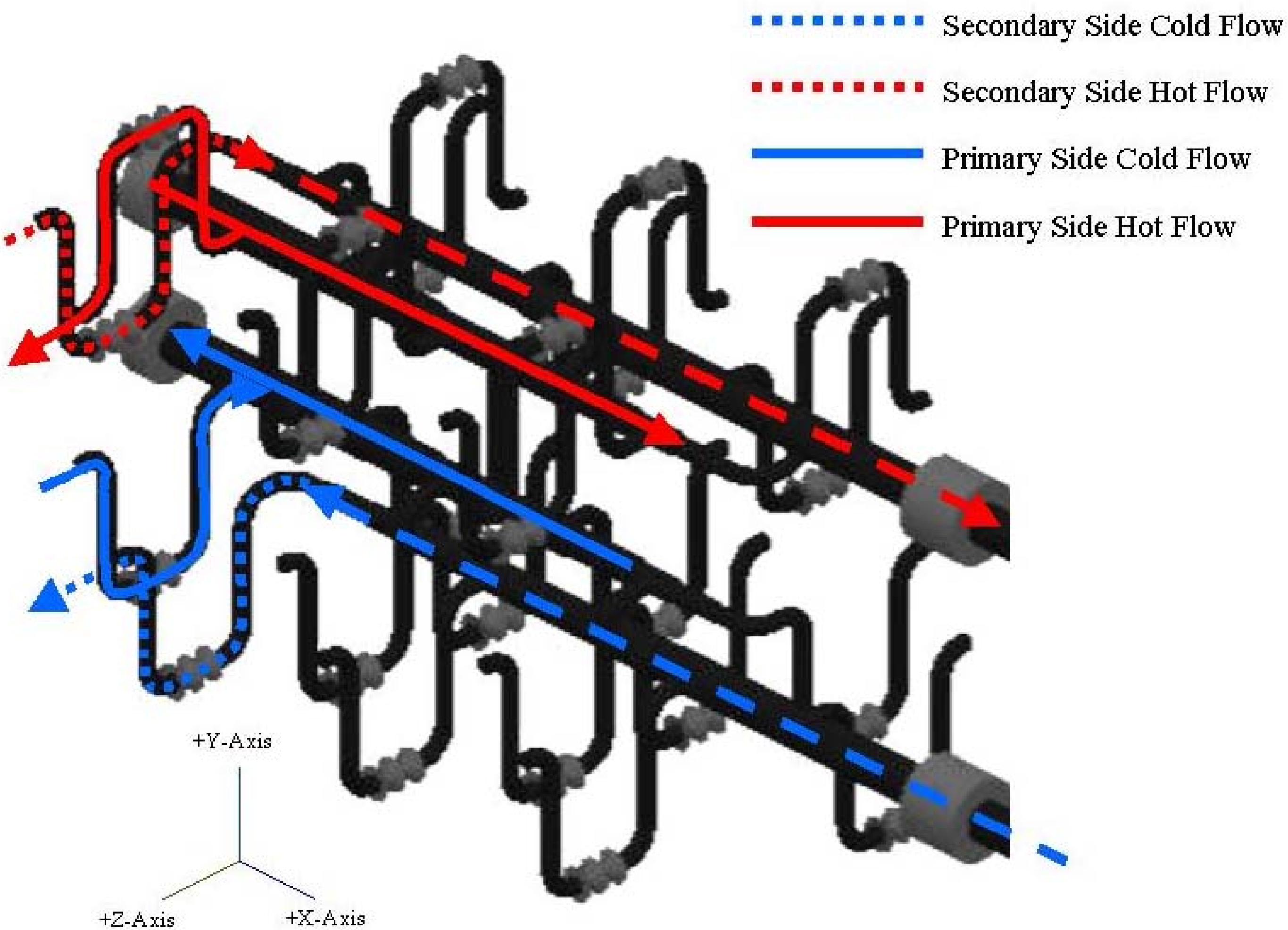
Space-Frame Concept

- Standardized Frame Size
- 2.4 x 2.6 x 3(n) Meter
- Standard Dry Cargo Container
- Attempt to Limit Module Mass to ~30t / 6m
  - ISO Limit for 6m Container
  - Stacking Load Limit ~190t
  - ISO Container Mass ~2200kg
  - Modified Design for Higher Capacity—~60t / 12m module
- Overweight Modules
  - Generator (150-200t)
  - Turbo-Compressor (45t)
  - Avoid Separating Shafts!
  - Heavy Lift Handling Required
  - Dual Module (12m / 60t)
- Stacking Load Limit Acceptable
  - Dual Module = ~380T
    - Turbo-generator Module <300t
- Design Frame for Cantilever Loads
  - Enables Modules to be Bridged
- Space Frames are the structural supports for the components.
- Only need to build open vault areas for space frame installation - RC & BOP vault
- Alignment Pins on Module Corners
  - High Accuracy Alignment
  - Enables Flanges to be Simply Bolted Together
- Standardized Umbilical Locations
  - Bus-Layout of Generic Utilities (data/control)

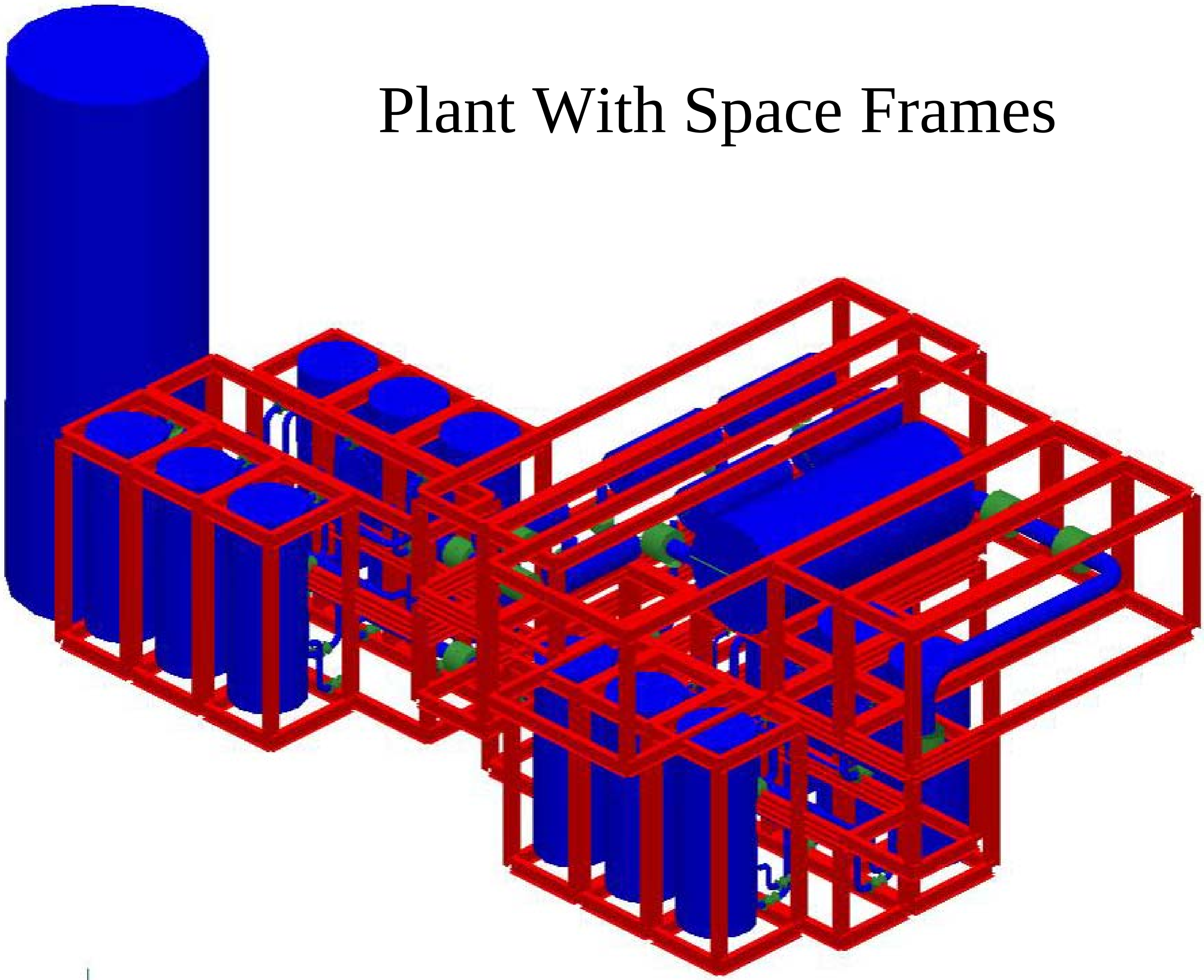
Present Layout



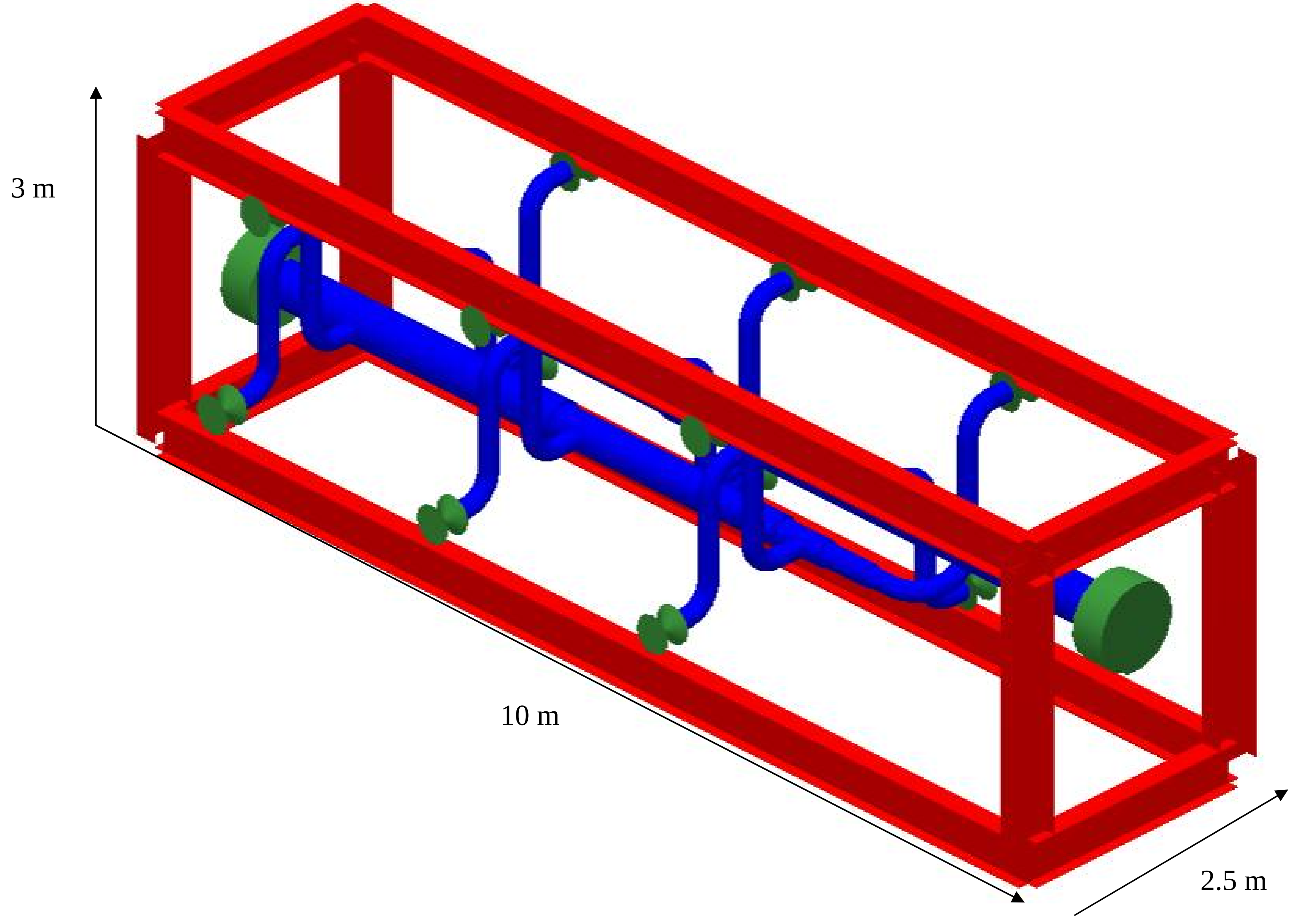
Main IHX Header Flow Paths



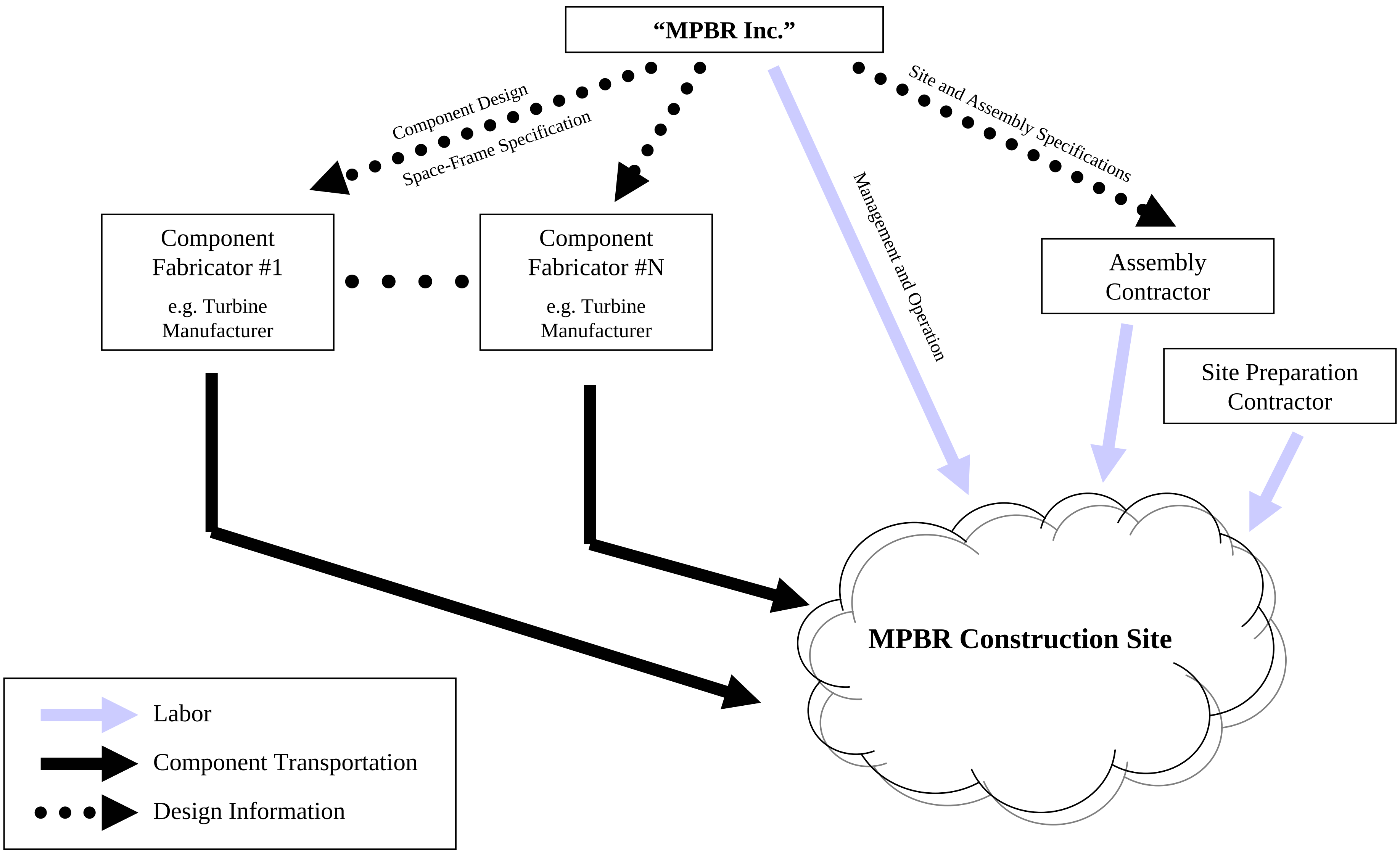
Plant With Space Frames



Upper IHX Manifold in Spaceframe



Distributed Production Concept



Generating Cost

PBMR vs. AP600, AP1000, CCGT and Coal

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

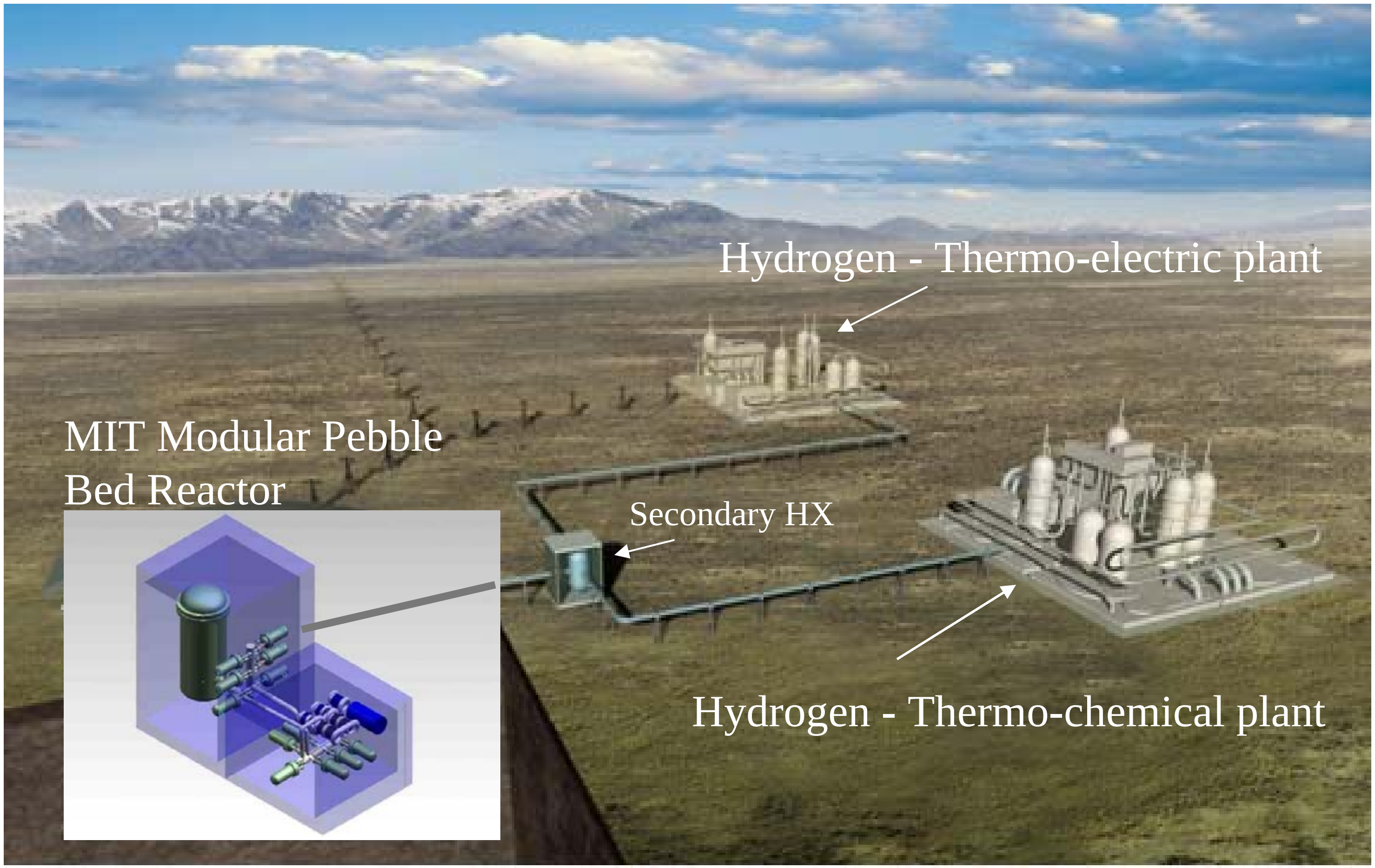
(All in ¢/kWh)		AP1000 @			Coal[2]		CCGT @ Nat. Gas = [3]			
	AP600	3000Th	3400Th	PBMR	'Clean'	'Normal'	$3.00	$3.50	$4.00	$5.00
Fuel	0.5	0.5	0.5	0.48	0.6	0.6	2.1	2.45	2.8	3.5
O&M	0.8	0.52	0.46	0.23	0.8	0.6	0.25	0.25	0.25	0.25
Decommissioning	0.1	0.1	0.1	0.08	-	-	-	-	-	
Fuel Cycle	0.1	0.1	0.1	0.1	-	-	-	-	-	
Total Op Costs	1.5	1.22	1.16	0.89	1.4	1.2	2.35	2.70	3.05	3.75
Capital Recovery	3.4	2.5	2.1	2.2	2.0	1.5	1.0	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	4.75

[1] All options exclude property taxes

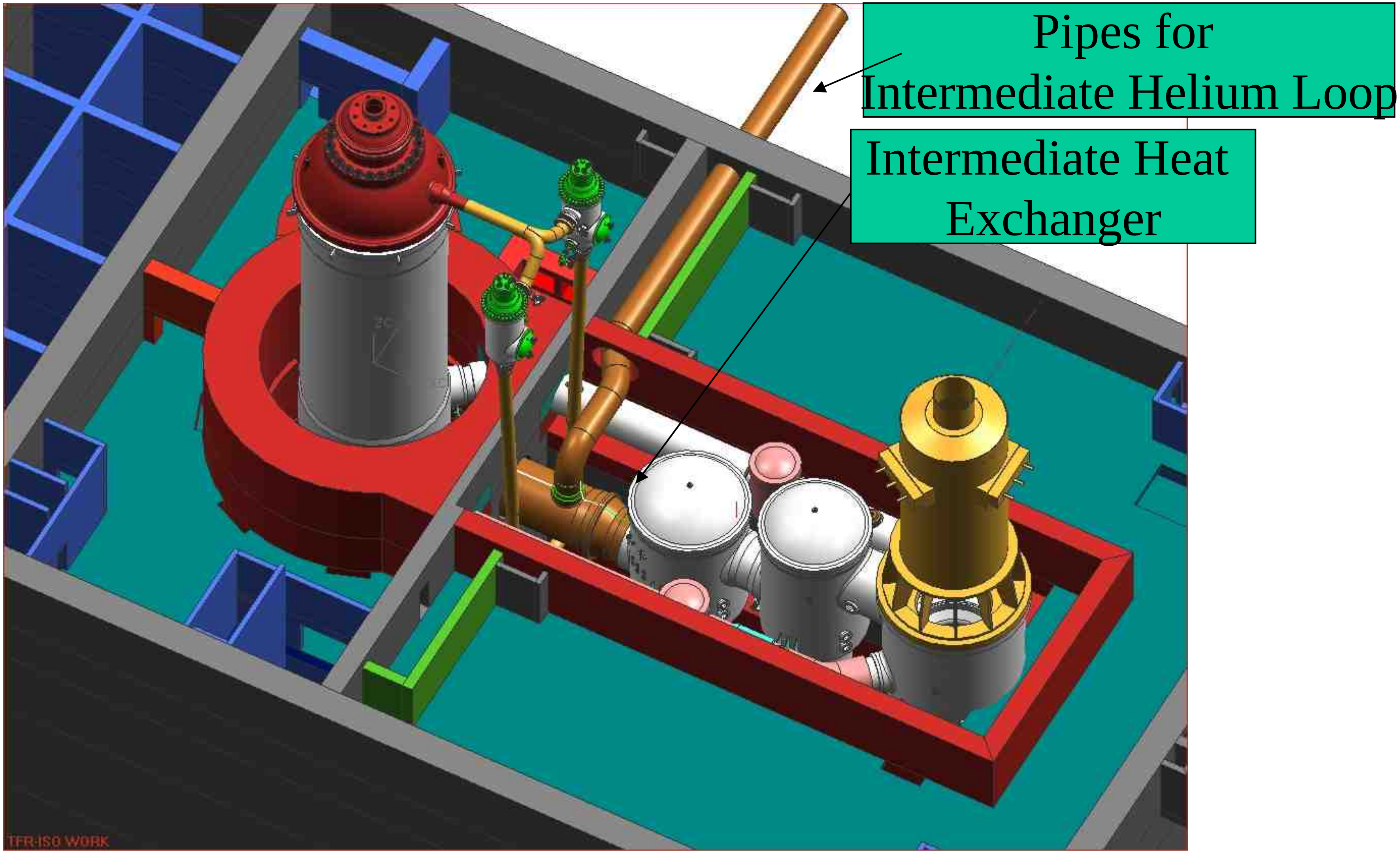
[2] Preliminary best case coal options: "mine mouth" location with $20/ton coal, 90% capacity factor & 10,000 BTU/kWh heat rate

[3] Natural gas price in $/million Btu

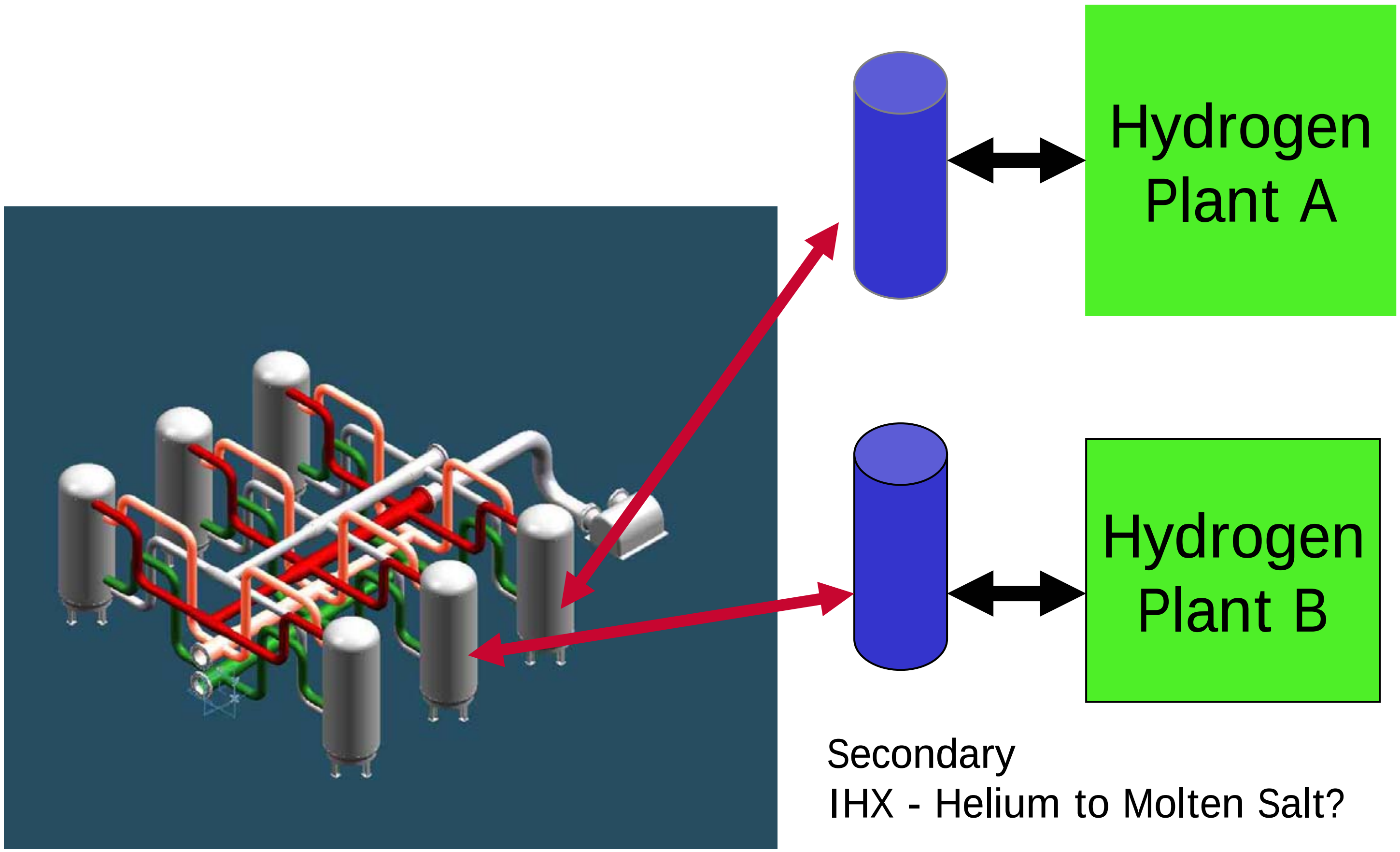
Next Generation Nuclear Plant



Intermediate Heat Exchanger (IHX) Installed In Hot Pipe for PBMR NGNP



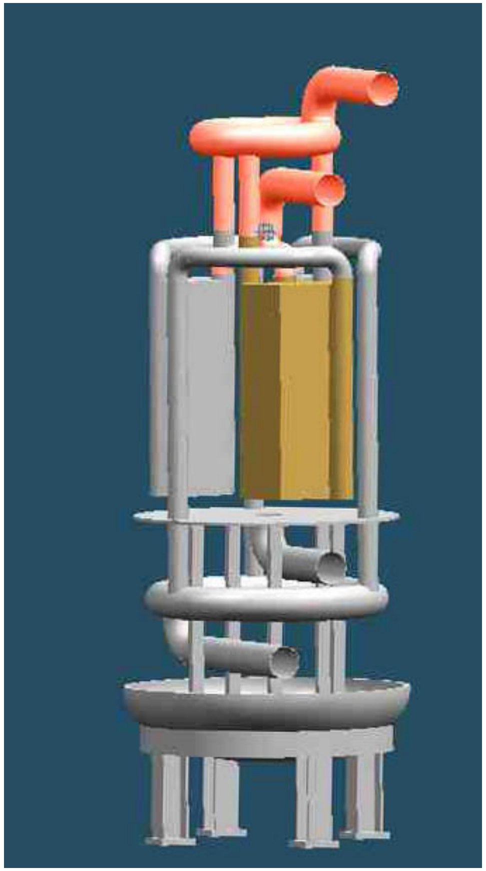
Hydrogen Mission
Modularity Flexibility



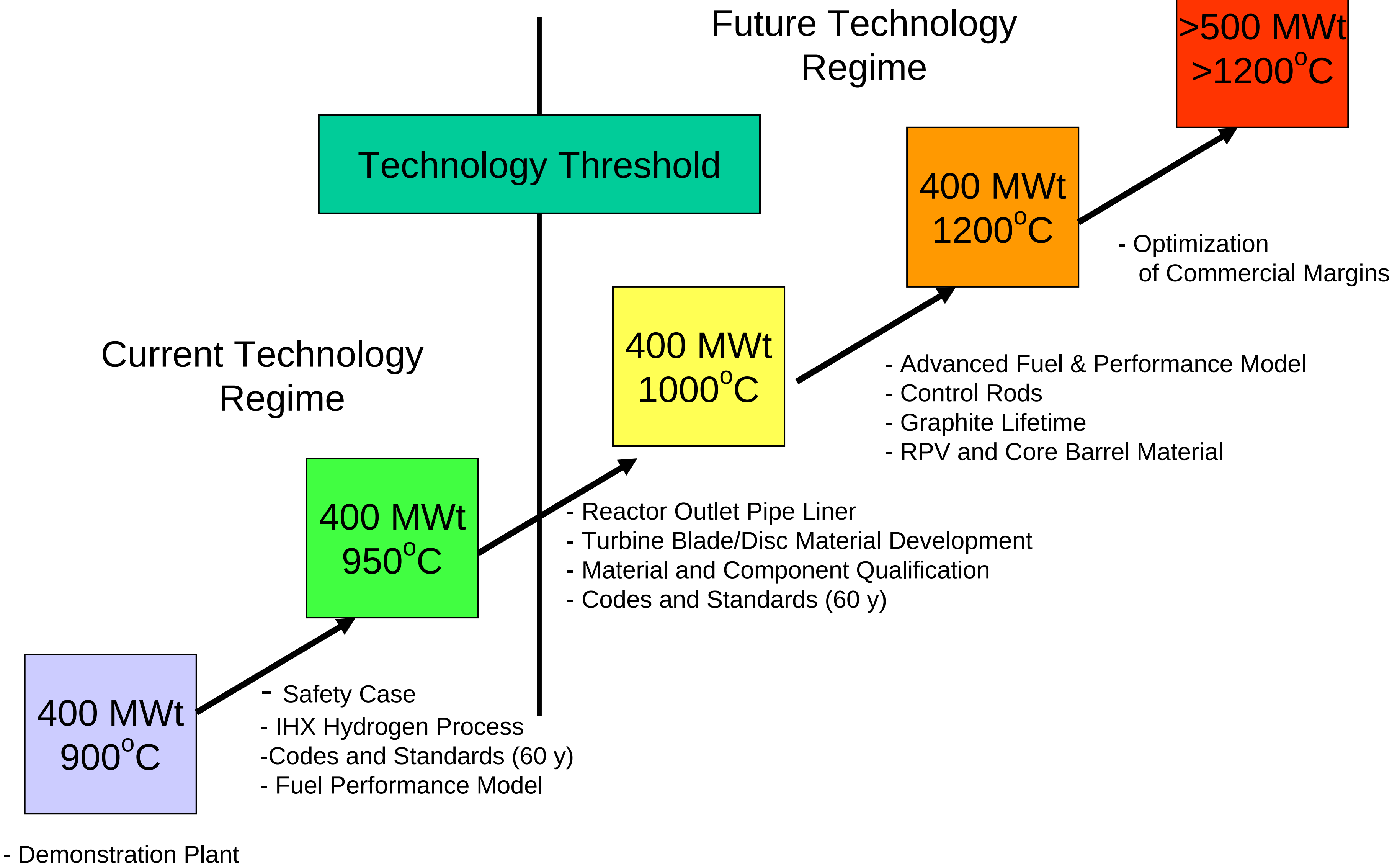
May use one or more IHX's from base electric plant for H_2

Primary Internals

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



VHTR Migration Path



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 manufacturing and QA integration

Summary

- Safety advantages of High Temperature Reactors are a significant advantage.
- Air ingress most challenging to address
- Fuel performance needs to be demonstrated in operational, transient and accident conditions.
- Validation of analysis codes is important
- Materials issues may limit maximum operating temperatures and lifetimes of some components.
- International cooperation is essential on key safety issues.

End of Presentation

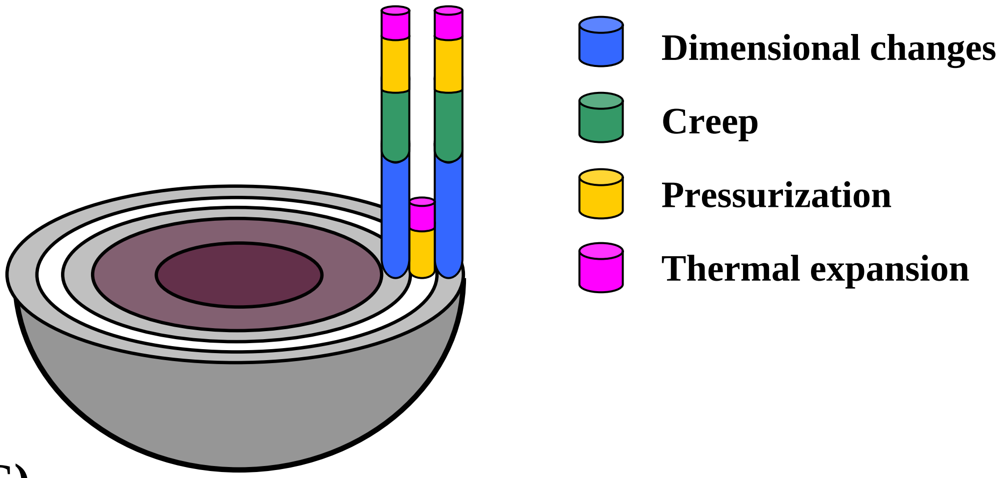
Back up Slides follow

Summary

- High Temperature Reactors are a viable future nuclear option.
- NGNP to be the demonstration plant
- Research to lead to Gen IV VHTR for hydrogen production
- Small size an advantage to deployment and cost if manufacturing modularity approaches followed.

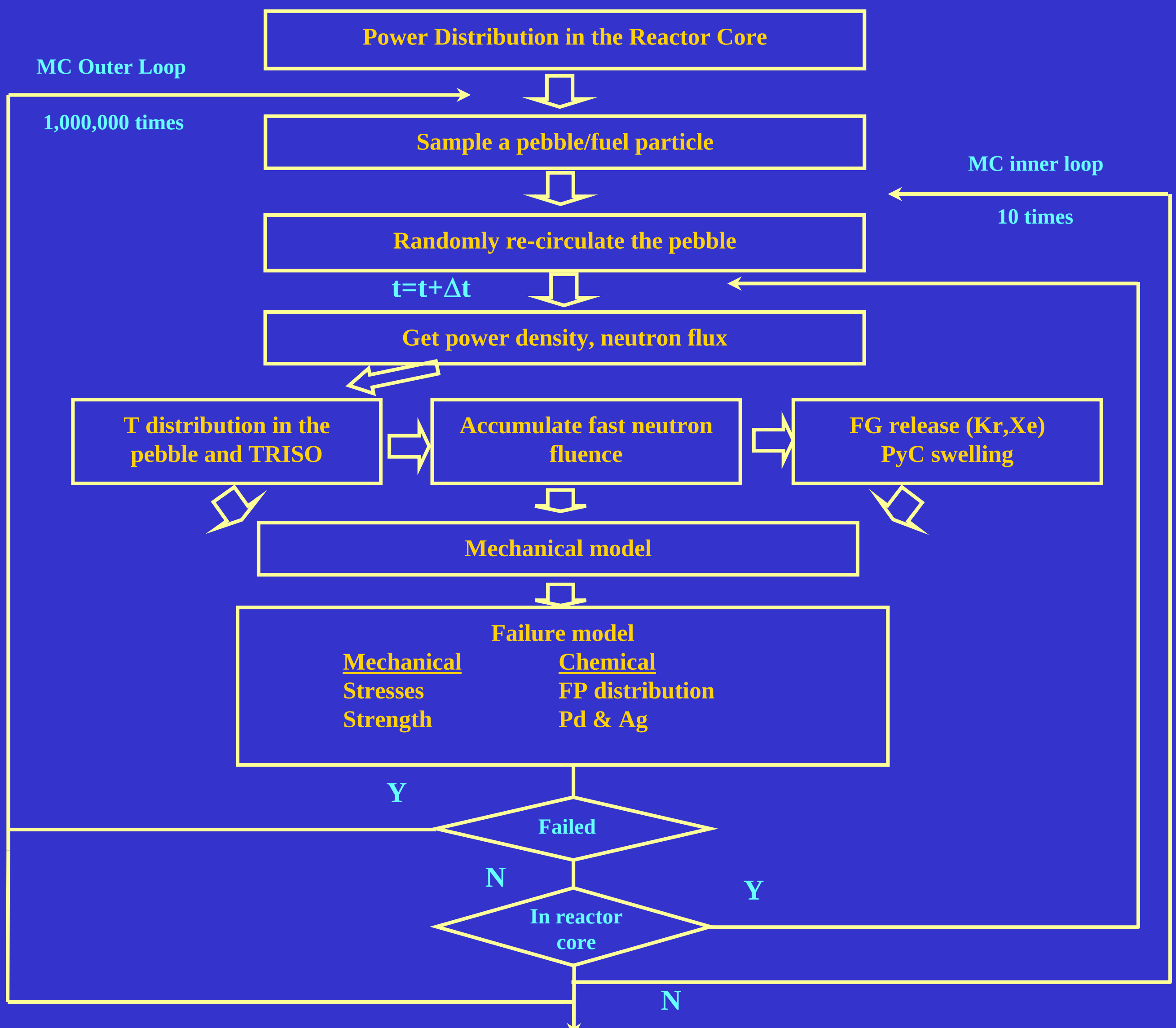
Mechanical Analysis

- **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



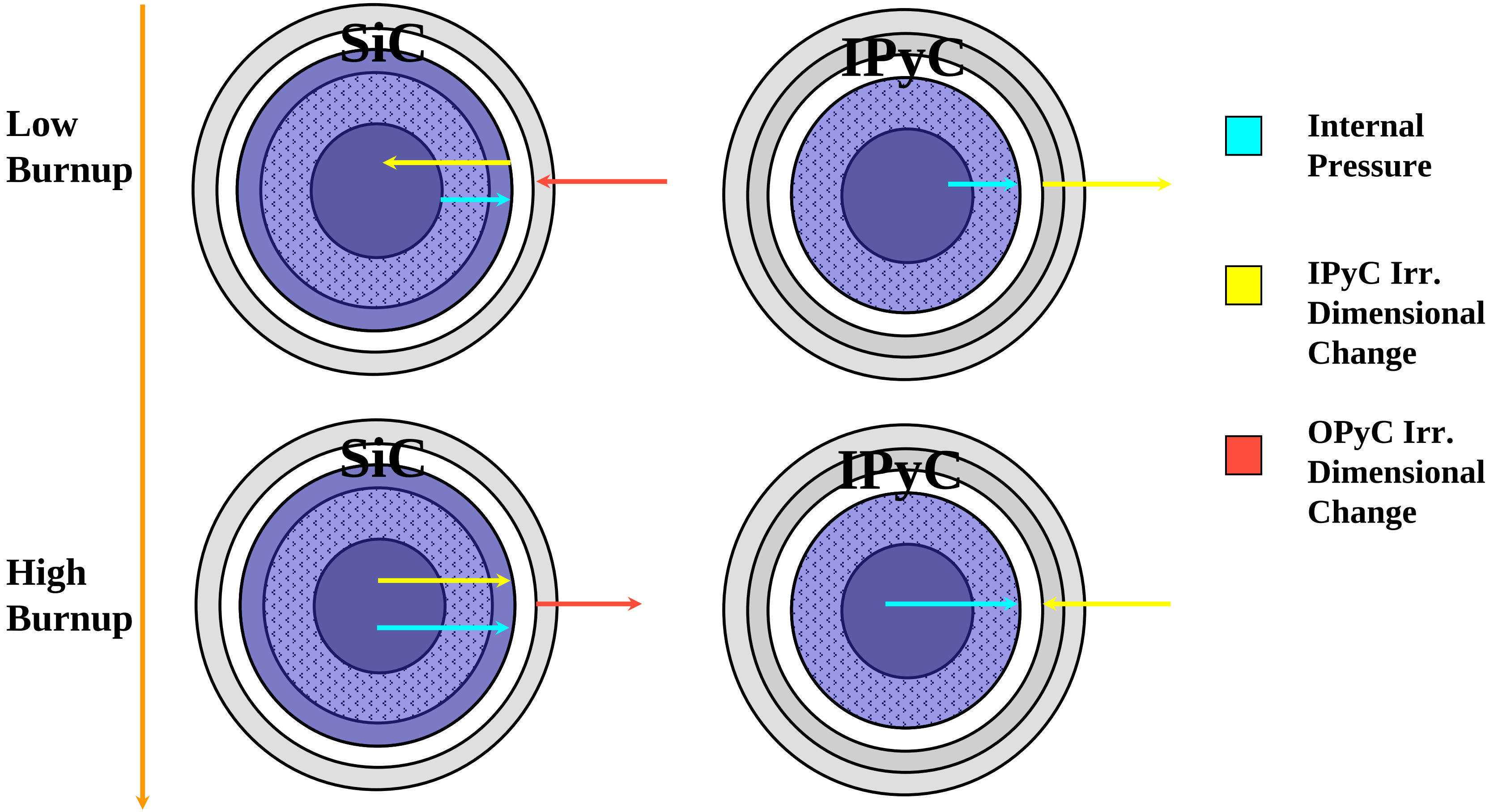
MC outer loop:

samples fuel particles of statistical characteristics

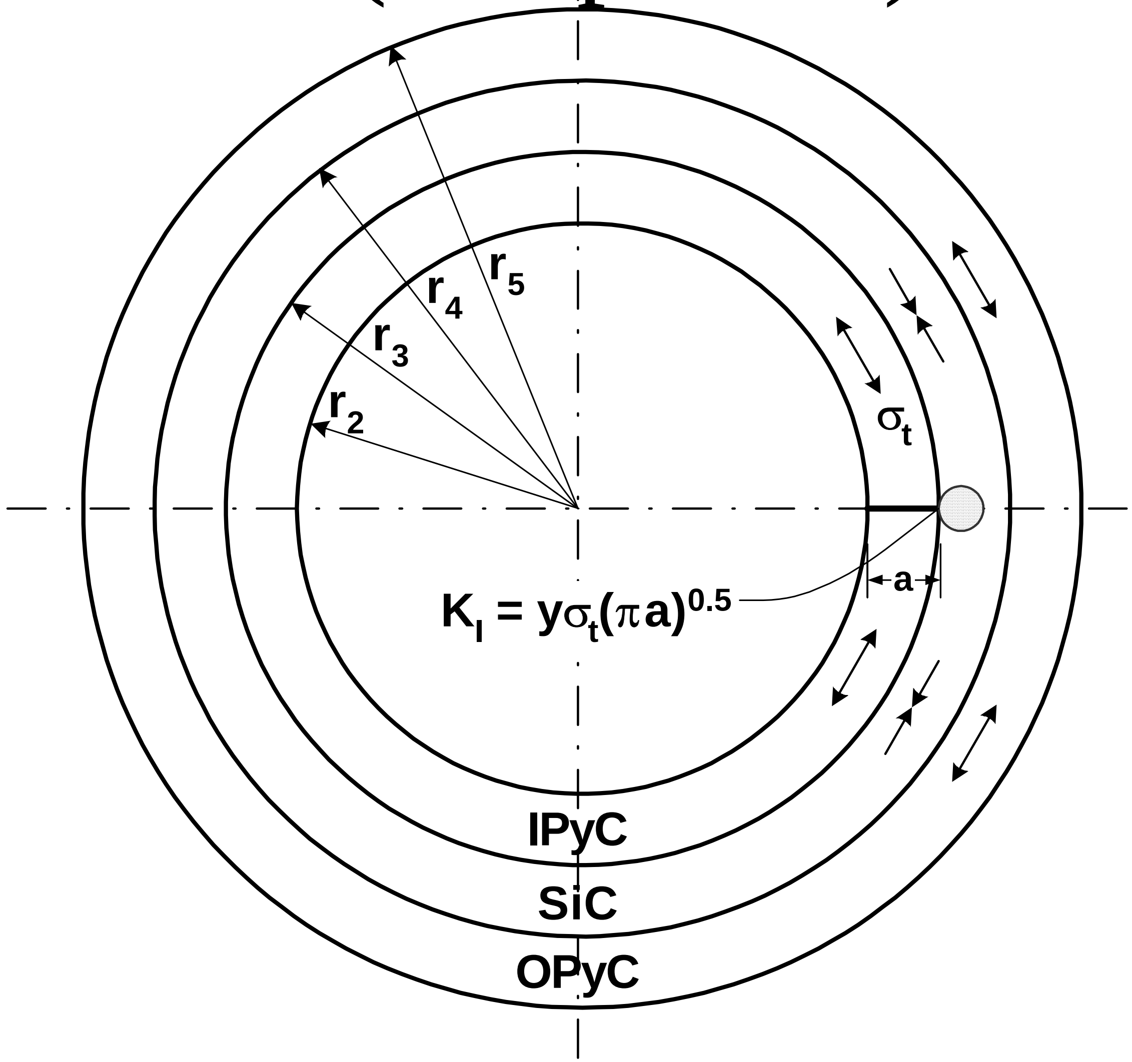
MC inner loop:

implements refueling scheme in reactor core

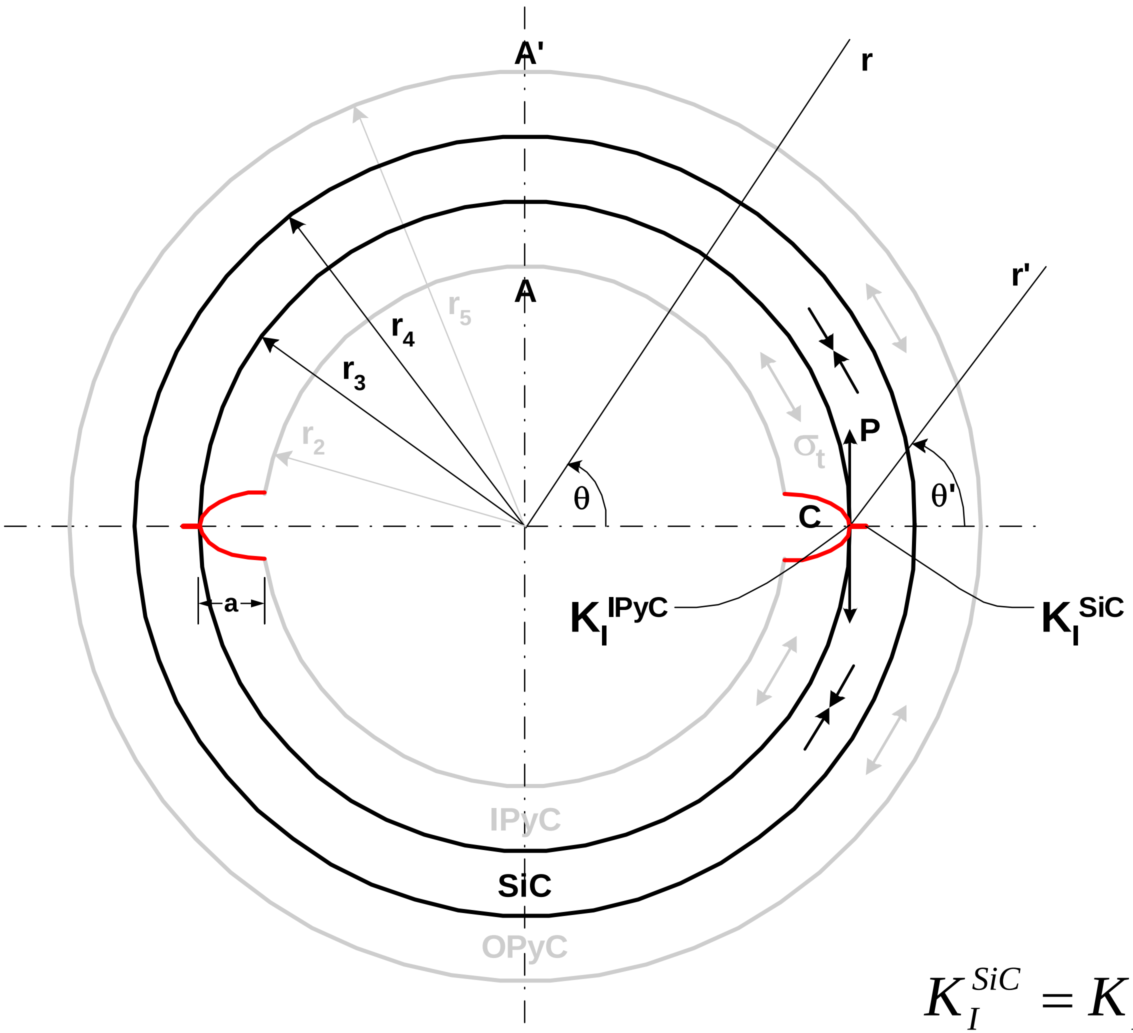
Stress Contributors



TIMCOAT Failure Model (Simplified)



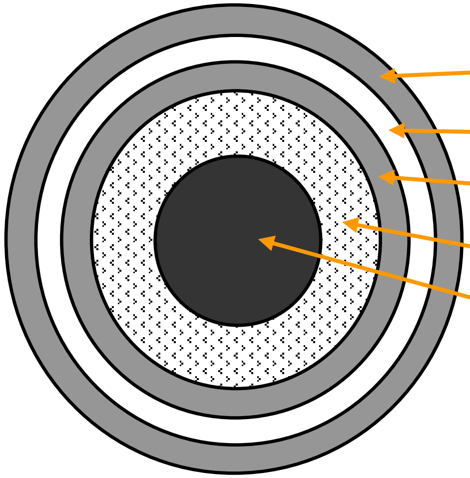
Evaluate Stress Concentration in SiC



$$K_I^{SiC} = K_I^{IPyC}\sqrt{d / a_{IPyC}} + \overline{\sigma}_{SiC}\sqrt{\pi d}$$

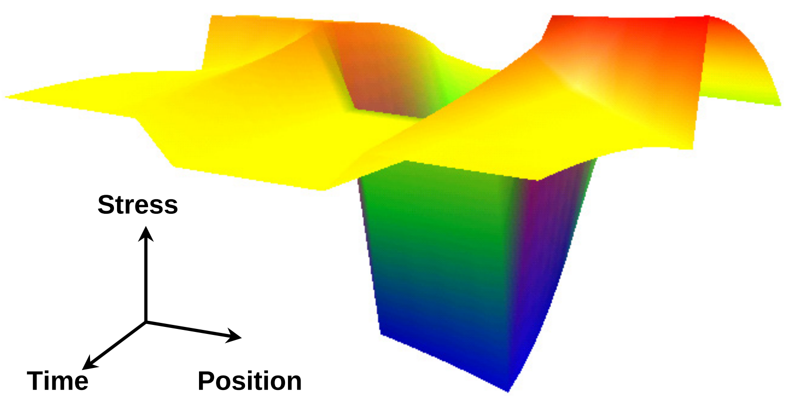
Modules in the Integrated Model

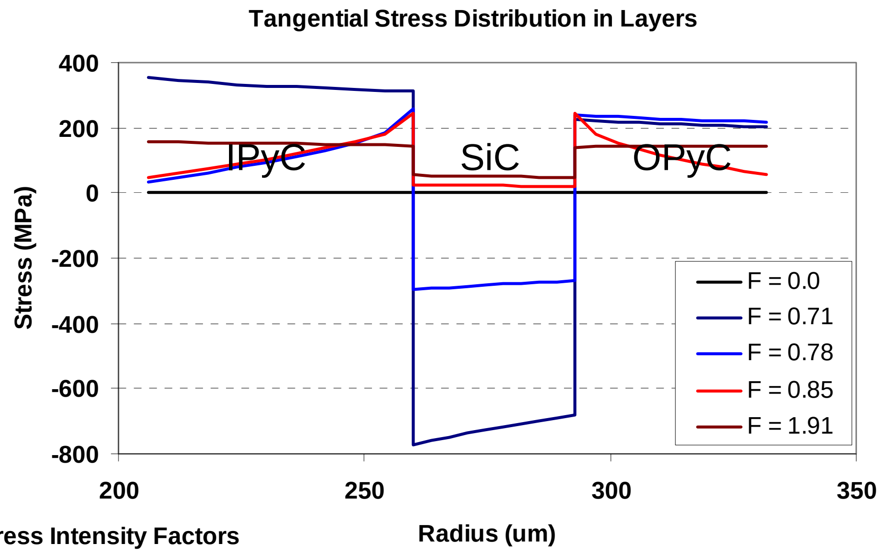
- **Fission gas release model**
- **Thermal model**
- **Mechanical analysis**
- **Chemical analysis**
- **Fuel failure model**
- **Simulation of refueling**
- **Optimization process**

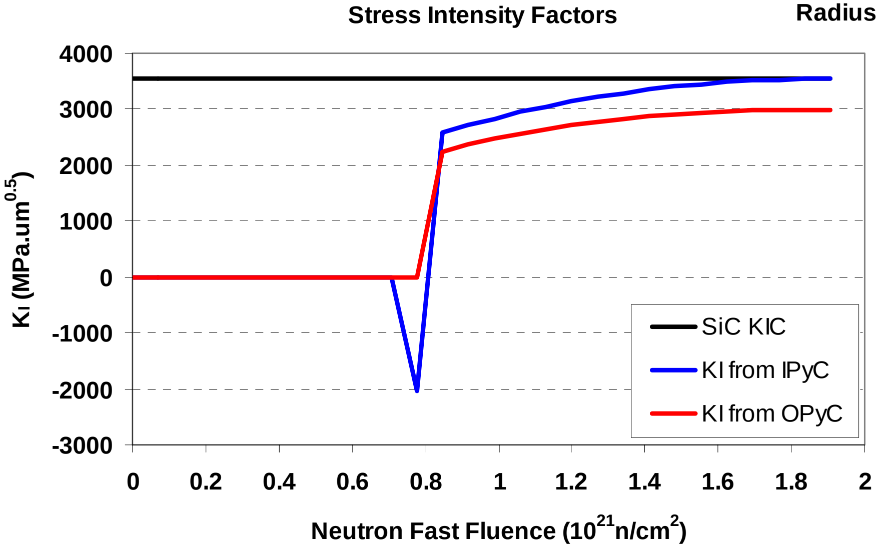


J. Wang, B. G. Ballinger, H. Maclean, "An Integrated Fuel Performance Model for Coated Particle Fuel",

Stress Development in a Failed Particle







Fuel Particle Types

Parameter	Design	As-Fabricated	Design Optimized [a]	As-Fabricated Optimized [b]	Design Optimized (Widened BAF) [c]
U235 Enrichment (%)	9.6 +/- 0.1	9.6 +/- 0.1	9.6 +/- 0.1	9.6 +/- 0.1	9.6 +/- 0.1
Kernel Density (g/cm^3)	10.4 +/- 0.01	10.4 +/- 0.01	10.4 +/- 0.01	10.4 +/- 0.01	10.4 +/- 0.01
Kernel Diameter (μm)	500 +/- 20.0	497 +/- 14.1	600 +/- 20.0	600 +/- 14.1	600 +/- 20.0
Buffer Density (g/cm^3)	1.05 +/- 0.05	1.05 +/- 0.05	1.05 +/- 0.05	1.05 +/- 0.05	1.05 +/- 0.05
Buffer Thickness (μm)	90.0 +/- 18.0	94.0 +/- 10.3	120 +/- 18.0	120 +/- 10.3	120 +/- 18.0
IPyC Density (g/cm^3)	1.90	1.90	1.99	1.99	1.99
IPyC Thickness (μm)	40.0 +/- 10.0	41.0 +/- 4.00	30.0 +/- 10.0	30.0 +/- 4.00	30.0 +/- 10.0
OPyC Density (g/cm^3)	1.90	1.90	1.99	1.99	1.99
OPyC Thickness (μm)	40.0 +/- 10.0	40.0 +/- 2.20	70.0 +/- 10.0	70.0 +/- 2.20	70.0 +/- 10.0
IPyC/OPyC BAF0	1.058 +/- 0.00543	1.058 +/- 0.00543	1.08 +/- 0.00543	1.08 +/- 0.00543	1.08 +/- 0.00816
IPyC/OPyC Strength (MPa.m$^{3/\beta}$)	23.6	23.6	27.8	27.8	27.8
IPyC/OPyC Weibull Modulus β	9.5	9.5	9.5	9.5	9.5
SiC Thickness (μm)	35.0 +/- 4.00	36.0 +/- 1.70	25.0 +/- 4.00	25.0 +/- 1.70	25.0 +/- 4.00
SiC Strength (MPa.m$^{3/\beta}$)	9.64	9.64	9.64	9.64	9.64
SiC Weibull Modulus β	6.0	6.0	6.0	6.0	6.0
SiC Fracture Toughness (MPa.μm$^{1/2}$)	3300 +/- 530.7	3300 +/- 530.7	3300 +/- 530.7	3300 +/- 530.7	3300 +/- 530.7

a: Optimized nominal values + Design Specified Standard Deviations

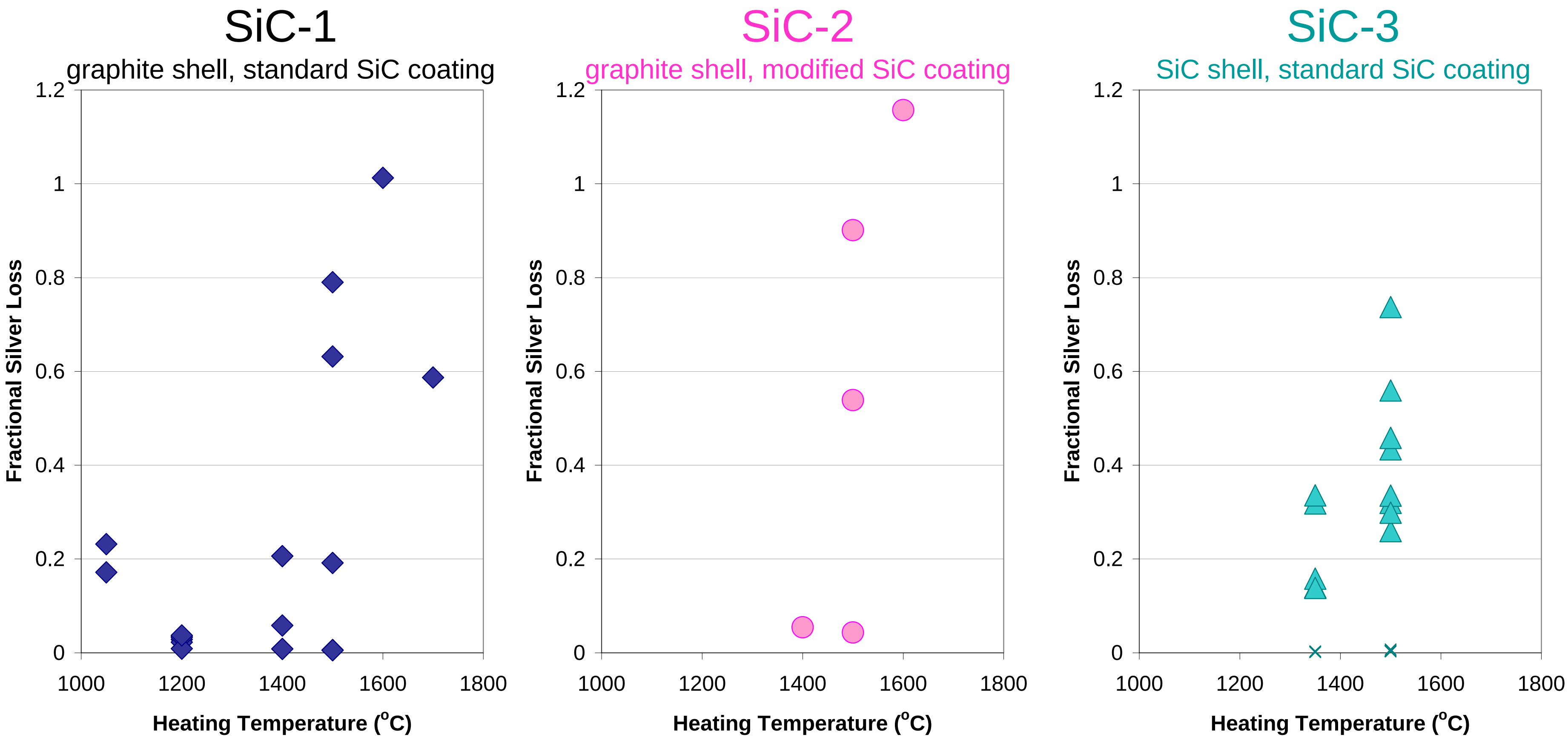
b: Optimized nominal values + As-fabricated Standard Deviations

c: Widened Standard Deviation of PyC BAF0 on “Case a”

Fuel Optimization Results

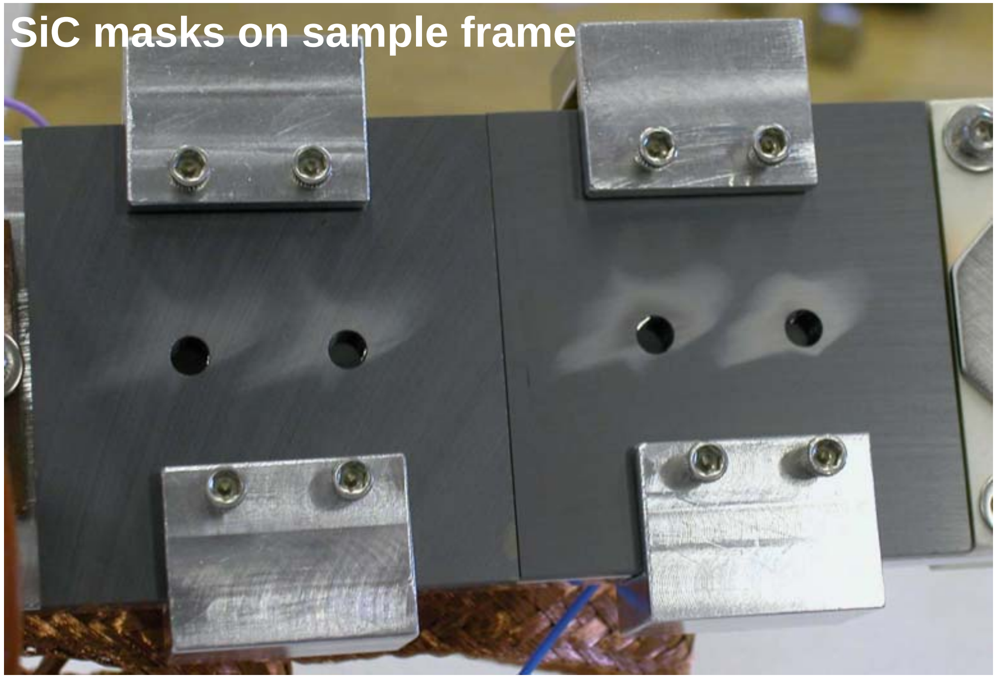
- Environment
  - Given Irradiation Temperature: 910 °C
- Particle Dimension
  - Kernel Diameter (upper limit): 600μm
  - Buffer Thickness: 120μm
  - IPyC Thickness (lower limit): 30μm
  - SiC Thickness (lower limit): 25μm
  - OPyC Thickness (upper limit): 70μm
  - Whole particle radius: 545μm
- Material Properties
  - IPyC/OPyC Density: 1.99g/cm^3
  - IPyC/OPyC BAF0: 1.08

Silver Mass Loss



(normalized to seam area)

Silver Ion Implantation



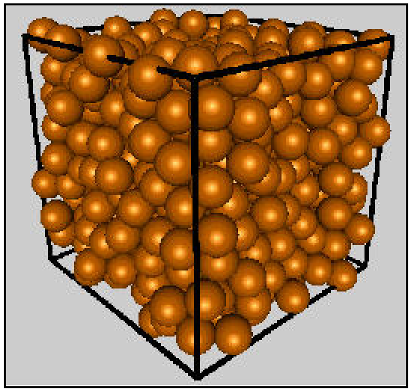
Light transmission through SiC mask and sample

- 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

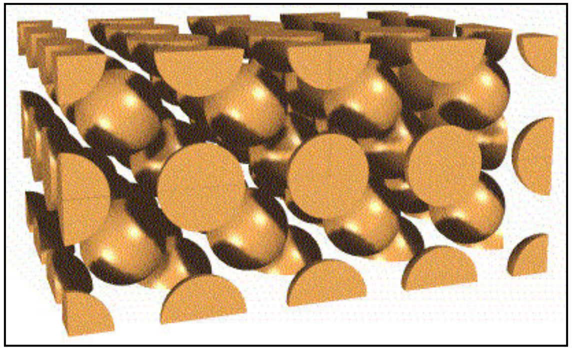
Modeling Considerations

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

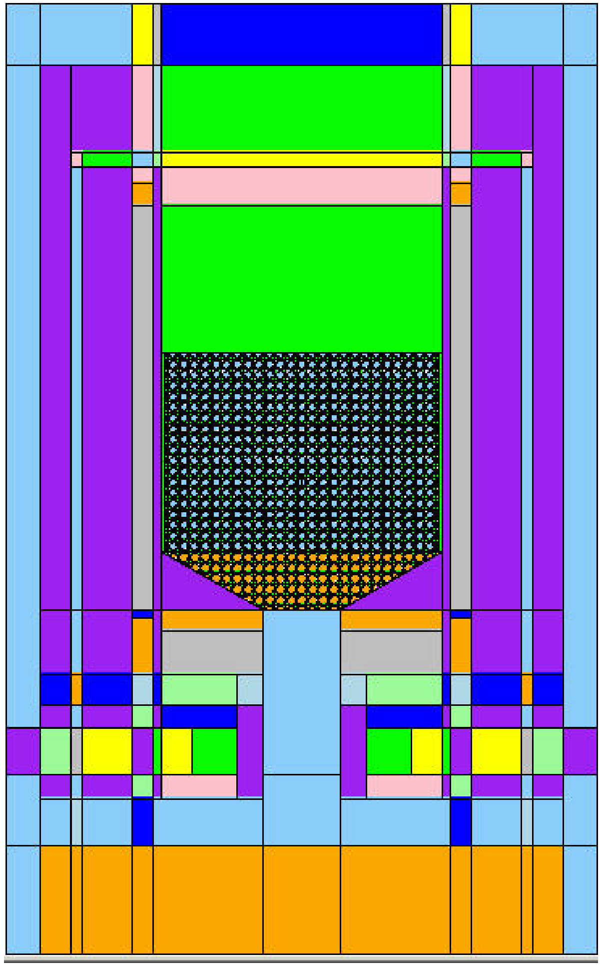


Random Close Packed

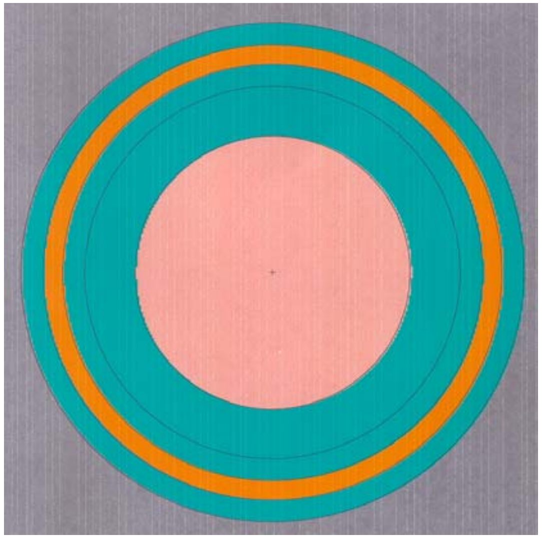


Body Centered Cubic

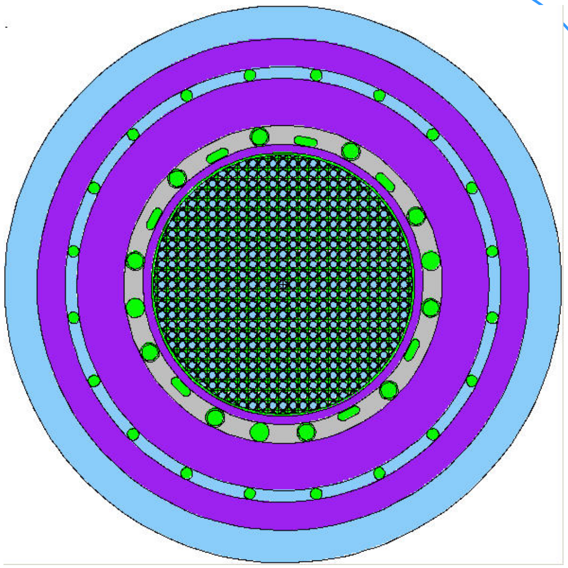
HTR-10
MCNP4B Model



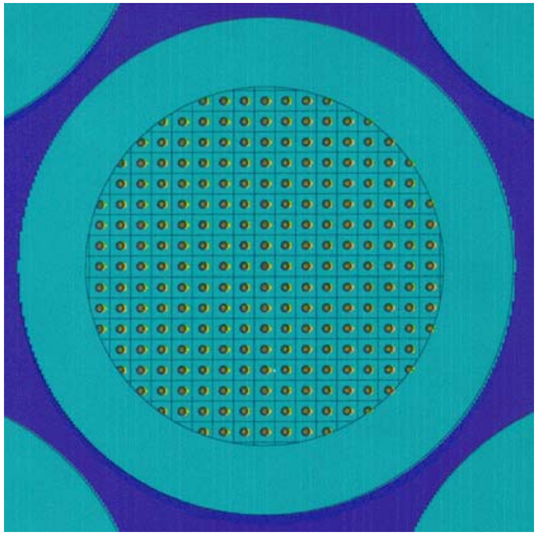
Reactor



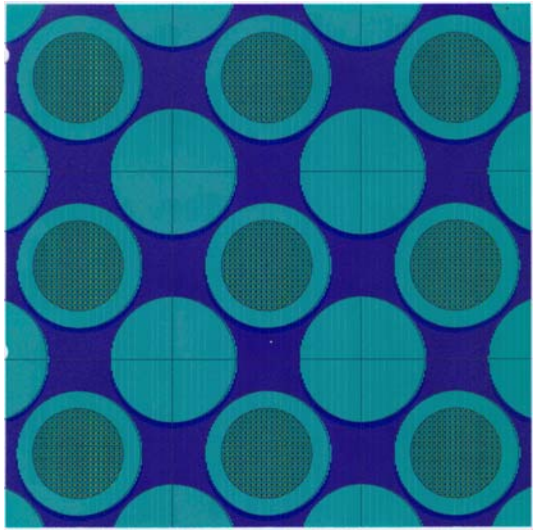
TRISO fuel particle



Core



Fuel sphere



Core lattice

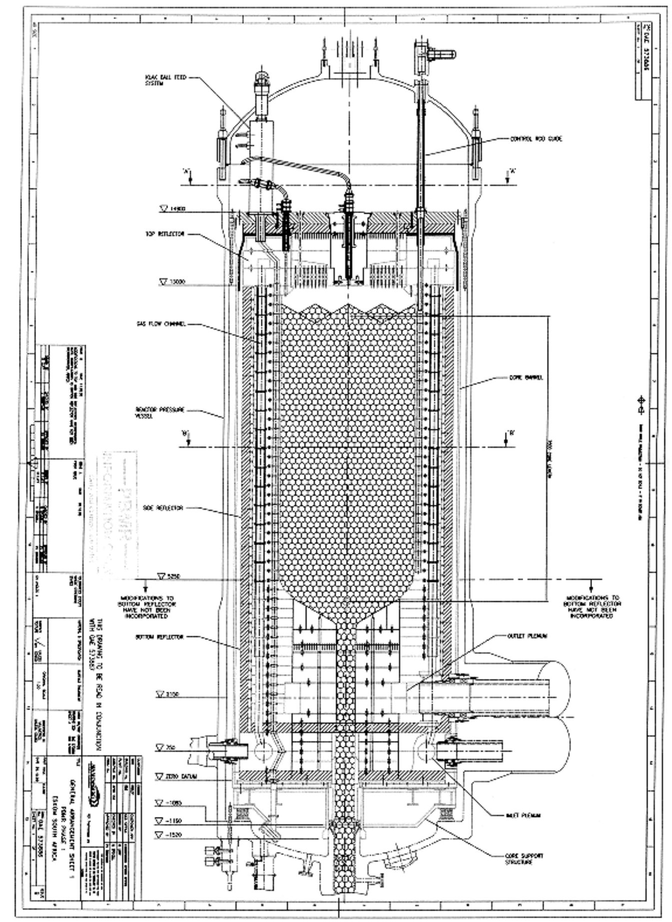
MCNP/VSOP Model of PBMR

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**



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.

Graphite Combustion

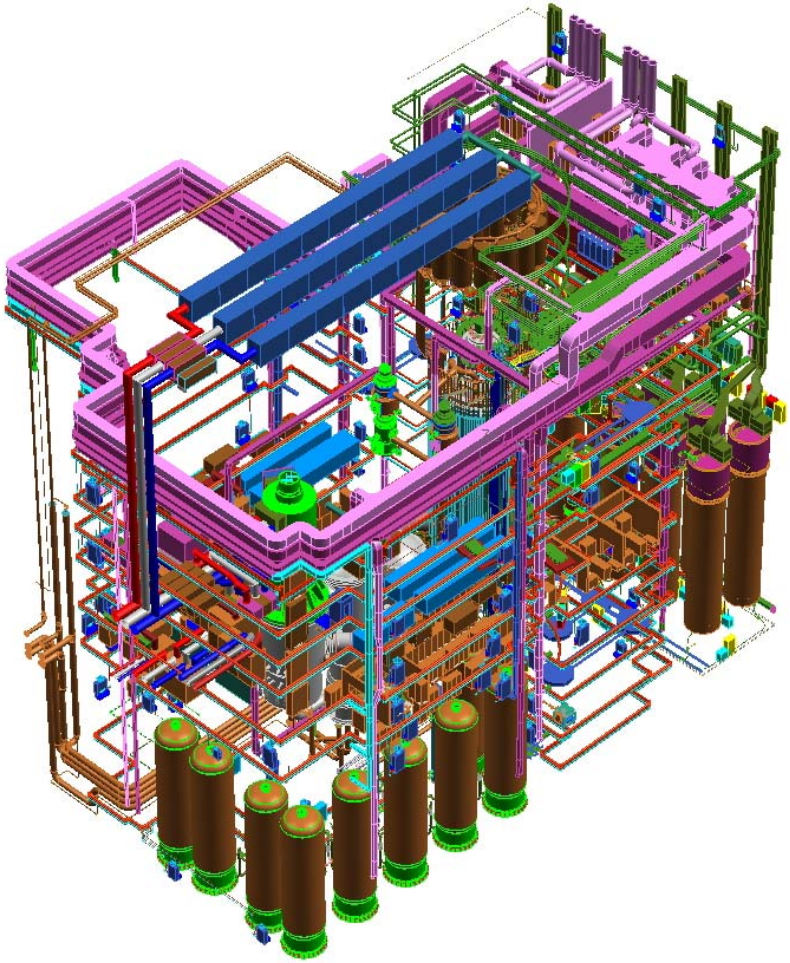
- **Robust, self-sustaining oxidation in the gas phase involving vaporized material mixing with oxygen**
- **Usually produces a visible flame.**
- **True burning of graphite should not be expected below 3500 °C. (From ORNL experiments)**

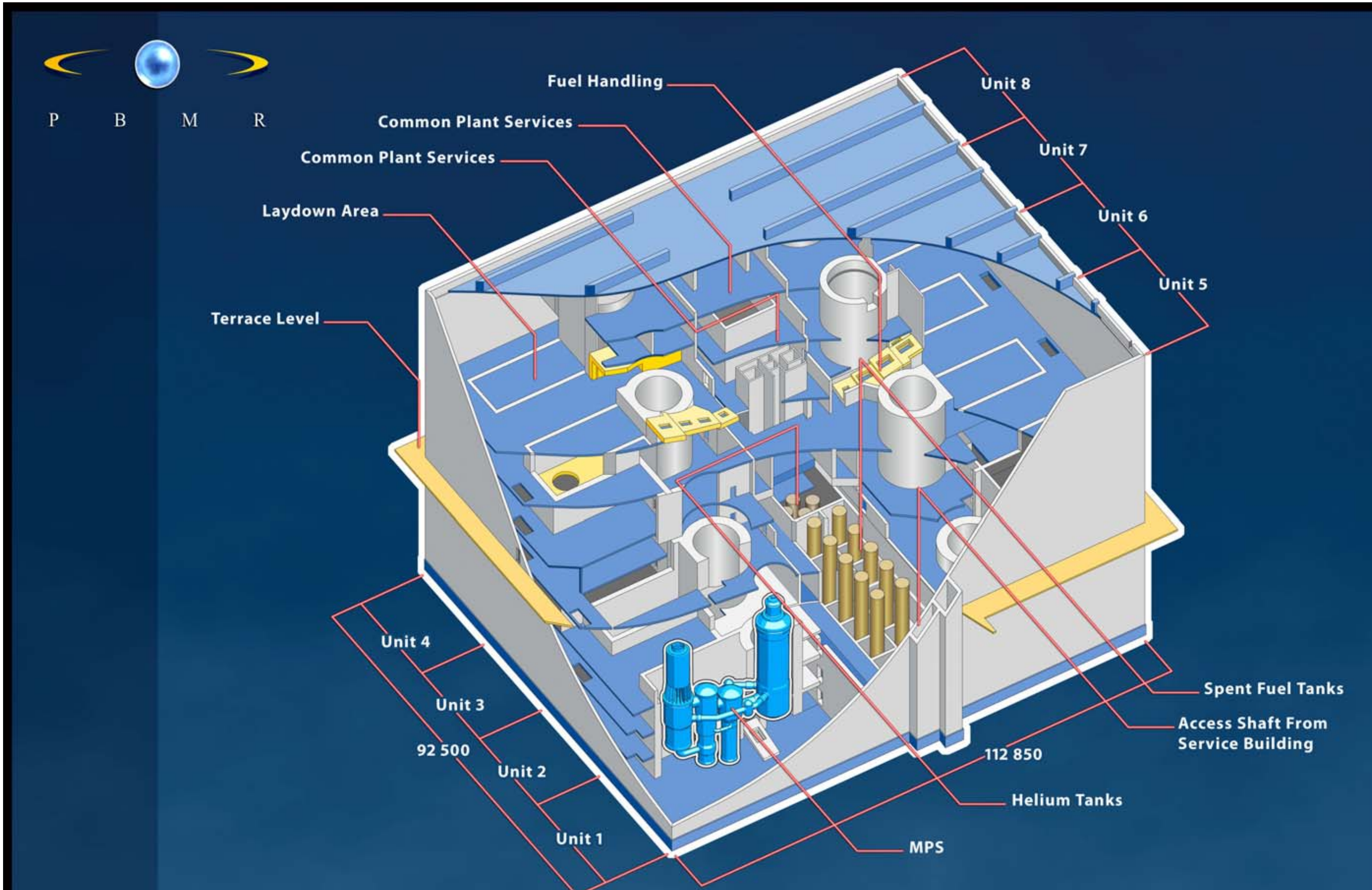
Air Ingress Mitigation

- Air ingress mitigation strategies need to be developed
  - Realistic understanding of failures and repairs
  - Must be integrated with “containment” strategy to limit air ingress
  - Short and long term solution needed

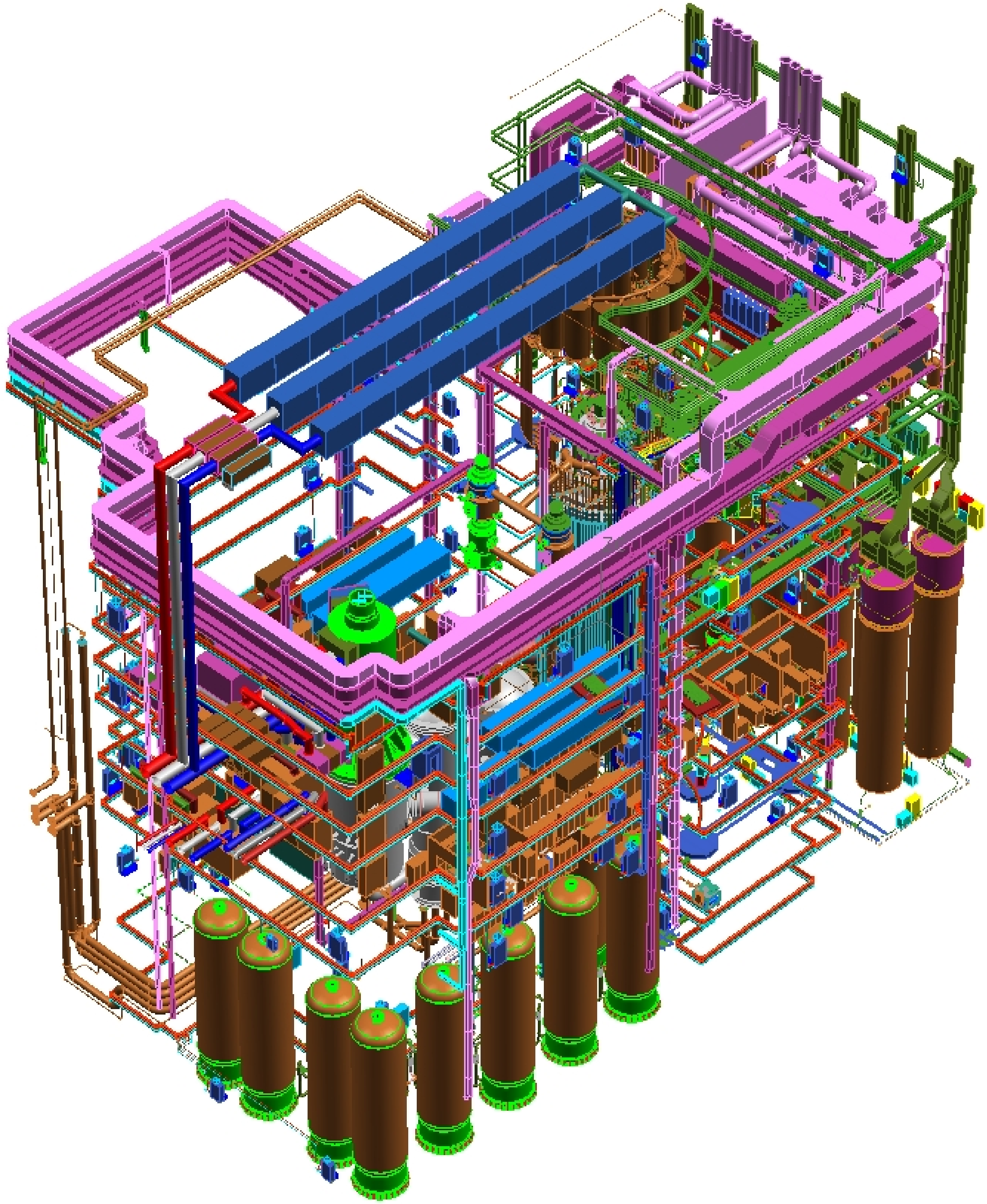
PBMR Design Maturity

- **Based on successful German pebble bed experience of AVR and THTR from 1967 to 1989**
- **Evolution of direct cycle starting with Eskom evaluations in 1993 for application to South Africa grid**
- **Over 2.7 million manhours of engineering to date with 450 equivalent full-time staff (including major subcontractors) working at this time**
- **Over 12,000 documents, including detailed P&IDs and an integrated 3D plant model**
- **Detailed Bill of Materials with over 20,000 line items and vendor quotes on all key engineered equipment**



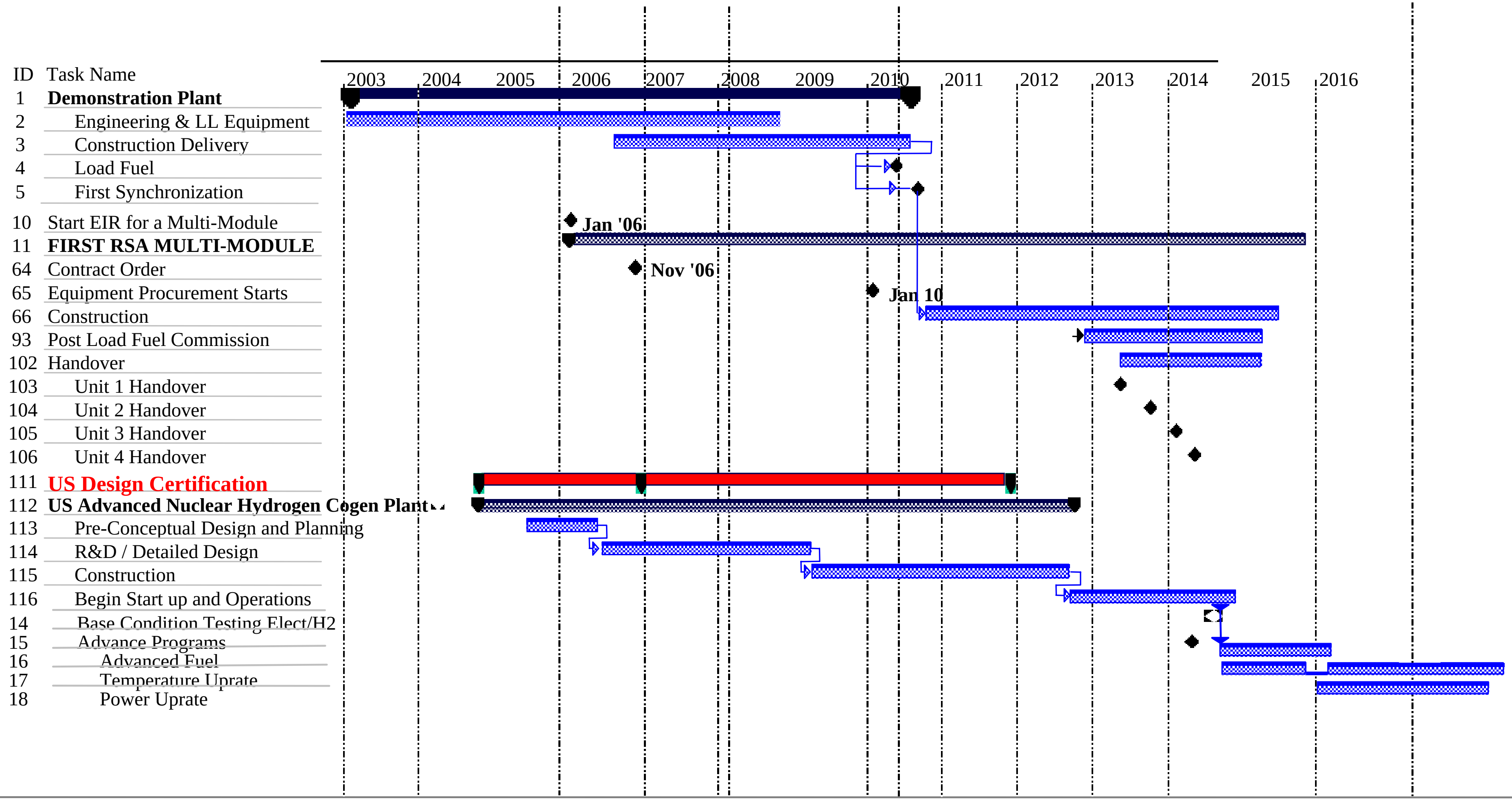


Cut Away Isometric of PBMR Multi Module Concept



TOP WORK

Integrated PBMR Program Plan



Time schedule