Manufacturability Assessment of the Navy Integrated Power and Energy Corridor (NiPEC)

by

Emily Alice Curran

B.S. Chemical Engineering, Auburn University, 2010

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of

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Authored by: Emily Alice Curran
Department of Mechanical Engineering
May 10, 2024

Certified by: Julie Chalfant
Research Scientist, Thesis Supervisor

Certified by: Michael Triantafyllou
Professor of Mechanical and Ocean Engineering, Thesis Supervisor

Accepted by: Nicolas Hadjiconstantinou
Chairman, Department Committee on Graduate Theses

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ABSTRACT

The growing electrical demands of sophisticated naval vessels necessitate the development of advanced power distribution methods. With the U.S. Navy's shift towards fully electric ships, exemplified by the Zumwalt class destroyer and the forthcoming DDG(X), the demand for electrical power on future ships is projected to exceed 100 megawatts. To meet this challenge, the Massachusetts Institute of Technology (MIT) Sea Grant Program's Design Laboratory, in collaboration with the Electric Ship Research and Development Consortium (ESRDC), is developing the Navy Integrated Power and Energy Corridor (NiPEC). This innovative system is designed to transform power management in all-electric warships through the use of modular units for energy management and power electronic building block (PEBB) technology.

Substantial groundwork has been established on the components and initial configurations of NiPEC. The collaborative team is working to develop not only a more robust power distribution system, but also an infrastructure that is simpler to construct, install, and maintain onboard. A next step of development focuses on evaluating the design's manufacturability and the feasibility of manufacturing and installing the system aboard ships. This study explored the principles of Design for Manufacturability (DFM) and Design for Production (DFP) and then defined how these concepts apply to the Power Electronic Power Distribution Systems (PEPDS) and the NiPEC project.

By leveraging the principles of DFM and DFP, this thesis proposes criteria for assessing the overall manufacturability of the NiPEC and its subsystems. By establishing criteria based on the principles of DFM as it pertains to NiPEC and naval applications, system designs may be objectively evaluated throughout the design phase. This thesis applies the proposed evaluation criteria to current NiPEC cooling system designs to illustrate the application of these criteria. This evaluation also highlights the trade-offs between manufacturability and other key metrics such as cost, reliability, and maintainability. These criteria may be useful in evaluating the design and functionality of systems and subsystems, steering design choices towards solutions that are not only technically sound, but also practical for manufacturing and installation. This approach ensures the alignment of the NiPEC system with the evolving needs of naval power management, and further enables its successful implementation on future all-electric warships. With this evaluation, this thesis begins to bridge the gap between the current state of research and the practical deployment of a next-generation shipboard power distribution system.

Thesis supervisor: Julie Chalfant
Title: Research Scientist

Thesis supervisor: Michael Triantafyllou
Title: Professor of Mechanical and Ocean Engineering

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Chapter 1

Introduction

In 2020 the United States Navy (USN) accepted delivery of its first all-electric warship in DDG 1000, the USS Zumwalt. Following the design and construction of the Zumwalt destroyer all-electric ship class, future USN ship development is expected to have even further increased electrical demands. Future warships of class DDG(X) will have all electric drives as well as other high-volume electrical loads such as detection and weapons systems. These ships must also support increasing electrical demands throughout the life of the ship in order to facilitate future modifications and modernization. In the 2019 Naval Power and Energy Systems (NPES) Technology Development Roadmap, Vice Admiral Moore, Naval Sea Systems Command, is quoted: "One of the things that is really important for us as we build these platforms, is to make sure that platforms have enough space, weight, and power so that you can modernize and adapt to future threats [1]." This emphasizes the importance of today's naval ship design solutions being adaptable and robust enough to support warfighter needs of the future. The shipbuilding community can only further improve the technology given to warfighters as long as the ship infrastructure, especially the power system, is built to meet these growing requirements.

1.1 Motivation

The major drivers of future naval ship power requirements are advanced sensor and weapons, advanced electric propulsion, survivability, unmanned systems, communications and cyber

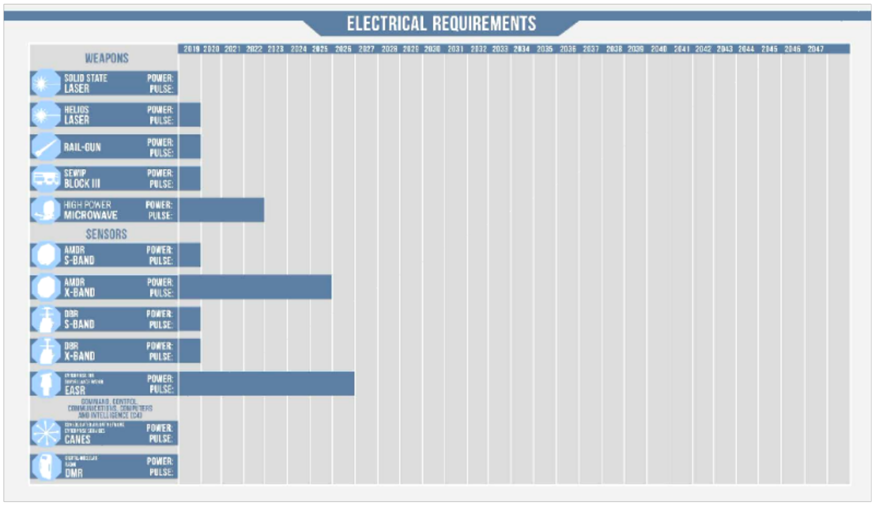


Figure 1.1: NPES Shipboard Electrical Requirements [1]

security, and flexible ship interfaces of modularity. As ship detection and weapons systems evolve to keep up with current technology and increasing threats, future ship power requirements will increase further. Furthermore, the resulting electrical power requirements affect other future ship requirements that must be considered, such as control, thermal management, and cooling systems. These ancillary systems also create challenges for future ship development with changing design requirements as technology develops [1]. Figure 1.1 lists the projected electrical requirements that contribute to the increase in power requirements. This illustrates the requirements through 2019, but it is reasonable to project requirements to increase further over the lifetime of the ship. These requirements may even increase before the next-generation USN ship, DDG(X), is designed and constructed. These newer systems, such as directed-energy weapons and advanced radars, are also high-power pulsed systems. This means a large burst of power is required as part of the system startup and/or operation that traditional ship power systems are not designed to support [2]. Figure 1.1 illustrates the pulse requirements of the electrical systems projected for future use on USN ships. Although many of these systems have been added to existing ships, this required backfitting energy storage and control solutions to support power pulses. The goal for future ships is to have a more advanced integrated power system that includes this functionality to support all electrical loads and propulsion on board. This further illustrates the need for an improved advanced ship electrical system.

In addition to increasing electrical power, the Navy is looking for opportunities to further improve fuel efficiency and reduce logistical requirements for its ships. An integrated power system that includes electric prime movers improves energy efficiency and, therefore, improves fuel economy. This improves the operational range of the ship and saves the Navy money over the life of the ship, both of which are significant motivators for the USN to pursue advanced electric ships [3]. The USN is motivated by both the growing technological requirements and fiscal constraints to seek the most technologically advanced all-electric ships possible.

One of the most critical elements of the ship infrastructure, both from a construction and operational perspective, is the power distribution system. To support the development of future all-electric ships, the Office of Naval Research (ONR) established the Electric Ship Research Design Consortium (ESRDC) developing the next-generation ship power solution, Power Electronic Power Distribution Systems (PEPDS). Ships of this future class are expected to have power loads greater than 100 megawatts and require complex systems that include propulsion, storage, and adequate support for directed energy weapons and high-energy sensors, as described above. ESRDC is working to develop not only a more robust power distribution system, but also an infrastructure that is simpler to construct, install, and maintain onboard. Another desired aspect of a future power system is flexibility. Flexibility is defined as the speed with which technology can be delivered to the fleet and the speed with which changes and modifications can be made, carrying the definition of flexibility throughout the life cycle of the ship. One method to achieve this goal is to create a modular system that is easily installed and modified [1]. A modular system also has the potential to improve the installation process of ship power systems. Installing traditional shipboard electrical cabling is a labor intensive and time-intensive process that costs a great deal of time and money for each ship construction project. Running bus tie cables shipboard can also cause injuries due to the weight of the cables being routed and due to the fact that much of the work is overhead. These injuries cost the ship builder even more time due to lost work. A novel approach to shipboard power delivery is to depart from the traditional cabling approach and pursue a modular system that is installed and connected one complete module at a time and extends the length of the ship, eliminating the need for traditional electrical bus tie cabling.

1.2 Power Electronic Power Distribution Systems

PEPDS represents a revolutionary approach to power and energy management for shipboard systems. The goal of PEPDS is to surpass traditional ship energy and power technology by adding control to the system so that it is all-encompassing by capitalizing on recent advances in energy distribution systems.

What makes this new power system and methodology especially valuable in ship design is the scalability to various sizes of ships and the ability to deliver both AC and DC power, providing a universal solution. This system can integrate various power sources, such as turbine generators and uninterruptible power supplies, and deliver energy to a wide array of loads, including motors and lasers, which will meet the requirements of the high-pulse loads previously discussed. It involves the use of Power Electronics Building Blocks (PEBBs), which can be programmed with applications for specific functions, allowing for manual override during maintenance or training.

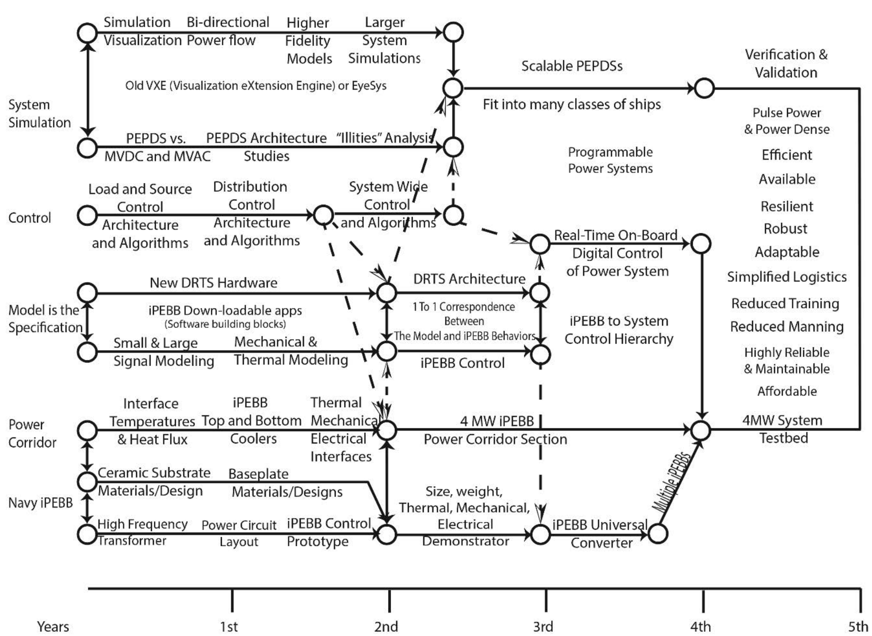


Figure 1.2: PEPDS Five Year Plan [4]

"PEPDS is far more than an energy and power system [4];" it is a new concept in energy distribution that encompasses complete control over the power and energy of the ship. It utilizes a combination of installed and inherent storage solutions to provide both point and distributed storage. It also offers transient control and active filtering, ensuring a quality power supply to all types of loads. Its advanced control capabilities surpass those of the Tactical Energy Management (TEM), allowing it to cater to any power requirement, regardless of whether it is alternating current (AC) or direct current (DC). It automatically adjusts the power and control interfaces for each specific requirement, providing customized energy solutions with high-quality conditioning and filtering. Its state-of-the-art medium voltage DC (MVDC) and AC (MVAC) capabilities include sophisticated energy management algorithms that operate much faster than traditional electrical distribution systems.

The PEPDS project has five program areas for focused research and development over a five-year plan: Navy integrated Power Electronics Building Block (iPEBB), Power Corridor, Model is the Specification, Control, and System Simulation [4]. The development plan is shown visually in Figure 1.2. The overall goal of this program is to be a scalable ship power solution that will support higher voltage, have a modular design, and be simpler to manufacture, install, and maintain.

1.2.1 Navy Integrated Power and Energy Corridor

In support of the future naval ship power system, the Massachusetts Institute of Technology (MIT) Sea Grant Design Laboratory developed the Navy integrated Power and Energy Corridor (NiPEC) concept, one of the five major areas of the PEPDS project, in support of the ESRDC efforts. NiPEC incorporates the entire power distribution system of a ship into a modular entity, supporting the goal of increased system flexibility. This encompasses all electrical components on the ship with the exception of power generation and final loads into a corridor. Figure 1.3 illustrates the concept of a power corridor that integrates several critical functions, distribution, conversion, isolation, and storage of the main bus power, into a single cohesive entity. This integration presents multiple advantages, including cost savings, improved survivability, and a more efficient ship arrangement. Each power corridor, designed to be capable of handling up to 20 MW, houses essential components such as bus cables, power converter stacks, interface junction boxes, and circuit breakers. The NiPEC is designed to be modular with maximum plug-and-play capability. The corridor is made up of redundant segments that can be customized to a space according to specific needs. This approach maximizes the value in modularity while still meeting the specific needs of the sources and loads interfacing with each NiPEC segment.

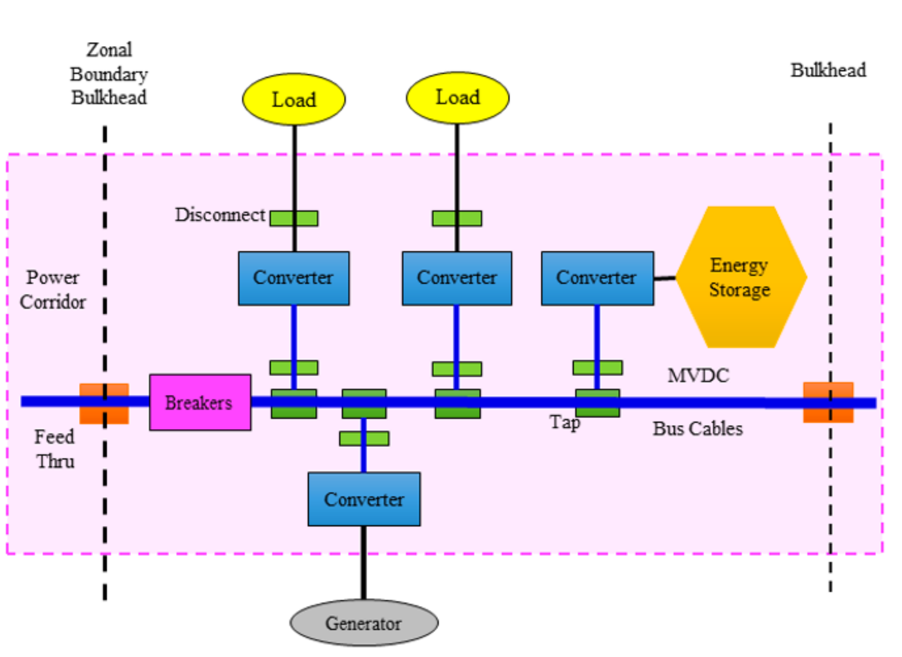


Figure 1.3: Power Corridor Elements [5]

To support power conversion and energy storage within the corridor, power electronics building blocks (PEBBs) are used. The current corridor design specifically utilizes the iPEBB, a modular, identical, programmable, and sailor-carriable power electronic building block that is an improved version of earlier PEBBs. iPEBBs are integral to creating a more flexible and uniform power distribution system. Their standardization not only simplifies the construction and maintenance of naval ships, but also leads to cost reductions in installation, supply chain management, and training.

Furthermore, portability and ease of replacement of PEBB units contribute to the resilience and reliability of the system. PEBBs are stackable in a manner that allows them to be added to a NiPEC segment to meet the segment-specific power requirement [6]. The PEBB design and integration into the corridor allow the programming of the corridor to provide the desired universal power solution. The overall design of the corridor prioritizes survivability through geographical separation of redundant capabilities and colocation of key functional units.

The design of the corridor with programmable PEBBs also aims to reduce construction and life cycle costs, improve maintenance efficiency, and support future all-electric navy ships [6]. This is possible due to the modular design with repeatable parts, as well as the timing of installation. Each segment of the corridor will be installed early in the ship construction sequence as a single unit. This creates opportunities for both cost and schedule savings compared to the traditional ship power distribution system. Modular design and redundant hardware are designed to improve the design process with fewer components and the ability to integrate early in the design as well as maximizing the use of repeatable parts and processes. The corridor is treated as reserve space early in the ship design process. This ensures sufficient space for the corridor while also minimizing the complexity of integration due to repeatable segments and less interference work, which reduce construction time and cost [4].

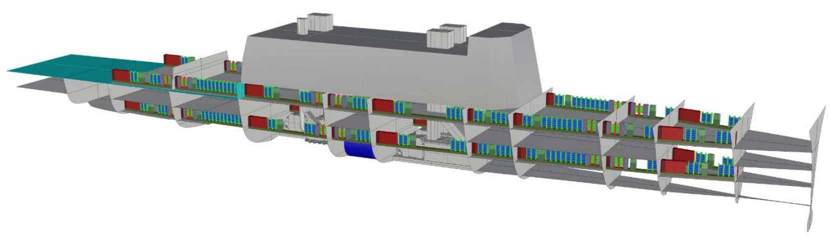


Figure 1.4: Whole Ship Corridor Concept [5]

The corridor design will also reduce installation labor by eliminating the need for traditional bus cable routing throughout the ship. Figure 1.4 shows a rendering of the corridor installed on a notional ship. The corridor is arranged longitudinally, running the length of the ship on two different decks on both the port and starboard sides. The distribution in the ship ensures survivability, with no loss of power in one compartment removing power from the entire ship. This highlights the benefits of modularity while being redundant; the NiPEC segments are repeatable, but can be customized to meet the needs of each space.

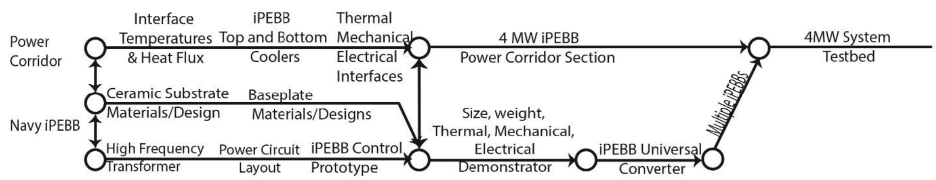


Figure 1.5: PEPDS Power Corridor Development Plan [4]

1.2.2 Previous Research

The MIT Sea Grant Design Laboratory has developed the initial concept of a modular power corridor system to meet future USN ship power and electrical distribution objectives. So far, solutions have focused on the ability to meet power requirements, as well as improved design and construction objectives [7]. Figure 1.5 shows the corridor-specific portion of the five-year PEPDS plan highlighting the lines of effort focused specifically on the power corridor, such as coolers and interfaces. The number of elements required for the development of NiPEC further highlights the complexity of the corridor. Independent research has been conducted on each of these areas of effort with the goal of combining them into a composite solution that meets the design and operation objectives of the entire consolidated system.

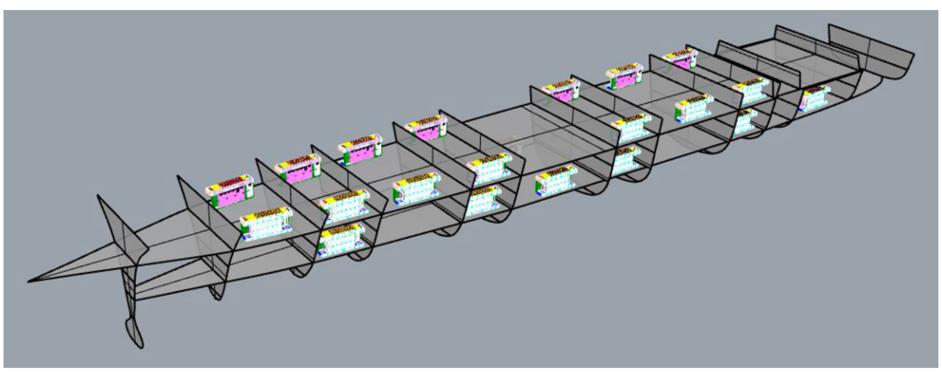


Figure 1.6: Power Corridor Ship Layout - Aft Perspective [8]

Previous work has been done investigating a proposed ship layout within a notional ship. Figure 1.6 shows a visual representation of a proposed ship power corridor arrangement. An individual NiPEC segment defined from the current research provides the starting point used in this thesis. These segments have not yet been evaluated as a composite unit, to include all subsystems, to manufacture, test, and install shipboard.

Research has also been conducted to evaluate the optimal method for providing cooling to the NiPEC segments on a notional ship. The current solution based upon the heat generated from the Navy iPEBBs and other internal components in each segment utilizes a closed-loop liquid cooling system. This is the assumption used in this thesis and serves as the example system studied to assess the manufacturability of a NiPEC segment and its support systems.

In this thesis, the current research solutions for a working model of a single NiPEC segment and supporting cooling system are used for evaluation. As further changes and improvements are made, this will impact the assessment of the manufacturability of the NiPEC segments and support systems.

1.2.3 Off-hull Testing and System Redundancy

When evaluating the ease of NiPEC manufacturing and installation, two additional factors to consider are the ability to test the system off-hull and the level of redundancy built into the system. These elements, two of many critical system performance parameters, of the design are important to meet the overall objective of improving the construction process and life cycle cost. The consideration of NiPEC testing and redundancy further develops the assessment and provides a working example of trade-offs that exist between manufacturability and other performance parameters.

Importance of Off-hull Testing Current practices in ship electric systems predominantly involve component-level testing prior to installation, followed by comprehensive system testing once integrated onboard, which is both time-consuming and costly [9]. To mitigate these challenges, NiPEC segments are designed to undergo extensive off-hull testing and are delivered as composite units. This strategy maximizes testing flexibility and minimizes installation time during ship construction, substantially reducing the risks and costs associated with on-hull testing and subsequent modifications or repairs. Such proactive testing ensures that potential issues are addressed prior to integration into the ship's more complex systems, where faults could have far-reaching and severe implications. Furthermore, by ensuring that ship systems are near operational upon installation, this method significantly cuts down on the resources needed for shipboard integration, testing, and rework.

System Redundancy as a Critical Factor In addition to testing, system redundancy is a crucial design consideration that enhances the reliability and operational safety of ship systems, especially in mission-critical applications. Redundancy ensures that alternative operational pathways are available in the event of a component failure, thus maintaining system functionality and safety. The design and integration of redundancy must be carefully balanced with manufacturability to avoid unnecessarily complicating the system. Effective redundancy not only supports operational dependability but also aligns with manufacturability by potentially simplifying maintenance and reducing life cycle costs.

Both off-hull testing and system redundancy are integrated into the NiPEC manufacturability assessment to create a robust framework that supports the NiPEC's strategic objectives. This dual consideration facilitates a nuanced assessment of trade-offs between ease of manufacturing and comprehensive system reliability, guiding the development of support systems that are not only manufacturable but also equipped to handle operational demands efficiently. The implications of these considerations were explored in this thesis, highlighting how they influence the trade-offs between system manufacturability, reliability, and operational efficiency. These two parameters represent a subset of many other ship performance parameters that must be considered when fully evaluating a system. This study describes a process that may be replicated for any chosen system performance parameter.

1.3 Problem Statement

Significant amounts of research have been done on the individual components of the NiPEC and the initial configuration. The next step in development is to determine the feasibility of the NiPEC design with respect to manufacturing, testing, and shipboard installation. A composite NiPEC design that encompasses all the constituent parts in a single segment must be evaluated for ease of manufacturing and maintainability throughout the life of the ship. Furthermore, manufacturability must be considered alongside other system performance parameters such as cost, testability, and redundancy. Evaluation of NiPEC system and subsystem design is incomplete without these considerations. This thesis aims to bridge the gap between current research solutions and a feasible ship construction solution in support of the next-generation ship power distribution system.

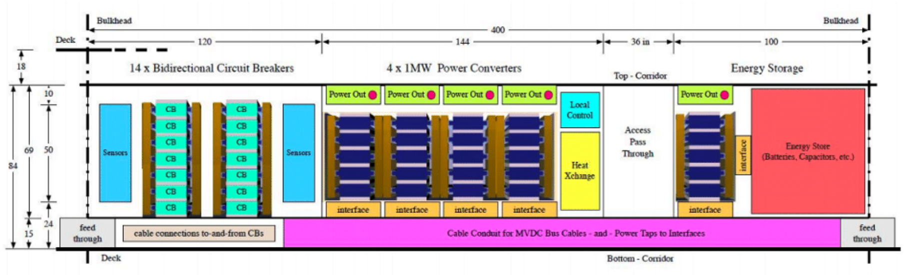


Figure 1.7: Nominal Power Corridor Section [6]

Figure 1.7 shows a visual representation of the components that make up a single NiPEC segment based on current research. This model will be the starting point for this thesis. This thesis assumes the use of both iPEBBs and PEBB 6000s as well as a water cooling system for thermal management. All ship parameters are those of the notional ship [10].

1.4 Thesis Outline

The goal of this thesis was to define a process by which the NiPEC and associated support systems may be evaluated for manufacturability with the goal to improve NiPEC manufacturability overall. The assessment process must be capable of evaluating elements of manufacturability as well as consider trade-offs that exist and guide in design decision making.

Chapter 2 explains the philosophies of design for production and design for manufacturability and demonstrates how they are applicable to the NiPEC development. This highlights how system design has the greatest opportunity for savings in cost and work volume early in the design process. This justifies why a manufacturability assessment is important in the current stages of NiPEC system and subsystem design.

In Chapter 3, a framework for assessing NiPEC manufacturability is laid out based upon the principles described in Chapter 2. Specific assessment criteria and weighting factors are defined, and their relevance to the overall manufacturability of the system is explained. Recommendations for additional performance parameter evaluation are addressed as well as an explanation of how to apply these criteria to other systems and factors to aid in design decision making.

Chapter 4 demonstrates the manufacturability assessment process by completing a case study evaluation of two current NiPEC cooling system design variants based on the process described in Chapter 3. This case study demonstrates the process of describing, scoring, and comparing two different systems. This serves as a demonstration of a process that may be repeated to compare any system variants in order to better aid in design decisions that support both technical and manufacturability objectives.

Chapter 5 provides conclusions of the work carried out in this research and recommendations for future work to further pursue the development of NiPEC as both a technical and feasible solution for future ship power solutions.

Chapter 2

Manufacturing & Production Design Considerations

In any manufacturing context, a good design is not only one that meets technical and performance requirements, but also one that may be manufactured and maintained adequately. In shipbuilding, this translates into a successful construction phase and life cycle support. Without adequate consideration for production and manufacturing early in the design process, ship construction can be more costly in both budget and schedule. Maintaining and modernizing may also prove more costly. These design considerations impact the industrial community's ability to create components to build the ship and impact how the ship systems are tested and maintained.

2.1 Design for Manufacturing

Manufacturability describes the degree to which a product can be easily manufactured. Design for Manufacturing (DFM) evaluates this in the design process to achieve maximum manufacturability of a product or component. DFM is a sustainable approach to drive the design process from suitability to low cost by incorporating the philosophy into the early design process. It requires ongoing dialogue between designers and manufacturers to ensure that there is continuous feedback in the design development process.

2.1.1 DFM Philosophy

DFM is a product development approach that focuses on simplifying the design of a product to optimize its manufacturing process. This concept is key to ensuring that a product can be manufactured efficiently, at the lowest cost, and with the highest quality. The most effective cost reduction is seen by focusing on the design process by implementing three fundamental guidelines: minimizing the design part count, creating modular assemblies, and removing extra fastners and connections. By integrating these principles, DFM aims to reduce the complexity of the manufacturing process, reduce production costs, and improve product reliability [11].

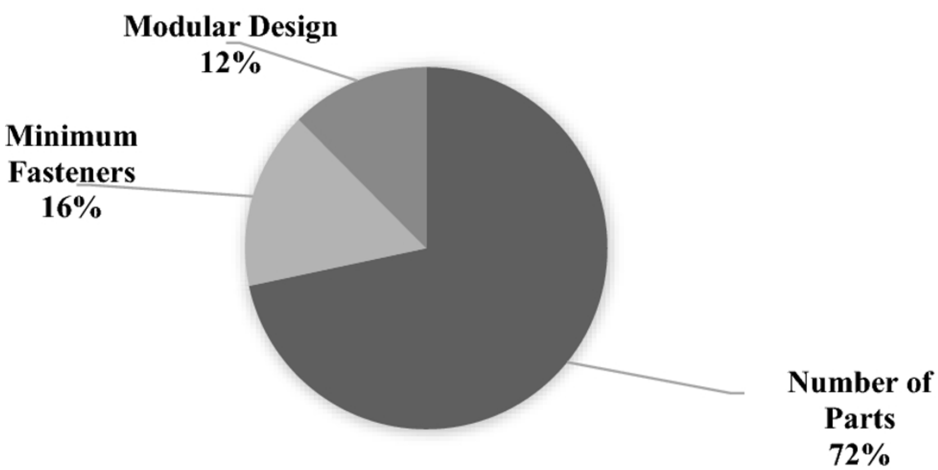


Figure 2.1: Manufacturing to reduce cost[11]

Recent studies on part count reliability analysis create tension with the traditional understanding that fewer parts are usually optimal for reliability. In more recent evaluations of power electronics systems, more parts were found to have been added, but the stress of all parts was reduced. This may actually increase reliability, although, contrary to the traditional mindset that the lower the part count, the better [4]. This is important to acknowledge and consider when evaluating part counts with respect to manufacturing. Although the reduction of the number of parts in the design is shown in Figure 2.1 to be a major area for potential cost reduction, this cannot be the only consideration. An upfront cost reduction that creates less robustness in a system or less modularity could result in greater life cycle costs in repairs and mondernizations.

Although reducing the total number of parts in a design is the greatest contributor to cost reduction by a significant margin, Moeeni et al [11]. found that the next two most influential factors are minimizing fastners and utilizing a modular design. Fastners result in an increased assembly time, so reducing the number helps minimize cost and improve quality. Modular design allows the use of common components and reduces assembly cost. Modular designs also simplify testing, maintaining, and modernizing due to the use of standard parts. However, modularity does often lead to an increase in fastners, so fastners are often the limiting factor. This again highlights the complexity of the process with no one-size-fits-all solution. It is important that each of these factors is monitored throughout design decisions to influence overall cost.

2.1.2 DFM In Ship Design

In the context of shipbuilding, DFM plays a critical role in streamlining the complex and resource-intensive process of constructing vessels. Shipbuilding involves numerous components, extensive labor, and significant material requirements, making efficiency in manufacturing paramount. Applying DFM principles to shipbuilding leads to several key benefits.

By reducing the number of unique parts and standardizing components, shipbuilders can simplify construction processes, reduce inventory requirements, and facilitate easier maintenance of ships. Standardized parts also allow greater flexibility in the procurement of materials and components, which is crucial given the global nature of the shipping industry.

Modularization in shipbuilding, a key aspect of DFM, involves constructing sections of a ship or system at different locations. These sections, or modules, are then assembled to form the final vessel. This approach not only speeds up the construction process but also allows for specialization in different parts of the ship, improving overall quality and efficiency.

DFM also encourages the design of ship components and systems in a manner that simplifies assembly. This includes considerations for access during construction and maintenance, reducing the complexity and time required for these processes. Efficient assembly is particularly important in shipbuilding due to the sheer scale and complexity of the vessels. These DFM tools can reduce not only the manufacturing costs, but also the life cycle costs of the ship.

2.2 Design for Production

Design for Production (DFP) is an approach in product design and development that emphasizes designing a product or component with a strong consideration of the manufacturing process. This approach considers a good design one that can be easily produced [12]. The goal of DFP is to be more cost-effective, since products are easier to produce. Producibility is one of many "-iliities" used to describe the degree to which a product or component is designed and arranged in such a way that it can be produced timely, economically, and with high quality. Like DFM, DFP requires designers to have extensive knowledge of the manufacturing process or processes to ensure product compatibility.

2.2.1 DFP Philosophy

DFP is a philosophy that emphasizes the integral relationship between design and manufacturing processes. The goal is to design to reduce production costs to a minimum, but still meet operational and safety requirements as well as reliability and efficiency [13]. The core tenet of this philosophy is that most product-related costs are committed in the early stages of design [12]. Therefore, by considering production aspects early in the design phase, significant cost savings and efficiency improvements can be achieved. This approach is rooted in the understanding that decisions made during design have far-reaching implications on manufacturing complexity, material choice, time requirements, and ultimately the cost and work volume involved in production. These early design choices have lasting effects on life cycle costs.

Figure 2.2 shows the effect of design decisions on life cycle cost over the course of a project. This highlights the opportunity for savings found early in the process. In the initial design stages, the incorporation of DFP principles involves a thorough analysis of the producibility of a product. This involves considering the limitations and capabilities of the production techniques. In doing so, DFP reduces the complexity and number of operations required in manufacturing, leading to a reduction not only in cost, but also in work volume. Work volume, in turn, provides further opportunity for cost reduction.

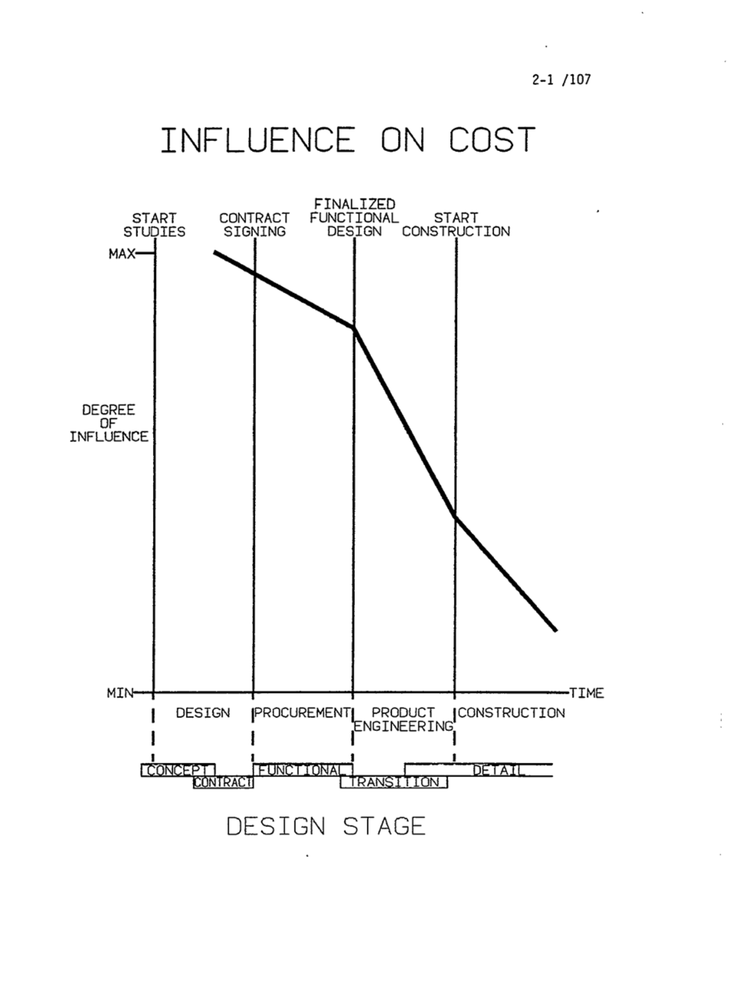


Figure 2.2: Design influence on cost [12]

Figure 2.3 visually depicts the relationship between design, production, and work content, or volume. By combining design and production engineering decisions, the volume of work required can be reduced. In addition to reducing work volume, integrating the production process into the design further improves producibility, which also enhances product quality by improving first-time quality and consistency of products.

To realize the benefits of DFP, there must be adequate documentation of the production facility or facilities with routine updates in the system and component design process. Knowledge of current production capabilities and the integration of design with regular feedback is key [12]. A continuous learning process is essential in both the design team and the manufacturing parties to continue to yield positive results.

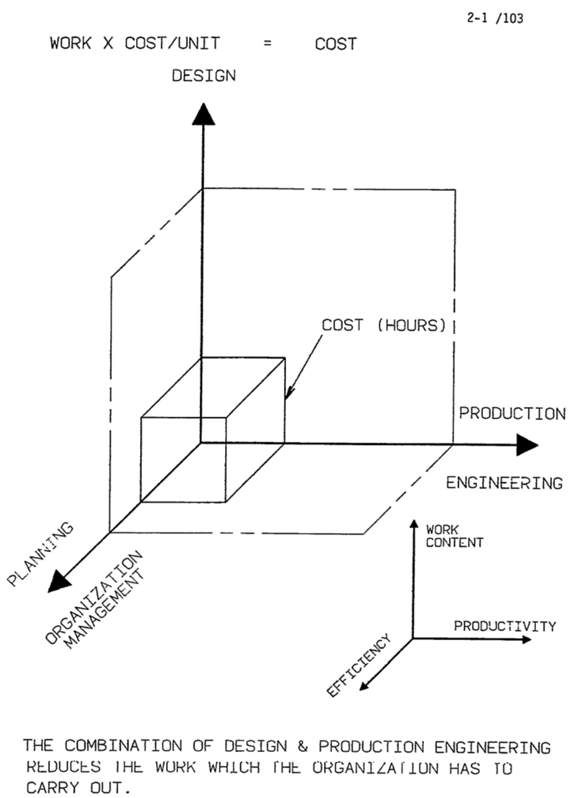


Figure 2.3: Design and production process impact on work content [12]

2.2.2 DFP In Ship Design

Design for production in the context of shipbuilding refers to the holistic approach of designing ships not only for their intended operational use but also for efficient production, assembly, maintenance, and decommissioning. This method includes considering the producibility of parts, the accessibility of components for assembly and maintenance, the integration of systems, and the optimization of shipyard processes and workflows. The aim is to reduce costs, enhance quality, and shorten the time from the design phase to the ship's delivery.

In order to apply the principles of DFP, close collaboration between the design team and the production staff is required. In order to successfully design ship components, a designer must have knowledge of the production processes to understand design choices that would make a system or component difficult and/or expensive to build [14]. Similarly, if no production mechanism exists for the component yet, the cost of production will increase significantly as the process must also be designed and constructed. Designers must have a deep understanding of the production capabilities and limitations of the shipyard. Production staff, on the other hand, must be adaptable and skilled in implementing new technologies and methodologies introduced by design. This synergy is critical to effectively applying the DFP principles. One suggested approach to ensure the design team fully understands the capabilities of a manufacturer and that of the shipbuilder completing ship construction, is that standard references be made available for use by designers and production engineers which include facility capability, build policy, standards, etc. [13]. Maintaining these tools up-to-date is vital to their usefulness. This is achieved with a continuous feedback process between the various entities as mentioned earlier.

In shipbuilding, reducing the work content translates into reducing the build time. First-time quality in components reduces the amount of rework which also aids in reducing the build time. This reduction in build time is another way that a shipbuilder can benefit from cost savings by incorporating DFP into their process [12]. Much as with overall cost, the ability to influence work content through design is highest at the conceptual and contract stages. As a project progresses, the design choices become more cemented and more difficult to alter. This further highlights the need to get design for production inputs and project decisions correct early in the design phase [12].

In addition to the design and build phases, design for production also influences the ship's life cycle support, focusing on ease of maintenance and upgrades, which directly relates to the total cost of ownership of the vessel. Ships designed with these principles in mind can be maintained and updated with new technologies more efficiently, extending their operational life and reducing long-term costs. This process also mutually benefits the continued improvement of both design and manufacturing organizations in shipbuilding.

2.3 DFP vs DFM

DFM and DFP while similar have slightly differing focuses as they relate to shipbuilding. In the context of shipbuilding, DFM would focus on the efficient manufacturing of individual ship components, such as hull sections or engine parts, ensuring that they are designed for cost-effective and high-quality fabrication. DFP, on the other hand, would look at the entire shipbuilding process, from the assembly of these components to the logistics of handling large structures, the integration of various systems on the ship, and even how the ship will be maintained and eventually decommissioned.

While DFM and DFP share the common goal of optimizing design to improve manufacturing and production efficiency, DFM is more focused on the manufacturability of individual parts, whereas DFP takes a holistic approach, considering the entire production process and life cycle of the product. Both approaches are complementary and are often used together to achieve the most efficient, cost-effective, and high-quality production outcomes. In the context of the NiPEC segment evaluation, the principles of DFM are more applicable to focus efforts of the design evaluation.

2.4 Ship Design Process

In addition to DFP and DFM, there are many other considerations in ship design. These considerations are often referred to as part of a larger list generally referred to as ship "ilities." Producibility, manufacturability, and maintainability are the most relevant topics for this discussion, but it is important to recognize that they fall into a larger list considered in the iterative process of ship design. This section highlights other areas that are applicable to the NiPEC design.

2.4.1 Ship Design Methodologies

The Design Spiral. Traditionally, ship design has been conceptualized through models such as the design spiral, as depicted in Figure 2.4. This model illustrates the iterative nature of ship design, where each aspect of a ship's development is revisited through cycles, fine-tuning decisions as design options are progressively narrowed. Although the "-ilities" such as manufacturability and maintainability typically appear at specific points in this spiral, they influence decisions across all stages of the design process.This provides a visual representation

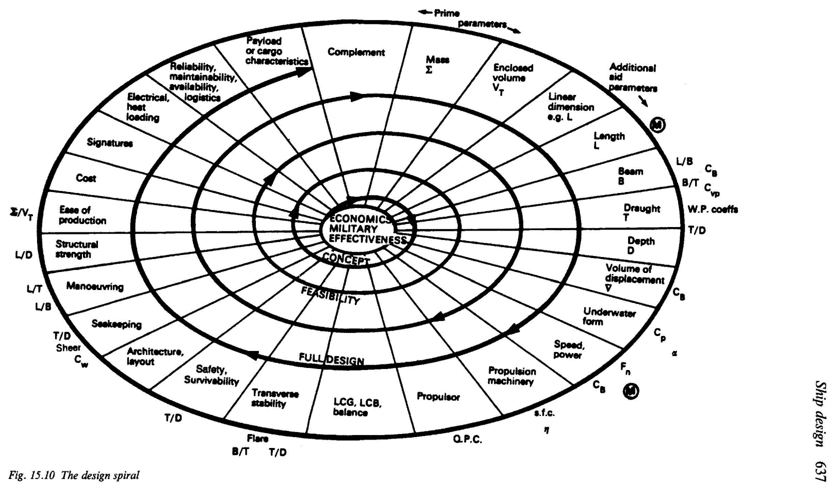


Figure 2.4: Historical depiction of the design spiral [14]

of where these assesssments fall into the overall design process and demonstrates that no single design decision is isolated from the others.

Despite its instructional value, the design spiral simplifies the dynamic and complex nature of modern ship design processes, resembling more a traditional, sequential approach rather than encapsulating the multi-dimensional decision-making that current technologies enable. This highlights the iterative nature often seen in design decisions and the increasing complexity of design changes further into the overall design process. Although the principles of DFM and DFP can and should be applied at any point in the design process, fine-tuning all aspects of the design to best support manufacturing and ship construction efficiencies, it is important to understand that the positive gains in cost and schedule are less as the design process progresses.

Design for the life intended. Ship design has many inputs and iterations and is highlighted by the design spiral discussion. An important, but difficult to qualify, aspect is the intended life of the ship. This includes not only the operational requirements and standards of the ship, but also the life cycle support of the ship. This includes planned or possibly not yet planned maintenance and modernizations for the future ship [14]. Designing a ship in a manner that supports future modernizations often looks like modularity and commonality.

Design Space Exploration. The contemporary approach to ship design has shifted towards design space exploration, a methodology that employs advanced simulations and computational models to evaluate numerous design scenarios at an early stage. This process allows designers to assess a broad spectrum of design variables simultaneously and to refine those options long before physical prototypes are considered.

Design space exploration effectively addresses the limitations of the design spiral by enabling a more flexible, responsive, and holistic exploration of the design space. It allows designers to identify and eliminate infeasible options early, focusing resources on the most promising designs. Again, the principles of DFM and DFP should be considered throughout the process. The earlier decisions are made, the greater the potential gain seen as a result of improvements in manufacturability.

While the design spiral provided a foundational framework for understanding the iterative process, design space exploration offers a practical methodology that adapts to the complexities of modern naval engineering. It supports a proactive approach to design, emphasizing early decision making that impacts cost, performance, and manufacturability throughout the life cycle of the ship.

Modularity. In line with modern design practices, modularity plays a crucial role in ship design. It allows for adaptability and scalability by standardizing components and systems, thus facilitating future modernizations and maintenance. This can be applied by utilizing repeatable parts or components that are simple to replace and manufacture. Not only do repeatable parts reduce the manufacturing and supply system requirements, they also reduce the training requirements. "A single common anything increases efficiency by reducing training requirements, maintenance complexity, and material support costs [15]." This approach not only simplifies the initial construction but also improves the long-term serviceability and compatibility with new technologies. Additionally, the Maintenance Policy for Navy Ships (OPNAVINST 4700.7M) instructs the use of standardized parts and equipment to the maximum extent practicable to minimize life cycle support costs. Modularity may also help reduce the complexity of testing and assembly.

In each of these areas of ship design consideration, there is no single solution to a given requirement. It is important to look at all areas of the ship, as well as construction and life cycle costs. Temple and Collette [16] conducted an analysis with three parameters, production cost, maintenance cost, and lifetime resistance, and found that focusing largely on any one of these parameters could result in much higher costs throughout the ship life cycle in the other two areas. By understanding the dynamic between cost and performance, designers can make more informed decisions to help reduce the overall life cycle cost of a ship.

2.5 Applicability to NiPEC

In shipbuilding, it is crucial to develop a detailed design that is production-friendly. This design must consider the manufacturing, assembly and construction processes, which also applies to the various components contributing to the overall ship design [17]. For the successful construction and installation of NiPEC, it is essential to incorporate production processes and manufacturability considerations into the design. This thesis begins with the evaluation of a single composite NiPEC segment, with the aim of enhancing its viability as a future ship component. To achieve this, the design of the NiPEC segment should be tailored to accommodate the current production processes and consider the ease of manufacturing for each element. Requirements to test and maintain the NiPEC are also important considerations for design. This thesis will apply the key principles of DFM and DFP to the design of a single NiPEC segment, evaluating the interfaces, accessibility, and material choices of the NiPEC segment to best meet both the manufacturing and the life cycle support requirements. The goal of the resultant segment design is to be a readily producible and testable component that is also simple to maintain and update throughout the life of ship.

The next section of this thesis aims to evaluate the major interfaces of the NiPECsegment through the lens of the DFM principles, evaluating ways to meet the design requirement but further improve the manufacturability. For the NiPEC segment, this evaluation will include common material and connector opportunities, current production capabilities, configuration concerns during ship installation, and the opportunity to reduce the number of parts and connections.

Additionally, accessibility and maintainability will be evaluated for ways in which manufacturing methods can improve ease of operation and maintenance for operators. The goal of this project is to evaluate the current shipbuilding methods and the current NiPEC segment model and take aspects of each to further improve the final NiPEC segment model as a feasible construction solution. The end-state model should be a segment that is readily manufacturable as well as able to be tested and operated in a manner that is both efficient and first-time quality.

Chapter 3

Consideration of NiPEC Design Manufacturability

As described in Chapter 1 of this thesis, the current design of NiPEC is a modular corridor construction containing power electronics technology. There are many parts and components that go into completing the corridor that must be evaluated for the optimal choice throughout the design process. Determining the feasibility and affordability to manufacture and construct this large shipboard system provides valuable information with which to make informed design decisions. This chapter will focus on a way to evaluate the manufacturability of NiPEC and also its constituent parts.

3.1 Evaluation Criteria

nd rinciples, as described in Chapter 2, are an important consideration in the final design of NiPEC and the supporting systems. These two philosophies are multifaceted and can be measured in many ways. No singular philosophy or attribute best meets the needs of the NiPEC project and future generation USN ships, so a holistic approach is required. nd in the context of shipbuilding, have different but supportive objectives that contribute to a successful design that supports efficient manufacturing and a successful shipbuilding process. This study applies the most applicable elements of these design philosophies to the NiPEC evaluation criteria along with other key considerations for the manufacturing and installation of shipboard systems. This thesis aims to use these key elements to create weighted objective evaluation criteria to measure the manufacturability of a system so that it can be applied to NiPEC and its constituent systems.

Evaluating the parts that make up a system is one of the most critical elements of evaluation. As discussed previously, an important element when considering the ease with which a system can be manufactured is the number of parts, both total and unique. These are strong indicators of cost in design, manufacturing, and maintenance. In general, lower part counts are less expensive to manufacture and maintain. Commonality with other hip systems is also useful in ensuring adequate and affordable parts support during the maintenance and sustainment phase. The design of a system also affects the number of man-hours required for ship installation. The modularity of a system and how much of a system is assembled prior to shipboard installation affect the overall system production and ship construction process. The volume of work generated by each system and subsystem is also a critical element when evaluating a complete ship construction project.

Each of these areas was considered to develop a useful set of criteria with which to evaluate and compare the proposed system designs. The evaluation criteria figures of merit chosen for this study based on the DFM and DFP principles are listed below.

- Total number of parts
- Extent to which the system may be tested off-hull
- Total number of unique parts
- Man-hours required for ship installation

3.1.1 Figures of Merit

These figures of merit can be used to compare different shipboard systems with reference to their manufacturability, which generally refers to the ease and efficiency with which a product can be produced. This section describes how each metric benefits the evaluation and how it can be applied to grade any system or set of systems for comparison and supporting design decisions.

Number of Parts. This measurement is a count of all the parts that make up the system being evaluated. Systems with fewer parts may be simpler to manufacture, as they can require less assembly time, fewer materials, less shipping requirements, and generally lower costs. However, there are systems with more parts that may be simpler to install or easier to produce because of their repeatability; sometimes a greater number of parts can be a sign of modular design, which can also be beneficial for manufacturability and modular ship installation. This conflicting aspect is why this metric cannot be used independently without consideration of other elements. However, the number of parts remains the highest accurate cost indicator [11], so it was chosen as the highest weighted element for evaluation.

Off-Hull Test. This measurement is an estimate of the percent of system testing that can be accomplished prior to shipboard installation. The ability to test a system off-hull implies a design that is conducive to early error detection and correction, which is advantageous in manufacturing and shipbuilding. Systems that can be extensively tested before installation can reduce the risk of costly rework and delays. Interviewing a subject matter expert from a major shipyard that supports USN ship construction projects revealed that a major contributor to growth and rework is failed shipboard testing [9]. By completing testing off-hull, prior to ship installation, faulty components or connections could potentially be identified sooner. This minimizes both rework and interference removal required should a major component need to be removed after the initial installation. If more system errors can be identified prior to installation, the ship construction schedule can be less impacted and, therefore, shorten the build cycle. This saves both time and money on a project and allows the timeline to be more predictable. Due to the significant impact testing has on a ship schedule and system performance, any grading system without a test consideration would be incomplete. For these reasons, off-hull test was included as a figure of merit in this evaluation to support the overall manufacturability assessment of systems.

Number of Unique Parts. A unique parts count is a measurement of how many different parts are included in a system design. A lower number of unique parts suggests that the system uses more standardized components, which can improve manufacturability and maintainability. Standard parts are typically easier to source and can be purchased in bulk, often leading to cost savings and simplifying inventory management. Fewer unique parts also require less design work to account for first-time production or installation considerations. Using parts that are already in the USN stock system further eases the logistical requirements to establish maintenance support for a system and can reduce long-term costs for maintaining the system.

Man-hours for Installation. This is the total estimated man-hours required for installation during ship construction of the system being assessed. Fewer man-hours for installation can indicate a system that is easier to manufacture or assemble. This could reflect a more efficient design, better pre-assembly before installation, or a system that requires less on-site customization. Reducing the man-hours required for installation leads to shortening the duration of the overall construction process, therefore lowering the cost. It also minimizes the risk of rework, as less installation work means that the system is arriving to the ship more assembled. This minimizes the opportunity for errors during the shipboard installation phase, further lowering the cost.

When comparing the manufacturability of different system designs, each of these figures of merit must be considered in context. For example, a system with a large number of parts might still be highly manufacturable if it has a high degree of commonality in parts, modular design, or if the assembly process is highly automated. Similarly, a system with extensive off-hull testing capabilities might be more complex to manufacture, but this complexity might be offset by the reduced risk and cost of post-installation failures. Therefore, these metrics should be used as part of a holistic evaluation of the system's design, cost, and production process. To best put these figures of merit to use, they were each assigned a grading scale. This allowed an objective application to any system or subsystem to be graded overall.

3.1.2 Applying a Weighting System

After determining the appropriate figures of merit, each element needed to be weighted against the others to accurately assess the prioritization of each element. Adding a weighting system and using a list of criteria to evaluate various system design attributes inherently involves accounting for trade-offs between those attributes. This method allows for a structured comparison of different options or solutions based on a set of predefined and weighted criteria. This approach accounts for trade-offs in three different ways.

1. *Prioritization of Attributes*: By assigning different weights to each criterion, it is possible to state the relative importance of that attribute compared to others. This inherently involves a trade-off, as increasing the weight of one criterion decreases the relative importance of the others. It reflects the understanding that, in system design, some attributes may be more critical to the project's success than others.

2. *Balanced Decision Making*: A weighted evaluation allows for a more nuanced decision-making process. It acknowledges that while one option may excel in certain areas, it might perform poorly in others that are also important. This balance means that an option does not need to be the best in every single criterion to be considered the overall best choice. It mirrors the real-world scenario where perfect solutions are rare, and trade-offs are necessary.

3. *Quantitative Analysis of Qualitative Attributes*: By converting qualitative attributes into quantifiable scores that can be weighted and summed, this approach provides a systematic method for comparing options that might otherwise be difficult to evaluate directly against each other. It offers a way to make informed decisions when dealing with trade-offs between different qualitative aspects of system design.

Since this evaluation was rooted in a desire to assess manufacturability, the highest weighted items were measurements of the system that have the greatest contribution to overall manufacturability. These were selected and weighted from the research referenced in Chapter 2 and include the total number of parts, the total number of unique parts, the man-hours required for ship installation, and the extent to which a system and its components may be tested off-hull. The highest weighted element was the total number of parts, since research supports this as the greatest indicator of cost and manufacturability.

Table 3.1 lists each of the evaluation criteria used in this study, the individual weights, and the preferred direction for each element. This provided a quantitative way to evaluate system designs and compare various design options for systems and subsystems.

Criteria	Weight	Preferred Option
Total number of parts	35%	Smallest
Extent to which the system may be tested off hull	30%	Largest
Total number of unique parts	20%	Smallest
Man hours required for ship installation	15%	Smallest

Table 3.1: Weighted Manufacturability Evaluation Criteria for Selection

3.2 Trade-Offs

For a perfect design, each of the described figures of merit would be met to the ideal state or preferred variation listed in Table 3.1. However, when evaluating a system holistically, it is not possible to maximize one element without impacting another. There exists a natural tension between these various system attributes as well as additional system trade-offs. This is important to acknowledge during the design process since no decision may occur in a vacuum independent of others.

3.2.1 Figure of Merit Trade-Offs

Incorporating a weighted grading system to evaluate various system designs options for NiPEC subsystems and interfaces inherently recognizes the existence of trade-offs between different design attributes. The weighting scale acknowledges that not all aspects of a system's design are equally important in evaluating manufacturability, and that improving one attribute might come at the expense of another. The weighted criteria framework allows the evaluation of these trade-offs by assigning relative importance to different attributes, thereby guiding decisions towards a design that best aligns with overall objectives. Given the weighted grading attributes described in Section 3.1.2, there are four key areas of potential trade-offs to be highlighted between various system designs.

1. *Complexity vs. Redundancy*: A fundamental trade-off exists between system complexity and redundancy. Enhancing redundancy, which is crucial for reliability, often results in an increase in the total number of parts and unique parts. This increment in parts not only elevates the system's complexity but may also extend the installation

duration and maintenance requirements.

2. *Efficiency vs. Thoroughness*: The balance between installation efficiency and the thoroughness of system testing and redundancy reveals another critical trade-off. A system that requires fewer man-hours for installation might be less complex but could compromise on redundancy or the extent to which it can be tested off hull. This reflects a trade-off between efficiency in installation and thoroughness in testing and reliability.

3. *Maintenance vs. Initial Complexity*: Another trade-off exists between minimizing maintenance efforts and the initial complexity of a system. Designs that aim to reduce maintenance hours may incorporate more complex components or systems upfront, possibly leading to longer installation times. Conversely, simpler systems, or even modular systems, might benefit from easier installation and lower initial complexity but could necessitate more frequent maintenance. This trade-off accentuates the importance of considering full life requirements and cycle cost in system design.

4. *Testing vs. Operational Practicality*: The extent to which a system can be tested off-hull versus its operational practicality presents another area of trade-off. The ability to test a system extensively off-hull might necessitate design choices that increase the number of unique parts or the overall system complexity, affecting maintenance and installation requirements.

3.2.2 Additional Trade-Offs

Also important for NiPEC design and construction is the volume of maintenance required to support ship systems and the level of redundancy designed into a system. These are important elements that have a large effect on an overall ship construction project's schedule and risk, as well as future operations. These trade-offs with manufacturability are two of many other system performance attributes that naturally may have tension with manufacturability. In this case, they will also be used to assess the support required and redundancy provided, encompassing more of the overall system cost and impact to the entirety of a ship life cycle.

Maintenance Hours. This is a measurement of the estimated man-hours of maintenance, or maintenance volume, required to support a shipboard system design through the operations and sustainment phase of the ship life cycle. For a hip system such as NiPEC, maintainability is a key consideration, as it is a major contributor to ship life cycle cost both due to parts and manning requirements. Although not directly related to initial manufacturability, maintainability is a key trade-off with manufacturability which contributed to the decision to include it in this assessment. Systems that require fewer maintenance hours might be designed with reliability and durability in mind, which are desirable traits from a manufacturing point of view, but they also may be more expensive to manufacture and install due to a greater number parts. A lower number of maintenance hours is also beneficial to the end user, the ship operators. Systems that are easier to maintain can reduce the long-term cost of ownership and can be a selling point for manufacturers. Lower maintenance hours require fewer operators to maintain which, in turn, further reduces the life cycle cost overall for the system and ship. Manning is the highest overall cost over the course of the entire life cycle of the ship. This element again highlights the importance of not evaluating a system with a single criterion in isolation. There is a natural tension between modularity and minimizing maintenance in many cases. Although modularity may result in fewer unique parts and fewer man hours required for installation, it often generates more maintenance hours. This shows how it would be an incomplete assessment not to evaluate the estimate maintenance requirements while evaluating the manufacturability of a system or subsystem, so this was also included with the manufacturability evaluation criteria.

Level of Redundancy. This is an assessment of whether and where redundancy is designed into the system. Redundancy is essential for reliability, but can be a double-edged sword for manufacturability making it another key trade-off to evaluate. On the one hand, redundant systems may require more parts and complex designs, which can complicate manufacturing. On the other hand, well-designed redundancy may not significantly impact manufacturability if it uses standardized parts and intelligent design to mitigate potential issues. This is less a quantitative measurement and more a qualitative measurement. This element is used to provide an additional comparison point between different system designs to further educate design decisions. This criterion is most useful supporting the other elements to assess a system's overall manufacturability.

To incorporate these two major trade-offs and demonstrate how to evaluate other attributes alongside manufacturability, a secondary attribute weighting was considered adding these criterion to the original list.

- Total number of parts
- Extent to which the system may be tested off-hull
- Total number of unique parts
- Man-hours required for ship installation
- Maintenance hours required
- Level of redundancy

Following an assessment on manufacturability with the described criteria, a determination could be made as to which variant was determined to be more favorably manufacturable. That was then incorporated into a grading scale alongside the chosen trade-offs for evaluation as shown in Table 3.2.

Level of Manufacturability	40%	Largest
Maintenance hours required	30%	Smallest
Level of Redundancy	30%	Largest

Table 3.2: Combined Evaluation Criteria

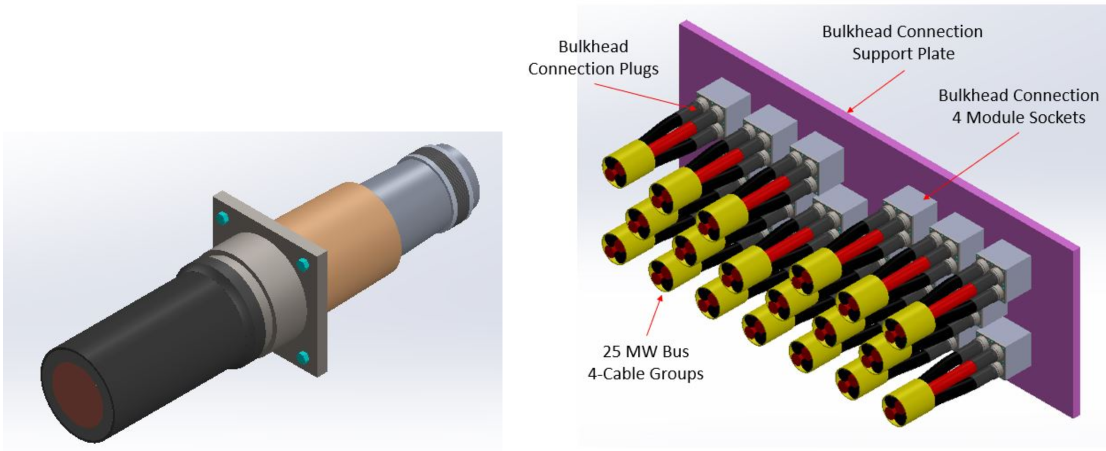
Manufacturability was weighted the highest in this scale, as this was still deemed to be a top priority consistent with overall NiPEC project goals. The additional elements that did not directly assess manufacturability were equally weighted to further assess a system in a more holistic view, taking into account all figures of merit. These elements included the estimated annual man-hours of maintenance required and the level of system redundancy. Each of these elements is a positive contribution to a system's appeal overall but must be taken into account in the context of the other elements assessing manufacturability, as they are trade-offs with manufacturability. These two elements are also two chosen from a longer list of performance factors that would also be considered in ship system design decisions, such as cost and survivability. These two were chosen for this study to illustrate the process and trade-offs. These could be replaced or augmented for future assessments according to project priorities.

By applying a weighted evaluation system, these trade-offs are not merely acknowledged but systematically analyzed. The weighting clarifies the relative importance of each criterion, guiding the design process towards solutions that optimize across a spectrum of competing priorities. It allows for a nuanced understanding that the most effective system design may not excel in every individual aspect but will perform optimally across a carefully considered set of weighted attributes. Furthermore, the grading evaluation may be applied to any system and the figure of merit weighting adjusted to reflect a project objectives and priorities.

3.3 NiPEC Components to be Considered

To make the construction and installation of the NiPEC more feasible, the design should take into account the manufacturability and characteristics described by the figures of merit in Section 3.1. For the purposes of this evaluation, this thesis considers a single NiPEC segment the representative component to be evaluated. The segment was then further broken down to consider individual subsystems and support systems that make NiPEC operation possible. The grading criteria in this thesis could be applied to many system design options, but only the support systems of NiPEC were considered for this evaluation. The subsystems, interfaces, and support systems of the NiPEC whose design options may be graded by the identified figures of merit are listed below along with some of the more important design considerations for each.

Segment Connectors. This describes the connectors between the segments of the corridor, between watertight compartments throughout the length of the ship. This is an element of the NiPEC not yet fully designed and a component not currently used on USN ships. A notional design is shown in Figure 3.1. These connectors remove the requirement for ship-long cable runs that are both costly and time consuming during the construction phase. Connectors between watertight compartments also facilitate installing the NiPEC one compartment at a time and allow these connections to be made as the ship is constructed rather than after the entire structure is in place. These construction improvements due to this connector design are expected to shorten the overall build time.



(a) Plug Perspective (b) Full Bulkhead Connection View

Figure 3.1: NiPEC Bulkhead Connections [8]

This is an example of a technology in which it is important to be intentional with making decisions about a new piece of equipment that impacts a time-consuming part of a ship construction project and will be required in a rather large quantity across all ships that implement the NiPEC design.

Human-Machine Interface. A human-machine interface (HMI) screen is mounted on the front side of each NiPEC segment. This will provide local system status and local control in the event that remote control is interrupted. Key considerations for this subsystem will be the level of complexity, control provided, and commonality to existing HMI designs used on current USN ships.

Figure 3.2 shows a rendering of what this will look like once installed on the ship. This will be a highly repeated component, at least one per each of the expected 28 watertight spaces housing NiPEC sections. Understanding the ease with which this component is produced and installed will be important to fully bound the requirements of the NiPEC overall.

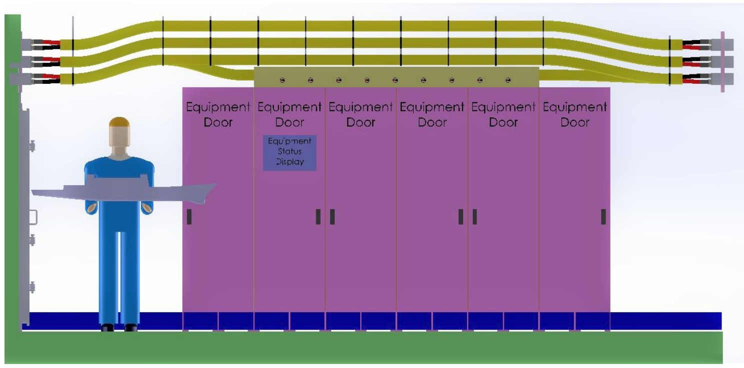


Figure 3.2: NiPEC Cabinet Arrangement with HMI [8]

Internal Assembly and Drawers. The NiPEC is designed as a modular system in which all internal components are arranged within a consolidated power corridor with cabinets arranged similarly to those in Figure 3.2. All internal replaceable parts shall not be installed in a permanent manner that requires soldering or welding removal. The NiPEC iPEBBs, assembly drawers, and other internal components shall be removable. The drawers must also be installed with locking mechanisms in the track in fully inserted and fully withdrawn positions [18], which facilitates maintenance and inspections as well as equipment removal in a safe and controllable manner. The internal design to accomplish this arrangement must be considered for ease of manufacturing and durability for long-term us as well as commonality to existing cabinet designs currently in use on current USN ships. This consideration is important because of its impact on production and installation as well as cost and long-term maintainability.

Power Electronics Building Blocks. The power electronics design has seen multiple iterations as part of the overall NiPEC design. In this study, both the iPEBB and PEBB 6000 are considered as the potential design choice for use in the power corridor. Figure 3.3 is a schematic of the iPEBB. This is a self-contained power conversion component that is capable of providing power-dense solutions to support a ship's electrical loads. The power corridor will house hundreds of PEBBs to support the loading of a notional all-electric war ship. This large quantity makes manufacturability especially important for these components. Any design element that affects production, installation, or maintenance will have far-reaching impacts on the overall life cycle of the ship and system.

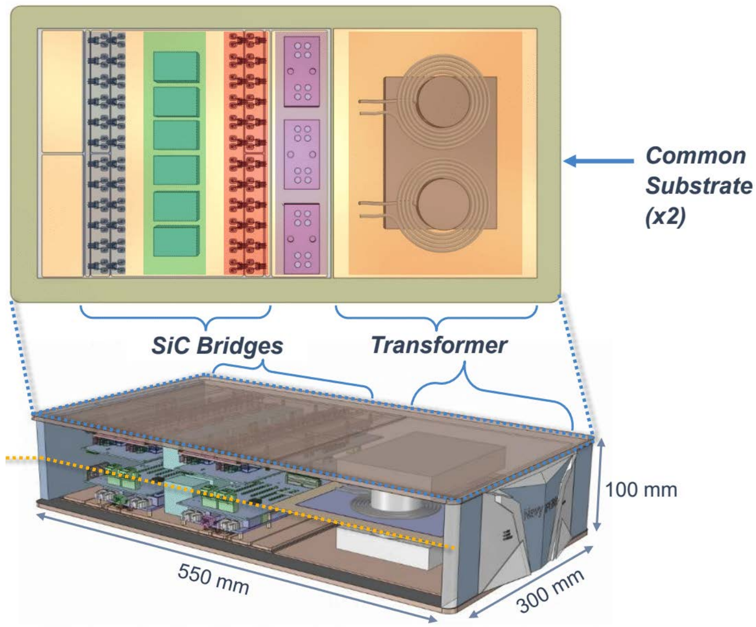


Figure 3.3: NiPEC iPEBB [19]

The final design used in the power corridor will need to be repeatable and easily maintained by ship operators. Considerations for PEBB construction, test, and installation will be important in the final design.

Monitoring and Control System. Monitoring and control systems for the NiPEC will be a vital ship control system that requires extensive testing. This system network will provide connectivity between the sections of the corridor and the operators, as well as provide a remote indication of the power corridor status. It will also require an extensive ship installation, as it will run ship-wide. Cabling material and connectors to interface with the corridor will be required in a large volume, making their manufacturability an important consideration. Design that supports testing and installation, as well as provides redundancy, will be critical elements when finalizing a design.

Cooling System. The current proposed cooling system designs utilize a closed loop demineralized water system. The system will use heat exchangers cooled by ship chill water to maintain temperature and will interface with the power corridor electronics via cold plates. The cooling system will need to connect to every NiPEC segment cabinet that houses PEBBs.

This will be a ship-wide system that requires an exceptionally high level of reliability due to the critical nature of the power electronics equipment it will cool. Maintenance considerations will also be important for this system, as it will be a large system and has the potential to create a cumbersome maintenance burden for operators. Since cooling systems were chosen as the case study for this thesis, these designs are described in more detail in Chapter 4.

Each of these NiPEC elements and support systems could be graded and design variants compared using the evaluation criteria described in this thesis. This would be useful in making more informed design decisions when selecting design variants for each of these smaller systems in support of the overall development of the final design NiPEC.

3.4 Evaluation Application

This structure provides a clear and systematic approach to incorporate the principles of nd nto the NiPEC design evaluation process, ensuring that both the manufacturability and the life cycle costs are optimized. The grading criteria serve as a quantifiable measure to compare different designs and will be instrumental in guiding the decision-making process for the most suitable NiPEC system and subsystem design. This grading criteria could be applied to any ship system and any element of the NiPEC overall design as described in Section 3.3. This thesis will apply this grading system to two separate designs for the NiPEC cooling system. The following chapter will use this evaluation method to compare the advantages and disadvantages of the two designs and be used to make a decision on which system design best meets the overall needs of the NiPEC and future ship objectives.

Chapter 4

Case Study: NiPEC Cooling System

To better illustrate the ideas presented in Chapter 3, two proposed NiPEC cooling systems are compared in this chapter using the manufacturability grading criteria. The grading criteria described were used to compare these two design options in order to highlight their merits and shortcomings with respect to their manufacturability. This also highlights the inherent trade-offs that exist when making design decisions such as maintainability and reliability. This specific example evaluates two design choices, but could also be applied to more than two choices by ranking the designs for each attribute and calculating the scores in the same manner as this example.

4.1 Application of Criteria

This section outlines the structured approach used to effectively compare two distinct designs of the NiPEC cooling systems. These criteria are designed to assess both the system manufacturability, influenced by the principles of DFM and DFP, and operational considerations such as maintenance and redundancy that contribute to the maintainability and reliability of the system and also contribute to life cycle costs. As stated previously, maintenance requirements and redundancy are two of the many system performance parameters considered when choosing ship system designs. These represent how to use the process to compare alongside manufacturability attributes and could be changed or updated to reflect other project priorities, like cost.

To implement the evaluation criteria for the two distinct NiPEC cooling system designs, a comprehensive application methodology was used, encompassing several structured steps in different aspects of the system evaluation:

Component and Part Analysis: This stage involved a detailed examination of the components that make up each cooling system design. The process started by breaking down each design into its constituent parts, followed by counting these parts to determine *Total Number of Parts*. This count helped in evaluating the system's complexity. Additionally, each part was assessed to determine its uniqueness—Identify and Count *Unique Parts*—where parts are classified as 'unique' if they are specific to certain functions or designs. This classification aids in understanding the design's standardization potential and parts inventory management.

Installation and Operational Analysis: The next step focused on the installation and operational viability of the designs. The *Man-Hours Required for Installation* were estimated based on the complexity of the design and its integration requirements with the ship's existing systems, which indicated the labor efficiency during the deployment phase. Furthermore, *Extent to Which the System May Be Tested Off-Hull* is evaluated to determine the feasibility of performing comprehensive system tests in a controlled environment outside of the ship, which is crucial to ensure system reliability and safety before onboard integration, as well as mitigation of project risks.

Maintenance and Redundancy Evaluation: The final phase assessed the ongoing operational demands and resilience of the system. This complimented previous assessments of manufacturability and identified the system trade-offs between manufacturability and maintainability. Calculating *Maintenance Hours* involved reviewing the expected maintenance schedules for each design and estimating the total annual labor hours required for maintenance. This estimate helped to gauge the operational cost and logistic demands of the system. Concurrently, *Level of Redundancy* was examined by analyzing features such as duplicate systems or fault-tolerant components within the design. This analysis was vital for understanding the capability of the system to withstand and function amidst operational stresses or component failures. Examining these attributes also highlighted the natural tension that exists between manufacturability and other system characteristics.

Together, these methodological steps enabled a holistic evaluation of each NiPEC cooling system design, providing crucial insights into their complexity, manufacturability, testability, maintainability, and reliability. Including the maintenance and redundancy evaluation added another element alongside manufacturability to complete a more well-rounded evaluation, as well as highlight key trade-offs between manufacturability and other performance parameters. This could be changed and/or expanded to include additional factors aligned with specific project objectives, such as cost and survivability. The process would be the same but would require grading adjustments to include these additional factors or make substitutions according to the priorities of the project. This thorough assessment not only presents an effective framework to aid in selecting the most appropriate design but also ensures that the chosen solution aligns with the operational and strategic goals of future naval vessels even as objectives may change.

4.1.1 Evaluation Criteria

Manufacturability Criteria

Tables 4.1 summarizes the manufacturability grading criteria described in Chapter 3, as well as the primary purpose of evaluating each element of the system.

Criteria	**Description**
Total Number of Parts	Assesses the complexity of the system by counting all components involved. Fewer parts generally indicate a simpler, potentially more robust design, and less expensive production.
Extent to Which the System May Be Tested Off-Hull	Indicates how much of the system testing can be completed before ship integration, aiming for improved risk reduction and safety.
Total Number of Unique Parts	Evaluates the inventory diversity required for the system. Standardization (fewer unique parts) simplifies production, logistics, and maintenance.

Continued on next page

Table 4.1 – *Continued from previous page*

Criteria	**Description**
Man-Hours Required for Ship Installation	Measures the labor input required for installing the system on the ship. Systems requiring fewer man-hours are typically more efficient to deploy.

Table 4.1: Manufacturability Evaluation Criteria for NiPEC

Trade-Off Criteria

Each of the chosen trade-offs considered in this study, as well as the reason for evaluating each element, is described in Table 4.2.

Criteria	**Description**
Maintenance Hours Required	Estimates the labor required for regular maintenance, with an emphasis on designs that minimize these hours to reduce operational costs and manning requirements.
Level of Redundancy	Assesses the system's ability to operate effectively under partial failure conditions, crucial for reliability.

Table 4.2: Manufacturability Trade-Off Evaluation Criteria for NiPEC

4.1.2 Comparative Analysis

Each cooling system design was evaluated and scored against the predefined criteria as described in Tables 4.1 and 4.2. These evaluations included both objective measures, such as the total number of parts and required man-hours for installation, and more subjective measures like testability and redundancy levels. The objective data were directly quantifiable, while the subjective assessments were based on publicly available data and reasonable estimates.

The manufacturability scores were calculated using a grading scale that incorporated weighting factors to reflect the relative importance of each criterion, as detailed in Section 3.1.2. A secondary evaluation was done using the weighting from Section 3.2.2 to assess manufacturability alongeside specific trade-offs. This approach ensured that critical aspects such as system reliability and maintenance demands were appropriately emphasized in the overall evaluation.

Each system received an individual score for each criterion, facilitating a direct comparison between the two different designs. This comparative analysis method allowed for a clear, side-by-side visualization of the performance of each system, highlighting their respective advantages and limitations. The analysis supported decision-making processes by underscoring how each design aligns with the operational requirements of the NiPEC and meets the broader objectives of naval system design.

4.1.3 Decision-Making Process

The decision-making process leveraged the scores and insights obtained from the application of evaluation criteria to determine which cooling system design optimally meets the requirements of the NiPEC project. The decision on the optimal cooling system design for the NiPEC project is based on a structured evaluation process that incorporates both DFM and DFP principles, alongside operational and maintenance considerations essential for naval applications. This process is critical to enhancing the power management capabilities of future all-electric warships and involves the following steps:

1. **Establish Evaluation Criteria:** Define clear, measurable standards for each criterion, such as the number of parts, which prioritize simplicity with higher scores for fewer parts.

2. **Apply Grading Scale:** Use a grading scale (e.g., 1-5 or A-F) that reflects the relative importance of each criterion, adjusting weights as necessary for the project's priorities.

3. **Perform Comparative Analysis:** Compare the two systems side-by-side in a summary table, assigning scores based on their performance against the benchmarks.

4. **Assess Trade-offs:** Discuss the trade-offs involved, considering that a design with greater redundancy might have lower manufacturability but higher operational reliability, which could be critical.

5. **Calculate Overall Score:** Derive an overall score for each design using either a simple average or a weighted sum to conclude which design best meets the NiPEC's needs.

This structured evaluation process provided a clear and systematic method to assess competing system designs, playing an essential role in guiding the final selection to ensure superior performance and seamless integration within the naval architecture. The analyses performed herein illustrates how to apply the criteria to evaluate each system comprehensively, then compile a composite score for comparison and final decision-making.

The manufacturability evaluation criteria outlined in Chapter 3 will be applied to two distinct NiPEC cooling system designs. Each design will be scored for each of the six criteria. These scores will then be aggregated into a summary table that presents an overall manufacturability score, thereby delineating each design's strengths and weaknesses and the trade-offs involved in these design decisions. Subsequent sections will detail the systems under evaluation and analyze each criterion relative to the designs. This comparative ranking will then be synthesized into a summary table that assigns grades or scores based on the established criteria, providing a quantifiable basis for comparison between the two design options.

4.2 NiPEC Cooling Concept

This section is designed to contrast two different cooling system designs for NiPEC, highlighting the differences between them. However, it is important to acknowledge that, because both designs are engineered to manage the thermal load of NiPEC, they share a number of requirements and design characteristics.

4.2.1 Design Requirements

The NiPEC system requires an efficient cooling solution to regulate the heat produced by its onboard power electronics. The typical layout of a corridor section, which is a key area for heat generation and therefore requires cooling, is detailed in Figure 1.7 in Chapter 1.

A significant source of this thermal challenge is the semiconductor technology employed in the PEBB, as shown in Figures 4.1, which features the design of an iPEBB and highlights the internal power electronics. Despite the PEBB's high efficiency in power conversion and storage, it still generates significant heat from electrical losses, leading to intricate thermal management issues that demand innovative solutions, as cited in [20]. The design and operational constraints of the PEPDS and NiPEC systems further complicate the application of conventional cooling methods. These constraints include the limited space available for cooling infrastructure, the necessity for modular and portable units for easy deployment or removal, and a stringent prohibition against placing any cooling water connections near electrical parts, thus excluding direct liquid cooling options.

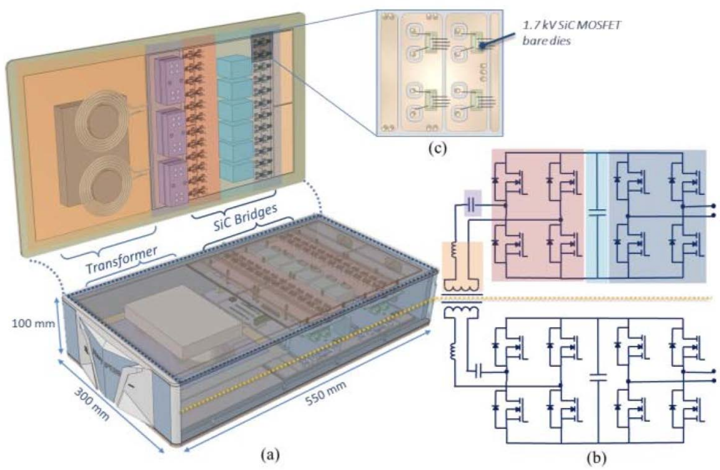


Figure 4.1: (a) iPEBB design with a top view of the primary side, (b) iPEBB topology, (c) Switching-cell portion of the SiC H-bridges. [21]

Investigations into new cooling methodologies have been prompted by the limitations of standard cooling approaches for PEBBs. Research by Yang et al. [20] indicated that while air cooling may be sufficient for smaller PEBB models, it falls short for the more power-intensive PEBB variants, making water cooling a favorable alternative. An innovative strategy involved an external liquid cooling system with copper piping in a cold plate, which eliminates the need for manual connections and ensures the PEBB remains dry, thus providing electrical isolation. Nonetheless, this solution encounters challenges in heat transfer efficiency, particularly due to contact resistance, a notable issue in environments susceptible to grit and dust, as ships may be.

Further enhancements by Padilla et al. [22] integrated a liquid-cooled cold plate with thermal interface material (TIM) to address contact resistance, efficiently dissipating up to 10 kW of heat. Building on this, Reyes [23] proposed a closed-loop, pressurized water cooling system utilizing demineralized water, capable of cooling up to 240 kW from 20 Navy iPEBB units, including a 20% safety margin. This initiative sought to meet the compact and lightweight design criteria essential for NiPEC's usability and to comply with industry and military standards, requiring a sophisticated approach to thermal management. The first-pass design is illustrated in Figures 4.2 and 4.3.

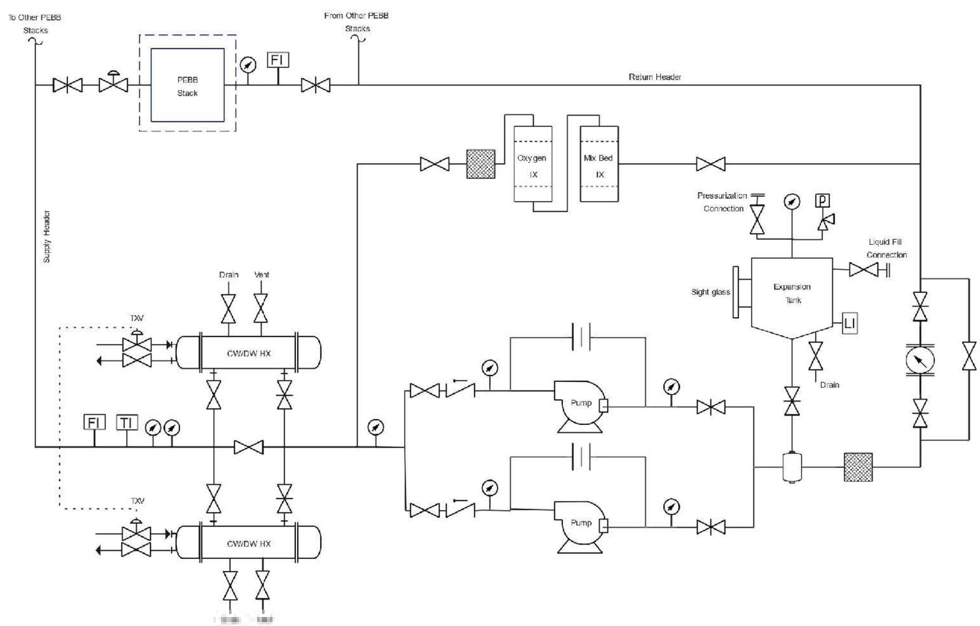


Figure 4.2: NiPEC Cooling System Design [23]

Figure 4.2 is a system line drawing of a single section cooling system to provide NiPEC cooling. Figure 4.3 shows a detailed schematic of the cooling connection to the internal PEBB stack, the system portion that would be repeated for each PEBB stack. This system solution was based upon a single NiPEC and used a notional electrical load for determining thermal requirements.

Expanding this cooling solution to entire vessels, such as a hypothetical destroyer with several power corridors, poses considerable practical challenges. The variability in power needs across different sections of a ship and the complexity of implementing numerous cooling systems raise substantial obstacles in terms of deployment, operational efficiency,

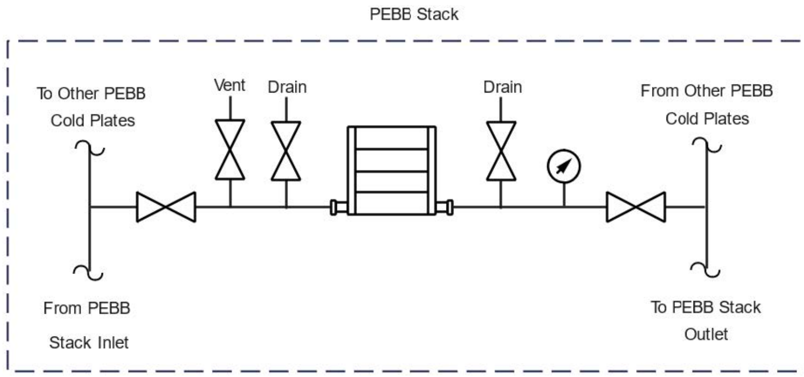


Figure 4.3: NiPEC Cooling System Design PEBB Stack Details[23]

maintenance, and cost-effectiveness. These issues have prompted ongoing research into alternative cooling system designs, further detailed in this chapter, based on the architecture of a four-corridor NiPEC system as introduced in Chapter 1.

Chatterjee [24] completed a detailed load analysis on the notional all-electric warship to better define the requirements. This translated into a detailed listing of the PEBB requirements to support the ship at maximum loading. The PEBB requirement directly correlates to the cooling requirements for the corridor. By defining the cooling loads throughout the ship spatially, this provides a spatial arrangement for the PEBB arrangement. This investigation determined that to support the system with only the Navy iPEBB, it would require 1152 iPEBBs be installed, a quantity that would generate a considerable challenge for both thermal management and physical arrangement within the corridor. To help alleviate these concerns, Chatterjee [24] proposed an arrangement that included both iPEBBs and PEBB 6000s in the design. This reduced the overall number and helped to make both the thermal and physical arrangement requirements more manageable. Table 4.3 shows the results of this analysis and ship-wide iPEBB and PEBB distribution.

Due to these improvements as well as the positive PEBB 6000 research that is ongoing, the six-zone cooling system designed by Chatterjee [24] assumed this hybrid PEBB deployment. The modular design also evaluated in this chapter assumes the same distribution and was used as the basis of the thermal management requirement. To support this dual PEBB distribution, water cooling is assumed to be the cooling method for both the iPEBBs and PEBB 6000s for the purposes of this study. This assumption allows for one cooling method

Compartment	iPEBB Stacks		PEBB 600 Stacks		Compartment Total	
	Port	Starboard	Port	Starboard	Port	Starboard
0	1	1	0	0	1	1
1	1	4	0	0	1	4
2	4	1	0	0	4	1
3	2	2	0	0	2	2
4	2	5	4	0	6	5
5	9	6	0	0	9	6
6	5	5	10	10	15	15
7	3	3	0	20	3	23
8	3	6	12	4	15	10
9	2	2	20	0	22	2
10	5	2	0	0	5	2
11	1	4	0	0	1	4
12	5	2	0	4	5	6
13	1	1	0	0	1	1
Stack Totals	44	44	46	38	90	82

Table 4.3: PEBB Distribution across Compartments [24]

to be utilized and creates continuity between the two design variants evaluated later in this chapter.

4.2.2 Common Design Elements

Both NiPEC cooling system designs evaluated in this chapter draw on previous research and incorporate a closed-loop system using demineralized water. The systems are designed to span the entire length of the corridor, leveraging the ship's service chill water system for cooling, and provide continuous cooling to the NiPEC power electronics equipment. Key common components of these systems include pumps, water chemistry control instruments, pipes, fittings, expansion tanks, cold plates, and water filters. Although the specific sizing and configuration of these components may vary, their fundamental elements remain consistent across both designs. The selection of materials for pipes, valves, and fixtures is guided by their compatibility with existing shipboard systems and compliance with current naval standards. These selection criteria are not unique between the two design solutions.

4.2.2.1 Identical Design Elements

Demineralized water. The choice of demineralized water as the coolant in the NiPEC systems helps reduce or eliminate electrical conductivity risks and minimizes corrosion of components and equipment, aligning with USN requirements for shipboard electronics [23]. Each system's pumps are engineered to deliver a continuous flow at the necessary pressure, while an expansion tank accommodates thermal expansion and contraction to stabilize system pressure during operation.

Cold plate. As shown in Figure 4.3, a cold plate is used to serve as the interface point for heat exchange with the PEBB stack. Padilla et al. [22] conducted a preliminary thermal analysis of PEBB heat dissipation strategies utilizing liquid-cooled cold plates across the dry interface of the PEBB's external surface shown in Figure 4.4.

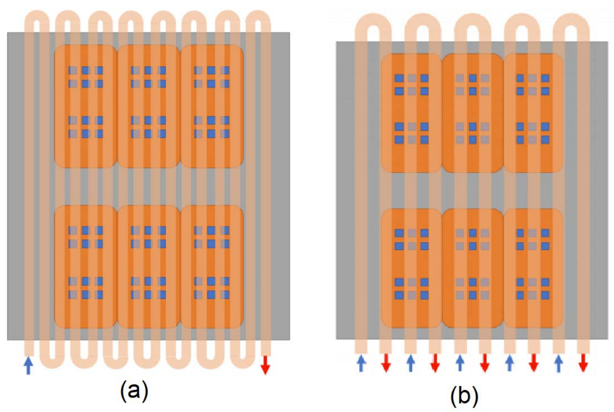


Figure 4.4: (a) Cold plate arranged as a single-pass heat exchanger, (b) Cold plate arranged as a counterflow heat exchanger [22]

Reyes [23] further developed the concept and implemented a cold plate arranged as a counter flow heat exchanger into the design of the initial cooling system. The cold plate is arranged in such a way that the inlet and outlet pipes are aligned with a hinge mechanism and are located at the back of the PEBB stack internal to the cabinet. The cold plate is hinged to open and fit around an individual PEBB to provide heat transfer surfaces on the top and bottom of each PEBB. The number of cold plates is dictated by the number of PEBBs in the corridor. This final cold plate design was carried forward into the six-zone and modular cooling system designs. Future iterations of the cold plate design would be integrated into future designs and are expected to remain consistent across cooling system design variations.

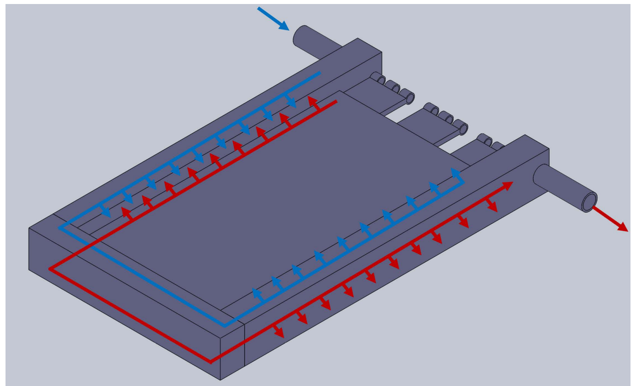


Figure 4.5: Cold plate arranged as a counter-flow heat exchanger. [23]

These shared design features are not further analyzed in the subsequent sections focusing on manufacturability assessments of the NiPEC cooling system designs since they will be identical. This allowed for a concentrated evaluation on distinct aspects that could influence critical design choices.

4.2.2.2 Varying Common Design Elements

The remaining common components are similar in function and design but will vary in size and quantity. Each of these design elements was included in the manufacturability assessment. The varying sizes and quantities of each component will impact the overall production and installation of the cooling system.

Cooling water piping. The chill water infrastructure required for the cooling system includes insulated pipes that run under the corridors on both sides of the ship. Figure 4.6 illustrates the cooling headers positioned beneath the NiPEC equipment cabinets in a preliminary NiPEC ship arrangement design [8]. The header size differs between the two designs, but the arrangement is the same to run from underneath the cabinets to facilitate interface with the internal cooling components.

If the corridor spaces are air-conditioned, the insulation requirement is one-half inch, increasing the total diameter of the piping [25], as detailed in Figure 4.7 that dictates the insulation requirements based on the temperature of the space and the control of the climate.

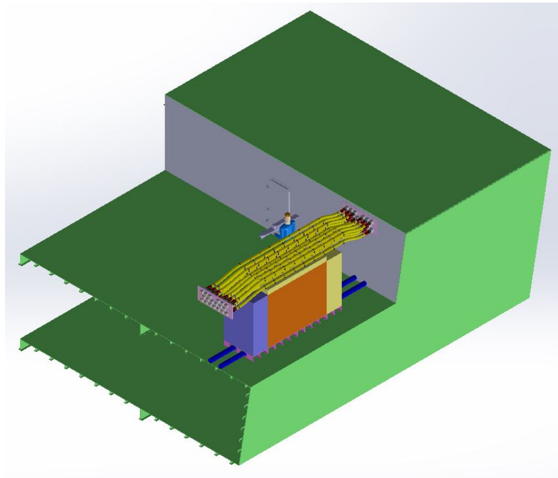


Figure 4.6: Cooling Piping (Colored Blue) Perspective View [8]

Pipe Size (inches)	Temperature Range (°F)	Nominal Thickness (inches)		
		Non-Air Conditioned Spaces	Air Conditioned Spaces	Air Conditioned Spaces Open to Weatherdeck 1/
All	-20 to -1	1½	1	2
	0 to 40	1	¾	1½
	41 to 125	¾	½	1
NOTE: Wherever possible, double layers or double thickness of insulation shall be used where piping is exposed to high humidity conditions. An example is a space that is in close proximity to the weather deck or outside doors and subject to outside air exposure.				

Figure 4.7: MIL-STD-769 Insulation Thickness Requirements [25]

The final specifications for these elements will be determined by the overarching NiPEC project, ensuring uniformity across all cooling system designs.

Pump. In both cooling system designs, as in the initial system designed by Reyes, centrifugal pumps are used to circulate the coolant. The pumps were sized for each system design based upon the flow rate of liquid the pump is required to deliver and the total differential head the pump must generate to deliver the required flow rate [24].

Chemistry control. Ion exchangers and filters are included in the cooling system designs to maintain system chemistry and remove any particulates that accumulate. This is illustrated in Figure 4.2 in the initial system design [23]. This remained consistent through future cooling system design iterations.

Expansion tank. Both cooling systems utilize an expansion tank to maintain the system pressure during operation. The expansion tank is sized for each respective system to accommodate thermal expansion of the system coolant, maintain positive pressure at points in the system at all times and under all conditions, and maintain sufficient net positive suction head to the system cooling pumps [24].

4.3 Six-Zone Cooling System

The first of the two cooling system variants evaluated in this chapter is a six-zone ship-wide system. Chatterjee [24] developed a six-zone NiPEC cooling system by further developing the initial concept design by Reyes [23]. The six-zone system refined the original design in Figure 4.2 and expanded it to a ship-wide system that could be scaled to meet the electrical load requirements of a complete all-electric ship. This design created a more centralized system capable supporting multiple portions of the power corridor and allowing fewer heat exchangers and also building in system redundancy.

4.3.1 Description

The six-zone system designed by Chatterjee [24] used many of the existing elements of the initial design but created centralized cooling skids to support cooling each of the four corridors, with each cooling skid configured to support normal operations and assume additional load in the event of a casualty. The greatest change from the initial system was in the arrangement and anticipated electrical and thermal loading, while the principles and components were mostly unchanged. Each of the cooling zones is capable of assuming the load of another zone if necessary due to casualty or maintenance.

During the development of the six-zone thermal requirements, Chatterjee investigated the PEBB distribution across the ship based on the notional all-electric warship at the most limiting condition, or the maximum power requirement. As described in Section 4.2.1, this included a detailed analysis of the iPEBB and PEBB distribution and thermal loading. This dictated the sizing of the system equipment such as heat exchangers and pumps.

In this design three zones exist on each side of the ship to support the two corridors on either side of the ship. Figure 4.8 illustrates the six-zone system main cooling headers and cooling skid locations on a notional ship. Each zone is cooled by a centralized two-pass shell-and-tube heat exchanger, modeled in Figure 4.9, similar to the initial four-pass design.

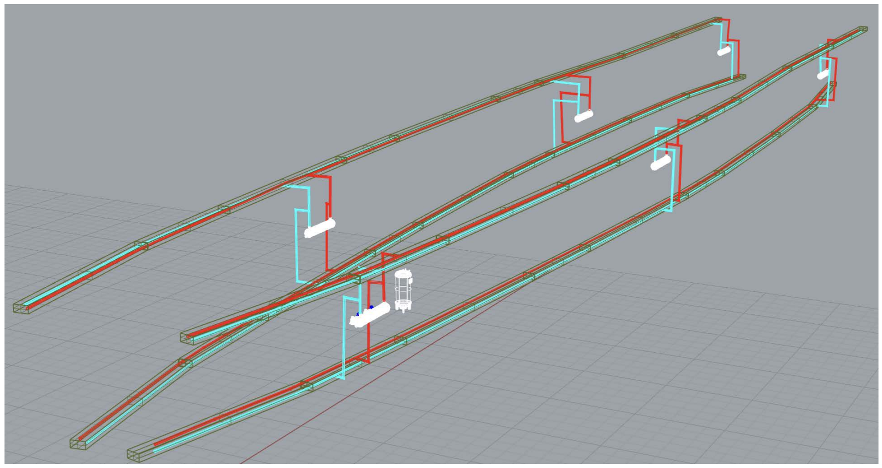


Figure 4.8: 6-Zone NiPEC Cooling System Main Header [24]

These heat exchangers were chosen for their ability to operate under high temperatures and pressures, their low pressure loss, ease of leak detection and repair, simpler maintenance, and resistance to physical damage [23]. They are sized 2 feet by 10.18 feet by 3 feet, sized to meet the most limiting condition thermal loading and also be feasible to install six throughout the ship [24].

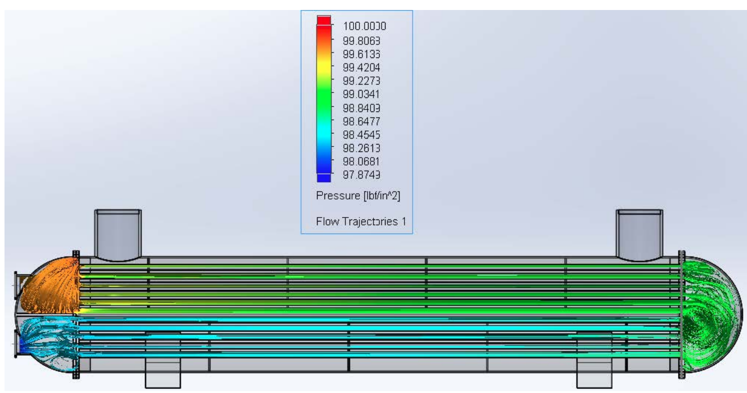


Figure 4.9: Two-pass heat exchanger chilled water flow pressures [24]

The six-zone system is arranged such that the cooling system equipment is located on cooling skids. This includes the two pumps, two heat exchangers, expansion tank, ion exchangers, and the filter. Each cooling skid constitutes one cooling source and supports one loop with the ability to support two additional zones in the event of a casualty.

Figure 4.10 illustrates the six-zone system with the predicted PEBB stack arrangements. This shows the location of each cooling source strategically located over the length of the

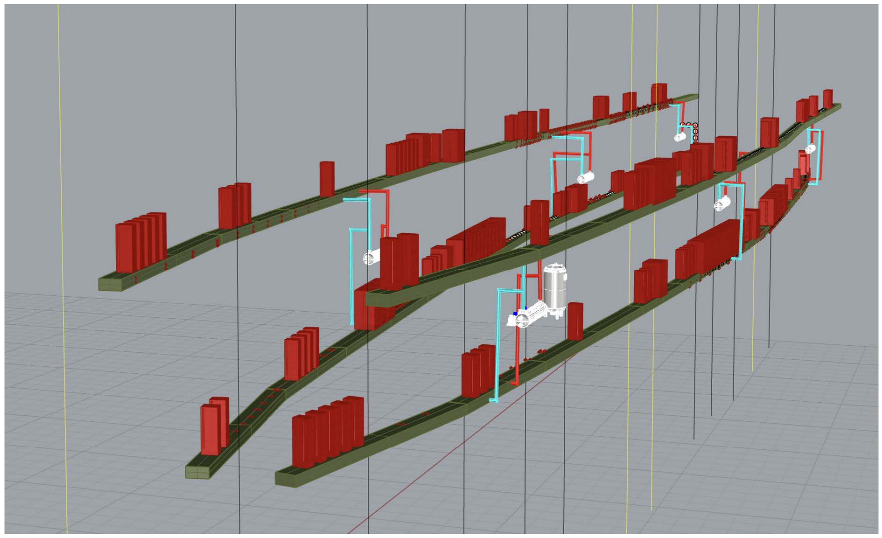


Figure 4.10: Model of six-zone NiPEC cooling system with PEBB arrangements [24]

ship. The system is designed to support the expected ship loading for the notional all-electric war ship. Table 4.4 indentifies the compartment number each of the six cooling skids is located within on the third deck of the notional ship.

Cooling Skid Identifier	**Compartment**	**Longitudinal Location (Aft of FP, m)**	**Transverse Location (m)**
Forward Port	3	33.1	-5.50
Forward Starboard	4	46.2	5.50
Mid Port	6	73.2	-5.50
Mid Starboard	8	87.7	5.50
Aft Port	10	118.0	-5.50
Aft Starboard	11	128.0	5.50

Table 4.4: Six-zone NiPEC cooling system cooling skid locations (all 3rd Deck) [24]

4.3.2 Manufacturability Evaluation

After considering the equipment and specifications of the six-zone NiPEC cooling system, the system was then evaluated on the basis of system manufacturability using each of the criteria described in Section 4.1.1. Each step of this evaluation is described in the following sections.

4.3.2.1 Number of Parts

As described in Section 3.1.1, the number of parts is a leading indicator of a system's manufacturability [11]. This system was evaluated for all parts required to make up the cooling system. The ship chill water header and connections as well as the cold plates were excluded from the evaluation, as these are consistent across all designs of the cooling system NiPEC.

To support cooling flow through the system, there are 12 centrifugal pumps included in the system design. The system is intended to operate with one pump operating in each of the six zones while the second pump is in standby to allow for redundancy in the event of a casualty or maintenance.

The largest components installed are the 12 shell-and-tube heat exchangers to facilitate heat transfer between the closed-loop demineralized NiPEC cooling system and the ship chill water system. There are six in operation at any given time. This allows for continued operation during routine maintenance and heat exchanger casualties.

Pipe Diameter (in)	**Location**	**Length Required (m)**
1	Cold Plate In/Out	19,328
2	PEBB Stack In/Out	860
5	Pump Suction Header	399
5	Pump Discharge Header	417

Table 4.5: Six-Zone Cooling System Piping Requirements

The piping required to make up the six-zone system includes various different diameters to complete different portions of the system. The largest portion of the piping is for pump suction and discharge, which also make up the supply and return headers of the cooling system. This is the longest length of piping, as it must traverse the ship from the six cooling skids to each of the watertight compartments containing sections of the corridor. The specific piping diameters required and lengths of the piping are listed in Table 4.5 [24] [23]. The total piping required for the cold plate and PEBB stack inlet and outlet branches are assumed to be the same in both the six-zone cooling system and the modular cooling system, since the number of PEBB stacks was assumed constant between the two designs.

Figure 4.11 shows what an arrangement of cold plates to support four PEBBs in a single

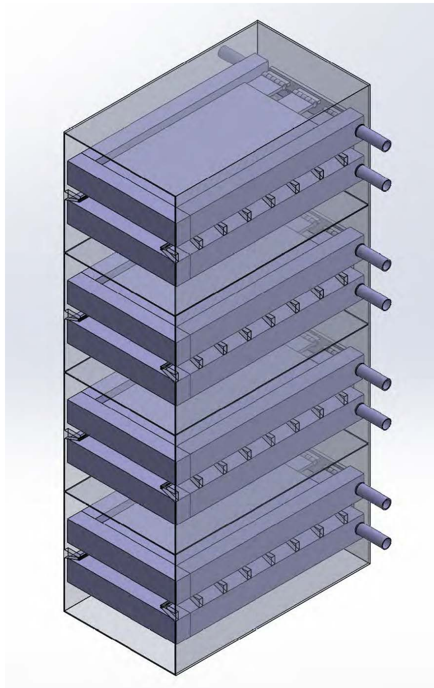


Figure 4.11: Idealized PEBB Stack Cold Plate Arrangement[23]

PEBB stack would look like. A 1-inch pipe connects to each cold plate inlet and outlet and extends outside the cabinet. Then connections would be made to two-inch branch piping to connect the entire stack to the supply and return cooling system headers. Two cold plates are required for each PEBB, resulting in 1208 cold plates based on the assumption of 604 PEBBs. Two-inch piping makes up the piping branches to each of the 172 PEBB stacks, and five-inch piping makes up the main coolant suppply and return headers.

The equipment required to maintain system chemistry is installed on each cooling skid, as each cooling skid is designed to operate independently from the rest. This requires a complete set of support equipment for each skid. This includes the ion exchanger resin beds and filters. A single expansion tank is also located on each cooling skid to support each of the six cooling zones.

Valves, fittings, and sensors are located throughout the cooling system. This assessment took the total number of these parts outside the PEBB stacks in the initial system designed by Reyes [23] and assumed that the same number would be present in each cooling skid arrangement. The components supporting each PEBB stack were then applied to the number of total PEBB stacks in the six-zone system (172 PEBB stacks). The number of components

Component	Total Part Count
Pumps	12
Heat Exchangers	12
Piping	21,004m
Valves	8,460
Fittings	36
Sensors/Gauges	1624
Expansion Tanks	6
Filters	12
Ion Exchangers	12
Total	**8,460 parts/21,004m piping**

Table 4.6: Six-Zone NiPEC Cooling System Total Number of Parts

supporting each cold plate were applied to double the number of PEBBs assumed to be in the six-zone cooling system (604 combined iPEBBs and PEBB 6000s), supporting two cold plates for each PEBB. Table 4.6 summarizes the total part requirements. This gives a total part count of 8,460 parts and 21,004 meters of piping for the six-zone NiPEC cooling system.

4.3.2.2 Off-Hull Test

Off-hull testing evaluates the readiness of a system and its components before shipboard installation, serving as a critical measure to reduce project duration and mitigate risks. Effective off-hull testing can significantly reduce the need for re-work during the ship construction phase by identifying and rectifying issues early. Extensive testing prior to installation improves the manufacturability of the system by minimizing both costs and risks associated with post-installation failures. The scale developed to assess the level of off-hull testing in this analysis is described below. This categorizes the extent to which system components are verified before shipboard installation.

- **Score 1 (Very Limited):** Only basic functionality checks are conducted to ensure the system powers on and off correctly.
- **Score 2 (Limited):** This includes static and limited dynamic testing under controlled conditions, focusing on specific subsystems without simulating full operational environments.

- **Score 3 (Moderate):** Tests all critical subsystems under simulated operational conditions, although not all environmental variables are included, potentially leaving some performance aspects unverified.
- **Score 4 (Extensive):** Nearly all operational conditions and environments are tested, except for a few extreme conditions.
- **Score 5 (Comprehensive):** Comprehensive testing is performed under all possible operational and environmental conditions to ensure the system is fully vetted for every anticipated real-world scenario.

Specific components such as fittings and filters, which are typically pass/fail items, require minimal testing and are categorized as low testability components. Piping testability is limited; individual segments can be evaluated according to system specifications, yet comprehensive testing of the entire piping network is only feasible post-installation. Header isolation valves and sensors/gauges can only undergo moderate testing off-hull, as full functionality tests necessitate complete system integration.

Components mounted on the six cooling skids, including pumps and heat exchangers, offer better testability off-hull due to their modular design. These components can be individually tested in isolation and potentially in conjunction with the entire skid, provided appropriate testing infrastructure is available. The assessment of the ability to test each component of the six-zone NiPEC off-hull is summarized in Table 4.7.

4.3.2.3 Number of Unique Parts

Then the six-zone cooling system parts list was evaluated for the number of unique parts. A unique part is each type of component or part. This is a subset of the previous part count and is a strong indicator of the system's standardization. This was the second-highest weighted factor used in the assessment of manufacturability in this study. Table 4.8 lists the unique parts for the six-zone cooling system, listing a total of 23 unique parts for the six-zone cooling system. Each similar but different-sized component, such as valves and piping, was accounted for as a unique part. In addition, different valve types were considered unique parts. Although the parts count was very large, the unique parts count is quite small. The

Component	**Testability Score (1-5)**	**Comments**
Pumps	2	Can be partially prior to installationExtensive due to modular design
Valves	2	Moderate; full testing requires installation
Heat Exchangers	3	Extensive, can be partially tested in isolation
Pipes	2	Limited; Dependent on installation
Fittings	1	Minimal testing needed beyond pressure test
Sensors/Gauges	3	Moderate; functional tests possible pre-installation
Expansion Tanks	4	Pre-installation testing feasible
Filters	4	Pre-installation testing feasible
Ion Exchangers	4	Extensive; Pre-installation testing feasible

Table 4.7: Six-Zone NiPEC Cooling System Component Ability to Test Off-Hull

standardization of parts in the system is a positive indicator of both the manufacturability and the maintainability of the six-zone system. This was a conscious design decision to use the same components for the six zones, limited by the most restrictive thermal loading case.

4.3.2.4 Man-hours for Installation

The manufacturability assessment of the NiPEC six-zone cooling system included an evaluation of the requirements for shipboard installation during the ship construction phase. This measure reflects the estimated man-hours to install the system, influenced by both the number of individual components and their installation complexity. The complexity ratings developed for this study are described below. The level of complexity also indicates potential risk to the installation; the greater the complexity, the greater the risk of error or rework.

- **Score 1 (Very Simple):** Minimal parts and connections. Plug-and-play components, requiring basic tools without specialized skills. Quick installation with a low risk of errors.

Component	**Unique Part Count**
Pumps	1
Valves	5
Heat Exchangers	1
Piping	4
Fittings	3
Sensors/Gauges	5
Expansion Tanks	1
Filters	1
Ion Exchangers	2
Total	**23**

Table 4.8: Six-Zone NiPEC Cooling System Total Number of Unique Parts

- **Score 2 (Simple):** Few additional steps with standardized components. Installation is well-documented, allowing for a straightforward process with little room for error.

- **Score 3 (Moderate Complexity):** Several parts requiring coordination. May need specialized tools or knowledge with some risk of minor errors or adjustments.

- **Score 4 (Complex):** Skilled technicians needed for installation. Involves precise alignment or calibration of multiple components. More prone to complications or delays.

- **Score 5 (Highly Complex):** Highly intricate systems requiring advanced expertise and specialized equipment. Installation is time-consuming with a high risk of errors and requires extensive calibration.

For the six-zone cooling design, a significant reduction in installation time is achieved through the use of six pre-assembled cooling skids. Each skid consolidates much of the system's supporting equipment, which simplifies the shipyard's task by enabling installation as composite units rather than multiple smaller components. This strategic pre-assembly significantly streamlines the process compared to a scenario where equipment is distributed across various watertight compartments. This installation strategy not only minimizes the labor hours but also reduces the potential for installation errors.

Piping is the largest contributor to this system installation. It is important to separate what will be installed as a pre-assembled assembly and what will be installed on-board. It is assumed that each section of the corridor as well as the six cooling skids will be installed pre-assembled. This removes the burden of installing the piping connections to each cold plate and the piping and connections between each of the components on the cooling skid. This leaves the cooling supply and return headers and the two-inch pipe to connect each PEBB stack to the main cooling headers. This reduces the estimated man-hours for piping installation from 24,441 to 2,755 man-hours, an 88% reduction in the shipboard piping installation requirement.

Pipe Diameter (in)	Schedule	Man-Hours per Meter
1.0	40	1.122
2.0	40	1.320
5.0	40	1.716
5.0	80	2.244

Table 4.9: Estimated Man-Hours per Meter Pipe Installation [26]

Estimated man-hours for system piping were calculated by piping length using the estimated values specific to the type of metal used [26]. The man-hour estimates for the handling and erecting of copper-nickel 90-10 alloy pipes are listed in Table 4.9. Insulating the piping with the required one-half inch adds another 1.32 man-hour/meter of very simple work. The estimates used are for straight-run pipe to provide first-pass estimates useful for comparison between to the two cooling systems. For a more detailed analysis, each section, bend, and connection would need to be estimated from the detailed design drawing. The cooling headers extend the length of the corridor and span 14 watertight compartments on either side of the ship. This level of ship integration and coordination makes the installation complex.

The simplification achieved through the pre-assembly of cooling skids is a pivotal factor in the updated six-zone design compared to the initial single compartment design, offering substantial improvements in installation efficiency and reliability. As a result, the pumps, heat exchangers (HXs), expansion tank, filters, and ion exchangers (IXs) are installed as one unit on each of the six cooling skids. Additionally, many of the valves, fittings, and sensors are also included in the pre-assembled cooling skids. The components remaining that require individual installation are the fittings to route the cooling headers up/down and aft/forward, header isolation valves, and sensors installed at the PEBB stack branches.

Additional fittings were added in the six-zone system to allow for the headers to connect the headers to the 2nd and 4th decks as well as tee-connections to extend the headers forward and after [24]. These fittings would be installed following each cooling skid installation. Fittings are frequently repeated simple installations.

There are 16 header isolation valves in the system to isolate the forward and aft zones on either side of the ship from the central zone as required due to maintenance or casualty. These valves were assumed to be motor-operated to support remote operation necessary for rapid system isolation. Motor-operated valves require testing and extensive calibration, an overall complex installation.

Flow and pressure sensors are included in the system at each PEBB stack. This accounted for the installation of 344 sensors beyond what is included in the cooling skid installations. Sensor installation requires mechanical and data connections and calibration making them moderately complex installations.

Finally, the six cooling skids containing most of the cooling system equipment must each be installed as a composite unit. These are complex installations as it requires to be lifted into the ship and closely coordinated in the ship build sequence. In addition, each skid will require mechanical, electronic, and data connections, making the installation highly complex.

Component	**Estimated Man-Hours**	**Complexity Rating (1-5)**
Cooling Skids (pumps, HXs, expansion tank, filters, IXs, sensors, valves, fittings)	93	5
Valves	619	4
Piping	2,755	3
Insulation	2,212	1
Fittings	14	2
Sensors	206	3
Total	**6,044 man-hours**	

Table 4.10: Six-Zone NiPEC Cooling System Estimated Installation Man-Hours [26] [27]

Table 4.10 summarizes the estimated man-hours and the installation complexity for each major component of the system, using the standardized complexity rating from 1 to 5.

4.3.2.5 Maintenance Hours

The assessment of the annual maintenance requirements for each major component within the six-zone NiPEC cooling system was fundamental to quantifying the total system maintenance needs over the course of a year. This analysis utilized notional data to estimate the workload and man-hour commitments necessary for maintaining optimal system performance.This was important for a trade-off dicussion between manufacturability and maintainability as well as a direct comparison between system design variants.

The annual maintenance man-hours required for the six-zone NiPEC cooling system are detailed in Table 4.11. This table categorizes maintenance requirements by system component, highlighting the estimated man-hours per item, the most frequent maintenance periodicity, and the total estimated annual man-hours. These estimates are based on publicly available data on comparable industrial components. The estimates were extended to account for the expected maintenance frequency for each key component over the year, enabling the calculation of an estimated annual total. Maintenance calculations assume single-unit operations, with the total hours representing the aggregated annual effort required for all units of each component, under the assumption that maintenance needs are consistent across all units. A comprehensive notional annual maintenance schedule for each major component of the system is available in Appendix B.

Components such as pumps and valves, which require daily or weekly checks, represent a significant maintenance burden due to their large numbers and critical operational roles. Conversely, components like pipes and fittings require less frequent maintenance, which reflects their lower risk of failure and easier accessibility. Understanding these maintenance requirements is essential for planning the necessary manpower and logistical support throughout the system's life cycle. Maintainability is a critical consideration in evaluating life cycle costs and making trade-offs in shipboard system design.

The maintenance estimates used in this assessment were derived from industry standards and rational assumptions based on both available data and previous operational experiences.

Component	Man-Hours/Unit	Highest Periodicity	Man-Hours/System
Pumps	597.25	Daily	7,167
Valves	22	Weekly	148,412
Heat Exchangers	72.5	Weekly	870
Pipes	4	Semi-annually	24
Fittings	8.25	Semi-annually	297
Sensors	9	Quarterly	14,616
Expansion Tanks	5	Semi-annually	30
Filters	6.5	Quarterly	78
Ion Exchangers	3.5	Quarterly	42
Total			**171,536 man-hours**

Table 4.11: Six-Zone NiPEC Cooling System Estimated Annual Maintenance Requirements [28] [29] [30] [31]

For future evaluations of proposed USN ship systems and existing equipment, leveraging current periodic maintenance system (PMS) data could refine these annual hour estimates. However, the methodology for aggregating total annual maintenance hours and their use in comparative analyses between different system designs would remain unchanged. The initial estimates provided in this study are sufficient for comparing the significant differences in maintenance requirements between the two system designs.

4.3.2.6 Level of Redundancy

The final parameter evaluated in this study for the six-zone NiPEC cooling system was the level of redundancy of the system components. Redundancy is a critical measure of expected system reliability and operational continuity, essential for extending system longevity and balancing equipment runtime. The levels of redundancy developed for use in this analysis, which indicate the likelihood of uninterrupted operation, are described below:

- **Score 1:** No redundancy.
- **Score 2:** Redundancy present but requires manual activation.
- **Score 3:** Basic automated redundancy for critical failures.
- **Score 4:** High redundancy with automatic fail over.

- **Score 5:** Full redundancy with no single point of failure.

Component	Redundancy Score	Details
Pumps	4	Automatic fail over
Valves	2	Manual operation needed
Heat Exchangers	2	Manual alignment to alternate
Pipes	2	Manual bypass available
Fittings	1	No redundancy
Sensors/Gauges	4	Multiple indication sources
Expansion Tank	2	Manual alignment to alternate skid
Filters	4	Dual filters
Ion Exchangers	2	Manual alignment to alternate skid

Table 4.12: Six-zone NiPEC Cooling System Component Redundancy

Component Redundancy Scores Table 4.12 lists the redundancy scores for key components of the system according to the scale of one to five. This provides a straightforward assessment of redundancy levels across different system components. Higher scores indicate better redundancy, significantly contributing to system reliability. These scores facilitate a clear comparison between components and help identify potential areas for improvement in system design and were later used to compare different system designs.

System-Wide Redundancy Beyond individual components, redundancy is integrated throughout the cooling system:

- **Pumps and Heat Exchangers:** Dual setups ensure that any single point failure does not compromise the system's functionality. The pumps are automatic in fail over, while the heat exchangers require a manual valve lineup change.

- **Sensors:** Multiple sensors are used to provide fail-safe operations and real-time monitoring, enhancing the system's response capabilities.

- **Six Cooling Zones:** The six-zone design supports four power corridors, with three zones capable of independently supporting two corridors. Each zone may assume the load of another in the event one fails, such that two corridors may be supported by two cooling zones.

- **Corridor Redundancy:** The ship is designed to operate efficiently even if one corridor is out of service, further providing system redundancy in the event of a cooling zone loss.

Overall, the six-zone NiPEC cooling system was assessed a score of four, indicating high redundancy with automatic failovers. The level of redundancy within the system components, as well as the overall system-level redundancy, provides a high level of system reliability.

4.3.3 Six-Zone Cooling System Summary

After considering the equipment and specifications of the six-zone NiPEC cooling system, the system was evaluated on the basis of system manufacturability using each of the criteria described in Section 4.1.1. The system's design incorporates a high degree of standardization, as evidenced by a low count of unique parts relative to the total number of components. This standardization significantly aids in simplifying the manufacturing process and reduces potential rework during assembly.

Moreover, the system's modular design, particularly the pre-assembly of cooling skids, drastically reduces installation complexity and man-hours required on ship. This modular approach not only facilitates easier and more reliable installations, but also enhances the system's maintainability and robustness through well-integrated redundancy measures.

Overall, the Six-Zone NiPEC cooling system demonstrates excellent manufacturability characteristics, making it a viable option for deployment to support thermal management for the power corridor. The careful consideration of each manufacturability aspect ensures that the system is not only efficient to produce, but also operationally dependable and easy to maintain over its service life.

Table 4.13 summarizes the manufacturability assessment for the six-zone NiPEC cooling system. This includes total part counts, unique part counts, estimated man-hours for installation, off-hull testability scores, estimated annual maintenance hours, and redundancy scores. These scores were used to compare with the results of the modular system design manufacturability and trade-off assessment described in the following sections.

Component	Total Parts	Unique Parts	Install Hours	Testability Score	Maint. Hours	Redundancy Score
Pumps	12	1	93	4	7,167	4
Valves	6,746	5	619	3	148,412	2
Heat Exchangers	12	1	-	4	870	2
Pipes	21,004m	4	4,967	2	24	2
Fittings	36	3	14	1	297	1
Sensors/Gauges	1,624	5	206	3	14,616	4
Expansion Tanks	6	1	-	4	30	2
Filters	12	1	-	4	78	4
Ion Exchangers	12	2	-	4	42	2
Total	**8,460/21,004**	**23**	**6,044**	-	**171,536**	-

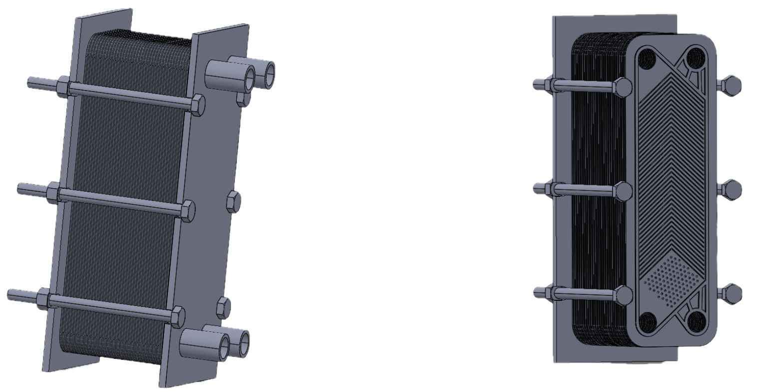
Table 4.13: Overall Assessment of the Six-Zone NiPEC Cooling System

4.4 Modular Cooling System

The second cooling system evaluated in this study is a more modular design. The power corridor by design is a modular entity that incorporates all components of the electrical distribution system for the main bus power throughout the ship [4]. Kruse [8] discusses the modularity of the power corridor design with respect to the PCM development and sizing. A modular cooling design furthers this idea and incorporates a key NiPEC support system into the corridor itself.

4.4.1 Description

The modular NiPEC cooling system concept is possible due to an updated heat exchanger design utilizing a plate and frame design. Based on the fundamentals of the six-zone cooling system, Meyers [32] designed and modeled a compact heat exchanger intended to support a modular NiPEC cooling system design. The heat exchangers are compact and designed to be integrated within the corridor structure to support thermal management. Each heat exchanger is capable of providing adequate cooling for two PEBB stacks. The supporting equipment will be located on a cooling skid similar in concept to that of the six-zone system previously described.



(a) Profile view (b) Front view

Figure 4.12: Modular plate heat exchanger [32]

Figure 4.12 is a visual depiction of the plate and frame heat exchanger. The heat exchanger will be part of a closed-loop demineralized water system and will be cooled by the ship service chill water system, similar to the shell-and-tube heat exchangers in the previous system. The benefit of this design is the compact nature that allows it to be located within the corridor structure. Although this design has not yet been fully explored, it is made possible with the newly developed compact heat exchanger design. This study made assumptions about the layout of the modular system for the purpose of assessing the manufacturability of the system and drawing comparisons to the six-zone system.

Figure 4.13 is a line diagram representing the proposed design of the entire modular system to support the integration of the modular heat exchanger. Figure 4.13 shows two modular heat exchangers supported by a single cooling skid. This is a preliminary design that will require future work to rate the pump and supporting equipment required to support multiple modular heat exchangers in the space. This study made the assumption that a single cooling skid will support each watertight space and the corresponding NiPEC section.

Included on each cooling skid is a single centrifugal pump similar in design and rating

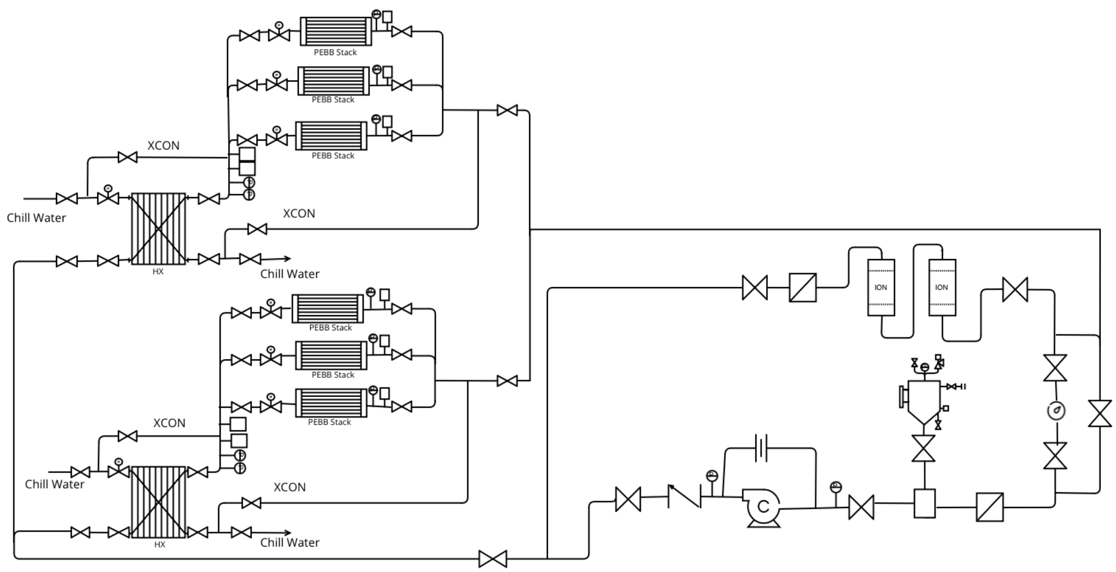


Figure 4.13: Modular NiPEC Cooling System Design

to those used in the initial cooling system design for a single compartment [23]. In this modular design, the backup coolant source is provided by a cross-connect to ship chill water. Differential pressure would force chill water directly through the heat exchangers and PEBB stack cold plates in the event the pump was out of service and the corridor section affected was required to continue operating. Also located on the skid is a series of two ion exchangers and a filter for water chemistry management as well as an expansion tank to maintain system pressure during operation. While sizing may vary, the design and operation of this equipment is the same as the six-zone system. This colocation of the cooling skids removes the requirement for support equipment in external spaces. The only external connection from outside the watertight space is chill water.

A major assumption for assessing the manufacturability of the modular cooling system is the number of heat exchangers required to support thermal management for the entire corridor system. This study made the assumption that the heat load is the same as calculated by Chatterjee [24] using the notional all-electrical war ship so the number of PEBB stacks remained consistent between the two cooling system designs assessed. Table 4.14 shows the iPEBB and PEBB 6000 ship distribution and the resulting modular heat exchanger requirement. Each modular heat exchanger is designed to have the capacity to cooling two PEBB stacks. Table 4.14 shows the PEBB stack allocation for each the port and starboard sides of the ship and the associated heat exchangers required. Based on the heat load assessment of Chatterjee [24], 58 modular heat exchangers would be required to support the NiPEC in its entirety.

Compartment	iPEBB Stacks		PEBB 600 Stacks		Compartment Total	
	Port	Starboard	Port	Starboard	Port	Starboard
0	1	1	0	0	1	1
1	1	4	0	0	1	4
2	4	1	0	0	4	1
3	2	2	0	0	2	2
4	2	5	4	0	6	5
5	9	6	0	0	9	6
6	5	5	10	10	15	15
7	3	3	0	20	3	23
8	3	6	12	4	15	10
9	2	2	20	0	22	2
10	5	2	0	0	5	2
11	1	4	0	0	1	4
12	5	2	0	4	5	6
13	1	1	0	0	1	1
Stack Totals	44	44	46	38	90	82
Heat Exchangers Required					**Total**	**86**

Table 4.14: PEBB Distribution across Compartments & Heat Exchanger Requirement [24]

4.4.2 Manufacturability Evaluation

Following a thorough examination of the equipment and specifications integral to the modular NiPEC cooling system, an assessment was conducted with a focus on system manufacturability. This assessment also adhered to the set of criteria delineated in Section 4.1.1. The following sections detail each stage of this evaluation process.

4.4.2.1 Number of Parts

As outlined in Section 3.1.1, the number of parts is a critical indicator of a system's manufacturability [11]. For the modular NiPEC cooling system, this evaluation focused on all parts required to assemble the cooling system. Similar to the six-zone system, cold plates and the main chill water headers were excluded from this count, as these components are consistent across all designs of the NiPEC cooling system.

The notional modular system includes a cooling skid in every watertight compartment containing a NiPEC section. As previously described, each cooling skid contains the supporting equipment for the cooling system. The proposed layout includes 28 of these cooling skids and its included equipment: pump, expansion tank, ion exchangers, filters, and piping.

For heat transfer between the closed-loop demineralized NiPEC cooling system and the ship's chill water system, the design incorporates plate-and-frame heat exchangers. Unlike the six-zone system's shell-and-tube exchangers, these are configured to be installed within the power corridor. Each heat exchanger is designed to support two PEBB stacks, so the number of PEBB stacks dictates the number of heat exchangers. The notional all-electric ship with the joint PEBB stack distribution described in Table 4.14 requires 58 plate-and-frame heat exchangers.

Pipe Diameter (in)	Location	Length Required (m)
1.0	Cold Plate In/Out	19,200
2.0	PEBB Stack In/Out	860
4.0	Pump Suction Header	294
3.5	Pump Discharge Header	294

Table 4.15: Modular Cooling System Piping Requirements

The piping architecture of the modular system varies in diameter and is structured to optimize the modular design. The largest segments of piping are those connecting the pump suctions and discharges, which form the primary supply and return headers of the cooling system. In contrast to the six-zone system, these headers are contained within a single watertight compartment. This reduces the length of piping and the required size for each modular system. For the purposes of this study, the supply and return headers were assumed to be consistent with the initial, single compartment design [23] since the piping will be restricted to a single space. The specific piping diameters and required lengths are summarized in Table 4.15.

Support equipment for maintaining system chemistry, such as ion exchanger resin beds and filters, is integrated into each modular skid, designed to operate independently. Each module includes a single expansion tank to accommodate fluctuations within that module's cooling zone.

Valves, fittings, and sensors are placed throughout the cooling system to ensure operational integrity and facilitate maintenance in the same manner as the six-zone system cooling skids. The key difference being 28 instead of six cooling skids, resulting in a total parts count of 9,588 parts and 20,776 meters of piping. Table 4.16 provides a summary of these components.

Component	**Total Part Count**
Pumps	28
Heat Exchangers	58
Piping	20,776m
Valves	7,470
Fittings	56
Sensors/Gauges	1808
Expansion Tanks	28
Filters	56
Ion Exchangers	56
Total	**9,588 parts/20,776m piping**

Table 4.16: Modular NiPEC Cooling System Total Number of Parts

4.4.2.2 Off-Hull Test

Off-hull testing critically evaluates the readiness of the modular NiPEC cooling system and its components prior to their installation on the ship. This process is essential to reduce the timeline of the project and mitigate risks by actively identifying and addressing potential issues, thus minimizing the likelihood of costly rework during ship construction. This is a way to maximize the benefits of a modular design.

In the same method as the six-zone system, the modular NiPEC cooling system was evaluated for the extent to which its components may be tested off hull on the 1 to 5 scale described in Section 4.3.2.4, ranging from very limited to comprehensive.

Certain components, such as fittings and filters which typically have binary outcomes in tests, require minimal testing and thus are deemed low in testability. Piping testability remains limited, with individual segments tested per specifications; however, a full system test of the piping network is feasible only after installation. Header isolation valves and sensors/gauges undergo only moderate off-hull testing since comprehensive functional testing requires full system integration.

Modular components, including pumps and heat exchangers, exhibit higher testability off-hull due to their design, allowing for isolated and collective testing within modular skids if the appropriate testing setups are available. The modular design of both the power corridor containing the heat exchangers and the cooling skids provide significant off-hull testing potential. The capabilities for off-hull testing of each component of the modular cooling system are summarized in Table 4.17.

Component	**Testability Score (1-5)**	**Comments**
Pumps	4	Pre-assembly enhances test thoroughness
Valves	3	Moderate; Full testing requires installation
Heat Exchangers	4	Pre-assembly enhances test thoroughness
Pipes	4	Limited; Pre-assembly enhances test thoroughness
Fittings	4	Pre-assembly enhances test thoroughness
Sensors/Gauges	3	Moderate; Functional tests possible pre-installation
Expansion Tanks	4	Pre-assembly testing feasible
Filters	4	Pre-assembly testing feasible
Ion Exchangers	4	Pre-assembly testing feasible

Table 4.17: Modular NiPEC Cooling System Component Ability to Test Off-Hull

4.4.2.3 Number of Unique Parts

Assessing the unique parts was completed by further breaking down the total parts list to identify each different kind of part in the modular NiPEC design. The design assumes a standardized number of these components across all modules, which simplifies procurement and maintenance logistics. The total number of parts, including valves, fittings, sensors, and additional necessary components, is significant yet optimized for modular assembly and maintenance. Simliar to the six-zone system, the modular system had a significantly lower unique part count than the total parts count.

Component	Unique Part Count
Pumps	1
Valves	5
Heat Exchangers	1
Piping	4
Fittings	2
Sensors/Gauges	5
Expansion Tanks	1
Filters	1
Ion Exchangers	2
Total	**22**

Table 4.18: Modular NiPEC Cooling System Total Number of Unique Parts

4.4.2.4 Man-hours for Installation

The notional modular cooling system design further explores the ability to create a fully modular and integrated system NiPEC by presenting a heat exchanger option that would be installed in each section of the corridor and installed simultaneously.

The only connection to support the NiPEC cooling system from outside each watertight compartment is chill water. This reduces the complexity of the ship installation process for the cooling system. The heat exchangers will be installed shipboard as part of the composite corridor section which will be installed one section, or watertight compartment, at a time. The supporting equipment for each space will be installed as a set, each on a self-contained cooling skid. This increased modularity descreased the shipboard installation complexity and the estimated man-hours required for installation.

In the same manner as the assessment of the NiPEC six-zone cooling system, the modular manufacturability assessment also included an evaluation of the requirements for shipboard installation during the ship construction phase. This measure reflects the estimated man-hours to install the system, influenced by both the number of individual components and their installation complexity. The complexity was again evaluated on a one-to-five scale, very simple to highly complex.

The modular cooling design also utilizes pre-assemblies that may be utilized in the ship installation sequence. Each skid consolidates the system's supporting equipment, which simplifies the shipyard's task by enabling installation as composite units rather than multiple smaller components. This strategic pre-assembly significantly streamlines the process compared to a scenario where equipment is distributed across various watertight compartments, reducing both labor hours and reducing risk of rework and delays.

Most of the equipment will be installed via pre-assembled components, the corridor sections and the cooling skids. The only additional installation required shipboard is the piping between the corridor and cooling skid as well as any required valves or fittings. This must be repeated for each space.

Pipe Diameter (in)	**Schedule**	**Man-Hours per Meter**
1.0	40	1.122
2.0	40	1.320
3.5	40	1.980
4.0	80	1.650

Table 4.19: Estimated Man-Hours per Meter Pipe Installation [26]

The estimated man-hours for the installation of the system piping were again calculated by the length of the piping using the estimated values specific to the type of metal used [26]. The man-hour estimates for the handling and erecting of copper-nickel 90-10 alloy pipes are listed in Table 4.19. Insulating the piping with the required one-half inch adds another 1.32 man-hour / meter of low-complexity work. These are the same values used in the six-zone installation assessment, so the assessments provided comparable results. The estimates used are for straight-run pipe to provide first-pass estimates useful for comparison between to the two cooling systems. For a more detailed analysis, each section, bend, and connection would need to be estimated from the detailed design drawing. Because the piping is confined to a singular space for each modular system, the level of installation is less complex than if it crossed bulkheads.

The 28 required cooling skids must each be installed as a composite unit. These are moderately complex installations as it is required to be moved into each space with coordination during the ship build sequence. Additionally, each cooling skid will require mechanical, electrical, and data connections adding to istallation complexity.

Not contained within the construction of the cooling skids or the corridor are two header

Component	Estimated Man-Hours	Complexity Rating (1-5)
Cooling Skids (pumps, expansion tank, filters, IXs, sensors, valves, fittings)	106.4	5
Valves	619	3
Piping	2,202	3
Insulation	1,911	1
Fittings	619	2
Sensors	206	3
Total	**5,460 man-hours**	

Table 4.20: Modular NiPEC Cooling System Estimated Installation Man-Hours [26] [27]

isolation valves and two chill water cross-connect valves per PEBB stack. These valves require shipboard installation after the corridor section and cooling skid are installed.

Table 4.20 summarizes the estimated man-hours and the installation complexity for each major component of the system, using the standardized complexity rating from 1 to 5. The total estimated man-hours for installation of the modular design is 5,460 man-hours.

4.4.2.5 Maintenance Hours

The evaluation of annual maintenance requirements for the modular NiPEC cooling system utilized theoretical data to forecast the workload and man-hour commitments required to sustain equipment performance. This assessment aids in understanding the trade-offs between manufacturability and maintainability and facilitates comparisons between the two cooling system design variants.

Table 4.21 delineates the estimated annual maintenance man-hours for the modular NiPEC cooling system, organizing the data by component. It highlights the estimated man-hours per item, the most frequent maintenance periodicity, and the total estimated annual man-hours per component. These estimates, based on data for comparable industrial components, have been adjusted to match the expected maintenance frequencies for each component, similar to the method used in the evaluation of the six-zone system. The assumption here is that maintenance needs are consistent across all units. Maintenance requirements for internal valve connections at each cold plate are omitted as they are uniform

Component	Man-Hours/Unit	Highest Periodicity	Man-Hours/System
Pumps	597.25	Daily	16,723
Valves	22	Weekly	164,340
Heat Exchangers	18.5	Quarterly	1,073
Pipes	4	Semi-annually	112
Fittings	8.25	Semi-annually	462
Sensors	9	Quarterly	16,272
Expansion Tanks	5	Semi-annually	140
Filters	6.5	Quarterly	364
Ion Exchangers	3.5	Annualy	196
Total			**199,682 man-hours**

Table 4.21: Modular NiPEC Cooling System Estimated Annual Maintenance Requirements

across designs. Annual notional maintenance schedules are available in Appendix B.

Components that require frequent maintenance, such as pumps and valves, significantly impact resource allocation due to their critical roles and the sheer volume involved. Conversely, components like pipes and fittings, which require less frequent attention, present lower risk and are easier to access. The modular system's architecture, which inherently includes a larger number of parts due to its design, correspondingly increases the overall maintenance burden.

4.4.2.6 Level of Redundancy

The evaluation of redundancy for the modular NiPEC cooling system was the final area evaluated. This is an indication of the system's reliability and operational continuity. The system and components were scored using the same 1 to 5 scale, no redundancy to full redundancy.

Component Redundancy Scores Table 4.22 details the redundancy scores for key components of the modular NiPEC system, providing a clear assessment of redundancy levels across various components. Higher scores reflect more redundancy. These scores are crucial for comparing components and guiding improvements in system design, as well as understanding trade-offs between levels of modularity and manufacturability.

Component	Redundancy Score	Details
Pumps	2	Manual bypass available
Valves	2	Manual operation needed
Heat Exchangers	1	No redundancy
Pipes	2	Manual bypass available
Fittings	1	No redundancy
Sensors/Gauges	4	Multiple indication sources
Expansion Tank	1	No redundancy
Filters	4	Dual filters
Ion Exchangers	1	No redundancy

Table 4.22: Modular NiPEC Cooling System Component Redundancy

System-Wide Redundancy Redundancy is comprehensively integrated across the modular cooling system:

- **Heat Exchangers:** Each plate-and-shell heat exchanger is designed to provide cooling for two PEBB stacks and integrated within the corridor. There is no backup heat exchanger; in the event of a heat exchanger failure or maintenance shutdown, the affected corridor section would be shut down.

- **Pumps:** Each cooling skid is equipped with a single pump to circulate cooling flow to the heat exchangers in the same compartment. The back-up to the pump is a cross-connect directly from the ship chill water system to each PEBB stack. This would require a manual change in valve lineup. This would not be a desirable lineup, as it would introduce chill water into the system, so only to be used when the section of the corridor cannot be shutdown.

- **Sensors:** Multiple sensors are used to avoid a single point of failure for any critical system indication.

- **Modular Design:** Each cooling skid operates independently, providing intrinsic redundancy throughout the system. This prevents a failure of one cooling system from impacting any other part of the corridor.

- **Corridor Redundancy:** The ship is designed to operate with an entire corridor out of service. This provides additional redundancy in the event one or more cooling systems is out of service.

Overall, the modular NiPEC cooling system was assessed a score of 2, indicating some redundancy with manual override. This is a relatively low redundancy score, but the overall impact of a single cooling system failure is also relatively low due to the modular design.

4.4.3 Modular Cooling System Summary

After considering the equipment and specifications of the modular NiPEC cooling system, the system was evaluated on the basis of manufacturability using the criteria described in Section 4.1.1. The system incorporates a high degree of modularity and standardization. This is seen in the low unique parts count and the reduced estimated installation man-hours requirement.

While the unique parts count is low, the overall parts count is high due to the high number of repeated systems. This is directly related to the number of corridor sections and PEBB stacks installed. The high parts count also contributes to a high annual maintenance requirement. The level of redundancy is also not high due to the modular design in which each cooling system is self-contained.

Component	**Total Parts**	**Unique Parts**	**Install Hours**	**Testability Score**	**Maint. Hours**	**Redundancy Score**
Pumps	28	1	106	4	16,723	2
Valves	7,470	5	619	3	164,340	2
Heat Exchangers	58	1	-	4	1,073	1
Pipes	20,776m	4	4,114	2	112	2
Fittings	56	2	50	1	462	1
Sensors/Gauges	1808	5	206	3	16,272	4
Expansion Tanks	28	1	-	4	140	1
Filters	56	1	-	4	364	4
Ion Exchangers	56	2	-	4	196	1
Total	**9,588/20,776m**	**22**	**5,460**	-	**199,682**	-

Table 4.23: Overall Assessment of the Modular NiPEC Cooling System

Table 4.23 presents a comprehensive manufacturability and trade-off assessment for the modular NiPEC cooling system. It includes total and unique part counts, estimated man-hours for installation, testability scores, estimated annual maintenance hours, and redundancy scores. Overall, this design's modular approach has both benefits and consequences for the manufacturablity. These scores were then used to compare the overall benefits and negatives with those of the six-zone system and to better understand the trade-offs made between improvements in manufacturability and reductions of other key system performance parameters.

4.5 Design Comparisons

After evaluating each of the two NiPEC cooling system designs for each aspect of manufacturabilty and the specified trade-offs, the two sets of scores were compared to determine ranking for each criterion. This section compares six-zone and modular NiPEC cooling system scores based on predefined criteria to determine the most suitable system for implementation. In this study there were two separate design variants to evaluate, but this evaluation and comparison could also be completed with multiple variants. The variants would be ranked and scored one through the number of designs for each criterion. The criterion weighting applies the same to then total and rank the systems overall. This section will walk through how each set of scores compared and which system design best meets each criterion.

4.5.1 Number of Parts

This section provides a comparative overview of the total part counts for both the six-zone and modular NiPEC cooling systems, allowing an assessment of their respective complexities and component distributions.

Table 4.24 illustrates the differences in component requirements between the two designs, highlighting the increased modularity and quantity of components of the modular system compared to the six-zone system. Although the piping length required for the six-zone system was slightly longer, the total number of parts to be manufactured is lower. When

Component	Six-Zone System	Modular System
Pumps	12	28
Heat Exchangers	12	58
Piping (meters)	21,004	20,776
Valves	6,746	7,470
Fittings	36	56
Sensors/Gauges	1,624	1,808
Expansion Tanks	6	28
Filters	12	56
Ion Exchangers	12	56
Total Parts/Piping	**8,460/21,004m**	**9,588/20,776m**

Table 4.24: Comparison of Total Part Counts for Six-Zone and Modular NiPEC Cooling Systems

evaluating these systems in the overall score, the six-zone system has the lowest total parts count and scored higher. From the aspect of parts manufacturing and procurement, the six-zone system is assessed to be more manufacturable.

4.5.2 Off-Hull Test

This section compares the ability of the two cooling system design variants to be tested off-hull, prior to shipboard installation. The evaluation is beneficial in understanding which system provides greater efficiency and reliability in the pre-installation testing phases.

Table 4.25 presents the testability scores for components within both cooling system designs, reflecting their respective capabilities for pre-installation verification. The composite cystem test score aggregates these component scores to provide an overall testability assessment, showing a slight advantage for the modular system due to its enhanced modular design features. This reflects both the ability to test components off-hull as well as the potential to test a self-contained system prior to installation. This proactive testing approach is crucial for minimizing potential operational disruptions post-installation. Due to the modular nature, the modular cooling design is rated slightly higher for off-hull test capability and potential.

Component	Six-Zone System Score (Comments)	Modular System Score (Comments)
Pumps	2 (Modular design aids isolation testing)	4 (Pre-assembly enhances test thoroughness)
Valves	2 (Requires installation for full testing)	3 (Pre-assembly enhances test thoroughness)
Heat Exchangers	3 (Can be partially tested in isolation)	4 (Pre-assembly enhances test thoroughness)
Pipes	2 (Testing dependent on full assembly)	4 (Pre-assembly enhances test thoroughness)
Fittings	1 (Testing dependent on full assembly)	4 (Pre-assembly enhances test thoroughness)
Sensors/Gauges	3 (Pre-installation testing feasible)	3 (Pre-installation testing feasible)
Expansion Tanks	4 (Pre-installation testing feasible)	4 (Pre-installation testing feasible)
Filters	4 (Pre-installation testing feasible)	4 (Pre-installation testing feasible)
Ion Exchangers	4 (Pre-installation testing feasible)	4 (Pre-installation testing feasible)
Composite System Test Score	3	4

Table 4.25: Testability Scores for Six-Zone and Modular NiPEC Cooling Systems

4.5.3 Number of Unique Parts

Table 4.26 compares the unique part counts for the six-zone and modular NiPEC cooling systems. This comparison helps in understanding the standardization and modularity aspects of each design.

This shows that the two systems are nearly equal in terms of unique parts. The six-zone design had an additional fitting type to account for the risers from the third deck to the second and fourth decks where the corridors would be located. Because the systems were only one part off, an insignificant margin, and the modular design is only a conceptual design expecting refinements to a final design, the two systems were scored equally for this criterion. Because both systems were designed following the principles of the initial design of the NiPEC cooling system [23], it is not surprising that they are mainly composed of the same components. This aspect of the consideration of manufacturability for the two

Component	Six-Zone System	Modular System
Pumps	1	1
Valves	5	5
Heat Exchangers	1	1
Piping	4	4
Fittings	3	2
Sensors/Gauges	5	5
Expansion Tanks	1	1
Filters	1	1
Ion Exchangers	2	2
Total Unique Parts	**23**	**22**

Table 4.26: Comparison of Total Unique Part Counts for Six-Zone and Modular NiPEC Cooling Systems

proposed system designs is equal.

4.5.4 Man-hours for Installation

This section compares the estimated installation man-hours required for the six-zone and modular NiPEC cooling system designs. The comparison is intended to illuminate the relative labor requirement and procedural complexities of installing each system configuration. These are leading indicators for both the build schedule and potential risk to a project.

Component	Six-Zone System (hours)	Modular System (hours)
Cooling Skids (Including pumps, HXs, tanks, filters, IXs, sensors, valves, fittings)	93	106
Valves	619	619
Piping	2,755	2,202
Insulation	2,212	1,911
Fittings	14	50
Sensors	206	206
Total Man-Hours	**6,044**	**5,460**

Table 4.27: Estimated Installation Man-Hours for Six-Zone and Modular NiPEC Cooling Systems

Table 4.27 succinctly outlines the estimated labor required to install each cooling system by component, with the modular system showing lower total man-hours than the six-zone system. The data highlights not only the efficiency of modular installation but also the extensive pipework and insulation efforts needed in the six-zone system driving up the man-hours. Of note, the cooling skid for the six-zone design only includes the heat exchangers. Heat exchangers were not accounted for in the modular design installation requirement as they would be pre-assembled within the power corridor. This analysis shows that the modular system design scored higher for the estimated installation man-hours criterion with a lower total estimated man-hours.

4.5.5 Maintenance Hours

Table 4.28 provides a side-by-side comparison of the maintenance workload for both cooling system designs. Notably, the modular system requires significantly more man-hours annually, reflecting its broader scope and potentially greater complexity in maintaining many modular systems ship-wide whereas the six-zone system is one collective system. Understanding these differences is crucial for planning effective maintenance strategies and understanding future manning requirements.

Component	**Six-Zone System (hours)**	**Modular System (hours)**
Pumps	7,167	16,723
Valves	148,412	164,340
Heat Exchangers	870	1,073
Pipes	24	112
Fittings	297	462
Sensors	14,616	16,272
Expansion Tanks	30	140
Filters	78	364
Ion Exchangers	42	196
Total Man-Hours	**171,536**	**199,682**

Table 4.28: Comparison of Estimated Annual Maintenance Hours for Six-Zone and Modular NiPEC Cooling Systems

There is a natural tension between modularity and minimizing maintenance in many cases. The NiPEC cooling system is one of these instances. To maximize modularity, each segment is designed with an independent heat exchanger. This results in as many heat exchangers to maintain as there are NiPEC segments. The modular cooling sytem has nearly twice as many estimated annual maintenance hours required. For this reason, the six-zone system was rated higher for maintainability.

4.5.6 Level of Redundancy

The final comparison was of the six-zone and modular NiPEC cooling system designs redundancy levels. Evaluating redundancy is essential for understanding the reliability and fault tolerance of each system design, another notable trade-off with manufacturability.

Component	**Six-Zone System Score (Details)**	**Modular System Score (Details)**
Pumps	4 (Automatic failover)	2 (Manual bypass available)
Valves	2 (Manual operation needed)	2 (Manual operation needed)
Heat Exchangers	2 (Manual alignment to alternate)	1 (No redundancy)
Pipes	2 (Manual bypass available)	2 (Manual bypass available)
Fittings	1 (No redundancy)	1 (No redundancy)
Sensors/Gauges	4 (Multiple indication sources)	4 (Multiple indication sources)
Expansion Tank	2 (Manual alignment to alternate skid)	1 (No redundancy)
Filters	4 (Dual filters)	4 (Dual filters)
Ion Exchangers	2 (Manual alignment to alternate skid)	1 (No redundancy)
Composite System Redundancy Score	3	2

Table 4.29: Comparison of Redundancy Levels for Six-Zone and Modular NiPEC Cooling Systems

Table 4.29 lists the redundancy capabilities of each component within the two systems, offering insights into their respective abilities to handle operational disruptions. The six-zone system generally shows higher redundancy levels, particularly in critical components like heat exchangers and pumps since they are designed with redundant pairs. The composite system redundancy score reflects the overall system redundancy and ability to withstand component failures. The six-zone system is scored higher due to its built-in redundant components and zonal layout.

4.5.7 Score Normalization and Weighting

After comparing both the cooling system design manufacturability criteria individually, the weighting factors described in Section 3.1.2 were used to consolidate the scores and compare the systems overall based upon the prescribed priorities for determining manufacturability. These weighting factors are also listed in Table 4.30.

Criteria	Weight	Preferred Option
Total number of parts	35%	Smallest
Extent to which the system may be tested off hull	30%	Largest
Total number of unique parts	20%	Smallest
Man hours required for ship installation	15%	Smallest

Table 4.30: Manufacturability Evaluation Criteria

In the comparative evaluation of the six-zone and modular NiPEC cooling systems, normalization of the scoring metrics was used to ensure a balanced assessment between various criteria with inherently different measurement scales and units. This process is essential to mitigate the disproportionate influence that certain scores, especially those with inherently higher ranges, could exert on the composite evaluation. In this study, both systems were considered to cover the entire ship. To aid in a more equitable comparison, the modular system was considered a full system with 28 subsystems. This was also evaluated in this manner, since the modular system would only be used as the entire solution for power corridor thermal management; it would not be reasonable to expect this system to be installed only partially.

Normalization Process Normalization is a critical step in preparing data for analysis, particularly when comparing metrics that are not on the same scale or when those metrics differ in the direction in which they imply improvement like the criteria for manufacturability do. Some factors are desired larger while others are smaller. This process transforms raw scores to a common scale which allows them to be equitably aggregated or compared. The normalization formula depends on whether a higher or lower score is preferred:

- For criteria where a **lower** score is preferred, such as the total number of parts or maintenance hours, the normalization formula used is:

$$\text{Normalized Score} = 1 - \left(\frac{\text{Score} - \text{Min}}{\text{Max} - \text{Min}}\right) \tag{4.1}$$

  where Score is the raw score to be normalized, and Min and Max are the minimum and maximum scores observed across all systems being compared, respectively.

- For criteria where a **higher** score is preferred, such as testability or redundancy, the normalization formula is:

$$\text{Normalized Score} = \left(\frac{\text{Score} - \text{Min}}{\text{Max} - \text{Min}}\right) \tag{4.2}$$

Normalization allows diverse criteria to contribute equitably to a composite score, preventing any single criterion from disproportionately affecting the outcome due to scale differences. This is particularly important in multi-criteria decision-making where the objective is to integrate various data types and scales into a single coherent analysis.

By applying these normalization formulas, each criterion is re-scaled to a [0, 1] range, where 0 typically represents the least preferred state and 1 the most preferred, aligning all criteria toward a common goal for aggregation. Each score was normalized using a range normalization technique, where the raw scores were re-scaled to a uniform range of 0 to 1. This was achieved by subtracting the minimum score observed across both systems from the raw score, dividing by the range of the score across the systems, and adjusting the formula to accommodate whether a higher or lower score was preferred. Specifically, for criteria where a lower score is preferable (such as total parts and maintenance hours), the normalized score was calculated as one minus the ratio of the score's deviation from the minimum over the range, thereby inverting the scale to align all criteria towards a 'higher is better' paradigm for subsequent weighting and aggregation.

This normalization not only standardizes the scores across diverse metrics but also simplifies the application of predetermined weights, thereby enhancing the reliability of the system comparison by ensuring that each criterion contributes equitably to the final decision. The weighted scores are then summed to produce a final score for each system, which reflects its overall suitability against the defined manufacturability metrics and weights.

Criteria	**Weight (%)**	**Raw Score**		**Pref**	**Normal Score**		**Weighted Score**	
		Six	**Mod**	**Direc**	**Six**	**Mod**	**Six**	**Mod**
Total Parts	35	8,460	9,588	Lower	1.0	0.0	0.35	0.0
Testability Score	30	3.1	3.8	Higher	0.0	1.0	0.0	0.30
Unique Parts	20	23	22	Lower	0.0	1.0	0.0	0.2
Installation Hours	15	6,044	5,460	Lower	0.0	1.0	0.0	0.15
Total Score	100						**0.35**	**0.65**

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Table 4.31: Comparative Manufacturability Assessment of NiPEC Cooling Systems

The final manufacturability scores for each system, shown in Table 4.31 were calculated by summing the weighted normalized scores. The modular system, with a higher composite score of 0.65 compared to 0.35 for the six-zone system, was found to align better with the prioritized manufacturability criteria, particularly excelling in areas crucial for reduced man-hours and testability. This composite scoring approach not only highlighted the relative strengths and weaknesses of each system but also provided a quantifiable basis for recommending the modular system as the more manufacturable system.

4.6 Trade-off Considerations

The previous section established which variant of cooling system design—six-zone or modular—is more manufacturable based on a set of developed criteria. Although the modular NiPEC cooling system design has been identified as more manufacturable, it is crucial to understand the inherent trade-offs between manufacturability and other key performance parameters, such as maintainability and redundancy. This section explores these dynamics, providing an analysis that further informs the decision-making process in system design.

For an optimal design, all the performance metrics specified would ideally meet their target states as described in Tables 4.30. However, maximizing certain attributes often negatively impacts others due to inherent system design constraints. Not only is it unlikely to optimize all manufacturability attributes, it is impossible to optimize manufacturability and all other system performance parameters with a single design. Acknowledging these trade-offs during the design process is crucial, as design decisions are interdependent and cannot be isolated from each other. The maintenance and redundancy performance parameters used in this study are a small subset of a much larger list of other factors that require consideration and are used to illustrate this tension in design choices. Understanding that each of these attributes must be considered in the overall design selection process to prevent the unintended consequences of inadvertently reducing one performance attribute while being overly focused on improving another.

A secondary weighted grading system, as introduced in Chapter 3 and employed in this case study, aids in balancing these considerations by quantitatively assessing each system against the following criteria:

- **Complexity vs. Redundancy:** Increased redundancy in the six-zone system enhances operational reliability but adds complexity, impacting manufacturability.
- **Efficiency vs. Thoroughness:** The modular system's design reduces installation efficiency but increases the burden of maintenance and limits redundancy, impacting cost and reliability.
- **Maintenance vs. Initial Complexity:** Lower initial complexity in the modular system correlates with higher long-term maintenance needs, highlighting a significant trade-off between upfront benefits and ongoing costs.
- **Testing vs. Operational Practicality:** While both systems allow for off-hull component-level testing, the six-zone's setup optimizes operational practicality by simplifying maintenance and redundancy management. The modular system has increased

potential for future full system off-hull test but is more complex in maintenance and less redundant overall.

Criteria	Weight	Raw Score		Pref	Normal Score		Weighted Score	
	(%)	Six	Mod	Direc	Six	Mod	Six	Mod
Manufacturability	40	1.0	3.0	Higher	0.0	1.0	0.0	0.4
Maintenance Hours	30	171,536	199,536	Lower	1.0	0.0	0.3	0.0
Redundancy Score	30	2.5	2.0	Higher	1.0	0.0	0.3	0.0
Total Score	100						**0.6**	**0.4**

Table 4.32: Manufacturability Trade-Off Assessment of NiPEC Cooling Systems

Table 4.32 is a composite table of the overall manufacturability score alongside maintenance requirements and system redundancy to quantify the trade-off between manufacturability and each of these other two attributes. This could again include other system parameters such as survivability and cost. Although the modular system was assessed as the most manufacturable of the two designs, the six-zone system still outperforms when considering both maintainability and redundancy.

4.6.1 Prioritizing Project Objectives

The assessments demonstrated in this chapter provides information on the overall manufacturability and trade-offs with other system parameters. Final decisions on the preferred system variant must align with the NiPEC's strategic objectives:

- If reducing initial complexity and expediting ship readiness are paramount, the modular system's design merits consideration due to its higher manufacturability score.
- Conversely, if maximizing operational reliability and minimizing long-term maintenance are critical, the six-zone system's benefits in lower maintenance requirements and redundancy become deciding factors.

This study evaluated these trade-offs not in isolation, but in the context of manufacturability, seeking a balance that acknowledges that the strongest design may not excel in every criterion, but will provide the most robust performance across the board. The weighting scale is not static, but dynamic and able to be calibrated to the unique demands and priorities of any given project, ensuring that the path taken is as informed as it is deliberate. In addition, the selection of the trade-off criteria and weighting must be intentional and reflective of the overall objectives of the project. This balanced approach is essential for designing systems that are robust, efficient, and aligned with the strategic goals of the NiPEC project, optimizing performance in a carefully considered set of attributes.

4.6.2 Balancing Cost and Performance

A major consideration not directly evaluated in this case study is the cost of the system, both initial production and installation, as well as sustainment. The economic implications are integral to the final design decision for the NiPEC cooling system and other support systems:

- The six-zone design, with potentially higher initial costs, provides cost-efficiencies over the life cycle due to its lower maintenance demands and streamlined redundancy.
- The modular design may offer cost savings on initial installation, but could incur higher operational costs due to its intensive maintenance requirements.

These costs require further investigation and analysis for future design decisions in order to understand the full life cycle cost of each variant.

4.7 Final Selection Guidance

The selection process involves synthesizing the data from the weighted criteria evaluation with a strategic overview of each design's alignment with project goals. The decision framework not only highlights the optimal system in terms of manufacturability but also considers which design best meets the overall operational and strategic goals of the NiPEC project after considering potential trade-offs.

In summary, the choice between the six-zone and modular cooling system designs is informed by a detailed understanding of their respective strengths and weaknesses in terms of manufacturability, trade-offs, and system priorities. By applying the principles of DFM and DFP through the manufacturability assessment criteria developed in this study, this analysis provides a solid foundation for a selection process to aid in choosing a system that not only meets manufacturability objectives, but also aligns with long-term operational strategies, ensuring that the NiPEC project achieves its manufacturability objectives, as well as other major system performance parameters.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

This thesis developed a process to assess NiPEC system and support system manufacturability via objective grading criteria developed from the fundamentals of DFM and DFP. Following evaluation of manufacturability, the process then evaluates select system performance trade-offs with manufacturability to highlight the tension between manufacturability and other performance parameters. The assessment process determines which evaluated system is the more manufacturable system, identifies trade-offs with manufacturability, and highlights areas of system design that require future research to improve overall performance and alignment with the objectives of the NiPEC program. This process is repeatable, so that it may be applied to other systems and objectives to aid in guiding future design decisions.

Manufacturability Assessment

Two proposed NiPEC cooling system designs were used as a test case, but this process may be extended to other NiPEC components, ensuring the evolution of system designs that are both technically superior and aligned with manufacturability and maintainability objectives. Additionally, the trade-off criteria used in the Chapter 4 case study may be augmented or altered to meet program objectives for overall performance. The decision between the six-zone and modular NiPEC cooling systems examined in this study extends beyond simply selecting the highest scoring option according to the developed manufacturability criteria. It involves a strategic alignment with the NiPEC program's overarching objectives, considering both immediate manufacturability and long-term trade-offs, identifying the modular cooling system to be the more manufacturable design in this case.

Criteria	**Six-Zone System**	**Modular System**
Total Number of Parts	0.35	0.00
Off-Hull Testability	0.00	0.30
Number of Unique Parts	0.00	0.20
Installation Man-Hours	0.00	0.15
Total Score	**0.35**	**0.65**

Table 5.1: NiPEC Cooling System Design Manufacturability: Six-Zone vs. Modular

A multi-criteria decision analysis framework was adopted to compare the six-zone and modular NiPEC cooling system designs systematically as a demonstration of the manufacturability assessment process. This analysis utilized four key attributes: total number of parts, off-hull testability, unique parts, and installation man-hours. These attributes, reflective of the principles from DFM and DFP, were normalized using a min-max scaling technique to ensure comparability across different scales and measurement units, optimizing each attribute based on whether a higher or lower score is preferable. Table 5.1 highlights the final normalized, weighted manufacturability scores for each system design.

Decision-Making Based on Trade-offs and Evaluation Scores

Criteria	**Six-Zone System**	**Modular System**
Manufacturability	0.00	0.40
Maintenance Hours	0.30	0.00
Redundancy	0.30	0.00
Total Score	**0.60**	**0.40**

Table 5.2: NiPEC Cooling System Design Trade-Offs: Six-Zone vs. Modular

Table 5.2 shows the manufacturability score was then rated against two key trade-offs. Utilizing the normalized scores and the detailed trade-off analysis in Tables 5.1 and 5.2

provides a multifaceted understanding of which design best meets the NiPEC project requirements:

- **Integration of Trade-offs and Scores:** The higher scores in total parts and redundancy for the six-zone system highlight its design effectiveness in balancing manufacturability with reliability.
- **Prioritizing Project Objectives:** If operational reliability and minimizing maintenance costs are paramount, the attributes of the six-zone system, such as lower maintenance hours and higher redundancy, are critical.
- **Balancing Cost and Performance:** Although the modular system might offer lower initial costs due to simpler construction, the comprehensive benefits of the six-zone system, including reduced ongoing maintenance, suggest lower life cycle costs.
- **Final Selection:** The decision to select the six-zone system over the modular design is supported by its higher total score and better alignment with the NiPEC's manufacturability goals, emphasizing both producibility and maintainability.

This process identified the modular system as more manufacturable, but then identified where it under performs the six-zone system in other areas and may not be the best overall choice to meet project objectives long-term. This example highlights both the tension that exists between these factors and manufacturability as well as the areas of system design that ought to be further developed in order to improve overall performance.

Future Applications and System-Wide Implications

This methodology and its findings are not only applicable to the NiPEC cooling systems but can also be extended to other NiPEC components and support systems. The approach provides a blueprint for evaluating and selecting designs based on a comprehensive set of performance metrics, facilitating decision-making that is both data-driven and aligned with broader strategic objectives.

In conclusion, the modular NiPEC cooling system design emerges as the most manufacturable design, but given the selected trade-off criteria, the six-zone option is the overall best option when evaluated against both manufacturability and the additional performance criteria chosen for this case study. This conclusion is supported by a detailed assessment framework that considers a range of trade-offs, ensuring that the chosen design optimizes manufacturability criteria as well as other selected key performance parameters. As NiPEC system and support system designs continue to evolve, this structured approach to system evaluation and design selection will aide in guiding the development of more manufacturable and maintainable solutions. This assessment begins to bridge the gap between technical solutions and feasible solutions that support the entire ship and system life-cycle.

5.2 Recommendations for Future Work

In the process of this study, several areas were identified in which future NiPEC system and subsystem development, as well as additional manufacturability assessments, could benefit from further research and development.

NiPEC Cooling System Evaluation

The following recommendations for future work are specific to further development of NiPEC cooling systems and continued evaluation of design variants.

PEBB 6000 Continued Research. The integration of the PEBB 6000 module is pivotal for the feasibility of the modular system. Without it, the number of required heat exchangers and associated equipment would render the system infeasible due to the number of components and significant maintenance burden. In this study both NiPEC cooling system variants depend upon a dual iPEBB and PEBB 6000 deployment. Continued research and development into this component are essential to balance the trade-off between manufacturability and maintainability.

Plate Heat Exchanger Development. Future iterations should explore the development of modular plate-and-frame heat exchangers that require minimal to no maintenance, significantly alleviating the maintenance demands of the modular cooling system. The current design iteration meets the thermal management requirements. Improving on this design to reduce the maintenance burden would further increase the feasibility of the modular cooing system design variant. This advancement could dramatically shift the balance towards favoring modular system configurations by reducing the long-term operational costs associated with extensive maintenance.

Modular System Design Refinement. This study's utilized an initial estimate for the NiPEC modular cooling system design based on the design of a modular heat exchanger [32]. Assumptions regarding the modular system's properties facilitated a preliminary manufacturability assessment. However, the design's actual feasibility and reliability require additional development and verification of the system detailed design. This will also validate the component and maintenance requirements. Particular attention should also be given to the redundancy design, especially the reliance on a single pump per system. Enhancing the design fidelity through detailed engineering studies will confirm whether the perceived benefits of modularity, such as improved manufacturability and testability, can be fully realized should the modular cooling system development be further pursued.

Future Manufacturability Assessments

Additional elements were identified for future development to support future manufacturability assessments and to further improve the manufacturability of the modular systems currently in development.

Testing Infrastructure Development. Current facilities, as discussed with subject matter experts, lack the capability to conduct full-system or compartment-wide tests on segments of both current ship power distribution systems and the future NiPEC power corridor [9]. To harness the full potential of off-hull testing capabilities of the proposed cooling system designs, significant development in testing infrastructure is necessary. Additionally, establishing the necessary infrastructure to support modular testing on the ship during installation process could further improve the ability to test systems earlier in the build schedule. As NiPEC segments are installed with their associated watertight compartment, a method by which to test each segment and its subsystems further capitalizes on the benefits of system modularity. This attribute could then be integrated into the system testability evaluation to fully capture the risk reduction capability of the system design. This involves development to support dynamic testing of the systems under real-world operational conditions in coordination with power corridor testing. Collaboration with USN shipbuilding partners will be crucial to develop these facilities, in order to minimize risk and rework during the ship construction phase. Reduction in rework has the potential to reduce the schedule and cost of ship construction projects. This would also increase the benefits of the modular cooling design if the ability to fully test off-hull exists.

Shipboard Installation Study. This study used publicly available information and estimates based on historical data and schematics of the current cooling system design. For future system assessments, known historical data from prior, similar USN war ship projects should be used to increase the fidelity of the estimates presented in the assessment. Additional consideration should be given to the effect of manufacturing the system utilizing pre-assemblies. A significant reduction in shipboard installation man-hours was due to the pre-assembly of cooling skids and NiPEC sections for each of the two cooling systems evaluated. While the labor required during shipboard installation is reduced, the overall labor is not reduced at the same rate. The work must be completed either by the shipyard workforce prior to ship installation or by another contracted manufacturer that assembles the NiPEC sections and support systems. The expected work plan should be investigated to clearly understand the man-hour savings. If the shipyard will manufacture the pre-assembled cooling skids, the manning plan must support this in addition to the shipbuilding manning plan and schedule. In that case, are the man-hours saved during ship install still a net gain? This may also be dicatated by other factors like the repeatability of the units being manufactured and installed as well as the off-hull testing capability the shipyard possesses and could benefit from further study.

Detailed Maintenance Analysis. Future research should delve deeper into the maintenance requirements for each component of the NiPEC cooling system designs. This involves a thorough analysis of maintenance periodicity and man-hour requirements, according to USN PMS requirements. This will increase the fidelity of this assessment and provide more detailed information when comparing system maintenance requirements. This study also only evaluated estimated annual maintenance; a more detailed study should account for all anticipated maintenance for the life cycle of the system to fully understand the overall cost. Additionally, strategies to reduce the maintenance burden should be explored, leveraging increased system modularity to enhance overall system maintainability and operational efficiency. If the modular design maintenance burden is lessened, the feasibility may be improved for this design variant.

5.3 Summary

This section has outlined several key areas for future research and development that will build on the findings of this thesis to refine and improve the designs of NiPEC cooling systems and the potential for further improved manufacturability and improved evaluations. By addressing these recommendations, future work can perform this assessment with increased fidelity and can be repeated as required to assess additional systems or designs. The ultimate system design can also be better prepared to meet the needs of the next generation ship power solution for the life of the ship.

In conclusion, this thesis has laid the foundation for a structured approach to assess the manufacturability of the system within the NiPEC program, using a comprehensive set of manufacturability and performance criteria. Future efforts should build on this foundation to improve system design, selection, and evaluation, ensuring alignment with immediate project needs and long-term objectives.

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Appendix A

List of Acronyms

DDG Guided Missile Destroyer

DFM Design for Manufacturing

DFP Design for Production

EMI Electromagnetic Interference

ESRDC Electric Ship Research Design Consortium

HMI Human-Machine Interface

iPEBB Navy integrated Power Electronics Building Block

MIT Massachusetts Institute of Technology

NiPEBB Navy Integrated Power Electronics Building Block

NiPEC Navy Integrated Power and Energy Corridor

NPES Naval Power and Energy Systems

ONR Office of Naval Research

PCM Power Conversion Module

PEBB Power Electronics Building Block

PEPDS Power Electronic Power Distribution Systems

PMS Periodic Maintenance System

USN United States Navy

USS United States Ship

Appendix B

Notional NiPEC Cooling System Annual Maintenance Plans

This appendix presents theoretical annual maintenance schedules constructed from widely accessible data and informed projections. These schedules serve to determine the estimated baseline maintenance hours for a comparative analysis of two different system designs. Maintenance routines are customized to the requirements and resilience of each element within the NiPEC cooling systems. It is important to note that these maintenance schedules are only preventative and general in nature; they do not take into account corrective or specific component variation maintenance.

It is assumed that, with the exception of heat exchangers, all components of the two proposed systems are analogous in both design and operation, albeit differences in dimensions and specifications may occur. Therefore, uniform maintenance schedules apply to both systems. However, heat exchangers differ in both configuration and design, necessitating distinct maintenance schedules for each type. The man-hours stated are provisional and would adjust based on the cooling system's specific characteristics and capacities.

B.1 Pump Maintenance Schedule

The following table outlines a comprehensive maintenance schedule for centrifugal pumps such as those within the NiPEC cooling system [28]. This schedule includes a variety of checks and inspections to ensure optimal performance and longevity of the pumps. This notional schedule was used to determine annual maintenance requirements for both the six-zone and the modular cooling system designs.

Description	**Comments**	**Maintenance Frequency**	**Man-Hours**
Visual Inspection	Check for leaks and loose components	Daily	0.25
Lubrication – Bearings	Use recommended lubricant	Daily	0.25
Lubrication – Seals	Ensure proper sealing	Daily	0.25

Table B.1 continued from previous page

Description	Comments	Maintenance Frequency	Man-Hours
Motor Operation	Monitor start-up and shut-down	Daily	0.25
Coupling Alignment	Check for misalignment	Daily	0.25
Impeller and Casing Inspection	Look for wear and erosion	Weekly	0.50
Bearing Housing	Monitor bearing temperature	Weekly	0.50
Seals	Check for signs of leakage	Weekly	0.50
Strainer or Inlet Screens	Clean or replace if necessary	Weekly	0.50
Vibration Analysis	Record and analyze vibration levels	Monthly	1.00
Motor Bearing Lubrication	Check and replenish lubricant	Monthly	1.00
Pump Baseplate and Foundation	Inspect for wear or settlement	Monthly	1.00
Pump Alignment	Verify proper alignment	Quarterly	1.50
Wear Rings	Examine for wear or damage	Quarterly	1.50
Impeller and Casing Wear Patterns	Check for irregular wear patterns	Quarterly	1.50
Disassembly and Inspection	Thorough internal examination	Annually	3.00
Bearing Replacement	Replace worn bearings	Annually	3.00
Seal Replacement	Install new seals	Annually	3.00
Motor Inspection and Testing	Comprehensive motor check	Annually	3.00

Table B.1: Centrifugal Pump Annual Maintenance [28]

B.2 Valve Maintenance Schedule

This table outlines the notional maintenance annual requirement for various types of valves, emphasizing regular checks needed to ensure operational efficiency, longevity, and safety.

Component	Maintenance Task	Frequency	Man-Hours
	General Valve Maintenance		
Visual Inspection	Check for leaks, corrosion, or damage	Weekly	0.25

Table B.2 continued from previous page

Component	Maintenance Task	Frequency	Man-Hours
Lubrication	Lubricate moving parts per manufacturer's guidelines	Monthly	0.75
Operational Test	Verify operation and closure integrity	Quarterly	1.00
Packing Adjustment	Adjust gland bolts, replace packing if necessary	Semi-annually	1.00
Cleaning	Clean body and internals from sediments and residues	Semi-annually	1.00
Full Disassembly	Inspect internal components for wear and damage	Annually	2.00

Table B.2: Annual Valve Maintenance [29]

B.3 Shell-and-Tube Heat Exchanger Maintenance Schedule

This table details the routine maintenance tasks necessary to support continued operation of shell and tube heat exchangers, highlighting their frequency and the estimated time required for each task.

Maintenance Task	Description	Frequency	Man-Hours
Visual Inspection	Perform visual inspections to check for signs of corrosion, fouling, leaks, or any physical damage.	Weekly	1.00
Cleaning	Address fouling issues using appropriate cleaning methods like chemical cleaning, mechanical cleaning, or high-pressure water jetting.	Quarterly	2.00
Fluid Analysis	Regularly analyze the properties of the fluids to detect issues like corrosion or scaling.	Semi-annually	1.00
Seal and Gasket Inspection	Examine gaskets and seals for wear, damage, or leakage and replace as necessary.	Annually	1.00

Table B.3 continued from previous page

Maintenance Task	**Description**	**Frequency**	**Man-Hours**
Tube Bundle Cleaning	Remove and thoroughly clean the tube bundle to eliminate fouling; typically scheduled during planned shutdowns.	Annually	5.00
Insulation Inspection	Inspect the insulation for any damage or deterioration to ensure energy efficiency.	Annually	1.00
Support and Alignment Check	Verify that supports and alignment are correct to prevent mechanical damage from vibrations or misalignment.	Annually	1.00
Tube Integrity Check	Conduct non-destructive testing (NDT) like ultrasonic testing or eddy current testing to assess the integrity of the tubes.	Bi-Annually	5.00
Fluid Velocity Monitoring	Ensure fluid velocity within the tubes is maintained within the recommended range to avoid issues like erosion or vibration.	Bi-annually	2.00

Table B.3: Annual Shell-and-Tube Heat Exchanger Maintenance [30]

B.4 Plate-and-Frame Heat Exchanger Maintenance Schedule

This table lists notional annual maintenance requirements for a plate-and-frame heat exchanger.

Maintenance Task	**Description**	**Frequency**	**Man-Hours**
Regular Cleaning	Perform Clean-In-Place (CIP) to remove scaling, fouling, and other residues using appropriate cleaning solutions.	Quarterly	1.00
Gasket Inspection	Check gaskets for any signs of wear or failure to ensure tight seals and prevent leaks.	Semi-annually	2.00

Table B.4 continued from previous page

Maintenance Task	Description	Frequency	Man-Hours
Plate Inspection	Inspect plates for alignment, integrity, and signs of wear or corrosion. Clean plates if necessary.	Annually	2.50
Tightening and Re-gasketing	Tighten the plates to manufacturer specified pressures and replace gaskets as needed.	Annually	3.00
Hydraulic Tests	Conduct hydraulic tests to check for leaks and ensure that the heat exchanger can withstand operational pressures.	Annually	2.00
Deep Clean	Open plate stack and deep clean	Annually	3.00

Table B.4: Plate-and-Frame Heat Exchanger Maintenance [31]

B.4.1 Pipe and Fitting Maintenance Schedule

This table consolidates the maintenance requirements for pipes and fittings.

Component	Maintenance Task	Frequency	Man-Hours
	Pipe Maintenance		
Visual Inspection	Inspect pipes for signs of wear, corrosion, and leaks. Check insulation and support structures.	Semi-annually	2.00
	Fitting Maintenance		
Visual Inspection	Check fittings for signs of mechanical wear, corrosion, and leakage.	Semi-annually	2.00
Tightening	Retighten or replace fittings that show signs of loosening or damage. Ensure all fittings are secure.	Annually	1.50
Gasket and Seal Replacement	Replace worn gaskets and seals to maintain a leak-free system.	Annually	2.00

Corrosion Protection	Apply or reapply corrosion protection measures, including painting or applying anti-corrosion coatings.	Bi-annually	1.50

Table B.5: Pipe and Fitting Annual Maintenance [33]

B.4.2 Sensor, Expansion Tank, Filter, and Ion Exchanger Maintenance Schedule

The tables below list the notional annual maintenance for generic sensors, expansion tanks, filters, and ion exchangers. Detailed tasks and frequencies vary based on component specifics, which are outlined below.

Component	**Maintenance Task**	**Frequency**	**Man-Hours**
	Sensor Maintenance		
Visual Inspection	Inspect sensors for damage or obstructions that could impair functionality.	Quarterly	0.50
Cleaning	Clean sensors to remove dust, dirt, or other contaminants.	Quarterly	1.00
Functional Testing	Test sensor functionality to confirm they are operating correctly.	Semi-annually	1.00
Calibration	Calibrate sensors to ensure accuracy in readings.	Annually	1.00
	Expansion Tank Maintenance		
Visual Inspection	Check for signs of corrosion or leakage.	Semi-annually	0.50
Cleaning	Clean the tank interior to prevent sediment build-up.	Annually	1.00
Seal Checks	Inspect and replace seals and gaskets as necessary.	Annually	1.00
Pressure Testing	Test pressure levels to ensure they are within safe operating parameters.	Annually	2.00
	Filter Maintenance		
Visual Inspection	Inspect for clogging and general wear.	Quarterly	0.25
Pressure Drop Testing	Monitor and record pressure drops to determine filter condition.	Quarterly	1.00

Table B.6 continued from previous page

Component	Maintenance Task	Frequency	Man-Hours
Replacement	Replace filters or clean as per manufacturer's guidelines to maintain flow and quality.	Annual	1.50
	Ion Exchanger Maintenance		
Cleaning	Thoroughly clean unit to prevent scaling and fouling.	Annually	1.50
Inspection	Inspect for any signs of wear or damage, especially at connection points.	Annually	1.00
Leak Testing	Check for leaks in the system, particularly at joints and seals.	Annually	1.00

Table B.6: Sensor, Expansion Tank, Filter, and Ion Exchanger Annual Maintenance [34] [35]

B.5 Consolidated Annual Maintenance Hours

The consolidated annual maintenance schedule, providing a quick reference to operational maintenance requirements based on multiple units of each component, is summarized below for each cooling system design.

B.5.1 Six-Zone Cooling System Maintenance Summary

Component	Man-Hours/Unit	Highest Periodicity	Man-Hours/System
Pumps	597.25	Daily	7,167
Valves	22	Weekly	148,412
Heat Exchangers	72.5	Weekly	870
Pipes	4	Semi-annually	24
Fittings	8.25	Semi-annually	297
Sensors	9	Quarterly	14616
Expansion Tanks	5	Semi-annually	30
Filters	6.5	Quarterly	78
Ion Exchangers	3.5	Quarterly	42
Total			**171,536 man-hours**

Table B.7: Six-Zone NiPEC Cooling System Estimated Annual Maintenance Requirements

B.5.2 Modular Cooling System Maintenance Summary

Component	Man-Hours/Unit	Highest Periodicity	Man-Hours/System
Pumps	597.25	Daily	16,723
Valves	22	Daily	164,340
Heat Exchangers	18.5	Weekly	1073
Pipes	4	Semi-annually	112
Fittings	8.25	Semi-annually	462
Sensors	9	Quarterly	16272
Expansion Tanks	5	Semi-annually	140
Filters	6.5	Quarterly	364
Ion Exchangers	3.5	Quarterly	196
Total			**199,682 man-hours**

Table B.8: Modular NiPEC Cooling System Estimated Annual Maintenance Requirements