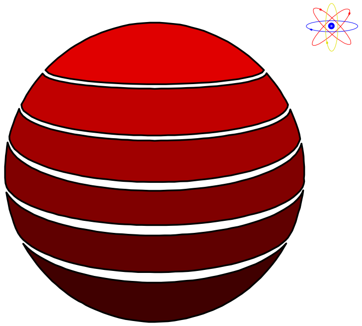
MIT/INEEL
Modular Pebble Bed Reactor



Andrew C. Kadak
Massachusetts Institute of Technology

March 22, 2000

Observations

- No New Construction of Nuclear Plants for Many Years
- Current Generation of Plants Can Be Competitive
- “Next” Generation of LWRs Are Not Competitive
- Focus of LWR Technology is Shifting Outside the US
- Nuclear Engineering Education is in Decline

However!!!

- We Are Learning to be Competitive
- Nuclear Technology is Can Play a Key Role in the Future
- We Need to Solve the Problems
- We Need to Regain US Position in Nuclear Technology

Requirements for New Nuclear Technology

- **It Must Be Competitive**
  Current Leader is Natural Gas
- **It Must Be Demonstrably Safe**
  And the Public Needs to Know It
- **It Must Be Proliferation Resistant**
  And the Public Needs to Know It
- **It Must Exist in the Current Political Climate**

↓

We Need a Good Product and Competent Operators

We Need To Change The Way We:

- Build Them
- Operate Them
- License Them

Presentation Objectives

- What’s A Pebble Bed Reactor ?
- MIT/INEEL Program Objectives
- International Activities
- Plan to Build a Reactor Research Facility
- Actions Necessary
- Opportunities

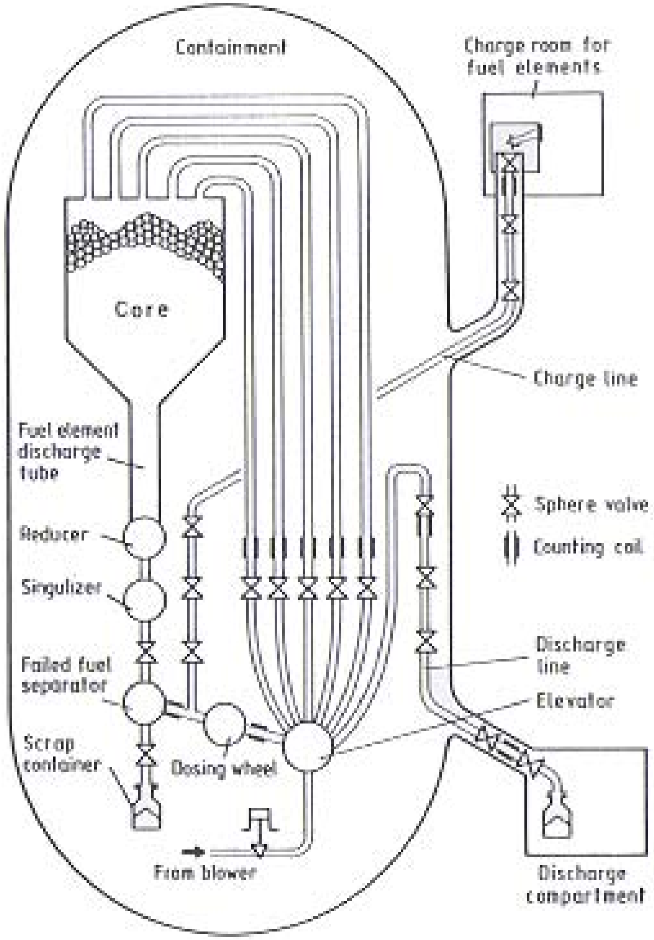
Project Objective

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

Modular High Temperature Pebble Bed Reactor

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

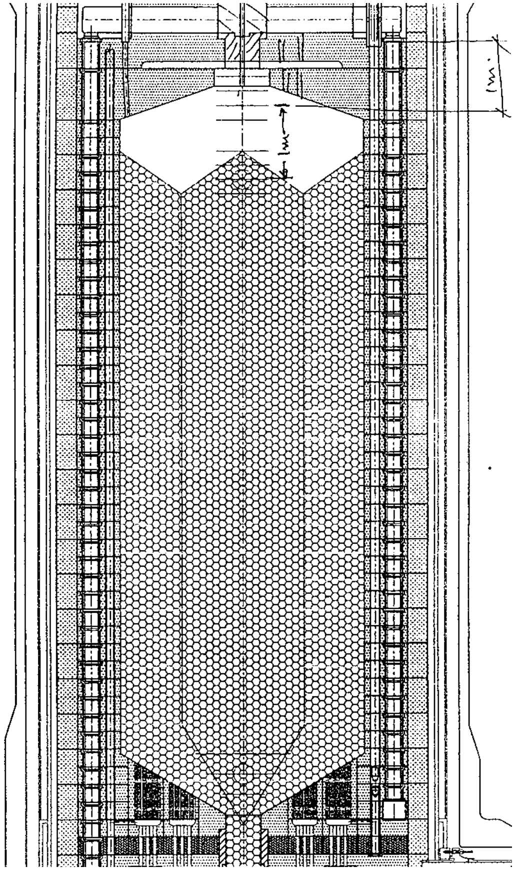
What is a Pebble Bed Reactor ?



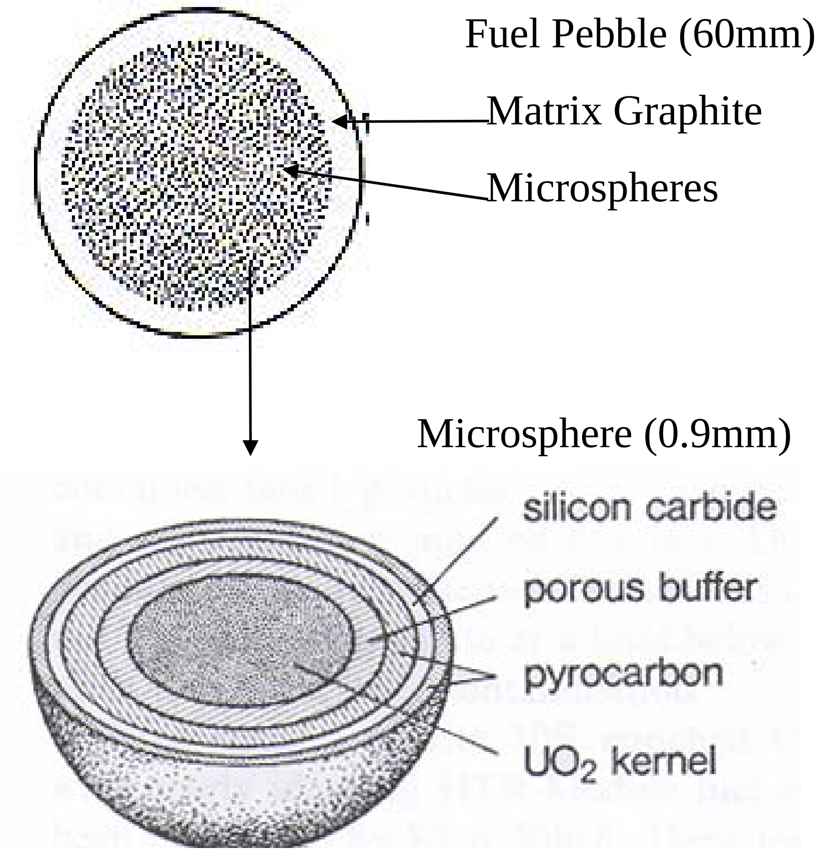
- 360,000 pebbles in core
- about 3,000 pebbles handled by FHS each day
- about 350 discarded daily
- one pebble discharged every 30 seconds
- average pebble cycles through core 15 times
- Fuel handling most maintenance-intensive part of plant

Core Neutronics

- Helium-cooled, graphite moderated high-temp reactor
- ~360,000 fuel balls in a cylindrical graphite core
- central graphite reflector
- graphite fuel balls added and removed every 30 s
- recycle fuel balls up to 15 times for high burnup



TRISO Fuel Particle -- “Microsphere”



Fuel Pebble (60mm)

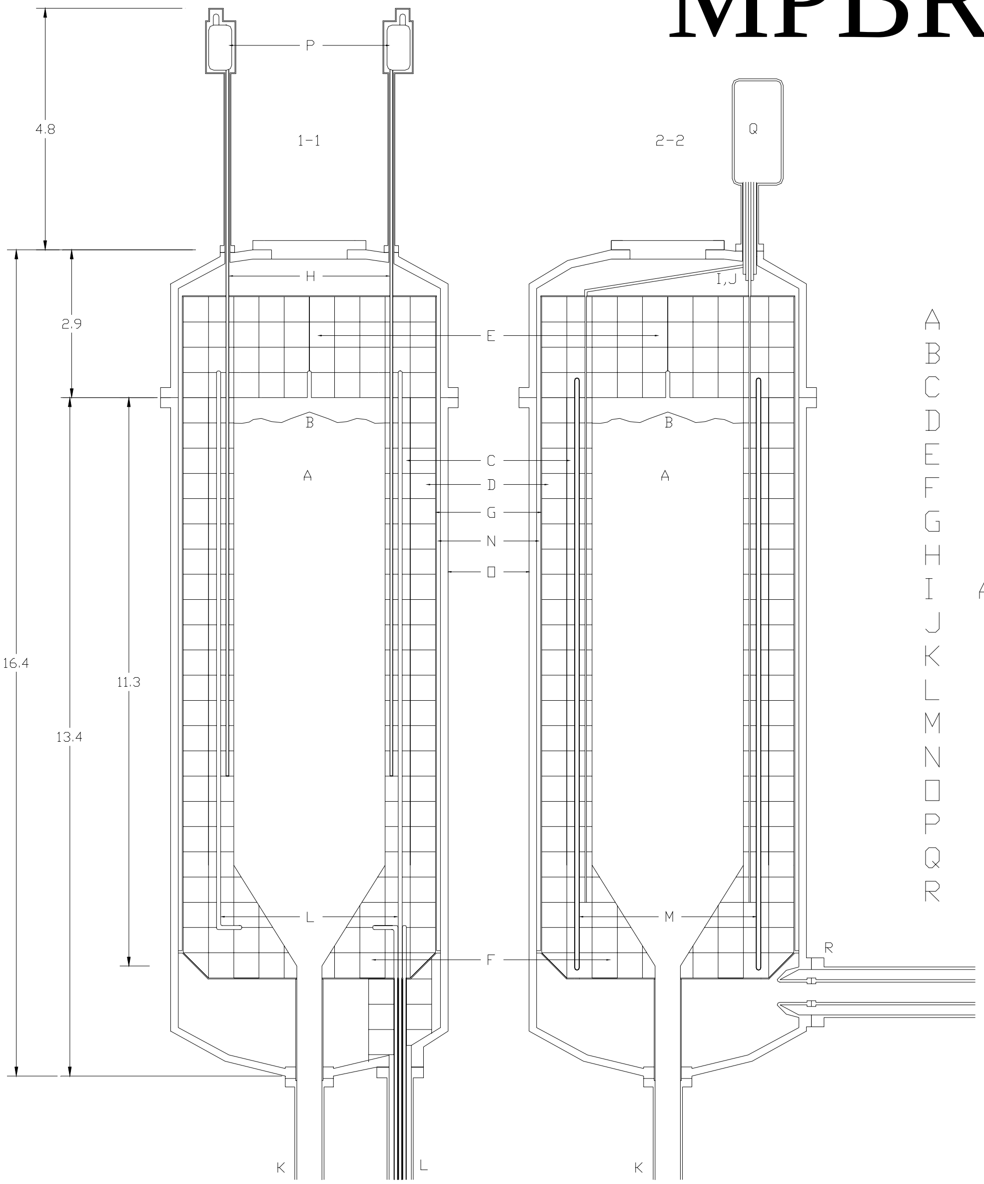
Matrix Graphite

Microspheres

Microsphere (0.9mm)

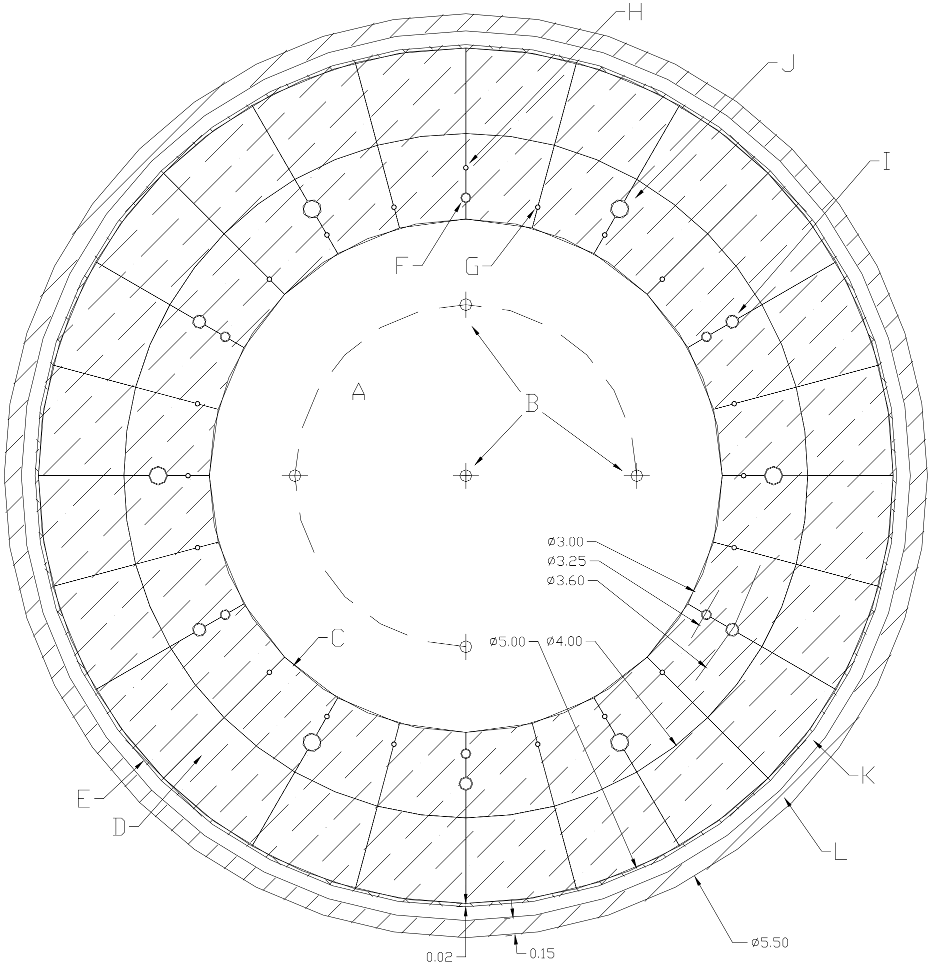
- 0.9mm diameter
- ~ 11,000 in every pebble
- 10^9 microspheres in core
- Fission products retained inside microsphere
- TRISO acts as a pressure vessel
- Reliability
  - Defective coatings during manufacture
  - ~ 1 defect in every fuel pebble

MPBR Side Views



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

MPBR Core Cross Section



A Pebble Bed Core

B Pebble Deposit Points

C Inner Reflector

D Outer Reflector

E Core Barrel

F Control Rod Channels

G,H Absorber Ball Channels

I Pebble Circulation Channels

J Helium Flow Channels

K Helium Gap

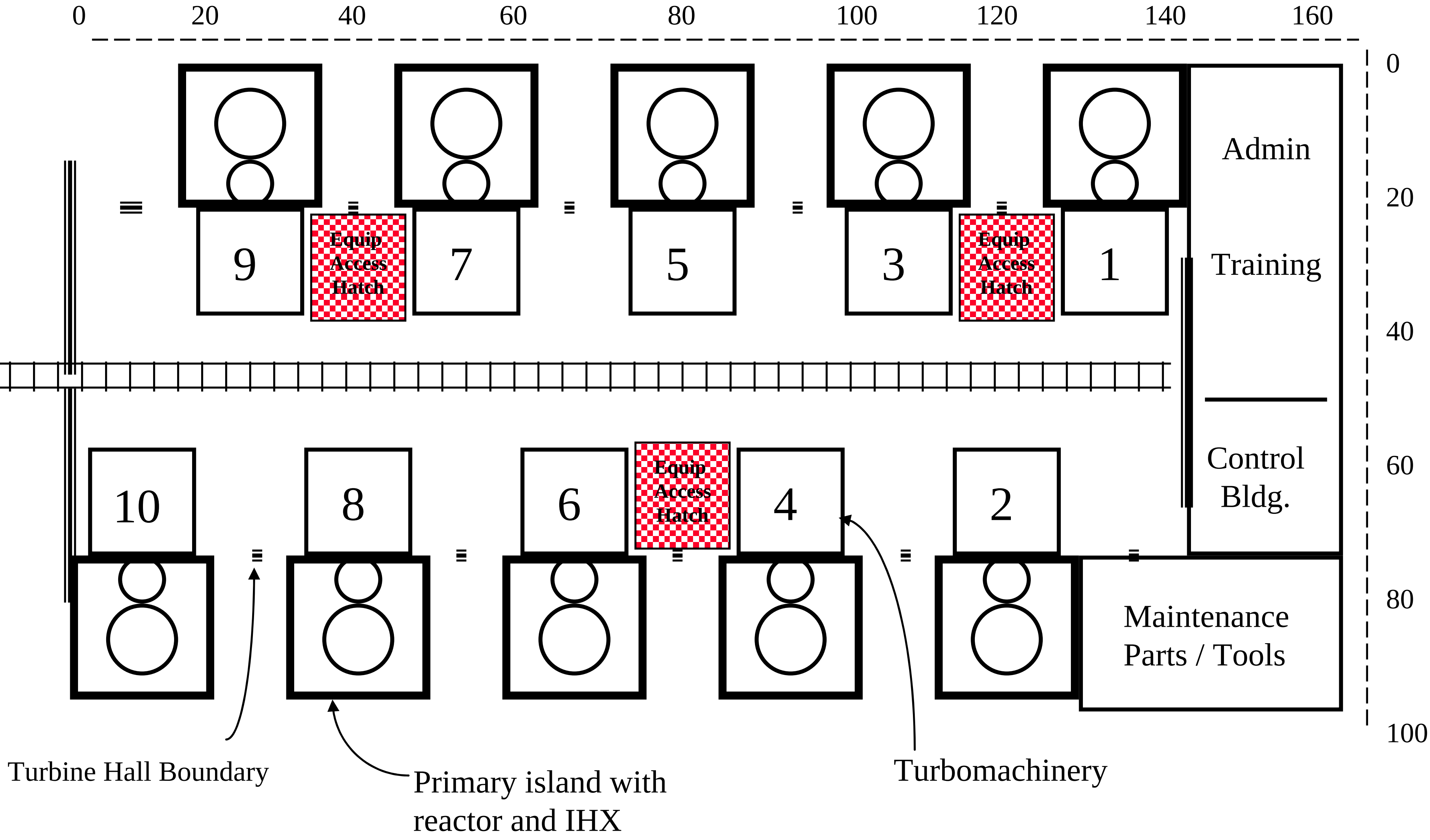
L Pressure Vessel

MPBR Specifications

Thermal Power	250 MW
Core Height	10.0 m
Core Diameter	3.0 m
Pressure Vessel Height	16 m
Pressure Vessel Diameter	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
Number of Absorber Ball Systems	18

Ten-Unit MPBR Plant Layout (Top View)

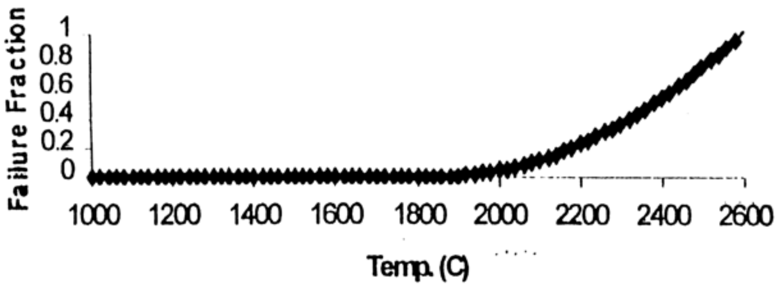
(distances in meters)



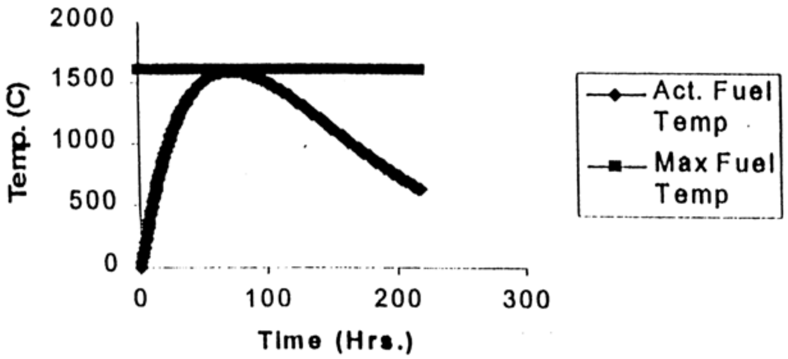
Safety Advantages

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

“Naturally” Safe Fuel



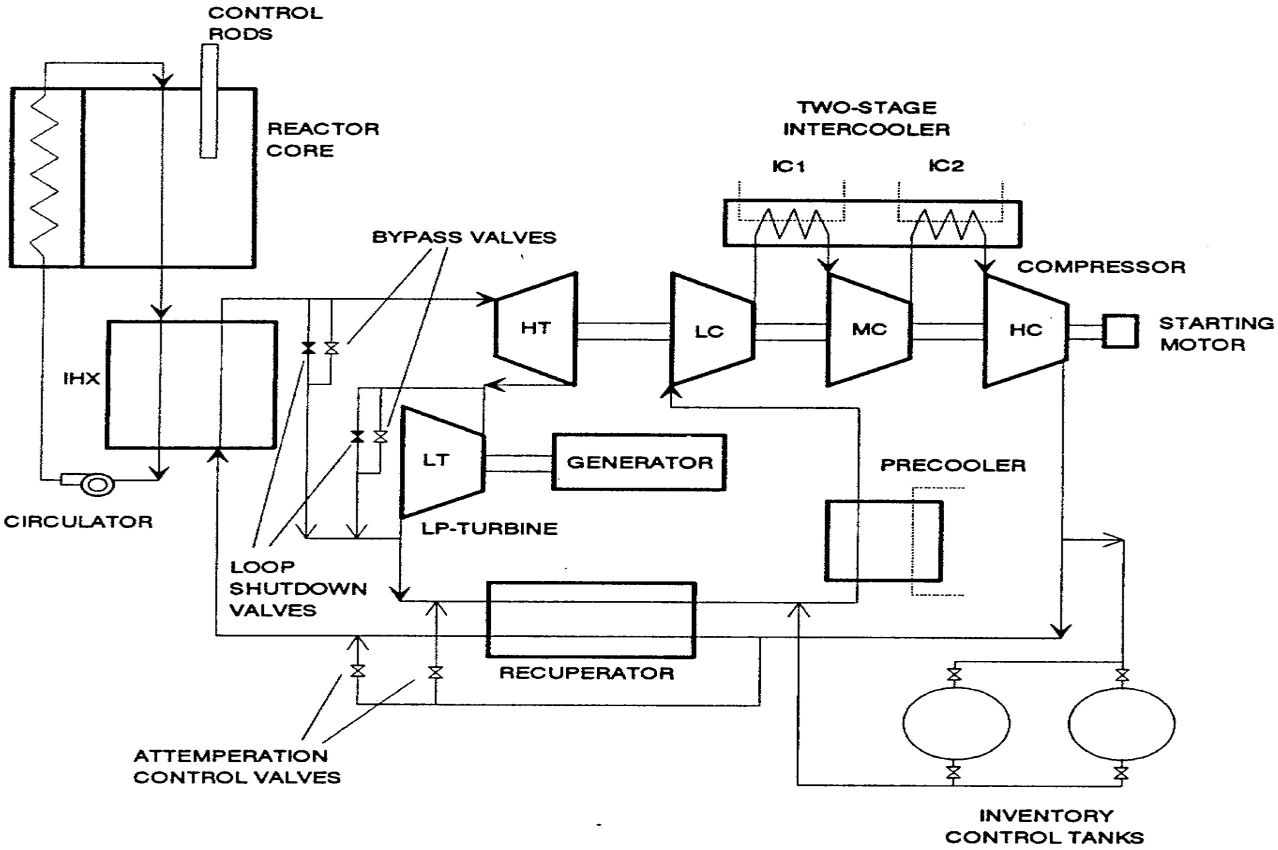
Fuel Failure



Time to Max Fuel Temp.

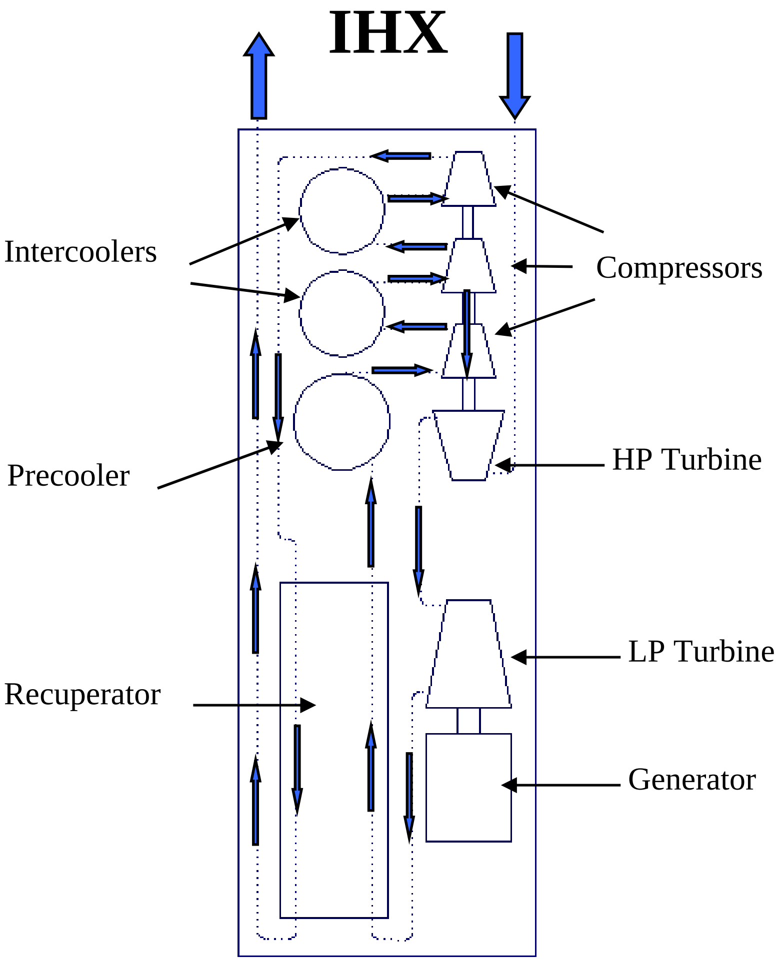
- **Shut Off All Cooling**
- **Withdraw All Control Rods**
- **No Emergency Cooling**
- **No Operator Action**

Thermal Hydraulics

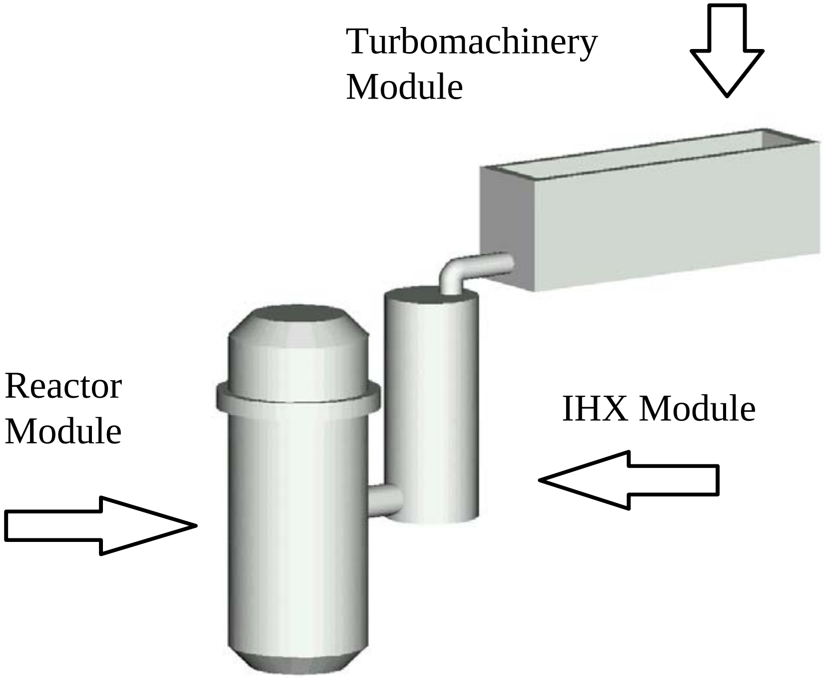


Major Components

- IHX
- Turbomachinery
- Generator
- Recuperator
- Precooler / Intercoolers
- Heat sink



Conceptual Design Layout

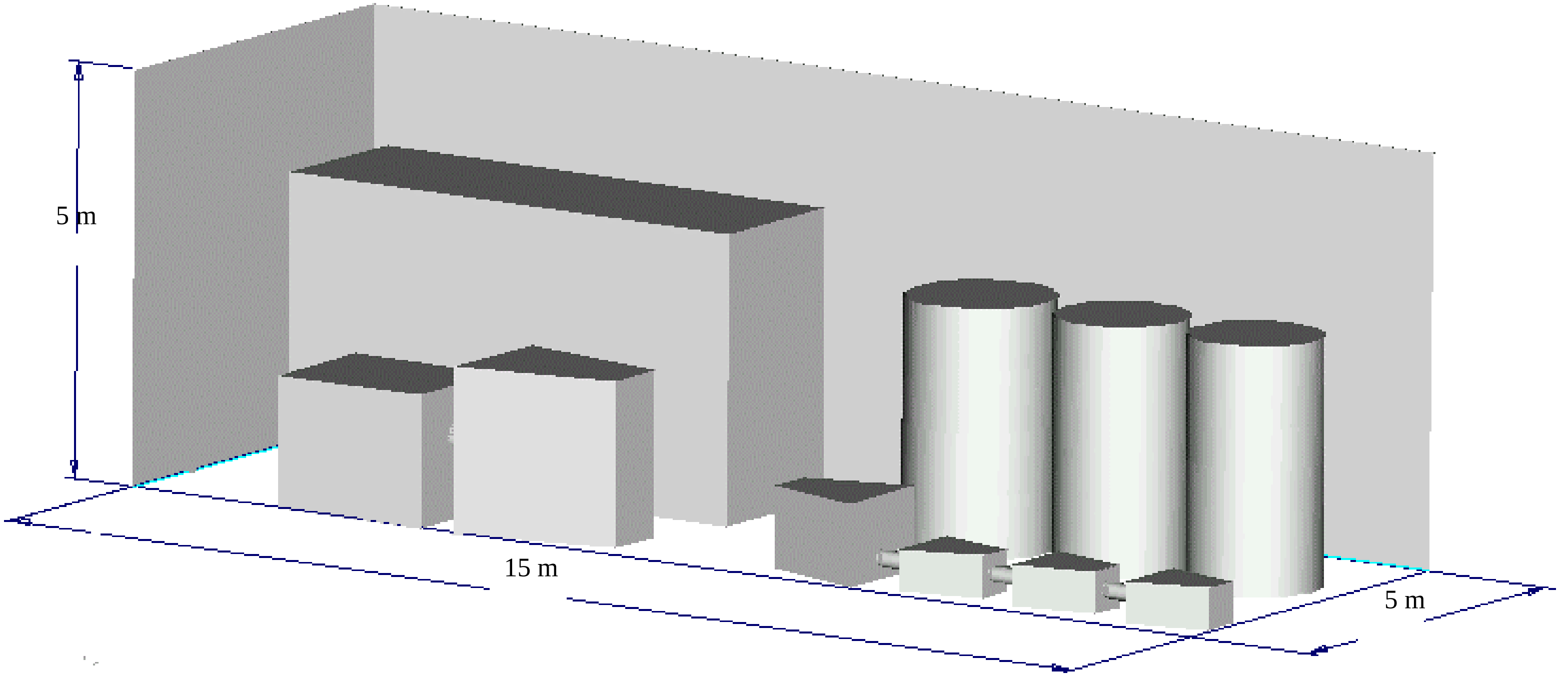


Turbomachinery
Module

Reactor
Module

IHX Module

Balance of Plant



Can Fit on a Flat Bed Truck

Competitive With Gas ?

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

Levelized Costs (1992 $ Based on NEI Study)

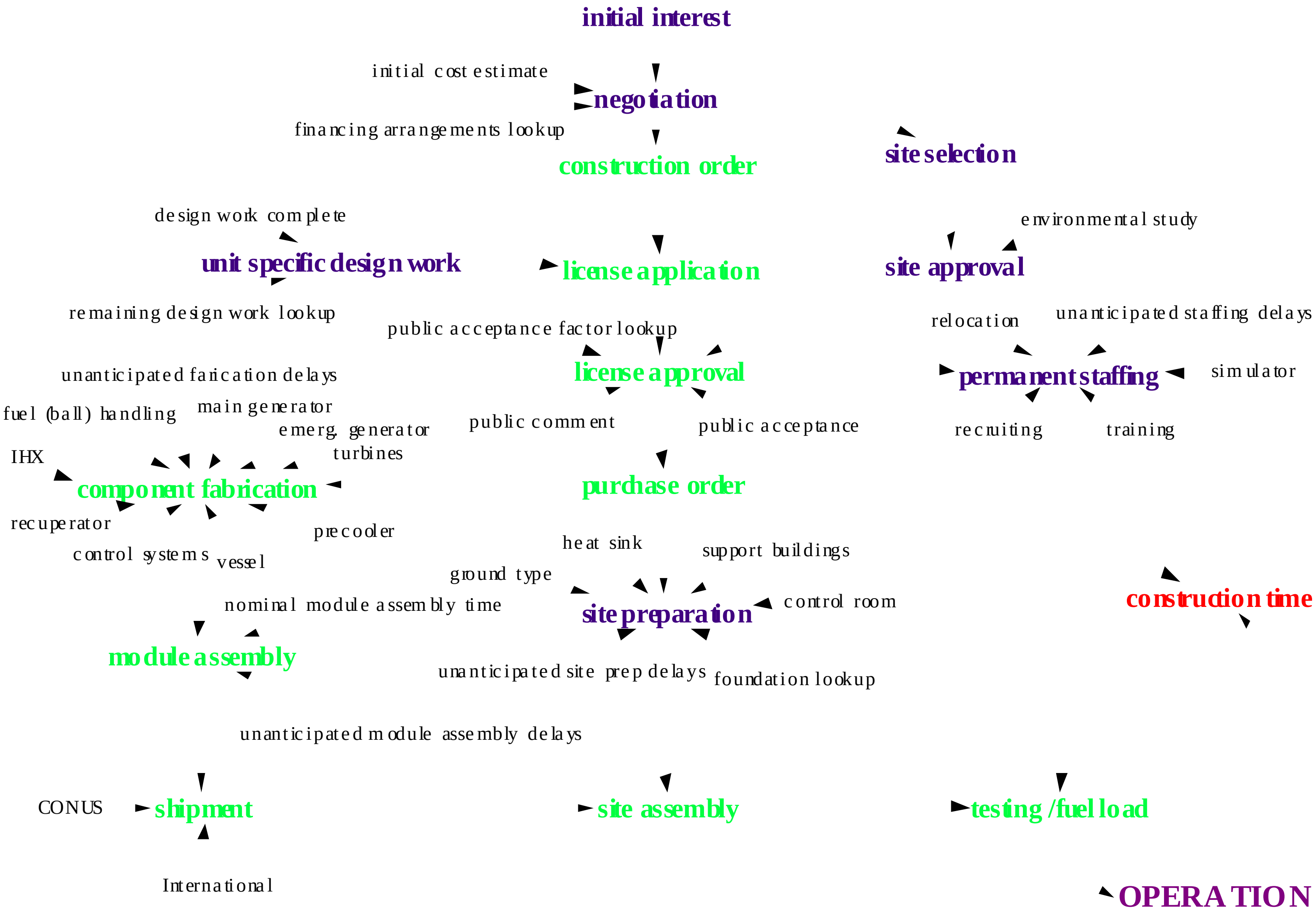
MPBR PLANT CAPITAL COST ESTIMATE
(MILLIONS OF JAN. 1992 DOLLAR WITHOUT CONTINGENCY)

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

Capital Cost

- Cost Savings Come From:
  - More Factory Fabrication, Less Site Work
  - Learning Effect From 1st to 10th Unit
  - Natural Safety Features
  - Shorter Construction Time
- Total capital Cost for 1100 MWe Plant
  - $2,296 Million

Construction Flowpath for a Standard Unit



initial interest

initial cost estimate

negotiation

financing arrangements lookup

construction order

site selection

design work complete

unit specific design work

license application

environmental study

site approval

remaining design work lookup

public acceptance factor lookup

relocation

unanticipated staffing delays

unanticipated farication delays

license approval

permanent staffing

simulator

fuel (ball) handling

main generator

emerg. generator

turbines

public comment

public acceptance

recruiting

training

IHX

component fabrication

purchase order

recuperator

precooler

control systems

vessel

heat sink

support buildings

ground type

nominal module assembly time

site preparation

control room

construction time

module assembly

unanticipated site prep delays

foundation lookup

unanticipated module assembly delays

CONUS

shipment

site assembly

testing /fuel load

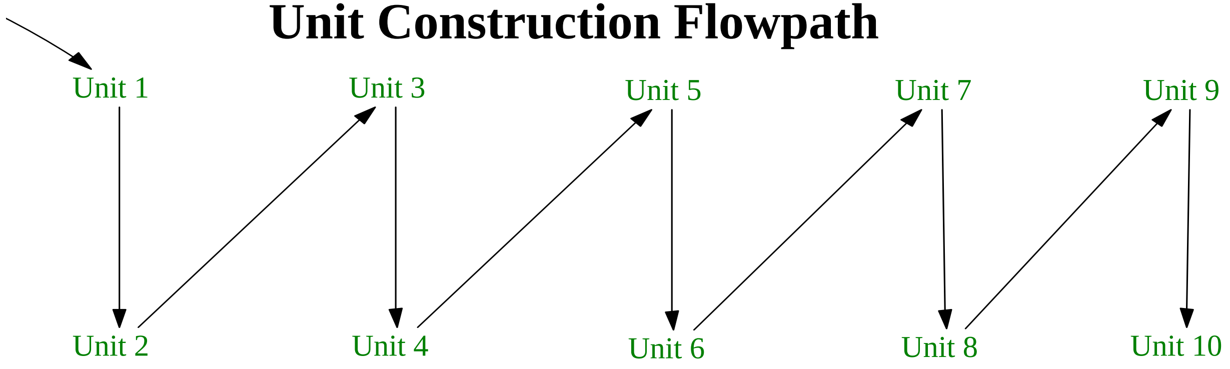
International

OPERATION

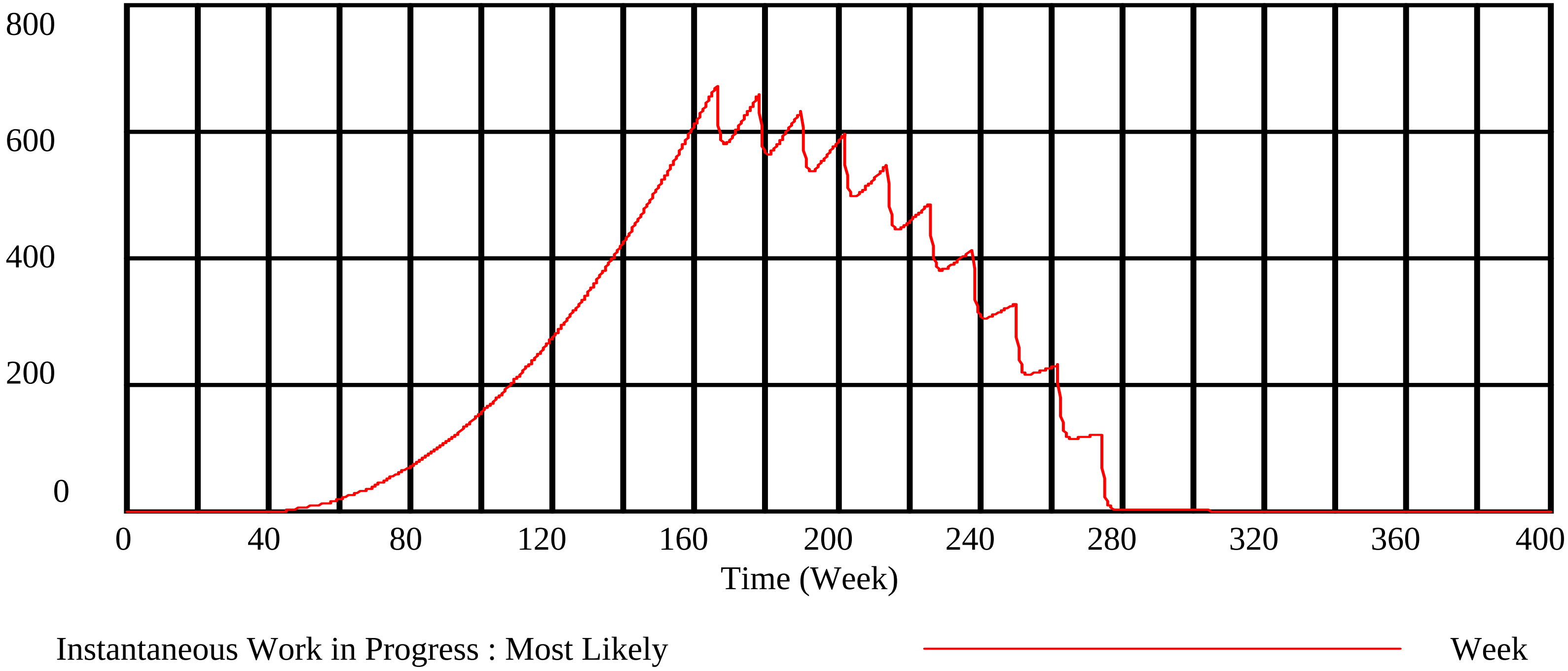
Construction Plan / Techniques

- Factory Assembly
- Existing Technology
- Modular Construction Allows:
  - Parallel Construction
  - Ease of Shipment
  - Rapid Assembly
  - Streamlined Testing

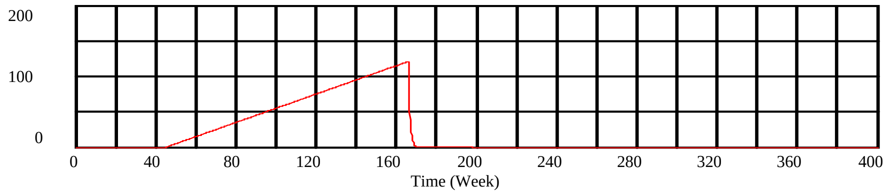
Unit Construction Flowpath



Graph for Instantaneous Work in Progress

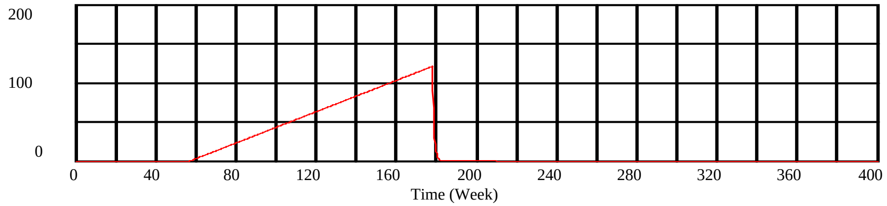


Graph for Unit 1



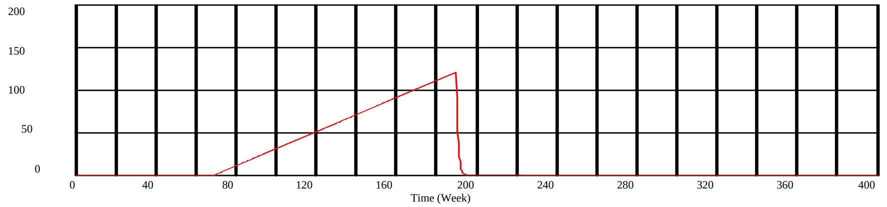
Unit 1 : Most Likely

Graph for Unit 2



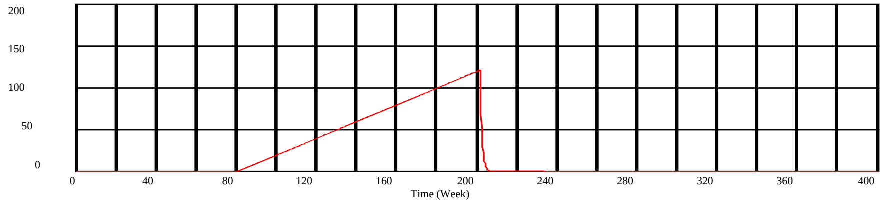
Unit 2 : Most Likely

Graph for Unit 3



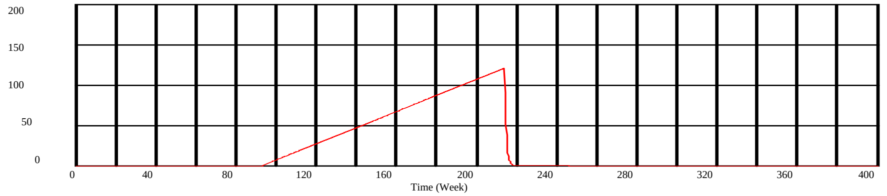
Unit 3 : Most Likely

Graph for Unit 4



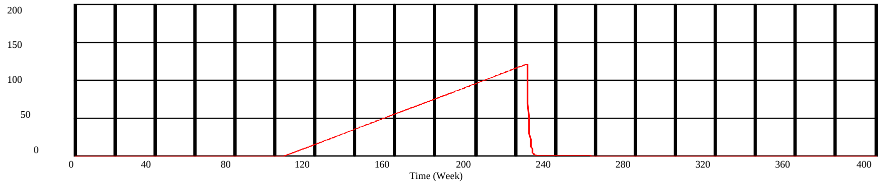
Unit 4 : Most Likely

Graph for Unit 5



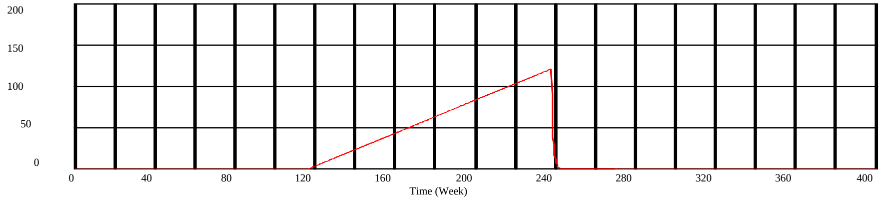
Unit 5 : Most Likely

Graph for Unit 6



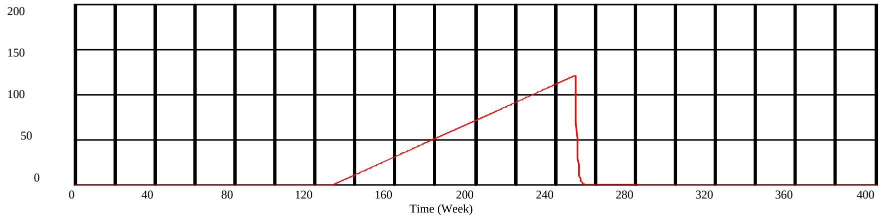
Unit 6 : Most Likely

Graph for Unit 7



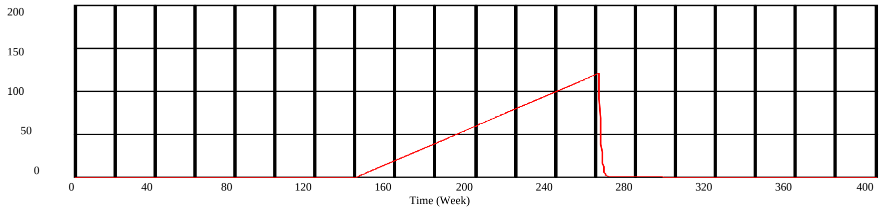
Unit 7 : Most Likely

Graph for Unit 8



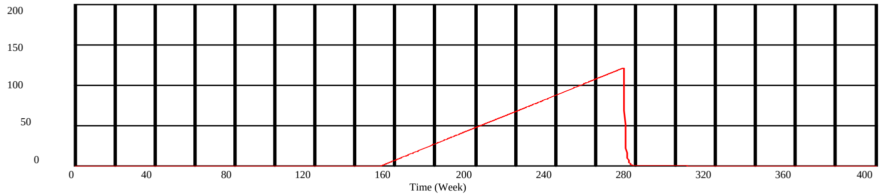
Unit 8 : Most Likely

Graph for Unit 9



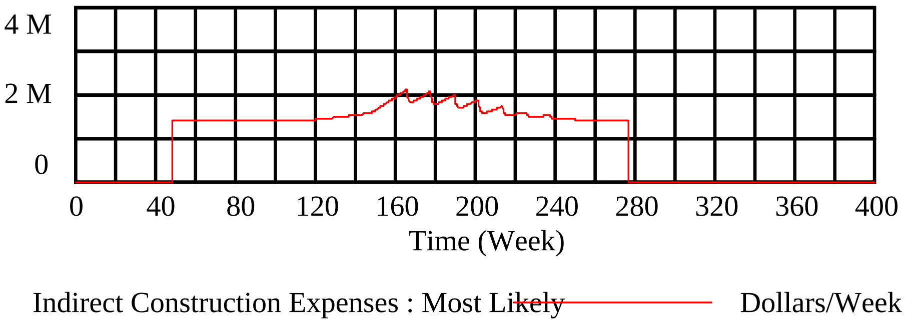
Unit 9 : Most Likely

Graph for Unit 10

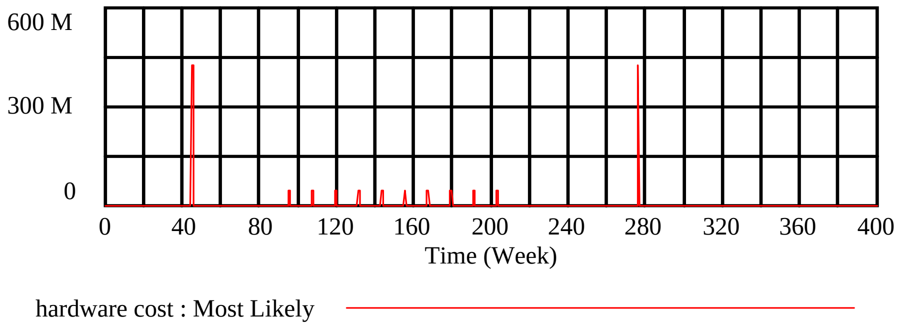


Unit 10 : Most Likely

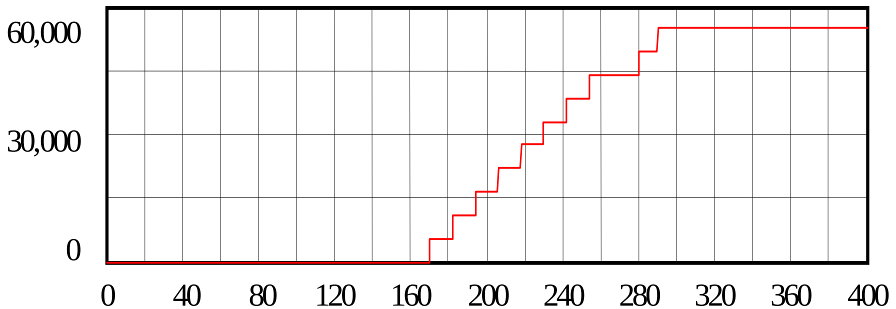
Graph for Indirect Construction Expenses



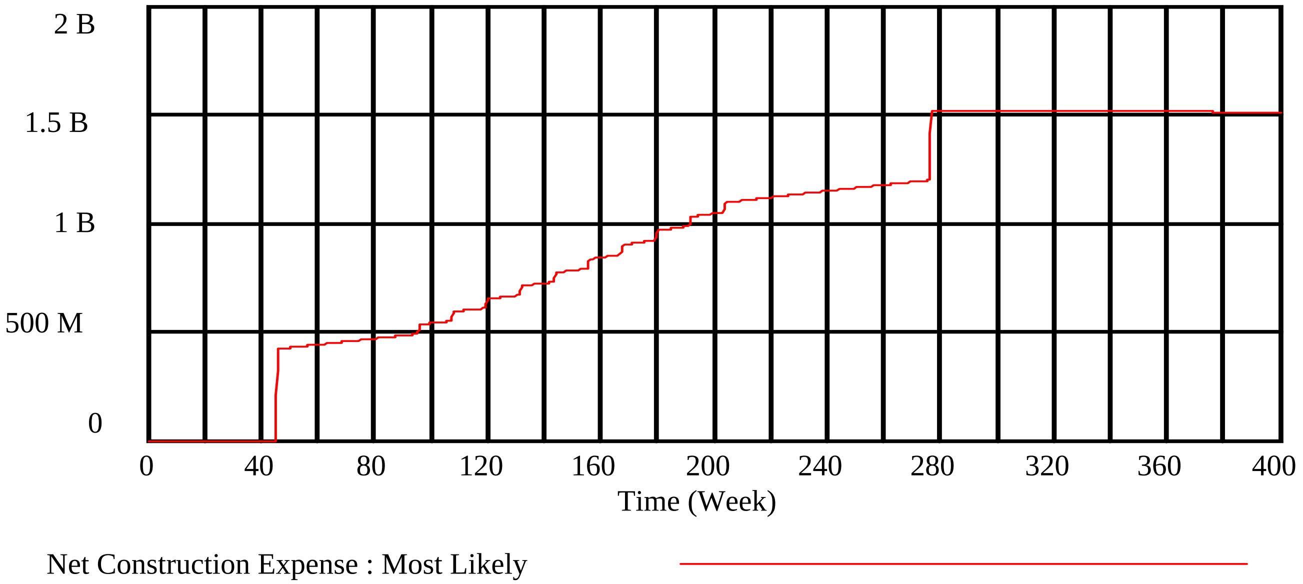
Graph for hardware cost

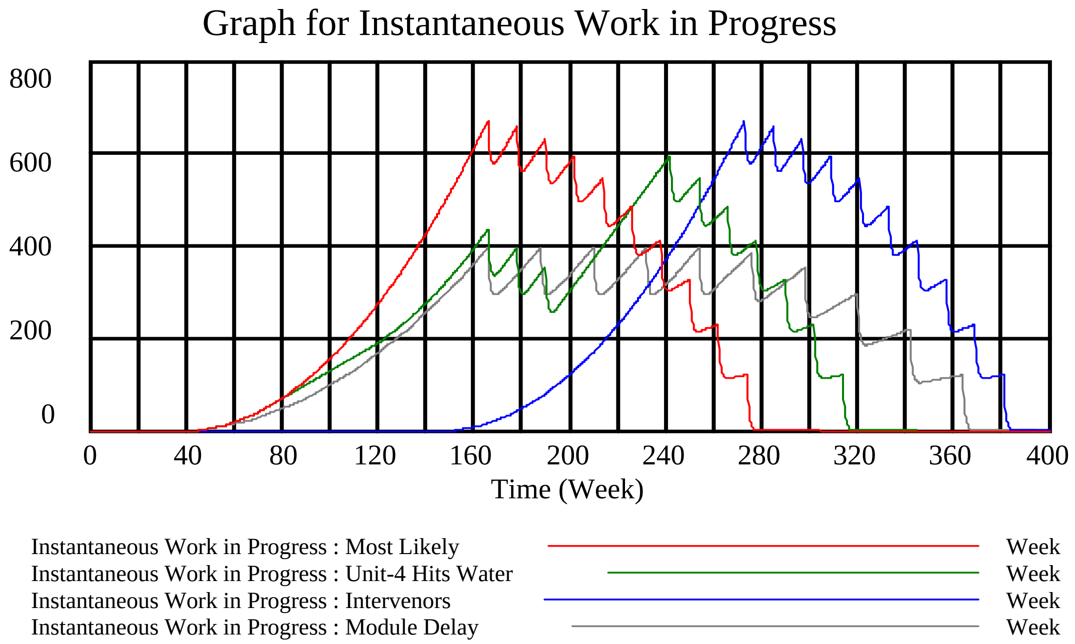


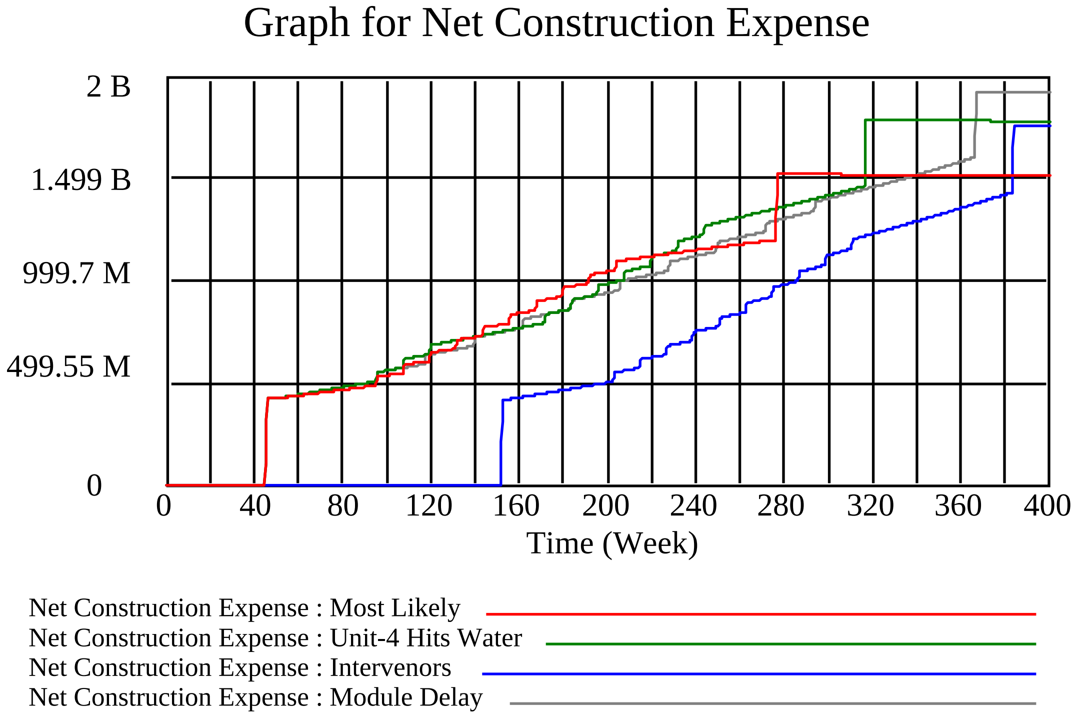
Graph for Income During Construction



Graph for Net Construction Expense




Graph for Instantaneous Work in Progress
800
600
400
200
0
0
40
80
120
160
200
240
280
320
360
400
Time (Week)
Instantaneous Work in Progress : Most Likely
Week
Instantaneous Work in Progress : Unit-4 Hits Water
Week
Instantaneous Work in Progress : Intervenors
Week
Instantaneous Work in Progress : Module Delay
Week


Graph for Net Construction Expense
2 B
1.499 B
999.7 M
499.55 M
0
0
40
80
120
160
200
240
280
320
360
400
Time (Week)
Net Construction Expense : Most Likely
Net Construction Expense : Unit-4 Hits Water
Net Construction Expense : Intervenors
Net Construction Expense : Module Delay

O&M Cost

- Simpler design and more compact
- Least number of systems and components
- Small staff size: 150 personnel
- $31.5 million per year

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/kWhr):	
Capital	25.0
O&M	3.6
Fuel	3.8
Decommissioning	0.6
Total	33.0

Generation IV Reactor

- Proliferation Proof
- Demonstrated Safety
- Disposable High Level Waste Form
- Competitive with Natural Gas
- Used Internationally to Meet Kyoto

Proliferation Advantages

- High Burnup - Bad Weapons Material
- Diversion from Closed System Unlikely
- Don’t need research reactors to train people to run plant safely.
- Need to steal thousands of balls for weapon.
- Can use Thorium cycle to reduce risk further
- Can be used as excess Plutonium burner

Waste Disposal Conclusions

- Per kilowatt hour generated, the space taken in a repository is 7 times less than spent fuel from light water reactors.
- Number of shipments to waste disposal site 10 times higher using standard containers.
- Graphite spent fuel waste form ideal for direct disposal without costly overpack to prevent dissolution or corrosion.
- Silicon Carbide may be an reffective retardant to migration of fission products and actinides.

Licensing

- Use “Risk Informed” Methods
- Demonstrate Safety Through Actual Test

International Activities

Countries with Active HTGR Programs

- China - 10 Mwth Pebble Bed - 2000 critical
- Japan - 40 Mwth Prismatic
- South Africa - 250 Mwth Pebble - 2003
- Russia - 330 Mwe - Pu Burner Prismatic 2007
- Netherlands - small industrial Pebble
- Germany (past) - 300 Mwe Pebble Operated
- MIT - 250 Mwth - Intermediate Heat Exch.

Technological Differences

- Intermediate Heat Exchanger
- Balance of Plant Flexibility in Design
- Ease of Maintenance
- Advanced Fuel
- Enhanced Modularity
- Automation Objective
- Cost Estimates
- Process Heat Applications

International Application

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

International Cooperation, University & Lab Involvement

- Germany
- South Africa
- China
- Netherlands
- Russia
- Japan
- US (GA)

- **Idaho National Engineering & Environmental Lab**
- Oak Ridge National Lab
- Ohio State
- U of Cinncinatti
- U of Tennessee

Highlights of Plan to Build

- Site - Idaho National Engineering Lab
- “Reactor Research Facility”
- University Lead Consortium
- Need Serious Conceptual Design and Economic Analysis
- Congressional Champions
- Get Funding to Start from Congress this Year - 2000

Reactor Research Facility

Full Scale

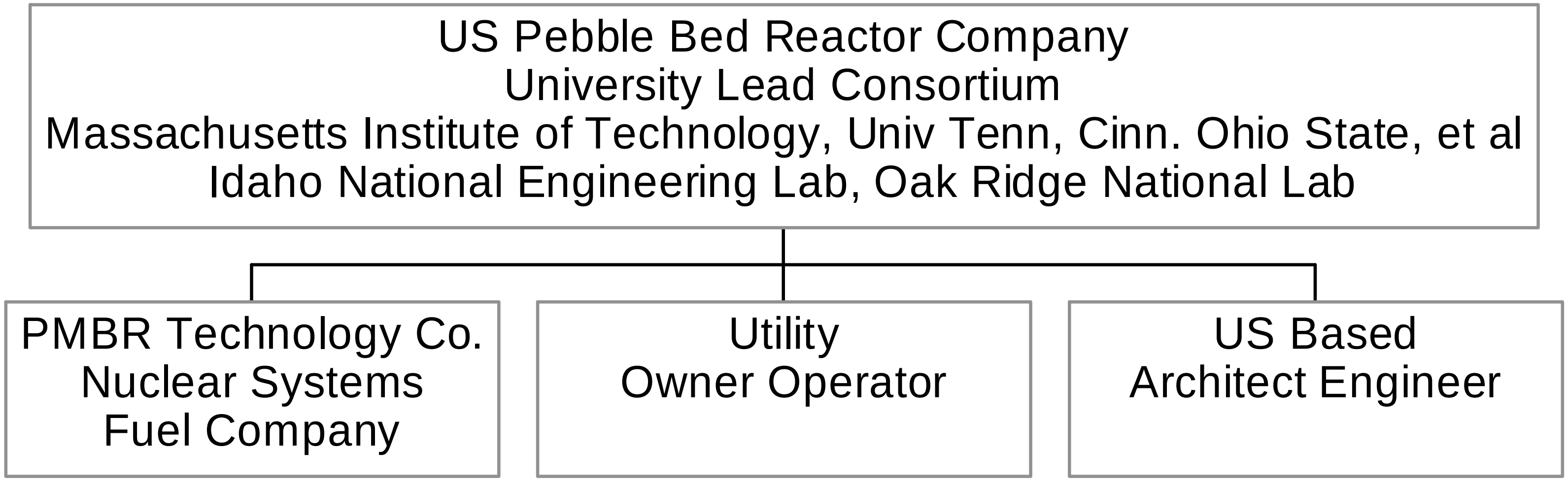
- License by Test as DOE facility
- Work With NRC to develop risk informed licensing basis in design - South Africa
- Once tested, design is “certified” for construction and operation.
- NRC licensing biggest obstacle to success of new reactor designs.
- Use to test - process heat applications, fuels,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

Sequence of Pebble Bed Demonstration

- China HTR 10 - December 2000
- ESKOM PBMR - Start Construction 2001
- MIT/INEEL - Congressional Approval to Build 2003 Reactor Research Facility
- 2003 ESKOM plant starts up.
- 2006 MIT/INEEL Plant Starts Up.

Modular Pebble Bed Reactor Organization Chart

(hypothetical)



US Pebble Bed Reactor Company
University Lead Consortium
Massachusetts Institute of Technology, Univ Tenn, Cinn. Ohio State, et al
Idaho National Engineering Lab, Oak Ridge National Lab

PMBR Technology Co.
Nuclear Systems
Fuel Company

Utility
Owner Operator

US Based
Architect Engineer

Opportunities

- Major New Source of Electric Generation
- Competitive with natural Gas
- Markets in US and worldwide including China.
- Introduce new way of manufacturing plants
- Build Demo plant in Idaho - $ 300 Million
- US Utilities will buy if competitive.
- Desalinization Market
- Process Heat Market
- Hydrogen Generation Market

National Importance of Project

- Need New Competitive Nuclear Technology - Generation IV
- Small Modular Plants Fit the Market
- Manufacture Plants vs. Construct Plants
- Need New Visions for Students & Industry
- US Viewed as Leader by Rest of World

Summary

- Many believe that HTGRs are not credible due to past failures.
- Our work is meant to turn that belief around with substantive analysis.
- If successful, propose building a reactor research facility to "license by test", explore different fuel cycles, process heat applications, and advanced control system design, helium gas turbines and other components. (Within 5 years !)