65 1.4

The Modular Pebble Bed Reactor Concept

A Presentation of the 22.33/.033 Design Course

for

University of Cincinnati / Ohio State University

September 29, 1998

Slide 1 of 58

1 EX 5

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IAP Conclusions

- A modular, pebble bed, high temperature gas reactor with a helium gas turbine generator has the best chance of meeting the future needs of the nuclear industry.
  - Safety
  - Economics
  - Payback Period
  - Government Support
  - Construction Time
  - Public Support
  - High efficiency
  - Regulatory transparency
  - Fuel integrity
  - Small Staff
  - Refueling time
  - On line maintenance
  - Operating Cycle
  - Proliferation
- The Result: Modular Pebble Bed Reactor (MPBR)

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MPBR System Design Criteria

- Naturally Safe?
  - Core cools down using only natural convection, conduction and radiation
  - No harmful fission product release
- Economically Competitive with Combined Cycle Natural Gas Plants?
  - Modular Construction in a Factory
  - Rapid On-Site Assembly and Testing
- Societal Acceptance?
  - Waste Disposal
  - Proliferation Resistant

MPBR Conclusions

- Naturally Safe (Regulatory / Safety Implications)
  - Constrained by Fuel Particle failure above 1600°C
    - Core power density chosen as 3.54 MW/m^3
    - Fuel pebble manufacturing defects are the most significant source of fission product release
- Economically Competitive
  - 3.3 cents/kWhr (natural gas = 3.4 cents/kWhr)
    - Producing revenue within 3 years (rapid construction)
    - Low staffing and O&M costs
    - Factory Assembly
- Societal Acceptance
  - Proliferation Resistance -- promising, but future work needed
  - Waste Disposal -- promising, but future work needed

Project Assignments

- Primary System Group
  - Verify the MPBR is Naturally Safe
  - Dimensions of the Pressure Vessel
  - Waste Disposal
  - Proliferation
- Secondary System Group
  - System Efficiency
  - Component Design
  - Construction Sequence
- Economics Group
  - Financing Plan
  - Economies of Production vs. Economies of Scale

Modular Pebble Bed Reactor Characteristics and Primary System Design

Characteristics of the MPBR

- Economics
  - Short construction time
  - Economies of production instead of scale
  - Ability to produce energy during construction
  - Customer size flexibility
- Safety
  - Under analyzed accident scenarios, core cools using only natural convection, conduction and radiation
  - Minimal fission product release from fuel pebbles

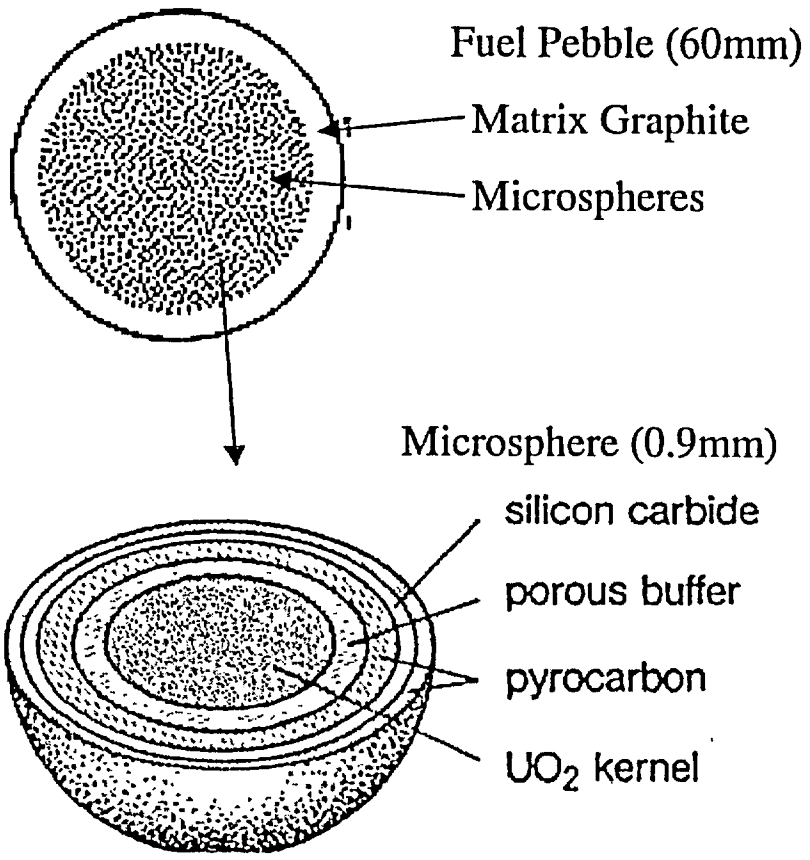
MPBR Characteristics, continued

- Proliferation
  - High Burn up (80,000 MWd/MTHM)
  - Hard to get fissionable material from inside spent Pebbles
- Waste Disposal

Advantages	Disadvantages
– Simple Handing	– High Volume
– Durable	– Transportation Costs
– Low Release of Activity	

- Regulations
  - Current environment established for LWRs.
  - Natural safety calls for a new look at licensing process

TRISO Fuel Particle -- "Microsphere"

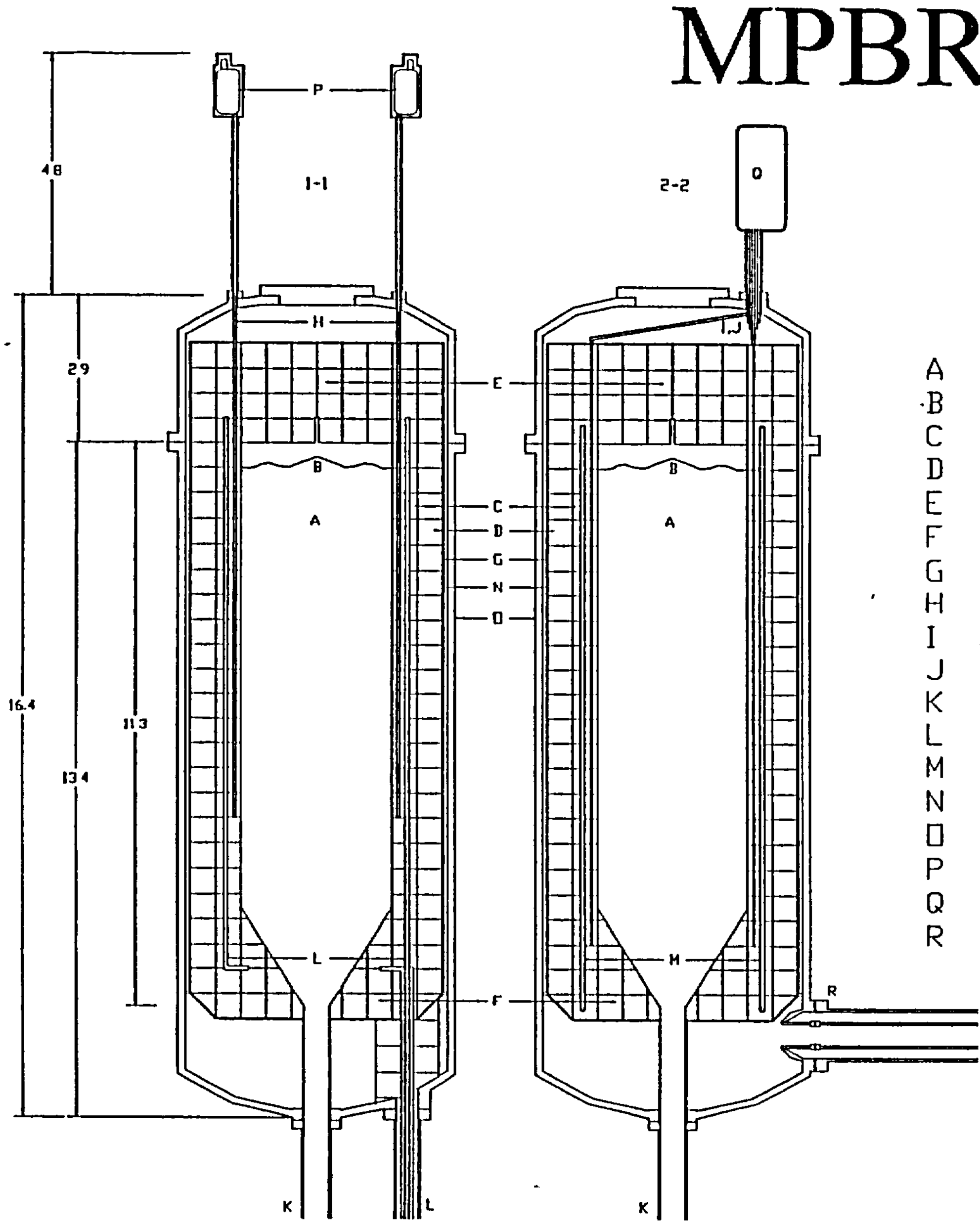


- 0.9mm diameter
- ~ 11,000 in every pebble
- 10^9 microspheres in core
- Fission products retained inside microsphere
- TRISO acts as a pressure vessel
- Reliability
  - Defective coatings during manufacture
  - ~ 1 defect in every fuel pebble

MPBR Specifications

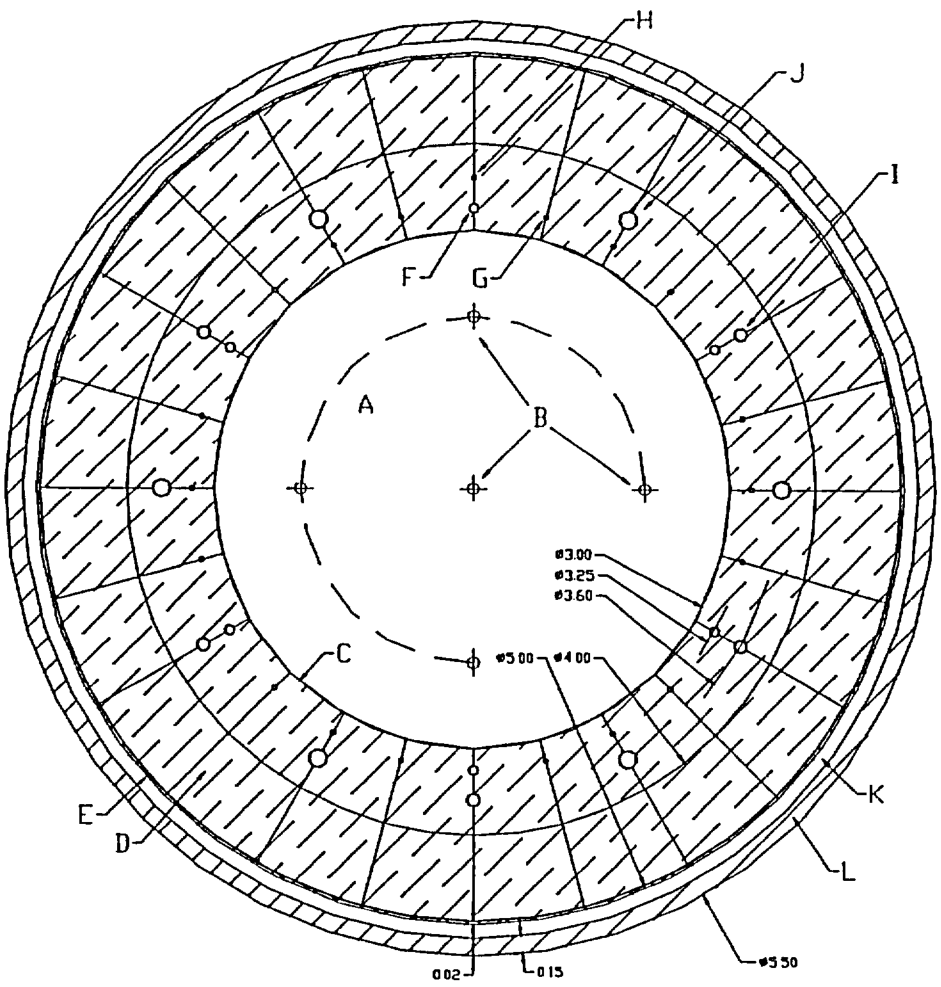
Thermal Power	250 MW
Core Height	10.0 m
Core Radius	3.0 m
Pressure Vessel Height	16 m
Pressure Vessel Radius	5.6 m
Number of Fuel Pebbles	360,000
Microspheres/Fuel Pebble	11,000
Fuel	UO_2
Fuel Pebble Diameter	60 mm
Fuel Pebble enrichment	8%
Uranium Mass/Fuel Pebble	7 g
Coolant	Helium
Helium mass flow rate	120 kg/s (100% power)
Helium entry/exit temperatures	450°C/850°C
Helium pressure	80 bar
Mean Power Density	3.54 MW/m^3
Number of Control Rods	6
Number of Absorber Ball Systems	18

MPBR Side Views



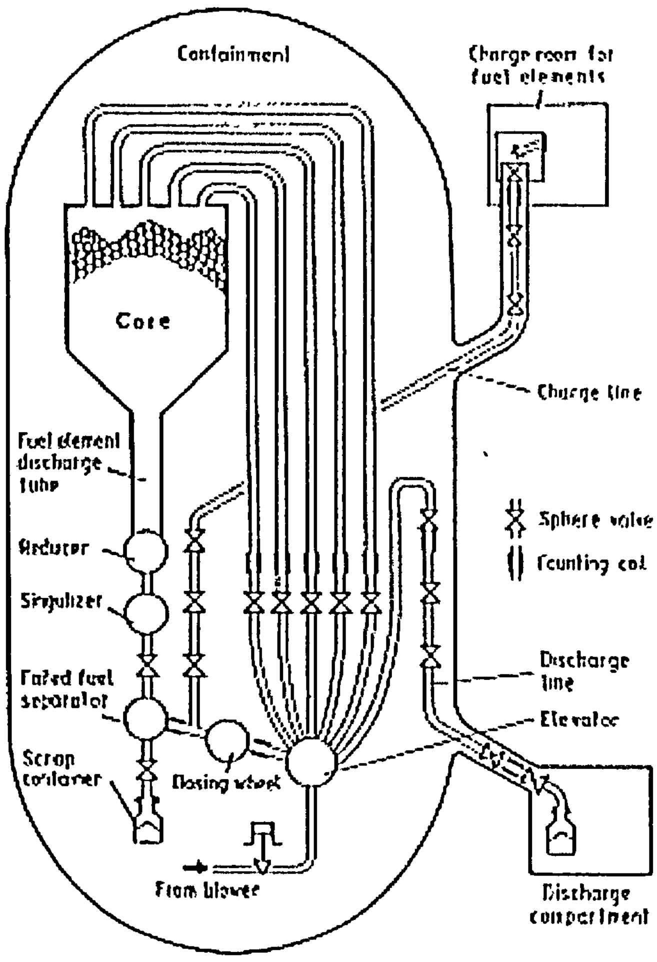
- A Pebble Bed Core
- B Fuel Drop Points (5)
- C Inner Reflector
- D Outer Reflector
- E Top Reflector
- F Bottom Reflector
- G Core Barrel
- H Control Rod Channels (6)
- I Absorber Ball Drop Channels (18)
- J Absorber Ball Lift Channel (1)
- K Fuel Discharge Tube
- L Pebble Fuel Lift Channels (5)
-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

Fuel Handling System



- 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

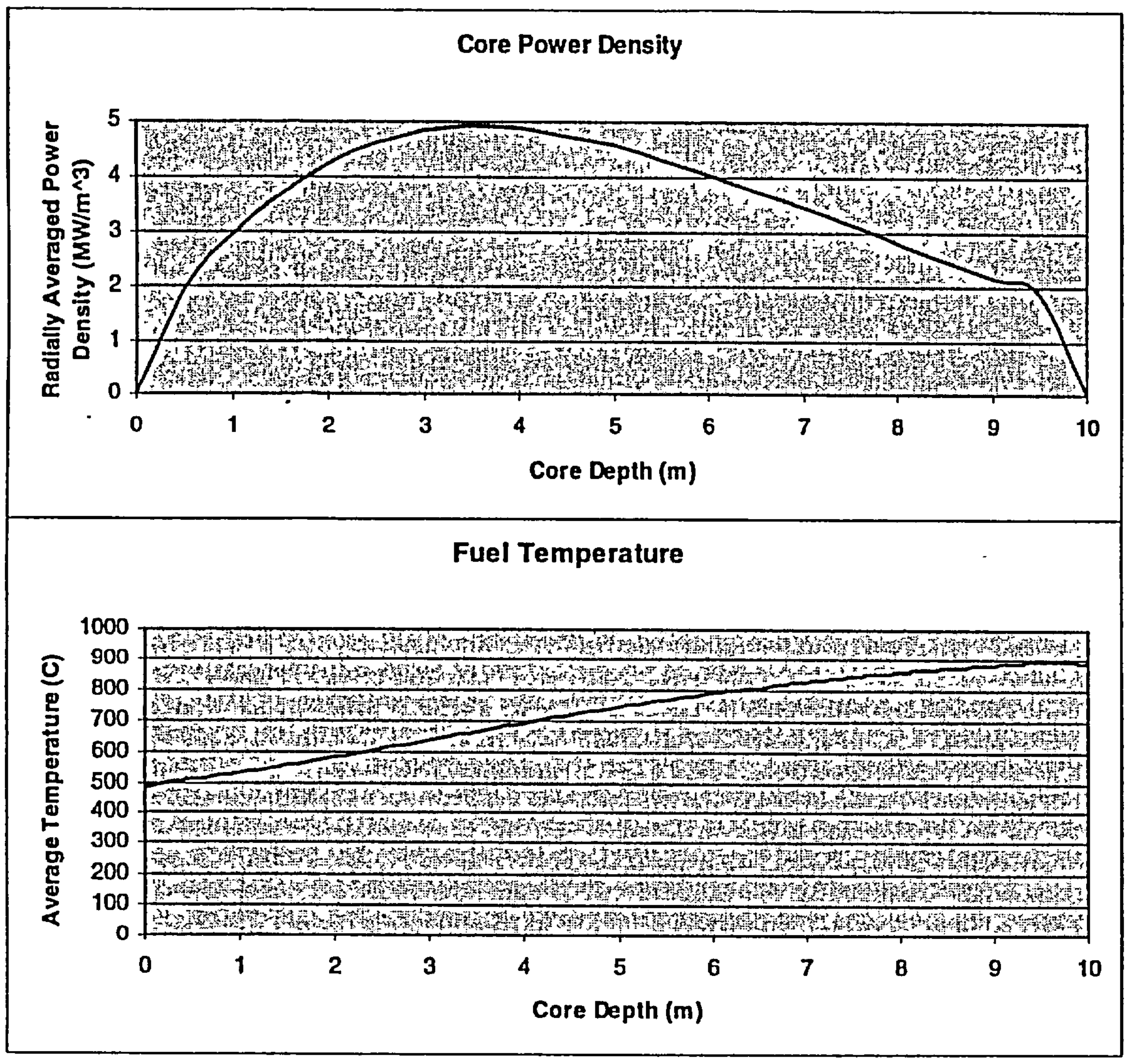
Primary Group Design Goals

- Validate the Natural Safety of the MPBR
  - What is the maximum power density allowable keeping the maximum core temperature below 1600°C?
  - Fuel Element Design
  - Fuel Element Manufacturing
  - Fission Product Release
- Design the Pressure Vessel to be shipped on a train (4m)
  - What is the minimum radius?
- Research Important Feasibility Issues
  - Waste Disposal
  - Proliferation

Natural Safety

- Enhanced fission product release at high fuel temperatures
- Design must limit pebbles to about 1600°C in worst-case accident scenario
  - Fission decay power known
  - Core geometry dictated by neutronics, pebble bed mechanics
  - Must constrain power density
- Motivating Questions:
  - What power density is needed to obtain adequate reactor power?
  - At this power level, can the reactor safely cool itself by natural means?
  - Could this power level be further increased?

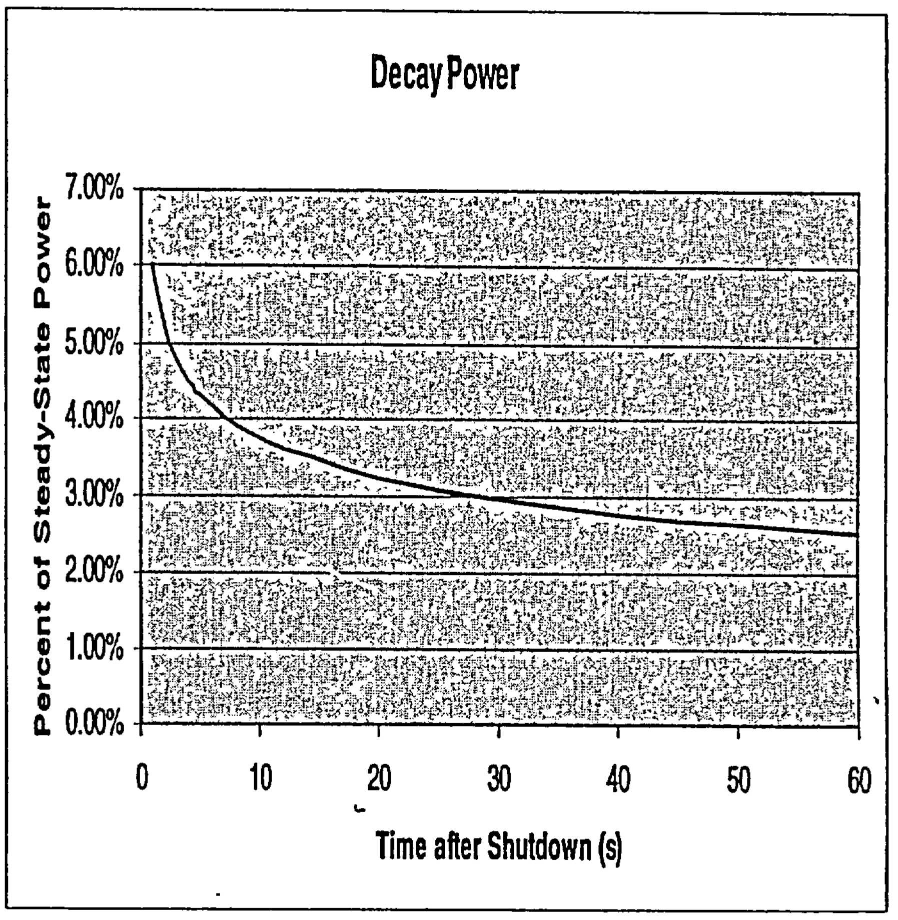
Reactor Operational Power and Fuel Temperature



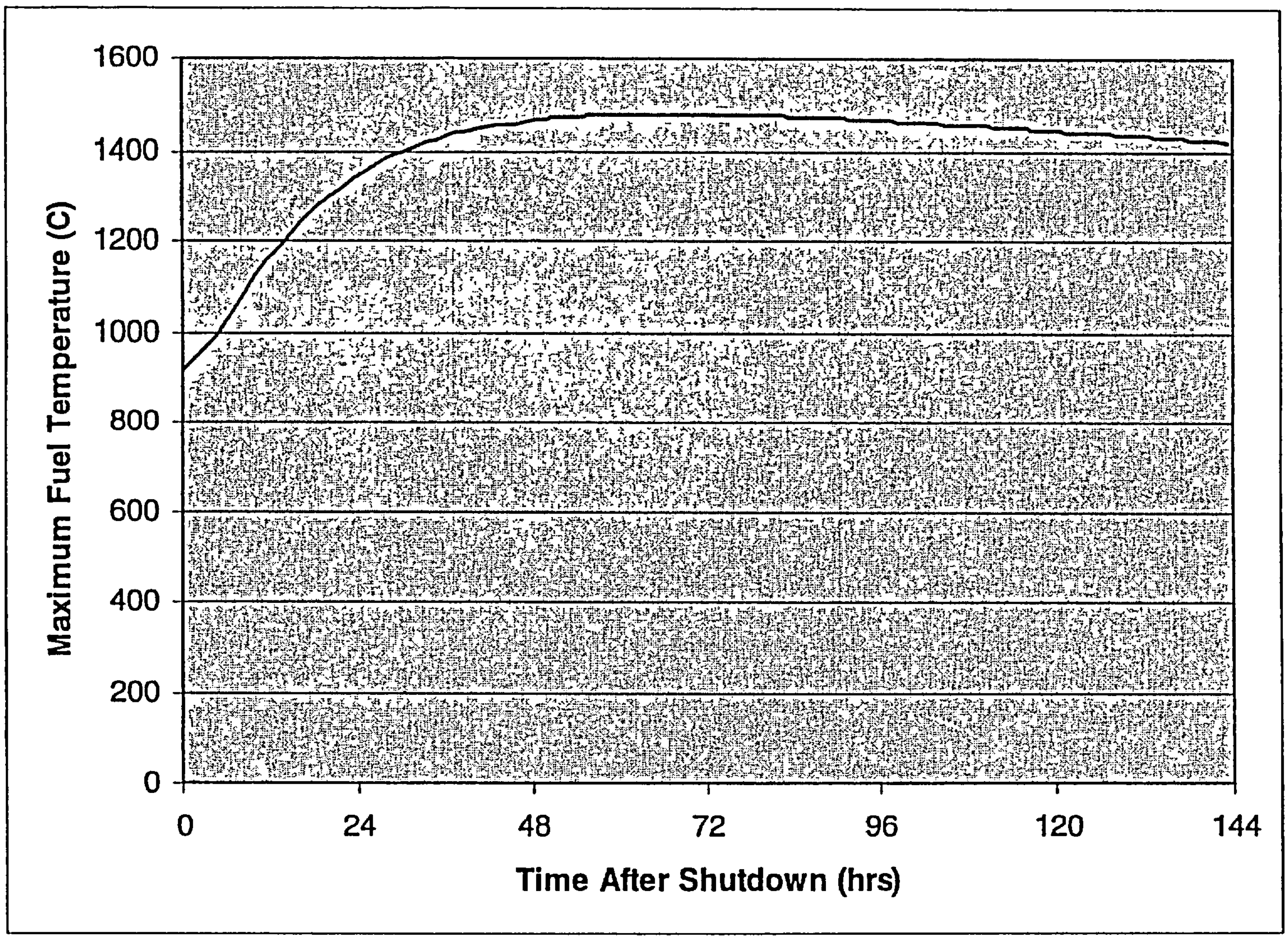
- Blow-down design
- Higher temperature, lower power density at core bottom

Worst-Case Accident

- Assume a depressurized core with no forced cooling of reactor afterheat
- Heat source determined by steady-state power density and natural decay heat
- Heat removal relying on natural processes
  - Radiation and convection across enclosures
  - Conduction into earth



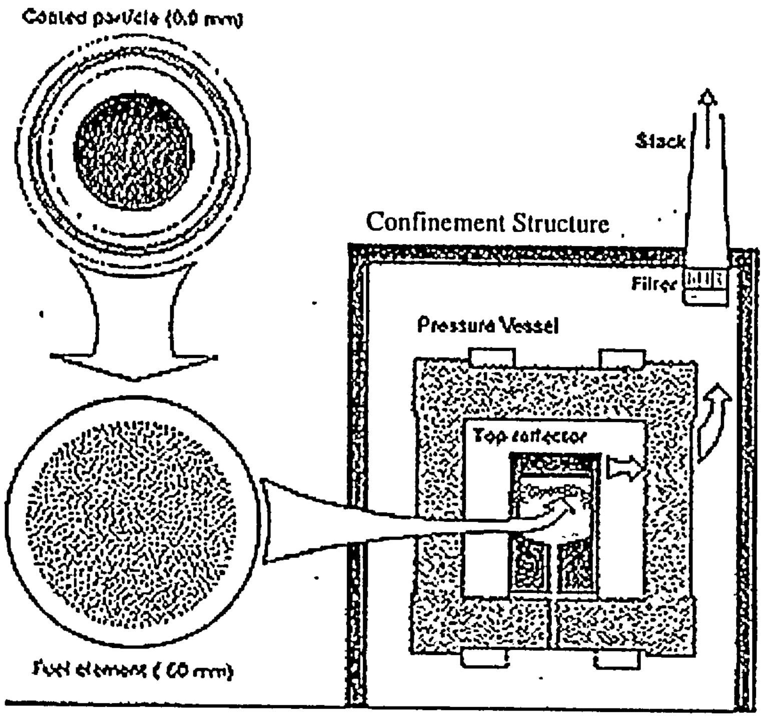
Maximum Fuel Temperature after Depressurization



Thermal Analysis Conclusions

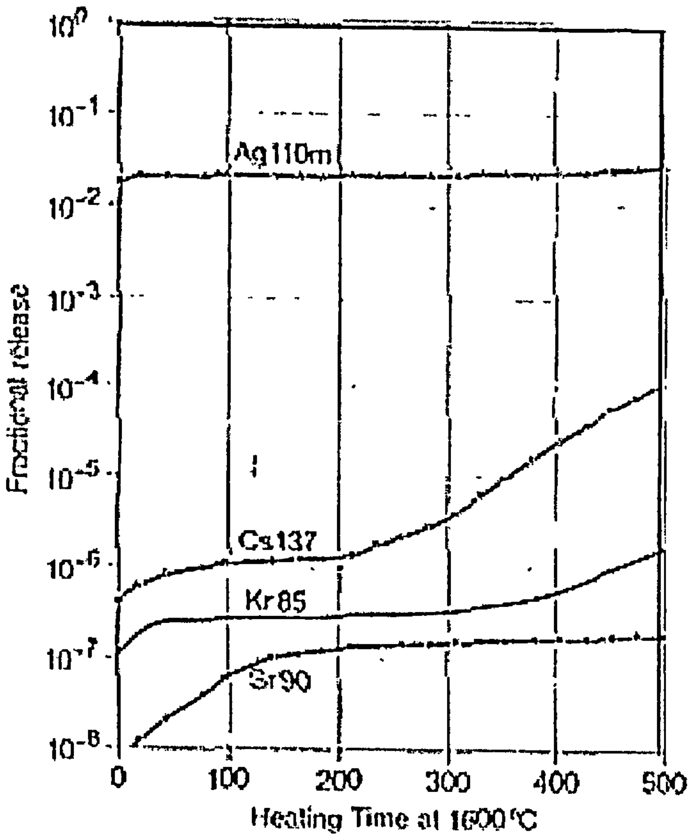
- 3.54 MW/m^3 average power density required for 250 MWt total power
- Maximum fuel temperature stays below 1600°C under depressurized conditions
- Power density could be increased further while maintaining natural safety

Fission Product Barriers



1. Fuel Element
   - Silicon Carbide layer
   - Graphite Matrix
2. Pressure Vessel
   - Plate Out
3. Filtered Stack

Fractional Fission Product Release



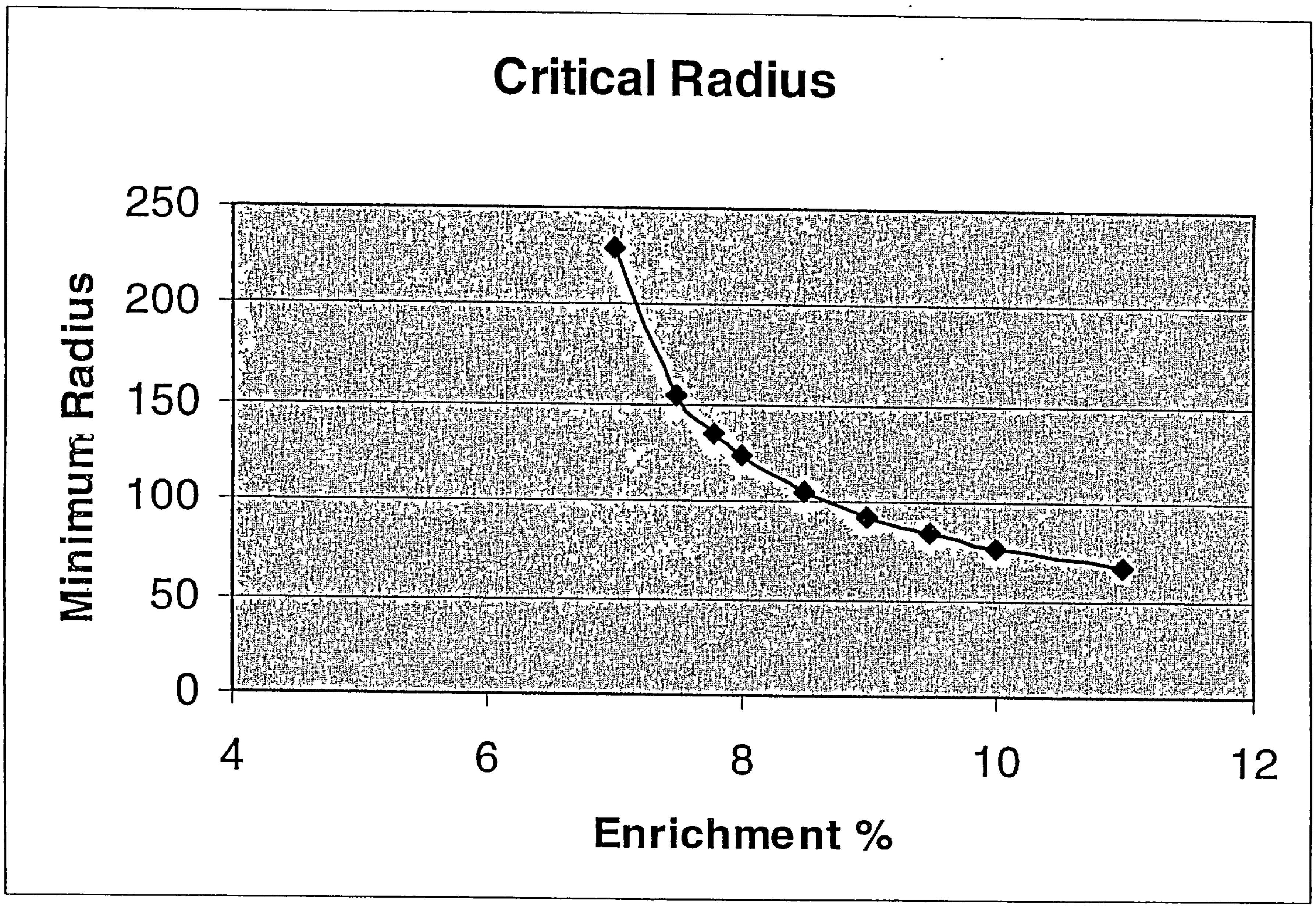
- ^{110m}Ag
  - largest fractional release
  - heating time independent
  - 250 day half-life
  - plates out on colder graphite surface
  - greatest migration through silicon carbide layer
- ^{137}Cs
  - time/temperature dependent
  - fractional release significant after breakdown of silicon carbide layer
- Maximum additional fractional release due to core heat-up: ~ 10^{-5}

Important Fission Products

Solid Fission Products	Half Life	
^{134}Cs	2 years	- dangerous to human health - important in accidents - quickest release from fuel kernel - highest sorption in buffer and matrix
^{137}Cs	30 years	- dangerous to human health - important in accidents - quick release from fuel kernel - high sorption rate in buffer and matrix
^{90}Sr	28 years	- dangerous to human health - important in accidents - good retention in fuel kernel and matrix - quick diffusion through silicon carbide
^{131}I	8 days	- dangerous to human health - important in accidents - released only from defective particles
^{110m}Ag	250 days	- significant during normal operation - quick transport through coating and matrix - highest release from fuel pebble
Fission Gases		
^{85}Kr	11 years	- indicator of particle defects
^{133}Xe	5 days	- indicator of particle defects

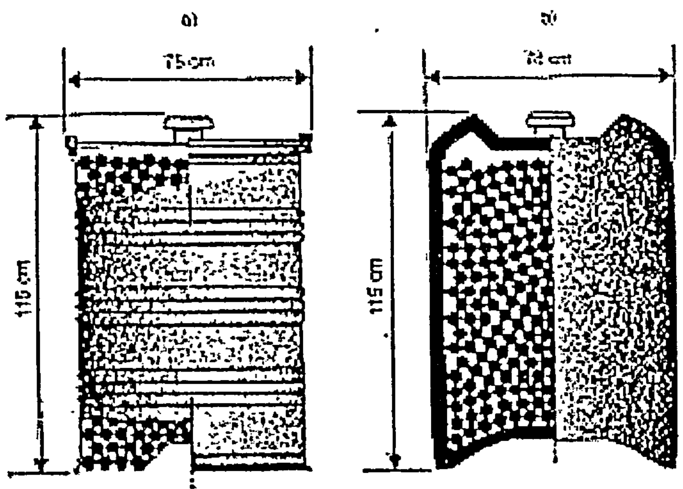
Size of Pressure Vessel

- Directly related to the diameter of the core
  - Maximum diameter of core is 3.0 meters because the control rods are located in the reflector.
  - What is the minimum diameter of the core?
- Approximation using 2D, 2-Group diffusion model
  - Minimum diameter with 11% enrichment -- 1.5 meters
  - Minimum diameter with 8% enrichment -- 2.4 meters
- Other Factors not Considered in calculation
  - Fuel pebble "Bridging" effect through fuel handling system
- Design Decision
  - Diameter of 3.0 meters with 8% enrichment
- Future work needed to determine more precise core dimensions



Critical Radius
250
200
150
100
50
0
Minimum Radius
4
6
8
10
12
Enrichment %

Waste Handling



- How the Germans Dispose of AVR Spent Fuel
  - 400 pebbles per canister
  - Cement matrix
  - On-Site Storage
    - Concrete waste storage building
    - No forced cooling
  - Dual Purpose Casks
    - Storage
    - Transportation

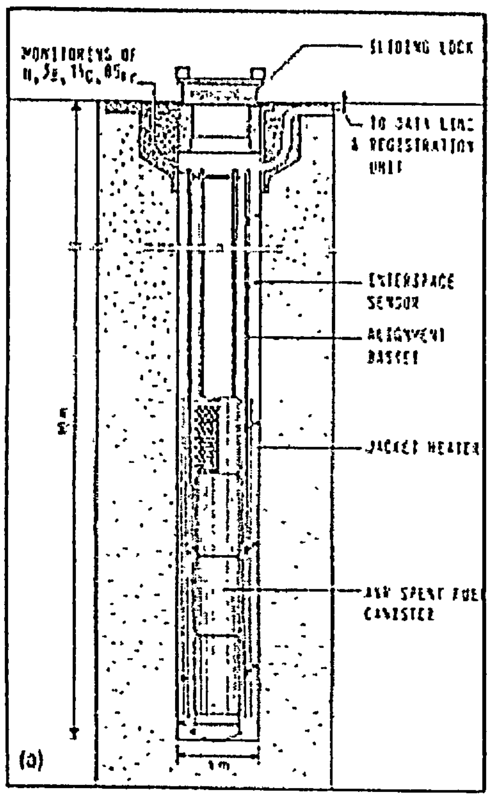
EX 5

Secondary System Operation

- Indirect Cycle
  - efficiency reduction
  - contamination control
  - simplification of control

- Cycle Control via Helium Pressure
  - inventory control
  - bypass control

Final Disposal



- Spent Fuel Characteristics
  - Low Activity
  - High Volume
  - Easy to handle
  - Extremely Durable
  - Pebble is a convenient waste form
- Long Term Storage effects must be studied

Secondary System / Construction Group Design Goals

- Evaluate adequacy of existing technologies
- Investigate alternatives to current designs
- Develop specific component design descriptions
- Develop system performance characteristics specific to our plant
- Determine feasibility of rapid plant construction
  - quantify influence of external factors
  - identify areas for improvement

Secondary System Operation

- Indirect Cycle
  - efficiency reduction
  - contamination control
  - simplification of control

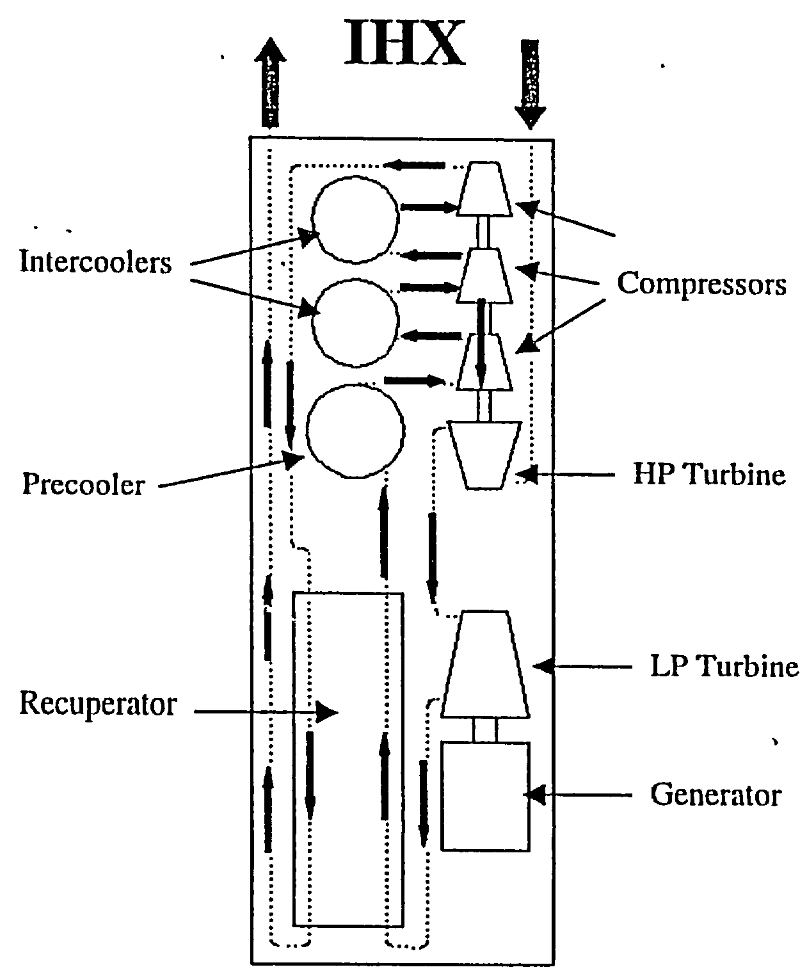
[redacted]

Ex 5

- Cycle Control via Helium Pressure
  - inventory control
  - bypass control

Major Components

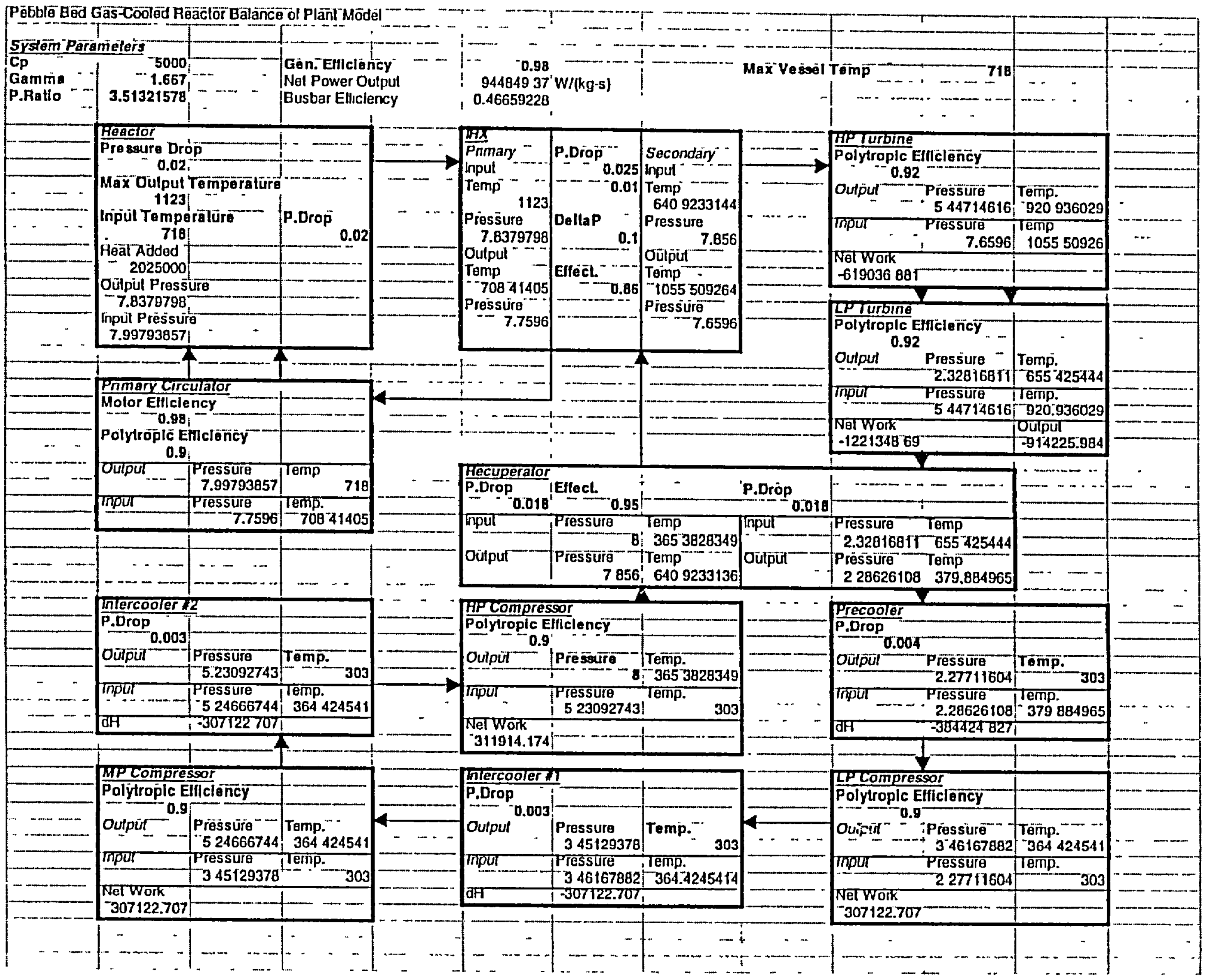
- IHX
- Turbomachinery
- Generator
- Recuperator
- Precooler / Intercoolers
- Heat sink



Turbomachinery

MPBR Turbine and Compressor Design Data					
Turbine			Compressor		
Parameter	HP	LP	LP	MP	HP
Machine Type	axial-flow		axial-flow, 2-stage intercooled		
Speed (rpm)	10,000	3600	10,000		
Power Rating (MW)	185	155	62	62	62
Load Driven	Comp.	Gen.	-----	-----	-----
Polytropic Efficiency	0.92	0.92	0.9	0.9	0.9
Pressure Ratio	2.26	2.59	1.84	1.84	1.84
Inlet Temperature (°C)	850	531	30	30	30
Inlet Pressure (MPa)	7.98	6.58	2.5	4.55	8.36
No. Of Stages	8	16	8	11	16
Max. Tip Diameter (m)	0.81	1.44	0.86	0.70	0.57
First Stage Hub-to-Tip Ratio	0.893	0.904	0.864	0.863	0.865
Last Stage Hub-to-Tip Ratio	0.835	0.836	0.899	0.899	0.900
Mean Stage Reaction	0.5	0.50	0.50	0.50	0.50
Mean Stage Loading Coefficient	1.19	1.22	0.34	0.38	0.38
Mean Flow Coefficient	0.51	0.47	0.52	0.54	0.53
Mean Blade Speed (m/s)	390	250	420	340	280
Max. Rotor Centrifugal Stress (kpsi)	-----	-----	14.4	9.54	6.4
Blade Material	Nickel-Base Alloy, IN-100				
Cost	$100/kWe '92 dollars				

Secondary Cycle Performance Model



Plant Construction

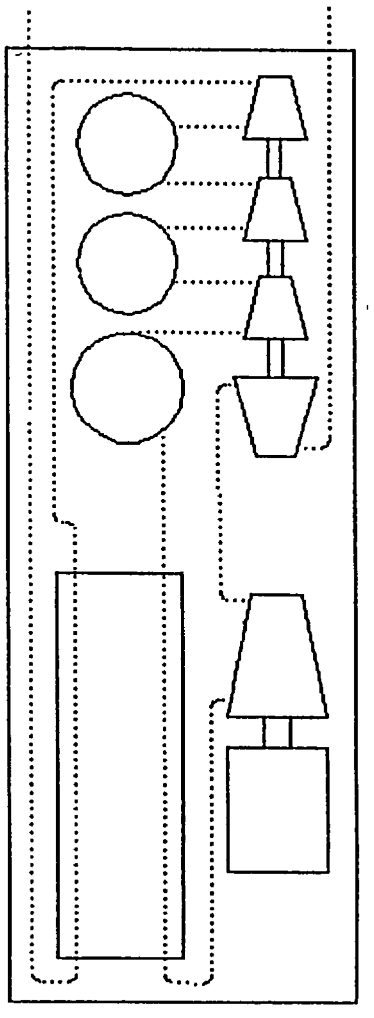
- Construction Plan / Techniques
- Plant Physical layout
- Construction Model

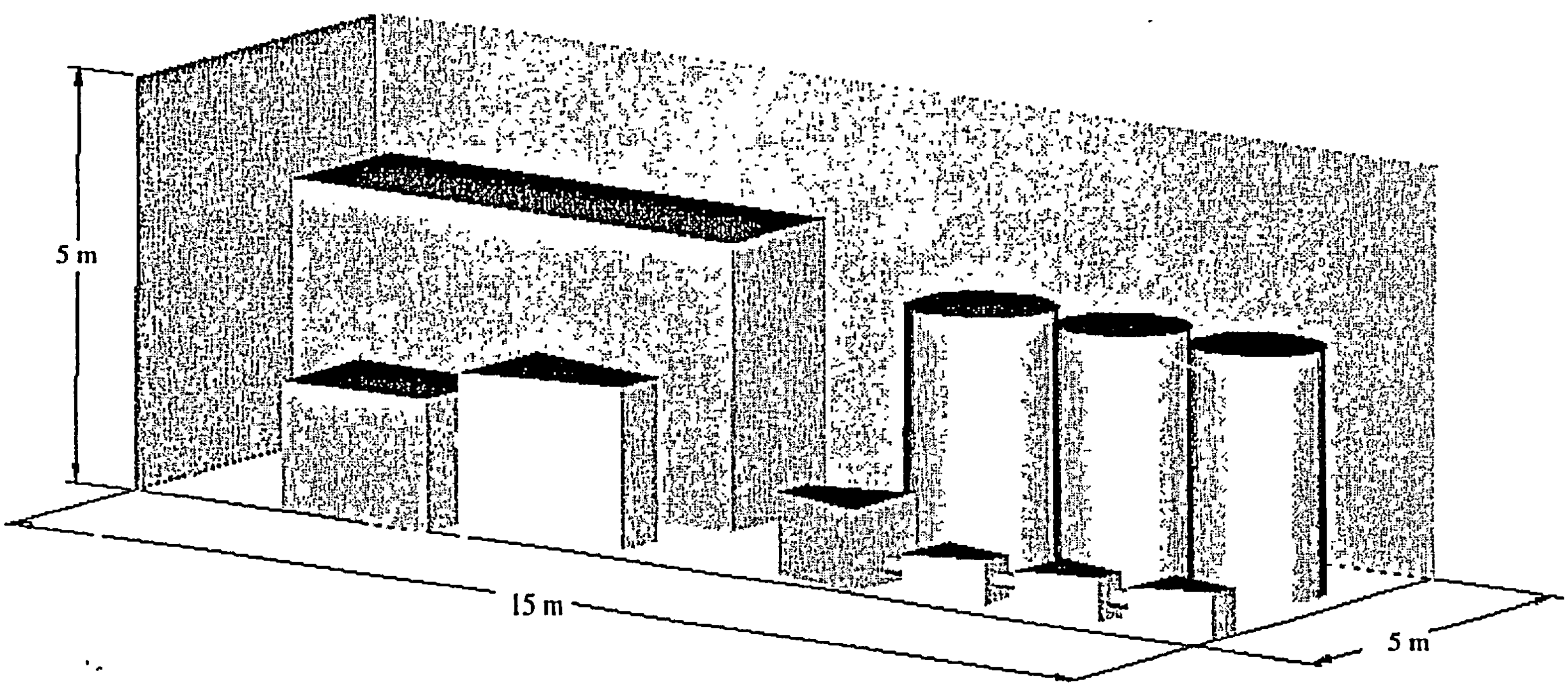
Construction Plan / Techniques

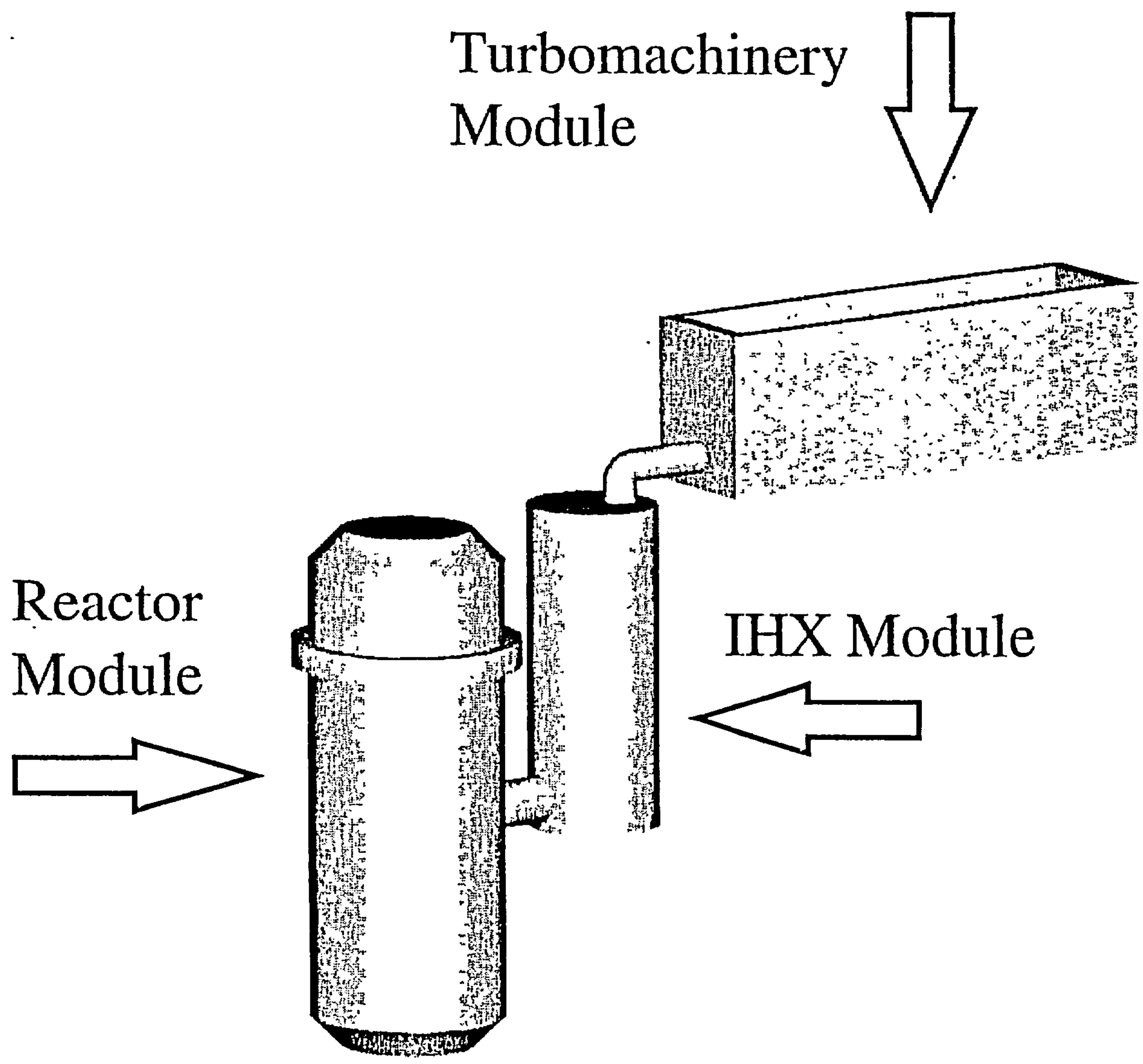
- Factory Assembly
- Existing Technology
- Modular Construction Allows:
  - Parallel Construction
  - Ease of Shipment
  - Rapid Assembly
  - Streamlined Testing

Power Generation Module

- Individual Components
- Centralized Module Assembly
- Pre-testing

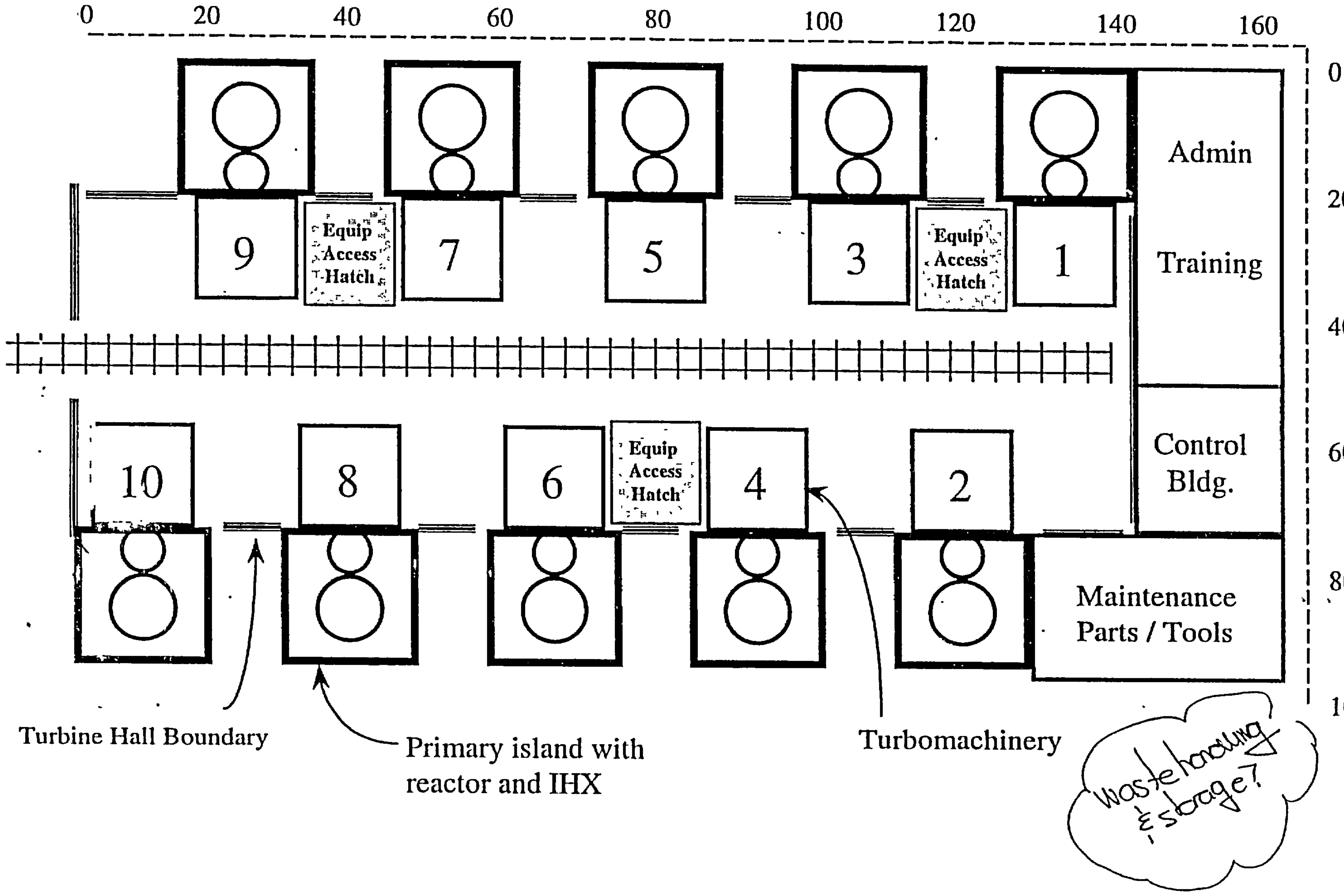



5 m
15 m
5 m


Turbomachinery
Module
Reactor
Module
IHX Module

Ten-Unit MPBR Plant Layout (Top View)

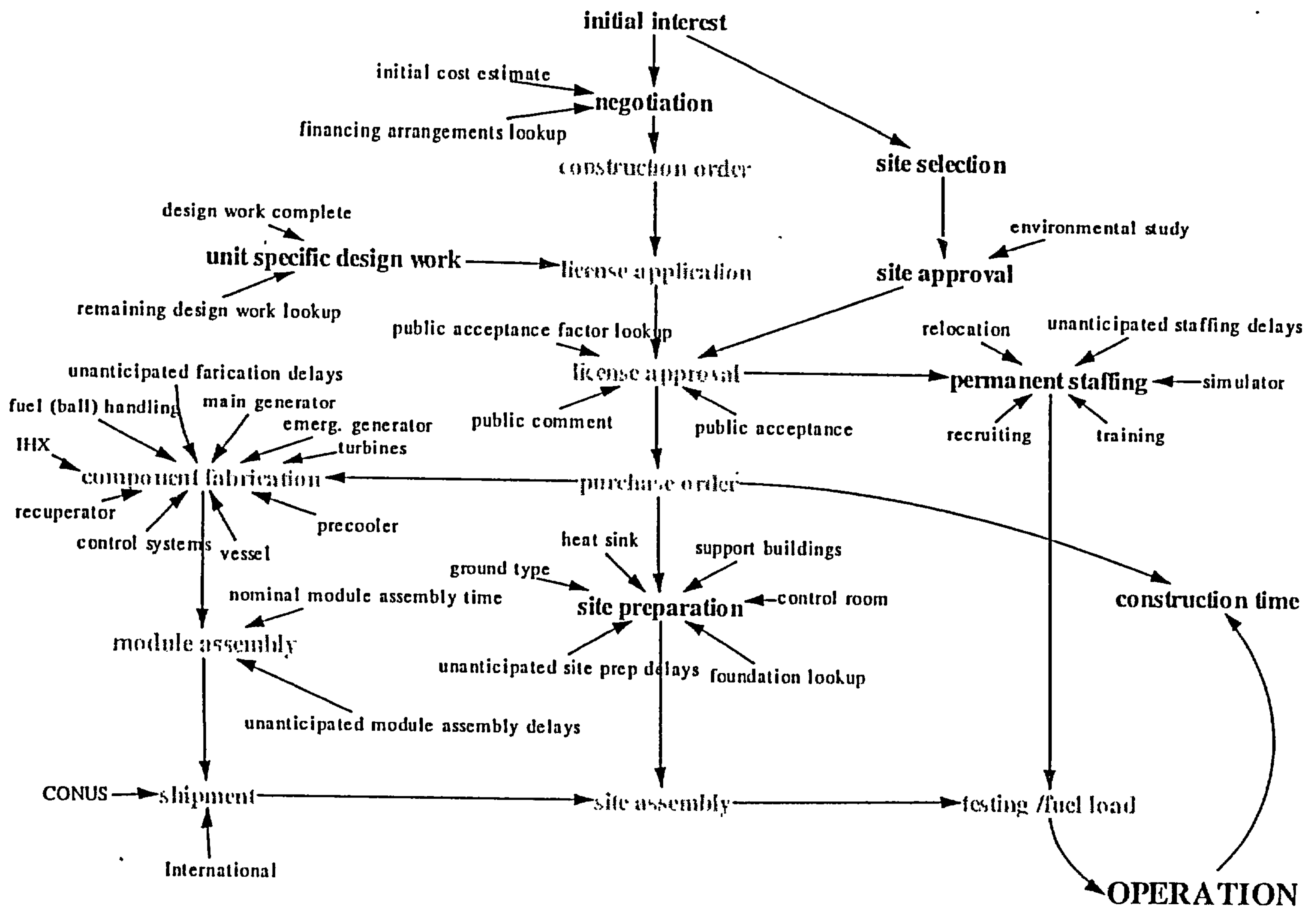
(distances in meters)



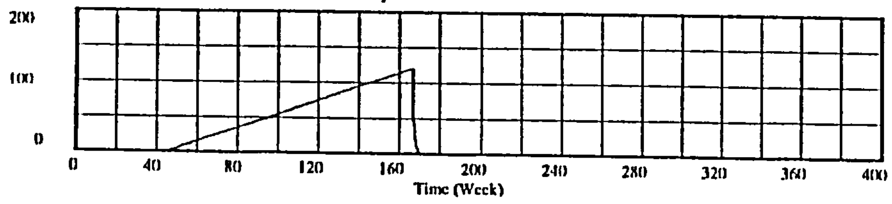
Construction Model

- Can it be done?
- Influence of external factors?
- What are vulnerabilities / areas for time and cost savings?
- What is the relationship between construction time and cash flow?
- Sensitivity analysis

Construction Flowpath for a Standard Unit

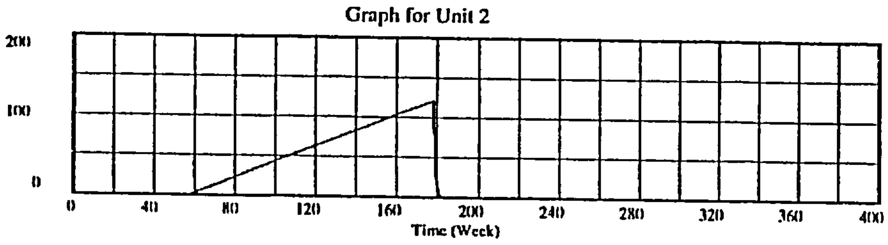


Graph for Unit 1



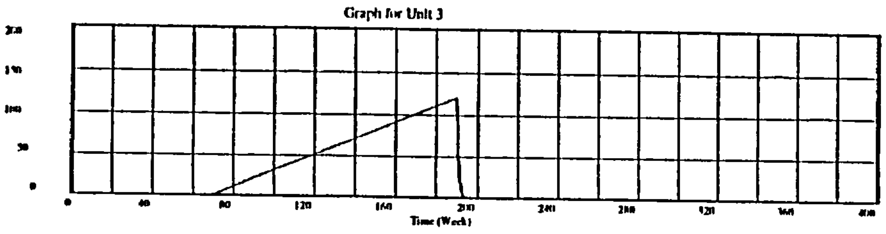
Unit 1 : Most Likely ______________________

Graph for Unit 2



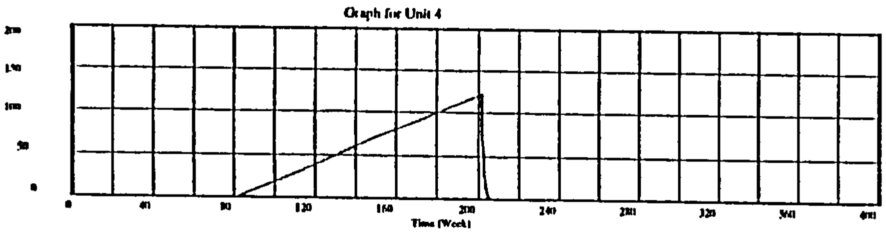
Unit 2 : Most Likely ______________________

Graph for Unit 3



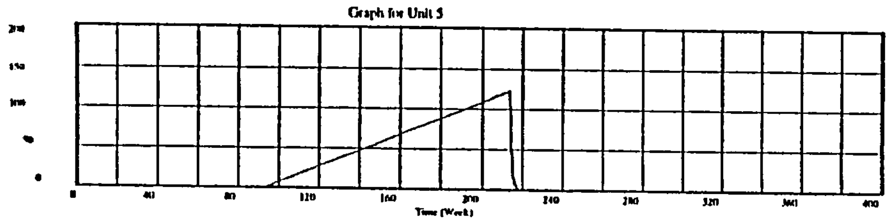
Unit 3 : Most Likely ______________________

Graph for Unit 4



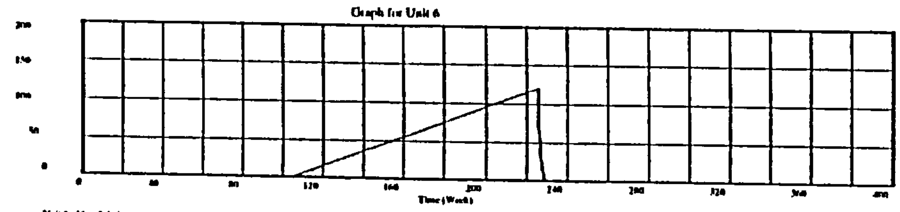
Unit 4 : Most Likely ______________________

Graph for Unit 5



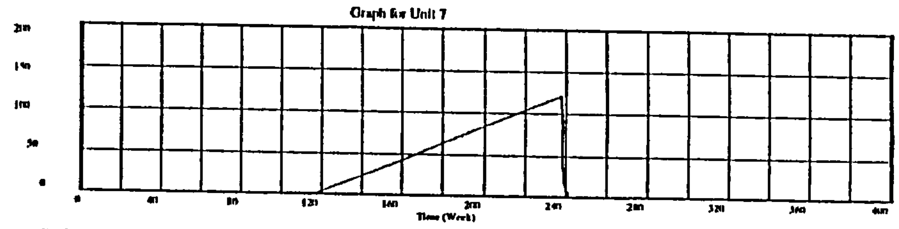
Unit 5 : Most Likely ______________________

Graph for Unit 6



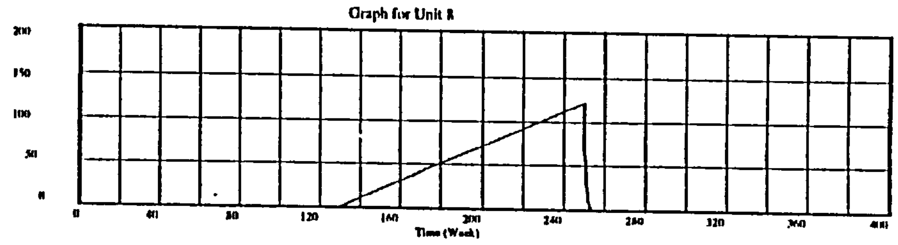
Unit 6 : Most Likely ______________________

Graph for Unit 7



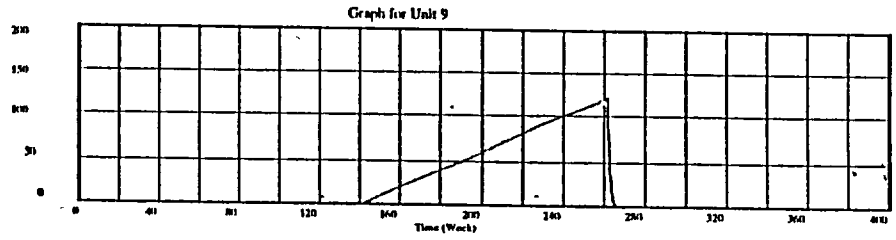
Unit 7 : Most Likely ______________________

Graph for Unit 8



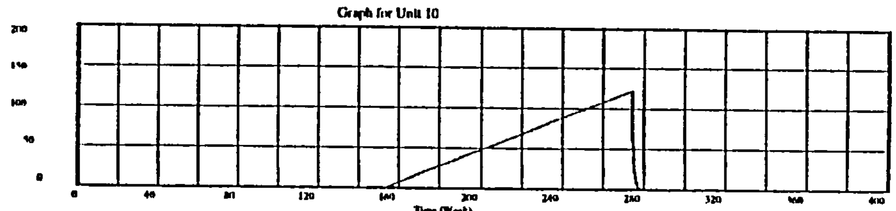
Unit 8 : Most Likely ______________________

Graph for Unit 9



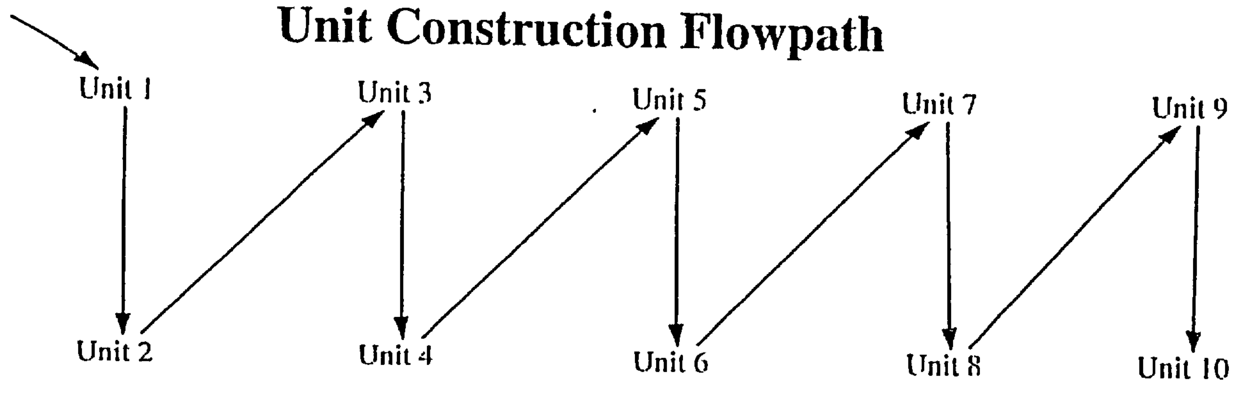
Unit 9 : Most Likely ______________________

Graph for Unit 10

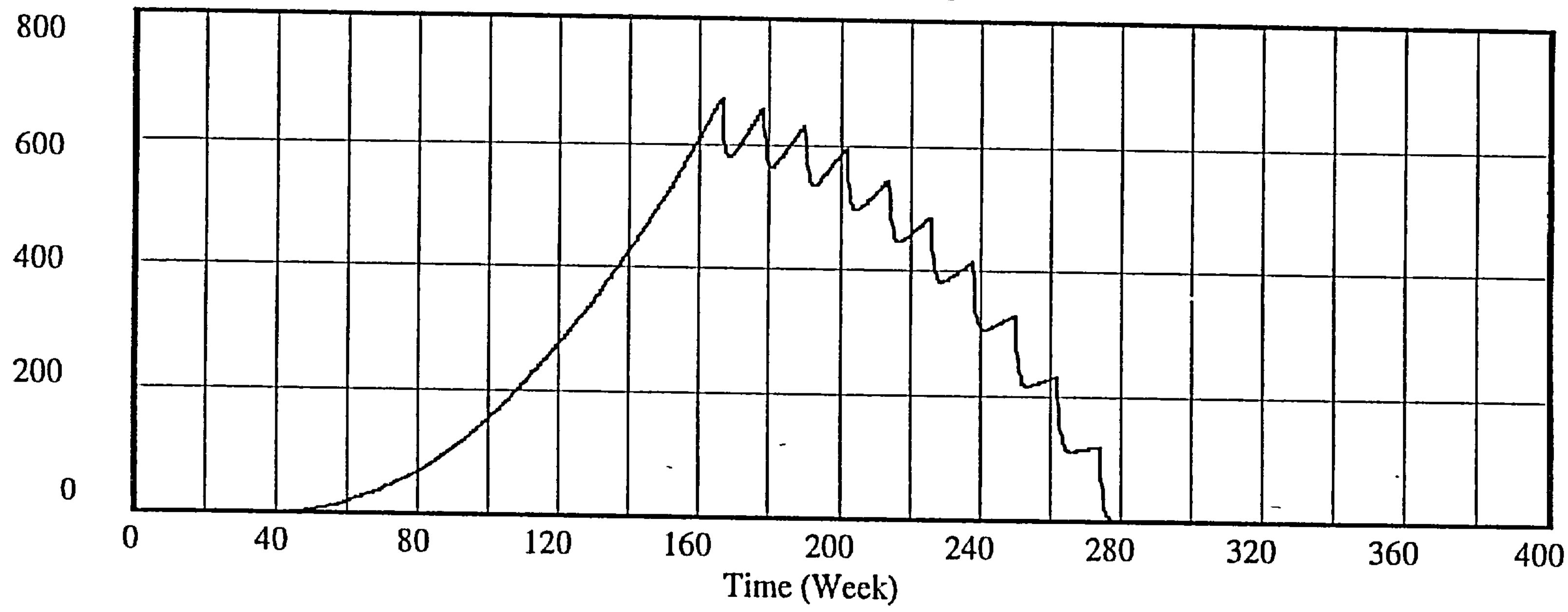


Unit 10 : Most Likely ______________________

Unit Construction Flowpath

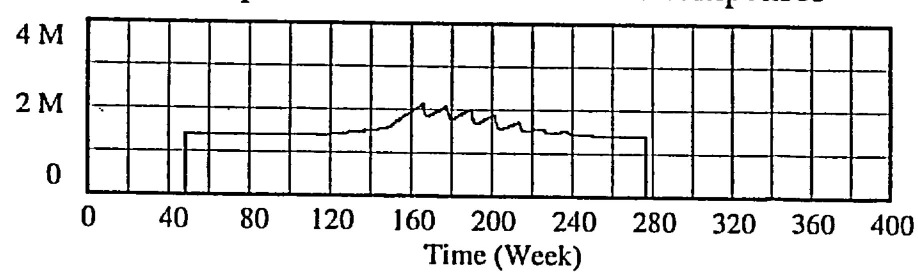


Graph for Instantaneous Work in Progress



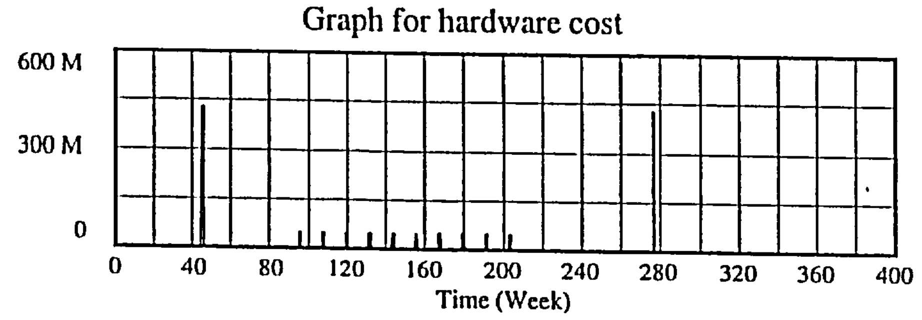
Instantaneous Work in Progress : Most Likely ———————— Week

Graph for Indirect Construction Expenses



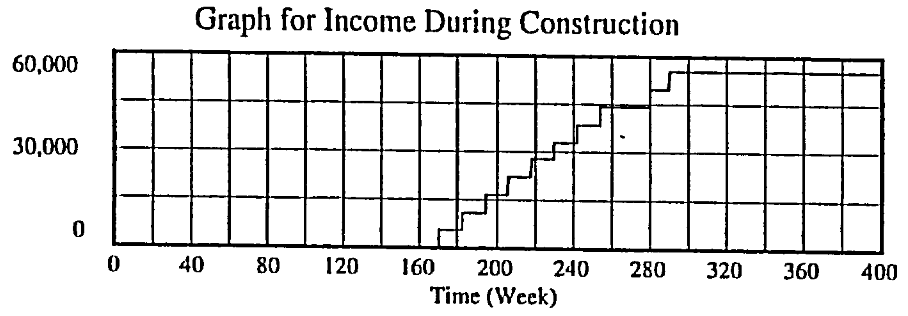
Indirect Construction Expenses : Most Likely ———— Dollars/Week

Graph for hardware cost



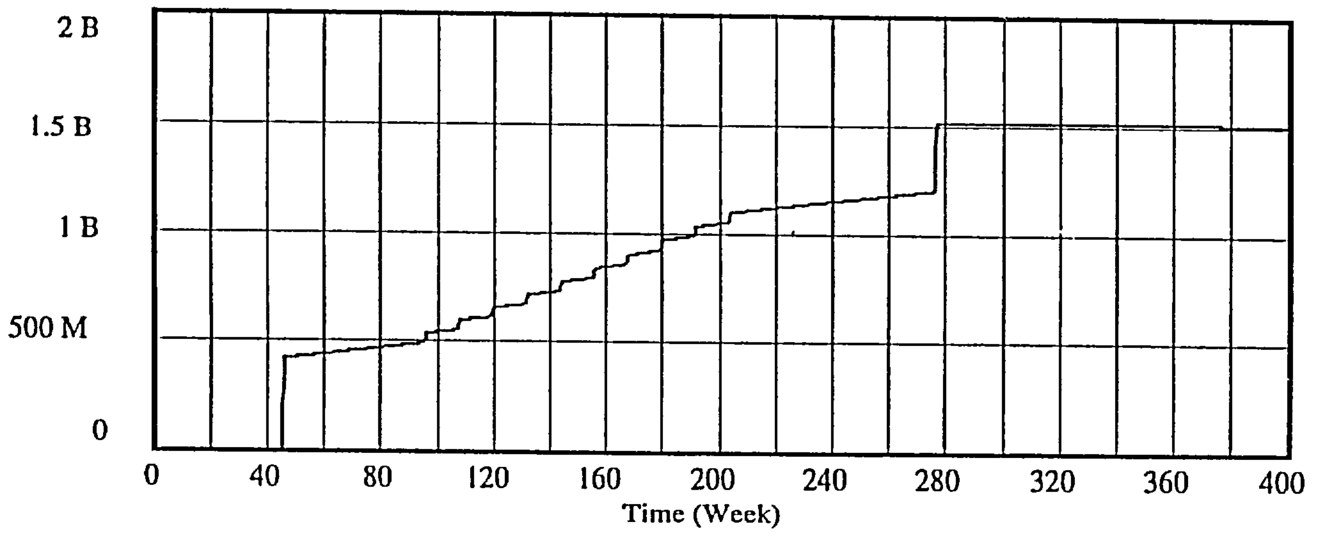
hardware cost : Most Likely ————

Graph for Income During Construction



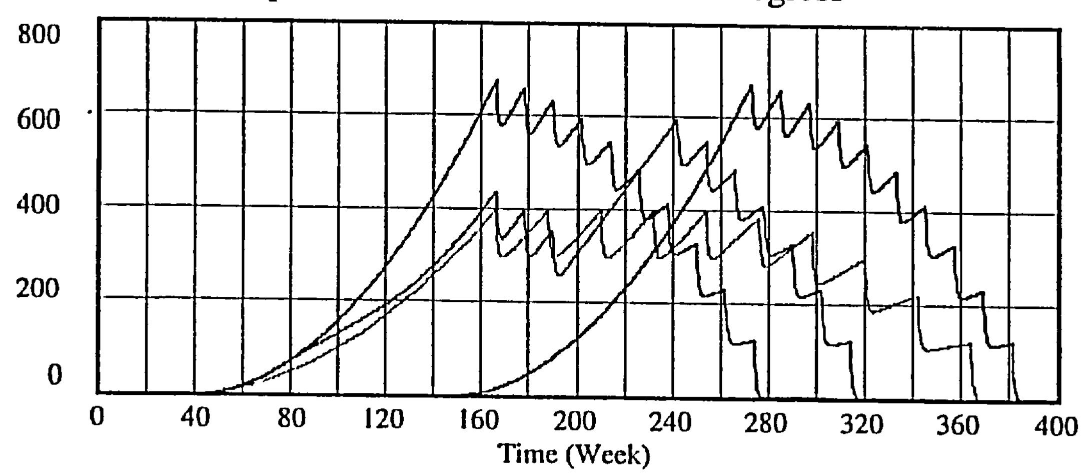
Income During Construction : Most Likely ———— Dollars/Week

Graph for Net Construction Expense



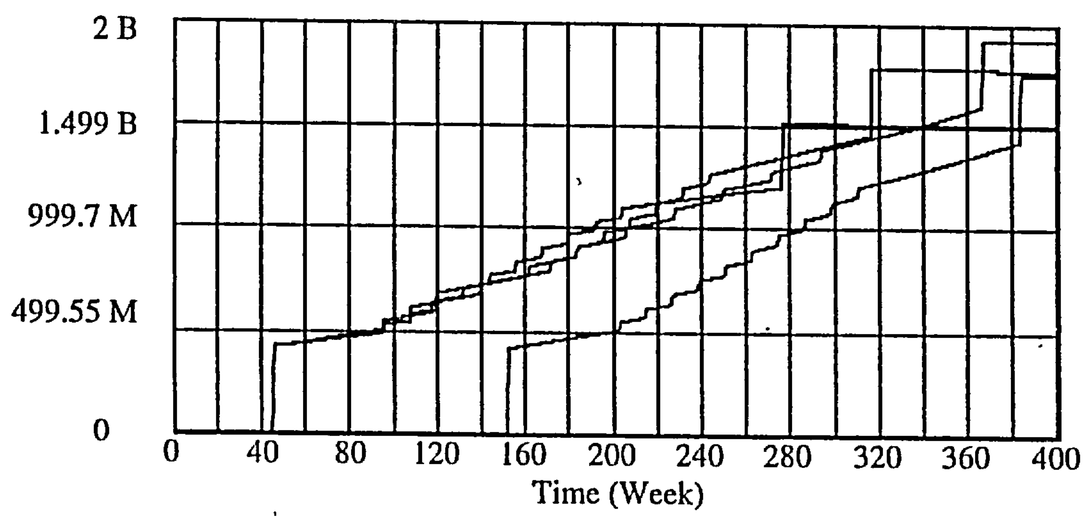
Net Construction Expense : Most Likely ————

Graph for Instantaneous Work in Progress



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



Net Construction Expense : Most Likely ——
Net Construction Expense : Unit-4 Hits Water ——
Net Construction Expense : Intervenors ——
Net Construction Expense : Module Delay ——

Economic Analysis

- Group Goals
  - determine cost estimate for construction
  - compare cost estimate with that of existing technologies
  - examine financing options
  - examine economies of scale vs. productivity

MPBR Cost Estimate

- Capital cost
- O&M cost
- Fuel cost
- Decommissioning cost

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

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

O&M Cost

- Simpler design and more compact
- Standardized units
- Small staff size: 150 personnel
- $31.5 million per year

Fuel Cost

- Assumptions:
  - One fuel pebble will cost $20.00 ('92$)
  - One third of the fuel pebble bed is replaced annually (120,000 per unit per year)
  - 1.0 mill/kWh for spent fuel disposal and radioactive waste management
- Cost: $32.7 million / year

Decommissioning Cost

- $211 million
- less than 1 mill/kWh levelized busbar cost

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

Cost Comparison ('92$)

- Levelized Generating Cost (cents/kWh)
  - 3.8 for ALWR1200
  - 3.62 for AP600
  - 4.2 for CCCT
  - 3.3 for MPBR

Financing Construction

- Cost of capital
  - debt-to-equity ratio
  - distribution of risk
- Consortium approach
  - share risk
  - lower return on investment

Amortization of debt

- Determine annual revenue requirements
  - debt-to-equity ratio
  - return on preferred equity
  - return on common equity
  - income taxes

Debt Service Coverage

- Ratio of total revenue generated to annual revenue required
  - depends on amortization length
  - distribution of risk
- Consortium approach best

Future Work

- Determine optimal capital structure
- Adjust cost estimate to design changes
- Create detailed cash flow statement

Major MPBR Conclusions

- Naturally Safe (Regulatory / Safety Implications)
  - Constrained by Fuel Particle failure above 1600°C
    - Core power density chosen as 3.54 MW/m^3
    - Fuel pebble manufacturing defects are the most significant source of fission product release
- Economically Competitive
  - 3.3 cents/kWhr (natural gas = 3.4 cents/kWhr)
    - Producing revenue within 3 years (rapid construction)
    - Low staffing and O&M costs
    - Factory Assembly
- Societal Acceptance
  - Proliferation Resistance -- promising, but future work needed
  - Waste Disposal -- promising, but future work needed

Future Work

- Optimization of Core Parameters
  - Diameter
  - Height
  - Average Power Density
- Better Understanding of Proliferation Issues
- Waste Disposal Plan
- Plant Layout and Maintenance
  - Reduction in Component Sizes
  - Control Systems Performance / Control Room Layout
  - Electrical Distribution
- Advanced Financing

Status of Tasks

This page contains links to any monthly, quarterly, and annual status reports. Links to all relevant reports will generally be made available within two weeks of the release dates. For information about scheduled events and project milestones, see the Schedule page.

Any specific updates with regard to the various research areas will be summarized here.

Fuel Particle Design (research updates):

During this reporting period MIT accomplished the following tasks: (1) A complete review of the current state of technology for coated particle fabrication and performance; (2) a review of the current state of the technology for coated particle failure modeling and; (3) based on the evaluation of the in-reactor test data for coated particle failure, a plan has been developed to improve the current failure model. Reviews were conducted of past INEEL tests of the General Atomics microsphere fuel compacts. The FUEL code was received, tested, and evaluated to determine its suitability for the work being planned.

Based on the analysis conducted thus far, the characteristics of the next generation failure model have been identified. The model will be based on a probabilistic fracture mechanics approach to the initiation and propagation of layer failure. Additionally the model will account for non-symmetric loading, which may result from localized debonding and/or layer cracking. Improved properties distributions, which more accurately represent fabricated bonds for layer dimensions, will also be incorporated. Lastly, finite element modeling for details of crack initiation, propagation and SiC/pyrocarbon layer failure will be used to validate the methodology used in the FUEL-II code. The new model will be jointly developed by the INEEL and MIT teams. In addition, silicon carbide was received and arrangements for the receipt of zirconium carbide were made to support the diffusion experiments to limit the silver diffusion through the fuel particle.

The INEEL used the ABAQUS stress analysis code to compute fuel particle stress distributions in particles with a variety of properties and defects, such as cracks in the outer and inner pyrolytic carbon layers and debonding between layers. These analyses provide insights into fuel failure mechanisms and the detailed thermo-mechanical response of fuel particles during irradiation.
Photomicrographs of fresh and irradiated fuel particles were examined. This information can help us resolve kernel swelling and carbon layer shrinkage issues. New correlations can be developed and compared with existing correlations.

Atomistic Basis for Radiation Damage of Fuel Materials (research updates):

The MIT effort on this task centered on the understanding of radiation damage in graphite. The graphite will be used as a test case for atomistic modeling of the effects of radiation damage of materials since there is a great deal of data available. The objective is to develop an atomistic model that can be used to predict behavior of fuel materials over time in the reactor environment. This information will be used as input to the fuel behavior model of the previous task. To date simple models have been developed for the simulation of long term behavior.

Spent Fuel Disposal (research updates):

This MIT task evaluated the loading requirements of pebble bed fuel in the Yucca Mountain repository. Since the pebble bed reactor is a low power density reactor, the volume of fuel is several times larger than that of equivalent light water reactor spent fuel. It is important to understand the implications of this on spent fuel disposal costs and repository performance. A preliminary conclusion has been reached that despite the higher volumes of spent fuel generated, the actual space required for the equivalent electricity generated is about 1/3 that of light water reactor spent fuel due to loading restrictions of the repository design. Data was obtained to model graphite dissolution to support experiments to determine radionuclide release potential through silicon carbide.

Non-Proliferation (research updates):

The primary activity on this task was developing a better understanding of proliferation issues and concerns. Literature reviews were performed on nuclear weapons design features and the fundamental characteristics of the discharged fuel from the pebble bed plant. The INEEL has begun to explore the use of thorium fuel cycles to enhance nonproliferation.

Thermal Hydraulics/Reactor Safety (research updates):

Past MIT work on gas reactor modeling was reviewed, and we determined that the code packages used were either not available or appropriate for this design. The simple heat balance calculations for the complete plant developed by the MIT study conducted in January 1998 were rerun to validate current design thinking. This simple model will be used for screening calculations until a more sophisticated code package is made available. A more detailed reference design is being established on a component level basis.

The INEEL performed a literature search on MPBR thermal hydraulics, installed the RELAP5/ATHENA code onto an INEEL HP712 workstation, and calculated the pressure drop across the pebble bed.

Neutronics (research updates):

The INEEL identified existing codes that can be used to model the neutronics of the MPBR. Questions remain about the availability of the German/South African codes such as VSOP. The transport code COMBINE was used to generate cross sections and neutron spectra for a standard (MIT) fuel pebble design and three different fuel particle types (HRB-21, NPR, and HFR-K5). Models of the three types of particles were incorporated into the pebble models. A pebble temperature distribution was computed using a two-region, one-dimensional spherical conduction-convection model and coolant temperatures based on ESKOM reactor design data. INEEL constructed an EXCEL spreadsheet that generates number densities, pebble temperatures, and other data required by COMBINE. The spreadsheet allows the user to vary enrichments, layer thicknesses, and other reference data in order to generate variations on the reference COMBINE model.

Cross section of the HTR primary circuit