Modularity Approach of the Modular Pebble Bed Reactor (MPBR)

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Project Objectives

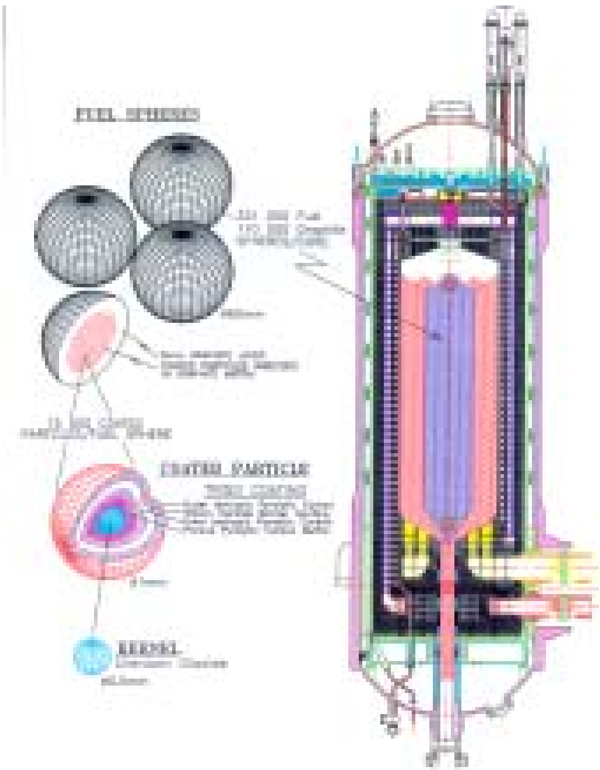
- To apply modularity principles to the design, construction and operation of advanced nuclear energy plants
- To employ manufacturing and factory assembly principles to nuclear plants.
- To minimize on site work by assembling plants on site rather than construct them as in the past.
- To allow for conventional truck and rail shipments of most components allowing for siting flexibility.
- To reduce overall construction time and cost.

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

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**

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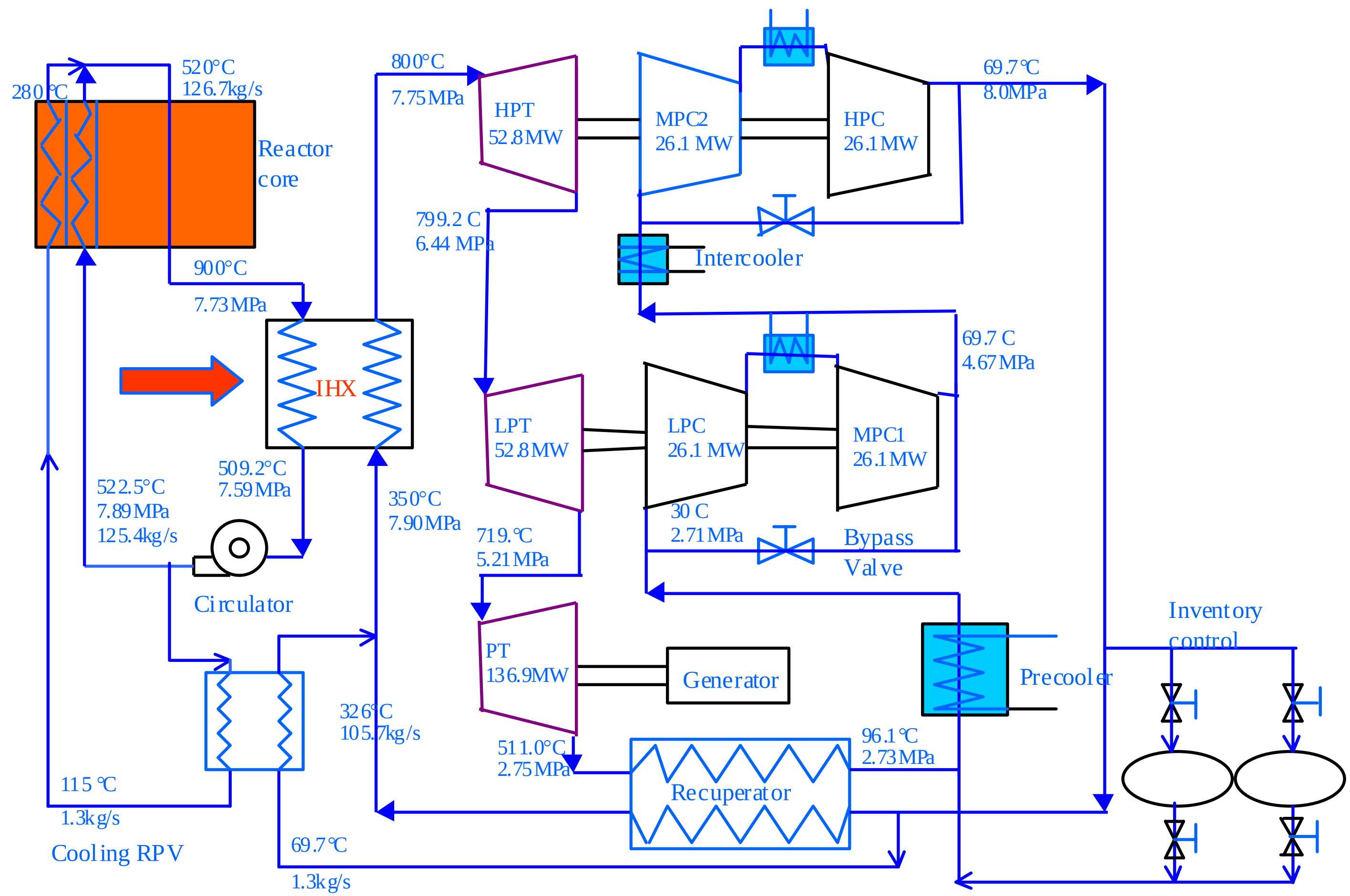
Indirect Cycle with Intermediate Helium to Helium Heat Exchanger

Current Design Schematic



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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

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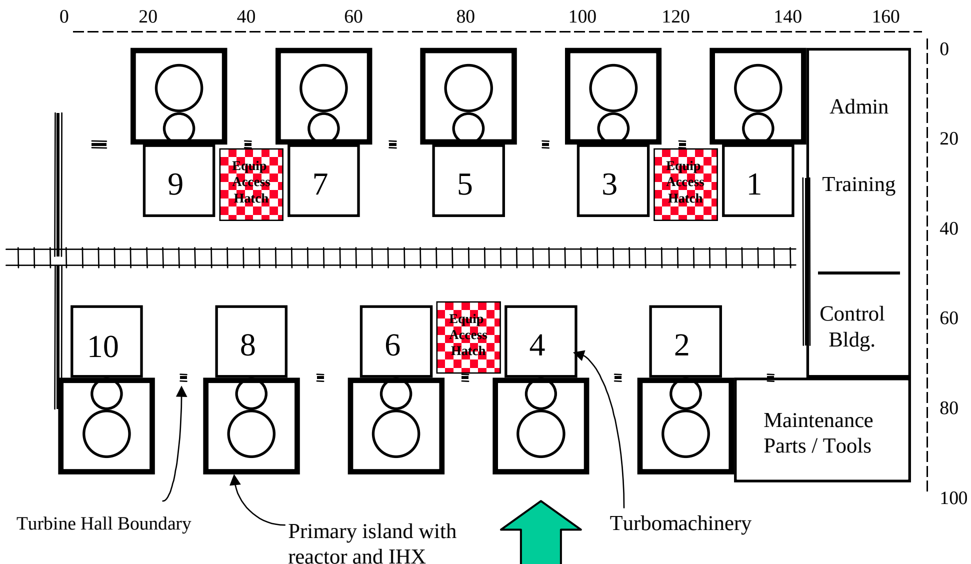
1150 MW Combined Heat and Power Station

VHTR Characteristics
- Temperatures > 900 C
- Indirect Cycle
- Core Options Available
- Waste Minimization

Ten-Unit VHTR Plant Layout (Top View)

(distances in meters)



Oil Refinery

Hydrogen Production

Desalinization Plant

Modularity Progression

- Conventional Nuclear Power Systems
  - Assembled on site
  - Component-level transportation
  - Extensive Site Preparation
- Advanced Systems
  - Mass Produced / "Off the Shelf" Designs
  - Construction / Assembly Still Primarily on Site
- MPBR
  - Mass Produced Components
  - Remote Assembly / Simple Transportation & Construction

This is different than other Generation IV approaches in that modularity is the objective which means smaller units.

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MPBR Modularity Plan

- Road- Truck / Standard-Rail Transportable
  - 8 x 10 x 60 ft. 100,000 kg Limits
- Bolt-together Assembly
  - Minimum labor / time on site required
  - Minimum assembly tools
  - Goal: Zero Welding
- Minimum Site Preparation
  - BOP Facilities designed as “Plug-and-Play” Modules
  - Single Level Foundation
  - System Enclosure integrated into modules
- ASME Code compliant
  - Thermal expansion limitations
  - Code material limitations

Design Elements

- Assembly
  - Self-locating Space-frame Contained Modules and Piping.
  - Bolt-together Flanges Join Module to Module
  - Space-frame Bears Facility Loads, No Additional Structure
- Transportation / Delivery
  - Road-mobile Transportation Option
    - Reduces Site Requirements (Rail Spur Not Required)
  - Module Placement on Site Requires Simple Equipment
- Footprint
  - Two Layer Module Layout Minimizes Plant Footprint
  - High Maintenance Modules Placed on Upper Layer

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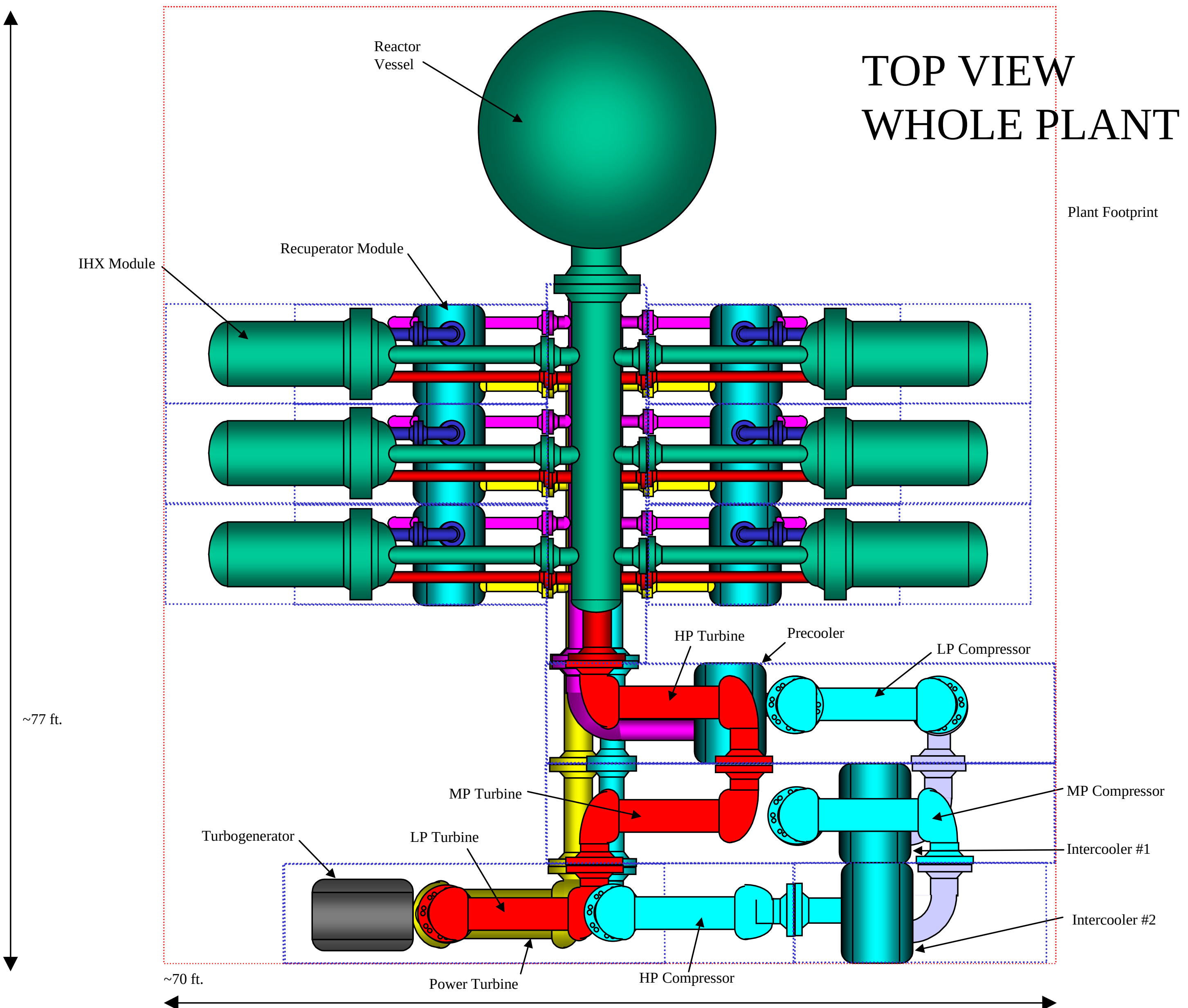
Top Down View of Pebble Bed Reactor Plant



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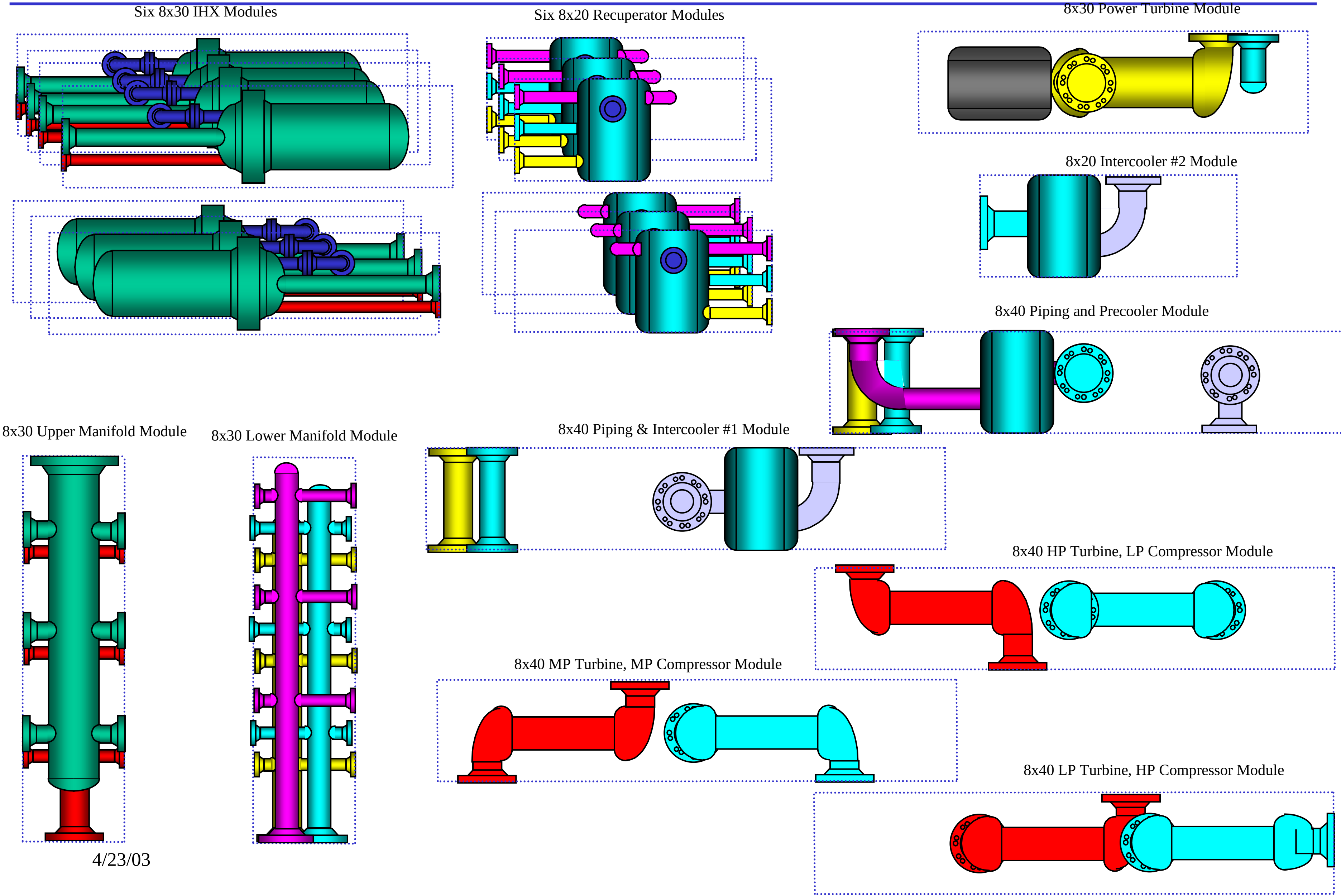
PLANT MODULE SHIPPING BREAKDOWN

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



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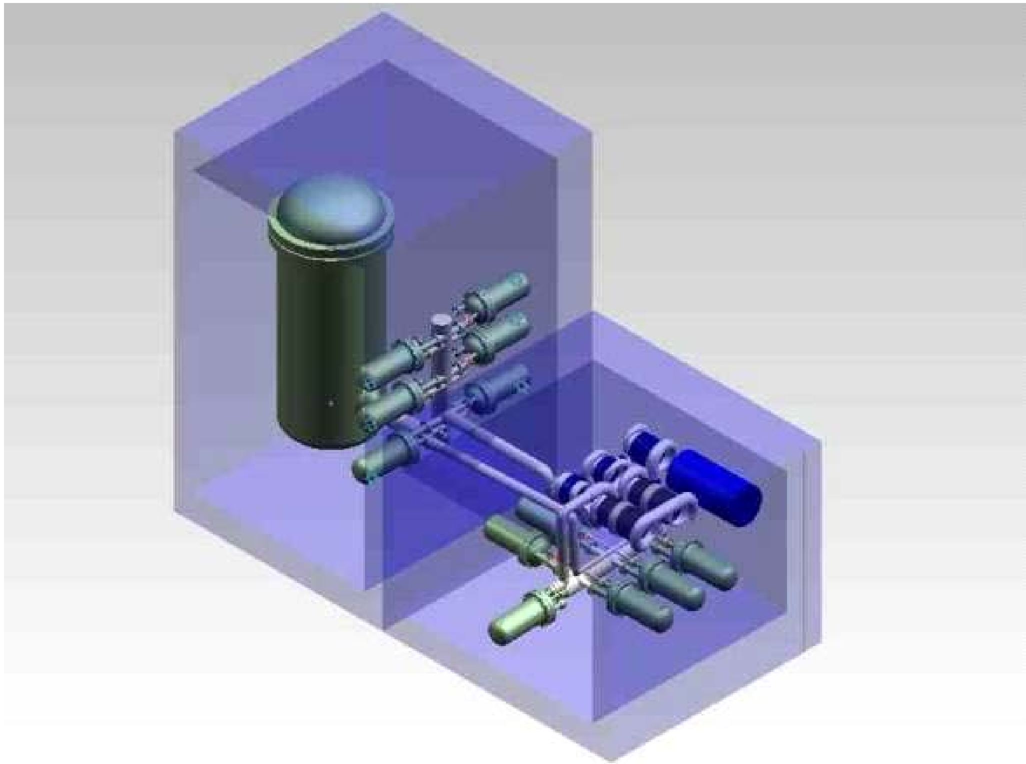
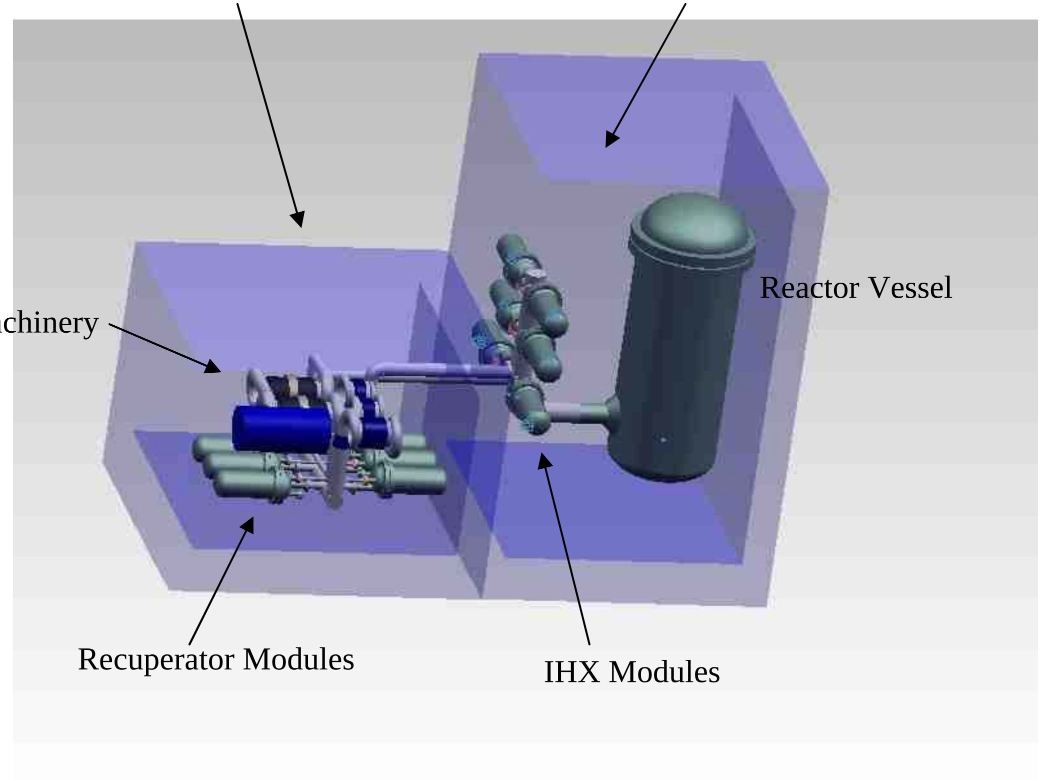
Concept

- **Modular Construction**
  - Space-frame modules
    - Stackable
    - Self-aligning
    - Pre-constructed off-site
  - Minimal Assembly On-Site
    - Connect Flanges / Fluid Lines / Utilities
    - Pre-Assembled Control Facilities
- **Distributed Production**
  - Common, Simple Module Design
  - Minimizes Transportation Req.
  - Eliminates Manufacturing Capital Expense
  - Module Replacement Instead of Repair—Modules Returned to Fabricator
- **Road-mobile Transportation**
  - Reduces Cost—Construction of Rail Spur / Canal Not Required
  - Reduces Location Requirements



- Plant “Farm”: ~10 MPBR Systems per “Power Plant”
- Containerized Fueling / Waste Disposal Minimizes Handling Costs
  - Fuel module (ISO container) is “plugged in”
  - Spent fuel module is packaged in ISO container and “unplugged” when full

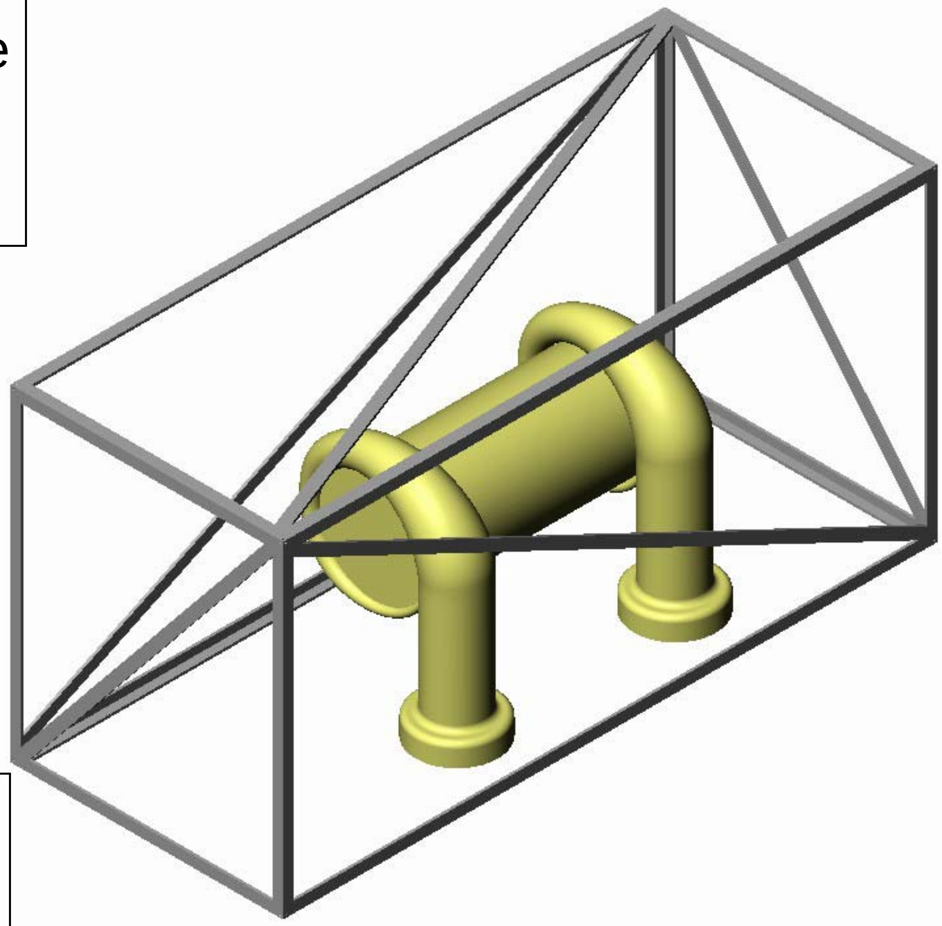
Example Plant Layout



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

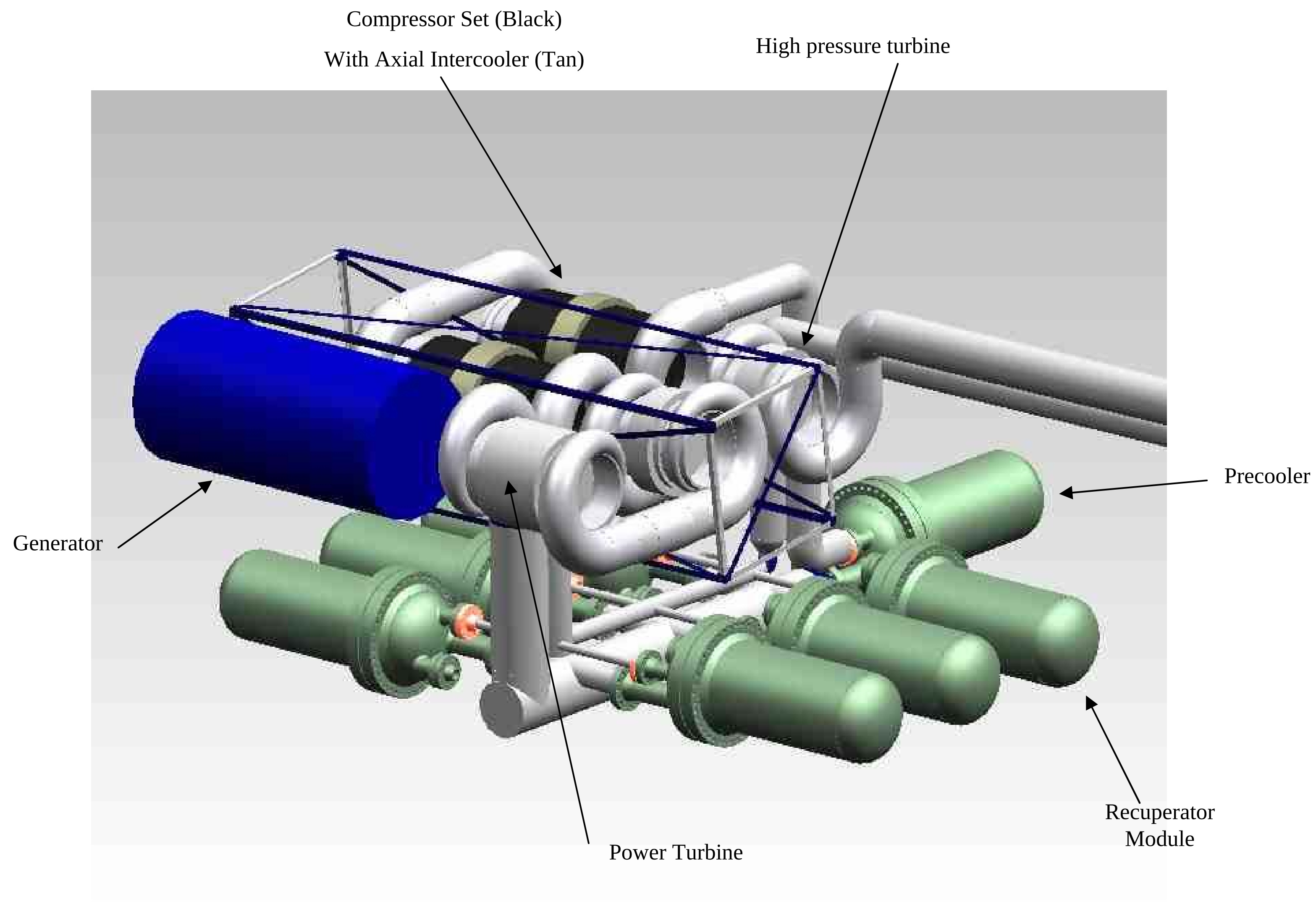
Space Frame Technology for Shipment and Assembly

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



Each space frame will be “plugged” into the adjacent space frame.

Balance of Plant Components



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)

Thermal and Mechanical Stress Analysis

- CAESAR II Pipe Stress Analysis Code
- ASME B31.3 Piping Code
- Pipe Material: A335 P2
- Spaceframe Material: ASTM A-36
- Preliminary Thermal Analysis Performed to Create Code Compliant Geometry
- Hangers not shown for clarity
- Preliminary Spaceframe structure
  - secondary elements not shown

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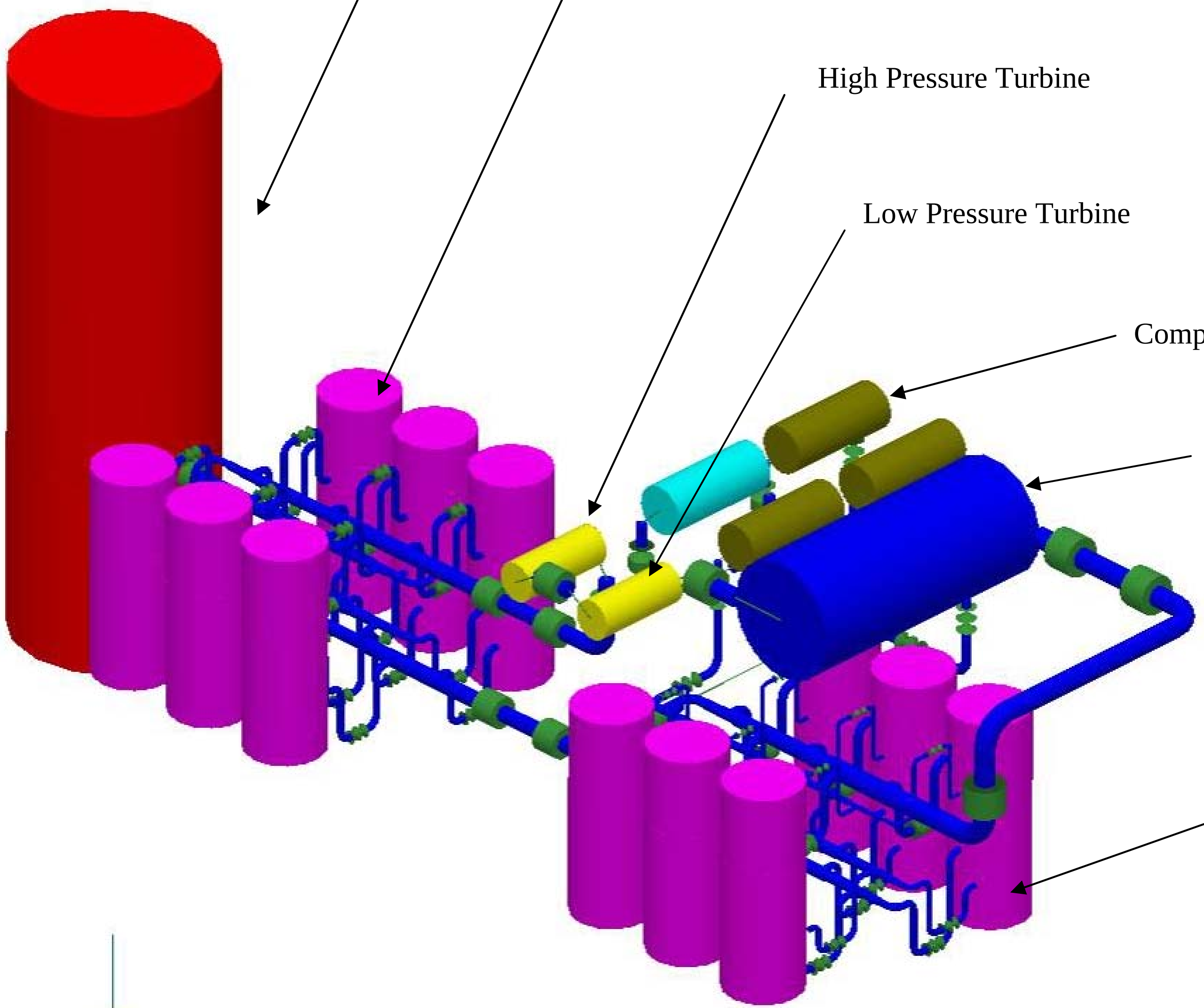
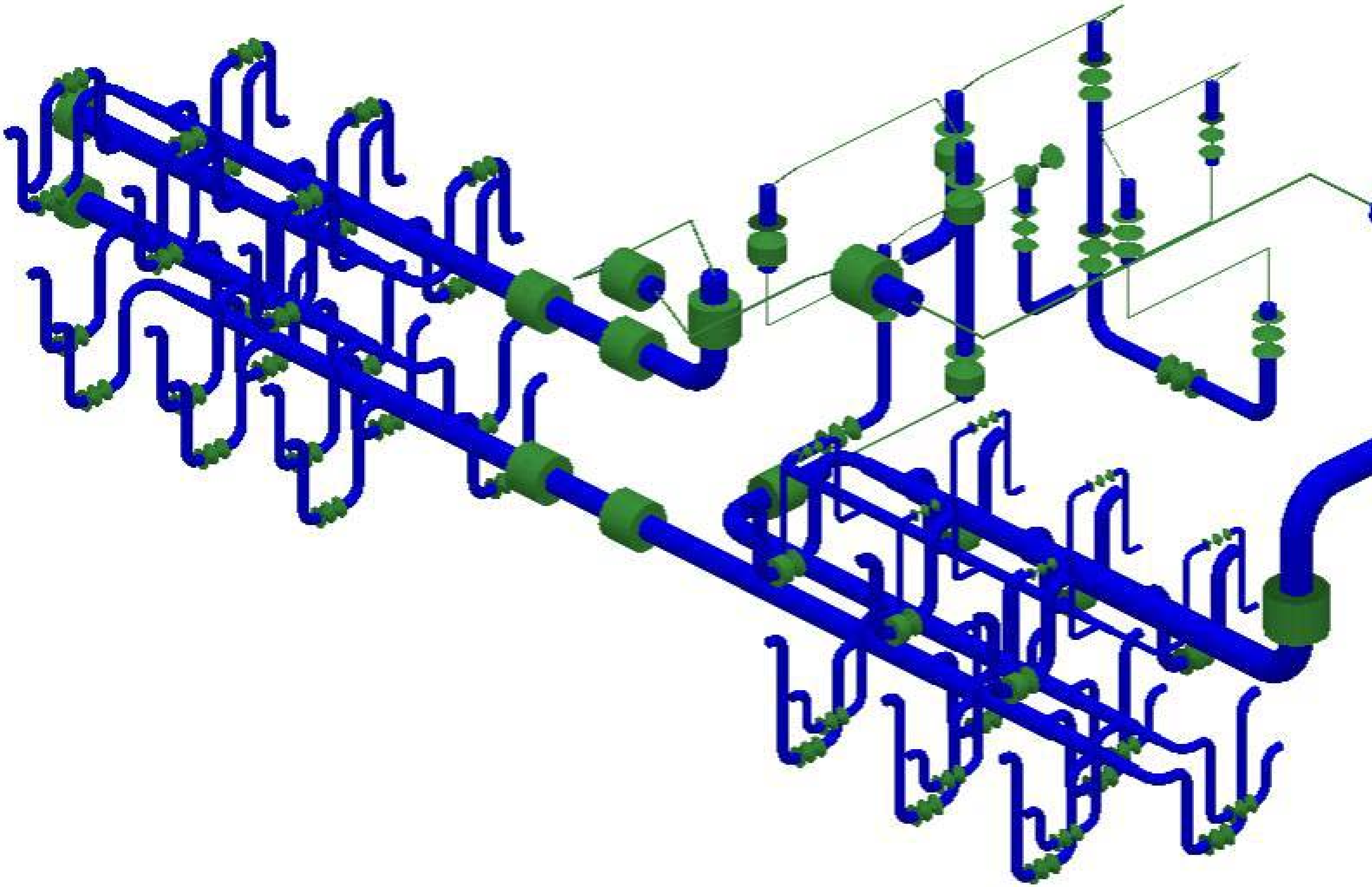
Present Layout



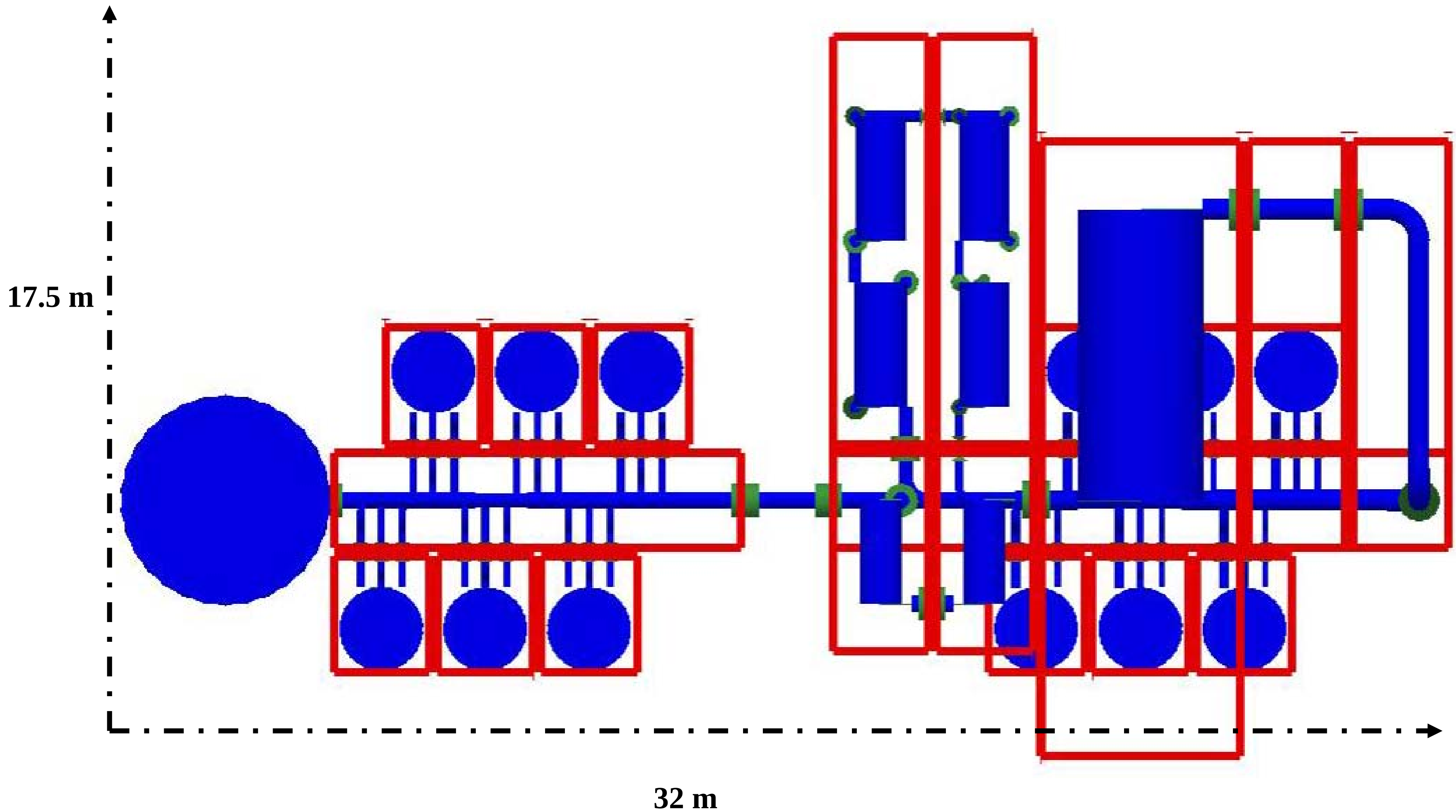
Detail of Connecting Piping



Piping Sizes

Pipe	OD (in)	Wall Thickness (in)
Reactor Vessel to IHX	16	0.5
IHX to Reactor Vessel	16	0.5
IHX to Turbine 1	16	0.5
Turbine 1 to Turbine 2	16	0.5
Turbine 2 to Power Turbine	18	0.5
Power Turbine to Recuperator	20	0.25
Recuperator to Precooler	14	0.125
Precooler to Compressor 1	13	0.125
Compressor 1 to Intercooler 1	12	0.125
Intercooler 1 to Compressor 2	10	0.125
Compressor 2 to Intercooler 2	10	0.25
Intercooler 2 to Compressor 3	10	0.25
Compressor 3 to Intercooler 3	8	0.25
Intercooler 3 to Compressor 4	8	0.25
Compressor 4 to Recuperator	8	0.25

Based on 400m/s internal helium flow velocity with metallic liner and internal insulation


17.5 m
32 m

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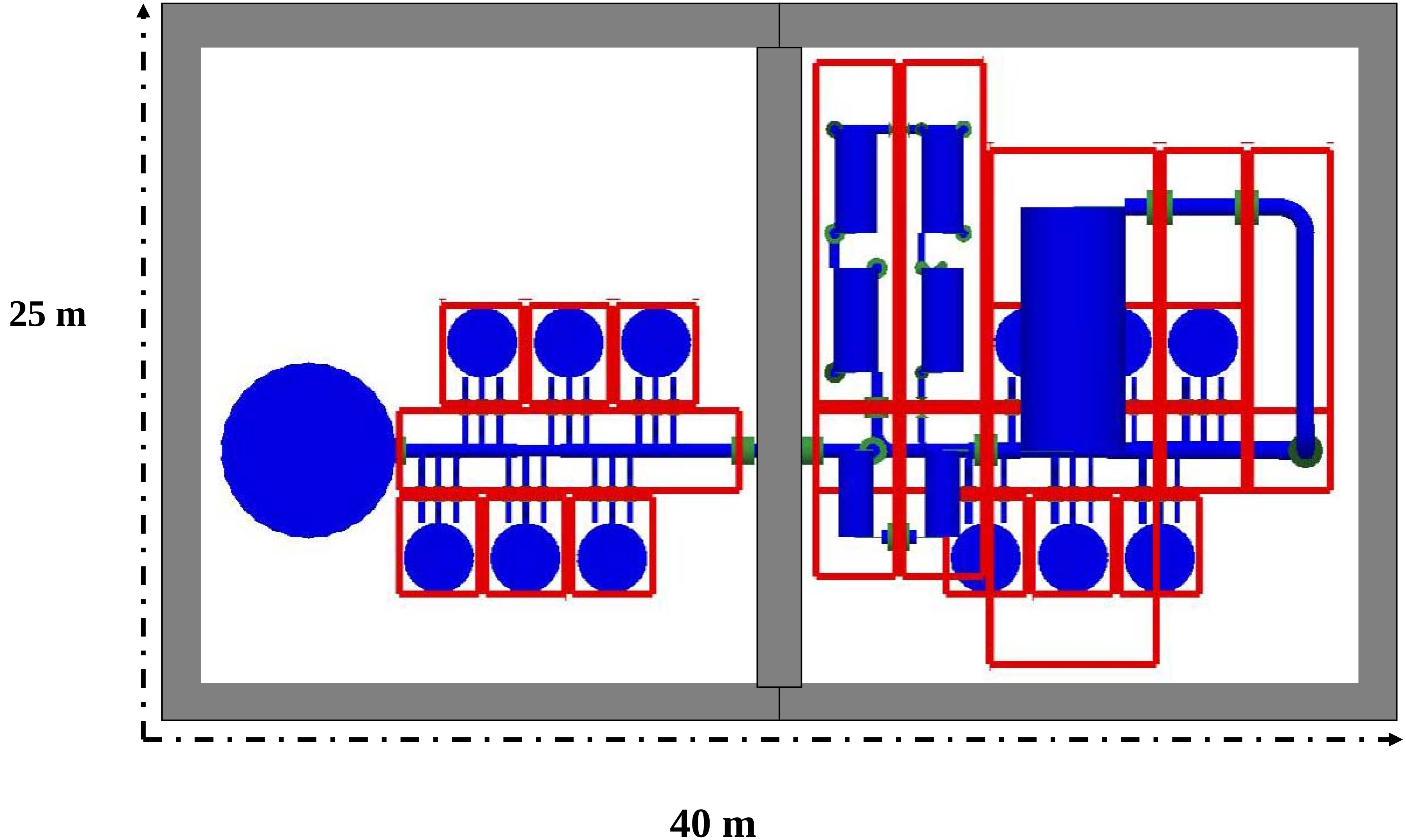
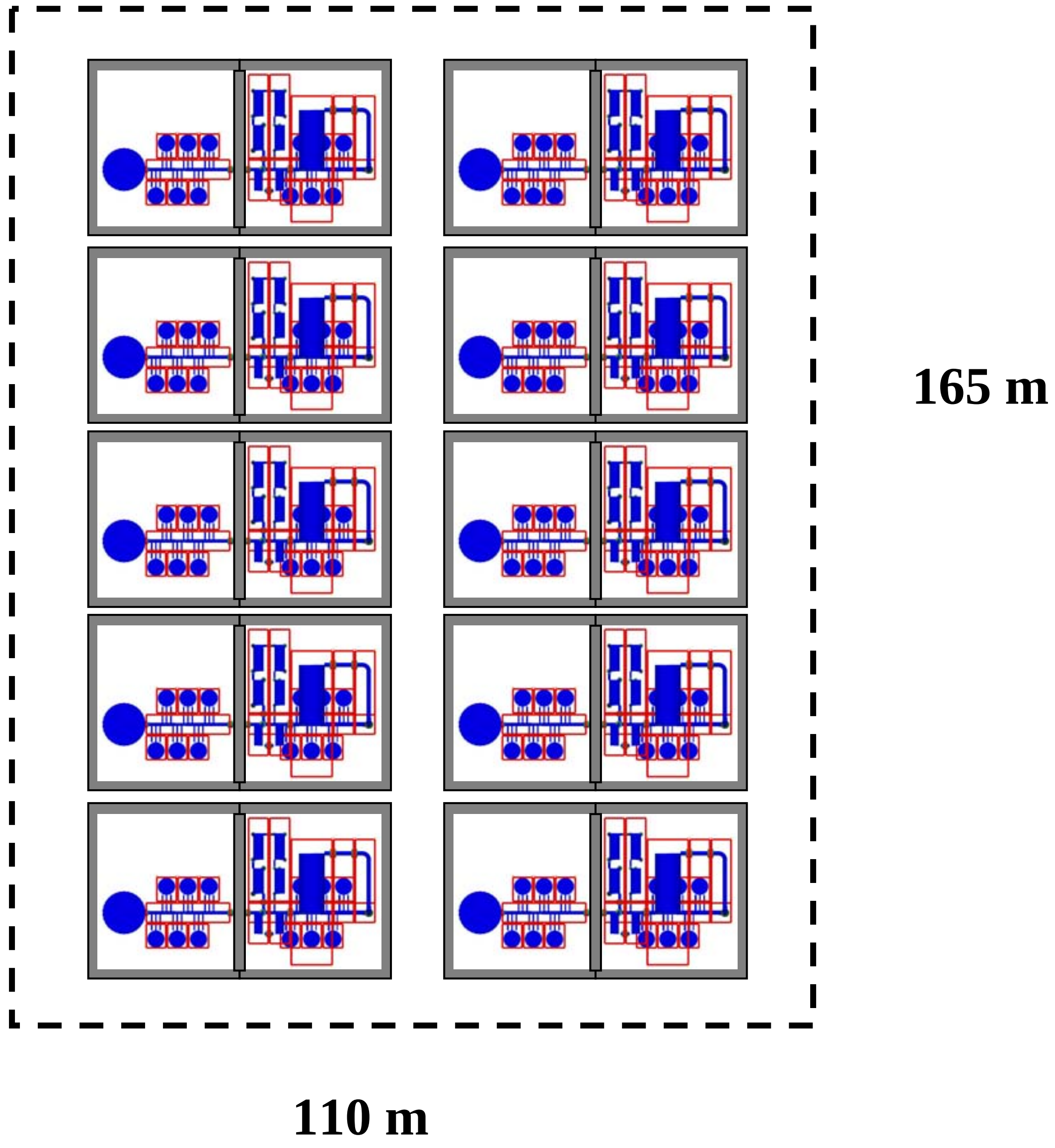
Overall Structure



10 Module Plant - 1200 MWe



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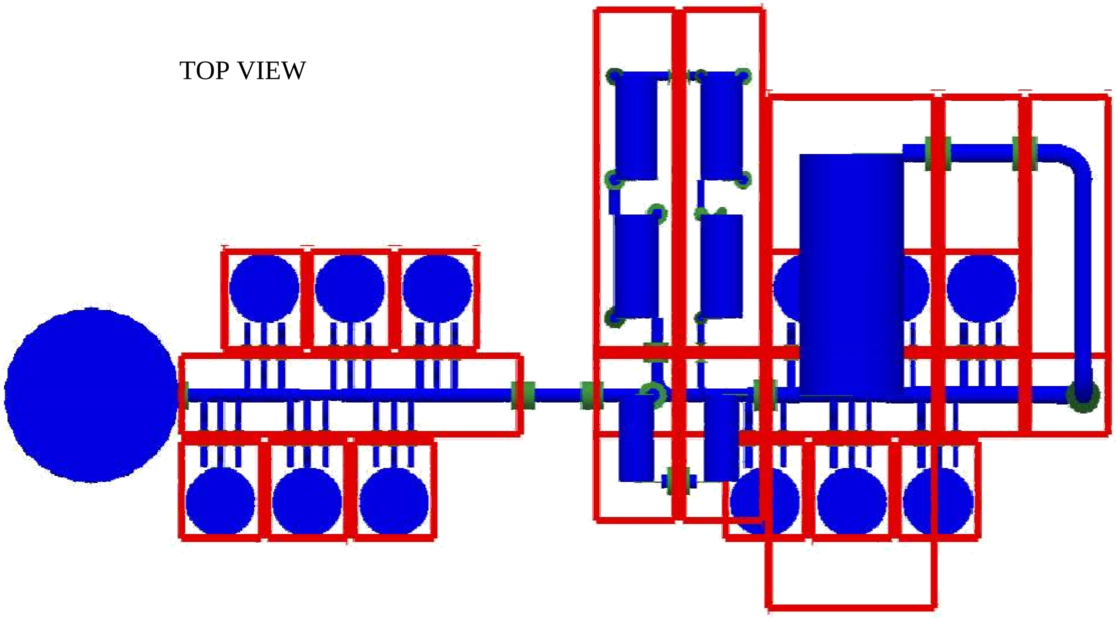
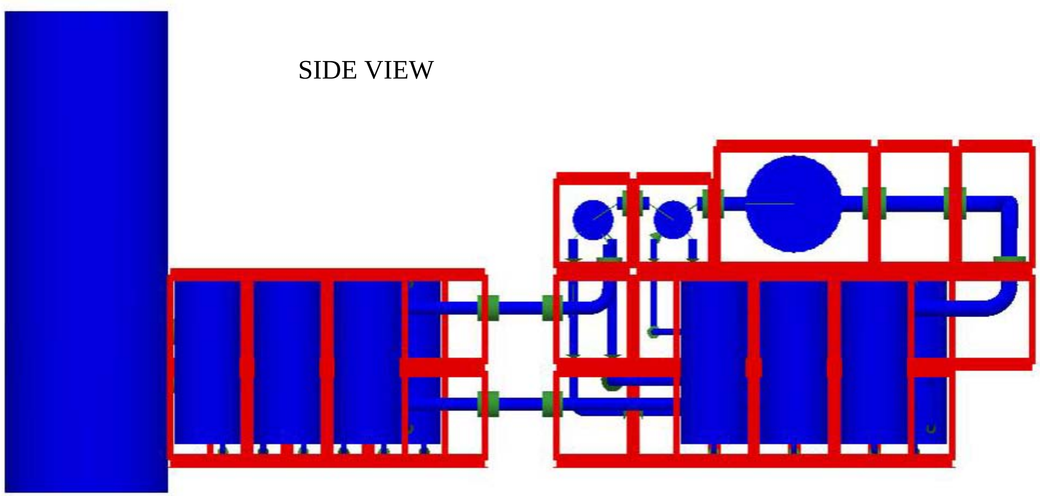
Views Of Plant Layout

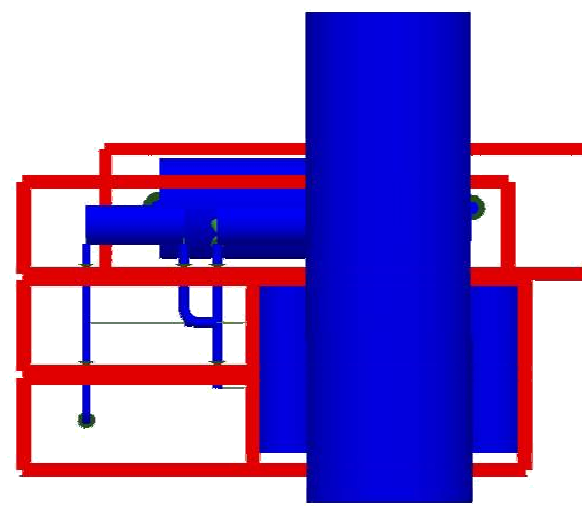
TOP VIEW



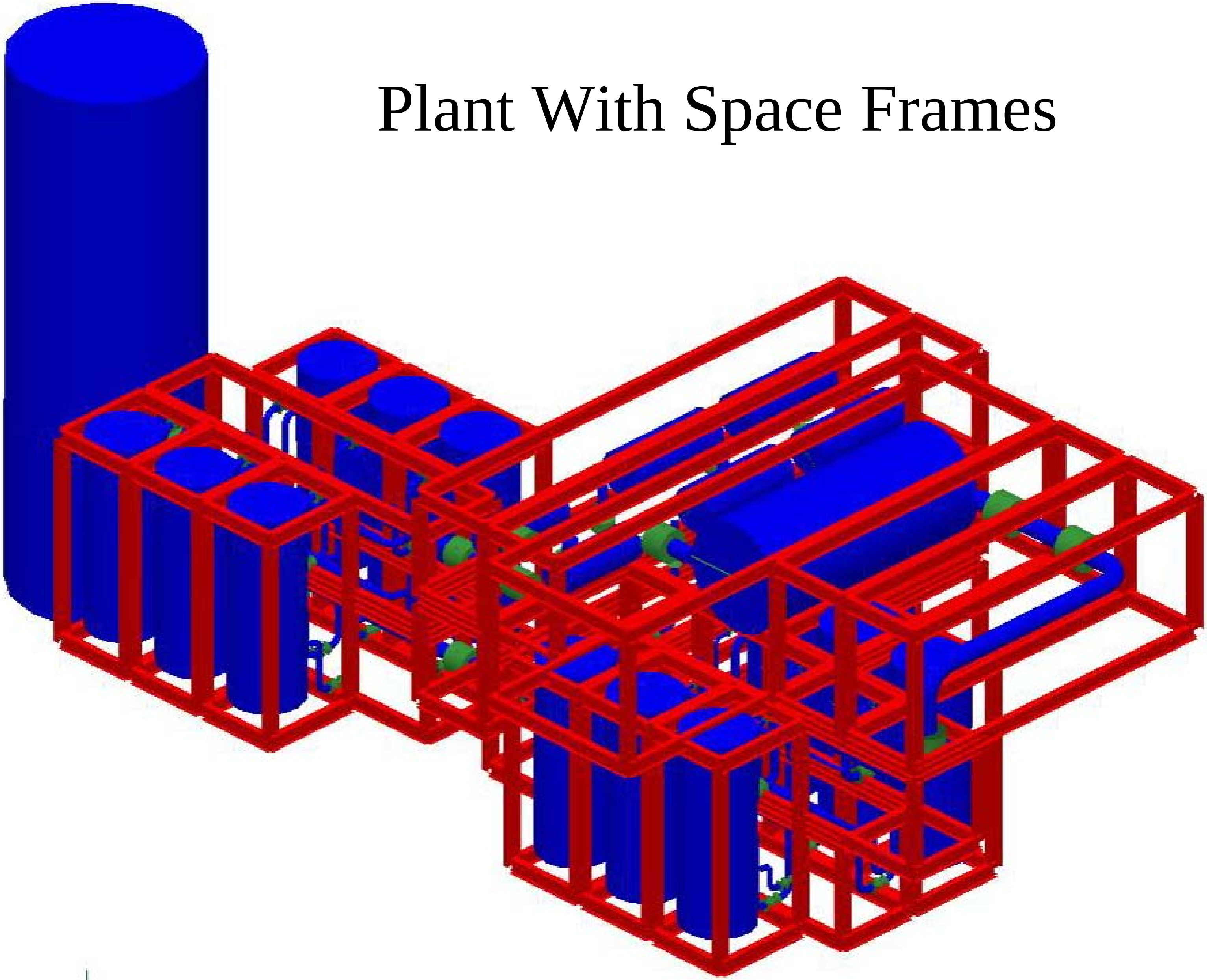
FRONT VIEW (FROM REACTOR VESSEL)

SIDE VIEW

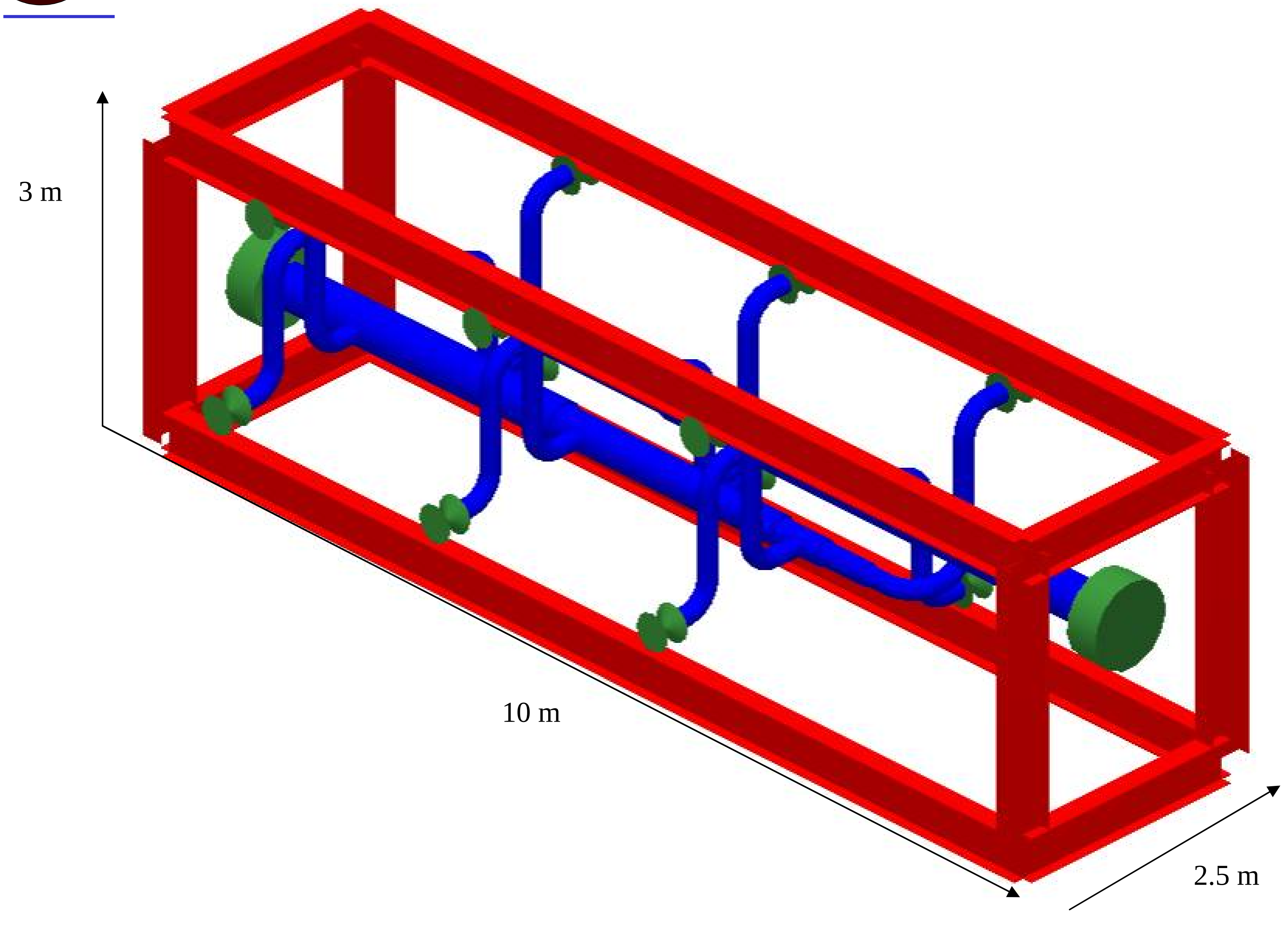




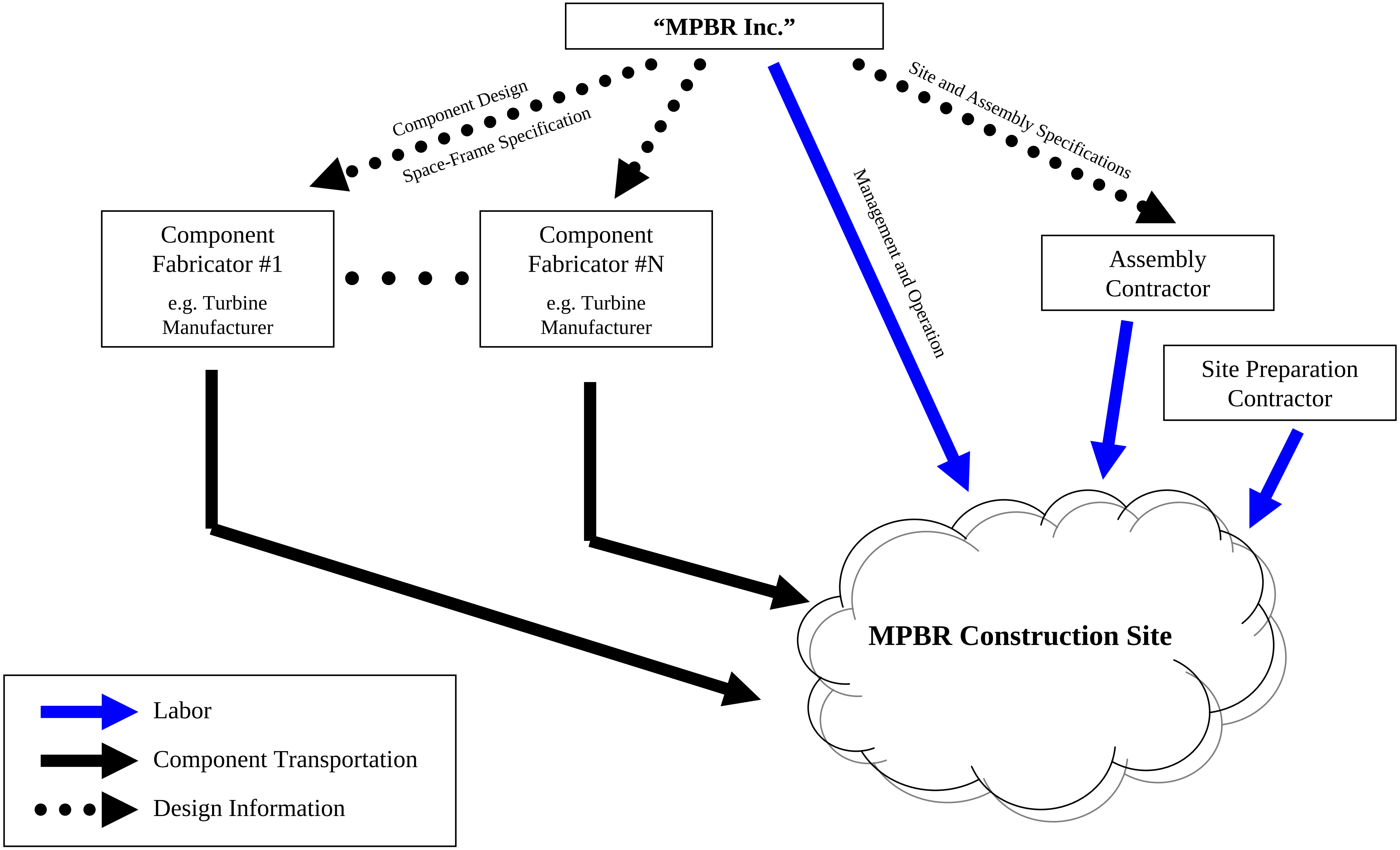
Plant With Space Frames



Upper IHX Manifold in Spaceframe



Distributed Production Concept



Distributed Production Concept - Virtual Factory !

- Evolution of the “Reactor Factory” Concept
- There Is ***NO*** Factory
  - Off-load Manufacturing Capital Expense to Component Suppliers
    - Decrease follow-through capital expense by designing to minimize new tooling—near COTS
    - Major component fabricators become mid-level integrators—following design delivered from HQ
  - Reduces Transportation Costs
    - Component weight ≈ Module weight: Why Transport It Twice?
  - Enables Flexible Capitalization
    - Initial systems use components purchased on a one-off / low quantity basis
    - Once MPBR demand established, constant production + fabrication learning curve lower costs

- Site / Building Design Does Not Require Specialized Expertise
  - Enables Selection of Construction Contractors By Location / Cost
  - Simplified Fabrication Minimizes “MPBR Inc.” Workforce Required

- Simple Common Space-Frame Design
  - Can be Easily Manufactured By Each Individual Component Supplier
  - Or if necessary sub-contracted to generic structural fabricator

- Modern CAD/CAE Techniques Enable High First-Fit Probability—Virtual “Test-Fit”

Current Design Issues

- Thermal Expansion
  - Piping Must Be Designed for Substantial Thermal Expansion—requiring Bulky Layout
  - Flexible Joints Not Possible Due to Code Constraints
- Space-Frame Loads
  - External (Seismic, etc) – Flexibility Limits
  - Self-Generated – Internal Supports for Component Dead Weight
  - Structural – Module to Module Loads
- Alignment Requirements
  - Module Construction Accuracy and Installation Alignment Drive Assembly Complexity and Component Design
    - Poor accuracy / alignment requires adjustment of component position within frame
- Plant Layout
  - Accommodate Remove/Replace Strategy
  - Accommodate Structural / Thermal Issues

Accomplishments

- Developed a modularity scheme that can be used to ship most of the components of the plant in truck capable space frames. (ex. RV)
- Established a fabrication strategy using space frame technology in a virtual factory environment.
- Minimized on site construction to large area rooms into which space frames are installed.
- Developed an design strategy that focuses on replacement rather than repair of components to minimize outage losses.
- If successful, this approach could revolutionize nuclear plant design and construction.

Future Work

1. Tolerance requirements for space frame fit-up and critical dimensions.
2. Development of “virtual factory” concept with industrial partners.
3. Establishment of infrastructure development plan for space frame concept with vendors.
4. Economic assessment of modularity under this concept with economy of scale for multi-unit plant