High Temperature Gas Reactors

Briefing to

DIGITAL
POWER
CAPITAL

by

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Professor of the Practice

Massachusetts Institute of Technology

Kadak Associates, Inc

Overview

- New interest in nuclear generation
- Plants performing exceedingly well
- Utilities making money with nuclear investments
- Price volatility reduced with nuclear
- Global climate concerns growing
- New products being developed

US Initiatives

- Nuclear Power 2010
- Next Generation Nuclear Plant (NGNP)
- Generation IV Nuclear Plants
- NRC Regulatory Changes
  - Combined Construction and Operating License
  - Risk informed Regulations
  - Early Site Permitting
  - Design Certification

MACHINE DESIGN

SEPTEMBER 27, 2001
www.machinedesign.com

A PENTON PUBLICATION
Periodicals
USPS 881 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 ker-

THE WORLD'S LARGEST SCIENCE & TECHNOLOGY MAGAZINE

Popular Science

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

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The Politically Correct NUKE

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

by Charles Wardell

bove 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
he pebbles heat
o more than
,000°C, the coat-
ngs trap the radi-
ation inside. The
particles decay
within 250,000
rears, but the
graphite ball
maintains
ts integrity for
nore than one
nillion years.

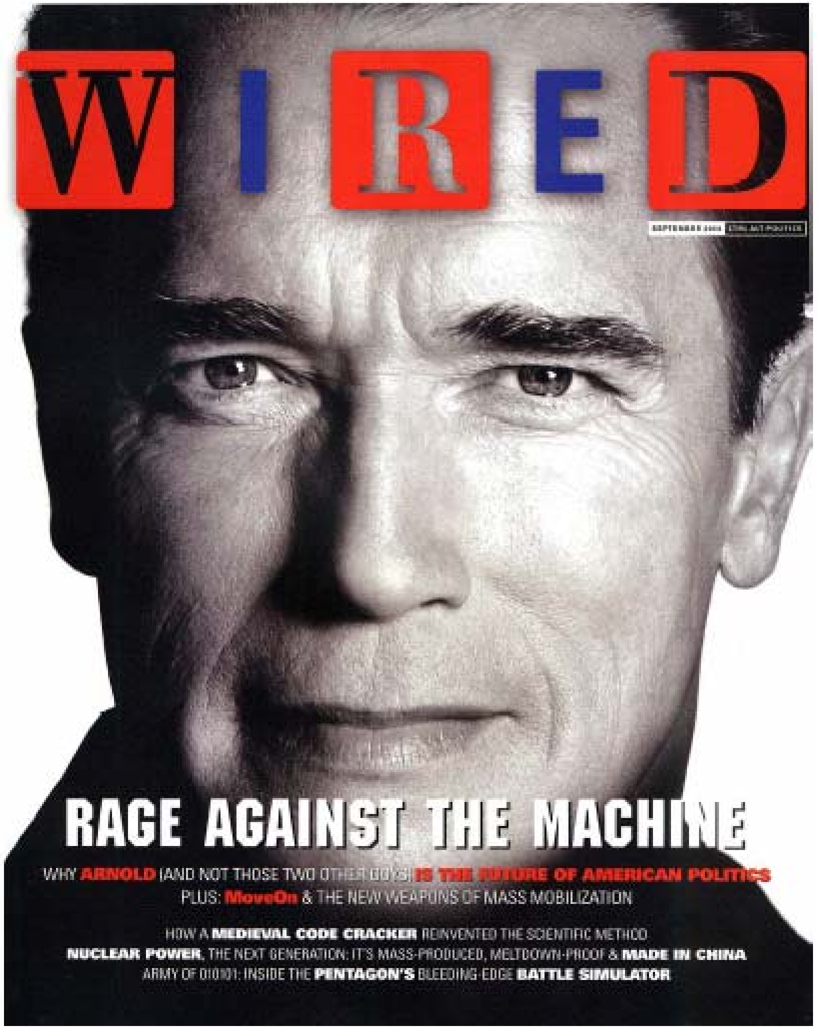
To truly understand the renewed buzz for nuclear, you have to travel to the Massachusetts Institute of Technology in Cambridge. Here, Andrew Kadak, professor of nuclear engineering, holds two billiard-size balls that many believe represent the future of nuclear energy. The balls are the "pebbles" in 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

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

Presentation Overview

- Introduction to Gas Reactors
- Pebble Bed Reactor
- Players
- International Status
- Target Markets
- Economics
- Future

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

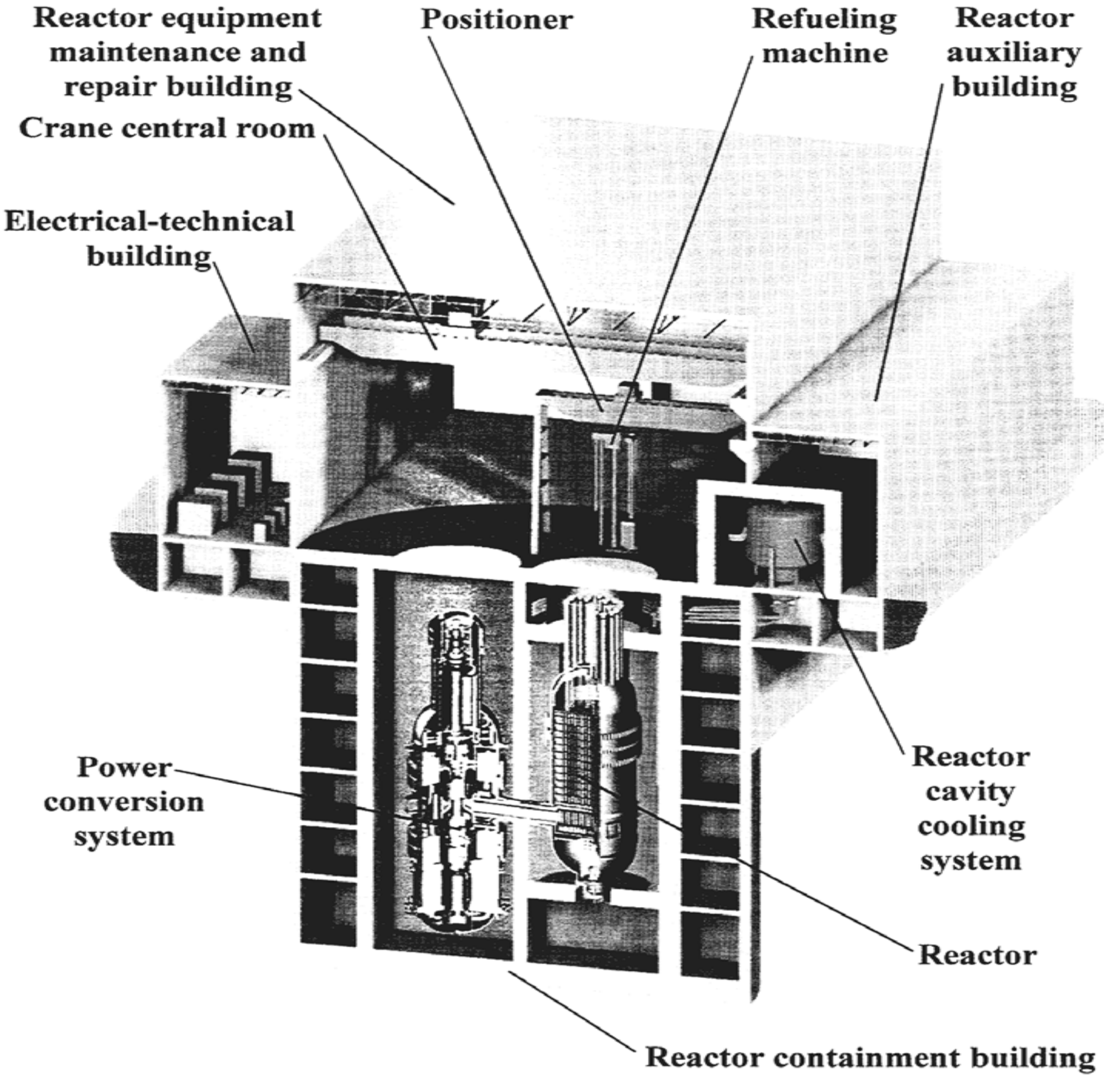
- Peach Bottom (40 MWe) 1967-1974
  - First Commercial (U/Thorium Cycle)
  - Generally Good Performance (75% CF)
- Fort St. Vrain (330 MWe) 1979-1989 (U/Th)
  - Poor Performance
  - Mechanical Problems
  - Decommissioned

Fort St. Vrain

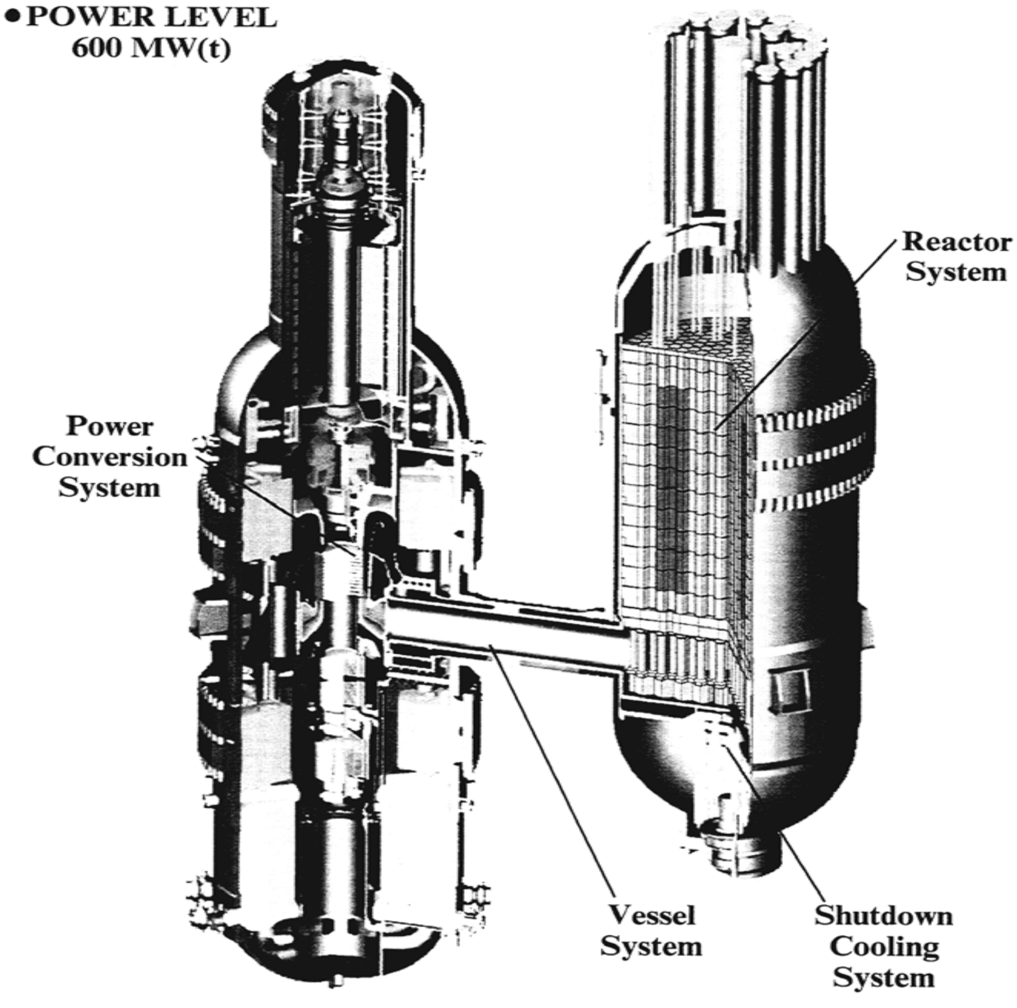
Different Types of Gas Reactors

- 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

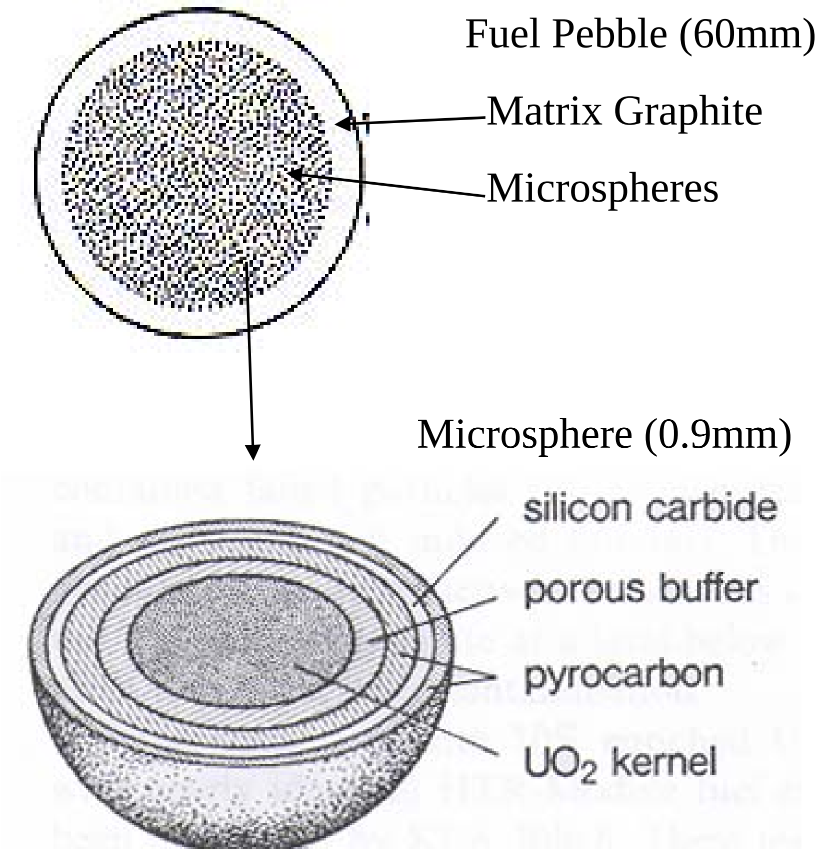
GT-MHR Module General Arrangement



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



TRISO Fuel Particle -- “Microsphere”


Fuel Pebble (60mm)

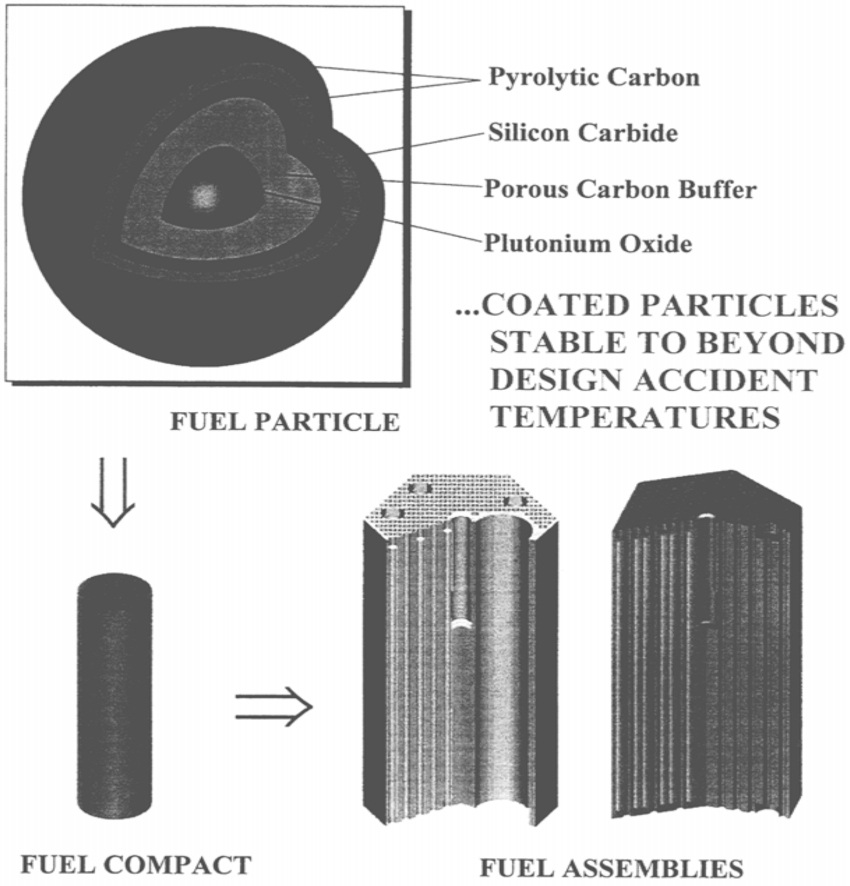
Matrix Graphite

Microspheres

Microsphere (0.9mm)

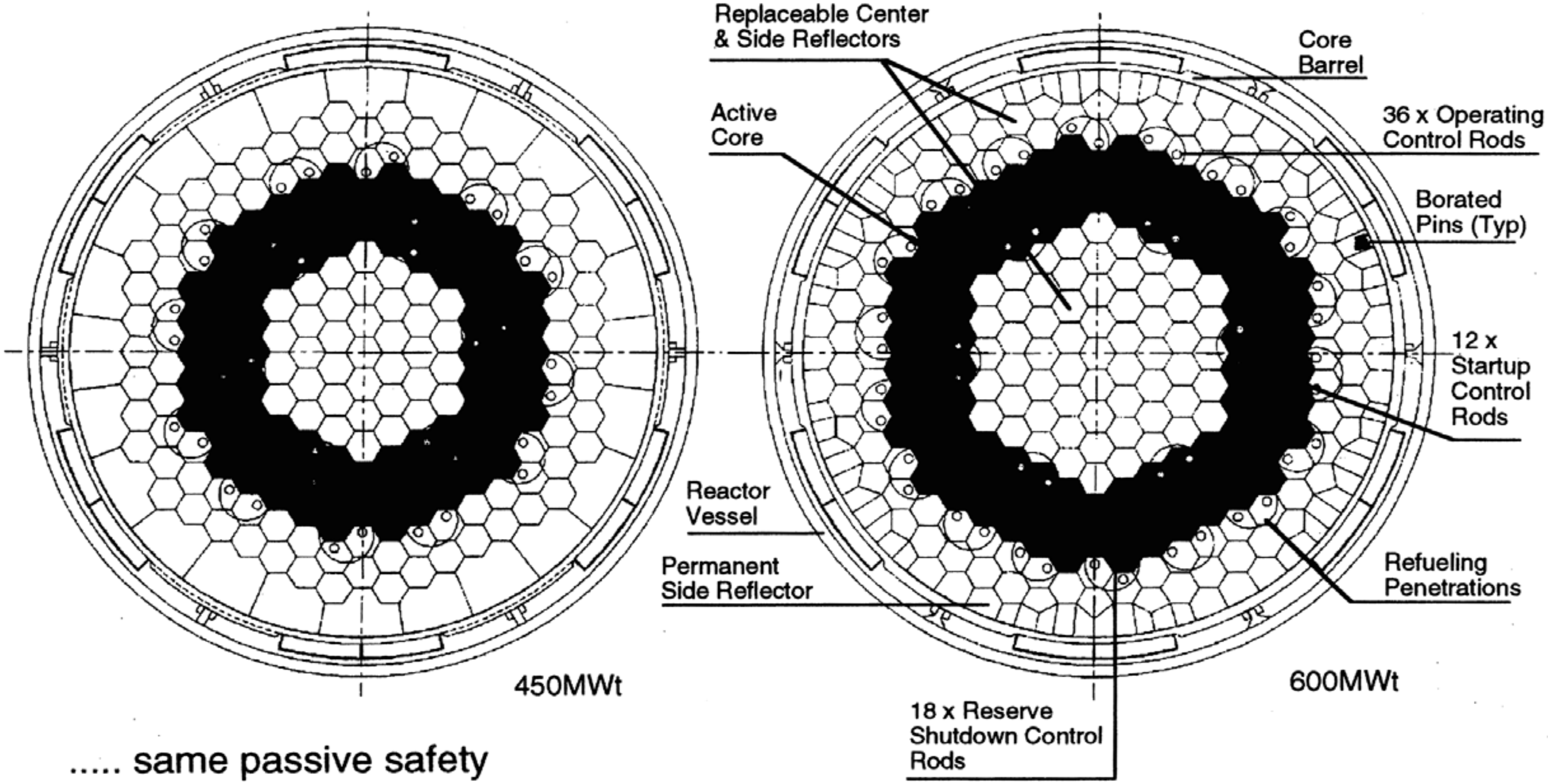
- 0.9mm diameter
- ~ 11,000 in every pebble
- 10^9 microspheres in core
- Fission products retained inside microsphere
- TRISO acts as a pressure vessel
- Reliability
  - Defective coatings during manufacture
  - ~ 1 defect in every fuel pebble

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

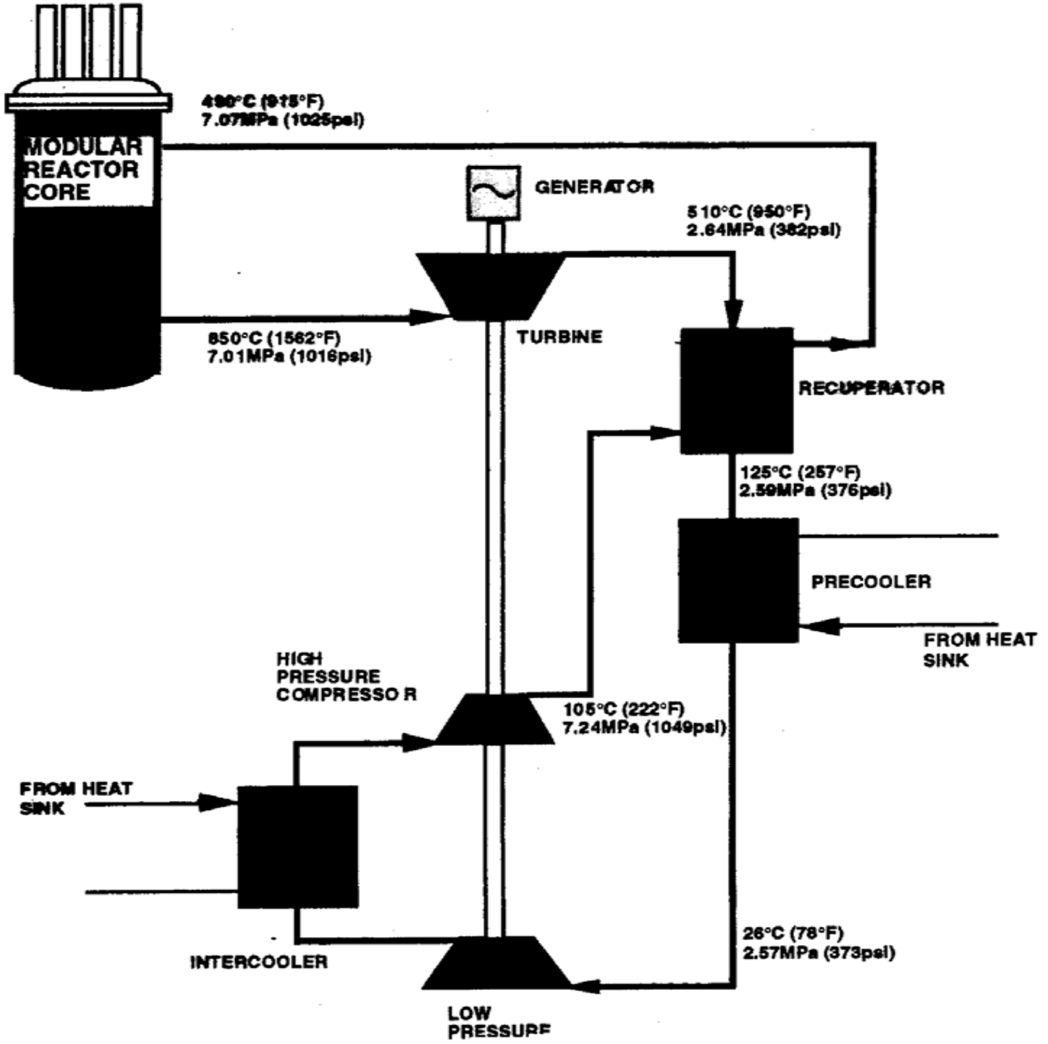


..... same passive safety

..... annular core using existing technology

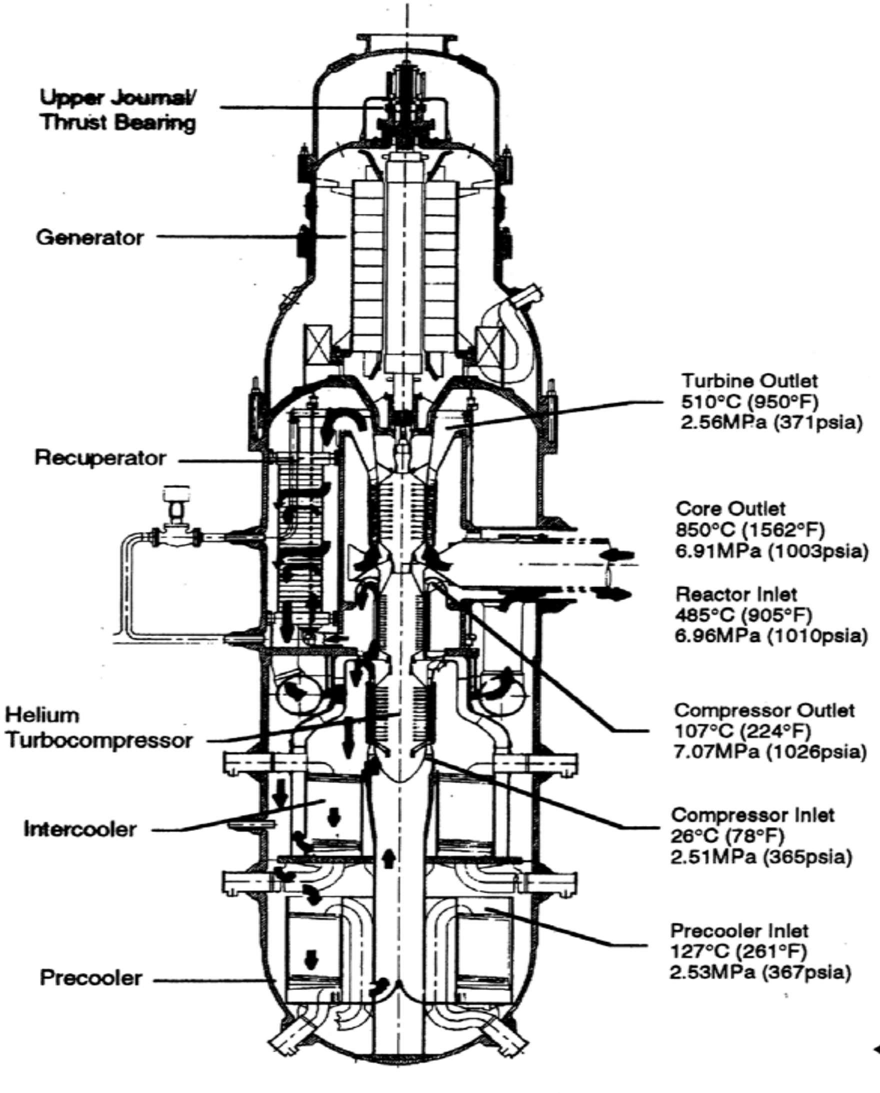
GENERAL ATOMICS

GT-MHR Flow Schematic

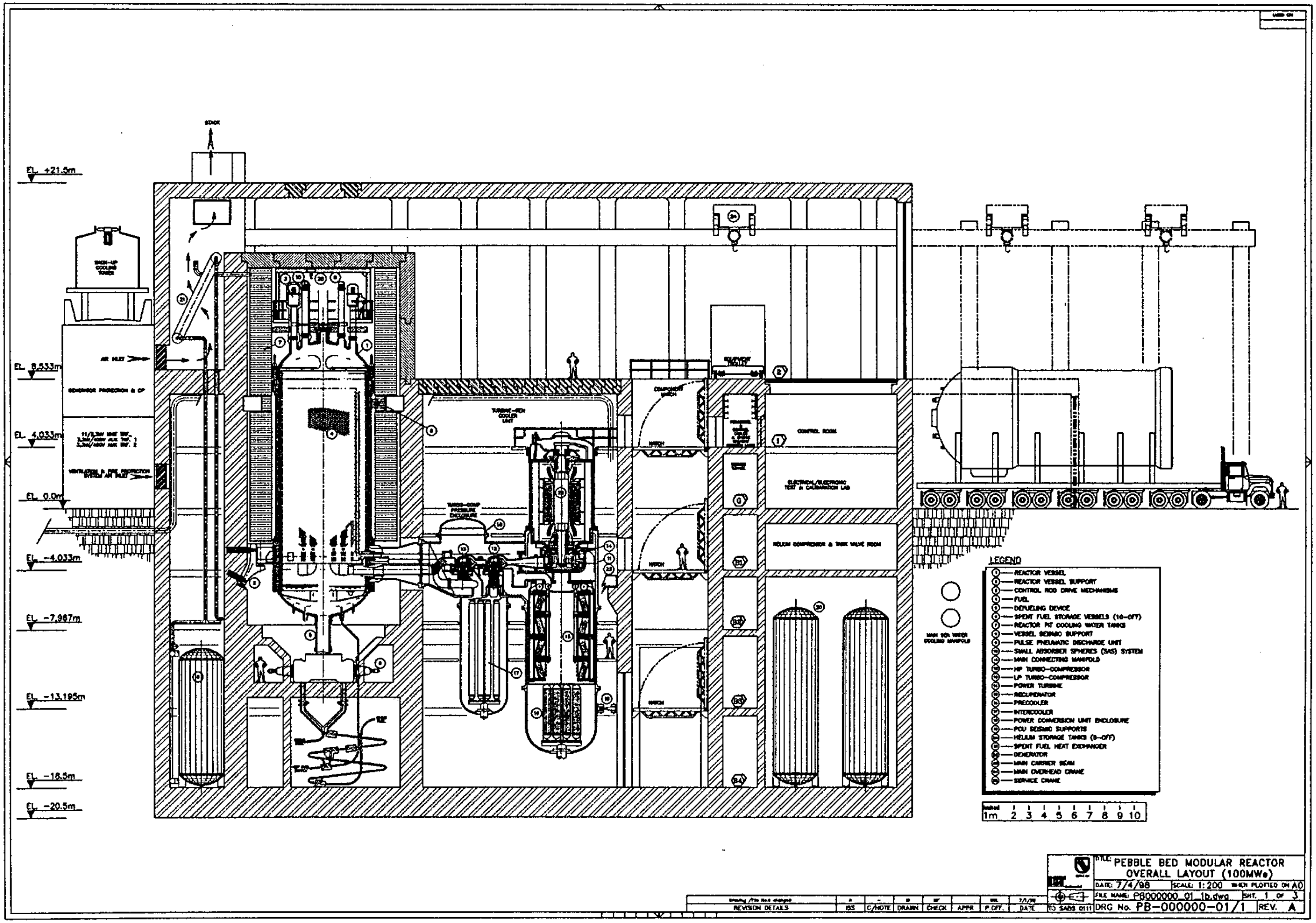


GENERAL ATOMICS

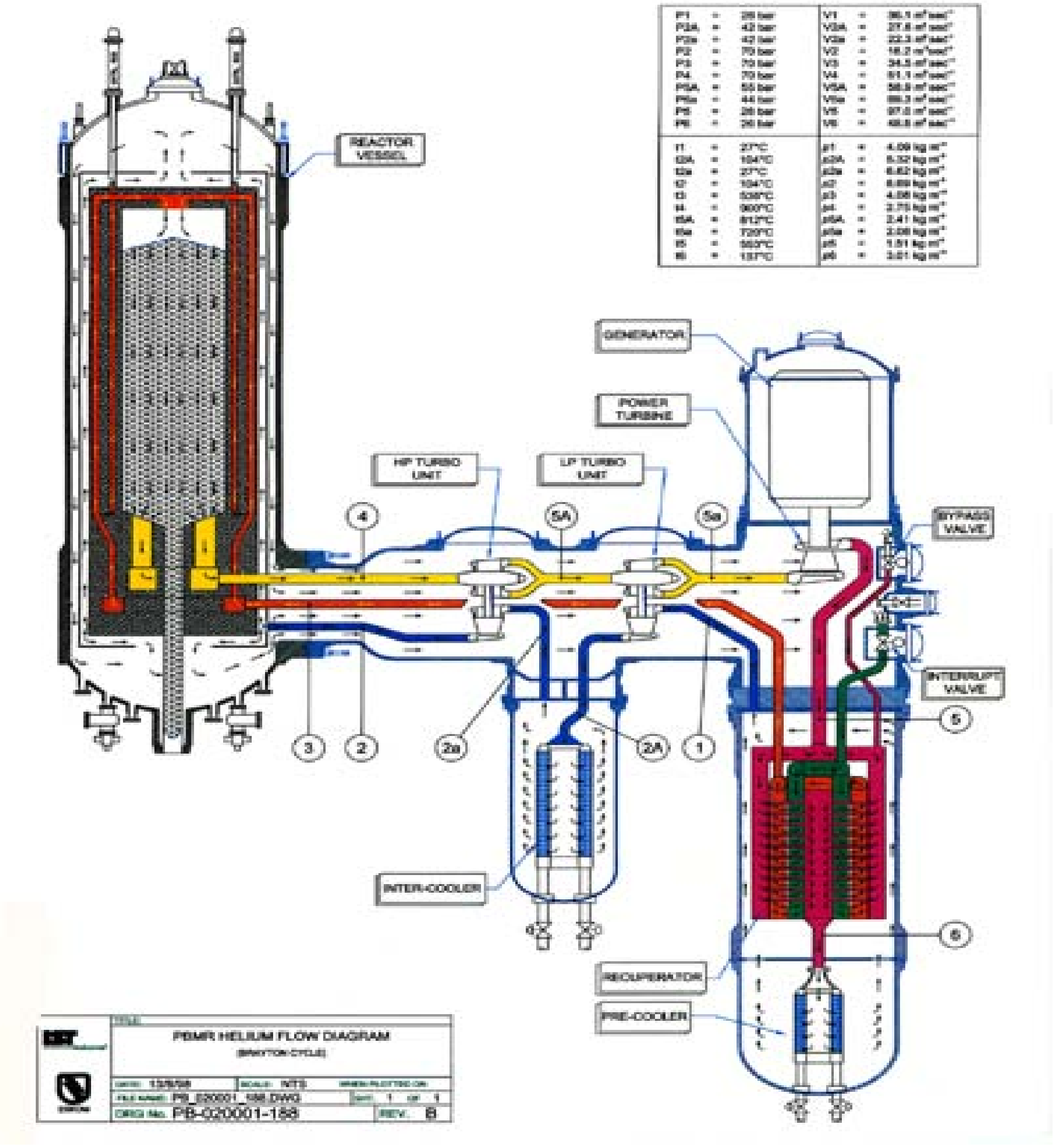
Flow through Power Conversion Vessel



ESKOM Pebble Bed Modular Reactor



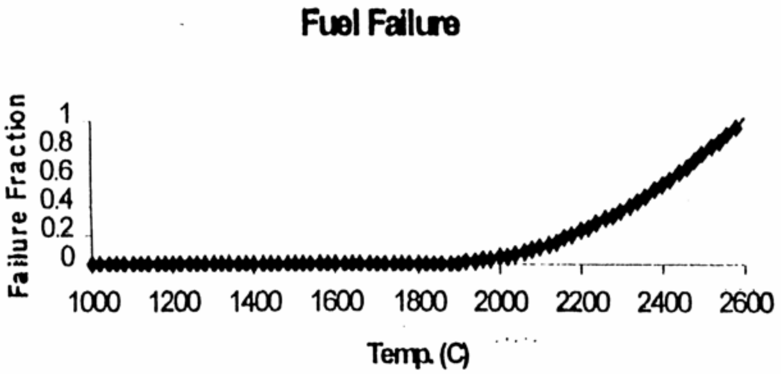
PBMR Helium Flow Diagram

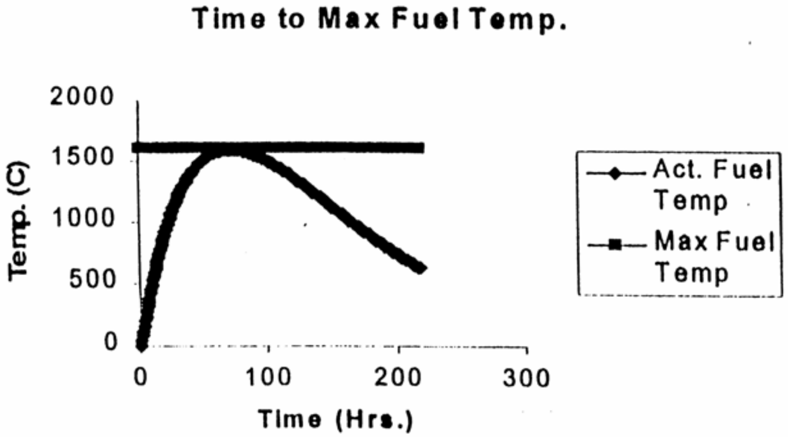


Safety Advantages

- 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

Differences Between LWRS

- Higher Thermal Efficiencies Possible
- Helium inert gas - non corrosive
- Minimizes use of water in cycle
- Utilizes gas turbine technology
- Lower Power Density
- Less Complicated Design (No ECCS)

Advantages & Disadvantages

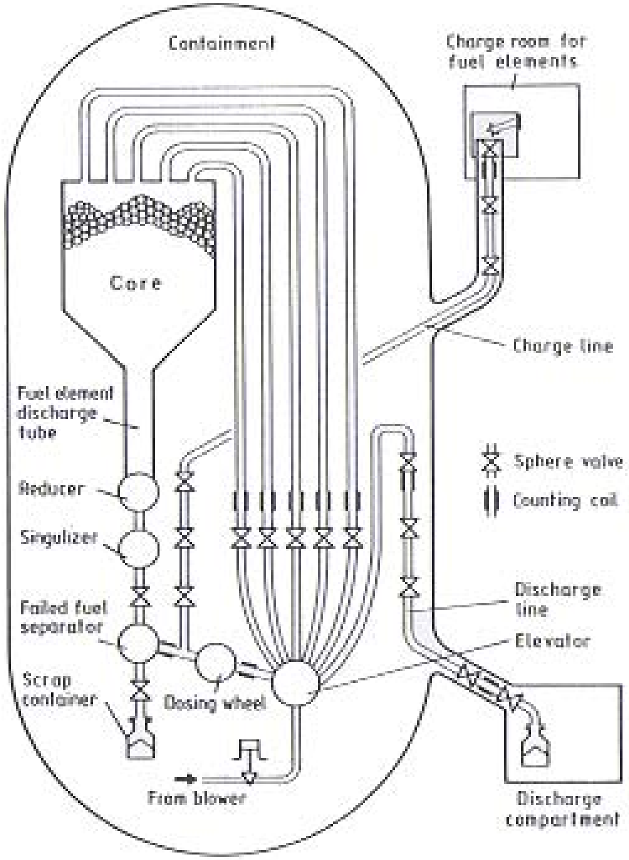
Advantages

- Higher Efficiency
- Lower Waste Quantity
- 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

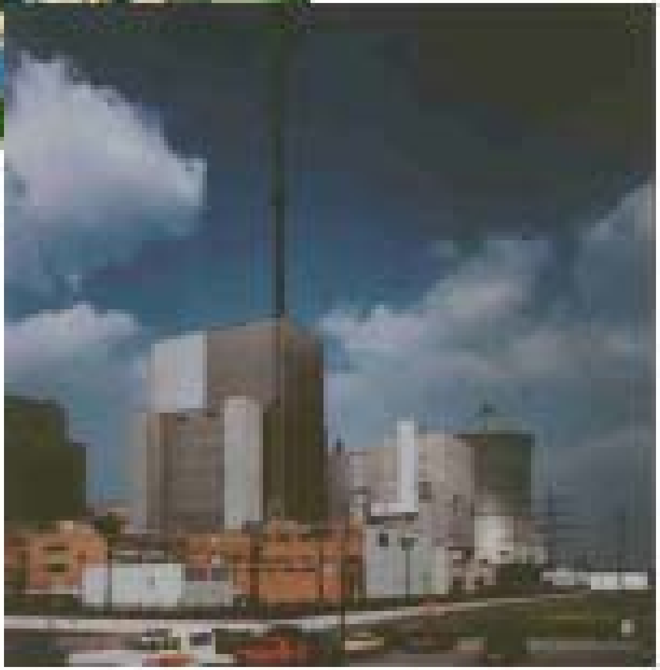
What is a Pebble Bed Reactor ?



- **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

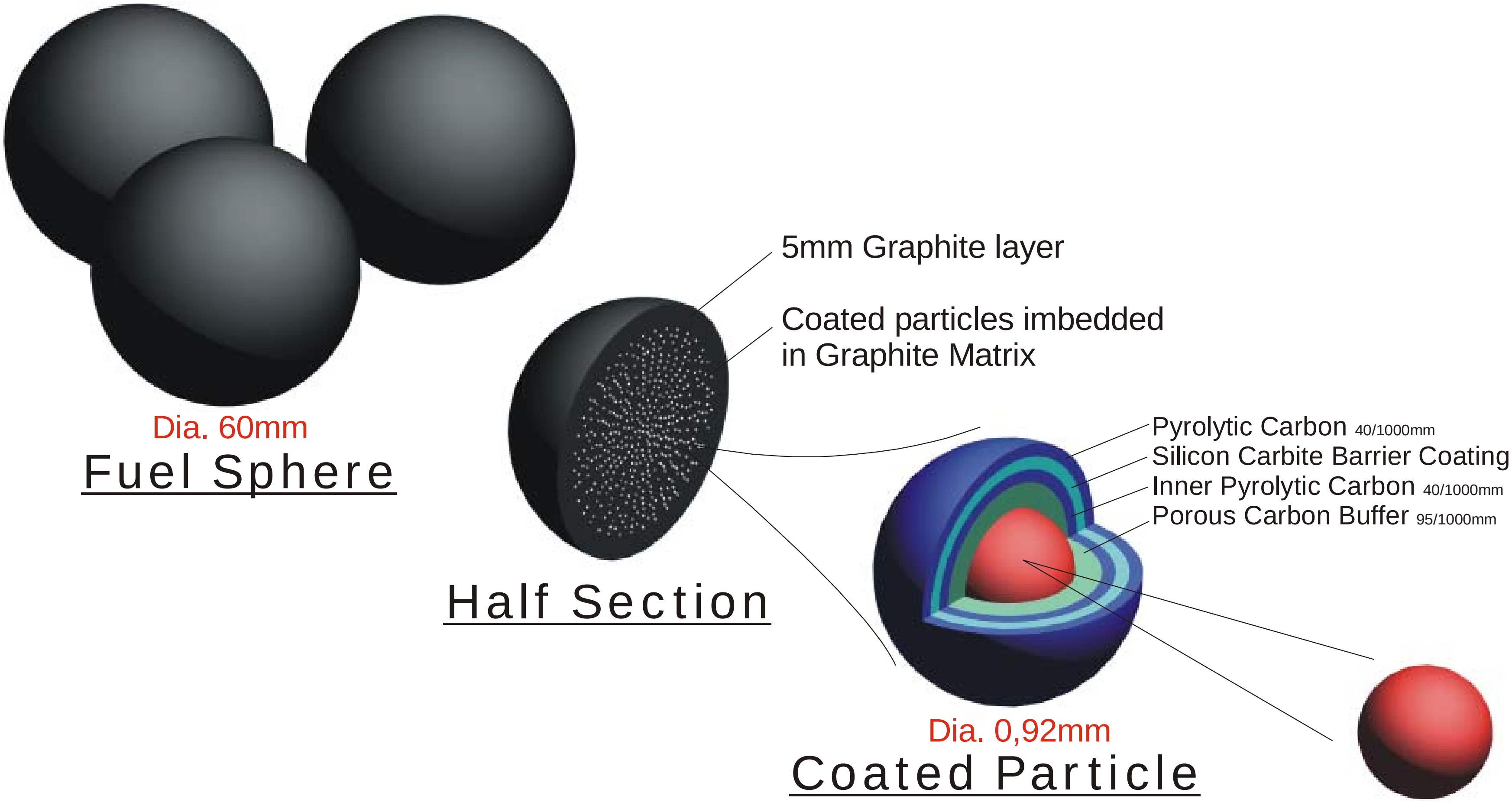
AVR (1967-88)
15 MWe



THTR (1985-89)
300 MWe

HTR- 10 China
First Criticality Dec.1, 2000

FUEL ELEMENT DESIGN FOR PBMR



Dia. 60mm

Fuel Sphere

5mm Graphite layer

Coated particles imbedded
in Graphite Matrix

Half Section

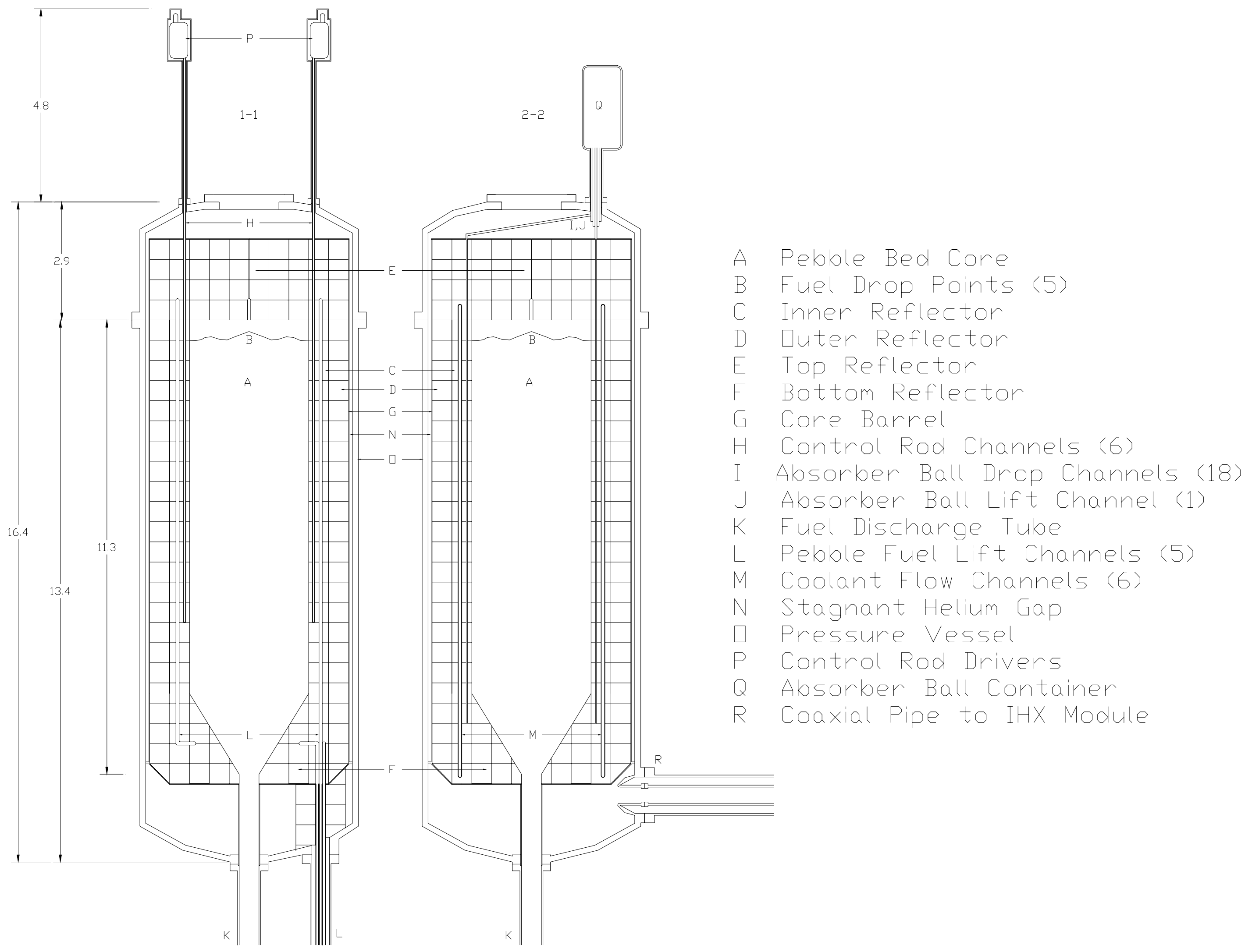
Pyrolytic Carbon 40/1000mm
Silicon Carbite Barrier Coating 35/100
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm

Dia. 0,92mm

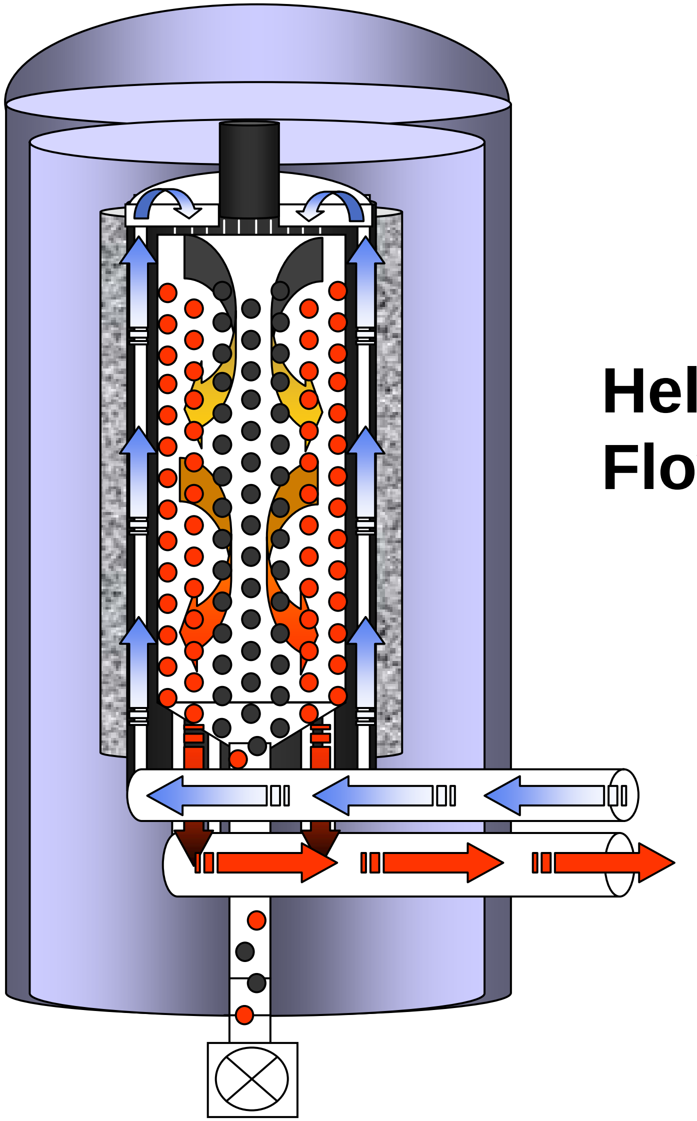
Coated Particle

Dia.0,5mm
Uranium Dioxide

Fuel

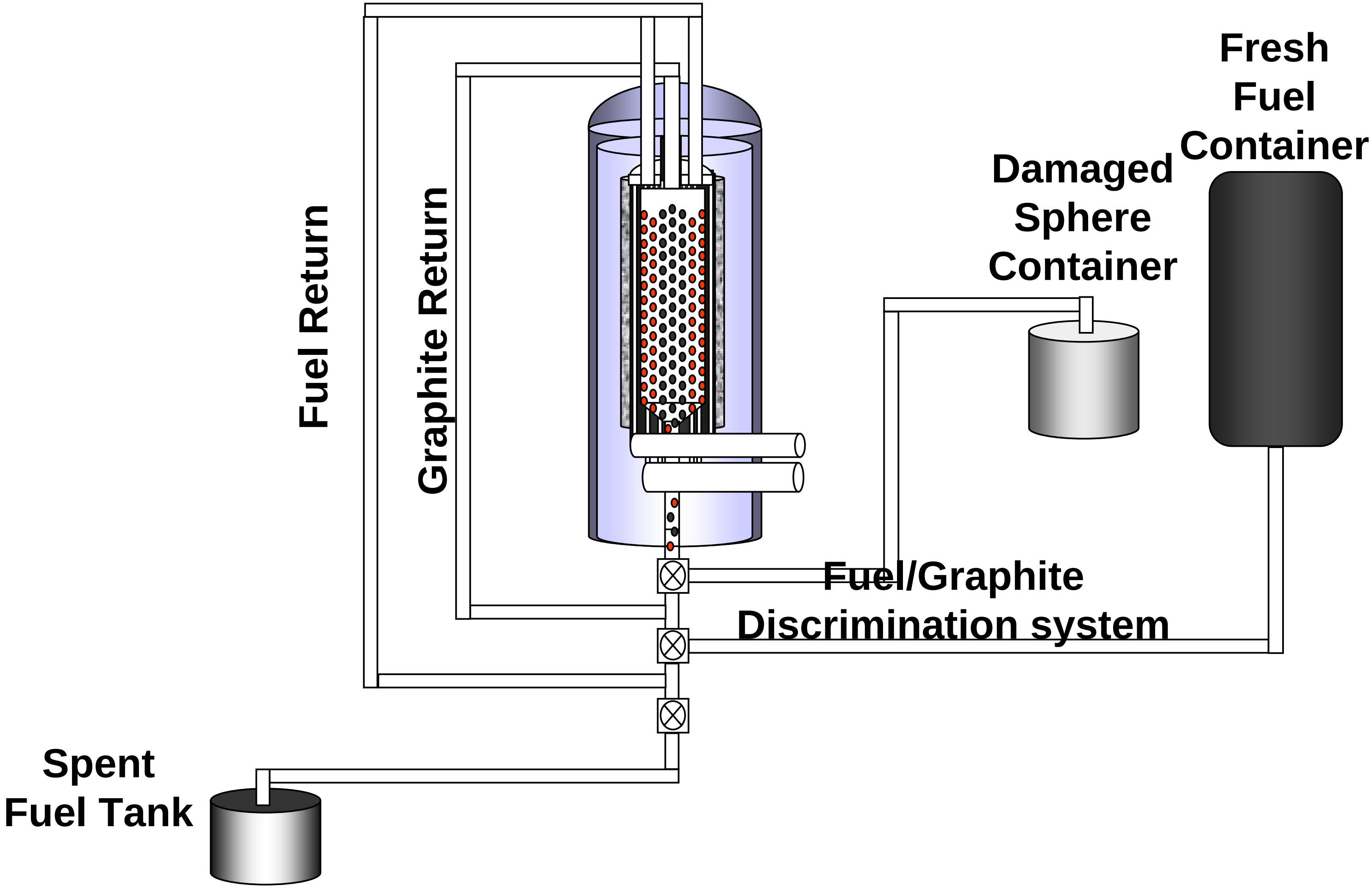

4.8
P
1-1
2-2
Q
H
I,J
2.9
E
B
B
C
D
G
N
O
A
A
16.4
11.3
13.4
L
M
F
R
K
L
K
A Pebble Bed Core
B Fuel Drop Points (5)
C Inner Reflector
D Outer Reflector
E Top Reflector
F Bottom Reflector
G Core Barrel
H Control Rod Channels (6)
I Absorber Ball Drop Channels (18)
J Absorber Ball Lift Channel (1)
K Fuel 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



Fresh Fuel Container

Damaged Sphere Container

Fuel Return

Graphite Return

Fuel/Graphite Discrimination system

Spent Fuel Tank

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

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

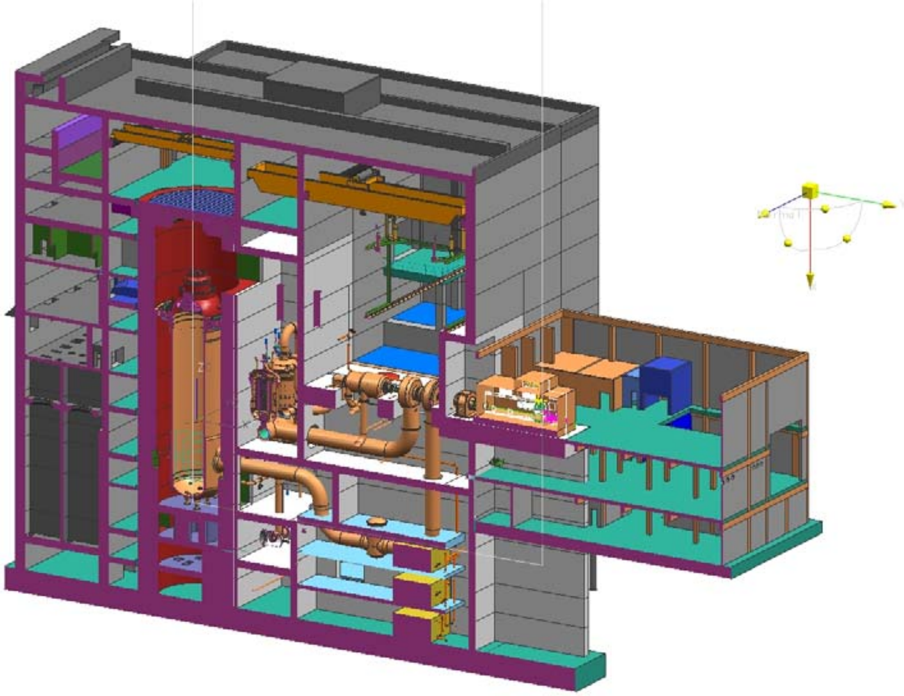
- 165 MWe Pebble Bed Plant - ESKOM
- Direct Helium High Temperature Cycle
- In Licensing Process
- Schedule for construction start 2007
- Operation Date 2011/12
- Commercial Reference Plant

South Africa Demonstration Plant Status

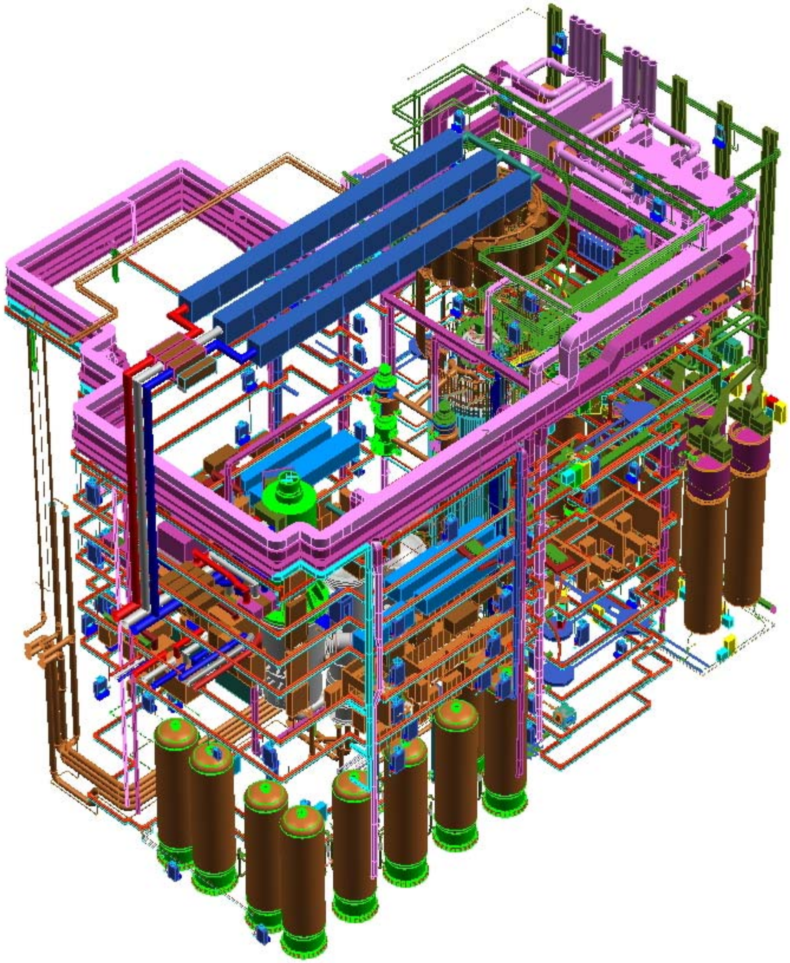
- **Koeberg site on Western Cape selected**
- **Designated national strategic project in May 2003**
- **Environmental Impact Assessment (EIA) completed with positive record of decision; appeals to be dispositioned by December 2004**
- **Revised Safety Analysis Report in preparation; to be submitted to 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 24 months (1st) Schedule**
- **Planned Outages 30 days per 6 years**
- **Fuel Costs & O&M Costs < 9 mills/kWh**
- **Availability >95%**

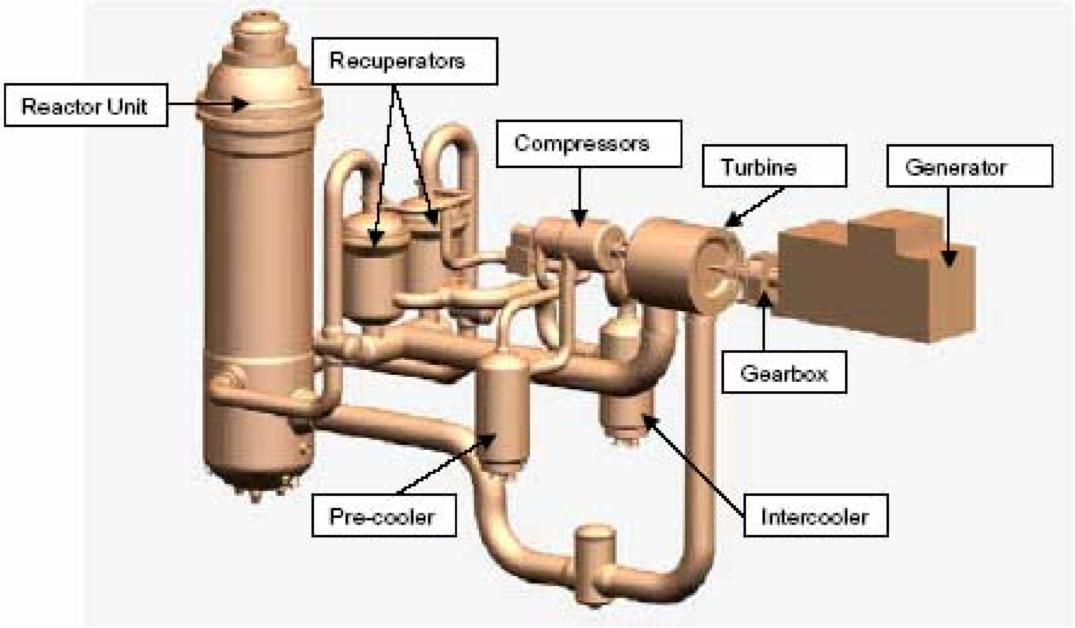


PBMR Design Maturity

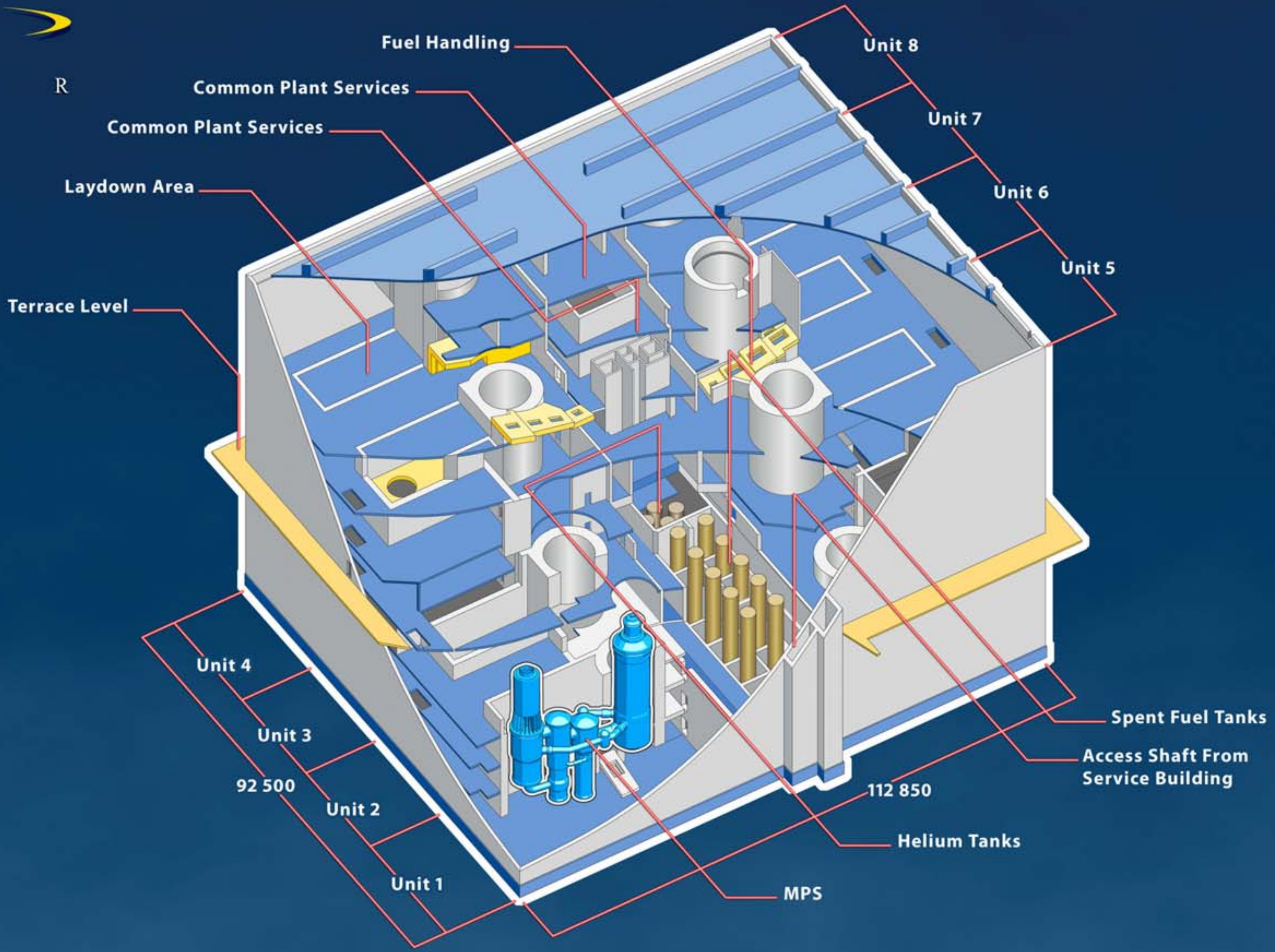


- **Based on successful German pebble bed experience of AVR and THTR from 1967 to 1989**
- **Evolution of direct cycle starting with Eskom evaluations in 1993 for application to South Africa grid**
- **Over 2.7 million manhours of engineering to date with 450 equivalent full-time staff (including major 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**

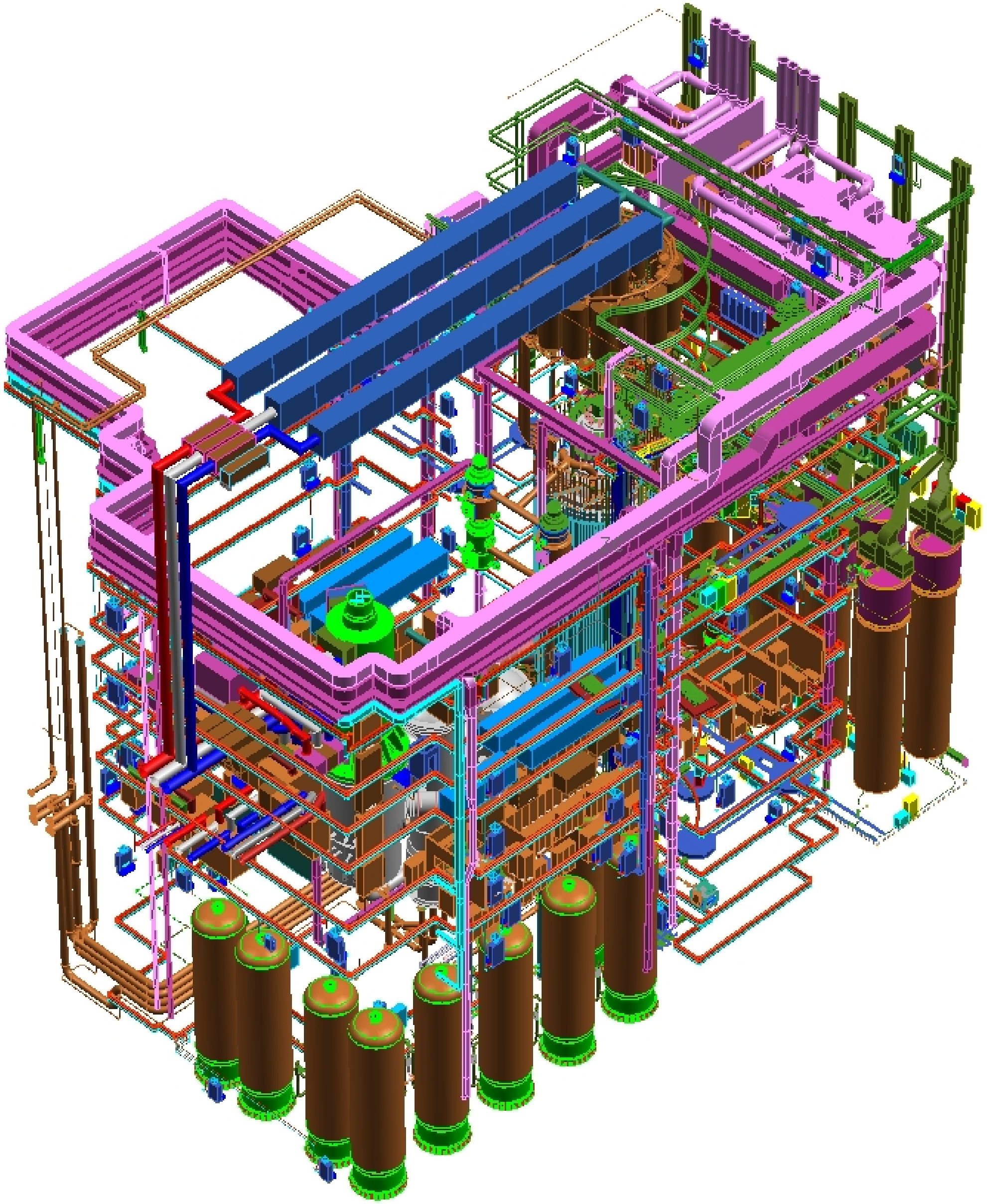
FIGURE 9. The 400 MWt single shaft main power system in the building.



P B M R

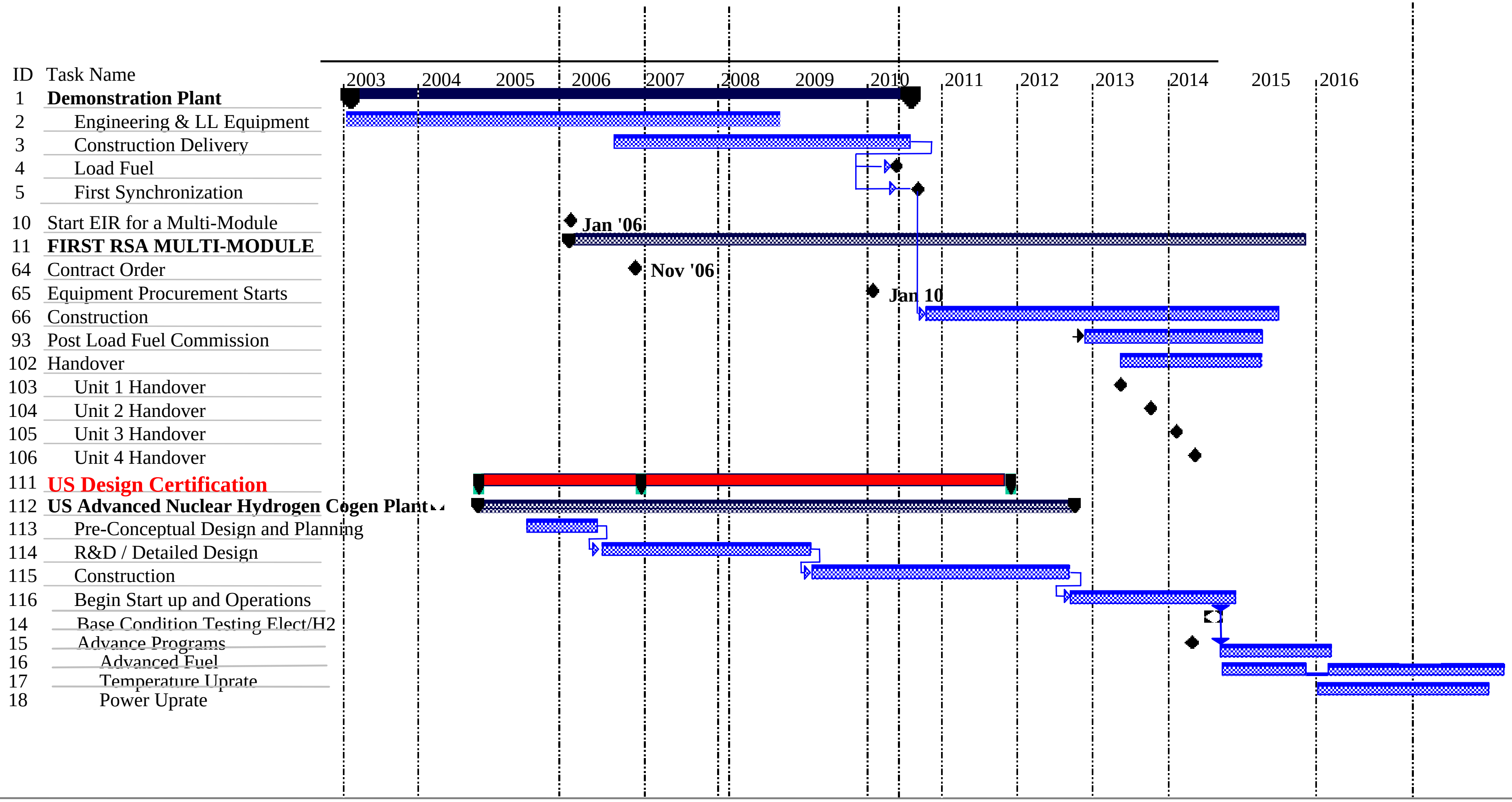


Cut Away Isometric of PBMR Multi Module Concept



TOP WORK

Integrated PBMR Program Plan



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

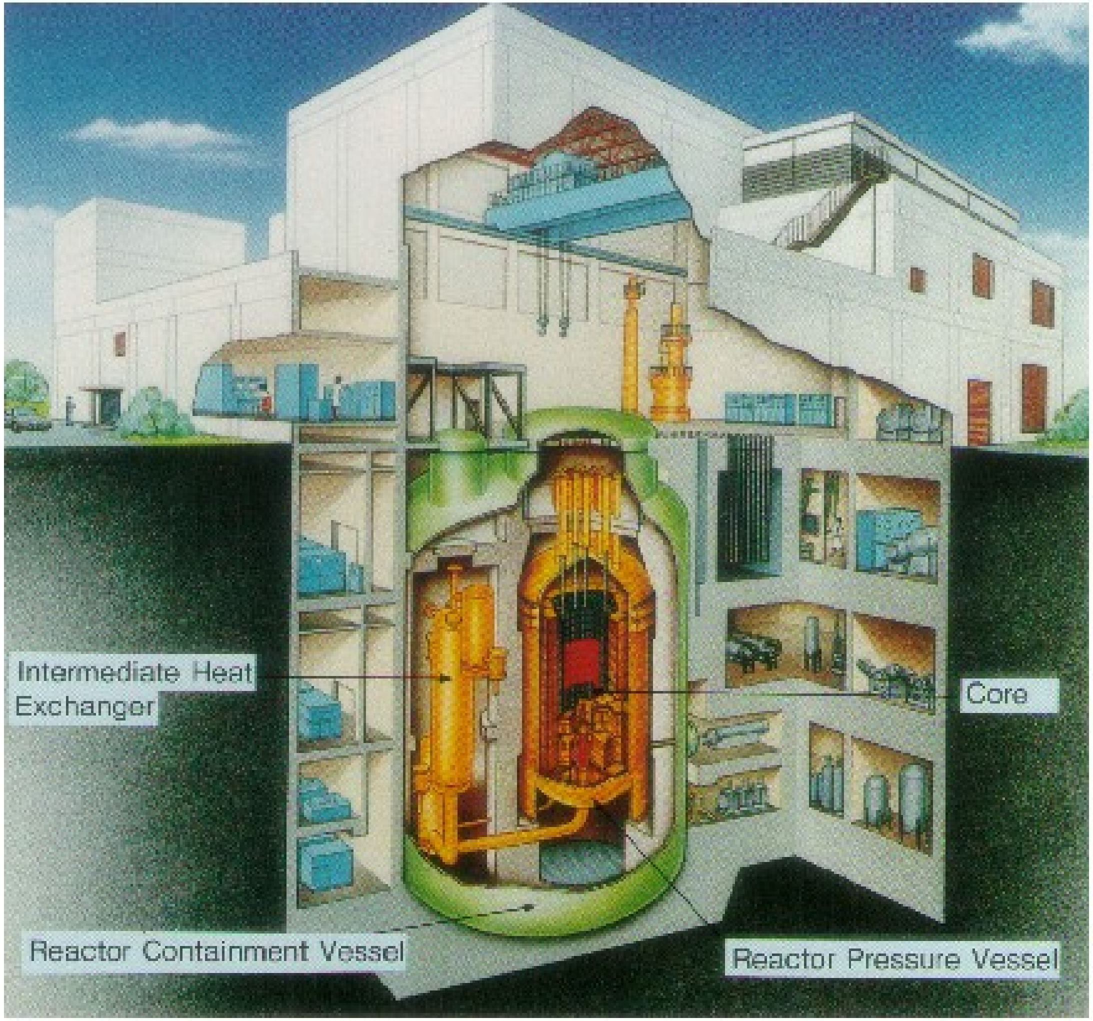
High Temperature Test Reactor

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)

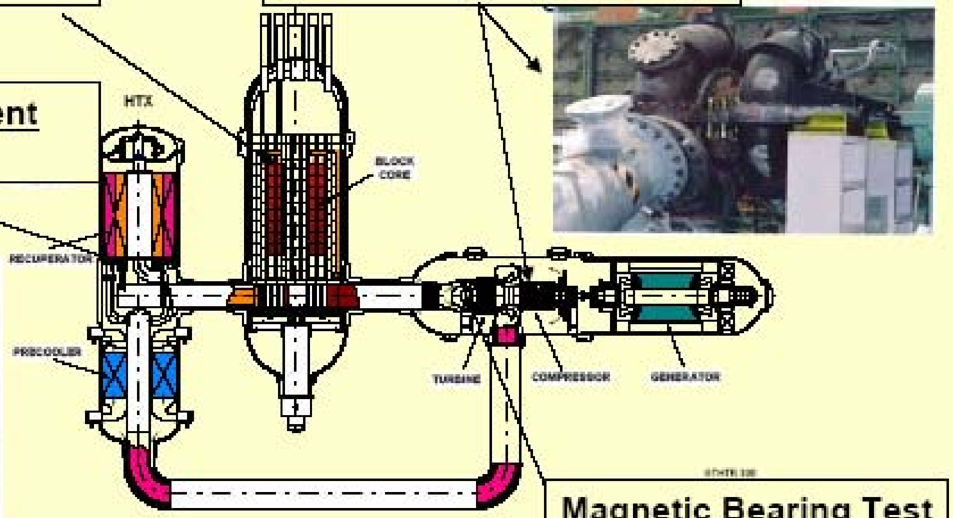


R&D Programs on Gas Turbine Power Conversion System

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
- Under Construction
- Initial Criticality Dec 2000
- Intermediate Heat Exchanger - Steam Cycle

HTR- 10 China
First Criticality Dec.1, 2000

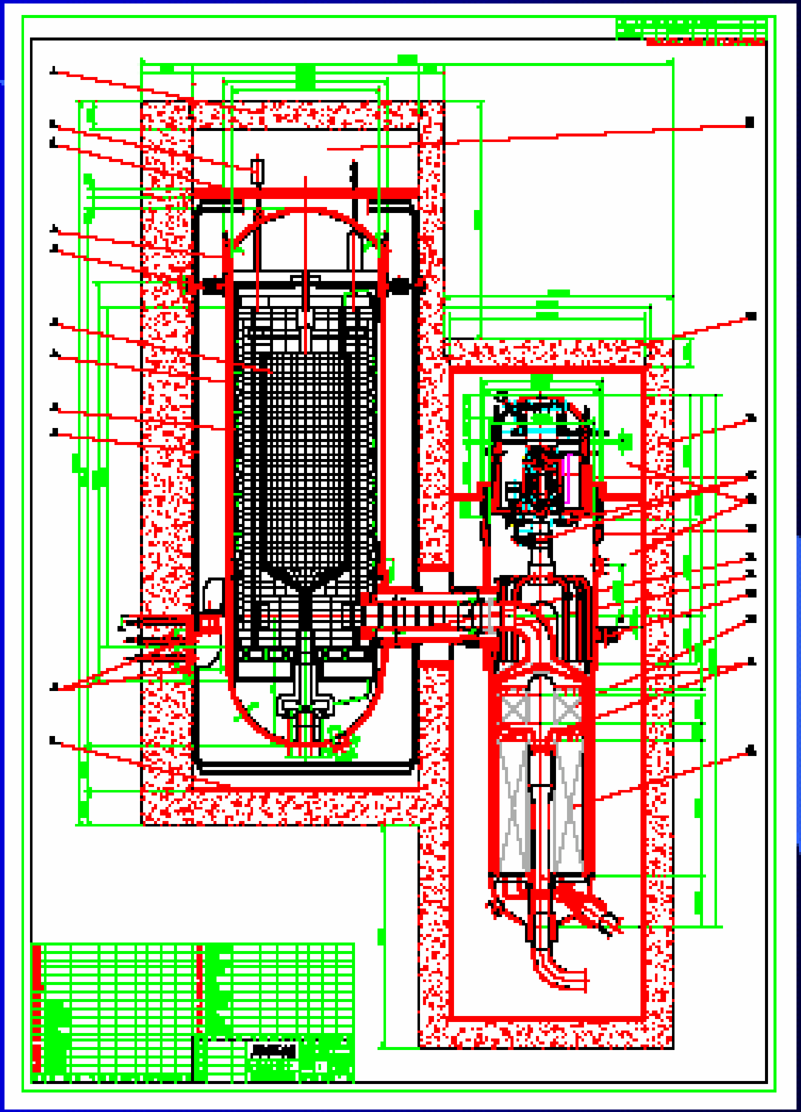
Roles of HTGRs in China

- 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

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

HTR-PM with the steam turbine cycle



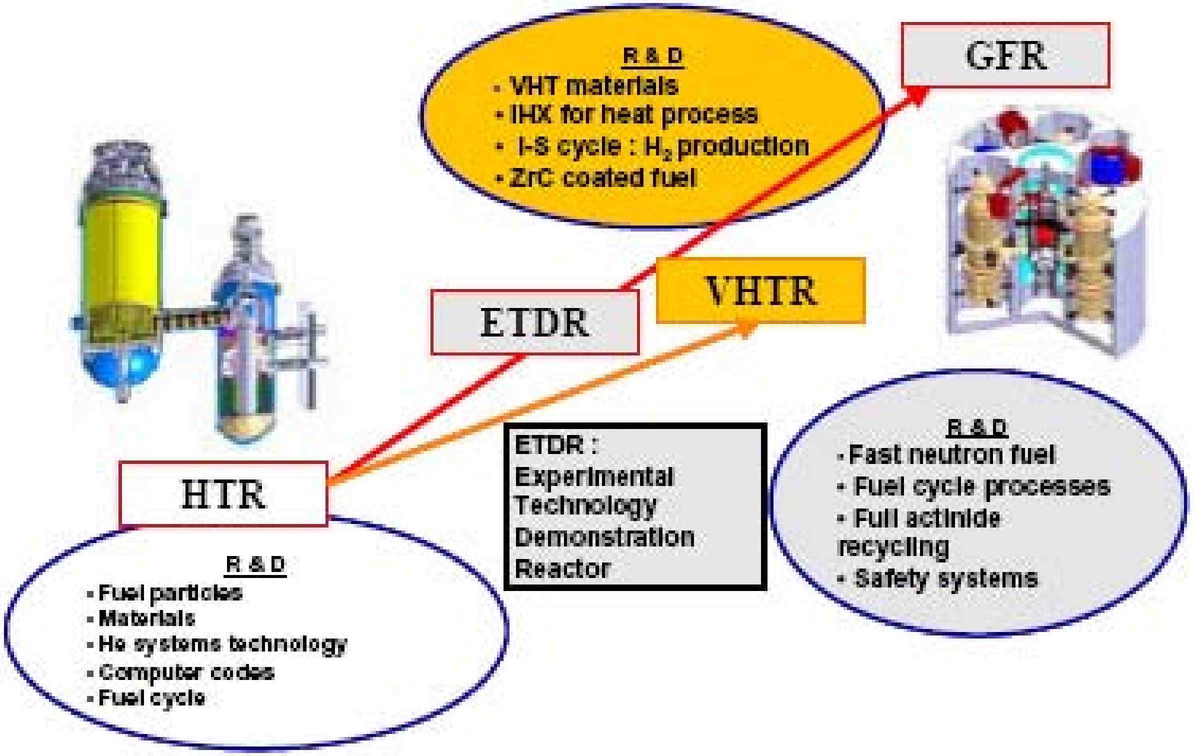
Time schedule

	00	01	02	03	04	05	06	07	08	09	10
HTR-10 criticality	▬										
HTR-10 hot commissioning		▬	▬								
HTR-10 power operation			▬	▬	▬						
HTR-10 safety experiments				▬	▬						
HTR-10 gas turbine cycle test		▬	▬	▬	▬	▬	▬				
HTR-PM feasibility study and design		▬	▬	▬	▬	▬	▬				
HTR-PM Construction							▬	▬	▬	▬	▬
R&D on hydrogen production					▬	▬	▬	▬	▬	▬	▬

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



GFR

R & D
- VHT materials
- IHX for heat process
- I-S cycle : H_2 production
- ZrC coated fuel

VHTR

ETDR

HTR

R & D
- Fuel particles
- Materials
- He systems technology
- Computer codes
- Fuel cycle

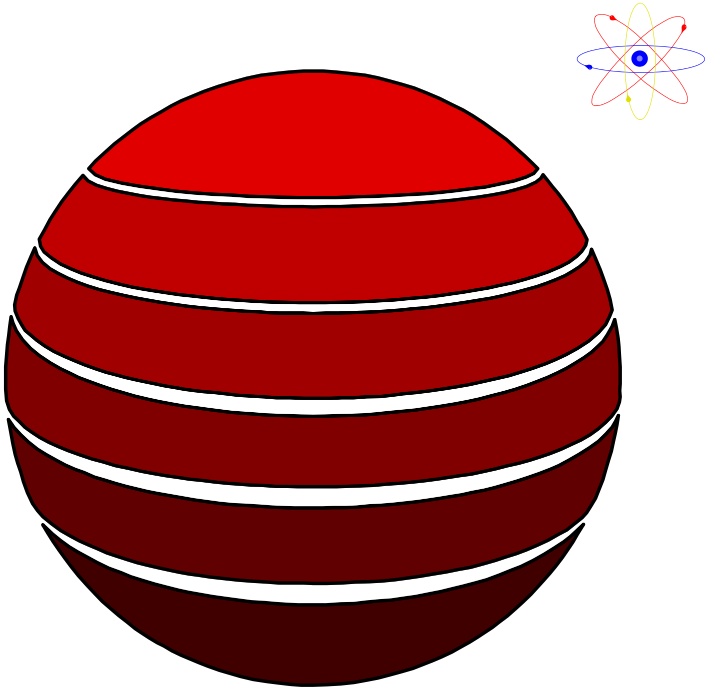
ETDR :
Experimental
Technology
Demonstration
Reactor

R & D
- Fast neutron fuel
- Fuel cycle processes
- Full actinide recycling
- Safety systems

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 Pebble Bed Reactor
MIT/INEEL

- Pebble Bed Design
- 120 MWe
- Intermediate Heat Exchanger
  Helium/Helium
- Similar Core Design to ESKOM
- Balance of Plant Different

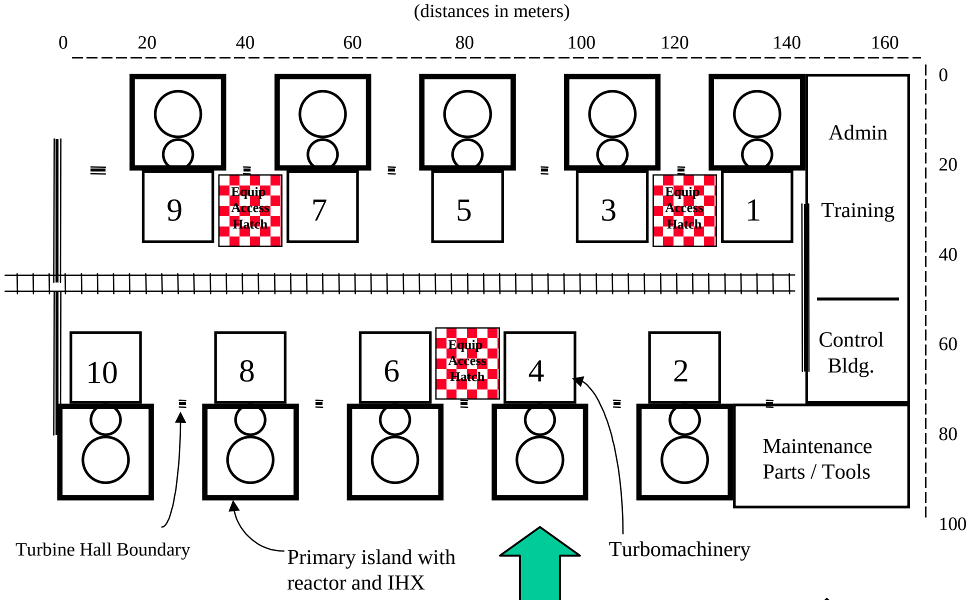
Modular High Temperature Pebble Bed Reactor

- 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

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

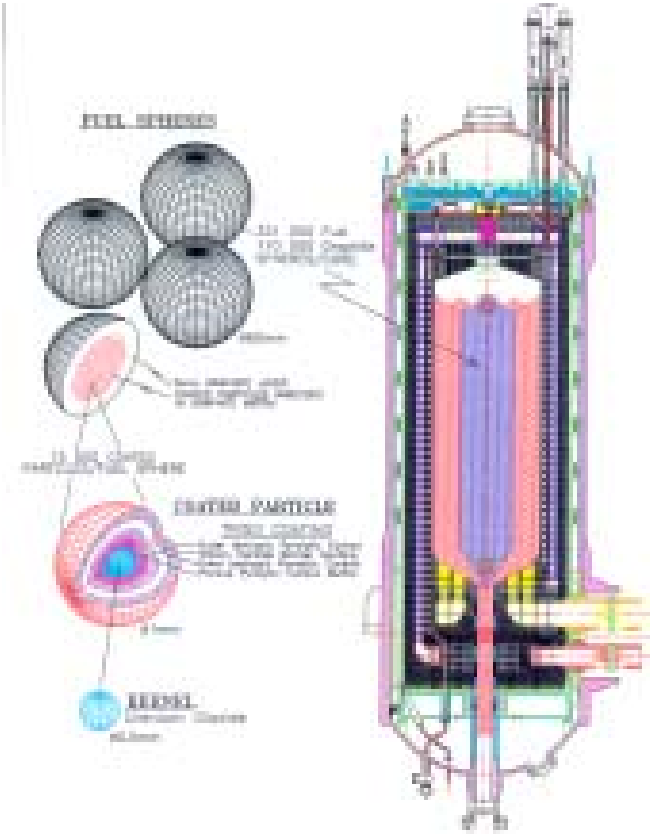
Oil Refinery

Hydrogen Production

Desalinization Plant

Reference Plant

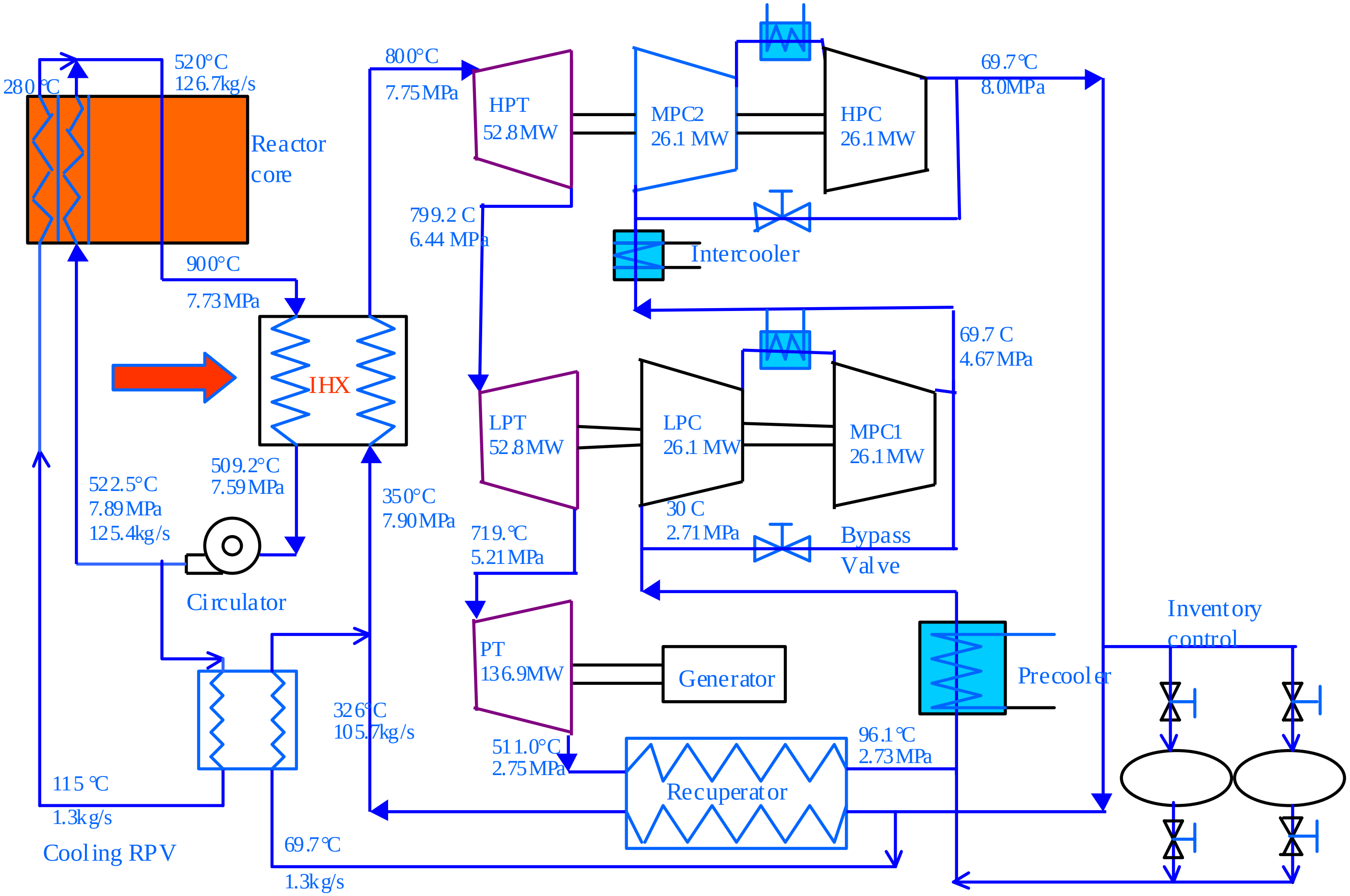
Modular Pebble Bed Reactor



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**

Indirect Cycle with Intermediate Helium to Helium Heat Exchanger

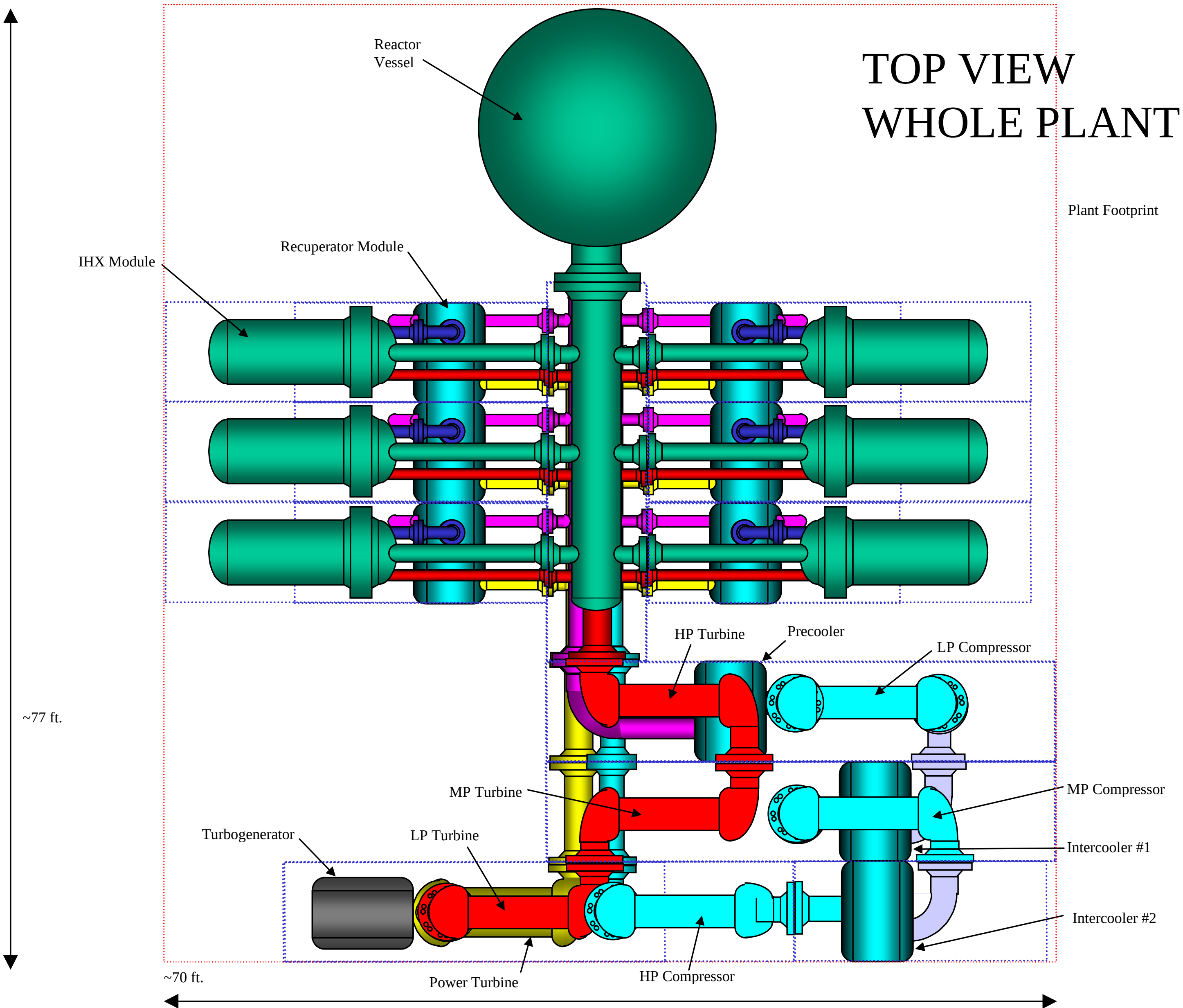
Current Design Schematic



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

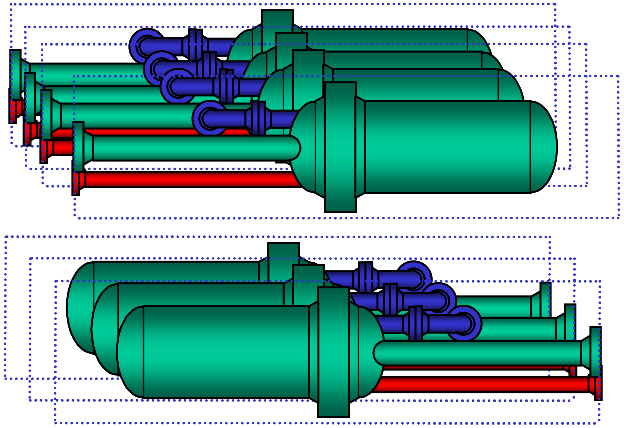
Top Down View of Pebble Bed Reactor Plant



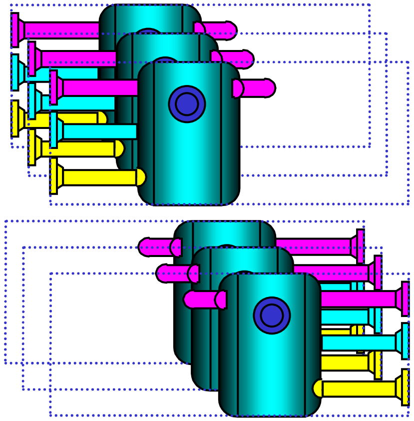
PLANT MODULE SHIPPING BREAKDOWN

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

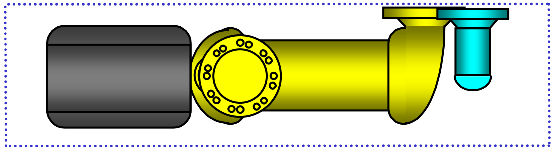
Six 8x30 IHX Modules



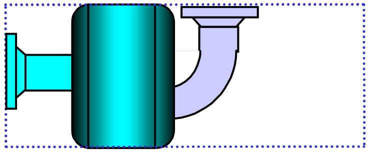
Six 8x20 Recuperator Modules



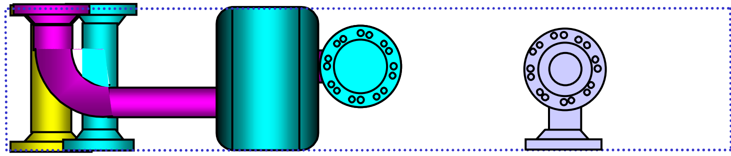
8x30 Power Turbine Module



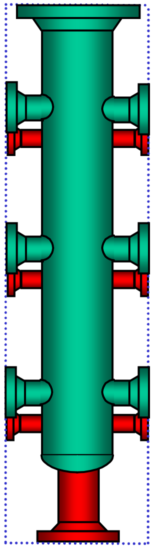
8x20 Intercooler #2 Module



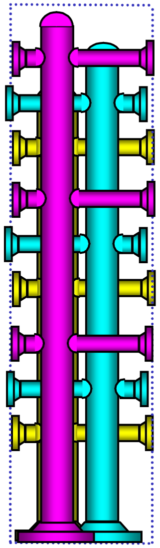
8x40 Piping and Precooler Module



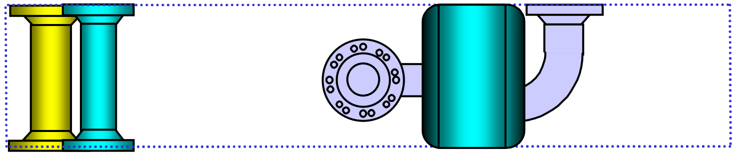
8x30 Upper Manifold Module



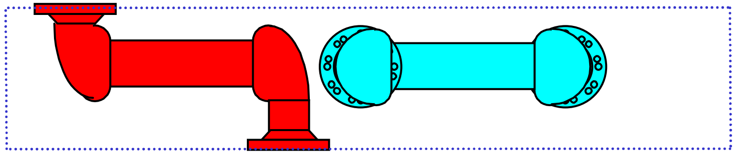
8x30 Lower Manifold Module



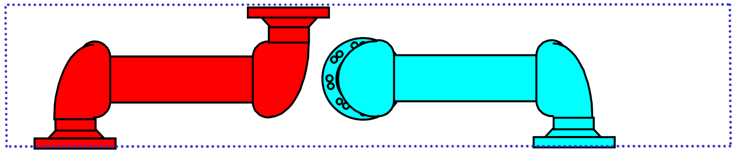
8x40 Piping & Intercooler #1 Module



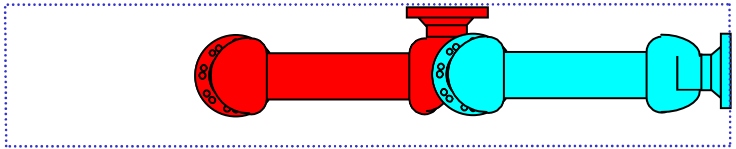
8x40 HP Turbine, LP Compressor Module



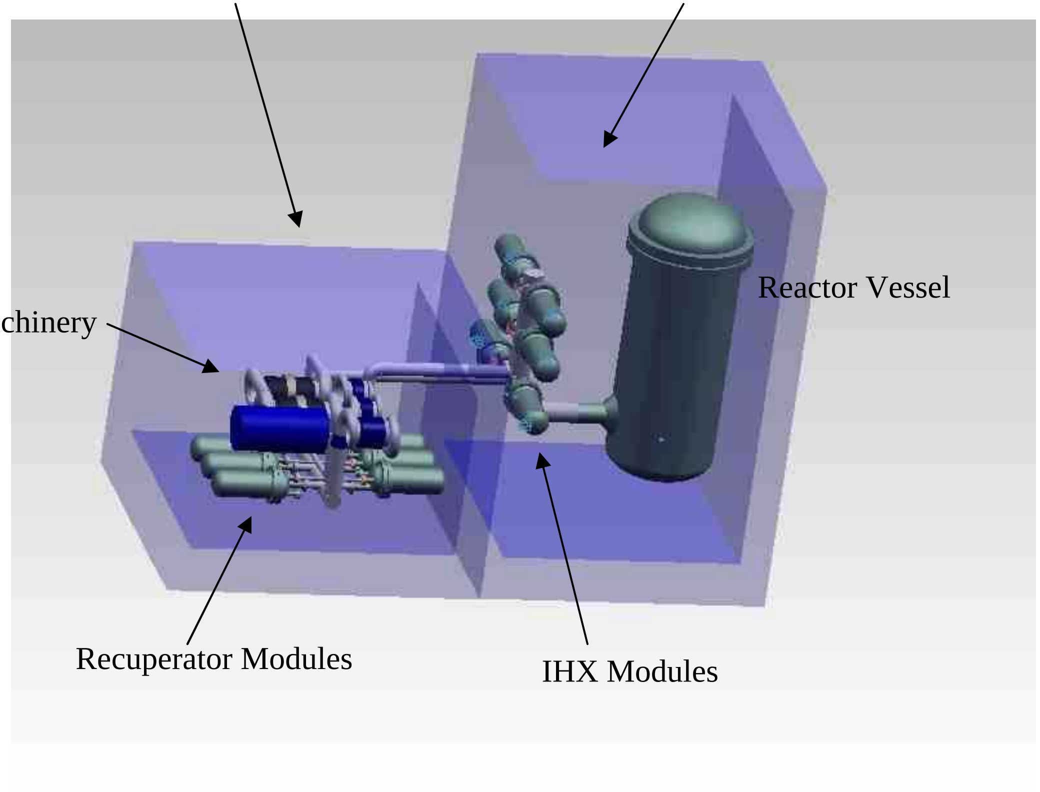
8x40 MP Turbine, MP Compressor Module



8x40 LP Turbine, HP Compressor Module



Example Plant Layout



Secondary (BOP) Side Hall

Primary Side Hall

Reactor Vessel

Turbomachinery

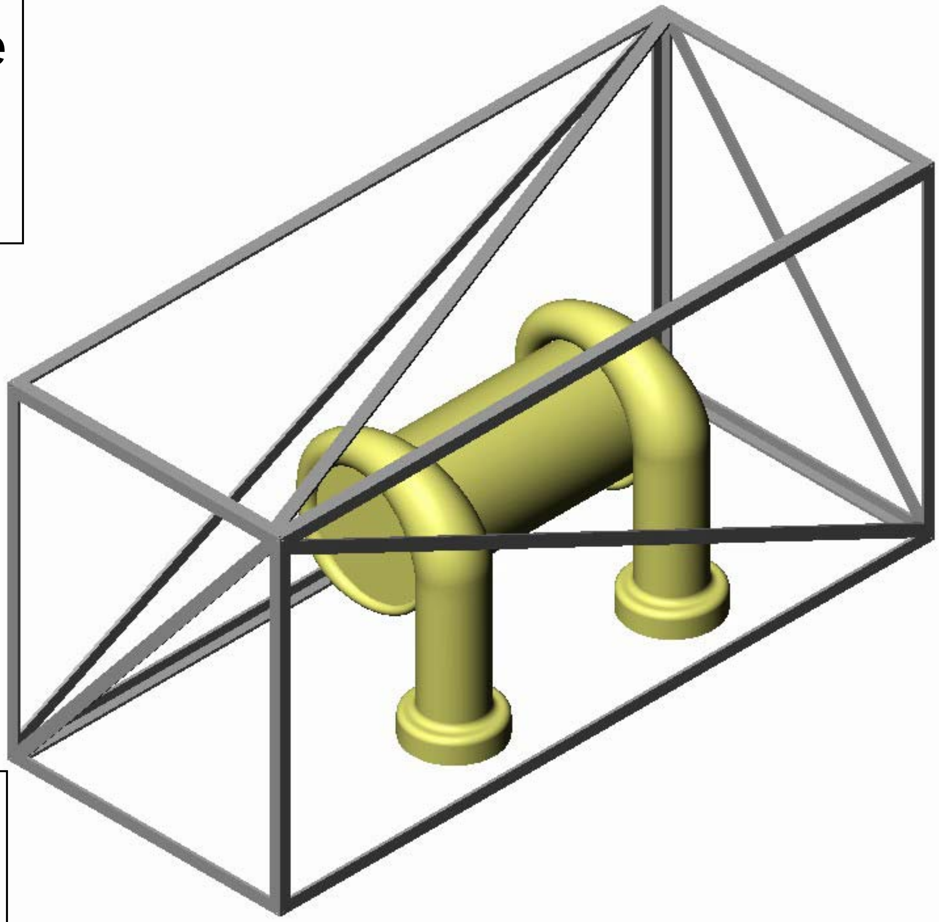
Recuperator Modules

IHX Modules

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.



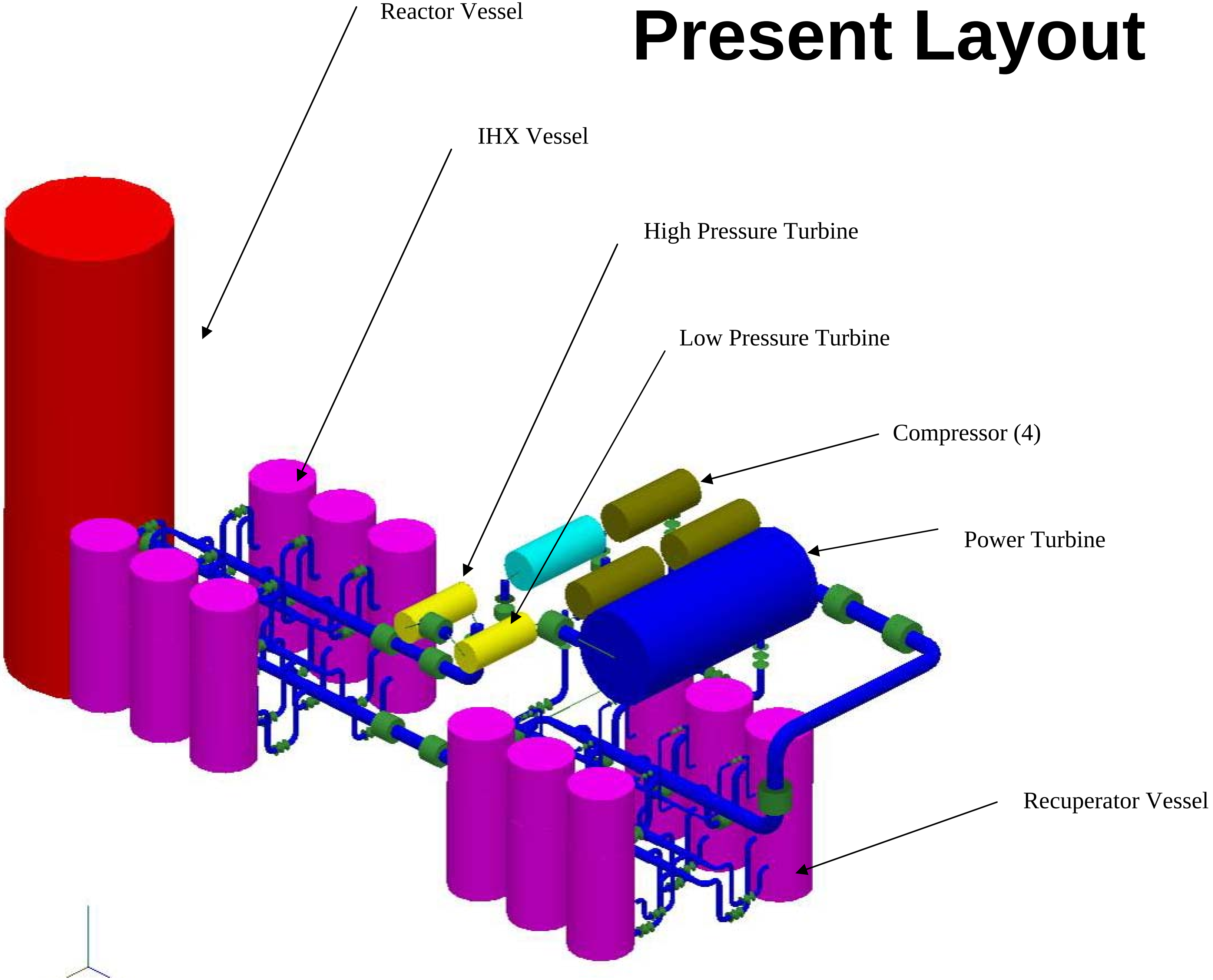
Each space frame will be "plugged" into the adjacent space frame.

“Lego” Style Assembly in the Field

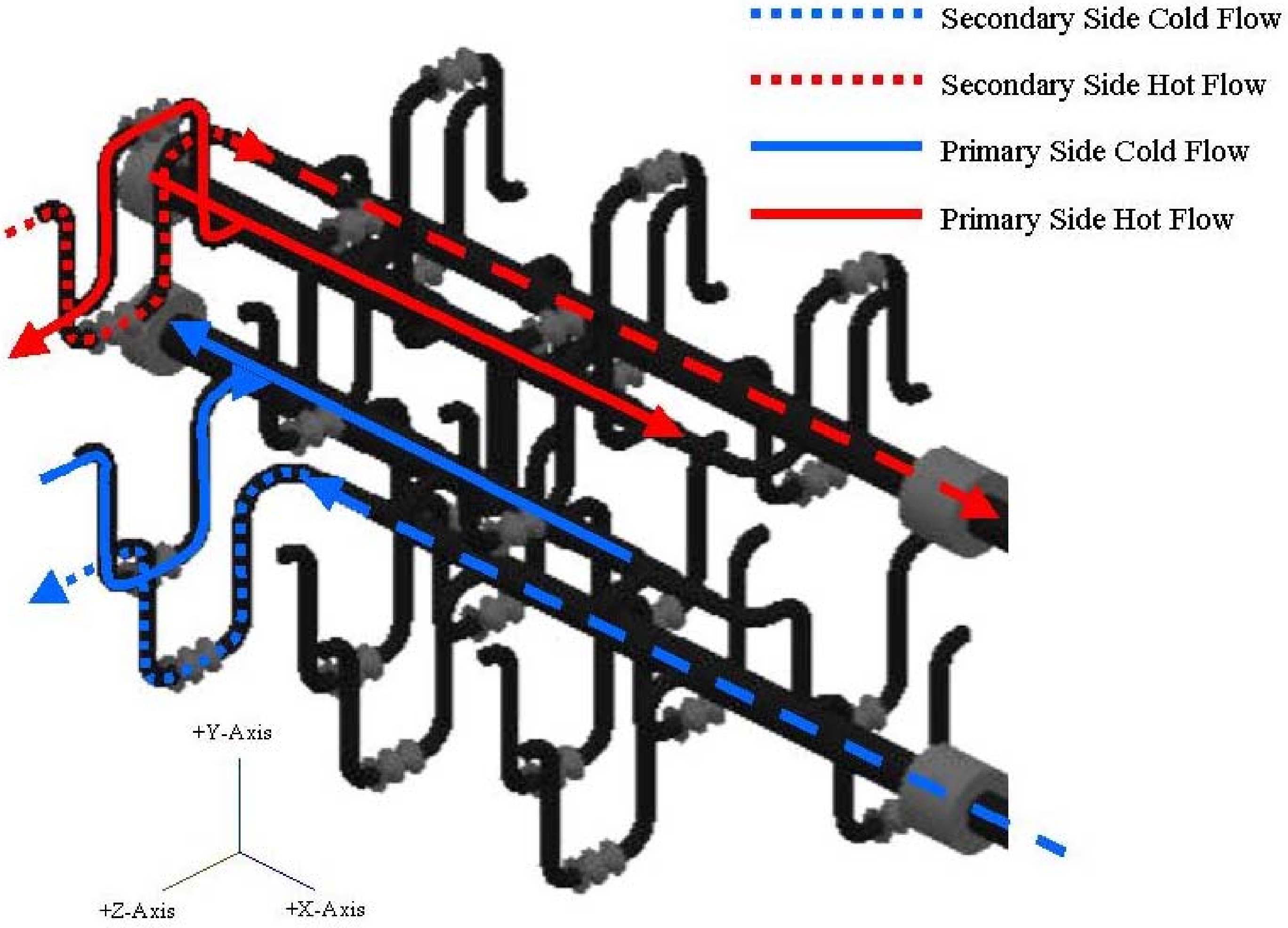
Space-Frame Concept

- 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)

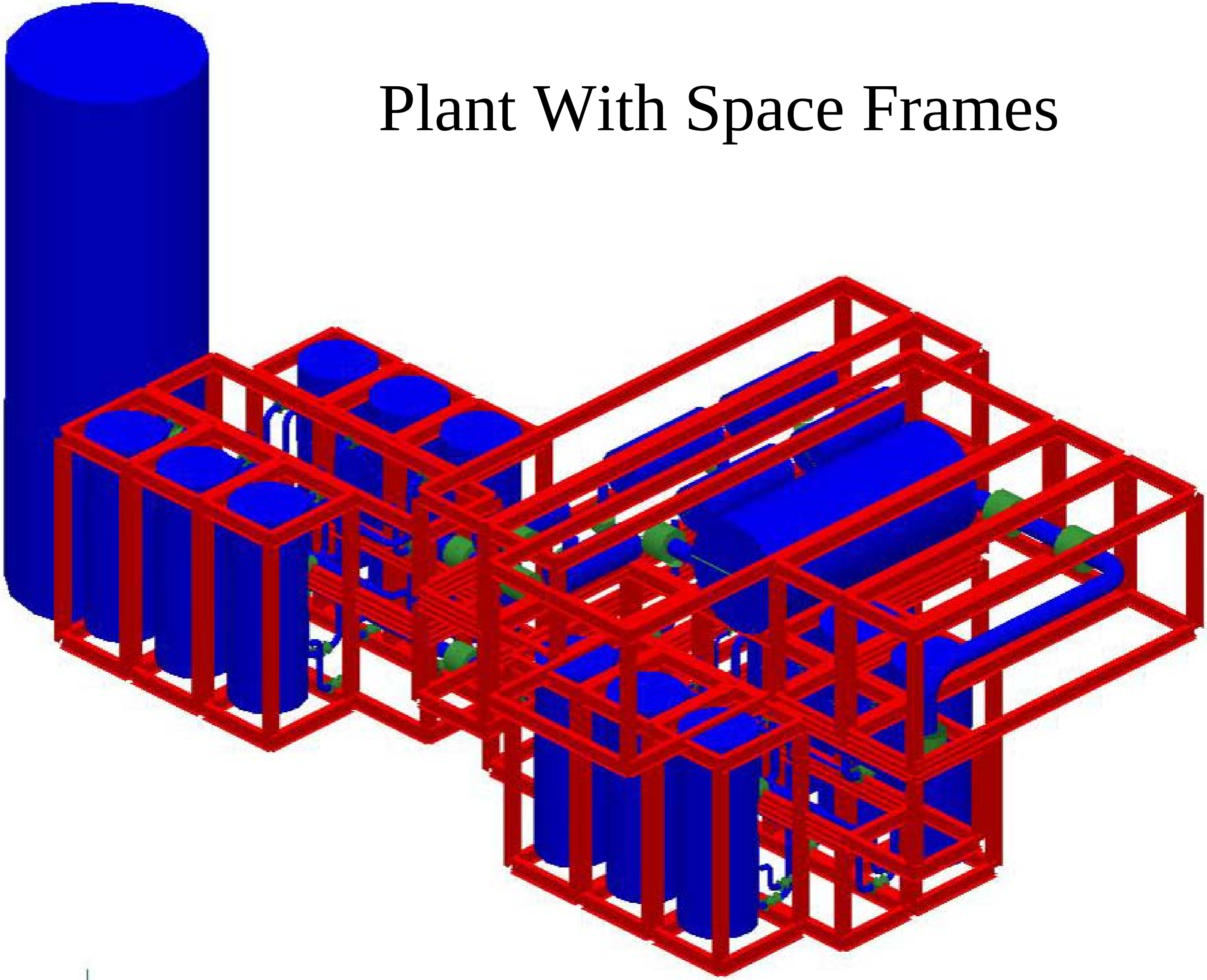
Present Layout



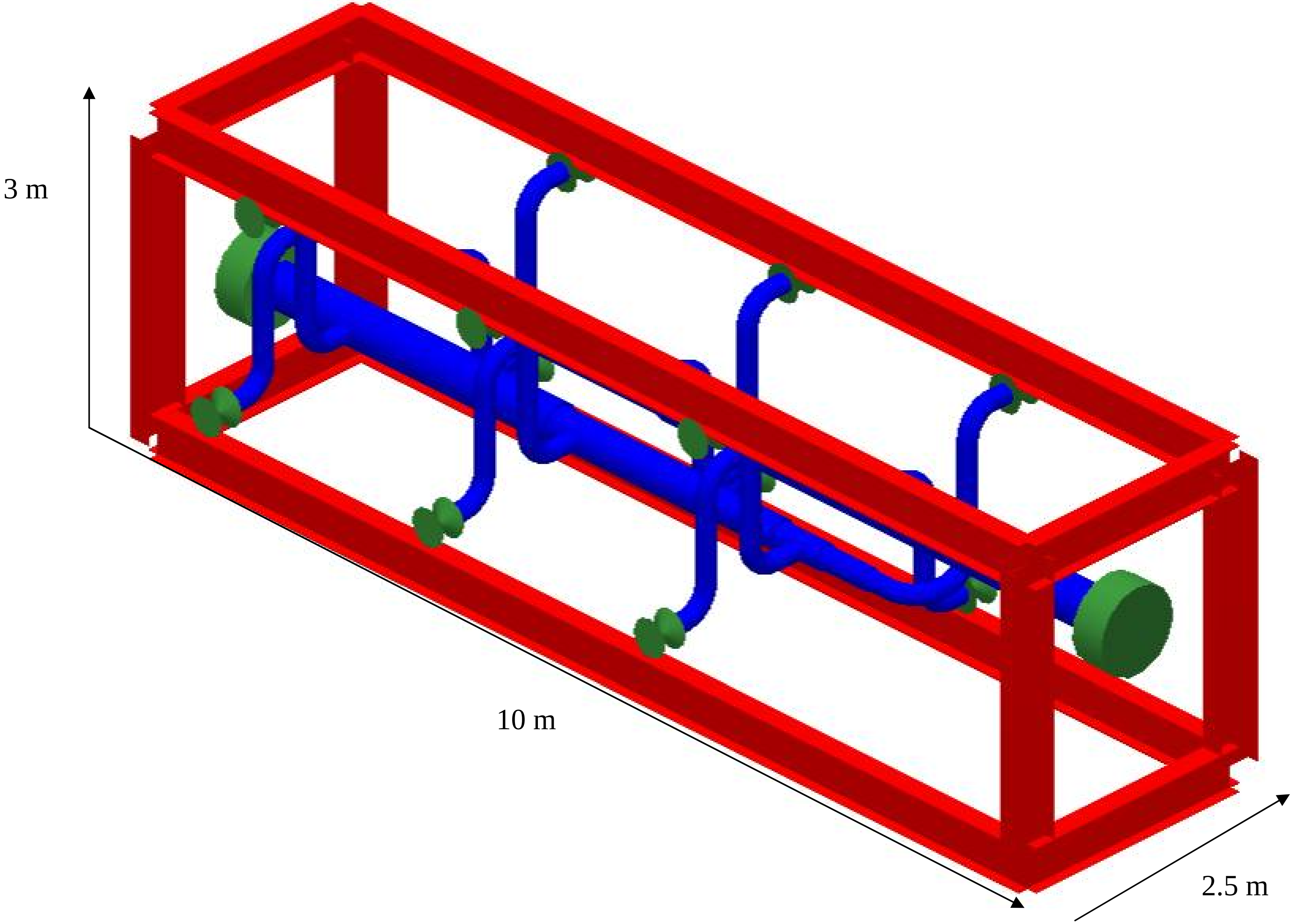
Main IHX Header Flow Paths



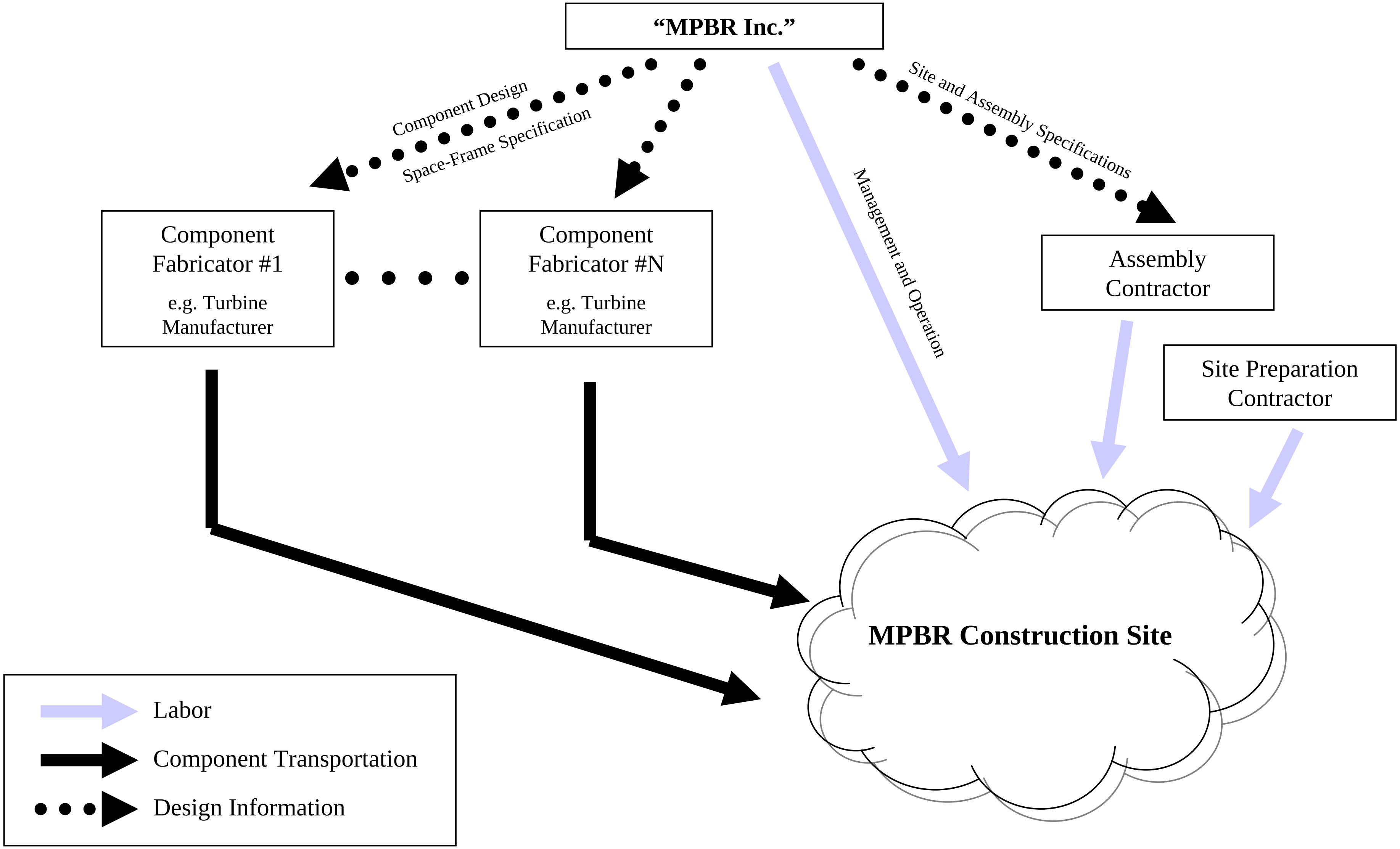
Plant With Space Frames



Upper IHX Manifold in Spaceframe



Distributed Production Concept



“MPBR Inc.”

Component Design

Space-Frame Specification

Site and Assembly Specifications

Management and Operation

Component Fabricator #1

e.g. Turbine Manufacturer

Component Fabricator #N

e.g. Turbine Manufacturer

Assembly Contractor

Site Preparation Contractor

MPBR Construction Site

Labor

Component Transportation

Design Information

Economics
Is Bigger Always Better ?

Andrew C. Kadak

Professor of the Practice

Massachusetts Institute of Technology

Center For Advanced Nuclear Energy Systems

Key Issues

- Capital Cost
- Operations and Maintenance
- Fuel
- Reliability
- Financial Risk Perception
- Profitability - Rate of Return
- Competitiveness Measure - cents/kwhr

Key Cost Drivers

- Safety Systems Required
- Time to Construct
- Staff to Operate
- Refueling Outages
- Maintainability
- NRC Oversight Requirements

Safety Systems

- The more inherently safe the design the fewer safety systems required - lower cost
- The fewer safety systems required the less the regulator needs to regulate - lower cost
- The simpler the plant - the lower the cost
- The more safety margin in the plant - the lower the cost

Time to Construct

- Large Plants take longer than small plants
- Modular plants take less time than site construction plants
- Small modular plants take less time than traditional large unit plants to get generation on line.

Modular Plants ?

- Are small enough to be built in a factory and shipped to the site for assembly.
- Modular plants are not big plants divided into four still big pieces.
- Small Modular plants can be designed to be inherently or naturally safe without the need for active or passively acting safety systems.

Factory Manufacture

- Modularity allows for assembling key components or systems in the factory with “plug and play” type assembly at the site.
- Navy submarines are an example.
- Minimize site fabrication work
- Focus on installation versus construction.
- Smaller units allow for larger production volume

Economics of Scale vs. Economies of Production

- Traditional view - needs to be bigger to improve economics
- New view - economies of production may be cheaper since learning curves can be applied to many more units faster.
- Answer not yet clear
- Function of Design and ability to modularize

Operations

- More complex the plant, the higher the operating staff.
- The more corrosive the coolant, the more maintenance and operating staff.
- The more automatic the operations, the lower the operating staff.
- Plant design is important

Refueling Outages

- Cost Money
- Create Problems
- Reduce Income
- Require higher fuel investment to keep plant operating for operating interval
- On-line refueling systems avoid these problems

Reliability

- More components - lower reliability
- More compact the plant, the harder to replace parts.
- Access to equipment is critical for high reliability plants
- Redundancy or quick change out of spare components quicker than repair of components

Financial Risk
Chose One

Option A

- Cost $ 2.5 Billion
- Time to Build 5 Years
- Size 1100 Mwe
- Regulatory Approval to Start up depends on events in 5 years.
- Interest During Construction High

Option B

- Cost $ 200 million
- Time to Build 2.5 years
- Size 110 Mwe
- Regulatory Risk - 2 years
- Build units to meet demand
- Income during construction of 1100 Mwe

Internal Rate of Return

- New Paradigm for Deregulated Companies
- Rate Protection no longer exists
- Need to judge nuclear investments as a business investment
- Time value of money important
- Merchant Plant Model most appropriate
- Large plants are difficult to justify in such a model

Competitiveness

- Capital Cost/Kw important but that isn't how electricity is sold.
- Cents/kwhr at the bus bar is the right measure
- Includes capital, operations and maintenance and fuel
- Addresses issues of reliability, maintainability, staff size, efficiency, etc.

Conclusions

- Bigger May Not be Better for economics or safety.
- Economies of Production are powerful economies as Henry Ford knew.
- Market may like smaller modules
- Market will decide which is the correct course - Big or Small.

Anything Nuclear Competitive With Coal or Natural Gas?

- ESKOM (South Africa) Thinks So
- Pebble Bed Reactor Busbar Cost Estimate

  3.5 cents/kwhr.
- Capital Cost < $ 1500/kw
- Operating Staff for 1100 Mwe plant -85
- Plans to go Commercial – 2011/12
- MIT/INEEL Working on Pebble Bed Reactor Design

Plant Target Specifications

Rated Power per Module (Commercial)	165 MW(e)
Net Efficiency	>43%
Four/Eight-pack Plant	660/1320 MW(e)
Continuous Power Range	20-100%
Module Construction Schedule	24 months (1st)
Planned Outages	30 days per 6 years
Seismic	0.4g
Aircraft (Calculations to survive)	747/777
Overnight Construction Cost (2004 $, 4pack)	<$1500/kWe
Fuel Costs & O&M Costs	9 mills/kWh
Emergency Planning Zone	<400 m
Availability	>95%

Commercialization Approach (PBMR)

- **Strict adherence to life cycle standardization**
- **Series build program to capture learning experience**
- **Total plant design responsibility because of closely coupled Brayton cycle**
- **Modularization and shop fabrication key elements to quality, short delivery time and competitive costs**
- **Strategic international suppliers as integral part of delivery team**

Mitsubishi Heavy Industries (Japan)	**Turbo Machinery**
Nukem (Germany)	**Fuel Technology**
SGL (Germany)	**Graphite**
Heatric (UK)	**Recuperator**
IST Nuclear (South Africa)	**Nuclear Auxiliary Systems**
Westinghouse (USA)	**Instrumentation**
ENSA (Spain)	**Pressure Boundary**
Sargent & Lundy (USA)	**Architect/Engineer Services**

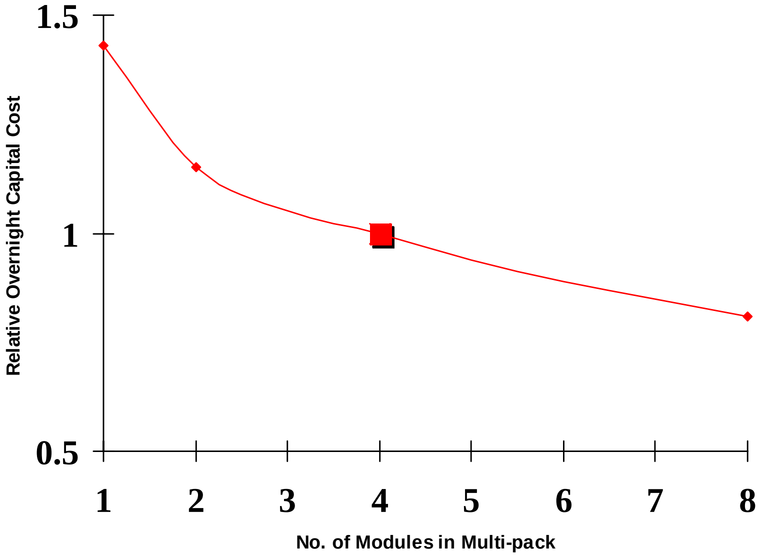
“All-in” Generation Costs <3.5 Cents Initially

- Capital Overnight Costs
- Operating and Maintenance Costs
- Fuel Costs
- Owner’s Other Costs
  - Insurance
  - Licensing Fees
  - Spent Fuel Waste Disposal Fees
  - Decommissioning Funding

Comparison of PBMR Capital Cost Economics (Nth 4-pack)

Base and Advanced Designs	400 MWth @ 900°C	400 MWth @ 1200°C	500 MWth @ 1200°C
Total Net Output - MWe	688	880	1100
Net Thermal Efficiency - %	43	55	55
U.S. Price - $/kWe	<1500	<1200	<1000

- Smaller configurations lose some
  - “economies of repetition”
  - advantages of full SSC sharing
- Modularization in factory offset this effect to some degree for SSCs that are common to all configurations
- 8 pack configurations provide even greater economies of scale due to additional sharing of non-safety structures and systems



System and Commodities Comparison

- **System Comparison**

	LWR	PBMR
Total Plant Systems/Structures	**142**	**68**
Safety Systems/Structures	**47**	**9**

- **Commodities Comparison**

	LWR	PBMR
Rebar (tons/MWe)	**38**	**16**
Concrete (cubic yards/MWe)	**324**	**100**
Structural Steel (tons/MWe)	**13**	**2**

Potential for Cost Savings from Full Shop Fabrication is High

- **High percentage of plant cost in relatively few components with high learning curves**
- **Low civil works cost**
- **High erection and project services cost**

Scope of Supply Item	**Percentage of Total (%)**	
	LWR	**PBMR**
Nuclear Island Equipment	**34**	**40**
Civil Works	**25**	**9**
Conventional Island Equipment	**15**	**13**
Erection	**11**	**20**
Project Services, including Commissioning	**9**	**13**
BOP Equipment	**6**	**4**

Capture Full Benefit by Module Fabrication, Assembly, and Testing

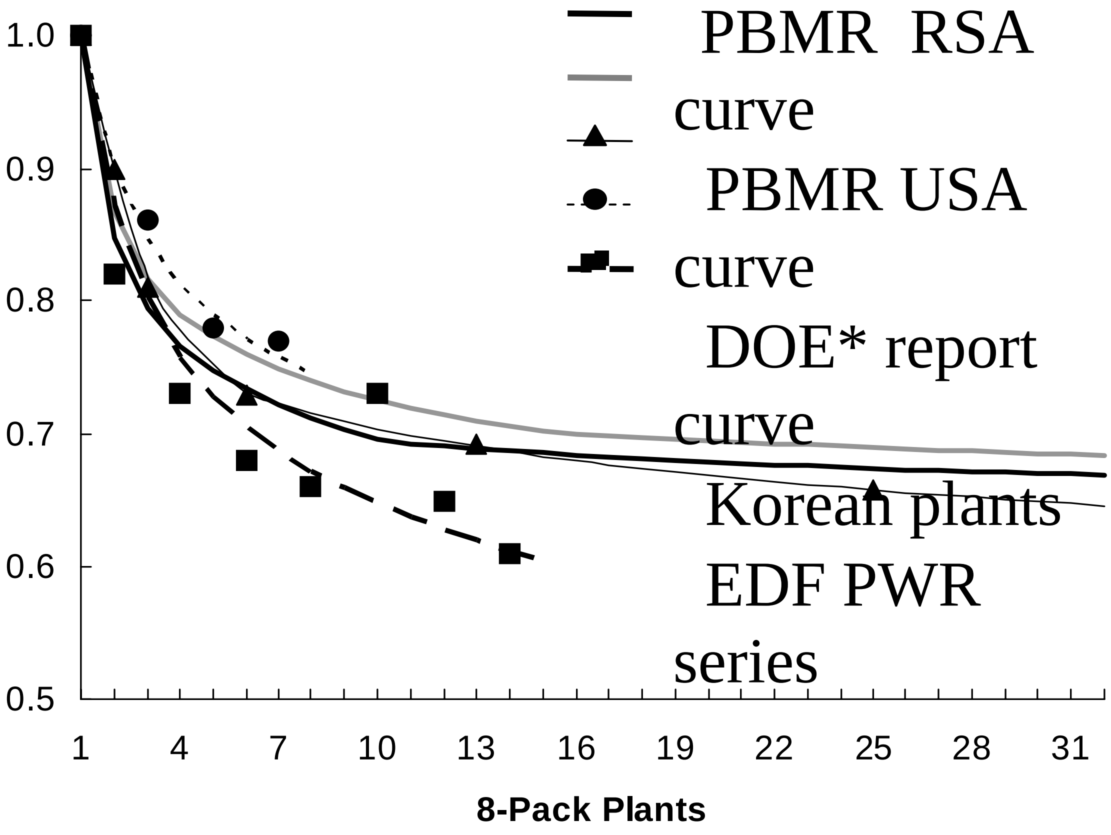
Learning Curves for Plant Cost Elements

- **Different curves used for each element of cost structure**
- **Rate depends on how often repeated during plant construction**
- **Limited by "flattening point"**
- **PBMR unique components will have higher learning than more standard components**
- **Field activities have low learning**
- **Learning depends on degree of complexity, automation, and mechanization in fabrication process**

Component	Percentage Reduction (%)	Flattening Point (Plant No.)
Turbo Machinery	54	7
Reactor Internals	35	3
Reactor Pressure Vessel	26	3
Fuel Handling and Storage System (FHSS)	33	9
Reactivity Control and Shutdown System (RCSS)	26	3

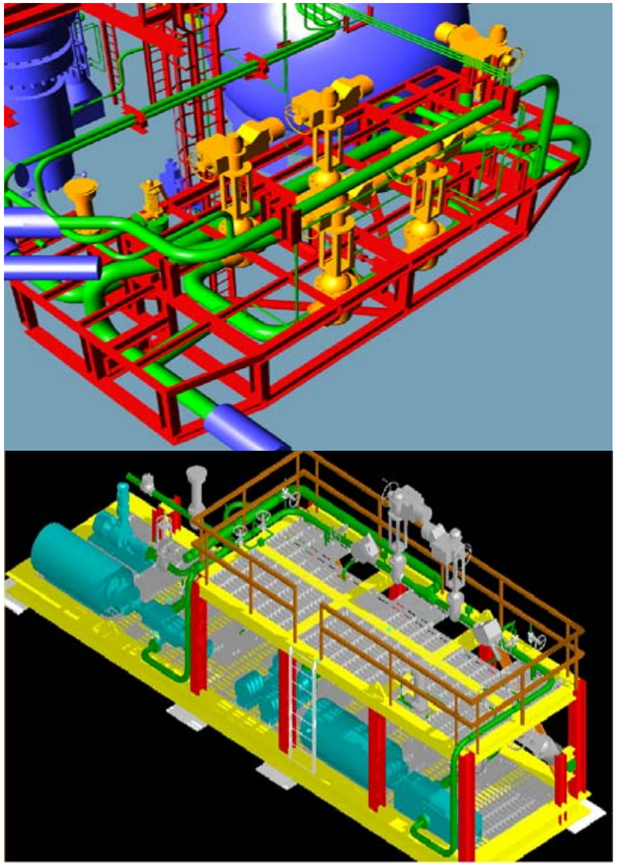
Commercial PBMR Composite Learning Comparison (Without Full Potential Realized)

- **Approximately 30% cost reduction**
- **Generally conservative compared to what has been achieved**
- **Shows difference in regional implementation as a result of labor productivity and wage rates**



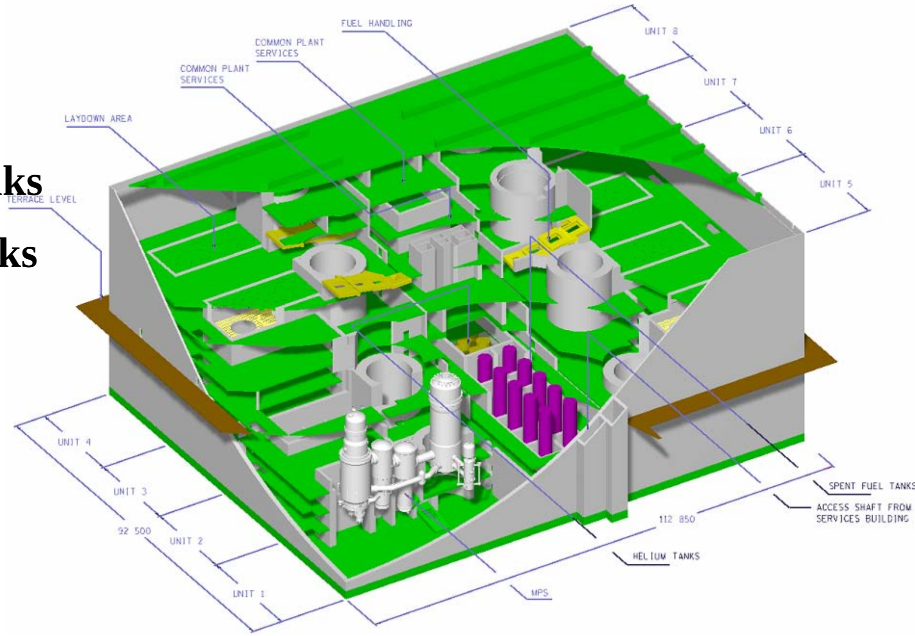
Some Specifics on Full Factory Production

- **Skid-mounted equipment and piping modules developed as part of detailed design**
- **Electric and I&C installed on modules with cabling**
- **All inspections and commissioning testing possible completed in factory**
- **Interfaces with other systems, structures, and components (SSCs) engineered into design**



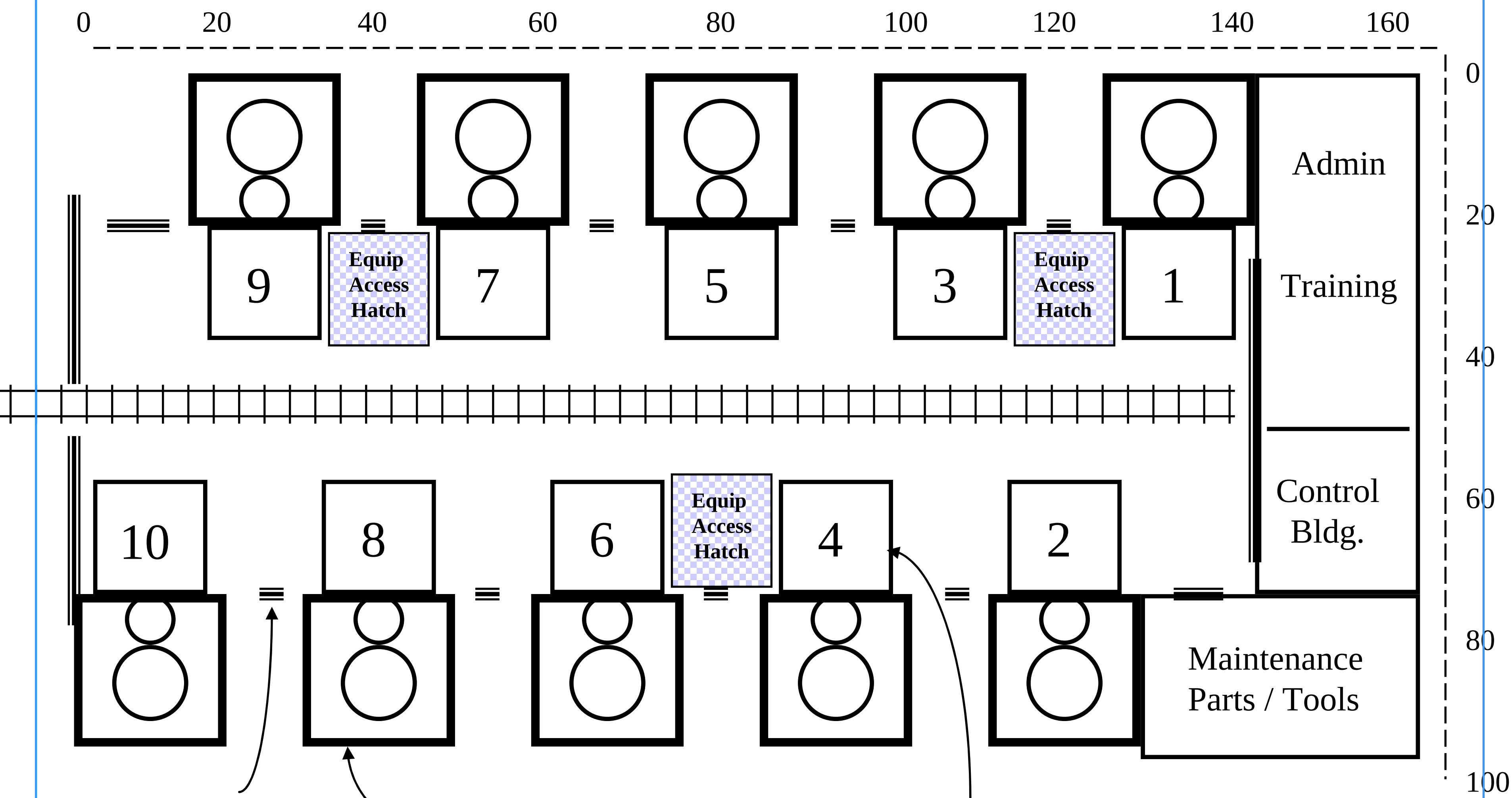
Shared Systems – Additional Opportunities for Multi-Module Plants

- **Helium Inventory Storage: 1 x 200% capacity**
- **Helium Purification: 2 systems**
- **Helium Make-up: 2 stations**
- **Spent Fuel Storage: 10 years capacity**
- **Used Fuel Storage: 2 x 100% capacity tanks**
- **Graphite Storage: 2 x 100% capacity tanks**
- **HVAC blowers and chillers**
- **One Remote Shutdown Room**
- **One set of Special Tools**
- **One Primary Loop Initial Clean-up System**
- **Selected Equipment Handling**
- **Fire Protection Reservoirs and Pumps**
- **Generator Lube Oil System & Transformer (shared per 2 modules)**



Ten-Unit MPBR Plant Layout (Top View)

(distances in meters)



Turbine Hall Boundary

Primary island with reactor and IHX

Turbomachinery

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

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$)

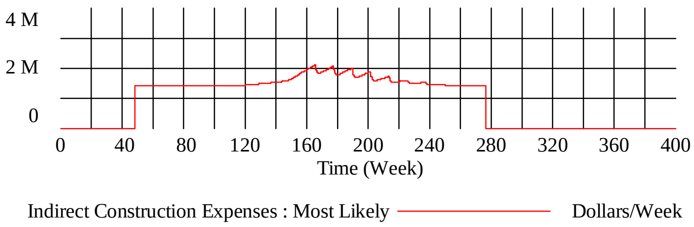
Reactor Thermal Power (MWt)	10 x 250
Net Efficiency (%)	45.3%
Net Electrical Rating (MWe)	1100
Capacity Factor (%)	90

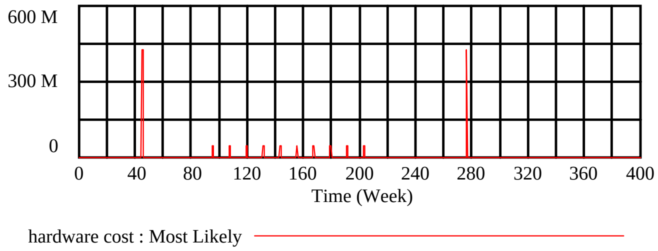
Total Overnight Cost (M$)	2,046
Levelized Capital Cost ($/kWe)	1,860
Total Capital Cost (M$)	2,296
Fixed Charge Rate (%)	9.47
30 year level cost (M$/YR):	
Levelized Capital Cost	217
Annual O&M Cost	31.5
Level Fuel Cycle Cost	32.7
Level Decommissioning Cost	5.4
Revenue Requirement	286.6

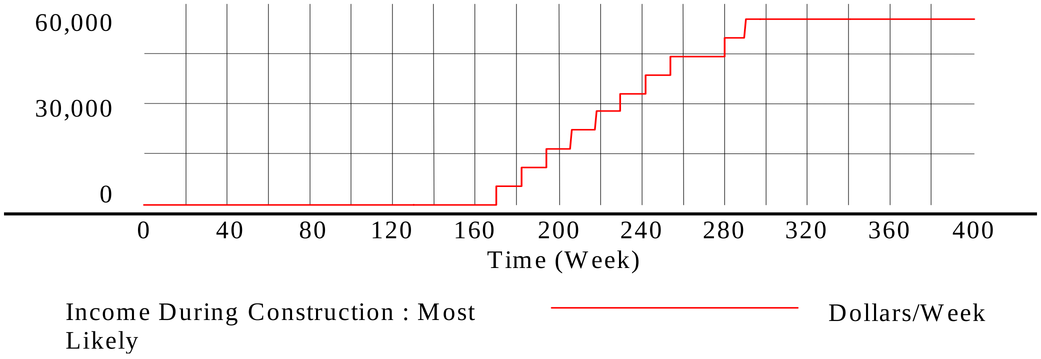
Busbar Cost (mill/kWh):	
Capital	25.0
O&M	3.6
FUEL	3.8
DECOMM	0.6
TOTAL	33.0 mills/kwhr

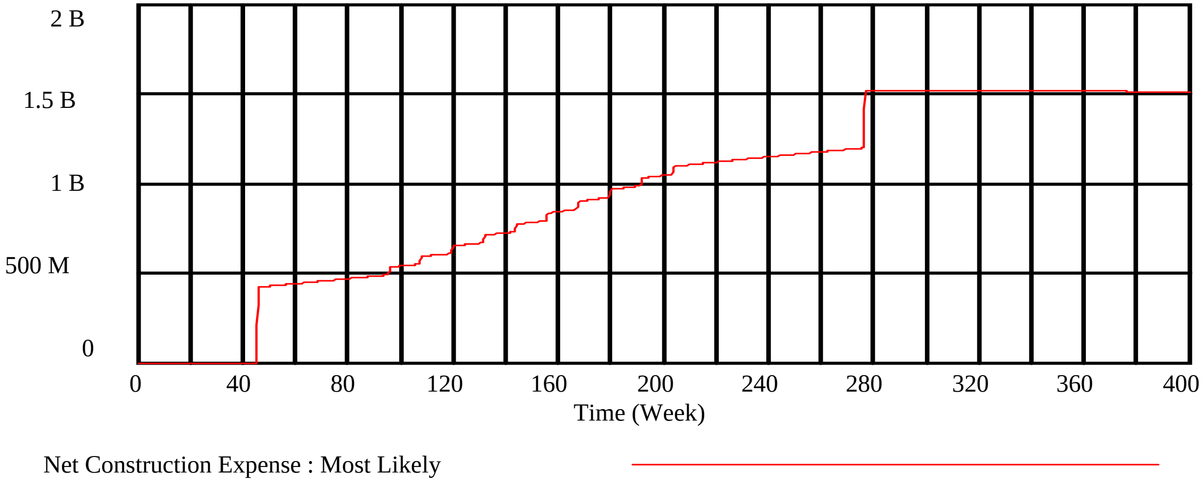
O&M Cost

- 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


Graph for Indirect Construction Expenses


Graph for hardware cost


Graph for Income During Construction


Graph for Net Construction Expense

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

Next Generation Nuclear Plant NGNP

- High Temperature Gas Reactor (either pebble or block)
- Electricity and Hydrogen Production Mission
- Built at the Idaho National Laboratory
- No later than 2020 (hopefully 2013)
- Research and Demonstration Project
- Competition to begin shortly to decide which to build

Hydrogen Generation Options

- **Sulfur Iodine S/I Process -** three T/C reactions

  $H_2SO_4 \rightarrow SO_2 + H_2O + .5O_2$ (>800°C heat required)
  $I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$ (200°C heat generated)
  $2HI \rightarrow H_2 + I_2$ (>400°C heat required)

- **Westinghouse Sulfur Process -** single T/C reaction

  $H_2SO_4 \rightarrow SO_2 + H_2O + .5O_2$ (>800°C heat required)
  $2H_2O + SO_2 \rightarrow H_2 + H_2SO_4$ (electrolytic at 100°C using HTGR electricity)

Sequence of Pebble Bed Demonstration

- China HTR 10 - December 2000
- ESKOM PBMR - Start Construction 2008
- China HTR-PM – Start Construction 2007
- US – NGNP operational date 2017

Pebble Bed Consortium Proposed

- PBMR, Pty
- Westinghouse (lead)
- Sargent and Lundy
- Shaw Group (old Stone and Webster)
- Air Products
- MIT
- Utility Advisory Group

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

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.

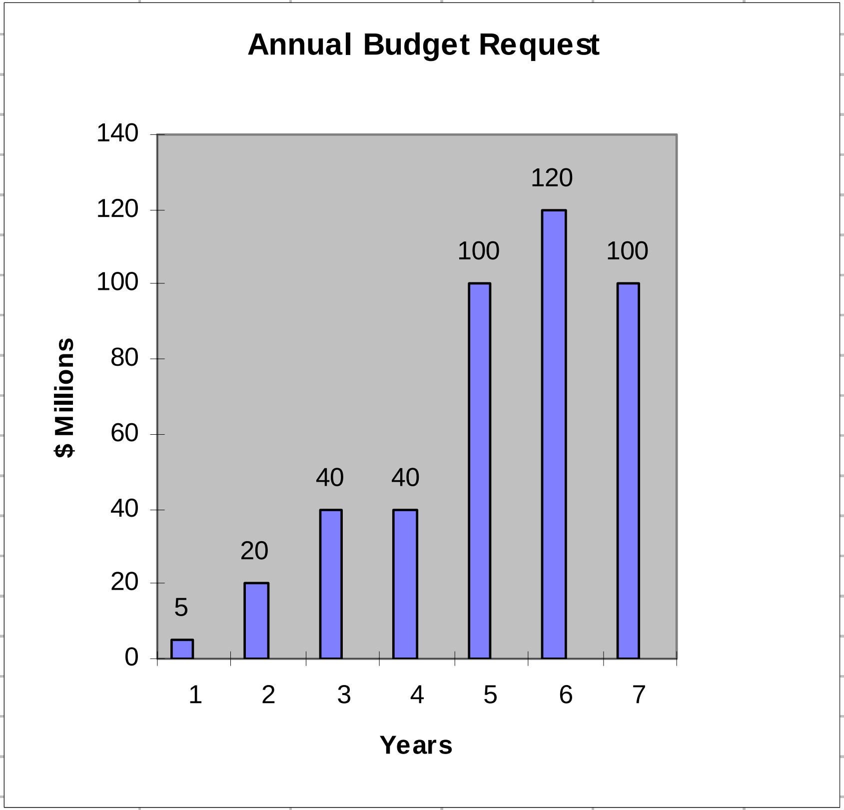
Cost Estimate for First MPBR Plant

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

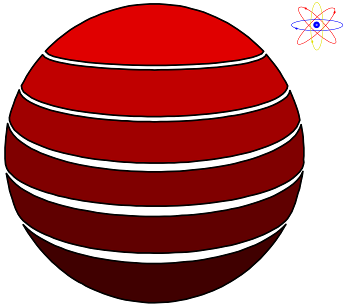
- Materials (metals and graphite)
- Code Compliance
- Helium Turbine and Compressor Designs
- Demonstration of Fuel Performance
- US Infrastructure Knowledge Base
- Regulatory System

Technology Bottlenecks

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

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



Modular Pebble Bed Reactor
High Temperature Gas Reactor

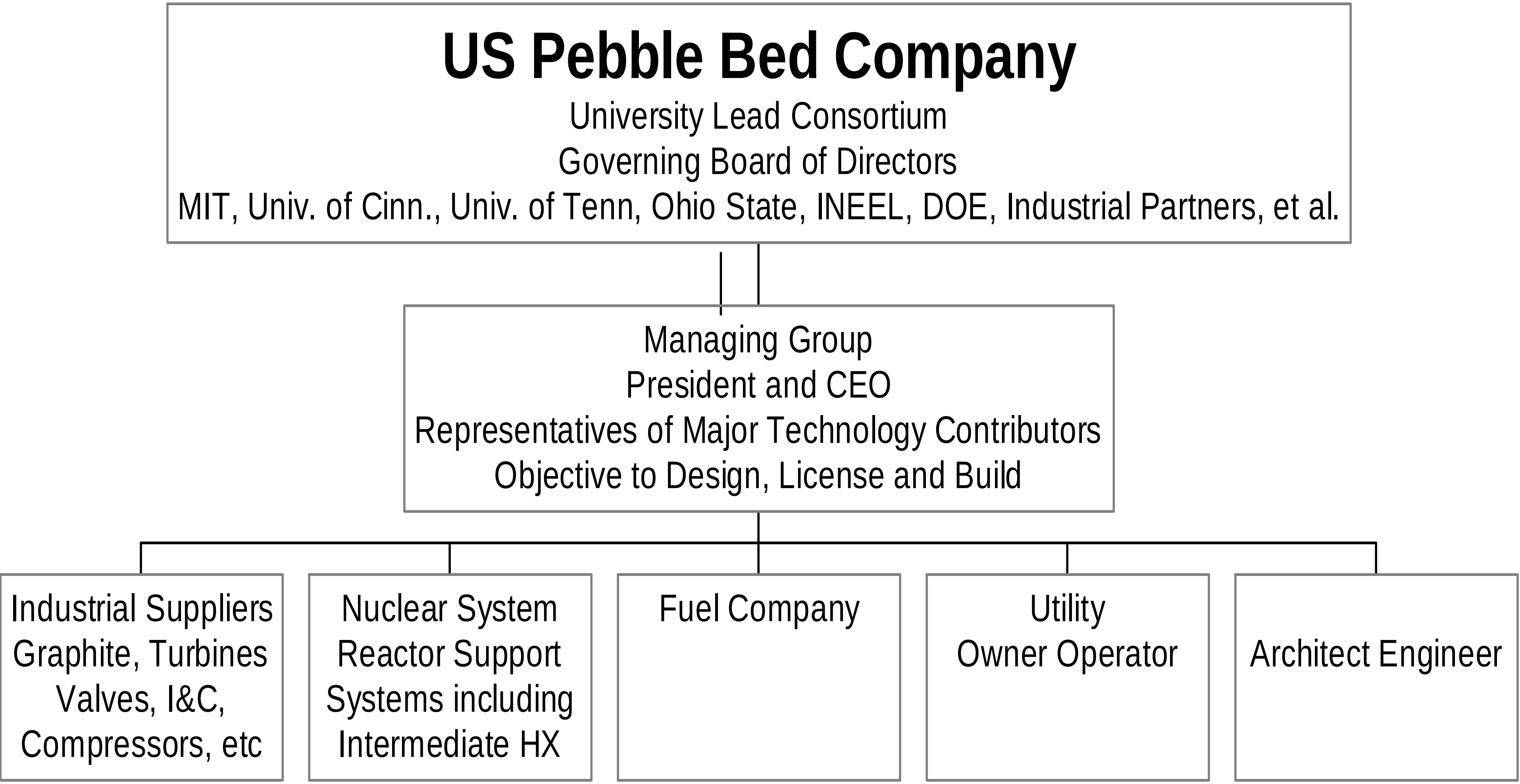
MIT has a different approach – more modular – simpler – smaller

Target markets broader

Developing nations

Smaller grids – less financial risk

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

Observations

- Small modular pebble bed reactors appear to meet the economic objectives
  - High Natural Safety margins - minimal costly safety systems
  - Rapid Construction using modularity principles
  - Small amount of money at risk prior to generation.
  - Small operating staff
  - On-line refueling - higher capacity factors
  - Follow demand with increasing number of modules
  - Factory fabrication reduces unit cost and improves quality

Future

- China and South Africa moving forward on pebble
  - Race to market
  - China less risk strategy
    - lower temperature
    - proven technology for balance of plant
    - friendly regulator
- MIT approach to design different more modular – maybe cheaper – sustainable
- Other nations will follow US lead – NGNP
- Room for merchant plants to beat NGNP
- Needs more detailed design and cost estimates to validate assumptions
- Prismatic reactors – no champions to build – Framatome/General Atomics competition