



## TECHNICAL STATUS OF THE PEBBLE BED MODULAR REACTOR (PBMR-SA) CONCEPTUAL DESIGN

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### Abstract

The reactor study is well underway seen from a broad spectrum of disciplines and technology. The objective power output with a high efficiency direct cycle power conversion unit remains promising after compiling the first critical analysis of the core and the power conversion unit. The stability and controlability of the system are demonstrated by the engineering simulator.

The main system and components are basically specified for costing purposes. A first plant layout has been completed demonstrating the positions of main components, personnel movement, installation methods for large components etc.

A cryptic report style presentation includes study objectives, indicating guiding documents, giving an overview of design and analyses work done as well as a few sketches and diagram are included in this paper. Most of these sketches and diagrams are small replicas of large drawings and are therefore not readable but can be used as references.

### 1. OBJECTIVE OF STUDY (CONCEPTUAL DESIGN)

The following technical and economical questions have to be answered before any recommendations can be made.

#### **Technical Feasibility:**

- Can we achieve a sufficiently high reactor power output within the required safety criteria?
- Is the Brayton Cycle with three separate shafts stable? (See attached .diagram (1))
- Can we fulfill the clients operational requirements (operating profiles)?
- Can we prove high system efficiency claimed for HTGRS worldwide?
- Is this reactor as safe as internationally claimed (Is it inherent-, passive- and catastrophe free/safe, is it licensible)?
- Is the technology basis, internationally seen, to such a standard that basic research and development is not required and that a first-off full scale plant can be constructed directly as reference plant?
- Is modularization possible?

#### **Economic Feasibility:**

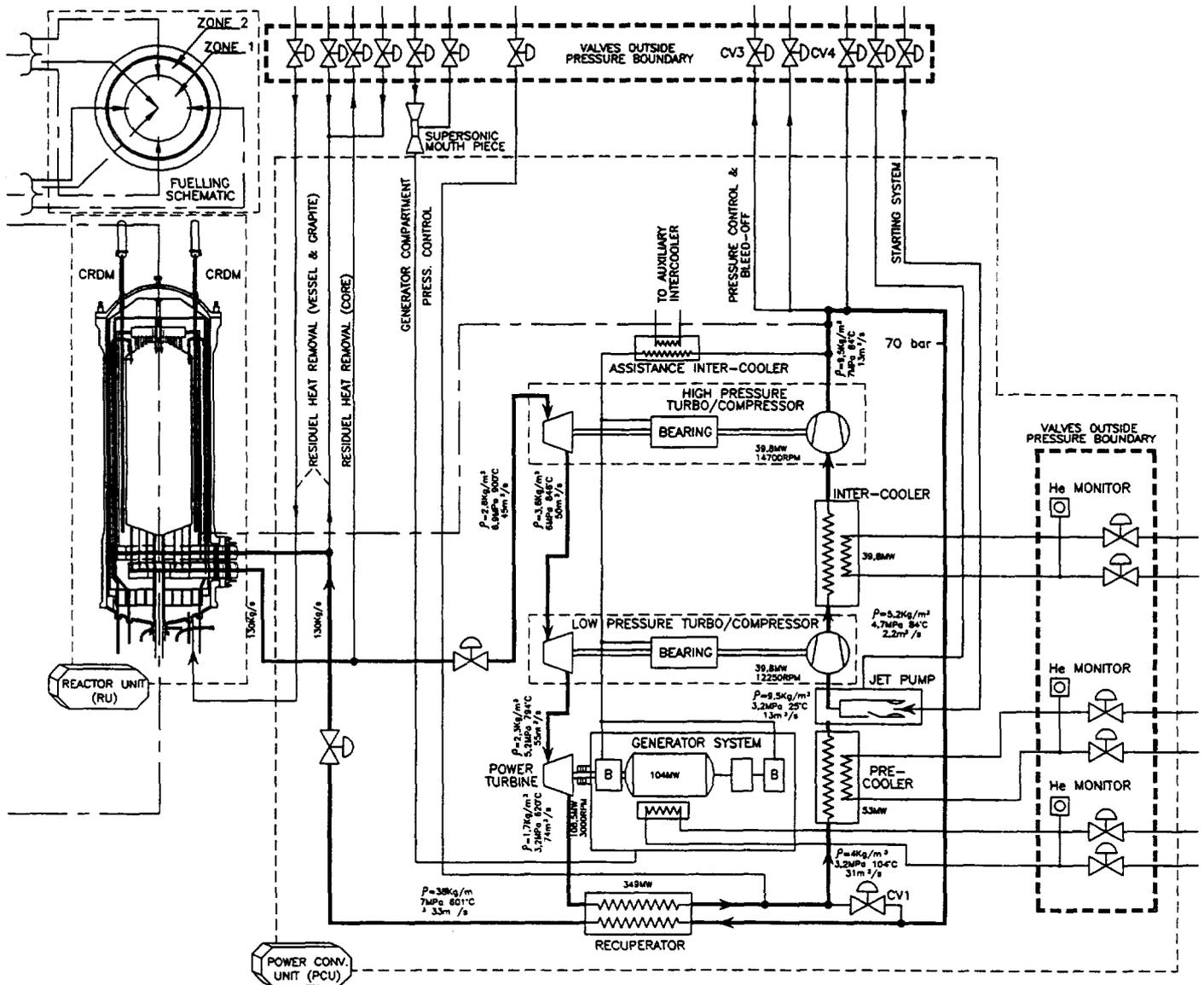
- Can we achieve the capital cost objectives for *first-off*, *pre-production* and *production* units?
- Is operational cost within the owners requirement specification?
- Is the owners investment protected by the said safety characteristics?

## 2. WORK PLANNING

The execution of work to meet the study objectives is basically captured in three diagrams, i.e.

**The Acquisition Plan indicating:** (See attached Figure 2)

- ◇ The global plan (long term planning)
- ◇ The prototype plant design and construction plan.
- ◇ The detailed conceptual design (1996 study) activities including milestones, milestone documentation and design reviews. (See attached Figure 3)

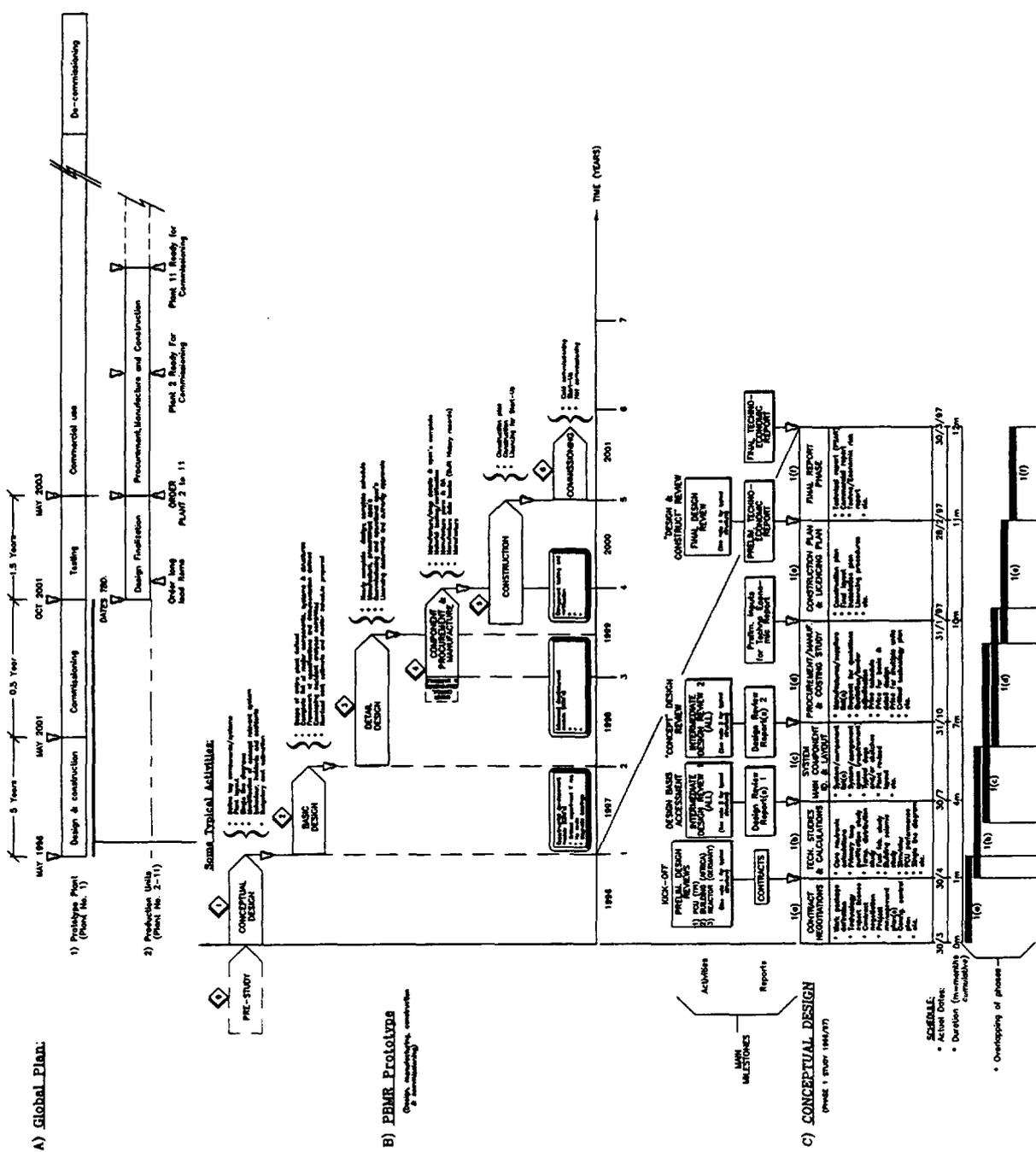


**MAIN POWER SYSTEM SCHEMATIC**

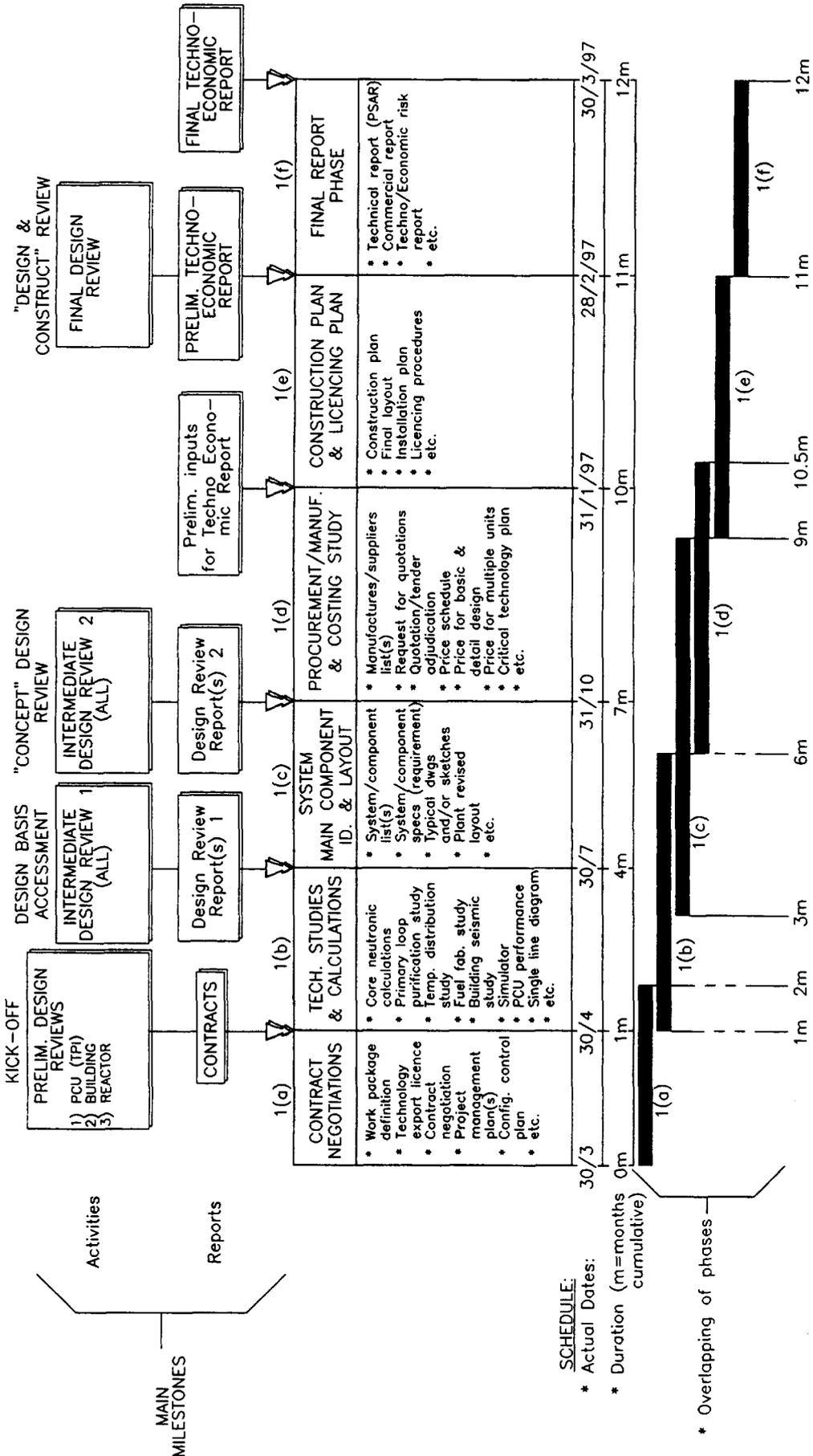
**FIG. 1**

**NOTES:**

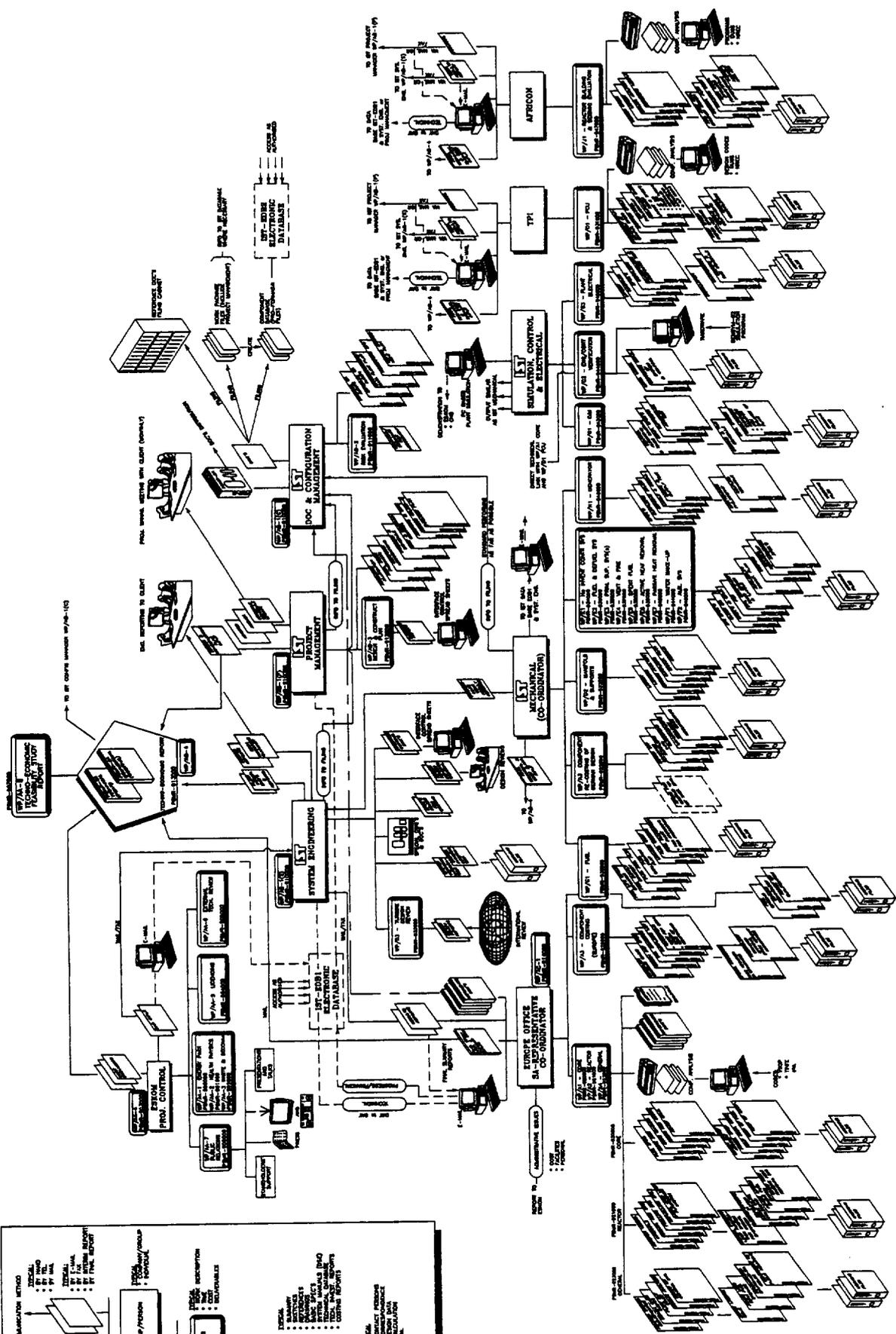
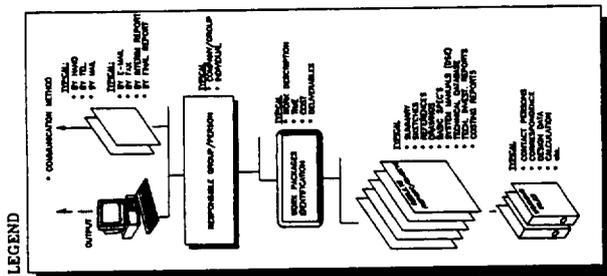
- 1) Preliminary design studies (CONCEPT DESIGN) (CONCEPT DESIGN)
  - a) Examples
    - German Technology (Chad)
    - Ingressives in Germany (epitaxial & core species)
    - PCU Work Package Needs
    - Control/Information Eng
    - Mechanical Eng (from TP)
  - b) Details
    - Work through reactor operating conditions eg
      - 1) NORMAL:
        - Starting study site
        - Ingressives
        - Steam routing
        - Heat
        - Emergency
      - 2) Update System Spec
      - 3) Safety Classification and Design
  - c) Details
    - The evolution, recommendations, assumptions etc. should be fully documented
    - An early start of an analysis is necessary to identify system functions and hardware
    - The system should be designed to meet the requirements of the system
    - The system should be designed to meet the requirements of the system
    - The system should be designed to meet the requirements of the system
- 2) Intermediate Design Studies (CONCEPT DESIGN) (CONCEPT DESIGN)
  - a) Examples
    - Representative of all major parties involved
  - b) Details
    - Design Basis Assessment
    - System Completeness
    - System Design Specification
    - Finalisation of Assumptions
    - Data/Technology/Information Base
  - c) Details
    - Design Review Output Report
    - Design Review Summary
    - Updated Assumptions List
    - Critical Component Identification
- 3) Intermediate Design Studies (CONCEPT DESIGN) (CONCEPT DESIGN)
  - a) Examples
    - Representative of all major parties involved
  - b) Details
    - Concept Design review
    - Layout
    - Critical Component Spec's Assessment
      - Safety
      - Reliability
    - Evaluation of Data Base
    - Costing Plan
  - c) Details
    - Design Review Output Report
    - Design Review Summary
    - Costing Plan
- 4) Final Design Studies (CONCEPT DESIGN) (CONCEPT DESIGN)
  - a) Examples
    - Representative of all major parties involved
  - b) Details
    - Design and Construction Review
    - Assessment of Critical Areas
    - Accuracy of Design
    - Accuracy of Costing
    - Proposal for Items for Techno Economic Report
    - Assessment of Preliminary Report's
  - c) Details
    - Design Review Output Report
    - Final inputs to Techno Economic Report
    - Critical Area/Item List
    - Identification of Future Studies (Critical Areas)



**PBMR ACQUISITION PLAN**  
**FIG. 2**



PBMR CONCEPTUAL DESIGN PLANNING  
FIG. 3



INFORMATION AND DATA FLOW PROCESS PLAN FOR PBMR PHASE 1 STUDY

FIG. 4

- **The Information and Data Flow Process Plan indicating:**  
(See attached Figure 4)
  - ◊ Flow of specialist data through the Systems Engineering and configuration management to the Final Report.
  - ◊ The use of communication methods e.g. paper copies, E-Mail, and Internet files.
  - ◊ Day-to-day database and system design data (System Manuals).
  - ◊ Licensing and international design reviews, etc.
- **Work Breakdown Structure indicating:**
  - ◊ The Architect Engineering responsibilities.
  - ◊ Other work packages and responsible parties.

### 3. THE WORKING TEAM

Presently a wide range of engineering disciplines are involved (*excluding* major manufacturing companies contribution):

Discipline	LOCAL		OVERSEAS CONSULTANTS
	Full time	Part time	
• Management, Promotion and Marketing	1	2	2
• Reactor Physics includes core design, shielding etc.	1		5
• Mechanical Systems & components	4	3	4
• Electrical and Control	2	2	
• Fuel		3	2
• Simulation		2	
• Special Materials Studies	2	2	2
• Reactor Building		3	
• Safety and Licensing	1	2	
• Documentation/Data Control	1	1	
<b>TOTAL</b>	<b>12</b>	<b>20</b>	<b>15</b>

A total of 47 technical and management, plus 3 administrative people involved, of which all technical people have vast nuclear experience.

4. **PLANT IMPORTANT FEATURES AND SPECIFICATION; AN ABSTRACT FROM OVERALL DESIGN BASIS** (See attached Figure 5)

CHARACTERISTIC (OBJECTIVE)	STATUS/REMARKS
<ul style="list-style-type: none"> <li>• 220 MW<sub>TH</sub></li> </ul>	Achieved
<ul style="list-style-type: none"> <li>• Pebble Bed Core</li> </ul>	Accepted
<ul style="list-style-type: none"> <li>• Fuelling scheme               <ul style="list-style-type: none"> <li>◊ on-line recycle</li> <li>◊ on line or off-line OTTO-P, use burnable poisons</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Recycle scheme accepted as reference</li> <li>• OTTO-P has good potential</li> </ul>
<ul style="list-style-type: none"> <li>• Modular design to suite most sites</li> </ul>	A compromised design approach is followed. eg. depth below ground level, seismic spectra etc.
<ul style="list-style-type: none"> <li>• Net power range 0 to 100%</li> </ul>	Full range load following possible (specified power step and ramping under discussion)
<ul style="list-style-type: none"> <li>• Spent fuel remains inside reactor building.</li> </ul>	<ul style="list-style-type: none"> <li>• Sufficient space for 20 full power years.</li> <li>• Passive, natural air cooling to be analysed still.</li> </ul>
<ul style="list-style-type: none"> <li>• Passive residual heat removal.</li> </ul>	<ul style="list-style-type: none"> <li>• Possible by natural air circulation.</li> <li>• Possible by water/air system.</li> <li>• Reactor vessel maximum temperature, and allowable temperature gradients through the wall under consideration.</li> </ul>
<ul style="list-style-type: none"> <li>• No active safety related systems required. (Therefore a new definition for Reactor Protection System).</li> </ul>	Believing the strong negative temperature coefficient of reactivity and believe the core neutronic design codes, e.g. the temperature of the fuel can never exceed the maximum safe allowable temperature under most extreme postulated accidents.
<ul style="list-style-type: none"> <li>• Core outlet temperature - 900°C.</li> </ul>	Limit by turbo-machinery maximum allowable temperatures ( specific technology limitation).
<ul style="list-style-type: none"> <li>• Core inlet temperature <math>\approx</math> 560°C for optimized cycle efficiency.</li> </ul>	This temperature exceeds allowable temperature for RPV materials (creep). The reactor coolant flow path design allows for this

	high temperature return gas.
<ul style="list-style-type: none"> <li>Reactor vessel operates at low temperature. (120°C)</li> </ul>	Introduce recuperator bypass for cooling purposes. This results in poor efficiency at low inventory operation.
<ul style="list-style-type: none"> <li>System maximum pressure = 70 bar</li> </ul>	Followed world trends. Cost vs. pressure optimization is not done.
<ul style="list-style-type: none"> <li>Minimum absolute pressure variation in the Alternator compartment.</li> </ul>	Achieved by orientation of power turbine to ensure minimum abs. pressure at shaft Labyrinth seal. This principle may change because of other considerations.
<ul style="list-style-type: none"> <li>All magnetic bearings.</li> </ul>	<ul style="list-style-type: none"> <li>He cooled</li> <li>No oil.</li> <li>Low maintenance</li> <li>Behaviour under environmental conditions to be investigated.</li> </ul>
<ul style="list-style-type: none"> <li>Water ingress into reactor impossible.</li> </ul>	<ul style="list-style-type: none"> <li>Cooling water pressure always lower than primary loop helium pressure under operational conditions.</li> <li>Total water inventory can be collected in the heat exchanger pressure housings.</li> </ul>
<ul style="list-style-type: none"> <li>Easy access to first turbine and generator.</li> </ul>	Housed in pressure containing housings (bells) which can be removed fairly easy. Couplings to pipes under investigation, e.g. for ease of removal.
<ul style="list-style-type: none"> <li>Design approach based on "many-off" and continuous production.</li> </ul>	
<ul style="list-style-type: none"> <li>Short construction time.</li> </ul>	Equipment grouped as modules, mounted on skids and factory tested. Civil construction after installation of equipment should be avoided.
<ul style="list-style-type: none"> <li>Installation and maintenance equipment to be shared between units.</li> </ul>	Capital cost for these equipment shared between units.
<ul style="list-style-type: none"> <li>Reactor building to be a low pressure confinement</li> </ul>	<ul style="list-style-type: none"> <li>A proper containment building is not required.</li> </ul>

	<ul style="list-style-type: none"> <li>• Break disks with large flow filters provided (Provide for blowdown accident)</li> <li>• Building act as energy absorber for aeroplane crash. Penetration of larger/faster aeroplane components possible. The reactor pit is the ultimate barrier.</li> </ul>
<ul style="list-style-type: none"> <li>• A gaseous waste system not required</li> </ul>	This topic is under discussion.

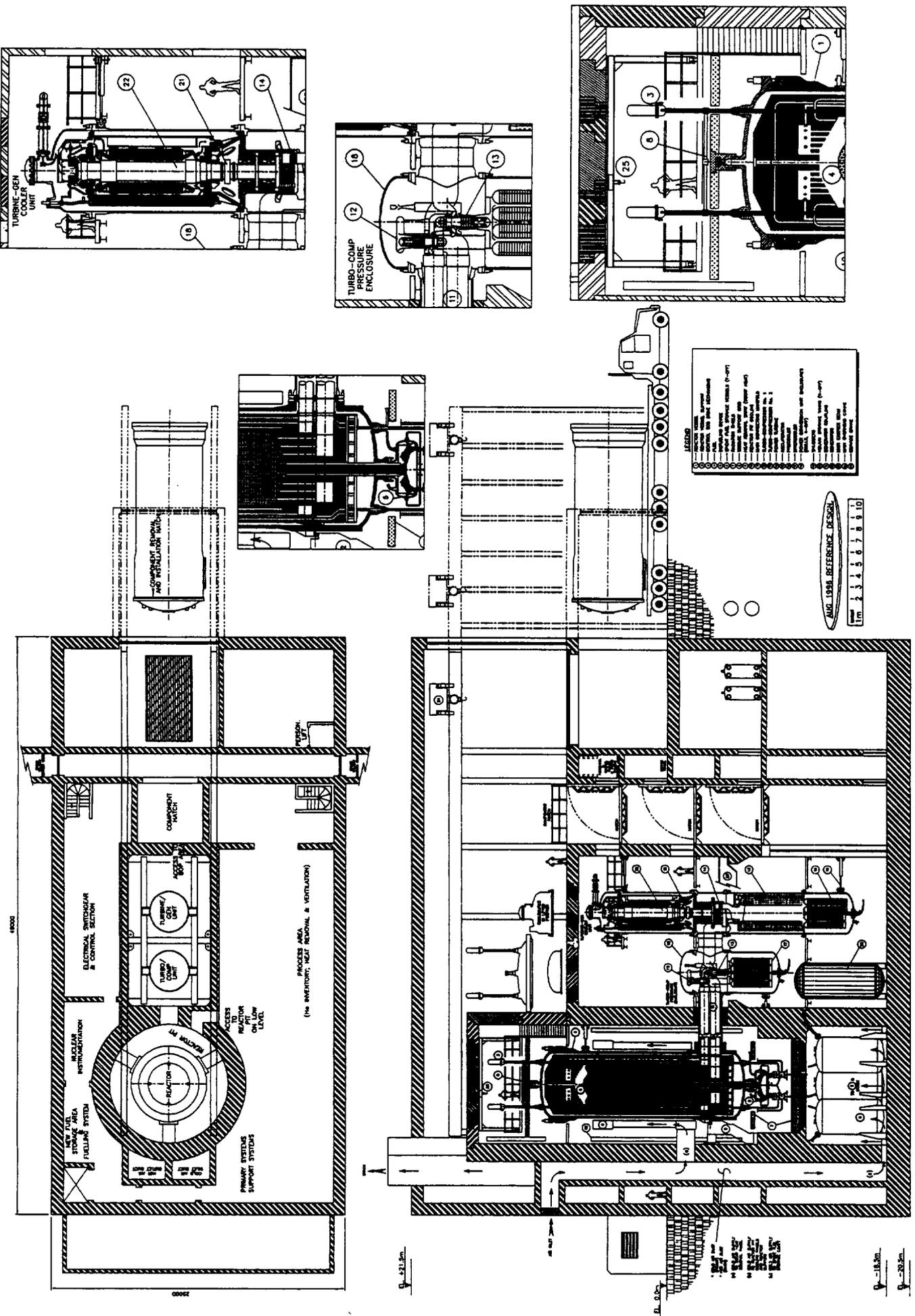
## 5. MAIN GUIDANCE DOCUMENTS

Apart from the Work breakdown structures, Hardware breakdown structures, time schedules etc., the following technical documents were compiled:

TOPIC	PURPOSE	STATUS
Technical Description.	Consolidation of 1995 discussions.	Outdated.
Quality Assurance Plan for the PBMR-SA.	Acquisition, information and data flow plans for the conceptual design study.	Active.
Overall plant Specification and Interface Control Document.	Quick reference of the plant characteristics and change control thereof.	Active.
Index of Techno-Economic Feasibility Study Report. Volume 1 - Commercial Volume 2 - Technical Description		Done
Design bases for most of the systems and main components.	Input for conceptual design of systems and components.	Done

## 6. PLANT OVERALL PROCESS AND LAYOUT.

- Overall process diagram has been developed. (See attached Figure 6)
- The systems have been functionally grouped for example
  - a) **Active Heat Removal** includes all active heat removal functions.
  - b) **Main Power System** includes all primary components needed for prime power production (this includes the alternator).
  - c) **Helium Inventory Control System** includes helium make-up, primary loop cleanup and inventory control etc.).



PEBBLE BED MODULAR REACTOR CONCEPT (100MWe)

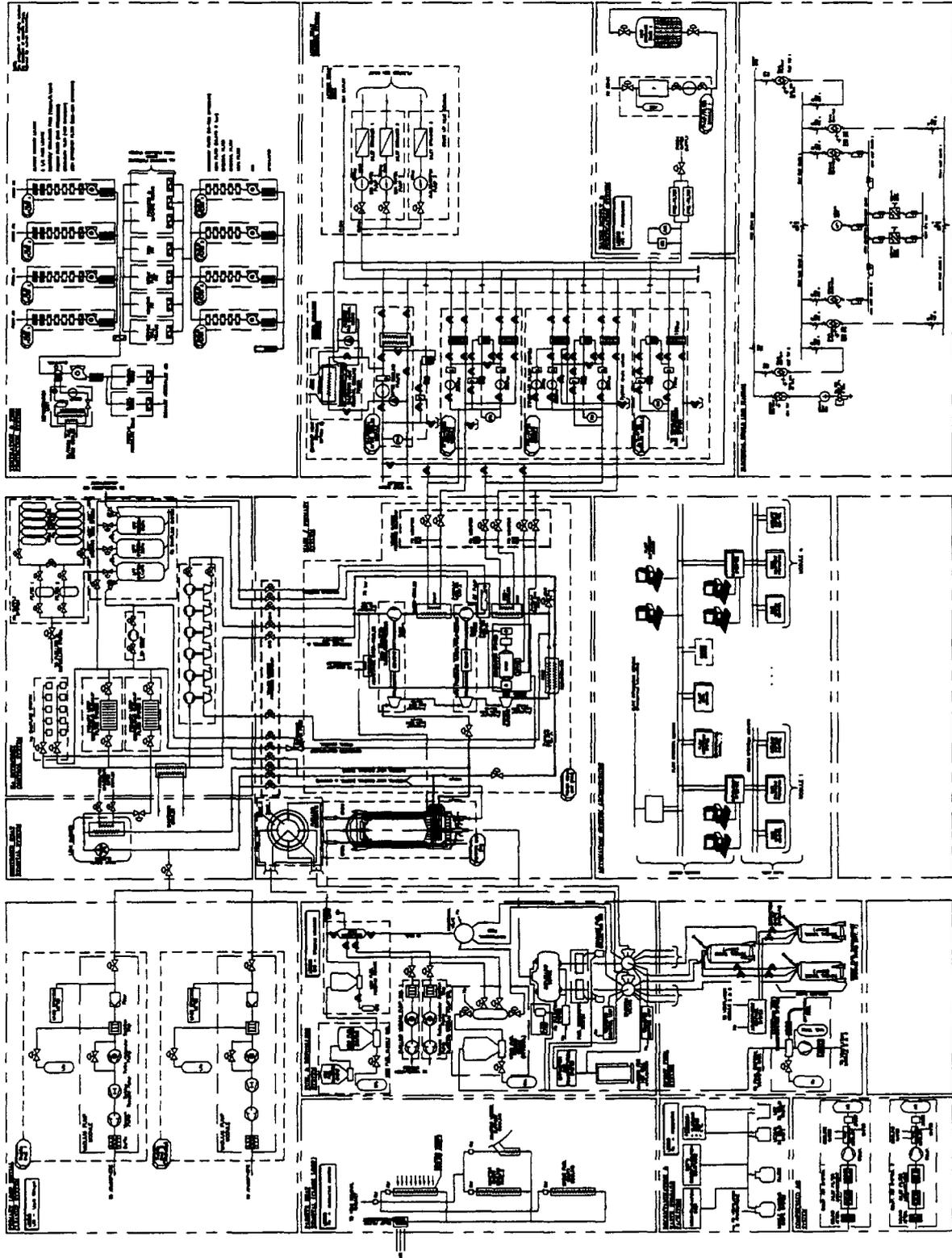
FIG. 5

REVISION "C" NOTES:  
 THIS DIAGRAM IS BASED ON DISCUSSIONS  
 DURING THE PRELIMINARY DESIGN JUNE 1998

CHANGES TO THE PREVIOUS ISSUE--

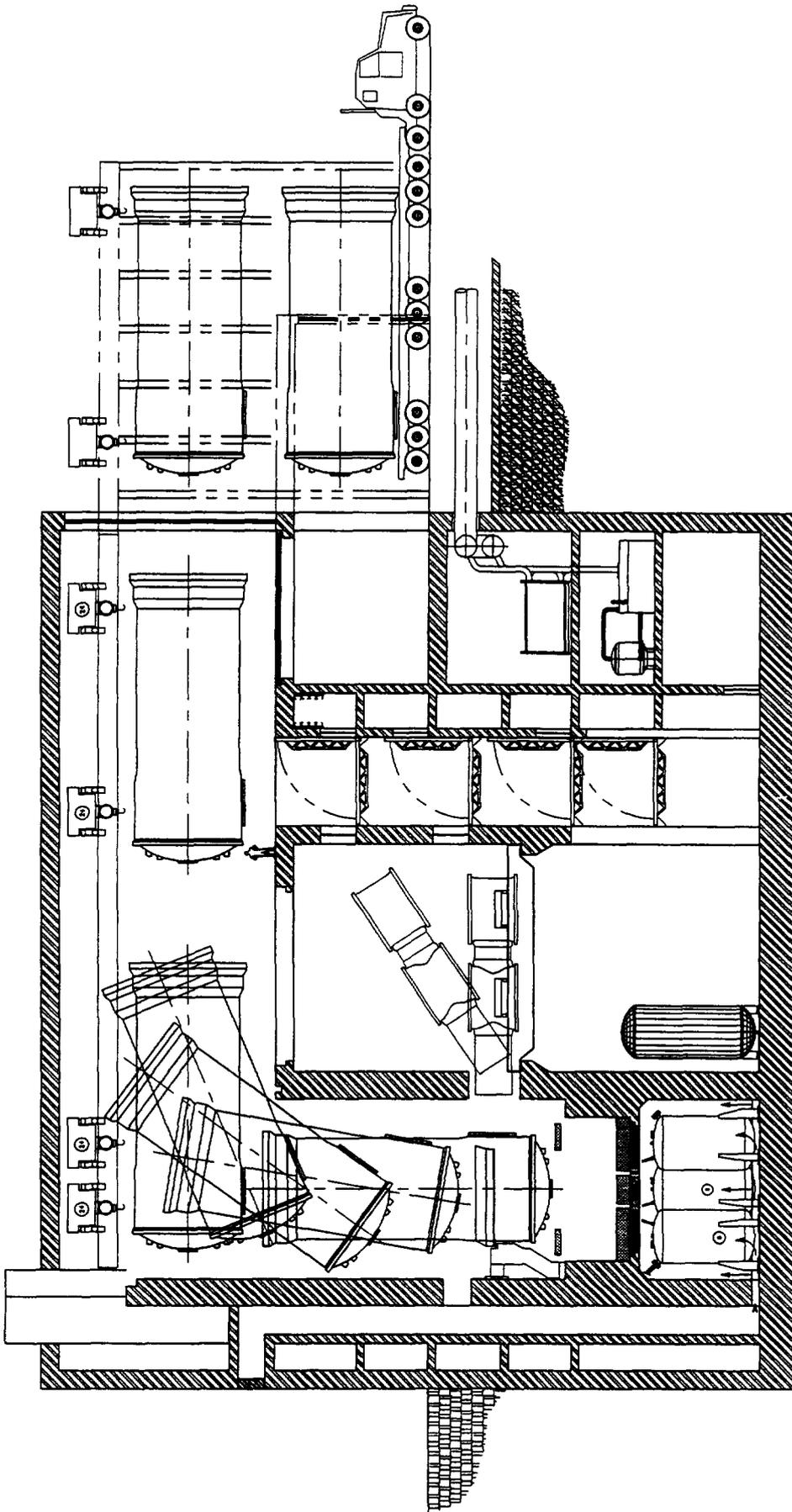
- RECYCLING OF FUEL (SEE ZONE 3 FUELLING SCHEM) (1)
- MULTIPLE SMALLER SPURT FUEL TANKS
- FUEL INJECTION IN GENERATOR COMPARTMENT
- REACTOR PRESSURE ZONE SEPARATION

REVISION "C" NOTES:  
 UPDATED THE INVENTORY CONTROL SYSTEM



PBMR - OVERALL SCHEMATIC DIAGRAM

FIG. 6



PBMR-SA PEBBLE BED REACTOR VESSEL INSTALLATION

FIG. 7

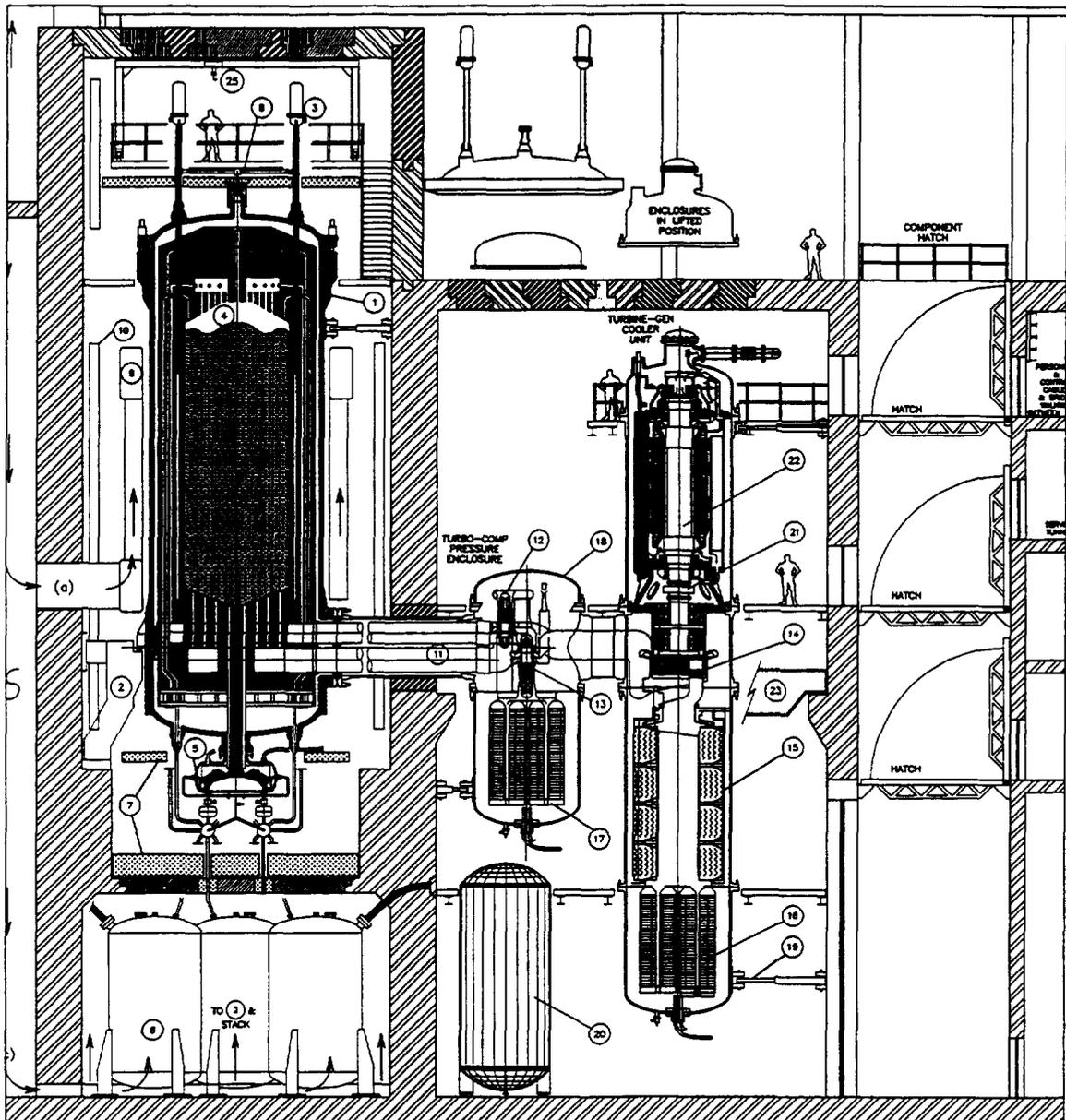
- The plant is designed in order to make extension possible (addition of a new modules) without hampering the operation of the other units.
- Space in the building is not yet optimized. Allocation of physical space for functional systems is to a large extent done.

## 7. SPECIAL STUDIES AND ANALYSIS

The following special studies have been done or approach completion.

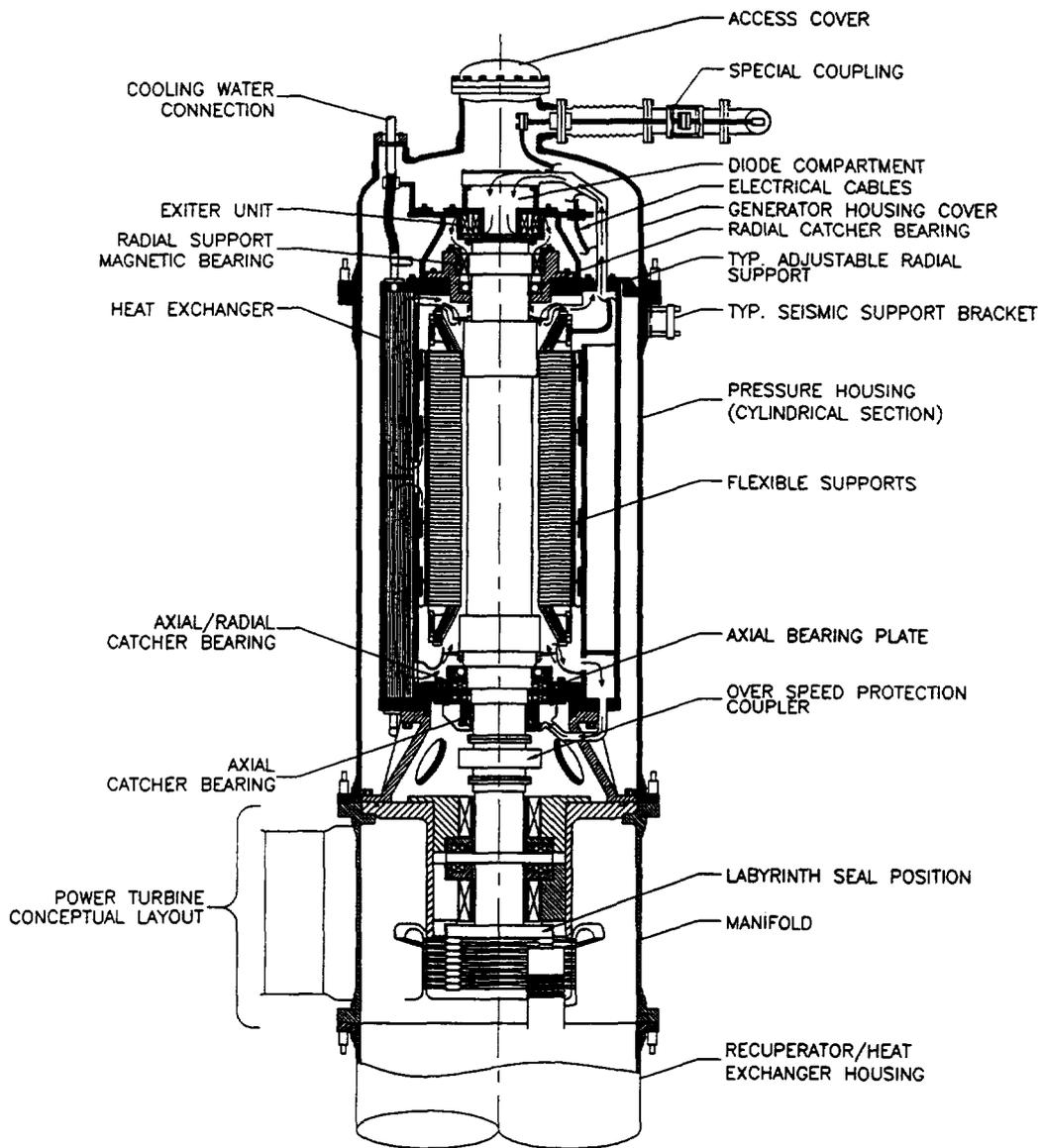
(See attached Figure 7)

- Installation of the reactor vessel.
- Reactor layout (See attached Figure 8)
- PCU layout.



MAIN POWER SYSTEM

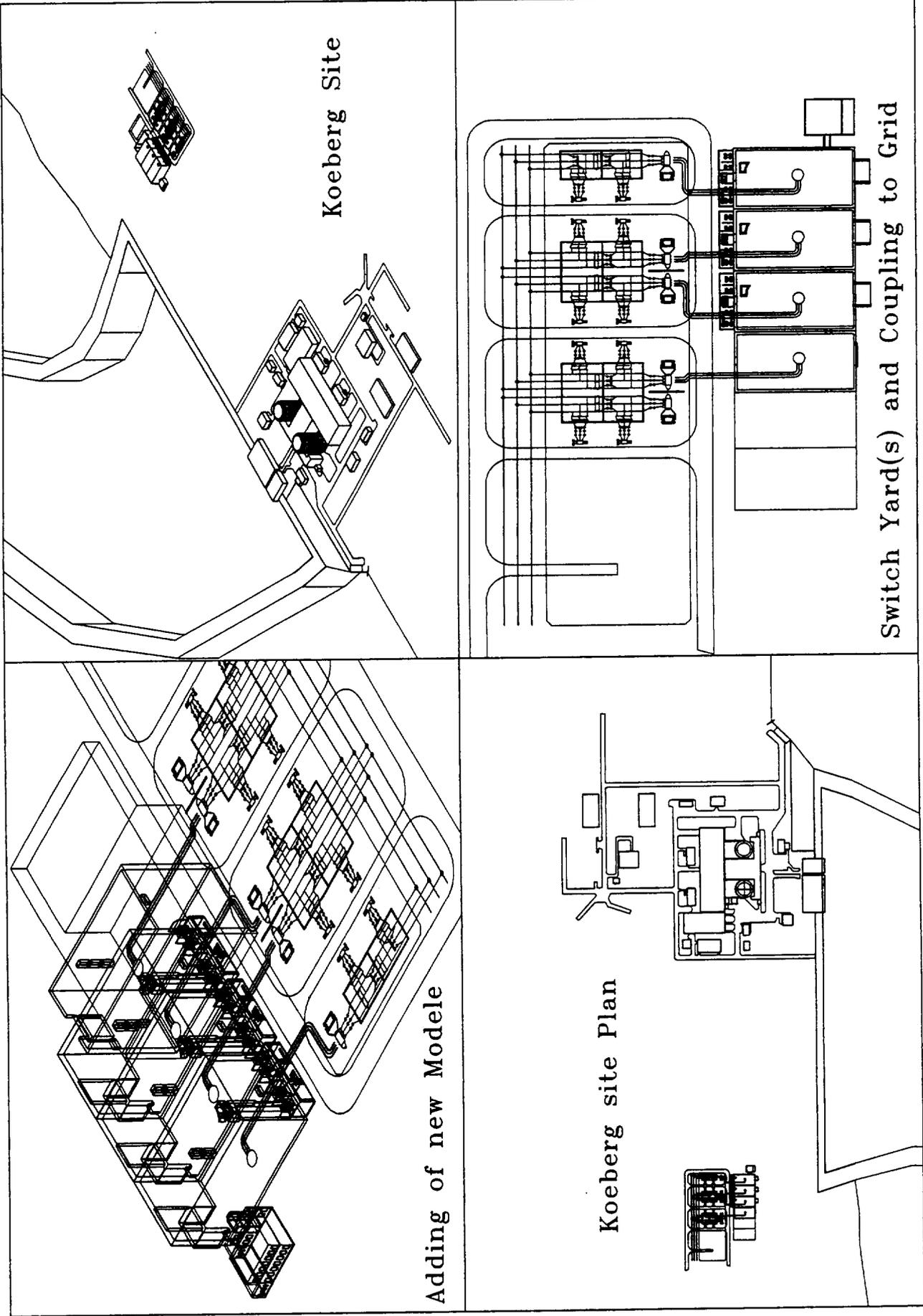
FIG. 8



## GENERATOR CONCEPTUAL LAYOUT

FIG. 9

- Connecting of PCU to reactor.
- Different helium inventory control system proposals.
- PCU system and component performances.
- Reactor core performance.
- Pressure and temperature equalization following a reactor trip.
- Electrical *house* power demand study.
- Passive heat removal analyses (including the chimney).
- Reactor vessel thermal stress sensitivity (sensitivity study)
- Reactor building and main power system seismic behaviour.



Koeberg Site

Switch Yard(s) and Coupling to Grid

Adding of new Modelle

Koeberg site Plan

KOEBERG SITE LAYOUT CONCEPT

FIG. 10

- Fuel supply and manufacturing options study.
- Alternator layout, supporting, coupling and operational modes. (Requirement study). (See attached Figure 9)
- KOEBERG site layout (See attached Figure 10)

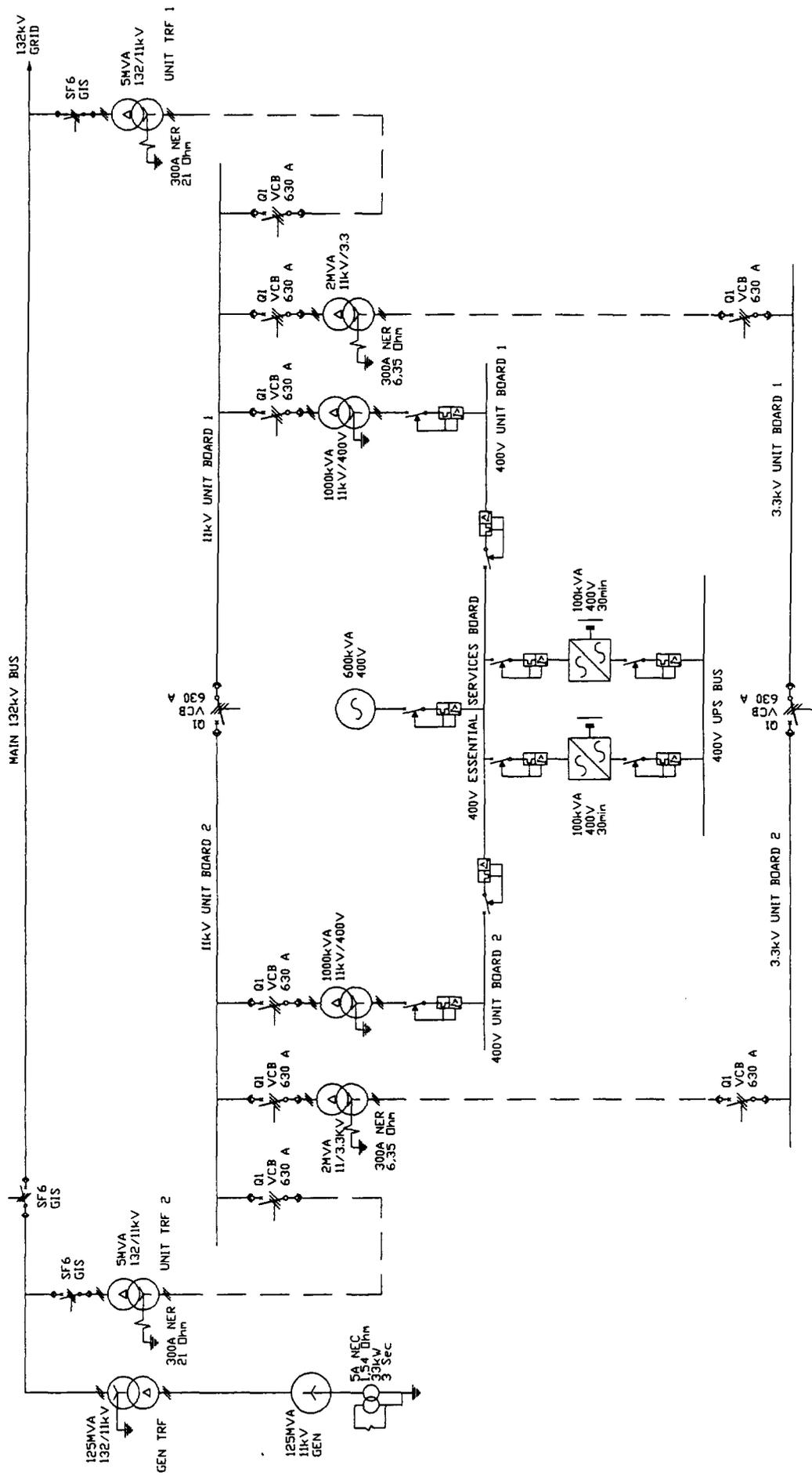
## 8. BRIEF OVERVIEW OF SOME OF THE INDIVIDUAL SYSTEMS

- Systems covered by other presentations during this TCM:
  - The Reactor (core design)
  - The Power Conversion Unit (PCU)
  - Helium Inventory and control system
  - Passive heat removal.
- Some comments on Systems of interest:
  - **Active heat removal system.**
    - \* The sea as ultimate heat sink
    - \* Cooling tower for shutdown, startup and maintenance.
  - **The shutdown heat removal**
    - \* basically keeps the reactor vessel cool when Brayton Cycle not functioning
    - \* Flow will be through the graphite reflector.
    - \* Core will remain hot during operation of this system.
  - **The fuel and defueling systems**
    - \* An on-line operable system.
    - \* This system is 100% redundant
    - \* 2 zone core loading capability.
  - **Electrical system** (See attached Figure 11)
    - \* A 132 kV main bus with step down transformers to 11 KV, 3,3 KV and 400V busses and switchgear.
    - \* Electric demand is split into startup, shutdown and run categories.
    - \* A 600 kVA diesel-generator will serve as startup and stand-by electric supply source if grid is not available.
  - **Automation System Architecture** (See attached Figure 12)
 

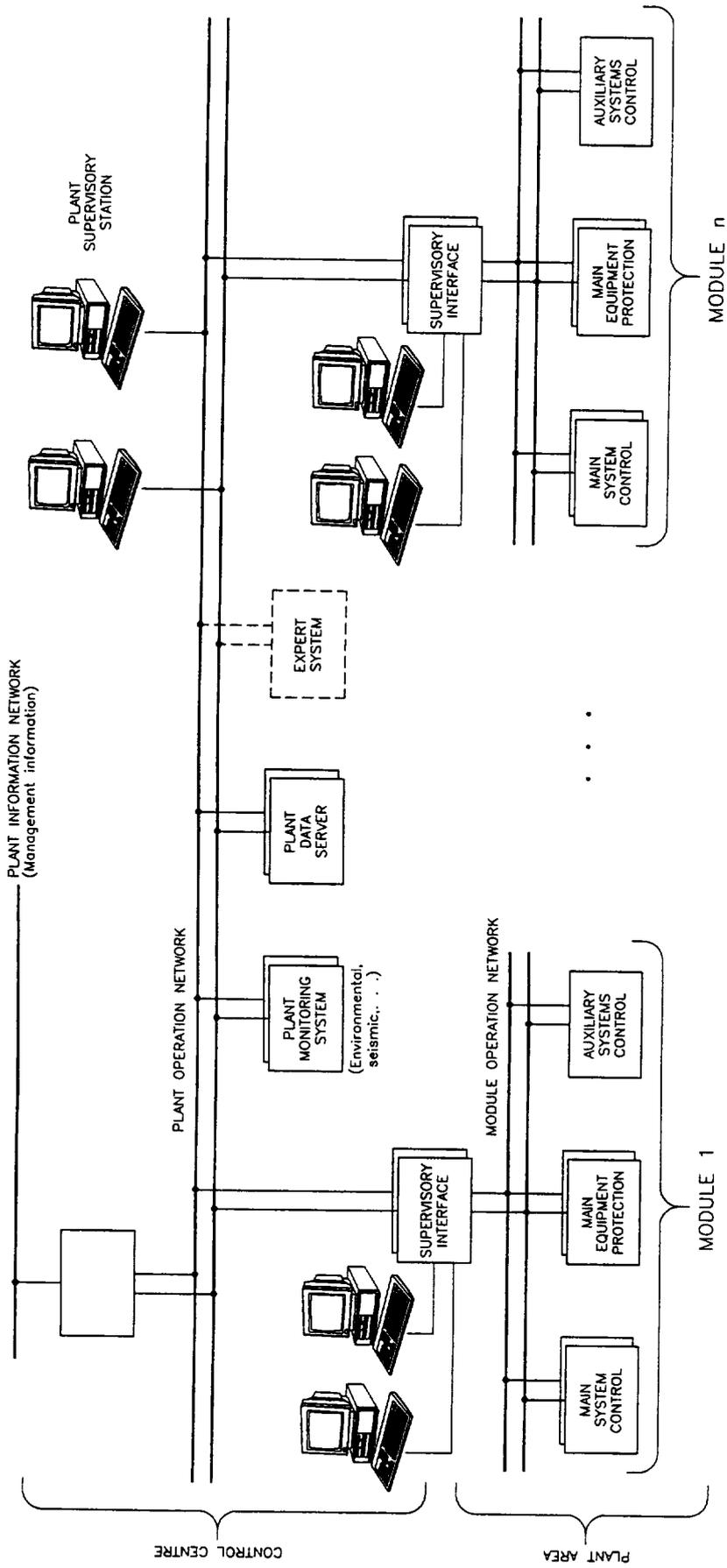
Minimum scope safety-related Reactor Protection System to ensure that the initial conditions preceding a possible accident are safe (e.g. reactor temperature and integral energy - which has to be removed as decay heat).

The rest of the system is normal industrial automation equipment. Use is made of:

    - \* programmable logic controllers
    - \* computer-based man-machine interface devices with an absolute minimum of discrete control buttons / indications)



**PBMR POWER SYSTEM SINGLE LINE DIAGRAMME**  
**FIG. 11**



AUTOMATION SYSTEM ARCHITECTURE

FIG. 12

- Networking between controllers
- redundancy of processors and networks as and where appropriate

Each reactor module has an independent automation system, situated in the plant area. Operator stations for all modules are in one common control centre. Provision is made for one plant supervisory station (but no technical support centre, no remote shutdown facility).

Plant common automation equipment (with a degree of redundancy as and where appropriate) may be:

- plant monitoring systems (environmental, seismic, ...)
- plant data server

## 9. COMPONENT SPECIFICATION AND COSTING

The following main components costing is at present under discussion. (tender inquiries out)

- The reactor vessel.
- The graphite.
- The fuel.
- The alternator.
- The turbo machinery and heat exchangers
- The building
- The electrical equipment include the main transformers.
- The active heat removal pumps and heat exchangers.
- The ventilation system.

## 10. THE ENGINEERING SIMULATOR.

- Acceptable level of stability of the Brayton Cycle is demonstrated.
- Operating at different levels of power showing correlation with other methods of predictions.
- The behaviour of the turbo machinery is demonstrated during *step* and *ramping* of power and helium inventory changes.
- The simulator already plays an important role in identification and simplification of a control system.

(Detail of the simulator is presented in a separate paper).

## 11. CONCLUSION

- The simplicity of the proposed reactor still prevails.
- The inherent safety is captured in the fuel and plant configuration.
- A new licensing framework is possible.
- The direct cycle is a non-omissible option for future power generation.
- The technology base internationally available makes it possible to design and build a fullscale prototype plant directly without extended research and development required.

- We foresee no technical and financial reason why the public cannot accept this power plant as an electric power production unit.
- Variations of the proposed concept are possible to suit potential clients requirements.
- It is one of the world's most fascinating new developments.
- Our study is basically on time as scheduled, and will be finished with great enthusiasm.