Modularity in Design of the MIT Pebble Bed Reactor

By

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Submitted to the Department of Nuclear Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Nuclear Engineering

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ABSTRACT

The future of new nuclear power plant construction will depend in large part on the ability of designers to reduce capital, operations, and maintenance costs. One of the methods proposed, is to enhance the modularity of the designs in which the basic plant is broken down into modules, each of which is built offsite at a "factory", transported to the plant site, and assembled into a working plant using a minimum amount of labor and tooling. The value of this approach is that it improves overall quality, reduces site field work and rework, and speeds the construction of the plant. This approach also takes advantage of economies of mass-production, rather than relying on economy of scale to reduce costs. The ability to remove and replace modules for repair and maintenance also leads to reduced costs and downtime. Past work at MIT has resulted in a reference design that takes into account modularity. This design includes the cycle parameters and component designs.

Based on this reference cycle design, a detailed analysis and modularity design of a power producing plant was performed. This design takes into account the goals for the modularity and construction approach. The plant takes the factory approach to its logical conclusion, resulting in a "virtual factory" where each major component is integrated into a modular space-frame by its manufacturer. Each module is designed to be transported by truck (although, if the necessary infrastructure is available the modules could be transported at potentially lower cost by rail or barge) to the construction site. The plant site itself requires only simple excavation and the plant containment building is a simple, reinforced poured concrete structure. Assembly of the plant is simple by comparison to conventional facilities as the modularity approach requires that each space-frame module be stacked together, pipe flanged bolted together, a self-test performed, and the plant started.

In order to make this assembly method possible a pressure-backed insulation system was designed. This insulation system reduces the temperature of the pressure boundary, enabling the use of lower-cost alloys for system construction. The metallic liner and insulation layer also reduce the temperature swings of the piping and vessel walls, reducing thermal expansion loads that must be borne by the structure of the system.

To enable flange-joints between component modules a scavenged flange design was created. This flange design enables redundant sealing of the pressure boundary, and also prevents Helium loss and contamination of the plant. This design also enables monitoring of the flange integrity.

This design should enable the MIT pebble bed reactor to meet the cost, operations and maintenance goals of an advanced reactor.

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It would also not have been possible to complete this thesis without the work done by other members of the MIT nuclear engineering department who furnished the necessary technical guidance and reference design information necessary. Worthy of specific mention are Dr. Chunyun Wang, Prof. Ronald Ballinger, and Peter Stahle, without which none of the needed information would have been available.

Thanks must also be given to my family, without their encouragement, the development of my engineering knowledge would not have been possible. Their continued support, especially when the outlook appear bleak was invaluable.

On a special note, I would like to personally dedicate this thesis to Prof. Lawrence Lidsky. His advisory role, academically, professionally, and personally throughout my undergraduate years in the MIT Nuclear Engineering Department was a key factor in my development as a Nuclear Engineer. His insights into how to deal with design adversity, and his encouragement of my efforts to seek out innovative solutions, anticipate potential design problems, and be ever watchful of the ultimate goal of any system provided fundamental guidance to both my academic and professional careers. His untimely passing was a blow to me personally and to the nuclear engineering community as a whole, and he will be forever missed.

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List of Units

Length	m = meter
	cm = centimeter
	mm = milimeter
Area	sqft = square foot
	m^2 = square meter
Volume	scf = standard cubic foot
	m3 = cubic meters
Mass	kg = kilogram
	t = ton (1000 kg)
Velocity	m/s = meters per second
Density	kg/m^3 = kilograms per cubic meter
Thermal power	MW = Megawatt
	GW = Gigawatt
Electrical power	MWe = Megawatt, electric
	GWe = Gigawatt, electric
Temperature	°K = Kelvin
	°C = Celsius
	°F = Fahrenheit
Pressure / Stress	psi = pounds per square inc
	ksi = pounds per square inch
	kPa = kilopascals
	MPa = megapascals
Thermal Conductivity	W/mK = watts per meter-degree kelvin

1. Introduction

The future of new nuclear power plant construction will depend in large part on the ability of designers to reduce capital, operations, and maintenance costs. One of the methods proposed, is to enhance the modularity of the designs in which the basic plant is broken down into modules, each of which is built offsite at a "factory", transported to the plant site, and assembled into a working plant using a minimum amount of labor and tooling. The value of this approach is that it improves overall quality, reduces site field-work and rework, and speeds the construction of the plant. This approach also takes advantage of economies of mass-production, rather than relying on economy of scale to reduce costs. The ability to remove and replace modules for repair and maintenance also leads to reduced costs and downtime.

This study concentrates on application of this approach to a reference nuclear power plant design. The plant is based on a small, ~300MWt pebble bed reactor core. The power conversion system operates using an indirect Brayton cycle—the heat is drawn from the core using a primary Helium coolant loop then transferred in an intermediate heat exchanger to a separate, secondary power conversion loop using Helium again as the working fluid. Past work on the design of the MIT Pebble Bed Reactor (MIT PBR) has proceeded with a modular approach in mind, and generated cycle and component designs that are used together as a reference or baseline design for this study.

The modularity approach, and system design proposed here also defines the primary design constraint governing the power level of the plant, in this case, 110MWe net power production. This size is advantageous for multiple reasons. First, there is a large market for small plants that can be quickly and inexpensively built in both the US and international markets. The small plant size results in an initial capital outlay an order of magnitude smaller than conventional 1000-1200MWe plants. The rapid construction allows for a reduced cost of money associated with the capital outlay, and the small plant power level enables utilities to add generating capacity in smaller increments, further reducing costs.

This first chapter provides a general overview and introduction to this study. First, the motivating design factor—energy generation cost—is defined in detail, along with a breakdown of the cost reduction areas targeted. The contribution of this thesis to achieving the design goals is then discussed, followed by an organizational breakdown of this thesis.

1.1. Motivation—Cost

The overreaching motivation of this project is to reduce the cost of producing power using a nuclear fission reaction. While conventional nuclear power plants have shown that the fraction of the cost associated with the nuclear fuel is small (~26%)[1], in order to be competitive with other energy production methods (natural gas and coal), the cost must be reduced further. Nuclear plant costs are concentrated in capital cost (63%), operations and maintenance costs (11%)[2]. While a safe design that is capable of being licensed as a design (rather than requiring each individual plant be licensed separately), would reduce the regulatory and licensing costs, the best results can be obtained by reducing the capital, and operations and maintenance costs[3].

Capital costs include the costs associated with the infrastructure needed to manufacture the plant and its components, transportation of the components to the site, preparation and construction of the site, and assembly of the system itself. Also included in the capital costs is the cost associated with the financing of the material costs. Operations and maintenance costs include those associated with operating the plant, maintaining the components, and any repair or replacement costs of plant components. Additional cost reduction may be obtained by a system design that enables a greater number of potential sites.

1.1.1. Capital Costs

Capital costs can be reduced through several methods, all of which are incorporated into the modularity principles of this design. First, the actual material costs of the plant can be reduced. The proposed system reduces these costs through the use of components sized to be produced by existing manufacturers, economies of mass production, and design choices to reduce material and fabrication costs. This is a relatively unique approach that has garnered increasing support recently in all areas of power production. Too often economy of scale—increasing the size of components and plants to reduce the specific cost ($/kWe)—is seen as the only method available. Even Gen-III reactors such as the AP-1000 and AP-600 concentrate on large systems (albeit with "modular" construction techniques to reduce construction time and cost)[4]. As shown in many other industries, and recently in the drive to install large numbers of low power (<100MWe) gas turbine generators either singly or in groups, economy of mass production (large numbers of identical systems) can be even more economical on a specific cost basis, while enabling other advantages in terms of financial and construction timelines and incremental delivery of finished modules.[5] Second, transportation costs can be reduced by minimizing the transportation infrastructure required to move the plant components. Third, cost can be reduced through a system design that minimizes the time from order to first production, and, in the multiple-plant group installation approach normally considered for this type of small plant, adds generating capacity to the grid incrementally as each plant in a group is completed—providing interim revenue to off set the capital outlay and cost of money for the remaining modules of the group.

1.1.2. Operations and Maintenance cost

Operations and maintenance costs include many different aspects of the plant. Typical operational costs such as plant operator labor, any resources needed by the plant during normal operation, refueling, and maintainence, along with fuel costs. In order to best analyze the cost improvements made possible by the MPBR design, the O&M cost must also include the downtime costs associated with repair and maintenance and the direct costs of such activities—parts cost, transportation of the components, and the labor and equipment needed to replace or repair the damaged components.

1.1.3. Increased Number of Potential Sites

Cost of producing power using the MIT PBR reactor will also be reduced by designing a plant that can be installed at a greater number of potential sites. A greater number of aavailble sites would increase the potential number of units built, decreasing individual plant cost according to the economics of mass production. A design philosophy to enable a greater number of sites requires careful attention to all aspects of the plant. Potential sites may be reduced by ambient environment such as hot or humid areas, lack of available water supply for cooling (as most power plants use either evaporative cooling or open cycle water cooling—both using large quantities of water from local sources), lack of available transportation resources (barge and/or heavy rail access). or political / social implications of large plant structures. Of particular interest is the elimination of hyperbolic cooling towers. The towers occupy a significant footprint and require vast amounts of make-up water to operate. While these issues are secondary for most conventional nuclear plants given the large land areas reserved for buffer space around the plants, and conventional location of plants near large natural water sources, replacement of this mode of cooling with closed cycle, forced draft systems, ideally integrated into the plant structure could result in a reduction of the land area and resources required for the MIT PBR. The political impact of eliminating the hyperbolic towers cannot be ignored as these towers have become symbolic of the negative aspects of nuclear energy, despite their use by all types of power plants.

Replacement of the ubiquitous towers with an advanced system would not only reduce the MIT PBR design's exposure to political pressure and protest (reducing legal costs during site selection and purchasing), but also reduce the negative effects on local property values (due to both the however misguided "Not in my backyard" syndrome and the very real impact of tall industrial structures on the view of the landscape, as these towers are typically well over 100m in height and can be seen for many miles).

1.2. Thesis contribution

Based on the reference cycle design, a detailed analysis and modularity design of a power producing plant is needed. The reference plant design, described in Chapter 3, is based primarily on the cycle and component designs described in *Design, Analysis and Optimization of the Power Conversion System for the Modular Pebble Bed Reactor System* by Dr. Chunyun Wang at MIT[6]. The motivation given above requires this design to take the various goals into account, develop a design to reduce cost in all the suggested areas, and be detailed enough to enable its use as a guide to follow-on, more detailed plant design.

This project meets these goals through contribution of a series of modularity principles, component designs, and an overall system design. While the modularity principles are the key points to be made, these principles require the development of specific component designs in order to maximize the cost and safety benefits of the principles. Additionally, the principles would be meaningless without contribution of a system design, based on the reference plant design, that would illustrate the implementation of these principles. The following is a specific list of contributions in each area—modularity principles, resulting required component designs, and system design.

Unique Approach—Advanced Modularity Principles

- Economy of mass-production based modularity approach
- Virtual factory concept for component construction
- Space-frame structure and assembly approach

Component / Subsystem Designs—Key Design Achievements

- Pressure backed insulated liner system for vessels and piping
- Redundantly sealed flange with internal scavenging for pipe connections
- Heat rejection system meeting the design requirements and goals of the project

System design

- Component / Module breakdown
- Pipe / Component layout
- Plant module layout
- Plant containment building design and plant construction

This design takes into account the goals for the modularity and construction approach. The plant takes the factory assembly approach to its logical conclusion, resulting in the concept of a "virtual factory" where each major component is integrated into a simple, low cost, modular space-frame (either constructed locally to spec. or, given its standard size and low empty weight, transported at low cost from one or more space-frame specific fabricators) by the manufacturer. Each module can then be tested by its manufacturer and transported by truck (eliminating any rail or barge infrastructure required) to the construction site. The plant site itself requires only simple excavation and the plant containment building is a simple, reinforced poured concrete structure. Assembly of the plant is simple by comparison to conventional facilities as the true modularity approach proposed requires that the modules simply be stacked and the various structural and pipe connections made.

1.3. Organization of thesis

This thesis is organized into six chapters. Chapter 2 reviews goals of this thesis, and, to provide the framework for the analysis and results, the design considerations and the requirements that the proposed system design must meet. The requirements detailed in this chapter are derived from the goals for the project—reducing the end-to-end cost of nuclear power production through the use of a modularized pebble bed reactor system. The requirements cover code and regulatory issues, net plant parameters (power level, efficiency), fuel and waste related issues, component transportation, and plant layout and construction. Design considerations described in this chapter are best described as the initial design assumptions made to guide the development of the contributions defined above. These considerations include, most importantly, the explicit use of the pebble bed reference plant design for system-wide cycle and component specifications. Additional design considerations include engineering preferences determined in prior studies, such as the aforementioned work by Dr. Wang, along with "Standards and Guidelines for Cost Effective Layout and Modularization of Nuclear Plants" by Westinghouse Electric Company[7], and the original MIT PBR plant design study performed in 1998[8] to be applicable to the goals of this project, including, component sourcing, and common design and construction elements.

Chapter 3 details the proposed modularity principles and the resulting design and construction strategy. Specific detail is given to the modularity principles contributed by this project. Economy of mass-production is described and compared to the conventional economy of scale approach. The concept of a Virtual Factory—complete elimination of the need for any construction or capitalization of a facility specifically dedicated toward the production, assembly, or installation of these plants, is further detailed in this chapter. The assembly approach and space-frame structure / module design is described, and its effects on the design strategy detailed. Also described in this chapter are the strategies associated with the concept of module transportation using only road-mobile vehicles, site preparation and facility construction, and the assembly off the plant itself.

Chapter 4 details the pebble bed reactor reference design. As stated above, and detailed in chapter 2, the reference design provides the specifications needed as a backbone for this analysis. As such, the plant cycle and the major components of the reference design are described, giving specific attention to the specifications and design choices that have specific bearing on the modularity principles of this project.

The most important contribution, the proposed system design incorporating these modularity principles and the reference design, is detailed in chapter 5. This chapter details first the general elements of the system design, including the unique component and subsystem designs contributed by this thesis, each of which is instrumental in meeting the defined goals of the system. The remainder of this chapter gives, in detail, the system design resulting from the application of the strategies described in chapter 3 to the goals and requirements defined in chapter 2 and the reference design shown in chapter 4. The design specifications given in chapter 3 for various components in the reference design are expanded to include details concerning their construction, transportation, assembly, and installation into the plant. Components omitted or only cursorily described in the reference design are described in detail, including the tertiary cooling system and heat rejection apparatus. While details of these systems were not necessary for the cycle optimization, control analysis, and individual component design performed to yield the reference design, they have significant bearing on the overall system design, and thus must be included. While the design presented in chapter 5 assumes the reference design specifications are static, there may be potential changes that could increase the design merit of the system—these suggested changes are described, estimated effects determined, and suggested additional work defined where applicable.

2. Requirements: Modularity Design Considerations and Requirements

The goals, requirements, and design considerations defined in this chapter provide the framework for the design analysis that follows. While the design goals are a direct result of the cost reduction motives, determination of the correct set of requirements and design considerations requires significant effort, given their complexity.

2.1. Goals

The MIT Pebble Bed Reactor design goals were defined in the original MIT PBR system study performed in 1998[9] and are centered on the bottom line--reducing the cost of the delivered power. The design must address all elements of the delivered power cost—capital cost, licensing, fuel, O&M. The design must ease siting requirements, enable design licensing and license by test, and require minimum site preparation and construction work. The modularity approach must simplify and speed component construction and plant assembly—reducing capital cost. Capital cost can also be reduced by decreasing the "cost of money" associated with the plant—reducing the time from financing the plant till it first generates income[10]. The approach must also enable operations and maintenance cost reduction through high availability and rapid repair / replacement of damaged components. Additionally, the plant must require a minimum staff to operate. Reduction in staffing requirements and onsite control facility requirements are a key method to reduce cost.

Based on these general goals, the MIT PBR modularity design must attempt to:

- Minimize module size and mass to enable low cost transportation by truck
- Reduce plant capital cost by enabling mass production and component commonality (design to fit—interchangable components)
- Reduce overall plant footprint through integrated plant services (heat rejection, control systems)
- Simplify construction to reduce timeline from plant order to operation

2.2. Requirements

The proposed modularity principles and the resulting design must meet certain requirements imposed by engineering, economic, or political pressures. These requirements include requirements based on code and regulatory policy, net plant parameters (power level, efficiency, capital cost), fuel and waste related issues, component transportation limits, and layout and construction requirements.

2.2.1. Code and Regulatory Issues

The MIT PBR design must meet basic code and regulatory issues that are applied to commercial nuclear power plant design. The system must meet NRC regulations, specifically those regarding materials, design, and safety systems. The design must also meet the ASME specifications regarding nuclear systems under pressure. These specifications are defined in ASME codes.

The MIT PBR system has a wider variety of applicable ASME codes than a conventional PWR system. The applicable ASME codes are dependent on whether or not the component or piping is part of the nuclear boundary (primary side). Since the code requirements of non-nuclear power plant or process piping are relaxed compared to those applicable to nuclear systems, the indirect cycle used by the MIT PBR is a distinct advantage. For example, the maximum allowable stresses of a typical alloy such as A508/533, are far higher, especially at elevated temperatures for non-nuclear systems[11].

The primary side (nuclear boundary) is governed by ASME Section III (Class I). The primary side boundary includes the reactor vessel, the piping and manifolds containing primary side Helium from the RV to the IHX modules, the IHX module vessels themselves (as the primary side IHX exhaust flows into the IHX vessel itself), the IHX core structures, and the secondary side IHX piping *inside* the IHX vessel. All other Helium piping and components are part of the secondary side (for ASME code considerations[12].

The secondary side of the MIT PBR is governed by ASME section VIII, and includes all piping not defined as part of the Sec. III (Class I) boundary, all of the turbo-machinery, the recuperator assemblies, and all the secondary side heat exchangers[13].

2.2.2. Net Plant Requirements

The MIT PBR has certain net plant requirements. These requirements define the overall power production and fuel requirements. The net plant requirements begin with the power level that the MIT PBR must produce when operating at full power. Based on prior analysis, the PBR must produce at least 110MWe[14]. This power production requirement is based on the goal efficiency and the thermal power output (268MWt) of one design iteration of the ESKOM pebble bed reactor core design[15].

With this output power requirement, the overall efficiency of the plant must also meet certain requirements. This efficiency is calculated by the ratio of plant output electrical power vs. reactor thermal power, and is directly related to the fuel cost of the power produced. In order to make the plant cost effective, the plant must have an overall system efficiency of 45% or greater[16].

2.2.3. Transportation of Components

The transportation constraints defined for this analysis have significant effects on the design of the system. To achieve the goals defined for this system, the transportation requirements are centered around a single philosophy—all the system modules must be road-transportable (as such road transportable modules could also be moved by rail or barge depending on the infrastructure present at the construction site, the cost of each method, as well as the size and load limits of each vehicle). Conventional plants use a wide variety of transportation methods including road transportation of small parts, but also rail and/or barge transport of large components and assemblies.

By constraining component and reactor module design to road-mobile transportation the goal of cost reduction is obtained through several methods. The most important reduction in cost is the elimination of any infrastructure costs associated with the installation of the plant. In a conventional plant, either a waterway or rail spur must be constructed to deliver the heavy components to the site[17]—unless these transportation elements are already in place (conventional plant site choice obviously takes into account the economics of obtaining the necessary transportation infrastructure). These modifications are not only extremely costly, but add a significant amount of time to the construction of the system—time during which the capital cost of money adds up. Road mobile transportation limits the infrastructure improvement costs to a minimum amount—primarily limited modification of any road-beds or overhanging wires that cannot support or pass any oversize components that must be transported. These types of road modifications are standard procedure in the current transport of outsize or heavy objects and does not involve significant cost[18].

Cost is also reduced indirectly by enabling a wider range of possible sites. Current systems, by requiring rail or water transportation are limited in their potential installation sites. Roads are must more ubiquitous, and if necessary, are easy to rapidly construct at low cost.

Road mobile transportation puts very specific limits on mass and size of the various modules. Wherever possible, the MIT PBR modules are sized to closely approximate a standard ISO shipping container (also referred to as an "intermodal" container). Certain exceptions to this sizing goal do occur, specifically, the power turbine / generator module, and the reactor vessel module(s). The module size was chosen to minimize any potential interference with bridges, etc. during transportation. The overall limits for road mobile transportation, which are used as design constraints, are grouped into mass and size constraints.

The size constraints for road mobile transportation are dependent on the type of transporter used. Conventional ISO container sizes are used as a baseline for the MIT PBR modules, as these sizes should encounter little if any height or width restrictions throughout the United States. A standard ISO (668:1995 series 1) container is 2.44m wide, 2.9m high (extended height "high cube" version, standard is 2.59m), and either 6.1 or 12.2m long (standard lengths, however, containers are manufactured in lengths from 7.3m to 17.2m)[19]. The MIT PBR modules are only slightly larger than these dimensions (2.5m wide x 3m high).

Wide load (non-intermodal) transporters can transport payloads that are dimensionally much larger than the ISO standard, however, transporting these outsize payloads results in a significant cost increase due to route survey requirements (locating potential height and width restrictions and either choosing an alternate route or removing the obstacle, transport restrictions (e.g. time-of-day restrictions on wide-loads), decreased speed limits, and any additional support or escort vehicles required. The overall size limits for trucking are established on a state by state basis, so a comprehensive list is not feasible, but limiting the Reactor Vessel (RV) module to ~6m width and 5m height (assuming the RV is transported as several separate parts) and Power Turbine (PT)/Generator modules to ~5m width and ~4m height, should be sufficient to eliminate any major concerns[20].

The mass limitations for trucks are difficult to define. While the DOT and its subsidiary state agencies define maximum loads per wheel or per axle, transportation of extremely heavy payloads is simply a matter of increasing the number of axles used to support the payload. There are many different types of vehicles used to transport heavy loads (heavy loads being defined in this case as greater than the ~3×10^4 kg gross maximum for a 20 foot ISO container, or ~4.5×10^4 kg for a 40 foot ISO flat rack container[21]). The vehicles range from low-boy style semi-trailers (used to transport payloads up to 10^5 kg) to multiple-dolly trailers capable of transporting nearly unlimited (past examples of long distance transport of 2.5×10^5 kg+ payloads exist) payloads. These types of transporters are depicted in the pictures below, along with their load capacities.

[heavy load transporter pictures and specs]

Estimating the cost of transporting the various modules is difficult without exact information as to origin, destination, mass, and size, but in order to better understand the costs, a notional route, mass, and size was used to obtain an estimated quote from a US heavy-load transportation company. Assuming an origin in the middle of the US (e.g. St. Louis, MO) and a destination on the west coast (Los Angeles, CA), a mass of 5×10^4 kg, and an envelope roughly the size of an ISO container, the company quoted a rough estimated cost of $75,000[22].

It is apparent from this cost figure, and from various surveys of the types of equipment needed to transport the MIT PBR modules, that it would be cost effective to implement the transportation part of the "virtual factory" concept with internal resources (i.e. trucks and trailers owned or leased by the proposed MIT PBR company), rather than outsourcing the transportation. Using internally owned/leased vehicles would also simplify transportation tasking as each module fabricator would have access to one or more transporters specifically chosen for its product. The transporters would operate on continuous loops between the supplier, new PBR plants under construction, and existing plants for spare / failed module transportation.

2.2.4. Layout Requirements

The module and internal plant layout of the MIT PBR system is constrained by the modularity approaches defined earlier. The layout must enable rapid stacking and connection of the modules during initial construction and assembly, allow for limited on-site diagnostics and repair, and most importantly, allow for modules to be removed and replaced rapidly, should their components fail.

Based on these requirements, the layout must enable cross-support of modules to permit a single module to be removed without sacrificing the structural stability of the plant. The layout must also reduce or eliminate the number of additional modules that must be removed to service a failed module. The layout must also minimize the amount of module handling apparatus required to perform module removal and replacement. Based on these requirements, such a layout should minimize the depth of the module stack in all dimensions.

2.2.5. Construction Requirements

In order to meet the modularity approach philosophy and goals defined earlier, the actual construction of the plant must meet several requirements. These requirements are best defined in two groups, those relating to the rapid construction of the plant, and those regarding the preparation of the site.

2.2.5.1. Rapid Assembly

Rapid construction of the plant requires the modules be easily manipulated with a minimum of tooling and equipment. The modules must also provide a significant degree of self-alignment to minimize the time required to assemble the plant. The modules themselves must also enable easy positioning of the components contained within each space-frame to facilitate alignment and connection of the piping and other assemblies.

2.2.5.2. Site Preparation

The plant site itself must be prepared with a minimum of effort and cost. As such, simplified construction of the plant building must be required. Such simplification must be applied to all aspects of the site preparation. First, the excavation of the site must be simple, and minimal. Second, the building construction must use low-cost construction methods such as poured-concrete slip-forming. Third, the required interfaces between the building and the installed modules must be simple—i.e. a minimum amount of support structure other than that built into the modules themselves.

2.3. Design considerations

The design considerations are the engineering choices that result from the requirements and goals of the MIT PBR design.

2.3.1. Design reference plant

The primary design consideration that guides the design of the PBR plant is the use of a design reference plant. The reference plant used has been analyzed and described in detail by prior work on this project and covers the cycle parameters of the closed Helium Brayton cycle. The reference plant also includes the individual design and specifications of the individual components of the plant. This plant reference design is based primarily on the prior MIT PBR work[23] with the reactor vessel and a few minor ancillary system based on one iteration of the ESKOM plant design[24].

2.3.2. Commercial-Of-The-Shelf Components

In order to meet the goals of cost, rapid development, and construction, design consideration must be made regarding the sourcing of the various components and structures. To minimize cost, a design which maximizes the number of components that are Commercial-Off-The-Shelf (COTS)—available in standard form from as many vendors as possible—will be the most successful.

2.3.3. Construction Methods—Simple Assembly

Design consideration must be given to the construction of the plant itself. As described in the previous sections simplified assembly of the plant is a requirement for the cost reduction required by the goals. As such the design consideration consists of maximizing the amount of assembly done off-site. One example of how this effects work is the "rule of three"—3 times the labor/cost is required to perform a task at an assembly area rather than the component shop, and 9 times the labor cost is required to perform this task at the delivery site. This is the result of the ease at which qualified labor and the required tooling and equipment is available at each site.

2.3.4. Reduced Control Facilities & Crew Size

Given the size of the control facilities at conventional plants (illustrated in Figure 2.1), and the number of people (XX personnel)[25] required for normal operation reduction or elimination of these facilities is a major design goal.

[picture of conventional plant highlighting control facilities]

Figure 2.1: Conventional Nuclear Power Plant Control Facility[26]

The pebble bed, Helium cycle plant was originally chosen as it requires far fewer systems for operation compared to conventional PWR or BWR plants. Various methods to reduce these costs include increased automation of plant processes (enabled by the fail-safe PBR design—the long accident timelines compared to current reactor designs enable simplified control and emergency systems). Other cost reduction methods, such as sharing a control crew among multiple MIT PBR modules, and reducing the necessary personnel to perform plant maintenance and repair (by incorporating internal self-test and non-destructive evaluation of plant systems and the proposed replace and repair strategy) are also possible. Costs can also be reduced by decreasing the size of the on-site control facilities—for example, by eliminating the large control building with a small facility containing the minimum instrumentation and control equipment (emphasizing modern computing, display and control systems), the small on-site command and control crew, and whatever backup systems are required. Such a compact control facility would enable something nearly impossible with current systems—a completely redundant control system with two or more totally separate, individually crewed and supported, control modules.

2.3.5. Repair / Replace

To meet the low cost goals, the design must consider the ease at which components can be repaired or replaced on-site. The design must compare the cost of performing a repair on-site (including the cost to the design of including sufficient access to the components to affect a repair in-situ) vs. the cost of removing the entire module containing the damaged component and immediately replacing it with a spare module. Given the proposed strategy of housing multiple (as many as 10) MIT PBR modules at a single site[27], a common set of spare modules could be kept on site—increasing the utility of rapidly removing and replacing a damaged module to maintain plant availablility. A transporter could then be dispached from the factory where that module is produced with a fresh spare, and the damaged module returned to the factory for repair by the same transporter.

2.3.6. Commonality of Component Design

If possible, design commonality must be considered—cost can be reduced by minimizing the number of independent component designs. For example by having a common compressor design for all four compressor sets rather than a specific design for each compressor would reduce the design and manufacturing cost. Other components where a common design could be attempted include the Precooler, Intercoolers, and, if possible, the Recuperator / IHX modules (if a common design were possible with a minimum impact in system efficiency). Part of future work should include an assessement as to the efficiency and cost impact of such common designs, but it should be noted that this type of assessment is key to a production system—while past systems have attempted to maximimize plant efficiency (and thus power production), the large fraction of cost associated with the capital expenditure of the plant may lead to an economically optimum plant that would be simpler and cheaper to build albeit at the loss of overall system efficiency.

2.3.7. Interchangable Components

Interchangable components is a fundamental design consideration of the PBR system. This would achieve cost reduction by enabling universal replacement of failed components. This is the goal of a design-to-fit engineering and construction process. Rather than assembling the plant, performing optical metrology on the various components, and having suppliers construct parts to fit the dimensions of the plant being constructed, tolerances and construction methods are chosen so that a module will fit into its position in any of the plants. In terms of engineering complexity, this is a far more difficult method. Design-to-fit requires far more work during the design and engineering phase of the system, and possibly more work in the prototype phase, however, the cost advantages in the long run appear to far outweigh the initial investment. This method is only applicable to systems with large production runs, and has currently been used with great success in the construction of other large, complex, high tolerance systems, such as the Boeing 777. In the case of the Boeing 777, parametric CAD/CAM engineering, along with a design-to-fit, high tolerance engineering philosophy enabled Boeing to construct the aircraft, and integrate components from a wide variety of subcontractors, with an unprecedented level of first-fit component installation success[28].

[Add in NNS / EB information from meetings and their information]

Optical metrology—eliminate reference lines

jig construction

laser-inscribed weld / placement lines and instructions

By ensuring universal dimensions across all the MIT PBR plants, costs can be reduced in several areas. First, final work and potential re-work of components can be reduced, or eliminated as each component will not need to be custom-fit to the dimensions of its final destination. Second, a group of MIT PBR plants installed at a single location (the proposed operational strategy) would be able to share a set of spare components, reducing the cost of maintaining a sufficient spare inventory to enable rapid replacement and repair. Third, any follow-on upgrades or improvements to MIT PBR components could be easily incorporated into both new plants, and existing ones (through either replacement of failed components or a standard replacement / inspection strategy), without redesign of the entire system—since each module must fit to a constant set of interface specifications (mating dimensions, etc), an upgraded module must simply be compatible with these specifications for it to be included.

3. Proposed Modularity / Construction Strategy

The proposed modularity and resulting design and construction strategy are detailed in this chapter. This topic describes what modularity approaches and design strategies are used within the requirements and design considerations described in Chapter 2 to best meet the goals of the system. Beginning with a description of the fundamental thrust—a design approach that leverages economy of mass production, this chapter continues with details of the method to implement this approach—the Virtual Factory. The remaining sections describe the plant structure and assembly approach, the module transportation strategy, the site preparation and facility construction approach, and the approach to assembling and building the plant itself.

3.1. Economy of mass-production vs. Economy of scale

The fundamental thrust to this approach is the emphasis on economy of mass production. Conventional nuclear plants rely on an emphasis on economy of scale—delivered power unit cost can be reduced by making each plant as large as possible. By constructing extremely large plants sunk costs such as site preparation, power distribution apparatus, transportation infrastructure improvements, and transport of the fresh and spent fuel to the system are spread out over a larger quantity of produced power. The MIT PBR approach is different but seeks to meet the same goals. By manufacturing a greater number of identical plants, this approach minimizes costs by taking into account the cost reduction learning curves associated with mass production. These cost reductions are obtained through several channels. First, it is easier for a vendor to meet low-cost goals if the internal design and tooling cost is spread out over a greater number of delivered components. Second, labor and tooling costs are reduced as the number of components increases due to techniques and equipment improvements developed during the production run—this is a common result shown in production of many products ranging from simple consumer goods to extremely complex products such as commercial aircraft. Third, the production of a large number of identical components enables production facilities to use mass-production methods such as assembly line production with standardized tooling. While construction of the tooling results in a higher capital cost than a one-off product, its existence enables lower labor and build cost for a large production run.

Typical cost reduction learning curves for various systems take the form of the following formula, Where $\boldsymbol{C_n}$ is the Nth unit cost, $\boldsymbol{C_0}$ is the initial cost, $\boldsymbol{N}$ the number of units, and $\boldsymbol{b}$ the learning factor.

$$C_n = C_0 N^b$$

This formula is applied to empirically determined variables for different types of processes, such as those included in Table 3.1, to determine the Nth unit cost. Even with the most conservative (least cost change per increase in N) learning curves shown, the cost reductions can be substantial for large values of N. Since the MIT PBR plant requires ~10 modules to produce the same power as a conventional 1000 MWe sized plant, combined with the design choices made to maximize the number of potential sites, the total number of component sets (N) can be extremely large, reducing the average unit cost and exemplifying the design choice of mass-production vs. scale size.

Table 3.1 Example Learning Curve Variables (b-values)[29]

Aerospace	85%
Shipbuilding	80-85%
Complex machine tools for new models	75-85%
Repetitive electronics manufacturing	90-95%
Repetitive machining or punch-press operations	90-95%
repetitive electrical operations	75-85%
Repetitive welding operations	90%
Raw materials	93-96%
Purchased Parts	85-88%

3.2. Virtual factory concept

To implement the mass-production concept described above the MIT PBR design will use a new concept in manufacturing—a Virtual Factory. Past modular power plant designs emphasized a "factory built" approach. In this approach, power plant components will be built and assembled into modules in an off-site facility, then shipped to the site and assembled. The MIT PBR approach is to eliminate the off-site facility entirely. The plant will be designed so each component is installed into its module by the vendor that constructed the component. The module is then shipped to the site and installed into the plant. This requires the design to limit the number of different components installed into each module, and a module structure design that can be easily built by the vendor or a subcontractor. This method also reduces transportation costs. Since the components define the mass and size of each module (the "wrapper" is relatively light weight compared to the component), the cost of transporting the module can be assumed to be nearly identical to the cost of transporting the component itself. Rather than transporting the component to a central factory where it is wrapped in its structure, then transported to the assembly site, a finished module is transported directly from the contractor to the assembly site. This approach yields two major results—reduced capital expense and outsourced module construction.

3.2.1. Reduced Capital Expense

Reduced overall capital expense to both the MIT PBR entity and the various contractors. First, by eliminating any requirement for a central facility, both the capital cost ammoratized over the production of the plants, and the time required to start manufacturing the PBR plants are reduced. Secondly, by simplifying the module "wrapper" each component is contained in, the component contractor's cost is reduced. The contractor is given a cost target to meet for a delivered module and given the choice of construction methods. While it is reasonable to assume there would be some capital investment by each component manufacturer, the proposed approach would limit these values by selecting manufacturers for each component that currently produce similar products.

3.2.2. Outsourced Module Construction

The contractor's ability to choose a module construction approach (provided it meets the interface and other requirements of the design) may result in the various contractors developing a shared source for common components. A contractor can choose to outsource certain aspects of the module construction. For example, rather than use up capital facilities and labor to build the space-frame specified for a given module, the contractor can outsource the frame construction to a local sub-contractor. What may also end up occurring is, if the locations of the various module fabricators were favorable, a groups of contractors may choose to outsource all the elements their modules have in common to a specific vendor—taking advantage of mass-production economics. The point of having of the components in a module fabricated at the primary component manufacturer (the primary component is the one the module is designed around. e.g. the recuperator vessel and core within the recuperator module) is to avoid the additional transportation cost of moving incomplete modules from location to location.

Each contractor is responsible for delivering a finished module that will require no additional assembly work before being installed into the plant. This will entail installation into the module of any plant system busses, ancillary components, or control / testing systems before delivery. Each module must also be tested, both for functionality and for dimensional requirements, before delivery, minimizing the amount of on-site testing required after assembly.

3.3. Plant Structure and Assembly Modularization Approach

Based on the mass-production and Virtual Factory approaches described above, a specific plant structure and assembly approach to modularization is easily gestated. The structure and assembly approach is based on the space-frame concept. Using this concept, a simplified bolt-together assembly approach is born. This bolt-together assembly will require the structure to provide alignment to the components that must be interconnected, and make assembly a "plug and play" effort.

3.3.1. Space Frame Concept

The space-frame concept is the fundamental modularization approach for the MIT PBR system. This is the final evolution of modularity design, which began with the least effective construction method—so called "stick building." The next step in the development of modular construction was the use of parallel / pipelined construction. This was followed by a large module approach. The space-frame concept follows by breaking down the system into smaller modules with a standardized interface—in effect, the assembly of the plant involves a small number of space-frame modules, rather than the large number of pipes and components contained within. The space-frame serves as an exoskeleton for each module, providing structural support for the components contained inside. At each stage of the evolution, more pre-production design effort is required, but as the ship-building industry has realized, the overall time from concept to delivered product is reduced, and in cases where a large number of systems are built, the cost is also dramatically reduced.

3.3.1.1. Stick Building

Stick building is the construction method currently used for nuclear plants, and until the advent of modularity, large ships. In this method, each minute component of the system is fabricated, transported to the final assembly site, and installed. This method requires the least pre-production design effort as only the finished design and an extremely detailed step-by-step construction plan is needed. The superstructure of the plant is constructed, then each component installed in turn, followed by installation of the required piping connecting all the various components, finalized by the installation of the ancillary / support components and busses, and finally any building finish work (the walls and roof covering all the systems)[30]. This method minimizes the pre-production effort into defining the tolerances of all the various components, as the required dimensions of each secondary component (for example, a pipe connecting one major component to another) are measured after the major components have already been installed into their final positions. The disadvantages of this approach are many.

First, this method is an extremely linear production method with, to borrow a term from computer science, little pipelining and parallelism. Since the final required dimensions of many of the components are not defined until other have been installed, production of those parts cannot begin until after a potentially significant amount of assembly has been performed (due primarily to the fact that the required tolerances operationally required for each component are typically tighter than the tolerances possible for installation of components within the superstructure). The stick-building method can either require high-tolerance installation of all components—dramatically increasing costs, or relax installation positioning tolerances and prolong the assembly / construction time by waiting till the final required dimensions for each part can be obtained.

Parallel construction and assembly is also limited by the stick-building method. For example, access to the entire structure during assembly must be ensured—limiting the installation of components which could restrict the space needed to maneuver a component to a point deeper in the plant.

These factors make the time required to build a system such as a nuclear power plant, or a large ship extremely long, more than 5 years in the case of conventional nuclear power plants[31]. Stick building requires all of the assembly take place at the construction site, making quality control much more difficult and vastly increasing the cost of any rework necessary, as either the facilities for rework must be constructed on site, or the component transported back to the original manufacturer, reworked, and transported back to the construction site.

3.3.1.2. Limited Parallel / Pipelined Construction

By expending additional design effort some of the disadvantages of stick building can be reduced. This step in the evolution of modular construction requires the design take into account the simultaneous construction and installation of several modules, and a "design-build-to-fit" part fabrication approach, enabling pipelining of the component construction. However, since this method still requires each component to be separately installed, tolerances can still build up and a substantial amount of refit may be required.

3.3.1.3. Large Module Construction

Module level stick building is the current level of modular construction applied to shipbuilding, and the next step in the evolution of modular design. In this method, whole sections of the plant / ship are constructed separately and simultaneously[32]. This method enables parallel construction of many modules, decreasing assembly and checkout time (as each module can be individually tested before final assembly). Dimensional control to ensure module-to-module connectivity is only required on the interfaces, rather than over the entire module. The module size used in this method is still quite large, with each module containing a wide variety of components and systems. This system works rather well for shipbuilding since the final assembly point tends to be very closely located to the module assembly area (even in cases where the modules are assembled remotely, they are typically transported as nearly a whole ship).

[describe EB/NNS method for the Virginia class]

internal components + external framework → assembly at a different location

testing before installation—control module testing

cost reductions (NNS report?)

For the MIT PBR system, this type of modularity approach is not nearly sufficient to meet the defined goals, as the modules are still extremely large, and contain components from many different vendors, requiring the module construction to take place at an additional integration facility (in the case of the SSN Virginia class boats, the final assembly is alternated between EB and NG:NNS, while the module integration location(s) remain constant, thus the module integration and the final assembly take place in the same facility at each location). This is not possible with the MIT PBR as the final assembly location is highly variable as at most 10 plants would be constructed at a single site. Therefore, elimination of the module-level integration facility by breaking the system down into smaller modules that can be integrated by the manufacturer of the component(s) contained in each module is the next step in the evolution of modular construction, and the proposed method for the MIT PBR.

3.3.1.4. Small Module Space-Frame Construction

The final stage in the evolution of modular design is the small module space-frame modular construction method. This method uses module sizes far smaller than those in the previous large module method. Each module is sized to be easily transported, and more importantly, contains only a single type of component—i.e. the entire contents of a module can be manufactured by a single vendor, with a minimum of sub-contracted ancillary components. This method is idea for the MIT PBR, but not efficient for ship-building, as it most likely results in a system envelope larger than that possible using the large module construction method. This inefficiency is why modular shipbuilding has ceased its modularity evolution at the previous level. However, for the PBR, the ability to eliminate facilities for module assembly, allocate each module's construction to a specific vendor, and easily transport the modules to the site outweighs any penalty in system size.

3.3.2. Simplified Interconnection and Assembly

Using the space-frames to provide structural support to the various components enables the actual plant assembly to be a bolt-together affair, similar to the stacking and attachment methods used for intermodal container transportation on ships. These containers are attached to one another using locking cams that fit into oval holes on all three faces of each corner, as shown in Figure XX[33]. This example has a maximum tension load of ~$5.1\text{x}10^4$ kg and a maximum shear load of ~$4.3\text{x}10^4$ kg.

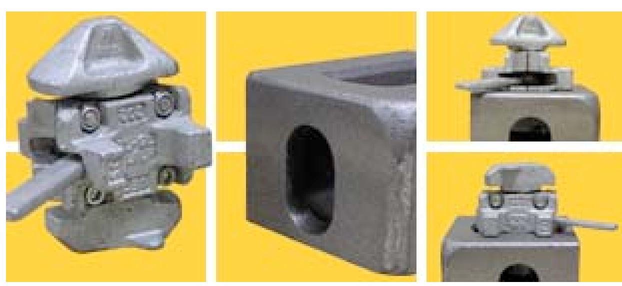


Figure 3.1 Tandemloc Inc. Double Cone Two Position Twist Lock[34]

In the case of the MIT PBR space-frames, a similar method can be used to temporarily join the modules, follwed by installation of high strength bolts to strengthen the interconnection.

As such, all the inter-module interfaces (pipe joints, etc.) must be also be designed for ease of attachment. This requires bolted flange joints in all large diameter piping, quick-disconnect or other type of connectors for small tubing, wiring, and other connections.

3.3.3. Installation and Alignment of Modules

The design of the modules must also take into account assembly difficulty. The space-frame encapsulating each component is a relatively low-tolerance structure (to reduce costs), as such, the structures supporting a component within the frame must be capable of positioning the component to fit with adjacent modules. This could be done with relative ease using adjustable transportation support links. The transport support links are detachable structural supports (adjustable length struts for instance) that support the components inside the frame during transport and assembly. The use of one set of supports for transport and assembly and another set of supports for operational use reduces the requirements of the operational supports (pipe hangers and the like) to handle off-design stresses. During plant assembly, these transport supports will be used to position a component for attachment to other modules. An example of a space-frame with both types of supports is shown below in Figure 3.2.

Figure 3.2 Diagram of a Generic Space-Frame Module Including Transport and Operational Supports

The modules must also be "plug-and-play" easy to assemble at the site. This requires each module to be not only easily connected to adjacent systems, but also perform self-test of its systems. Using this approach, the assembly on site will consist solely of stacking the modules, attaching their structural interfaces, alignment and connection of major components, removal / disconnection of the transport supports, and connection of the ancillary interfaces. As each module can be tested individually both before and after assembly (using internal self-test systems) the potential for installation of faulty components during initial construction is markedly reduced.

The testing at the manufacturer could range (depending on licensing and economic requirements) from simple non-destructive inspection of components to installing the module into a jig that would simulate the plant around it—for example, a turbo-compressor module could be tested mechanically using an external drive, a hot-gas blow-down facility, or an integrated test system using a flow loop simulating the temperature, pressure and flow loads each part operates under (i.e. the compressor would be fed Helium at the operational pressure and temperature, and its output either boosted or restricted to the input pressure of the turbine, and heated using an electrically heated or eternally fuel-fired heat exchanger). Additional design and analysis of the economics and licensing requirements would be required to choose the optimum test methods, but across the range of possible methods, the capital cost of such a test jig would not be dramatic—especially given the small physical size of the component and the relatively low power levels, pressures and temperatures used by the plant (conventional gas turbines operate at much higher turbine temperatures and shaft power levels[35], high pressure gas handling compressors used in the petrochemical / natural gas industry also operate at higher shaft powers and pressures than the MIT PBR requires[36], and these components are currently factory tested).

[You will need a section here to discuss the fabrication of the components such that they can be aligned in the manner you describe above. Example, what you are proposing is the equivalent of building the plant and then disassembling it and putting it into space frames for shipment and assembly. You will need to show that modern CAM can align matching parts within the specs required for alignment - you mention this in the 777 example but it needs explanation here.]

jig and optical verification of module dimensions and plant dimensions

design-to-spec/fit—needed for interchangeable modules—tolerance stackup, etc. (cite concerns by NNS)

given a reasonably short transport time, and the small number of modules needed for the plant, module metrology can occur both at fabricator and on-site to verify design-to-specification

3.4. Module Transportation Strategy

To meet the transportation cost reduction goals, a transportation strategy using only road-mobile vehicles is used. While conventional plants require the use of heavy rail or barge transport, the MIT PBR system will use conventional COTS heavy lift road transports. While rail and barge have a lower cost per kg., they require substantial infrastructure (rail line or waterway) to operate effectively. This infrastructure is needed at both the assembly site and the component fabrication (vendor) location.

Assuming the existence of suitable roads, which should not be a problem as road-mobile heavy lift transports put no more weight/tire down than conventional trucks, this means that the MIT PBR plant could be constructed virtually anywhere (subject to site and political requirements and constraints). The transportation analysis required for a new site would be a simple survey of the route to ensure there are no weight or dimensional limitations that would be a problem. This type of survey is done extremely often as the transportation of heavy and outsized loads on road-mobile heavy lift transporters is an extremely common process.

Based on this strategy, the module specifications must be constrained by the size and weight limitations of available transporters. While it is doubtful contracted transportation would be used (assuming of course a reasonably high rate of PBR production), the cost associated with purchasing a fleet of transporters for the sole purpose of ferrying modules between the various vendors and PBR sites would be quite low.

3.5. Site Preparation and Facility Construction

The site preparation and facility construction strategy is defined to meet the cost reduction goals of the system. This design strategy has two major thrusts. First, the site preparation (grading, excavation) must be simple and inexpensive. Second, the actual plant building (including non-modular internal structure) must also be simple and inexpensive.

3.5.1. Simple Site Preparation and Excavation

To make site preparation simple and inexpensive, the necessary improvements must take into account the difficulties associated with the various methods and their limitations. While grading a site level and installing conventional improvements (parking lots, concrete aprons, etc) will likely not have dramatic effects on cost, the necessary excavation of a large area, deep pit for the plant building assuredly will. As such, the design of the plant must ensure that the specifications of the necessary excavation do not require overly costly methods or equipment. For example, the cost of excavating a pit increases non-linearly with depth—due to additional equipment, labor, and safety precautions that need to be taken.

For this analysis, the reactor vessel is assumed to be completely below grade, resulting in a required pit depth of close to 20m. This is required for decay heat rejection to the surrounding earth. Future work should include an analysis as to the necessity of below-grade RV placement, as a wholly above grade structure could be far more economical.

3.5.2. Simple Building Construction & Internal Skeleton

The plant building and internal non-modular support structure must also be designed with cost reduction in mind. The best method for achieving a low installed cost for these elements is to use low cost construction (poured concrete with modular reinforcement and low-cost forms), and an extremely simple design. The internal support structure can be quite minimal, as with the exception of the reactor vessel, all the components are self-supported by their space-frames. As such the only internal support structures that must be installed are the reactor vessel support structure, and reinforced floor pads where the space-frame feet will be. The reactor support structure is a simple annular reinforced concrete pedestal with a load bearing steel structure on top to support the three RV support lugs (the support method defined for the ESKOM reactor vessel)[37]. Figure 3.3 shows a cross-sectional diagram of the lower portion of the ESKOM Reactor vessel, with the support structure for the reactor vessel highlighted and circled (the hatched area denotes reinforced concrete). The MIT PBR support structure would be designed similarly however, instead of annular wall continuing up past the support level, it would stop slightly above the horizontal plane of the support surface.

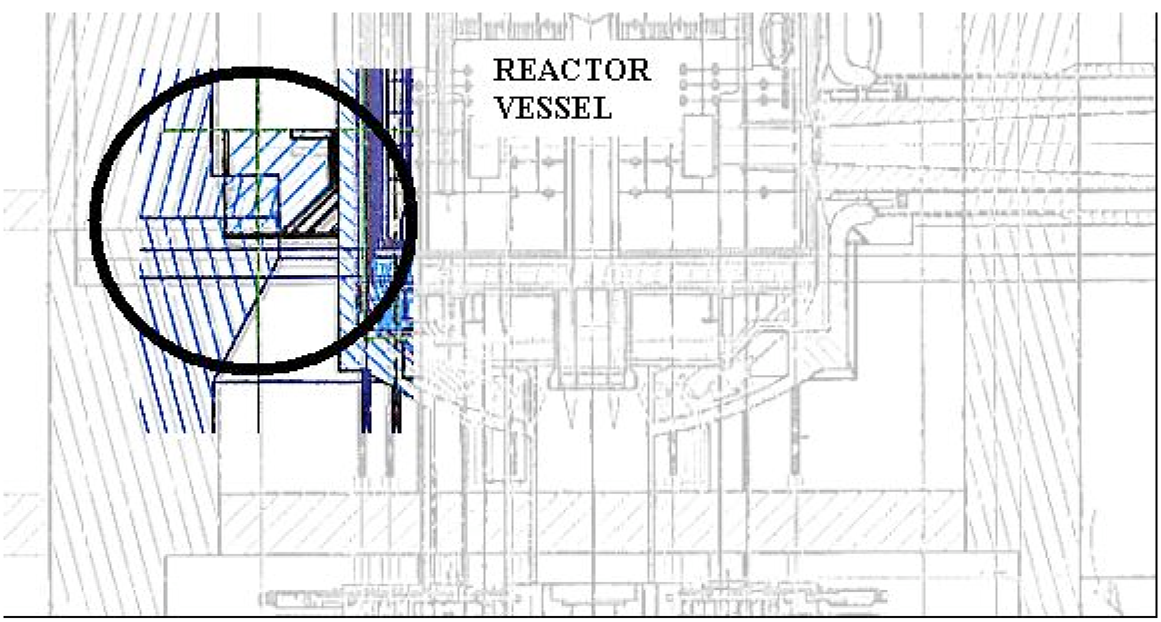


Figure 3.3 Annular Support Structure for ESKOM Reactor Vessel[38]

Load bearing rails may also be installed to ease maneuvering the modules during installation and removal. These rails enable a module to slide laterally for placement or removal. Since the modules are stacked two or three high for most of the plant, the space frames must be able to bridge a gap created by removing a lower module, at least temporarily. As some module replacement would require removal of more than one adjacent module, temporary supports would be installed to bear the loads of the upper modules during removal and replacement.

The building design must also not interfere with the easy installation of the various modules, and their eventual removal and replacement. While the reactor vessel will require special access to the building, it is also the only non-replaceable component, so its installation will most likely be done through a different access than the rest of the modules (such as a removable roof section in the containment building, through which the RV can be lowered). A segmented reactor vessel would enable installation without requiring a roof penetration and an external crane.

3.6. Assembly Strategy

The actual assembly of the plant once the building is finished must be rapid, simple, and require a minimum of time, labor, tooling, and equipment. The space-frame modularity approach makes this relatively easy to accomplish. As each module arrives, its transporter is maneuvered into the module delivery area inside the building, and the module is lifted and placed in its final location by an overhead gantry crane and/or a set of simple rails built into the floor of the facility. Once in its final location, the equipment and tooling required is limited to the stud tensioning equipment to assemble the bolt-together flanges, and whatever limited equipment is needed to attach the ancillary connections and adjust / remove the transportation supports.

4. MPBR Reference Plant Design

In order to advance the design of the MIT pebble bed reactor, the analysis needs to be based on past work. For this analysis, the proposed design of the plant is based on several past analyses including the proposed ESKOM PBR[39], and Dr. Wang's dissertation[40].

4.1. Design Introduction

The reference design used for this analysis is defined in detail by Dr. Wang. The cycle is detailed in Figure 4.1, and features a 3 shaft design (two turbo-compressors and a power turbine-generator). Reactor inlet temperature is 900°C, and reactor inlet temperature is limited to 520°C[41]. Using a plate-fin heat exchanger design, the system optimizes with a pressure ratio of 2.85, produces 130.61MWe (gross power), of which 7.11MWe is used for hotel loads and circulator power,[42] leaving 123.5MWe (Net) or an overall system efficiency of 49.4%. The system. Additional cycle specifications are also listed in Table 4.1.

Table 4.1 Reference Plant Cycle Specifications[43]

Thermal power	250 MWth
Core outlet/inlet temperature	900/520 ° C
Pressure ratio of PCU	2.86
Helium mass flowrate (primary/secondary)	126.7/126.7 kg/s
System maximum pressure	8.0 MPa
Core pressure drop	1%
Plate-Fin IHX	Effectiveness: 95% Pressure drop: 0.5% (primary) 1.4% (Cold side)
Recuperator (Plate-fin HX)	Effectiveness: 95% Pressure drop: 0.8% (low-pressure side) 0.33%(high-pressure side)
Precooler , Intercooler #1, #2, #3.	Helium pressure drop: 0.8% , 0.5%, 0.3%, 0.3%
Turbine polytropic efficiency	92%
Compressor polytropic efficiency	90%
Generator efficiency	98.5%
Circulator isentropic efficiency	90%
Circulator motor efficiency	98%
Turbine shaft mechanical loss	1%
HP compressor and MP compressor #1 extra leakage rate	1%
HP compressor and MP compressor #1 extra cooling rate	3%
Losses Circulator power	3.57MWe
Other station load	2.5 MWe
Switch-yard loss	0.6%
System radiation loss	0.5 MWth
Gross power output	130.6 MWe
Net electric power (zero turbine cooling flow)	123.5 MWe
Net plant efficiency (zero turbine cooling flow)	49.4%

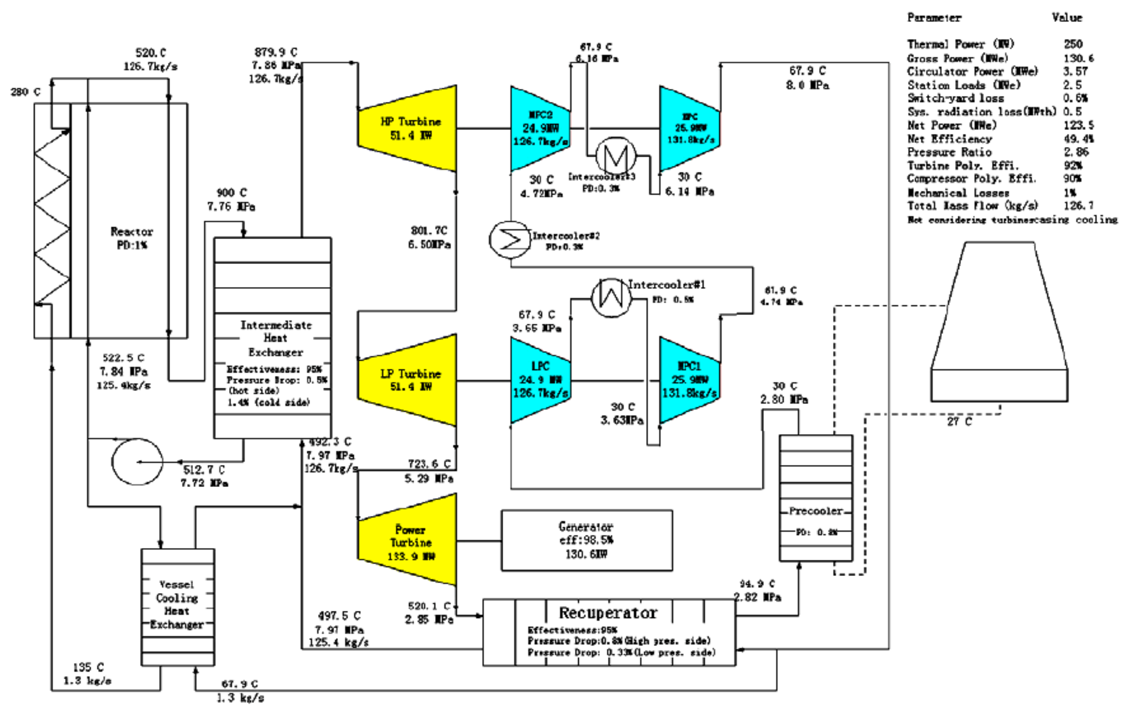


Figure 4.1 Reference Plant Cycle Schematic[44]

4.2. *Primary Side*

The primary side of the plant includes everything within the ASME Section III (Class 1) boundary, i.e. everything containing radiological materials or coolant that contacts these materials. This includes the reactor vessel, primary side piping, and the IHX core modules and outer vessels.

4.2.1. Reactor Vessel

The MIT pebble bed reactor vessel is closely based on the vessel used in the ESKOM pebble bed reactor. The reactor vessel is modified to accommodate the piping differences between the ESKOM and MIT system described later in Section 4.2.1.2. To enable modularity and road-mobile transportation, a segmented version of this reactor vessel is proposed (limiting each section to an overall envelope of approximately 6m dia. x 5m tall and a mass less than 2.5×10^5 kg). While a segmented vessel requires more installation time and additional seals, it would eliminate the cost and time required to transport the large (6m dia x ~20m long) and heavy (greater than 7×10^5 kg without reflector or internals) reactor vessel from the fabricator to the plant site. Another option would be to use a Prestressed Cast Iron Vessel (PCIV). Such a vessel could significantly ease both the vessel cooling and transportation requirements. Further discussion of this option can be found in Chapter 6—Future Work.

4.2.1.1. Design and Specifications

As the MIT PBR reactor vessel is based on the ESKOM design, a detailed description of the ESKOM reactor vessel is necessary as a baseline to determine what modifications would be required for the MIT system.

The ESKOM design for the pebble bed reactor vessel is a multiple vessel structure. The core itself is contained within a metallic core barrel installed within an outer, thicker, pressure vessel. The core barrel provides structural support to the core volume itself, the various reflector assemblies, and other reactor structures and is shown in Figure 4.2. The core barrel is supported by a bearing structure on the bottom, which transfers loads to the primary vessel. Based on ESKOM drawings, the MCB (metallic core barrel), is a 5cm thick, 14.9m tall cylinder with a 5.5m inside diameter. The MCB top plate is a 0.30m thick plate bolted to the top of the MCB. Both structures are composed of the standard high temperature steel alloy (A508/533)[45]. The MCB and its top plate mass ~10^5 kg and 5.6×10^4 kg, respectively.
[ESKOM MCB diagram(s)]

Figure 4.2 ESKOM Metallic Core Barrel Diagram[46]

The core volume itself is a 3.5m diameter, 7.75m cylinder with a 120° (included angle) conical extension at the bottom[47]. This conical section constricts the pebble flow down to the ~0.65m diameter of the pebble discharge tube[48].

ESKOM Reflector Design

The ESKOM reactor requires a large annular reflector with top and bottom cylindrical elements to increase neutron flux inside the active region of the reactor and level the flux to ensure adequate burnup and power leveling in the core. The reflector is a large nuclear graphite structure composed of many small blocks contained within the MCB. The reflector is broken down into three sections, a bottom reflector below the core volume, an annular assembly around the core volume, and a top section above the core. For the mass estimates given in this section, a nuclear graphite density of 1.40×10^3 (kg/m^3)[49] and an A-533 density of 7.85×10^3 (kg/m^3)[50] are used. Where there are large cavities (such as the inlet and exhaust plenums, Helium flow and reactivity control borings), these volumes are taken into account in the mass estimate, however, small penetrations are not included to ensure a conservative mass estimate.

The ESKOM bottom reflector is a cylindrical structure with a conical cavity on top forming the bottom of the pebble bed core. The structure is 5.5m in diameter and contains two large annular plenums for the Helium inlet and exhaust flow from the reactor vessel[51]. The inlet plenum is 5.5m OD, 2.6m ID, 1m tall and starts ~0.75m from the bottom of this reflector section. The exhaust plenum is 3.2m OD, 2.4m ID, 0.75m tall, and starts 2.15m from the bottom[52]. The 4.25m tall cylindrical section of the reflector is topped with a 1m tall conical section for an overall height of 5.25m[53]. The ESKOM design for the bottom reflector section is shown in Figure 4.3.

[ESKOM BOTTOM REFLECTOR DESIGN]

Figure 4.3 ESKOM Bottom Reflector Design[54]

For the MIT PBR, the bottom reflector is contained in a section of the MCB (which has been segmented to enable simplified transportation). The segmentation of the MCB for the MIT PBR design is described in detail in Section XX along with the segmentation ndesign of the outer pressure vessel. The MCB segment is a ring 5cm thick, with a 25cm long, 10cm thick transition to a 25cm long 15cm thick upper ring. The ring is welded to a 10cm thick bottom plate. These structures are composed of the same A508/533 high temperature alloy used for all the core structures. The overall dimensions of the bottom reflector section are 5.7m dia x 5.35m in height, with a total mass of ~2×10^5 kg (1.4×10^5 kg for the graphite reflector and 6×10^4 kg for the lower MCB section. If future analysis leads to the conclusion that a bolted joint in the MCB is not necessary, and the additional time to weld the various MCB sections together is cost effective, replacing the upper thicker sections of the lower MCB section with a single, 25cm long 10cm thick ring would reduce the overall lower reflector module mass by ~3.3×10^3 kg.

The ESKOM side reflector (shown in Figure 4.4) is an annular structure 7.75m in height surrounding the main core volume. It is composed of an inner and outer section. The inner section is 0.75m thick contains a series of borings for reactivity control. The reactivity control borings are on a 3.75m diameter circle and are each 0.13m in diameter[55]. The outer reflector section is 0.5m thick, yielding a overall outer diameter of 5.5m. The outer section contains borings for Helium gas flow on a 4.52m circle. Each Helium flow boring is ~0.25m in diameter[56]. For the MIT PBR, the annular reflector module contains ~1.36×10^5 kg of nuclear graphite and is contained in a segment of the MCB 7.75m tall, incorporating similar thicker ring sections for attachment to that used on the lower section. The middle MCB segment has a mass of ~6.3×10^3 kg. If, as mentioned before, a welded MCB is chosen, mass of this section would decrease by ~6.8×10^3 kg. Diagrams of the middle reflector section are shown below.

[ESKOM annular reflector diagrams]

Figure 4.4 ESKOM Annular Reflector Diagram[57]

The ESKOM design for the top reflector assembly (shown in Figure 4.5) is a flat cylindrical section with a 1.3m active length[58]. This 4.3×10^4 kg graphite assembly is topped with a 0.3m tall empty region and, for the MIT version of the reactor vessel, contained in the upper segement of the MCB. The upper MCB segment is 1.9m in overall height (including a 0.3m thick top plate). The ring portion of this segment consists of two thickened ring sections on the top and bottom, with a 0.6m tall central region (with the same thicknesses respectively as the thickened and standard sections of the other MCB sections). The upper reflector module is 5.7m in overall diameter, and 1.9m in height. Mass consists of ~4.3×10^4 kg of nuclear graphite, an ~2.1×10^4 kg ring section of the MCB, and an ~5.6×10^4 kg top plate for a total module mass of ~1.2×10^5 kg. Again, if welds are used to join the various sections, module mass would decrease by ~6.8×10^3 kg.

[ESKOM upper reflector diagrams]

Figure 4.5 ESKOM Upper Reflector Diagram[59]

For the segmented reflector / MCB approach used for the MIT PBR, and shown schematically in Figure 4.6, the overall MCB and reflector assembly requires transportation of three modules, massing $2x10^5$, $2x10^5$, and $1.2x10^5$ kg respectively. Installation of the modules into the reactor vessel is performed in several steps. Using the segmented reactor vessel proposed, and detailed following this section, the lower reactor vessel segment is installed first to provide a platform for the MCB sections. The MCB sections are then installed and either bolted or welded together. The remaining vessel sections are then installed around the MCB, using the MCB supports attached to the interior of the vessel segments as a guide[60].

Figure 4.6 Schematic Diagram of Segmented MCB & Reflector Design

Outer Pressure Vessel Design

The ESKOM reactor vessel (shown in Figure 4.7), and its modification to meet the modularity goals of the MIT PBR system consists of a thick, 6m ID pressure vessel with various thickness changes to accommodate support lugs, mating flanges, and the various penetrations for coolant flow and control systems.

Figure 4.7 ESKOM Reactor Vessel Design[61]

The primary thickness of the pressure vessel is 14cm, based on an allowable stress of 26.7ksi at a maximum temperature of 371°C and an internal pressure of 8MPa (~1160psi). This thickness of A-533 steel has a mass of $\sim 2.07x10^4$ kg per meter of length.

Based on analysis of the published ESKOM design drawings, the ESKOM vessel comprises two pieces. The main cylindrical section is capped on both ends by a tori-spherical vessel heads, with the lower head welded to the vessel, and the upper head attached using a bolted flange.

The reactor vessel contains various structures to support the MCB. These comprise guide rails along the inside cylindrical wall of the vessel along with large steel bearings on the lower cap of the vessel to support the weight of the MCB, reflector and core. The mass of these structures is small compared to the vessel weight, and as such, are not included in the mass calculations of the ESKOM and MIT PBR vessels performed below.

The base thickness (+4.75 to 14.6m vertical span in the ESKOM RV picture coordinate frame) of the cylindrical section is thickened below the level of the core bottom (6.25m in length, Figure 4.7 vertical location: –1.5m to +4.75m) to provide structural support and reinforcement to the vessel and its internals. Above the core the thickness is also doubled for 1m of length, and increased to triple the normal thickness above the upper reflector to form a 1.5m long (total triple thickness length, head-interface is roughly halfway through this section) flange to which the upper vessel head is bolted (using studs sunk into the thick flange). The base thickness cylindrical section is 9.85m long. Estimating the vessel head sections to be 50% height ellipsoids (minor radius of one half the major radii) with a thickness of 14cm, and assuming a density of $7.85x10^3$ kg/m^3 for the pressure vessel steel, the ESKOM vessel has a mass of roughly $6.86x10^5$ kg (with the vessel head and its 0.75m long, 42cm thick reinforcement ring composing ~$1.37x10^5$ kg of this total).

Since this mass is extremely high (RV without top cap is ~$5.5x10^5$ kg), road mobile transportation would be costly and require extremely large equipment. As such, for the MIT PBR design the reactor vessel is segmented into several sections to minimize the maximum transported mass for any one component.

Figure 4.8 Segmented Reactor Vessel, MCB and Reflector

For transportation concerns, limiting load to $2x10^5$ kg, assuming triple thick flange sections are needed 0.75m tall for each fastening, and 1m for each thickness decrement, 5m sections are possible, though increasing the design load limit to $2.5x10^5$ kg would yield 7.5m sections (end cap is $9x10^4$ kg Including flange). While the two-component ESKOM vessel only requires one bolted flange (sealed using multiple, high pressure metallic seals), the segmented reactor vessel would use as many as 4 sealed flanges.

The proposed vessel is broken down into 5 separate components (Figure 4.8). The uppermost section is a 50% height half ellipsoid cap with a 0.75m long, double thickness (30cm) skirt and a 0.75m long triple thickness flange section (overall length 3.15m), total mass $1.36x10^5$ kg. The main cylindrical section is divided into two main sections each 6.84m overall diameter (6m ID plus the 42cm thick flange ring) and 5.7m long (individual mass $2.15x10^5$ kg). The lower, thicker segment of the main cylinder (comparable to the lower, double thickness support section of the ESKOM design) is shorter, only 4.5m in length to limit its mass to $2.2x10^5$ kg. The bottom cap is similar to the top cap, but with a shorter skirt, yielding a total length of 2.65m and a mass of $1.15x10^5$ kg. This segmented reactor vessel requires the transport of 5 loads instead of the two in the ESKOM design, but the loads are limited to less than $2.2x10^5$ kg, far easier to transport at low cost. If determined necessary for leakage or safety considerations, seal (non-structural) welds could be easily incorporated into the segments using automated welding machines running circumferentially on pre-installed rails.

While further analysis is necessary to determine any potential negatives to this segmented design, a backup method would be to deliver the vessel in weldable sections which would be stacked and structurally welded together circumferentially at the construction site. While the goal of this modularity design is to eliminate labor-intensive assembly processes such as welding, the few circumferential welds required to assemble the vessel could be performed using automated welding machines (traveling around the vessel on pre-installed and aligned rails). Additionally, the reactor vessel has no real space constraints, or components that would interfere with access to its surface for welding, unlike the tight space constraints in the balance of plant modules.

A weld-together reactor vessel would also significantly decrease the mass of he transported components, by eliminating the triple thick flange sections required for the bolted together vessel. By replacing all of the joints except the top cap flange with double thickness, 0.75m long (per side) thickened sections, welded together onsite, the module weights (using the same dimensions as the segmented vessel described above) would be reduced to $2x10^5$, $1.85x10^5$, and $2.2x10^5$ kg for three cylindrical sections, and $1x10^5$ kg for the bottom cap section. If the middle segment's lower double thickness section is increased by 0.75m and the lower segment shorted by the same amount, the weights would be equalized at $2x10^5$ kg for all three segments, a maximum load savings of $5x10^4$ kg vs. the bolted reactor vessel design.

4.2.1.2. Piping / Interfaces

The piping joining the ESKOM reactor vessel to its balance of plant is composed of several pipes providing Helium flow for the power conversion system and core cooling system (CCS) (Figure 4.9). The main pipes are separated vertically by 1.35m[62]. The centerline located 0.67m ID outlet pipe is composed of a high-alloy (A508/533-like) steel outer pipe with a lined Incoloy 800 internal hot pipe[63]. The two inlet pipes are 0.39m ID, unlined high alloy pipes located off-center on the reactor vessel[64]. The ESKOM CCS uses two sets of inlet / outlet pipes, each with a 0.28m ID. The pipes are located 90° to each side of the primary outlet pipe[65]. For the MIT PBR system, the two cold primary helium inlet ducts of the ESKOM system are replaced with a single pipe at the same vertical level, but located on the centerline of the reactor vessel.

Figure 4.9 ESKOM Three Pipe Reactor Vessel Interface[66]

4.2.1.3. Reactor Vessel Structural Supports

The ESKOM reactor vessel uses a series of structural supports to accommodate the dead-weight loads of the RV and its internal structures as well as any seismic forces. The main loads are supported by 3 large support lugs at the same local elevation as the cold inlets[67]. These lugs are supported by a large concrete structure and are cooled to protect the concrete from thermal failure due to heat transfer from the reactor vessel[68]. The support lugs are slotted to permit radial thermal expansion of the reactor vessel. Seismic force protection is provided by high force dampers attached to the top of the reactor vessel. These dampers accommodate the slow displacement from thermal expansion while resisting high rate seismic forces.

4.2.2. Reactor Vessel Cooling

Both the ESKOM design and the MIT PBR reference plant design proposed in past studies require the reactor vessel to be cooled to maintain its temperature below the maximum defined code limitations. This cooling is provided by diverting a small fraction (1-2%) of the primary Helium flow through an additional water-cooled heat exchanger to reduce its temperature. This Helium flows through the vessel in the space between the MCB and the RV. Additional systems are provided to cool the core and MCB as well during shutdown and startup when the primary balance of plant is inoperative. While the ESKOM and MIT PBR systems do not require active systems to reject decay heat in an accident case, in order to prevent excessive heating or thermal damage to the reactor vessel and structures, the CCS (core cooling system) is used to maintain core temperatures within limits when heat cannot be rejected through the normal power conversion system.

The ESKOM RPVCS (Reactor Pressure Vessel Conditioning System) provides the cooling for the reactor vessel itself (the Helium flows through the space between the RV and the MCB). The system consists of 4 blower/cooler units (each sized at 1/3rd the required capacity for redundancy) bolted to the bottom of the RV[69]. During normal operation these units do not cool the Helium as the ESKOM direct cycle has an inlet temperature low enough to provide cooling for the RV, but the blower units remain active to ensure uniform RV wall temperature. The coolers can reject 100kW of heat per unit, and each blower can deliver a flow rate of 3.15×10^3 m^3/hr (5.55kg/s @ 7.2 MPa, 280°C)[70].

The ESKOM CCS uses two 50% capacity units to provide core cooling. Each unit is composed of a blower, a water cooled heat exchanger, a counter-flow recuperator and a mixing chamber (which mixes incoming hot flow with cold exit flow to ensure a flow temperature below 630°C for material considerations)[71]. The recuperator outlet temperature is ~330°C, the recuperator outlet flow is then cooled by 40°C in the heat exchanger, yielding a blower inlet temperature of 290°C[72]. The two modules are capable of rejecting 5 MWt for core pressures 0.7-4.5 MPa, 2 MWt @ 0.2 MPa, and 1 MWt @ atmospheric pressure[73]. Approximately 25kg/s of Helium mass flow is required to reject 5 MWt over a 40°C delta-T.

The MIT PBR reference plant cycle used in past work uses a core / vessel cooling system that provides the function equivalent to the ESKOM RPVCS. In the MIT system, the heat rejection required by the system is far larger than in the ESKOM case due to the use of an indirect cycle. Since the indirect cycle has a much higher RV Helium inlet temperature than a direct cycle, RV cooling is required during normal operation. The reference plant RV cooling system uses a water cooled heat exchanger to reduce the cooling flow to 135°C. The 1.3 kg/s Helium flow requirement is based on a 10m core barrel height with an emissivity of 0.6. Total heat rejection to the cooling system is ~700kWt (nearly double the heat rejection of the ESKOM RPVCS)[74].

While not addressed in past MIT PBR work, a system like the ESKOM CCS must also be used to provide startup and shutdown cooling. Unlike the ESKOM system, this could be done by using the primary side circulators to flow Helium through the RV and including a water cooled heat exchanger into the primary side. While the detailed design of the MIT PBR circulators is left to future work, small water cooled heat exchangers could be incorporated into the circulators, or the design of the MIT RV cooling system modified to ensure it has the flow and heat rejection capability to deal with decay heat during shutdown.

While in both the ESKOM and reference MIT PBR designs do not insulate the reactor vessel as insulation could potentially hamper the ability of the RV to reject decay heat during an accident, it may be possible to develop a design that could provide the necessary accident case heat rejection, while limiting the heat loss and vessel cooling required during normal operation. Such a design is proposed in chapter 6 under potential design changes.

4.2.3. Intermediate Heat Exchanger (IHX)

The IHX is used in the MIT PBR reference plant to transport heat from the primary side Helium flow to the radiologically cold secondary Helium flow. The IHX design is extremely important to the overall system performance and a defining characterisitic of the MIT PBR design.

4.2.3.1. General Design

The reference design of the IHX is based on two different heat exchanger designs—a printed circuit (PCHX) design and a plate-fin (PFHX) design. Both designs have been investigated in past MIT PBR work and a final down-select was not made.

Details of the two designs and preliminary analysis of the design considerations is given in section 3.5 of Dr. Wang's dissertation[75]. The HEATRIC printed circuit (PCHX) design (Figure 4.10) uses a series of plates, chemically etched with flow paths and diffusion bonded together. The plate-fin heat exchanger (PFHX) design (

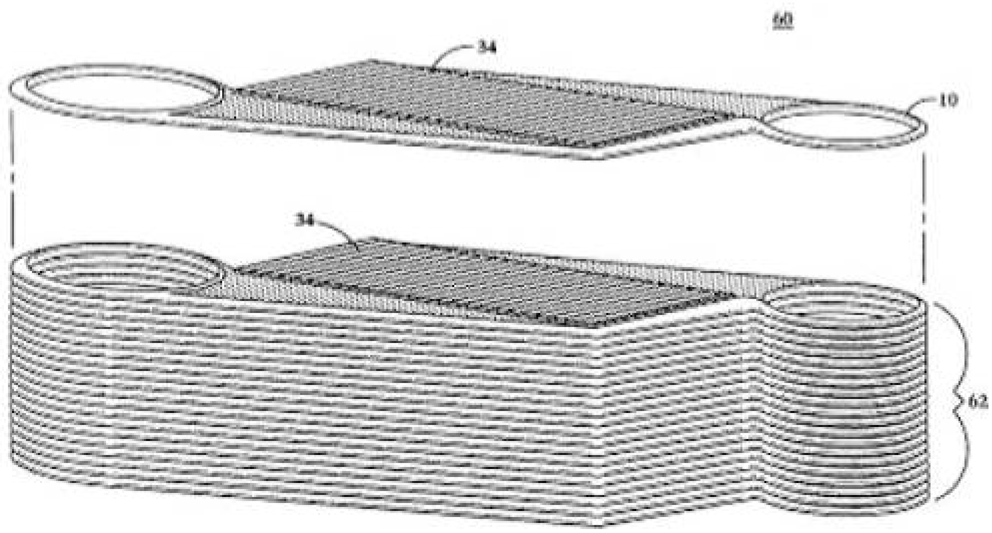


Figure 4.11) uses fins brazed to plates in a bellows-like configuration. Each design has its own advantages and disadvantages.

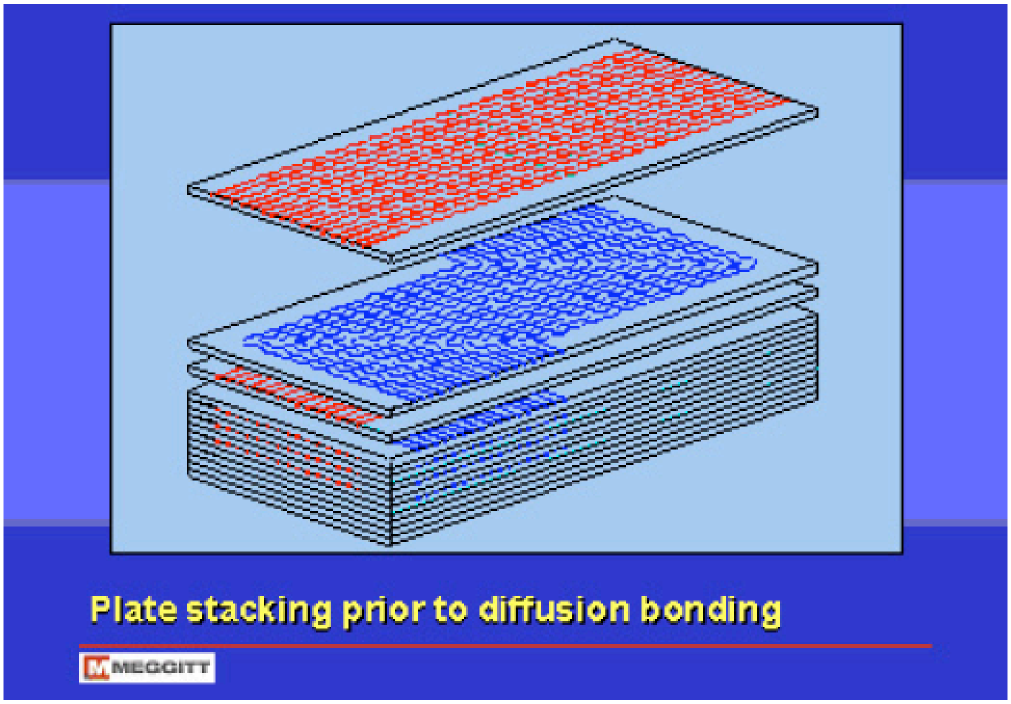


Figure 4.10 Printed-Circuit Heat Exchanger Schematic Diagram[76]

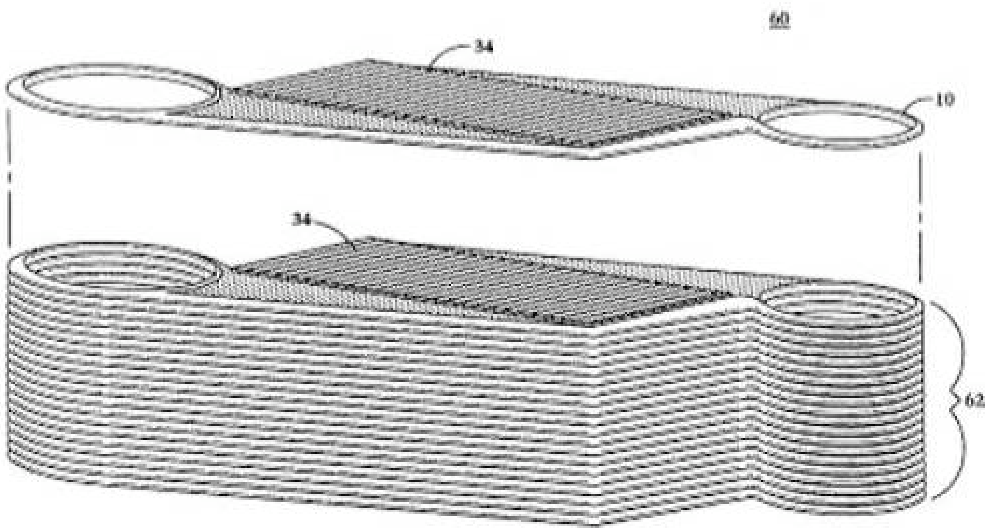


Figure 4.11 Plate-Fin Heat Exchanger Schematic Diagram[77]

The printed circuit design is very mature and has been used in many applications at the power densities, pressures, and nearly the temperatures [CHECK THIS OUT (750°C vs. MIT PBR IHX T_{max} = 900°C)] required by its use as an IHX for this system. However, there may be issues with diffusion bonding the IHX if Incoloy 800HT is required. The PFHX design is far lighter than the printed circuit design, but is a less mature design for use at the pressures and temperatures required. Additional issues with the PFHX design include the potential code compliance issues of the brazed joints, as these joints form part of the ASME Sec. III (Class I) boundary. The key issues of concern to this analysis are the weight of the IHX modules and the cost of each approach. While the PCHX design requires less development than the PFHX design, but is more expensive to fabricate in quantity. Fabrication cost is dependent on both material quantity and fabrication method. The PFHX design requires less material than the PCHX design, and the fabrication of the individual plate/fin elements of the PFHX design and brazing them together may require less time, equipment capability and cost than the chemical etching and high temperature diffusion bonding of the PCHX design. Given these potential risks, and the importance of size and mass constraints to the modularity approach, the PFHX design is the preliminary choice for the MIT PBR system.

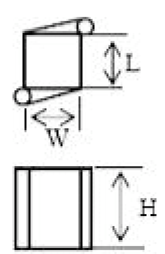
4.2.3.2. IHX Design and Specification

The PFHX design for the MIT PBR IHX consists of 18 heat exchanger modules, assembled in groups of 3 and installed into 6 modular pressure vessels. The reference plant specifications for the PFHX IHX are listed in the 95% Effectiveness column below.

Table 4.2 PFHX IHX Reference Design Specifications[78]

Effectiveness	95%	92.5%	90%
Hot side pressure loss, %	0.49	0.46	0.65
Cold side pressure loss, %	1.41	1.39	1.40
Number of modules	18	18	18
Module width, W, mm	635	635	432
Module length, L, mm	676	475	411
Module height, H, mm	1143	1003	1125
Total core volume, m^3	11.2	7.49	5.15
Estimate total core weight (kg)	26,310	17,620	12,120
Approximate HX cost, US 2001 $M	3.1	2.1	1.4

NOTES:
A "module" design as following:



The three modules are contained inside a thin internal vessel and supplied with Helium flow from the piping penetrations in the outer vessel by a series of pipes and manifolds (Figure 4.12—The primary side piping is shown on the left, the secondary side piping, on the left). This assembly is constructed of Incoloy 800HT (the same material as the core structures)[79], and contained inside an outer vessel composed of the standard pressure vessel material of they system (A-508/533).

The outer vessel is 6m long and 2.3m in diameter, and supported externally by three support legs during operation. The vessel itself is a cylindrical tube, capped by two flanged, flattened ellipsoidal caps as shown in Figure 4.13.

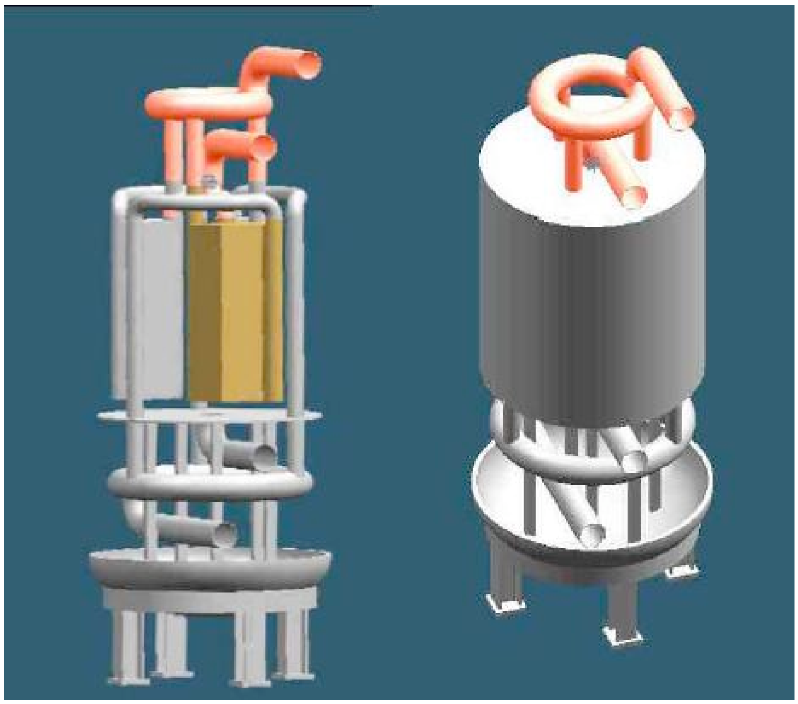


Figure 4.12 Internal Diagram of IHX Module[80]

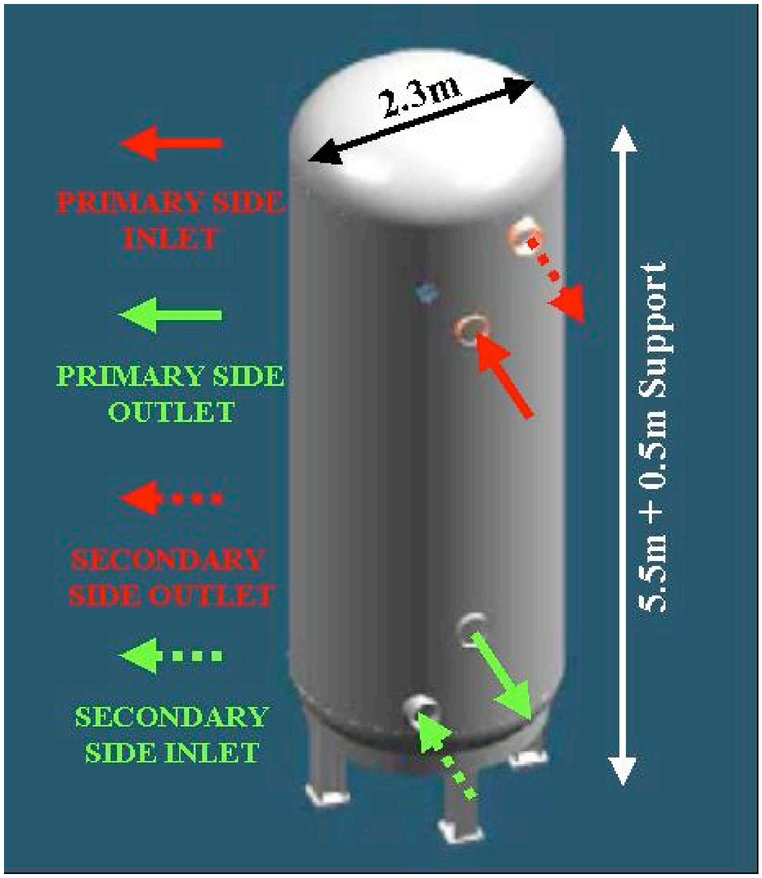


Figure 4.13 External Diagram of IHX Module[81]

The wall thickness of the vessel required to contain the internal pressure while limiting material stress to 26.7ksi (the allowable stress limit at the operational temperature—280°C) is 6cm. The ends of the cylindrical section are thickened to 12cm over a length of 25cm to accommodate the end stresses induced by the internal pressure acting on the end caps. The caps themselves are 75% height half-ellipsoidal sections, with a thickness of 6cm. Based on these dimensions, the mass of the outer vessel is ~2.05×10^4 kg (not including vessel supports and internal piping, which should be small in comparison)

The heat exchanger modules are constructed out of Incoloy 800HT, as are the high temperature pipes and internal structures supporting the three modules inside the IHX vessel[82]. The internal piping and heat exchanger plates form the Section III (Class I) boundary, along with the outer pressure vessel of the IHX module. In order to maintain the pressure vessel temperature below the 280°C maximum, the vessel has the same lined, internal insulation as the rest of the high temperature piping in the system.

4.2.4. Circulators

The MIT PBR reference plant, being an indirect cycle requires an externally powered circulator to move Helium through the primary side of the system. The circulator provides a pressure rise of 0.12MPa (pressure ratio of 1.015). Assuming a 98% motor efficiency, the circulator requires 3.57MWe to operate[83]. Due to the complexities of the circulator design and its associated piping, detailed design of the circulator system has not been performed and is reserved for future work on the MIT PBR system.

4.2.5. Inventory / flow control / ancillary systems

The Helium inventory of the PBR system must be maintained during operation and shutdown. During operation, the inventory is controlled to vary the overall system pressure to provide for deep throttling (~50% of normal power output)[84]. Part throttle control of the system is performed with bypass valves[85]. Inventory control is also required to depressurize the system during shutdown, and as the MIT system is an indirect cycle, rapid depressurization of either side of the system to prevent damage to the IHX due to the large pressure differential or primary side leakage into the secondary side through any pinhole leaks in the heat exchanger.

The ESKOM system uses a series of compressors and tanks to provide inventory control. Eight 120m^3 tanks provide the storage element of the system, with each tank operating at a different pressure (3.5MPa → 6.5MPa). The tanks hold a total of 9x10^3 kg (of which 3.7x10^3 kg is the full inventory of the power system, and 5.3x10^3 kg of residual Helium in the tanks. The tanks are filled by diverting flow from the high-pressure side of the power system, and can transfer roughly 10% of the power system inventory per minute (~5.5kg/s). A positive displacement compressor is used to reduce the inventory further, pumping 20L/s from the power system into the inventory storage tanks. The compressor can reduce the inventory from 40-20% in ~1hr. (an average of 0.33%/min). Further reducing the system pressure to ~1.5% (atmospheric pressure) requires an additional 9 hours (~0.033% / min)[86].

The tanks used in the ESKOM system dominate the size of the plant (assuming a 3:1 diameter ratio, each tank is 3.7m in diameter and 11m long. The installation of these inventory control tanks are shown highlighted in Figure 4.14 below.

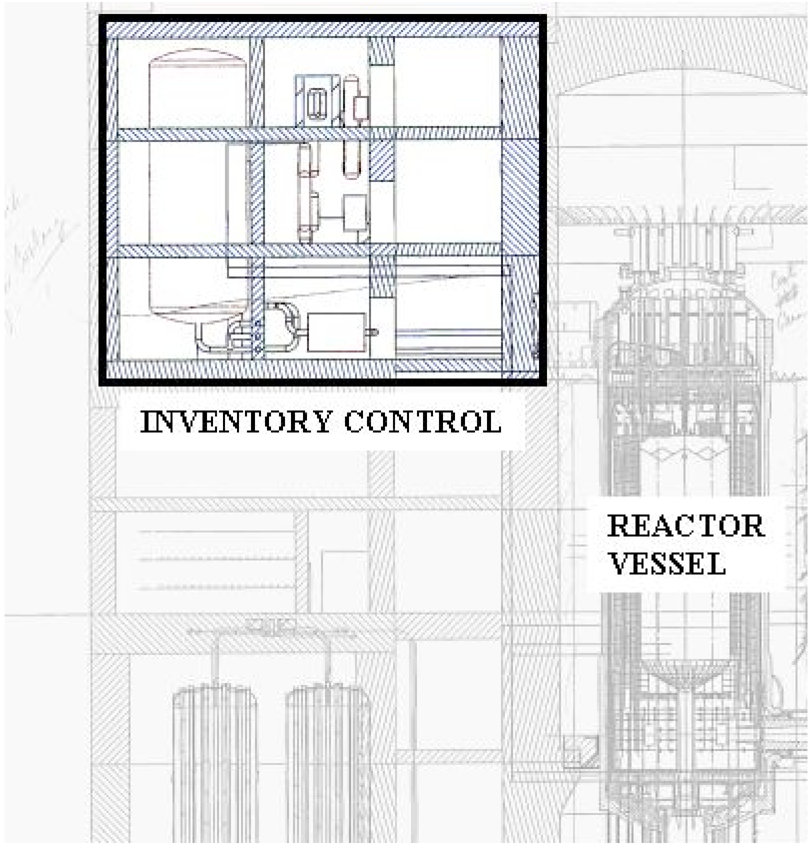


Figure 4.14 ESKOM Inventory Control Tanks[87]

Given a maximum stress of 26.7ksi in the tank walls, the 6.5MPa tank would have walls ~5cm thick and a tank mass of nearly 5.9×10^4 kg (assuming 7.85×10^3 kg/m^3 wall density). If the tanks were sized to fit within the standard 10m long MIT PBR module, each tank would have an inner diameter of 2m, an internal volume of ~30m^3, and a tank weight of ~1.7×10^4 kg. Thus 32 of these modules would be required for the volume used in the ESKOM system. Since the inventory of the MIT PBR system is greater, even more tank volume would be required if a similar inventory control strategy were applied.

The past work on the MIT PBR plant did not address the inventory control system and thus as part of the modularity and plant design, this analysis included a preliminary design and specification of the system required. For the MIT PBR system, the inventory control system must be able to slowly depressurize the system for shutdown, re-pressurize it during startup, and vary the inventory for load following. Additionally, there must be a way to rapidly depressurize either side to prevent damage to the system in the event of an accident. The inventory control must also be as compact as possible to reduce its impact on the volume of the plant, and the cost associated with its transportation and installation. The detailed design of the inventory control system is included in Chapter 5.

4.2.5.1. Purification / Contamination Control

In order to maintain the purity of the Helium coolant, the ESKOM plant incorporates a system to remove particulates and gas impurities. The system is designed to remove the predicted impurities—H_20, O_2 and N_2 from atmosphere ingress, CO and CO_2 from oxygen interaction with graphite, and Tritium from radiological decay. The ESKOM system bleeds Helium flow after the high pressure compressor and passes it in turn through a dust filter, a heater (raising the temperature to 250°C), a CuO catalytic converter, a cooler to lower the temperature to ~40°C, a molecular sieve, and finally a cryogenic loop and adsorber operating at –180°C [88]. The system is capable of processing 50kg/hr (~1.5% of the total inventory) and has an inlet temperature of 105°C[89].

For the MIT PBR plant, purification of both the primary and secondary Helium flow is also required. Given the flanged attachments, the possibility of atmospheric contamination of the Helium is greater, however, because of the IHX separating the two flows, there is little particulate contamination in the secondary flow. Past reference plant analyses did not address this element of the plant, and while a detailed design of this system is not required for the modulation approach, the scavenged flange attachment method described later makes incorporation of such a system simple, as such, a preliminary design was performed and detailed in Chapter 5.

4.2.5.2. Helium Inventory Makeup

As Helium has an extremely high diffusivity, leakage must be expected. In the ESKOM system, Helium leakage is estimated at ~3.7kg/day (~0.1% of the active inventory). This is made up using high pressure Helium from small, commercially sized and supplied gas cylinders[90]. Using 125scf (3.5m^3) 2215psi (15.2MPa) cylinders, this level of makeup would require a reasonable, 6 cylinders per day.

The MIT PBR would most likely require a higher level of Helium makeup due to the longer piping, many flanged connections, and large heat exchanger vessels. While the proposed scavenged flange design would in theory reduce the quantity of Helium lost, a conservative assumption would be that the MIT system would have a substantially higher loss rate than the ESKOM plant.

4.3. Secondary Side

The secondary side of the MIT PBR system comprises the balance of the heat exchangers and rotating machinery necessary for power conversion including the turbo-compressors, power turbine and generator, recuperator, precooler and intercoolers.

4.3.1. High & Medium Pressure Turbines

The MIT PBR utilizes two identical high-speed turbines to power the compressors of the secondary side. The specifications guiding the design of these components has been detailed in past MIT PBR work and takes into account the advantages of using Helium as a working fluid. As stated previously, using Helium enables turbo-machinery to operate at extremely high speeds, but the high specific heat and low atomic weight of Helium requires more stages to be used for a given pressure ratio than turbo-machinery used for other gases.

4.3.1.1. General Turbine Design Considerations

The Helium turbo-machinery is designed for operation with little or no internal cooling of the turbine elements. Given the low operational temperatures (maximum turbine inlet temperature of 880°C[91]) of the MIT PBR relative to petroleum fired open cycle turbines, modern single crystal super alloys can be used to fabricate uncooled turbine blades. Past analysis does present the potential need for Helium cooling of the blade roots and turbine disks. If required, diverting 1-2% of the total mass flow for cooling of the turbines would reduce overall cycle efficiency by ~0.21%[92].

The turbines are enclosed in a multi-layer vessel with a similar lined insulation design to the IHX vessels and high temperature piping. In the case of the turbo-machinery, the insulation liner is substantially thicker as it must be structurally stable when exposed to vortices generated by the whirling turbine blades, and also support the stator blade assemblies. The liner is not subjected to substantial pressure loads, reducing the need to fabricate a thick pressure vessel out of high temperature alloys used for the turbine components. The Helium flow into and out of the turbine is contained by this liner, and inlet / exhaust volutes. A volute is a nautilus-shell shaped structure that efficiently changes the speed and direction of the Helium flow. These structures are required to change the Helium flow path from the tangential, circular cross section pipe inlet / exhaust to the axial, annular flow path inside the turbine. The volute also accelerates / decelerates the Helium flow. The volutes are lined, insulated structures like the piping and turbine casing. With this design, all the major pressure loads are borne by the thick, cooler, exterior vessel.

4.3.1.2. Turbine Design & Specifications

The high-pressure (HPT) and medium-pressure (MPT) reference plant turbines are 5900rpm, 4-stage axial devices. They are compact (1.168m blade diameter, 1.032m hub diameter)[93] high axial flow velocity (162m/s at HPT inlet to 210m/s at MPT outlet), devices. Other than the general turbine spool design, past reference designs did not address the turbine vessel, spool design, or piping and support designs. As part of this project, these designs were addressed, and described in Section 5.3.1.

One issue that is present in the MIT PBR that is not present in the ESKOM design is the need for extremely low-loss Helium seals. In the ESKOM system, the turbo-machinery is encased in the large power conversion system vessel, containing the cold return flow to the reactor, as such, Helium loss from shaft seals only reduces the system efficiency (and given the low leakage from even simple shaft seals, the efficiency loss is negligible), while in the MIT PBR system where the turbines and compressors are contained in mechanically separate vessels, shaft seal loss would result in major Helium loss to atmosphere. While it may be possible to use a single vessel for the each turbine-compressor combination (as these components would be replaced as a single module in the case of failure), eliminating the shaft seal loss, the power turbine (which drives the generator) would still have shaft seals that lead to the atmosphere.

4.3.2. Power Turbine

The MIT PBR system uses a large multistage turbine to mechanically drive the large generator to produce output power. The power turbine is a synchronous (3600rpm) speed, axial flow machine. The spool and blade diameter are larger than the HPT and MPT components, and the number of stages is far larger (given the much greater enthalpy change through the power turbine). The reference design uses a 3m blade tip diameter, with a 2.5m diameter hub[94]. The 23-stage system[95] is contained in the same type of multi-layer casing as used for the HPT and MPT. The power turbine generates 136.9MW of shaft power[96] which is transferred to the generator by a large shaft. As with the HPT and MPT, details of the volutes, casing, and structural supports have not been addressed previously and were defined as part of this study (Section 5.3.2).

4.3.3. Recuperator

Past MIT PBR studies have performed a significant amount of analysis on the design of the recuperator. The recuperator significantly increases the system efficiency by transferring heat from the PT exhaust to the HPC exhaust. Based on past analysis, the decision to use the PFHX design for the recuperator appears to be in line with the modularity and design goals of the MIT PBR system. The recuperator core in the reference design is described in Table 4.3 below, and is made from 347 steel[97].

Table 4.3 Reference Plant Recuperator Design Specifications[98]

Effectiveness	95%	95%	95%
Hot side pressure loss, %	0.80	1.38	1.77
Cold side pressure loss, %	0.334	0.575	0.738
Number of modules	18	18	18
Module width, W, mm	762	762	762
Module length, L, mm	561	660	711
Module height, H, mm	1455	1118	991
Total core volume, m^3	15.3	13.2	12.4
Estimate total core weight (kg)	35,960	31,220	29,320
Approximate HX cost, US 2001 $M	0.60	0.52	0.49

4.3.4. Precooler

The Helium flow exiting from the recuperator is passed through a precooler. The precooler is a Helium / water heat exchanger, rejecting heat to the water loop of the heat rejecting system. The reference plant design of the MIT PBR precooler is based on past studies that have been performed. The most detailed PBR precooler design to date is the ESKOM system, detailed below, that was the initial reference design point for this study.

The ESKOM precooler, shown in Figure 4.15, provides one design point for the design of the MIT PBR system. It is a shell and tube heat exchanger with 3 annular sets of U-tubes. The three bundles are, as follows, a two pass, 6 column, 203 row, triangular pitch outer bundle, a 2 pass, 5 column, 142 row, triangular pitch middle bundle, and an inner 2 pass, 5 column, 83 row bundle. The tubes are finned and have supporting radial tube sheets. The water flows through the inner and middle bundles in parallel, and then through the outer bundle[99]. The system limits water pressure to 2.5MPa to limit spillage in the event of a break, and the flow rate is ~620kg/s[100].

[ESKOM precooler diagram]

Figure 4.15 ESKOM Precooler Diagram[101]

As the precooler requirements of the MIT PBR are different from the ESKOM system, due to temperature, pressure, heat load, and size constraints, the design must be modified for these requirements. Due to the relatively fragile nature of shell and tube heat exchangers, and their high labor cost in assembly, fault detection, and repair, the precooler design for the MIT PBR is a compact heat exchanger design, with the performance requirements given by Dr. Wang in his reference plant design. The Helium pressure drop is limited to 0.8%, and the Helium is cooled from 96.1°C to 30°C[102]. Since heat exchanger effectiveness is not a significant impact on overall system efficiency, but rather the lowest possible Helium outlet temperature is, only the water inlet temperature, assumed to be 27°C[103] is important to the cycle-level optimization and analysis performed in the past (as it defines the lowest temperature of the Helium in the system, and dramatically affects system efficiency). Based on these specifications, a preliminary design, described in Section 5.3.5 suitable for modularity was created.

4.3.5. Compressors

The MIT PBR reference plant design uses four compressors, arranged on two shafts to provide the pressure rise required on the cold side of the closed Brayton cycle. The reference design for the compressors is a 9-stage, 8000rpm combine axial-centrifugal flow compressor[104]. The first 8 stages are axial flow, with a final centrifugal flow stage before the exhaust, as shown in . The reference design specifications for the compressors are as follows. [CYW axial-centrifugal compressor specs]

Figure 4.16 Axi-Centrifugal Compressor Cross-Section[105]

As with the turbo-machinery, the design details of the compressor, other than those presented above, were not included in the reference design, including the design of the compressor vessel, and an estimate of the component masses. An analysis of the specifications relevant to the modularity approach of the MIT PBR were performed as part of this thesis research, and are presented in Section 5.3.1. This analysis included a preliminary design of the compressor vessel, inlet and exhaust volutes, rough spool design, and an estimate of the mechanical supports required to accommodate the dead weight and thermal expansion loads on the compressor.

4.3.6. Intercoolers

The MIT PBR system uses three identical intercoolers to chill the Helium after it passes through the first three compressors. The MIT PBR intercoolers, like the precooler, is a compact Helium-to-water heat exchanger. The reference plant requires each of the three intercoolers to cool the Helium flow from 69.7°C to 30°C using 27°C inlet temperature water[106]. The percentage pressure loss through each intercooler is 0.8%[107] [, following the path of the Helium, 0.8%, 0.5%, and 0.3% **NOTE, why is the chart on p64 different than the chart on p186]**

As with the precooler, while the ESKOM system uses a shell and tube heat exchanger[108] (as its annular design enables easy integration with the vertical, cylindrical arrangement of the components in the MPBR), a compact heat exchanger based on the PCHX design is proposed for the MPBR, and described in Section 5.3.6. The PCHX is an extremely robust structure that should present little repair or maintainence problems for the MIT PBR. The intercooler design proposed is presented in Chapter 5.

While not included in the reference plant design, but described as a potential future analysis task in Chapter 6, a design with fewer intercoolers could, while less thermodynamically efficient, prove to be more economical due to reduced capital cost.

4.4. Reference Design of Piping, Seals and Flanges

The piping network connecting all the various components is of utmost importance to the operational capabilities of the plant, and the key to this analysis. Past reference systems did not approach the piping in a method suitable for use in the small module construction proposed for the MIT pebble bed system. These systems, along with nearly all past nuclear systems use built in place piping systems connected with welded joints. While seal welded joints provide the best possible structural attachment, and the least probability of leakage, they require far more time to install, and make removal of damaged modules labor intensive and time consuming. The MIT pebble bed system will use a flanged attachment method to enable rapid construction and easy replacement of damaged modules.

The ESKOM system uses insulated piping installed inside an outer vessel. This enables the use of bellows and hinges to accommodate thermal expansion of the high temperature piping without compromising the nuclear boundary[109]. These joints cannot be part of the ASME Section III (Class 1) boundary, thus preventing their use in a system installed in the United States[110]. The piping insulation used for the ESKOM system is composed of a layer of fibrous insulation 50-200mm thick inside the pressure pipe, lined with a perforated (to ensure pressure balance) metal tube. Helium flow velocities in the ESKOM system range from 40-200m/s and the piping is designed using standard pipe sections and a factor of safety of 1.5[111]. This type of lined pie will also be used for the MIT PBR system, with several minor differences, described in detail in Section 5.1.1.

[ESKOM LINED PIPE EXAMPLE]

5. Results: Detailed System Design

Based on the design requirements and modularity approach, a detailed system design is the major product of this thesis. The system takes the information described in Chapter 4 and expands it to address the modularity approach described earlier. The system design is broken down into several separate areas—general elements of the design, primary side design, secondary side design, and ancillary system design (inventory control, heat rejection, etc). These sections are followed by the most important sections describing the actual layout and analysis of the plant piping. Based on this analysis, the next section describes the module by module design and layout. Completing the system design are sections detailing the construction of the containment building and its required site preparation and construction. The final section details potential changes to the design assumptions, specifically, the reference plant design, that could potentially improve system performance and cost.

The general design elements section describes system elements that are common across the entire system. These elements include the general design of the system piping and its innovative pressure backed insulation concept, the flanges used to join the various modules and the scavenged seal design that permits their use, and a general design overview of the space-frame design and the associated alignment and support structures.

The detail of the primary side system design covers the design elements not addressed in the reference plant design—those relating to modularity and assembly. This section also describes the specific design of components not previously addressed in detail, including designs for the circulators, RV and vessel cooling systems, contamination control systems, and a detailed analysis of the primary side inventory control systems.

The section covering the secondary side of the plant is similar to previous section, detailing design elements not previously covered. In addition, this section details the tertiary cooling and heat rejection systems. While these systems have received little attention in prior work, their effects on the overall design is significant and thus their design must be addressed in detail.

The most important sections detail the layout and design implementation of the plant—how the reference cycle is implemented and the associated analysis performed. First, the piping and layout analysis is detailed. The various analysis tools and assumptions are detailed along with the pipe and component specifications used in this analysis. The analysis method is then described in detail, including the layout iteration method.

Second, the overall implementation strategy is addressed. This includes details of the space-frame and module design and how the design constraints dictate where the system is split into the various modules. From this generalized layout / module split data, details of the space-frame design are addressed—the general beam and pillar sizes, space-frame structural attachment, and the various mounting hardware used to support, position, and restrain the various components within the space-frames during transport and operation.

The final sections of Chapter 5 detail potential changes to the design assumptions, including the reference plant design, that could result in potential improvements to cost and performance. These changes include modification of the cycle, such as cycle simplification through reducing the number of intercoolers, changes to the various component specifications, and finally, any additional minor changes.

5.1. General Elements

This section describes system elements that are common across the entire system. These elements include the general design of the system piping and its innovative pressure backed insulation concept, the flanges used to join the various modules and the scavenged seal design that permits their use, and a general design overview of the space-frame design and the associated alignment and support structures.

5.1.1. Piping

The component most ubiquitous in this design is the various sized piping that connects the cycle components. While simplified in most cycle based analysis to merely lines connecting various components and "black-box" parameters, when expanding a reference cycle design to an implementation design following the modularity approaches detailed earlier, piping is quite possibly the most important component.

5.1.1.1. General piping design

Two important general piping design choices were made in order to make the modularity approach proposed possible—high Helium flow velocity (~400m/s) for both the primary and secondary Helium loops and the use of pressure-backed insulation lined piping. The Helium flow velocity chosen is much higher than the velocity specified in both the ESKOM and past MIT PBR designs (120-200m/s depending on pipe and component)[112]. This increase in system flow velocity results in much smaller diameter plant piping that can be readily packaged into the proposed MIT PBR space-frame modules.

The maximum reasonable pipe flow velocity is dependent on both the thermodynamic properties of the fluid, and consideration of the design of the pipe system. Conventionally, the maximum reasonable fluid velocity for a gas is Mach 0.2 – 0.4. As the sonic velocity of Helium is dependent only on its temperature, the lowest temperature Helium in the system (the precooler exhaust @ 30°C) defines the Mach-limited maximum flow velocity—200-400m/s (sonic speed for Helium @ 30°C is 1024m/s).

In the ESKOM system, the Helium flow velocity in the pipes was limited to <200m/s in order to prevent erosion of the pipes and/or liners by graphite dust entrained in the Helium flow (the graphite dust is generated by the reactor fuel pebbles rubbing against the core structures and each other)[113]. This erosion is less a cause for concern since the MIT PBR operated using an indirect cycle. Thus, only the primary side components are exposed to any graphite debris. This entrained debris, generated in the reactor vessel, would encounter the IHX modules first after leaving the reactor. Since the flow velocity in the inlet plenums of the IHX, and the IHX cores themselves, is significantly lower than the piping velocity, the vast majority of the debris would fall out of suspension (most likely in the inlet plenum where the Helium simultaneously slows down dramatically and turns 90° to enter the IHX core) before leaving the IHX. Thus the primary side circulators (the only rotating machinery exposed to the primary flow) would not be subjected to bombardment by entrained debris.

The high Helium flow velocity also has an impact on system efficiency. Since the higher velocity flow will be inherently more turbulent, especially when disturbed by piping bends and cross section changes, piping pressure losses could be significantly higher. However, since, as assumed in the reference plant design, piping pressure loss is small compared to the total pressure loss of the various power conversion components[114] (heat exchangers, turbo-machinery volutes, etc), an increase in pipng pressure loss should not significantly affect system efficiency.

[cycle efficiency sensitivity to pressure losses]

Additional efficiency affects are due to the need to accelerate / decelerate the Helium flow to match the required flow velocities in various components. Efficiency effects would be due to losses proportional to the dynamic pressure difference between the Helium flow at the beginning and end of each diffuser/nozzle section—the high piping velocity would require a greater degree of acceleration and deceleration of the Helium flow. However, the additional losses even at high velocities, while necessary to include in system analyses, are much smaller than the pressure losses in the heat exchangers and anisentropic losses in the turbo-machinery.

Considering a Helium density of ~10kg/m^3 (8MPa, 90°C), and a velocity of 400m/s, the stagnation pressure of the flow is given by the dynamic (velocity dependent) portion of the Bernoulli equation.

[Bernoulli equation]

Using this equation, the dynamic pressure at the highest density & velocity point (HPC exhaust) the system is ~0.8MPa (roughly 10% the static pressure at that point). Thus a nozzle or diffuser efficiency of 90% would only result in a pressure loss of ~1% the total pressure. Considering the vast majority of the flow transitions in the MIT PBR system occur at far lower dynamic pressures (the turbine inlet dynamic pressure is ~0.2 MPa), the pressure loss effects on the overall efficiency should be minimal.

This type of design choice is in keeping with the modularity approach proposed—while the plant efficiency may decrease slightly, the higher velocity is required to make the plant piping small enough to be contained in the standard size modules. Additionally, the smaller diameter piping is more flexible and thus better able to accommodate thermal expansion of the system.

Pressure Backed Insulation

The key points of the insulation system are as follows:

- Solid silica fiber composite insulator sandwiched between internal non-load bearing liner and exterior pressure bearing pipe.

- Internal liner need not be leak-tight, slip fittings possible to accommodate thermal expansion.

- Liner is pressure backed by bleed Helium from HPC

- During normal operation near zero bleed Helium flow (since the liner thermally expands more than the outer pipe, the slip fit liner joints will seal radially)

- Under accident case (liner and insulation are torn away), arteries provide a high flow rate path for cold Helium to shield exterior pipe until system can be shut down.

- ~2cm of COTS silica fiber insulation is required to reduce the inside temperature of the pressure bearing pipe to <280°C based on natural convection cooling of a smooth exterior pipe. If necessary fins can be added to the exterior of the piping to further reduce the temperatures with insignificant impact on overall efficiency (the heat flow through the insulation to maintain pipe temperatures of <280°C is on the order of 500-1000 W per meter of pipe).

- Low Helium flow pressure backed insulation system reduces cooling parasitic losses to <<500kW (~1kW/m of pipe).

- Since the entire exterior shell of the plant piping and vessels can be maintained at a much lower temperature, minimizing thermal expansion design issues. Additionally, since the exterior piping is maintained at a constant 280°C throughout the hot-side of the system, differential expansion is minimized (since the internal flow ranges from >900°C to ~500°C).

The drawing below illustrates the insulation design proposed. The brown and light grey components are the internal liners (this picture is of a joint between two pipes). The green and dark grey components are the insulation tiles themselves, and the blue component is the outer pressure-bearing pipe (thicknesses are not to scale and are shown enlarged to illustrate the design). The first drawing is an enlarged image of the slip-joint itself. The joint is a multiple tongue and groove joint, where the inner liner of one side (brown) fits within the liner of the other side (grey), while the insulation tiles of the grey side (green insulation) fit within the insulation tiles of the brown side (dark grey). This type of joint minimizes the leakage flow from the interior of the liner. Assembly of this type of structure is surprisingly easy, as the insulation can be held to the interior liner by simple tension bands. The banded insulation / liner can be slipped inside the exterior pipe during assembly (if necessary, the insulation / liner structure can be cooled and the exterior pipe heated to facilitate this insertion). Under operation, since the liner and insulation are far hotter than the exterior pipe, thermal expansion forces the interior structures against the exterior pipe, mechanically stabilizing the system.

[insulation diagrams from 2002 june quarterly report]

Figure 5.1 Pressure Backed Insulation Diagram

5.1.1.2. Pipe design (sizing / materials)

To determine the proper size piping to use in the analysis of the modularity and thermal stress issues, the necessary flow diameter, insulation thickness, and pipe thickness must be determined. The first step in this analysis is to determine the diameter of the inner flow region of the pipe. Using the Helium pressure and temperature at each point in the system, the bulk density is determined using the online NIST gas property database[115]. This database confirms that since Helium has near zero inter-atomic forces, its density can be accurately approximated by the ideal gas law. As such, the formula for Helium pipe ID given mass flow, pressure, temperature, and bulk velocity (400m/s) is given below.

[equation pipe ID vs. mdot, velocity, temp, pressure]

The Helium pipe ID along with temperature, pressure, and bulk density for the various system pipes is given below in Table 5.1.

Table 5.1 Helium Pipe Internal Diameter

[Helium pipe ID, temp, press, bulk density]

The thickness of the pressure bearing outer pipe is partially a function of its inner diameter, which, for these lined pipes is dependent on the internal insulation thickness. Thus, the next step in the analysis is to determine the insulation thickness required to maintain the pipe wall at 280°C or lower. To do this, the heat transfer from the Helium to the outside atmosphere must be broken down and a computational model created.

The heat transfer is broken down into 4 sections, force convection heat transfer from the Helium flow to the inner wall of the pipe liner, conduction through the insulation layer (due to its extremely small thickness and high thermal conductivity relative to the insulation layer), conduction through the outer pressure pipe, and natural convection from the outer pipe surface to the atmosphere.

The forced convection heat transfer from the Helium to the inner wall is calculated assuming the internal flow is fully developed. The porous insulation layer is modeled purely conductively (which appears reasonable given the small porosity and torturous flow paths impediments to convective flow). The outer pipe is also modeled as a purely conductive heat flow. The exterior natural convective flow was modeled for two cases, a vertical pipe and a horizontal pipe. The governing equations for the heat transfer through the various regions is given by the equations and diagrams below:

[insulation calculation equations]

[heat transfer analysis schematic diagram]

Figure 5.2 Heat Transfer Analysis Schematic Diagram

As the temperature at the various radial points, and the heat flow through each region are mutually dependent, the solution method used was to solve the equations working backwards from the outer layer, and use MATLAB to solve the problem iteratively. The known parameters are the temperature of the inside of the pressure pipe (280°C), the Helium flow and atmospheric properties, and the conductivity of the inner and outer pipe materials [insulation and pipe thermal conductivity]. The outer pipe thickness is determined by the required inner diameter, and the maximum allowable hoop stress of the material (given by ASME Section II) (26.7ksi)[116], and the formula below.

[pipe stress formula]

Using this MATLAB code (The input and output files are included in Appendix XX), and the results summarized in Table 5.2.

Table 5.2 Pipe Specifications

[table of pipe ID, OD, insulation thickness, etc]

Since the pipe sizes given by this table are not necessarily standard pipe sizes, the OD of the piping was changed for the pipe stress analysis and modularity design to an integer nominal pipe size (OD) in inches by rounding.

5.1.2. Flange Design

One of the main design advancements of the MPBR system is the use of a scavenged seal flange to join the Helium plumbing between modules. This system prevents Helium from leaking out of the system without the use of seal-welds. By eliminating seal-welds and the time and cost associated with their installation, not to mention the difficulty of rapidly removing and replacing modules if they are welded together, the overall MPBR system can be constructed much more rapidly and at lower cost.

5.1.2.1. Scavenged Flange

The flange design proposed is a conventional ASME B16.5 flange modified with two O-rings flanking a hollow scavenged volume. The innermost o-ring provides the primary pressure seal of the joint. The annular scavenge volume is maintained at a pressure lower than atmospheric by external pumps. The outer o-ring then limits the amount of atmosphere that leaks into this scavenge volume. This design positively prevents Helium from leaking into the atmosphere, as any Helium that leaks past the internal o-ring is scavenged at a low enough pressure to ensure any leakage past the outer o-ring is entirely composed of air leaking in, rather than Helium leaking out into the containment building. The scavenge volumes of all the flanges are pumped by a redundant set of external pumps (with separate systems for the primary side flanges and secondary side flanges). The scavenged flow is cryogenically separated to ensure only Helium is returned to the system. This system also enables simple monitoring of potential leaks as an inner o-ring failure would result in increased Helium flow into the cavity, while an outer o-ring failure would result in increase air flow into the cavity.

The primary concern for this type of sealing system regards a massive failure of the inner seal. If such a failure were to occur, the blow-down flow into the scavenged volume could overrun the ability of the scavenging system to deal with the flow, pressurizing the seal volume and resulting in a pressure spike on the outer seal. This pressure spike must be contained by the outer seal to prevent a massive leak.

Potential methods to deal with this type of failure are two-fold. First, the outer seal must be designed to handle a temporary pressure spike should the inner seal fail. A control system to detect the pressure spike and trigger a system shutdown should also be installed. Second, through careful design of the flange itself, inner seal failure and blow-down into the scavenge volume can be minimized. Such a design would likely take the form of a labyrinth seal on the flange to minimize leakage flow in a failure case. The scavenge flow piping must also be large enough to deal with the flow—a potential system design to accommodate such a flow would be to network all of the primary side scavenge volumes together with relatively (as compared to the recycling / atmospheric separating parts of the scavenge system) large diameter piping and include an accumulator volume in the scavenging system. Leak detection equipment installed on the accumulator could easily detect a seal failure by sensing either a significant pressure rise on the accumulator (which would be maintained during normal operation at a lower pressure than the rest of the system) or sensing a significant amount of atmospheric contamination of the volume (simple thermal conductivity measurement would easily detect atmospheric contaminants given the significant conductivity difference between the Helium coolant and air).

5.1.2.2. Flange design (sizing & materials)

The flange sizing on the system is governed by ASME code B16.5[117]. Based on this code, flange sizing and pressure limits at various temperatures can be defined. The chosen steel alloy for the system A508/533. As this alloy has the roughly the same strength across the temperature range of concern as A335 P91 (9Cr-1Mo-V)[118], it is reasonable to assume that the flange specifications for ASME material group 1.15.[119].

Group 1.15 materials, when applied to Class 900 flanges at an operating temperature of 375C (~700F) are limited to a pressure of 1705psi. Actually, for Class 900 flanges, with the exception of material group 2.3, all material groups have maximum pressures greater than the ~1200psi maximum system pressure (group 2.1 is limited to 1275 psi)[120]. These high-pressure class 900 flanges are only needed on a few specific sections of the system, while other sections can use the smaller and lighter lower classes of ASME flanges. Based on material group 1.15, the flange dimensions for each of the nominal pipe sizes used in the system are given in Table 5.3.

Table 5.3 Flange Specifications[121 122]

[NOTE include flange specs for 280C insulated wall temperature]

[INSERT TABLE FROM PIPING HANDBOOK p237]

[table of flange dimensions and weights from Tioga pipe website, compare to calculated numbers]

5.1.3. Space-frame design

The space-frame modules used are composed of standard structural steel and designed to be easily transported. With the exception of the power turbine / generator module, all the modules used have a cross section of 2.5 x 3 m, and a modular length of some multiple of either 2.5 or 3m. Using ASTM tubular square section beams (TS 8x8 with 0.5" web thickness)[123], the basic frame work will mass ~1500kg + ~900kg for every 3m increment in length (730kg for every 2.5m increment). This is based on a 73kg/m unit mass for the TS 8x8 beam section, assuming ASTM A36 structural steel[124]. Angle braces on the ends mass ~570kg (both faces, single diagonal), and the long dimension angle braces have a mass dependent on module length.

The choice of a square section, hollow (TS) beam of this size instead of a more conventional channel or I-beam section is for several reasons. First, the small cross sectional area is required to ensure adequate clearance for inter-module flange connections. The closed element beam also more accessable mounting surfaces for alignment and positioning devices, without the need for additional flanges to be welded to the beams. While structural calculations to determine the stresses in the space-frame structures are beyond the scope of this thesis (since it would require a more detailed layout of the various pipe hangers and component supports), if necessary, the web thickness of struts can be increased to accommodate higher loads.

5.1.3.1. Construction / Alignment

The space-frames must incorporate features to enable the modules to be lifted from the transporter, installed in the plant, aligned with other modules and physically attached to the integrated space-frame structure.

The lifting / installation features of the space-frame are difficult to define in detail without further extensive design. However, it is reasonable to assume that lifting lugs could be easily installed at various locations on the top of the space-frame. With the exception of the IHX and recuperator modules, all the modules are transported in the same orientation they are installed in. The IHX and recuperator modules are transported horizontally and lifted into a vertical position before installation. As such, these modules must have lifting lugs on two separate faces.

The space-frames provide the support structure and the devices to align the components within the frame with adjacent components. An example of the types of transport and positioning struts is shown in Figure 5.3 below.

Figure 5.3 Diagram of Transport and Positioning Struts in Spaceframe

5.2. Primary Side

Descriptions of what it takes to put the reference plant components into this system and any changes or additional information is needed

5.2.1. Reactor Vessel

The reactor vessel for the MIT MPBR system is little changed from the ESKOM design, with the exception of the piping. In the ESKOM design, the cold inlet piping to the reactor vessel is two smaller pipes, while in the MIT MPBR design, the cold inlet is a single pipe (installed at the same elevation, but aligned with the hot outlet pipe). The modularity / segmentation approach described in Chapter 4, may also be incorporated into the MIT MPBR design if the transportation of the vessel requires the RV to be broken down into lighter sections.

5.2.2. IHX

As described earlier, the IHX is broken down into 18 core sections, grouped into six modules. Each set of three cores is contained in an insulated pressure vessel which forms part of the Class 1 boundary. The IHX containment reference design was proposed by Peter Stahle (MIT Nuclear Engineering) and is a vertical steel pressure vessel 2.3m in diameter and approximately 5.5m long[125]. The vessel has a 4.5m cylindrical section with 0.5m long ellipsoidal end caps. One of the end caps is welded directly to the cylinder while the upper (when installed) cap is bolted to a thickened section of the cylinder. This removable end-cap enables installation of the internal structures. The internal piping and high temperature structures of the IHX is formed of the same Incoloy 800HT super-alloy as the RV internal structures and pipe liners. The internal piping is connected directly to the liners of the incoming pipes. The vertical installation of the IHX module enables it to bend to accommodate thermal expansion of the external piping, however, to enable a conservative thermal design, the attachments of the pipes to the IHX vessel are assumed to be fixed anchor points (all three linear and all three angular displacements are fixed). The internal expansion of the IHX pipes inside the vessel is accommodated in similar fashion. Based on the reference design, the IHX vessel has a wall thickness of 5cm[126], an insulation thickness of XX cm., an end cap thickness of 5cm, and a thickened flange section (for end cap attachment) 10cm thick and 25cm. in length. Composed of the standard A508/533 alloy as the rest of the system, each IHX vessel has a mass of ~1.9×10^4 kg.

The three IHX core modules inside each vessel have a mass of 630kg[127], and are contained inside a thin internal vessel that provides a manifold for the primary side return flow (the primary side intake manifold is the triangular volume in the center of the three core modules). Given a thickness of 1cm this 1.7m diameter x 1.5m tall internal vessel (dimensions estimated from reference plant diagrams)[128] has a mass of ~900kg. Since this vessel, and the internal piping in the IHX has to support very little differential pressure, the thickness required is defined by structural concerns rather than pressure induced stresses. While a primary side depressurization accident would put the internal pipes under considerable stress, given their small diameters (~18cm) and short lengths (<2m), their mass compared to the rest of the structure is negligible. Given these parameters, each IHX module will have a mass of ~2.2×10^4 kg. (not including the space-frame, internal pipes, and manifolds).

The IHX space-frame has external dimensions of 2.5m x 3m x 6m. Neglecting any additional diagonal or cross bracing, the IHX spaceframe contains 46m of TS8x8 (0.5”) beams, with a mass of $3.4x10^3$ kg. Thus the total IHX module mass is approximately $2.54x10^4$ kg.

5.3. *Secondary Side*

5.3.1. Turbo-Compressors

Based on the reference plant turbo-machinery design, a preliminary design of the casings for the various turbine and compressor components was performed. The two turbines that drive the compressor sets are each encased in a multi-layer casing that structurally supports the turbine spool and its bearings and resists the internal pressure of the Helium flow. This casing consists of an inner ~1cm thick metallic lining that provides support for the stator blades and a smooth flow surface, followed by an insulation layer similar to that used on the high temperature piping, and an outer 5cm thick A-508/533 pressure vessel. The inlet and exhaust volutes are integral with this pressure vessel. A cross-section schematic diagram of the turbine design is shown in Figure 5.4.

The turbine spool is a hollow structure ~2m long and 1.2m in diameter. The spool is constructed of the same high temperature super-alloy as the turbine blades and is approximately 10cm thick (calculation method for this, and the other rotating machinery specifications is described in Appendix XX). The spool is supported on both ends by 20cm diameter (18cm inner diameter) hollow axles. While the material specification for these axles (and the end plates of the spool has not been determined, such a material must be able to support the stresses imposed (shear stress of ~365MPa) at the temperatures reached during normal and accident case operation. Determining these temperatures is beyond the scope of this thesis, as to do so would require extensive finite element modeling of the entire turbine assembly, however, it is reasonable to assume that the alloys used in the construction of the spool and blades would also be suitable for the end plates and axle shafts. Using a estimated material density of $\sim 8x10^3$ kg/m^3 (typical of high alloy steels), the turbine rotor has a mass of $\sim 5.5x10^3$ kg. The outer casing has a mass of $\sim 7.5x10^3$ kg for a total turbine mass of $\sim 1.3x10^4$ kg.
SCHEMATIC DIAGRAM OF TURBINE

Figure 5.4 Cross-Section Schematic of High and Medium Pressure Turbines

The four compressors in the reference plant design are 8+1 stage axi-centrifugal spools[129] inside the same type of two-shell vessel as the turbine casing. The compressor spool is a hollow 0.6m diameter structure with a loaded wall thickness of ~5cm (based on the same material assumptions as the turbine spool calculations). Total compressor rotor mass is $\sim 2x10^3$ kg. The compressor vessel is composed of a 1cm thick inner casing, a layer of insulation, and a 3cm thick pressure vessel. The mass of a single compressor is roughly $5.5x10^3$ kg.

SCHEMATIC DIAGRAM OF COMPRESSOR

Figure 5.5 Cross-Section Schematic of Compressor

Each turbine is paired with a set of two compressors and installed in a single space-frame module, shown in Figure 5.6. The mass of each turbo-compressor set is ~2.4x10^3 kg not including piping, support structures, and the space-frame itself. The basic mass of the TC spaceframe (neglecting any diagonal or cross-braces) is based on a 2.5m x 3m x 15m space-frame (containing 82m of TS8x8 (0.5") beams). Without any additional bracing, the turbo-compressor space-frames would each have a mass of ~6x10^3 kg. Thus the total mass of each of the turbo-compressor modules is 3x10^4 kg.

DIAGRAM(s) OF TC MODULES

Figure 5.6 Turbo-Compressor Module With Spaceframe

5.3.2. Power Turbine

The reference plant power turbine (23 stage axial turbine, 2.9m blade tip diameter, 6m active blade length)[130] design incorporates many of the same elements as the smaller turbines used to power the compressors. The power turbine spool is ~2.5m in diameter and ~6m long (active blade length). Based on a rotational speed of 3600rpm (synchronous speed for a 60Hz AC generator) and a hoop stress limit of 365 MPa [verify hoop stress limit], the power turbine spool has a thickness of ~4cm and a mass of ~1.5x10^4 kg. The rotor is contained in a two layer containment vessel—a 1cm inner flow control / stator support layer, and a 6cm thick, XXm in diameter, outer pressure vessel (Figure 5.7). Total mass for the containment vessel is ~3.7x10^4 kg for the circumferential part and ~5,6x10^3 kg for each 10cm thick end cap. Total mass of the power turbine assembly is roughly 6.4x10^4 kg.

[SCHEMATIC DIAGRAM OF PT INCLUDING DIMENSIONS]

Figure 5.7 Schematic Diagram of Power Turbine

5.3.3. Generator

The details of the generator of concern to this analysis are its size, mass and any equipment or layout concerns. Based on the 130MW gross electrical power of the reference plant generator[131], two generator options are possible—air cooled or hydrogen cooling. Hydrogen cooling is typically used on extremely large (1000MVA class) generators, while air-cooling is used almost without exception on <100MVA generators[132]. Air cooling has been used on generators at power levels greater than 160MVA[133], though air cooling extracts a significant weight penalty when compared to hydrogen cooling. Assuming a power factor of unity (MVA = MWe), a 130MVA generator would have an estimated mass of 2.03x10^5 kg (with hydrogen cooling) and ~2.21x10^5 kg if air-cooled (assuming a mass penalty of 10%). These figures are based on exponential interpolation (0.66 scaling exponent R-squared value 0.97) of reference generator weights between 13.5 and 70.6 MVA[134]. Hydrogen cooling would require a substantial amount of auxillary equipment for heat rejection, so in the interest of simplicity, air cooling appears to be the best choice for this application. Assuming a 30°C temperature rise, ~66kg/s of cooling air is required to absorb the ~2MW of waste heat from the generator. Limiting airflow velocities to 25m/s would require roughly

~2m^2 of inlet and exhaust ducting. Given the generator modules location on the very top of the balance of plant assembly, providing easily removable ducts to transport the hot exhaust out of the plant would not be difficult.

Estimated generator size is 3.6m (H) x 4.6m (W) x 4.8m (L) to fit within the 4 x 5m generator module cross section (assuming 0.2m space-frame beam width and height). This volume (~80m^3) is based on a power density of ~1.6MW/m^3, which is similar to the power density of medium voltage (4kV) air cooled large frame synchronous motors (e.g. 4kV, 3600rpm, 5000hp Siemens Type CG Frame 6813 motor)[135]. This is a conservative estimate as power density of AC synchronous machines increases with both power and operating voltage.

5.3.4. Recuperator Design

Based on the reference plant recuperator design

30 modules, each 0.6m x 0.65m x 2.75m (with the 0.65x2.75m face comprising the flow area) and 5.2x10^3 kg [CYW p203]

5 core modules per recuperator vessel [internal arrangement]

Using PCHX design, 95% effectiveness, 0.8% hot side dp, 0.13% cold side dp.),

no internal vessel, hot, high pressure flow into vessel (puts pressure loads radially inward on internal structures

Recuperator vessel same dimensions, weight, materials, etc as IHX vessel. (same 1.9x10^4 kg. vessel mass)

Core mass per vessel 2.6x10^4 kg.

Overall module mass 4.84x10^4 kg.

5.3.5. Precooler

Based on the reference plant precooler design requirements, it was necessary for this study to generate the preliminary design for such a component. Since size and component mass are extremely important in this design, a compact, robust design is necessary. While past reference designs have assumed the use of shell and tube heat exchangers, a compact heat exchanger format may have advantages.

The design proposed for the precooler uses a PCHX design. Conservatively assuming the same volumetric heat transfer rate as the IHX design, the active, counter-flow part of the core of the precooler is ~7cm long. Including the cross-flow sections of the PCHX, the overall length of the core in the Helium flow direction is ~25cm.

Assuming the Helium is moving slow enough through the core to be in a laminar flow regime, the pressure drop through the core is linearly proportional to the length of the core and the velocity of the Helium, as shown by the equations below.

[pressure drop equations from engineering handbook]

Thus, to maintain a pressure drop of ~0.8%, the Helium side core area must be ~10m^2 (assuming the same 0.282mm channel diameter as the PCHX IHX design)[136]. To package the precooler and the similarly sized intercoolers in the space required by the layout, a maximum core width in the water flow direction of 1.2m is required. Thus, the precooler heat exchanger is comprised of 4 identical core sections, each 0.25m x 1.2m x 2.5m. The following design for the core and its Helium manifolds is shown in Figure 5.8.

[Precooler / intercooler design]

Figure 5.8 Precooler and Intercooler Cross Section Schematic

This design results in a module that is 2.2m tall, 1.3m wide, and 3m long. Since the core segments are based directly on the parameters given for a PCHX version of the IHX[137], the core density, 4.85×10^3 kg/m^3, should be identical. Thus the 4 core sections have a total mass of 1.46×10^4 kg. With a wall thickness of 2.5cm, the vessel required would have a mass of ~5.4×10^3 kg. As such, the total precooler mass is 2×10^4 kg.

The precooler water flow is ~150kg/s (for a water temperature rise of 65°C). An estimated 200kPa water pressure drop requires a pump power of 30kW (given ~70% pump efficiency and 98% motor efficiency, this requires ~43kWe to power the pumps).

The PCHX design is extremely robust, and requires a minimum amount of labor to assemble. Due to the low operating temperature of the precooler (95°C normal operating Helium inlet temperature), conventional stainless steels can be used in its construction, alloys which have been well studied by PCHX, and are extremely resistant to corrosion by the water side of the system. The PCHX design also maintains a high effectiveness, maximizing the water outflow temperature. The parallel flow design provides a significant amount of flow-path redundancy, albeit at the expense of requiring fine filtration of the water flow to prevent blockage of the narrow flow channels. This fine filtration would present a significant issue if the MIT PBR rejected heat using evaporative cooling towers—which require a large quantity of make-up water, and can easily absorb debris and/or impurities that must be dealt with. By using the closed-loop heat rejection system proposed, the tertiary water cooling loop purity can be maintained, and if necessary, include additives to increase heat transfer (viscosity and surface tension modifiers) and prevent corrosion.

As this proposed precooler design is based on the heat exchanger specifications optimized for the PCHX version of the IHX, optimization of the design for the flow parameters of the precooler Helium flow could result in a much better design with lower pressure drops and a lower heat exchanger mass.

5.3.6. Intercooler

The proposed intercooler design is nearly identical to the pre-cooler design presented in the previous section. Due to the lower Helium inlet temperature (68°C vs. 95°C), and the smaller quantity of heat transferred (~24MW vs. ~41MW in the precooler), the intercooler core thickness is ~4cm. In order to maintain a significant level of design conservativism, 100% of the heat transfer is assumed to occur in the counter-flow core section. Given the long flow length in the cross-flow manifold region, this is an extremely conservative assumption. The three intercoolers used in the reference plant have the same Helium inlet and outlet temperatures, with different required pressure drops (0.5% for the first IC, 0.3% for the 2nd and 3rd). Even assuming the same core thickness as the precooler, the Helium flow through the intercoolers is at a much higher density. Since the pressure loss is not dependent on the density or pressure of the flow, as shown in equation XX [reference pressure drop equation from previous section], the 20kPa pressure drop in the precooler, is only 0.6% in the first IC, 0.48% in the second, and 0.37% in the 3rd. Since the core area of the three intercoolers is the same as the precooler, the higher density of the Helium flow results in a lower Helium flow velocity in the core, and thus a lower pressure drop. The Helium velocity in the intercoolers is 0.77, 0.59, and 0.45 times the velocity in the precooler. The resulting pressure loss is as a result reduced to 0.46%, 0.27%, and 0.17%, as these values are well below the reference plant required values, this design is quite conservative.

5.4. Other systems

5.4.1. Inventory control

The conventional approach to inventory control in Helium cooled reactor systems is to have a large volume of low pressure Helium storage. The storage is filled from the high pressure compressor outlet—maximizing the pressure into the system. The volume required is far larger than the Helium volume in the reactor and balance of plant enabling the system to "blow-down" into the storage vessels. A rapid blow-down of the primary side in particular is necessary under accident scenarios to prevent failure of the IHX heat exchange surfaces if the secondary side depressurizes.

While this type of system is simple, and enables a rapid decompression of the plant, it has many negatives. The biggest disadvantage of this system is the extremely large volume required, many times larger than the internal volume of the system. The storage tanks into which the primary side exhausts into must be treated to the same contamination precautions as the reactor vessel and primary side hardware, complicating the inventory control process.

The total Helium inventory of the MIT PBR is . For example, the internal volume of the six IHX vessels is ~125m3, larger than the internal volume of the reactor core (3.5m diameter x ~9m tall, ~87m^3). Since the core volume is partially (~61%[138]) filled with fuel pebbles, the volume remaining in the core is only 53m^3. The primary side therefore contains 178m3 of 980°K (bulk average) Helium at an average pressure of ~7.8MPa[139] or ~3.9x10^2 m^3-MPa of Helium (at 273K). The Helium inventory of the secondary side under normal operation is broken down into (temperatures and pressures are averaged through component) 15.5m3 @ 8 MPa, ~560°K plus 5.4m3 @ ~2.75MPa, ~560°K in each of the six recuperator modules, 6.5m3 @ ~2.75MPa, 336°K in the precooler, and a total of 19.5m3 @ 4.76MPa, 323°K (average) in the three intercoolers. The Helium volume in the power turbine (assumed to be approximately equal to the annular volume swept by the blades) is equal to 10m3 @ ~4MPa, ~890°K (mean pressure in the turbine). The volume in each compressor is ~0.5m3 at 323K and a mean pressure (for each compressor) of ~3.2MPa, ~4.1MPa, ~5.4MPa, and 7.1MPa. Thus, the approximate inventory of the secondary side is ~8.2×10^2 m^3-MPa (at 273K). This total inventory of ~2160kg (700kg in the primary side) of Helium is ~42% less than the ESKOM operating inventory (3700kg)[140]

In a direct cycle system, a rapid decompression is required in case of leaks to prevent significant contamination of the containment building. In an indirect cycle system leaks in the secondary side would not result in contamination of the containment, however, since the IHX is designed to deal with only a certain level of pressure differential between the primary and secondary sides, a sudden decompression of the secondary side would require a rapid decompression of the primary side to prevent IHX failure—failure that if it occurred could potentially contaminate not only the secondary side equipment, but also the containment building.

Based on these factors, a number of solutions are possible. The simplest, yet least effective from a contamination standpoint is to use a pumped, high pressure inventory system, used only for shutdown and startup (i.e. the Helium flow rate into the inventory control system is relatively slow, and limited by the available compressor power). The rapid depressurization of the primary side in the event of a secondary side loss of coolant accident would be accomplished by simply venting the primary side inventory through a particulate filter (to remove radioactive debris) and into the containment building. Obviously the radiological concerns of such a system would likely be unacceptable.

A more suitable method would be to create a sealed, low pressure volume within the containment building (such as smaller, walled off volume within the primary side vault), with a sealed steel liner. Assuming 1m thick walls, an 8m x 8m x 20m volume adjacent to the reactor vessel could be used as a temporary ~650m^3 (3.6 times the volume of the primary side) blow-down tank. In the case of a secondary side accident, the primary inventory could be released into this tank, reducing the system pressure dramatically in only a few seconds (the normal circulating flow would reach this pressure in ~5 seconds, without exceeding the 400m/s maximum helium velocity). With the Helium inventory temporarily contained, the pumped storage system can then empty the primary side over a much longer time. The equilibrium pressure should be low enough to prevent damage to the IHX modules, though further analysis is required to confirm this, as well as determine the blow-down times for each side of the system.

The detailed design of the pumped storage system itself is also left open. Such a system should seek to minimize the required modular volume needed for long term inventory control. Using the 10m long inventory control modules discussed in Section 4.2.5, operating at an internal pressure of 15MPa, 3 such modules would be needed for storage of the primary side helium, and 2 for the secondary side. The necessary pumping work to evaucuate the primary side of the system (pumping Helium from the temprorary storage vault) is ~1.3MJ/kg of Helium. Therefore the time required to evacuate the system is equal to ~3200/(Pη) seconds. (P is compressor shaft power in MW, η is the compressor efficiency). Further design is left for future work.

5.4.2. Heat Rejection

The heat rejection system of the MIT PBR is an important part of the overall system. The temperature of the heat rejection has a direct affect on overall system efficiency, as shown in the Figure 5.9.

[CYW cycle sensitivity to CIT chart]

Figure 5.9 Reference Plant Cycle Efficiency and Optimum Pressure Ratio Vs. Compressor Inlet Temperature[141]

Based on this sensitivity the reference plant assumes a CIT (compressor inlet temperature) of 30°C, which requires the cold-water inlet to the precooler and compressors to be at a temperature of about 27°C[142]. To meet the modularity goals of the MIT PBR system, the following design choices were made to conceive the heat rejection system. First, the system will use a non-evaporative, closed-loop cooling method. Second, the heat exchangers must be intrinisic with the structure, eliminating the plan area required for external cooling towers, and must have a low installed height in keeping with the low profile of the plant structure. Third, the heat rejection modules must be installed in such a way to permit easy replacement and repair, along with multiple redundant units to permit operation even with single unit failures.

The non-evaporative, closed-loop cooling method enables the plant to be installed in locations not normally suitable for large power plants given their reduced access to large quantities of cooling water. The high temperature heat rejection of the system also permits high efficiency plant operation in areas where the ambient temperature is high—such as locations in the American south-west (where water is a precious resource and average ambient temperatures can be extremely high, especially during the summer months).

Intrinsic installation of the heat exchangers required for non-evaporative, closed-cycle cooling with zero increase in plan area and a low increase in plant installed structural height is achieved by breaking the heat rejection system down into many redundant modules, installed around the perimeter of the plant structure. Normally heat rejection systems require high chimneys to generate enough buoyancy for adequate airflow (unless large fans are used to generate a sufficient forced draft. By using a counterflow heat exchanger, the exhaust air temperature can be quite high (60-90°C), which generates a large amount of buoyancy, reducing the fan power necessary.

Modular design of the heat exchangers is a simple matter of breaking the necessary HX surface into standard size modules each with its own forced draft fans and enclosure.

Each module can be isolated with valves in the water flow loop, enabling removal and replacement of a failed module without shutdown of the plant.

The heat rejection modules proposed are fan-driven forced draft counter-flow water-to-air heat exchangers. The intercooler and precooler water outputs are mixed (resulting in a water flow of ~600kg/s at a temperature of 76°C. The counterflow design yields an air temperature rise of 49°C through the heat exchanger, requiring an airflow of ~2500kg/s (roughly 2000m^3/s). Each of the 16 module is 2m wide by 10m long, and 3m high during transport. The heat exchanger within each module is a vertical, square, array of, 1cm OD stainless steel pipes, spaced 6cm apart, and connected by 5cm wide stainless steel fins (1.5cm fin-fin spacing). These fins provide ~5.3x10^3 m^2 of surface area. The mass of the tubes (assuming ~1mm wall thickness), multiplied by 1.5 to account for the mass of the manifolds, and fins (0.5mm thick), is ~25,500kg per module. Each module has a 1m tall, curved intake duct below the heat exchanger (as shown in Figure 5.10), along with a 1m tall louvered chimney (installed on site from four sections packaged inside the space-frame with the unit for transport) above the core. Ten 1m diameter fans force 125m3/s of air through the core (inlet velocity ~12.5m/s). Assuming a 0.5% pressure drop through the heat exchanger (~0.5kPa), the required fan power is ~62.5kW per module, or ~90kWe given a fan + motor efficiency of ~0.7. Total forced draft fan power for all 16 modules is 1.44MWe. Including the fans and a simple enclosure composed of a standard space-frame along with 1mm thick steel sheet exhaust and intake ducts, heat exchanger side covers and assorted louvers, the total mass of each module is ~3.2x10^4 kg.

Figure 5.10 Diagram of Heat Rejection Module

5.5. *Piping layout / analysis (overview)*

The key achievement of this project is the development of a pipe stress analysis method for this plant. In order to ensure a layout is workable, the pipe design must be capable of accommodating both the dead loads of the pipes and components, but also the thermal expansion of the elements as the piping heats up from ambient to operating temperature. The method beings with the proper assumptions to bound the analysis.

5.5.1. Assumptions

The assumptions used as constraints for the pipe stress analysis cover analysis methods, pipe parameters, and model simplification methods. The first set of constraints cover the codes used to model the piping. In this case, the applicable codes are ASME Section III, class 1 for the primary side boundary, and ANSI B31.1 power piping code[143]. The second set of constraints and assumptions concern the properties of the piping and components within the system—specifically, the temperature, pressure and size of the piping, how the pipe dimensions are calculated (in bends and other non-straight sections), and how the various pipes and components are anchored.

5.5.1.1. Pipe Temperatures

The temperature of the various pipes during operation is necessary to determine their thermal expansion displacements and thus, their internal loads. These temperatures are defined by the internal Helium flow temperatures, and the pipe insulation design proposed earlier. Based on these parameters, the pipe temperatures used for the piping model are given in Table 5.4 below.

Table 5.4 [Table of pipe temperatures and pressures]

5.5.1.2. Pipe Materials, Sizes, and Wall Thicknesses

The operating assumptions of the model include a set of pipe engineering specifications such as the pipe material, size (OD, ID), and pipe thickness. These parameters define the necessary dimensional inputs to the pipe analyses. The pipe material used for all the pressure and load bearing piping in the system is the high alloy steel A508/533, as defined in the reference section. This pipe material has a maximum allowable stress of 26.7ksi at 280°C[144]. While the lower temperature piping of the plant could, within code constraints, use different materials to potentially reduce costs, for this design, all the piping will use the same A508/533 alloy, and the same allowable stress level—this results in a more conservative design for the system and prevents potential interface issues (for example, if the colder piping was formed of a different alloy, the weld joint between that pipe and a higher temperature A508/533 vessel would require substantial analysis to ensure weld material compatibility). As such, the pipe dimensions calculated and shown earlier in the general design section are assumed as inputs for the piping analysis.

5.5.1.3. Piping Model-Specific Assumptions

The pipe layout is also governed by a set of assumptions regarding dimensions and rules other than the gross diameters of the pipes. First, the model assumes "long-radius" bends, with a bend radius equal to 1.5 times the pipe outside diameter. While there isn't a code constraint limiting the use of short radius bends, this is a reasonable assumption as the longer radius bends work to reduce both the thermal stresses (long radius bends are inherently more flexible) and potential flow turbulence and pressure losses in the piping (as the longer bend radius permits smoother internal flow and less dynamic pressure concerns on the inner pipe liners).

The layout is also governed by a series of assumptions as to how the pipes are connected to various components and structures. These assumptions are made to simplify the model, while at the same time ensuring the resulting design is both conservative and indicative of an actual system. As such the anchor points of the piping can take the form of 6-Degree-Of-Freedom (zero displacement in all 3 linear and 3 rotaitonal axes) anchors or other, less constrained attachments (e.g. snubbers), depending on the component of concern.

The piping attached to the reactor vessel is modeled as 6-DOF anchored, reasonable considering the stiffness of the ~14cm thick reactor vessel wall, and the fact the RV is anchored directly to the plant structure. The reactor vessel itself is anchored in such a way that its radial thermal expansion causes zero displacement at the pipe-interface (by making the RV anchor collinear with the pipes radially fixed, and having the radial expansion taken up by linear displacements at the other two RV anchors). The piping attached to each of the IHX vessels is also assumed to be anchored in all six degrees of freedom. This results in a conservative piping design, as the pipes are required to accommodate any thermal expansion present in the system. This assumption also enables the IHX vessels to be rigidly attached to the plant structure without the need to allow for movement of the IHX vessel. In each of these cases, the vessel wall is substantially thicker than the pipe thickness, so the vessel wall stiffness can be assumed to be much greater than that of the pipe.

Finally, the model does not take into account any secondary piping associated with distribution of Helium for RV or pipe cooling. The model also does not include the bypass valves and piping required for load following, startup, and shutdown. To include these smaller pipes and valves at this stage of the plant design would unnecessarily complicate the model—since the goal of this phase is to create a process for layout and design verification, and to prove such a design, albeit a preliminary one, is possible. The major result of limiting the model to this level of fidelity concerns the incorporation of pipe hangers and supports and their affects on the piping stress level. Since the design of each individual hanger, and determination of their optimal location would require not only a level of effort incommensurate with this study, but also a component design maturity that does not exist at this time. Details of how this fidelity limitation affects the results are discussed later.

5.5.1.4. Rigid Element Assumptions

In order to simplify the analysis certain components are modeled as rigid elements with no internal deflection (i.e. the relative position of the two ends of the element is fixed, while the absolute position of the element is free in all axes. This is done in several cases in the model of the MIT PBR system. The rotating machinery (the two turbo-compressor units and the power turbine) are modeled as rigid elements connecting the inlet and outlet pipes. The turbo-compressors are also modeled with a rigid element connecting the three components (the turbine and two compressors) as a rigid assembly. The precooler and intercooler vessels are also modeled as rigid elements, as these elements are extremely rigid relative to the thin piping connecting the various cold side elements.

5.5.2. Analysis Method

The analysis method used to verify the viability of the proposed plant layout involves an iterative process using a piping analysis code. The code used, CAESAR II, is a generic pipe stress and structural analysis code. Once the code assumptions are considered, the iterative design process can begin. Once the results are obtained—specifically a layout that results in the maximum stresses in the piping being below the allowable stress determined by the ASME code limits for the chosen pipe materials—these results are used to determine the module by module design of the system.

5.5.2.1. Pipe analysis code—CAESAR II

The CAESAR II piping analysis code, produced by COADE engineering software is a generic piping and structural modeling code. Certain assumptions used by this code are important to address for this analysis. First, the model assumes the use of long radius (bend radius = 1.5 time pipe diameter) pipe bends[145]. Second, the allowable stress limits used are the ASEM Section II allowable stress limits for the alloys used, in this case A508/533. The code also models the piping as having a constant through thickness temperature, a reasonable assumption given the low temperature drop through the thickness of the pipe[146].

[any other assumptions?]

5.5.2.2. Iterative Design Process

The design process used to form an acceptable layout from the initial reference design is an iterative one. The general iterative process proceeds along the following steps. First, a notional layout design is created. This notional design consists of the relative layout of the individual components, derived from a component interconnection matrix. An example of such an interconnect matrix is shown below.

[component interconnect matrix]

This matrix describes which components must be connected to each other. From this matrix, the general layout constraints and design considerations are applied. Examples of these constraints and considerations include the maximum depth of the structure in terms of modules (assuming each component is enclosed in its own individual module), and the general design of the system—such as the horizontal array of IHX modules surrounding a central manifold module.

This notional layout is then entered into the CAESAR code as an input deck. During the input process, certain issues must be addressed to ensure proper operation of the software. First, when a pipe bend is entered into the code, the length of each leg of the bend must be equal to the bend radius. While the code does not specify this as a necessity, it appears (as evident in the rendered models of the proposed layout) that the rendering components of the software have difficulty dealing with bends that are described as having leg-lengths greater than the bend radius. As such, for future CAESAR II models, careful attention must be paid to this issue.

Second, the flange database included in CAESAR II is limited in depth and does not include the necessary size flanges for the proposed layout. Two approaches can be used to deal with this issue—model each flange side as a rigid element with a mass taken from an external database (such as the Tioga pipe flange information shown earlier), or by conservatively assuming the flange is a larger size / higher pressure class flange that is in the database. Since CEASAR II models flanges as rigid elements of a constant mass, and does not compute (at least at the model fidelity used for this iterative process) the flange mating stresses and pressures, either approach is valid.

Third, tapered reducing or expanding sections are modeled as conventional pipes with nominal diameters and thicknesses equal to the median values of the two interconnected pipes.

For the components such as turbo-machinery or heat exchangers, the necessary inputs are simply a series of rigid elements connecting the pipe inputs and outputs of each component. Based on the assumption that the components will be supported in such a way to cause zero dead-weight loading, and enable, when not modeled as anchored pipe ends, them to move with the thermal-expansion induced displacements, the rigid element inputs (rotating machinery, precooler, and intercoolers) are modeled as having zero mass, and are not restricted in displacement relative to the absolute coordinate frame of the system (since they will be supported externally, this eliminates their mass as an effect on the deadweight loading of the pipes—i.e. the pipes do not provide structural support to anything except other pipes. Since it is obviously not possible for the large, heavy components such as the turbo-machines or heat exchangers to be easily installed in such a way to permit this total freedom of movement (nor would it be wise given potential seismic load effects), in future work attention must be paid to defining a system layout to minimize the displacements allowed by the component supports, either in overall values, or by restricting their displacement to certain limits for each axis.

Once the input deck is created a stress analysis is performed, with two different operational cases. The first is the non-operational dead-weight only case where thermal expansion and internal pressure is not addressed. This case determines the stress level of the piping when the plant is shutdown and depressurized and is purely dependent on the deadweight of the piping and flanges (due to the zero-mass rigid element models used for the remainder of the components, only the pipe dead weight is a factor). The second case is an operational analysis where the internal pressures, and pipe operational temperatures (both defined earlier) are addressed. In this case the thermal expansion induced stresses are shown.

Comparing the results of both stress analysis cases to the maximum allowable stresses will show which specific pipe elements have unworkable stress levels. The layout is then modified to attempt to rectify these stress issues and the input / analyze / adjust process repeated. The methods used to reduce the stress levels of individual pipe elements include incorporating U-pipes, changing the thickness of the pipe walls, and including various pipe supports, as typified by the generic pipe hanger.

U-pipes

One of the bulkier, yet most effective method to reduce stresses in the piping system for the MIT PBR is to use a U-pipe design. In this design method, rather than have a long run of pipe be a simple straight pipe, the pipe is bent into a U- shape. This U-shape enables the pipe to withstand thermal expansion loads (both the expansion of the piping run itself and thermally induced displacements of its end points) by allowing the pipe to bend at each of the 4 elbows in the U, and bend along each of the legs. In terms of the iterative design process, the U-pipes must fit within the modules themselves, thus the variables to iterate are the lengths of each of the 3 sections of the U (each leg, and the base).

Thickness changes

In many of the highly stressed locations on the piping layout, a simple increase in the pipe thickness is sufficient to bear the required loads. In these locations, the applied stress from deadweight or thermal expansion is extremely high in relation to the stress from internal pressure, thus, the minimum thickness required to contain the internal pressure is not sufficient for the design, and an increased thickness provides for more material to bear the loads. This method has the least effect on the design as a whole, as it does not require the additional space as the U-pipes, and the overall mass increase is comparable to other methods.

Hangers

Since a significant amount of the loads placed upon the pipes are deadweight loads (supporting the various piping runs against the force of gravity), hangers are used throughout the system to reduce the pipe stresses caused by these loads. A notional pipe hanger is a spring loaded, vertical strut that supports a section of pipe. The flexible nature of the spring enables the hanger to flex with thermal loads—preventing the hanger itself from applying additional loads on the pipe by resisting the expansion. The position of the various hangers in this design is preliminary, as more detailed analysis will no doubt determine a more optimum configuration of pipe supports and hangers. However, for the iterative process described here, the hangers are installed in areas of high pipe stresses, and the results of their installation analyzed. As long as the result is beneficial, the hanger is left at that location. These hangers will define, in design iterations done in future work, the location and loading of cross-braces installed on the space-frames (as shown in Figure 5.11).

Figure 5.11 Space-frame Example with Hangers and Cross Braces

Limits of results—determine end-point

The end point of this analysis, for the purpose of this thesis, is the design of a piping layout that meets the requirements of allowable stresses, based on the assumptions stated earlier. While this result may not be the most optimum layout, configuration, or pipe specification, it answers the question as to whether or not any layout is possible that meets the system requirements while complying with the code and material limitations of such a system.

5.5.3. Results

This process was performed for the proposed design and iterated to result in a preliminary design that best meets the goals for this study. The resulting design must be easily broken down into modules of transportable size and mass, take into account the constraints in terms of module depth, and the design considerations defined earlier. Given the immaturity of the component designs, and the limitations placed on the fidelity of the model, the resulting layout should not be considered in any way the final layout for the MIT PBR system, rather it should serve as an example or starting point for future work on this part of the MIT PBR project. In this role, the proposed layout should illustrate the important result of this study—the definition, and where possible, quantification of the method, constraints, design considerations, and potential issues affecting follow-on work.

The proposed layout is shown in the figures below, with embedded coordinate axes, in multiple views as it, at first glance seems extremely complex.

Figure 5.12 Piping Layout Isometric View

Figure 5.13 Piping Layout View Toward –X axis

Figure 5.14 Piping Layout View Toward –Z axis

Figure 5.15 Piping Layout View Toward –Y axis

The layout takes the form of two distinct sections, a primary side and a secondary side. This two-section approach permits the plant to be housed in a structure with two independent volumes. The primary side volume contains all the components that comprise the ASME Section III Class 1 boundary of the system, while the secondary side volume contains the balance of the plant. This way, a failure of the primary side boundary would not result in contamination of the bulk of the components, and a secondary side component failure would not require access to any potentially radiologically contaminated areas for removal, repair and replacement.

The primary side section, isolated in the diagrams below, consists of the reactor vessel (here shown schematically as a simple cylinder for a size comparison to the rest of the components), two IHX manifold modules stacked vertically, and six IHX vessel (also shown schematically as simple cylinders for size comparison) modules arrayed horizontally around the manifold. The two rows of three IHX modules are offset in the x-axis by 1.25m to eliminate the need for 4-way pipe intersections and permit greater piping compliance to deal with thermal expansion. Each module is spaced 2.5m from its neighbors in the x-direction (as the IHX modules, as installed are 2.5 x 3 x 6m (x,z,y) (when transported the module is rotated so that the piping is vertical). The pipes between the manifold and IHX are flanged and the module boundary is midway along the base of each U-section. These U-sections are limited in dimensions by interference of the flanges with the module frames—as the ports on the IHX vessels are defined in the reference plant design, and the main manifold pipe vertical spacing is determined by the location of the ports on the reactor vessel.

The primary side is connected to the secondary side of the system by two, 2m long interconnect pipes. These pipes are the only portion of the layout not to be enclosed in a space-frame, as they penetrate the concrete separator between the two sections. Because of the need to seal the two sections from each other, these pipes would be installed through portholes in the wall, and seals of a TBD nature added (the seals must be compliant with the necessary NRC and ASME codes required to ensure the secondary side of the system remains a non-nuclear (i.e. work can be performed with no concern of radiological hazard other than monitoring to ensure the Section III Class 1 boundary has not been compromised)). If these pipes need to be replaced, the necessary modules on either side must be removed, or, if the wall included a removable plug to enlarge the porthole, moved aside for replacement—only ~2m of lateral movement would be required to allow the pipes to be extracted into the primary side of the building.

The secondary side of the system, delineated in Figure 5.12 through Figure 5.15 by the dotted line labeled as such, is best described by following the Helium flow through the system.

The Helium flow enters the secondary side of the system through the upper interconnect pipe. The pipe bends upward and enters the high-pressure turbine (HPT). From the high-pressure turbine, the flow moves in the +x direction to the medium pressure turbine (MPT), and from the MPT, laterally again into the power turbine (PT), as shown by the arrows in the diagram below (the turbo-machinery has been schematically represented in these diagrams as simple cylinders with dimensions equal to the maximum envelope dimensions of the components).

Figure 5.16 Helium Flow from the Primary to Secondary Interconnect Pipe Through to the Power Turbine

From the power turbine, the Helium flows through the large pipe at the extreme +x end of the secondary side assembly, and down into the high-temperature / low-pressure ("hot side input") recuperator manifold. This manifold distributes the Helium to each of the six recuperator assemblies, as shown below.

Figure 5.17 Helium Flow From Power Turbine to Recuperator Modules

From the recuperators, the Helium flow is recombined in the cold-side exhaust recuperator manifold, and directed to the precooler (shown only by the rigid-element lines in the CAESAR layout diagram below). From the precooler, the flow enters the first compressor set, followed by the first intercooler, as shown below.

Figure 5.18 Helum Flow From Recuperator Modules Through to the First Intercooler

Once chilled by the first intercooler, the Helium flows through the second compressor, then the second intercooler, followed by the third compressor.

Figure 5.19 Helium Flow From the First Intercooler Through to the Third Compressor

After exiting the third compressor, the Helium passes through the third and final intercooler, and into the fourth and final compressor.

Figure 5.20 Helium Flow from the Third Compressor Through to the Fourt h Compressor

From the final compressor stage, the Helium piping drops down and enters the cold-side input manifold of the recuperator, where the flow is diverted into each of the six recuperator modules.

Figure 5.21 Helium Flow from the Fourth Compressor to the Recuperator Modules

Once through the recuperator heat exchangers, the Helium flow is again consolidated by the hot-side exhaust recuperator manifold, and flows to the primary side of the system through the lower interconnect pipe.

Figure 5.22 Helium Flow from the Recuperator Modules to the IHX Manifold, Through the Primary to Secondary Interconnect Pipe.

5.5.3.1. Stresses / stress limits

Description of CAESAR stress output data

[in appendix, table of pipe element stresses]

[multiple images of color coded stress plots]

5.5.3.2. Hanger locations / requirements—preliminary

Hanger types—preliminary CAESAR default type / spring specifications defined by CAESAR

[show hangers in images to show preliminary locations]

[hanger specification output from CAESAR in appendix]

5.5.3.3. Pipe lengths / weights

The masses of each of the individual pipe sections are calculated based on the dimensions of the piping, and totaled for each module. For simplicity and design conservatism, the weight of each pipe bend is calculated as if the bend was simply two straight legs, each with a length equal to the bend radius. Based on the layout proposed, the piping mass associated with each module is given in Table 5.5 below.

Table 5.5 Piping Total Mass for Each Module

[table of pipe masses for each module]

5.5.4. Module specifications

From the proposed layout, the individual module specifications can be determined. First, the total mass of each module's contents (components and piping) is determined based on the pipe masses given above, and the component masses defined in prior sections. The size of each module is also calculated based on the proposed layout and the design constraints and considerations of the system. Figure 5.23 is a diagram of the plant including the preliminary space-frames around each module (diagonal and cross braces are not shown).

[plant diagram with space-frames]

Figure 5.23 MIT PBR Plant Isometric View With Space-Frames Shown

Table 5.6 lists all of the modules required for the plant (with the exception of ancillary modules whose impact to the overall layout is minimal and thus have been left for future work (e.g. fuelling, waste management, inventory control, and secondary systems), along with the total component mass contained in each module, and the size of the space-frame required.

Table 5.6 Mass Breakdown, Space-Frame Dimensions, and Number Required Per Plant of Each MIT PBR Module

[table of module weights (not including space-frame) and dimensions]

5.6. Plant Layout / Construction

Based on this layout, a general description of the overall plant, and a preliminary plan for its construction were made. While detailed design of the plant structure and specific construction planning information is not possible at this stage, a preliminary design is necessary to define how these tasks should be performed in the future in keeping with the proposed modularity approach and design considerations. The first step in this part of the study involves the preparation of the site (primarily excavation), while the second step concerns the design and construction of the plant building and structure.

5.6.1. Site preparation

The plant design must be chosen to minimize the site preparation required. Given the wholely sub-grade placement of the reactor vessel and balance of plant (for accident case thermal concerns as described earlier), a substantially sized deep pit must be excavated. Given the layout proposed, the pit required would be roughly 20m deep and 48.5 x 29m (though this is dependent on the module removal strategy proposed, as defined in the following section). While this pit is well within the norm for many types of commercial construction (roughly the size excavation required for a 20,000sqft ($2.15x10^5$ m^2) plan area commercial building with a 4-5 level sub-grade parking garage), its cost must be taken into account in future design optimization and analysis of specific types of sites (e.g. low bedrock depth would require blasting or other methods for excavation and thus have a dramatically high excavation cost).

Once the pit is excavated, foundation supports would be installed. The determination of what types of sub-structure foundation supports are required is left to future work as it is both dependent on the specific plant location (type of earth, bedrock depth, seismic concerns). However, the ground pressure (~230kPa) of the system, effectively defined by the $5.4x10^4$ tons (~$1.97x10^4$ m^3) of concrete (assumed to have a bulk specific gravity of 2.75, including the steel liners and rebar structures) required for the 2m thick containment structure, is actually quite reasonable. (as compared to conventional structures [estimate of ground pressure of conventional buildings], it may be possible for the plant to be installed on a floating foundation (if direct bearing on bedrock is not possible) without significant pilings (other than what may be required to fix the position of the structure). In fact, given the total volume of the sub-grade portion of the plant (~$3.6x10^4$ m^3), the plant is actually quite buoyant (Positive buoyance at soil densities >$1.5x10^3$ kg/m^3). This may become a significant design issue, as if installed in a location where the soil is heavily saturated, the buoyant force may require ballasting of the structure to ensure stability. On the other hand, this may be advantageous as it would prevent settling of the structure in such an environment (reducing the need for pilings)—only future analysis will yield an answer.

5.6.2. Building design

Once the site is prepared, construction of the plant can commence. Given the goals for this plant design—rapid low cost construction, the plant building and structure have a significant impact on the design. The basic design of the structure is a reinforced concrete, prismatic structure containing two large, separate, vaults. The structure has an overall footprint of 53.5 x 43.5m. The floor, exterior walls, and roof are 2m thick, steel lined, internally reinforced 4000psi[147] concrete structures. This 2m thickness is based on the floor thickness of the AP600 plant (6 feet)[148], and enables transportation of the steel components of the walls using conventional trucks. Conventional construction of this type of structure would involve placement of interconnected, steel rebar assemblies (either fabricated onsite or shipped as modular units) in the floor, pouring the concrete for the floor. The walls would typically be constructed using similar rebar assemblies, surrounded by concrete using a continuous-pour, slip-form method. However, even if the rebar assemblies are mass-produced offsite, the time required to assemble the modules and cast the concrete is substantial. The proposed construction method to speed the assembly of the concrete structure is to use pre-fabricated rebar assemblies installed into leave-in-place steel liners—in effect, the resulting structure has an inner and outer steel layer, filled with reinforced concrete[149]. Using this method, the prefabricated modules are simply stacked, bolted together using conventional tools, and filled in a continuous pour fashion with the specified concrete blend. The material cost of this method is higher than the slip-form method, as the forms are left in place, but the time required is dramatically reduced[150]. Given the relatively low cost of the steel forms (composed of inexpensive low-grade steel plate), the material cost impact should be significantly outweighed by the reduction in labor and time required—especially if the concrete can be poured as each layer of wall-modules is added. An added benefit of this method is additional installation time and cost associated with adding a steel liner and/or exterior cover to the containment building is eliminated. The steel liners also provide a highly-dimensionally controlled surface for plant interior structures to be attached to, further reducing the onsite labor required (as interior structures will not need to be independently surveyed).

Based on a maximum module size of 2.5 x 3 x 18m, the floor of the structure would require 36 modules. A further 60 modules would be needed to line the sub-grade section of the structure. The above grade walls would require 36 modules (for an internal ceiling height of 9m above grade), plus 9 modules for the floor of the loading area. Thus the total modules is less than 141 modules. Each module (assuming 1.25cm thick steel walls and a 30cm spacing 3-D grid of 2.5cm diameter rebar) would have a shipping weight of roughly 3.5×10^4 kg, well within the transport capabilities of low-boy type tractor-trailer combinations. The roof of the structure could either be composed of these types of modules (45 would be required), or a combination of these modules along with long beams of steel or pre-stressed concrete.

Mounted to the structure on a steel reinforced niche in each the long (53.5m dimension, x-axis) walls are steel rails for a bridge crane system. A bridge crane, an example of which is shown in Figure 5.24, is a massive steel beam supported on each end by a rail dolly. One or more electrically powered winches are slung under the beam on movable trolleys, thus enabling 2-axis positioning of the winches (in this case, the whole beam moves in the x-axis, while the winch trolleys move in the z direction). Each of the vaults in the system has a separate bridge crane system. The cranes are used to lift the plant modules from transporter vehicles parked on the grade level loading area adjacent to each pit, lower them to the below-grade floor level, and position them as required. The cranes are also used to remove and replace modules for maintainence. Detailed design of the crane system is left for future work, as the span (39.5m) and load requirements (the PT-Generator module has a mass approaching 3×10^5 kg) are rather extreme. It is reasonable to assume that given current bridge crane capacities, these requirements can be met, if necessary by using multiple beams controlled as a single unit.

Figure 5.24 Example of Heavy Lift, Wide Span Bridge Crane[151]

The size of the two vaults is determined by the layout of the plant, along with the clearances needed to remove and replace the various modules. The primary side of the system requires a plan area of 17 x 8.5m (assuming the RV has two, 1m long stub pipes that connect it to the IHX manifold modules). Additional plan area to enable removal or replacement of the modules is not required, as the only module that cannot be simply lifted out of position is the lower IHX manifold. If it is necessary to remove this module, the upper manifold module would be removed and placed adjacent to the primary side systems, then the lower modules removed and replaced.

Design of the secondary side vault to include the required space for module removal is substantially more involved. The basic secondary side system has an envelope 15 x 17.5m (x,z) with an installed height of 10m. The required space for module removal is dependent on the strategy used. The most involved strategy would assume only lateral removal of all lower-level modules. Using this method, 10m of clear space in the –z direction would be required to remove the piping / heat exchanger modules that are underneath the turbo-compressor modules (highlighted in Figure 5.25)

Figure 5.25 [secondary side diagram highlighting these modules]

15 Meters of space in the +x direction would be required to remove the recuperator manifold modules (by translating them laterally in the +x direction), along with 3m of clearance in the +z direction to remove the +z row of recuperator modules (these modules highlighted in Figure 5.26)

Figure 5.26 [secondary side diagram highlighting these modules]

If the removal strategy is changed to permit removal of the top level modules (which would be removed and placed adjacent to the system, enabling access to he lower levels), the required clearances can be substantially reduced. If removal of the turbo-compressor modules is allowed, only 3m of clearance in both the +z and –z directions is required. Recuperator manifold failure (which in all probability would be rather rare compared to maintainence or failure necessitated removal of other systems) would require the power turbine / generator module to be removed. Given the enormous mass of this module (~2.9x105 kg with simplified space-frame, potentially 3×10^5 kg with additional bracing and ancillary components) relative to the other modules, and potential sensitivity of the generator and power turbine to damage, either 15m of clearance in the +x direction would be provided, or removal would be required.

With the exception of the lateral removal strategy, additional floor area is required to place the modules removed for access to lower level modules. If removal of the PT/Generator module is possible, the secondary side of the system requires an area 25.5 x 32.5m. This area is comprised of the 15x17.5m plant, an additional 7.5m of clearance in the z dimension for lateral removal of the recuperator elements (to reduce the need to remove the upper modules), a 10x20m area adjacent to the plan in the +x direction for placing the removed upper modules, and a 0.5m space between the secondary plant modules and the wall separating the two vaults (1m thick wall). These areas are shown schematically in Figure 5.27.

Figure 5.27 [loading, stacking, plant area schematic diagram]

The modules will be installed, removed, and maneuvered using an overhead bridge-crane. To reduce the need for external equipment for construction of the plant, the crane would be installed before installation of the roof of the plant. This crane would span the sub-grade portion of the building, and an additional 7.5m wide (z-direction) grade-level loading platform adjacent to each of the vaults (as shown in the above diagram). The semi-trailers used for module transport would be backed into the building through side doors, and the module lifted from the trailer using the bridge crane.

Based on this design, and the 2m wall thickness specified earlier, the plant has an overall footprint 48.5 x 36.5m (if the bridge crane were unable to rotate the modules before setting them down temporarily, the footprint would grow to 53.5 x 43.5m). For a 10-module group of plants, a row of 5 modules would have a footprint of 48.5 x 182.5m. Given a 30m spacing between rows (for transporter access to the loading door of each of the units), the overall 10 module footprint would be 127x182.5m. The AP1000 power plant design has an estimated footprint of 156x100m[152], only slightly smaller than the MIT PBR 10-module plant footprint, and given the large buffer zones required around nuclear power plants, the additional 30m in each direction should be inconsequential. A comparison of these two plan areas is shown in Figure 5.28.

Figure 5.28 [comparison diagram of PBR vs. ap1000]

The two interior vaults provide the necessary containment volume for the system, in the event of a loss of coolant accident. In this respect, the MIT PBR systm requires minimal containment compared to conventional PWR and BWR systems. Conventional PWR and BWR reactors need high strength pressure containment buildings to contain the stored energy of the liquid phase coolant (when it rapidly converts to vapor in a loss of pressure accident)[153]. The MPBR Helium coolant does not undergo a phase change (with its associated volume change) if pressure is suddenly released. Since the overall coolant volume is ~$1.2x10^4$ m^3 of Helium (at STP). The internal volume of the MPBR building is ~$3.2x10^4$ m^3 (the primary side vault is ~$1.3x10^4$ m^3). In a worst case primary and secondary blow-down (assuming adiabatic expansion of the Helium and a worst case bulk Helium temperature of 1173°K, the system contains ~$4.65x10^3$ m^3 (at STP) of Helium. Distributed through the reactor volume, this will raise the pressure of the containment by approximately 30kPa (~4.4psi). The temperature of the released Helium is not a factor, as purely adiabatic expansion of the Helium from 8MPa to ~0.1MPa would reduce its temperature to <300°K. Thus in a blow-down accident, the building must only withstand 4.4psi internal pressure at normal ambient temperatures. By comparison, in the case of a PWR system operating at ~700°F, 2500psi, if the pressure is suddenly released, the energy in the coolant would flash evaporate ~60-70% of the water. Assuming the PWR system has a similar containment volume, and ~40% the coolant volume, the PWR system would have to withstand a pressure pulse of almost 0.28 MPa (~40psi). While this pressure would slowly decrease as the vapor condensed, the structure would, for a short time, be exposed to a pressure 9 times greater than the blow-down pressure in the MIT PBR system.

6. Results: Summary and Discussion

The proposed design presented in the previous chapters achieves the goals put forth for this study, in that it is a preliminary system design that takes into account the cost, complexity, and design goals proposed for an enhanced modular nuclear power system. The modularity approach described is a significant step beyond conventional approaches to nuclear power system designs, and, when applied to future work, and taken to its logical conclusion, should enable the construction of a system at significantly lower costs than currently possible.

The design considerations described in detail, along with descriptions of the various engineering and code compliance constraints, when applied using the design and analysis method presented here, provides the necessary guide for future, more detailed design work on this system. Prior to this study, work on the MIT PBR system has proceeded along two paths—detailed design and analysis of individual elements (e.g. fuel performance, neutronics, etc), and system-level analyses of specific design concerns (e.g. dynamic models of the system to address control issues). Other than the initial MIT PBR study, integration of the various elements to determine the proper method to proceed on the design as a system has not been addressed. The information presented here attempts to put the design in context by establishing the system goals, design considerations and constraints needed to achieve these goals, and a method for integrating all the past analysis into a coherent approach to meeting these goals.

This method—determine system level constraints and design considerations, apply individual component and reference system designs, model the system as a real-space system (taking into account the end-to-end effects of design choices, dimensions, weights, etc), and iterating that design to yield a workable (within the applied constraints) design, is the most significant result of this study, as it provides the aforementioned guide to follow-on analysis. Too often in the design of complex systems, a bottom-up approach is used without regard for the overall system goals—detailed design of various parts of the system proceeds before the effects of the individual design choices of each part on the ability of the whole system to meet its goals can be determined. By providing a top-down guide, this proposed method, and the preliminary design presented here, should help to prevent component level design choices that would negatively affect the ability of the system to meets its goals from being made.

6.1. Proposed Potential Design Changes and Future Work

In the course of this study, areas where potential modifications to the reference plant and component designs could result in increased performance (in terms of the system goal—reduction in delivered energy cost) were found. These areas, along with other areas where additional work is required to increase the detail of the design, should be addressed in future work on this project.

6.1.1. Cycle Parameters

The first area where potential changes could be made to the reference designs in order to better achieve the system goals involves various aspects of the reference plant thermodynamic cycle, and their affects on the efficiency and cost of the plant. To often in past work on this system have the plant overall efficiency and output power been the driving factors for optimization. Given the primary goal of the system to reduce the power generation cost, optimizing the system to maximize efficiency and output power may be counter-productive. Since the majority of the cost associated with generating power in a nuclear plant is the amoratized capital cost of the plant equipment, with the operation and maintainence of the equipment as a singnificant secondary cost, potential cycle changes that result in a lower cost, simplified plant, albeit at the expense of system efficiency and thus net power output, may result in a more economical design.

6.1.1.1. Number of Intercoolers

The current reference system uses a 4-compressor, 3-intercooler cycle. Reduction in the number of intercoolers and compressors would be one design change that should be analyzed further—in terms of its affect on the generated energy cost. Prior analyses show that reducing the system to a dual-compressor, single intercooler design would result in a reduction in overall plant efficiency from 50% to 48%[154]. Such a modification could, given the cost of the intercooler assemblies, the additional cost associated with multiple compressors (additional shafts, bearings, seals, volutes, etc), and, as illustrated in the piping layouts shown previously, the vastly more complex piping, potentially reduce the capital cost enough to compensate for the loss in revenue.

6.1.2. Control System / Load Following Design Changes

The reference system uses a series of bypass valves, along with inventory control systems to provide the necessary level of load following. The individual components of the system are also designed to ensure adequate system efficiency at a wide range of system loads. For example, in order to achieve adequate performance at low load levels, the compressor design would be changed to a 5 stage centrifugal design, as opposed to the 8+1 axi-centrifugal design, also analyzed in the reference design[155]. The centrifugal design offers substantially higher off-design performance compared to the axial system, as it does not have nearly the level of succeptability to compressor surge at low flow levels (to perform adequate load following, the system pressure ratio is kept relatively constant, while the base pressure of the system is reduced—compressor surge occurs when the flow rate is inadequate for a given design relative to the pressure ratio demanded). However, the centrifugal design requires a lower rotational speed (which increases the diameter, mass, and modularity issues) of the driving turbines, and is significantly larger than the axial design. The larger compressor, along with the complex internal flow path of a multi-stage centrifugal system, result in a compressor assembly that is significantly more massive than the axi-centrifugal design. Based on these issues, it may be possible to approach system load following in a way designed to reduce system complexity and cost.

6.1.2.1. Shallow Throttling

Since the generally accepted notion of how the MIT PBR plant would be sited is a multi-module plant (5-10 individual MIT PBR plants at a common site)[156], it may be possible to combine shallow throttling (which does not require anywhere near the design changes associated with deep throttling) with shutdown of one or more of the individual modules to perform load following—for example, a 10 module plant, each with a 10% load following capability could "digitally" load follow down to ~9% by simply shutting down modules. This method could be done literally—full shutdown of individual modules (which would probably only be effective if the cycle fatigue life of the system was extremely high and long duration (e.g. day/night) load cycle), by the incorporation of a hot-standby mode where the system inventory is maintained and the plant operated at a very low power (<10%), inefficient standby mode, or using a cooled bypass temporary shutdown method.

6.1.2.2. Cooled Bypass Load Following

Given the low fraction of the energy cost associated with the nuclear fuel itself, there exists an interesting potential to provide temporary load following using a cooled bypass on the power turbine. Rather than alter the cycle parameters for throttling, by simply diverting flow around the power turbine through an auxillary heat exchanger (similar to the pre-cooler), the generated power can be changed, with the excess being "wasted." Such a system could eliminate all of the systems normally needed for load following, and reduce the inventory control system use to solely startup and shutdown Helium storage. Given the conventional use of nuclear power as base-load generation (combined with fast-reacting gas turbine generators for rapid load following), not only may deep throttling be unnecessary from an economic standpoint, but a waste-power throttling method may be sufficient for the load following required. Further analysis is necessary to determine not only the design of such a system, but more importantly, the level of throttling required, and the cost of the additional fuel required to operate the plant at full power during these times.

6.2. Other future work

Other future work that needs to be performed on this system

Spaceframe integration, tolerance stackup etc (what jeff was going to do)

Common component designs

below grade RV vs. above grade RV

[FUTURE WORK—change port locations on IHX for thermal expansion concerns—increased U-pipe length?]

automated welding of vessel on site

PCIV design

circulator design\

component supports vs. system layout, displacements etc.

excavation design w.r.t. different ground / bedrock data

substructure foundation supports

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