Preliminary Shipboard Layout of Navy Integrated Power and Energy Corridor (NiPEC)

by

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B.S., Nuclear Engineering, Missouri University of Science and Technology (2014)
Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of
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and
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Abstract

Naval ship systems increasingly require more electricity. The Zumwalt class destroyer was the Navy's first modern fully electric ship. Through its integrated power system, the prime movers provide electric power to meet propulsion, ship service, offensive, and defensive systems requirements. The next generation destroyer, DDG(X) is also planned to be an electric ship. The ships of the future can thus be anticipated to employ upwards of 100 Megawatt (MW) or more electric power. With such a rise in electrical power comes the requirement to move electricity efficiently over compact and reliable power distribution systems.

To increase a ship's electrical infrastructure density, MIT is developing a new electrical power distribution structure called the Navy Integrated Power and Energy Corridor (NiPEC). The distribution cables, load centers, power panels, and power conditioners are all co-located into the NiPEC [1]. This allows for electrical energy to be efficiently routed through the ship and increase electrical redundancy. Individual NiPEC sections will fit into reserve-space ship locations and may use the new Navy Integrated Power Electronics Building Block (iPEBB) to control and condition power. The NiPEC will include space to accommodate future power requirements with little refit needed to the ship or the power corridor.

This thesis used a notional ship developed by Electric Ship Research and Development Consortium (ESRDC), past research into NiPEC electrical components, open source military specifications, and open source literature to build a power corridor concept 3D model within a single ship compartment. As this is the first 3D model concept, all components were based on existing technology to establish a benchmark of size and power conversion density. Once a single power corridor compartment was modeled, the components were duplicated throughout the notional ship. The 3D concept includes major power corridor elements with attention given to ease of construction, maintenance, and repair.

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The second group of people I want to thank are all my friends and fellow Naval Officers. In particular LT Avi Chatterjee, LT Katie Spaeth, LT Asia Allison, and LT Heather Willis, I would not have completed my degree or had any free time to enjoy Boston without your help and friendship.

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I finally want to thank my children (Nathanael and Abigail) and wife (Jessica) for your support through my time at MIT. You are my whole world and I would not be the person I am today without you.

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Chapter 1

Introduction

The United States Navy (USN), through the Office Of Naval Research (ONR) is funding research on the next generation of shipboard power distribution. ONR established the Electric Ship Research and Development Consortium (ESRDC) "to stimulate a multidisciplinary approach to the electric naval force system complexity, and to develop the necessary tools for the complex system design and engineering to reduce the risk and costs of early decisions" [12]. ESRDC is focused on designing Power Electronic Power Distribution Systems (PEPDS). The Massachusetts Institute of Technology (MIT) through the MIT Sea Grant Design Laboratory is focusing on the development of the Navy Integrated Power and Energy Corridor (NiPEC). The NiPEC is a modular entity that, in theory, could be dropped into a ship during construction and contain all the equipment for power control and distribution. Within the NiPEC could be modular Power Conversion Module (PCM)s that contain Power Electronics Building Block (PEBB), power conversion elements [13].

The next generation of power distribution will operate at higher power levels and voltages than most of today's warships. Today's warships typically operate in the 4 to 6 MW power range at 450 Volts (V) Alternating Current (AC). Future ships will operate at higher powers of approximately 80 MW with voltages ranging from 1 Kilovolts (kV) Direct Current (DC) (+/- 0.5 kV) up to 12 kV DC (+/- 6 kV) [1].

When looking at the layout of power components within current ship designs, they use a point-to-point design where wiring is run directly from an electrical generator to a PCM to a load. This leads to a less flexible and reliable system [14]. Hence a better approach to electrical power distribution is needed.

1.1 Power Corridor Concepts

The power corridor will include all elements needed to distribute electrical power throughout the ship. These elements could include bus cables and conduit, power converters, interface junction boxes, energy storage, circuit breakers, and bulkhead penetrations [1]. A conceptual electrical diagram of the layout of these components is shown in Figure 1-1. The power corridor could operate with zonal electrical boundaries which could eliminate the need for circuit breakers in every power corridor compartment section.

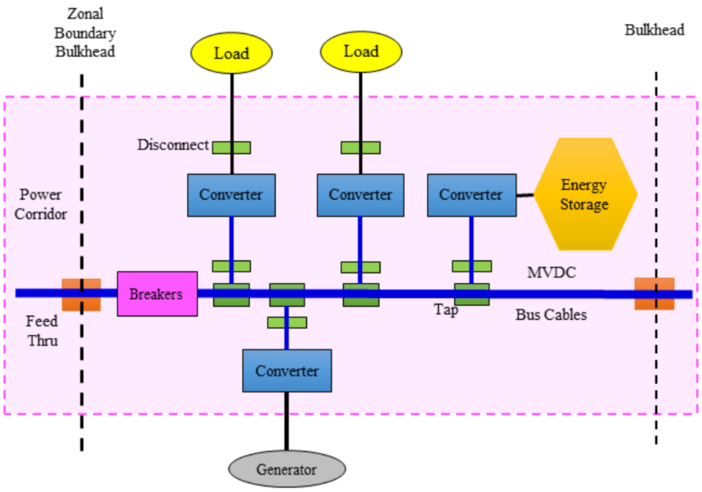


Figure 1-1: Corridor Concept Electrical Diagram [2]

Conceptual two dimensional layouts of the needed power corridor elements are shown in Figures 1-2 and 1-3. Figure 1-2 shows a concept of how all the required electrical elements could be physically arranged in the corridor. This set of elements would need to fit within a ship compartment.

Figure 1-3 shows an end view concept of how four corridors could be placed within the ship's hull. The corridor is placed within the ship such that it does not interfere with the ship's structural members. This would allow for the majority of the corridor to be built off hull since it can be fitted without modifying the ship's structure for increased efficiency and lower cost [1].

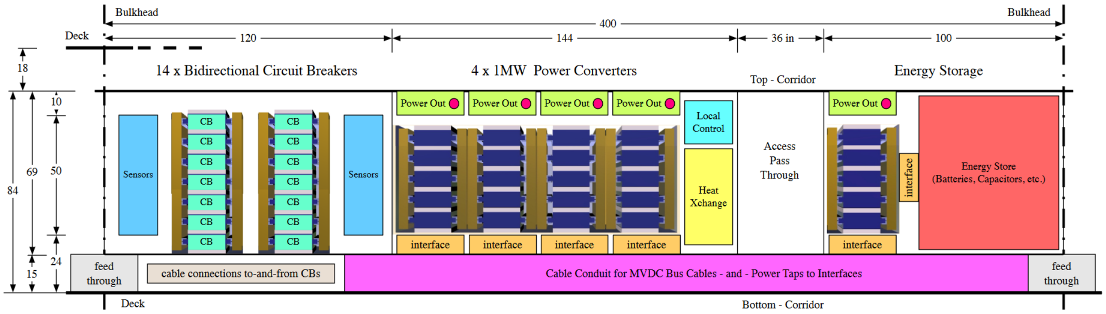


Figure 1-2: Two Dimensional Corridor Concept Side View (Dimensions in Inches) [1]

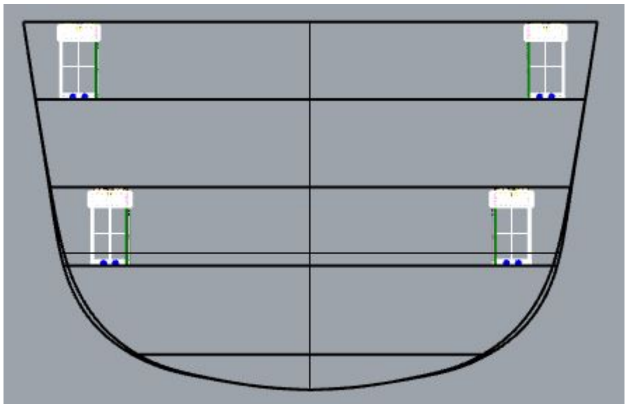


Figure 1-3: Corridor Concept Section View Looking Aft

Figure 1-4 shows the integration of the power corridor into a notional ship. In this concept, there are 4 individual power corridors running bow to stern. These corridors are positioned on port and starboard sides on decks 2 and 4 (similar to Figure 1-3). This is done to increase the redundancy of the overall electric distribution system and decrease the volume of electrical wiring needed within an individual corridor. In the notional ship, each corridor is required to distribute 25 MW of power at 1000 VDC. This allows the ship to theoretically lose one whole corridor and still operate at 100 % electrical capacity.

Additionally, Figure 1-4 shows a varying number of elements within each compartment. Discussed in further detail in Section 1.2, flexibility in the number of elements is a key aspect in the power corridor design.

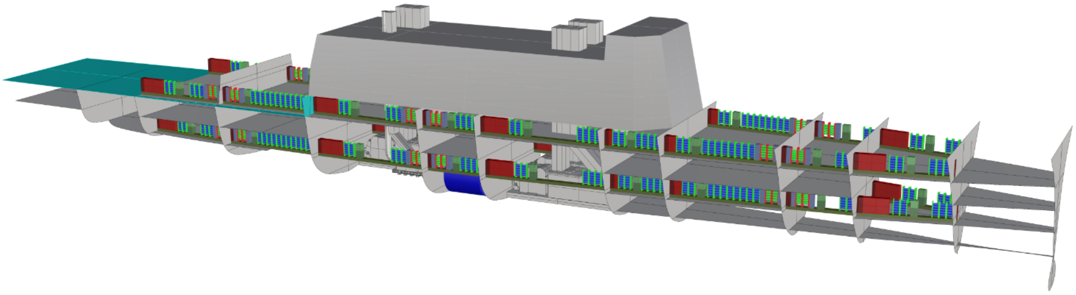


Figure 1-4: Whole Ship Corridor Concept [2]

1.2 Reserve Space Concept

The power corridor is a primary aspect in the ship's design. Similar primary aspects are propulsion equipment and electrical power generation. Because of this, the power corridor needs space reserved for it early in the ship's design for an optimal layout of the power corridor. The reserve space approach allows for high power levels to be safely distributed throughout the ship while building in margin for growth of electric loads in the future. Designating space for electrical components early in the a ship's design is vital to the success the design as the ship's power infrastructure interacts with all electrical components. This leads to the concept of the integrated power corridor. All electrical distribution equipment is located within the power corridor with multiple power corridors needed in a ship for redundancy and electrical capacity requirements [14].

Each compartment along the corridor will have the same base NiPEC electrical elements. The number of base NiPEC elements in each compartment will vary based on electrical demand within the specific ship section. A detailed concept of NiPEC component arrangement within one ship compartment will provide a great value to NiPEC research as the components within one compartment can be repeated along the corridor and to the other corridors within the ship.

1.3 Power Corridor with Traditional Equipment

The power corridor inherently includes essentially all major components needed to distribute electrical power throughout the ship. These components have been identified as bus cables and conduit, power converters, interface junction box, energy storage, circuit breakers, bulkhead penetrations [1]. To provide a baseline for the power corridor layout, this thesis will develop a power corridor design with existing technologies and devices. Thus research currently under development on devices such as the PEBB are not directly implemented here, but can readily be substituted for devices used in this thesis when they become available.

The NiPEC PCMs PEBB 1000 and PEBB 6000 have been researched in the past with the Navy iPEBB actively being researched. The physical dimensions, weight, cooling requirements, and electrical operating characteristics are not yet fully defined. They are also expected to take a significant amount of space within the power corridor. By using traditional equipment as a demonstration of NiPEC concepts, many of the unknowns are removed allowing for an evaluation of size constraints aboard a marine vessel. Key design factors will be identified and be carried forward to improve future NiPEC concepts and research.

Existing power conversion equipment for marine applications operates at around 1000 V DC. The company ABB developed the OMD880LC, a marine DC distribution system operating at 1000 V DC [10]. The ABB documentation provided information on the concept and rough sizes of equipment in pictures of the DC grid, but insufficient information needed to accurately model the equipment in a 3D environment.

Another company, SATCON Technology Corp., provided a brochure that includes sizing and power details of power conversion equipment [4]. The SATCON equipment was designed specifically for use on USN vessels and operates at 1000 V DC. This makes the equipment data ideal for research into future USN electrical applications. SATCON filed for bankruptcy in 2012 and which has made it difficult to find open source information [15]. Because of this, a copy of the SATCON brochure has been provided in Appendix B. Quantifying all of the ABB and SATCON data will be discussed further in section 3.1.

1.4 Power Corridor Economic Benefits

By manufacturing the power corridor off hull, manufacturing time could be significantly reduced and thus cost is also reduced. Ship builders often refer to the 1-3-8 rule when calculating ship construction and repair time. If a component is being constructed or repaired off hull in a manufacturing facility with good lighting, ventilation, tools, and materials on hand, it will take 1 hour of time. If the same component is being worked within a ship module, the same work that took 1 hour in the manufacturing facility, will now take 3 hours of time. Finally, if this component is being being worked within a ship's hull, it will now take 8 hours of time to complete [16].

Additionally, the USN does not allow splicing of electrical distribution cables [17]. This means all electrical distribution cables within current USN vessels have to be individual hand run through the entire ship and connected to their respective switchboards or loads.

Manufacturing the power corridor off hull include distribution cabling, there is a large potential economic advantage both in time and cost.

1.5 Assumptions

The following are assumptions used through the design of this power corridor concept.

- A notional ship developed through ESRDC is used as the platform for the example NiPEC
    - Notional ship displacement will be 10000 tons
    - Each corridor will run 85% the length of the ship.
- Utilize a reserved space approach for placement of the corridor

- Each compartment will use the same base NiPEC electrical elements
- Electrical distribution bus operates at 1000 VDC
- Multiple corridors are implemented enable redundancy
- A total power level of 75 MW is selected for the design
- All used power corridor components are based on existing technology
- Corridor is designed with modularity in mind and major components could be assembled off ship
- US Navy standards and requirements are used throughout as much as possible

Chapter 2

Ship Model

Starting with a representative ship model is critical to developing a power corridor concept and understanding the space limitations within the ship. The power corridor concept is being researched for use in future USN ships and thus, the ship model should be based past USN ship designs. This chapter will discuss the development of the notional 10,000 tonne ship model.

2.1 ASSET

Advanced Ship and Submarine Evaluation Tool (ASSET) is a software developed by Naval Surface Warfare Center, Carderock Division (NSWCCD). It is a tool used to determine the validity of ship concepts. There are many factors that need to be entered into ASSET in order to generate an output. These input are managed within ASSET in a hierarchical database with the primary components of the ship being the propulsion plant, electrical plant, and hull. The primary components can be subdivided into secondary and tertiary components to input further detail into the model [18].

An important note for future users of ASSET is the USN has incorporated ASSET into a software called Rapid Ship Design Environment (RSDE). A limitation of ASSET is every change to the ship concept (speed profile, payload, hull form, etc.) needs to be inputted by a user and synthesized to see if the concept is feasible.

RSDE was developed to in order to quickly evaluate a large trade space of ship concepts. A user can input a range of desired ship parameters and RSDE will evaluate a specified number of designs and generate relationships between inputted parameters and desired outputs to inform designers and decision makers [19]. Additionally, both of these program have distribution controls placed on them and not available to the general public.

The specific notional ship model used for this thesis was previously developed by Sea Grant Design Laboratory using ASSET. The hull form and structural layout is similar to the DDG-51 with a plug installed to increase length and displacement to approximately 10,000 metric tons [11]. Figure 2-1 shows the general concept of the ship form.

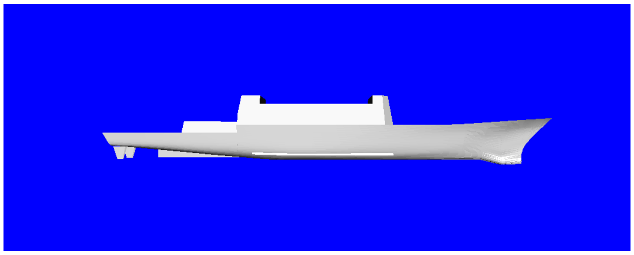


Figure 2-1: 3D Notional Ship Model

2.2 Solidworks

Solidworks is a 3D modeling software developed by the French based company Dassault Systemes. Solidworks has many available tools including structure and fluid analysis. For the development of the Power Corridor, the main benefit of using Solidworks was to analyze the size and arrangement of needed components within a 3D environment.

2.2.1 Transferring Notional Ship data to Solidworks

The majority of notional ship's structural information was taken from provided hull structures and hull subdivision data. Sizes and locations of ship structural members were in the hull structures data, and locations and sizes of ship compartments were in the hull subdivision data.

The notional ship's structural calculations were performed on the longitudinal location (bow to stern) of the ship hull that is exposed to largest sagging and hogging moments. Generally these moments are the largest around the center of the ship. The calculated the structural design is at location 0.52. Location 0.0 is defined as the forward perpendicular and 1.0 is defined as the aft perpendicular. At location 0.52 of the notional design, decks 5 and 6 were removed for the structural modeling and calculations because the centerline of the ship model contains a machinery space. Machinery spaces require two open decks due to the size of installed equipment.

Given the data available from the notional ship, this thesis will utilize a model of the ship center with decks 1, 2 and 3.

2.2.2 Modeling In Solidworks

The data obtained from the notional ship design was drawn into Solidworks to create a 2-dimensional model (Figure 2-2).

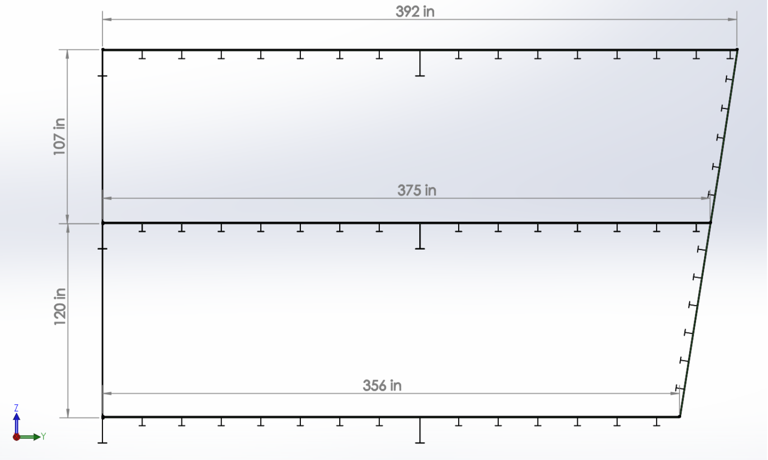


Figure 2-2: Solidworks 2 Dimensional Structure Viewed Looking Aft

Table 2.1 displays the dimensions of all the stiffeners used in Figure 2-2. The small stiffener spacing is the average of all stiffeners in the corresponding deck. The notional ship provided more detailed stiffener spacing than required for this thesis. Averaging the spacing was acceptable for concept purposes as it didn't change the number of stiffeners in the deck and structural analysis was not being performed. The notional ship contained varying deck plate thicknesses for each deck level. Again, because structural analysis was not being performed, all the plate thicknesses were set to 0.75 in.

Stiffener	**Web Height (in)**	**Web Thickness (in)**	**Flange Width (in)**	**Flange Thickness (in)**	**Stiffener Spacing (in)**
Deck 1 (small)	4.75	0.25	4.0	0.25	24.5
Deck 1 (large)	15.25	0.25	5.5	0.25	196.0
Deck 2 and 3 (small)	3.75	0.25	4.0	0.25	22.0
Deck 2 and 3 (large)	11.75	0.25	4.0	0.25	22.0
Hull	3.75	0.25	4.0	0.25	15.75

Table 2.1: Notional 'T' Stiffener Dimensions

The 2-dimensional model shown in Figure 2-2 was "stretched" within Solidworks by 6 meters (236 inches) to add a third dimension to the model. Then the 6 meter ship section was linearly copied to give a total of 4 compartments on two decks. Compartment doors, a 6 ft person, and a scaled model of the ship's hull, were added for a frame of reference [20] [21]. Figure 2-3 shows the completed four compartment ship model.

2.2.3 Detail Example of One Compartment

The majority of the work will focus on arrangements in one compartment of the ship. All of the elements within one compartment could be repeatable to other compartments.

Figures 2-4, 2-5, and 2-6 show different views of the one compartment model. Figure 2-5 is from the point of view with the ship centerline on the left side and the ship hull on the right side. Figure 2-6 is from the point of view with the left side the

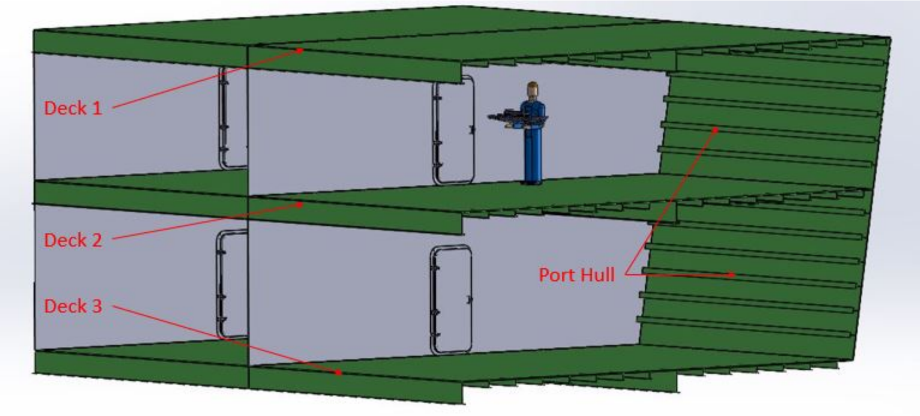


Figure 2-3: Solidworks 3-Dimensional Structure

aft end of the compartment and the right side the forward end of the compartment.

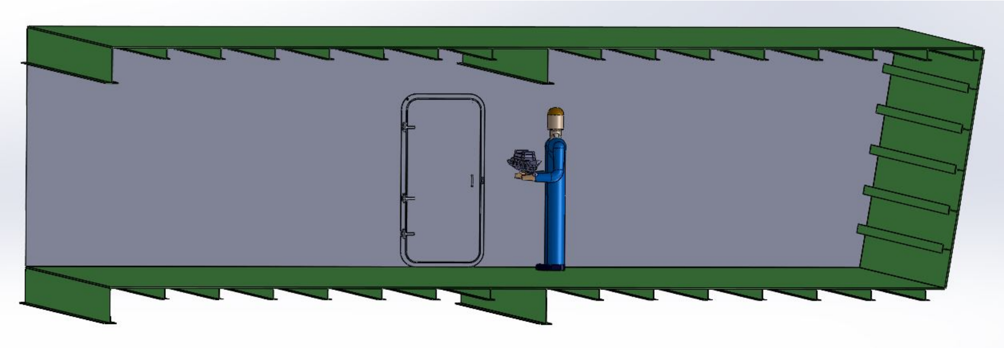


Figure 2-4: One Compartment Perspective Looking Aft

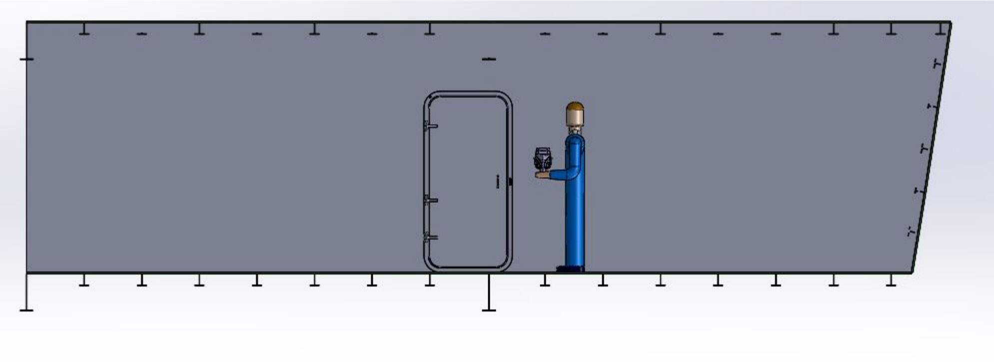


Figure 2-5: One Compartment View Looking Aft

Figure 2-6: One Compartment View Looking Towards the Port Hull

Chapter 3

Electrical Components of Corridor

3.1 Power Conversion Module (PCM-1)

A PCM is a power conversion module capable of taking an input voltage (either AC or DC) and outputting another voltage (either AC or DC). The PCM-1 is a PCM with specific capabilities as outlined in "NGIPS Technology Development Roadmap" [22]:

> PCM-1: Converts 1000 VDC Power from PCM-4 to 800 VDC power, 650 VDC Power, or another user-needed DC voltage. Also segregates and protects the Port and Starboard 1000 VDC Busses from in-zone faults.

The PCM-1 is one part of a whole ship electrical generation and distribution system. Additional power conversion modules are the PCM-2 and PCM-4. The PCM-2 converts DC to 60 or 400 Hertz (Hz) AC and the PCM-4 rectifies AC power from an electrical generator to DC [22].

A literature review of DC electrical systems designed to operate aboard marine vessels yielded results from two companies. The PCMs from these companies are possible surrogates for what can be achieved with today's existing technology. The first was from ABB, a company head quartered in Zurich, Switzerland that specializes in electrification and automation. They designed a marine DC micro grid that operates at 1000 VDC [10]. A 3D rendering of the ABB PCM is show in Figure

3-1. The center section of the module contain 5 individual power conversion sections with the outside sections containing switching and control equipment. The technical data for the ABB PCM is listed in Table 3.1.

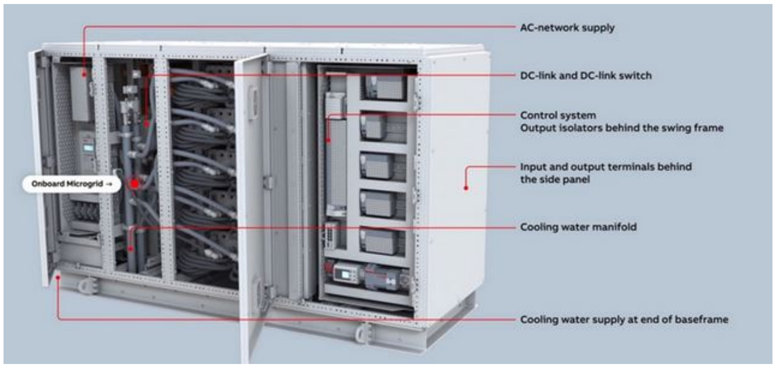


Figure 3-1: ABB PCM [3]

Dimensions	85” (2154 mm) W 33” (827 mm) D 51” (1294 mm) H
Input Voltage	750-1000 VDC
Power Conversion	5 sections 100-650 kW

Table 3.1: ABB PCM Data [9] [10]

The second company that yielded results on marine DC electrical systems was SatCon Applied Technology based in Boston, MA. The SatCon PCMs were specifically designed for USN use. Their PCM was built to military specifications and was tested at Naval Surface Warfare Center, Philadelphia Division (NSWCPD) in Philidelphia, PA. There is limited data available from open sources on SatCon military equipment as the company filed for bankruptcy in October 2012 and transitioned away from military application [15]. As such, all the data for SatCon equipment is from a brochure that is attached in Appendix B. Key SatCon PCM-1 data pulled from the SatCon brochure is summarized in Table 3.2.

Dimensions	96” W, 48” D and 75” H
Input Voltage	925 – 1035 V DC
Output Voltage	350 – 800 V DC
Power Conversion	9 sections rated at 125 kW (1125 kW total)

Table 3.2: SATCON PCM-1 Data

A built SatCon PCM-1 is shown in Figure 3-2 being tested at NSWCPD. The SatCon PCM-1 had four cabinets 24" wide associated with it giving it the final dimensions of 96” W, 48” D and 75” H. This height does not include any structural foundation for the PCM-1. Nine power conversion sections can fit within the PCM-1. These sections are changeable as seen in Figure 3-3.

Figure 3-2: SATCON PCM-1 [4]

Figure 3-3: SATCON PCM-1 Conversion Sections [4]

The ABB and SatCon PCMs power conversion density can be compared to understand the current state of marine power conversion technology. The general equation used to calculate the power conversion density is equation 3.1. The results for each PCM model is displayed in Table 3.3. Notably the ABB PCM and SatCon PCM-1 had power densities of 7.9 and 5.6 $\frac{kW}{ft^3}$.

$$\text{Power Conversion Density} = \frac{\text{Maximum Power Converted}}{\text{Total PCM Volume}} \tag{3.1}$$

	Total PCM Volume (ft^3)	Maximum Power Converted (kW)	Power Conversion Density ($\frac{kW}{ft^3}$)
ABB PCM	82.8	650	7.9
SatCon PCM-1	200	1125	5.6

Table 3.3: PCM Power Density

Since specific information on the internal layouts of the two PCMs is limited, it is assumed that the power densities of the power conversion sections between the two models are similar. The difference in power densities listed in Table 3.3 can be attributed to differing layouts and equipment used in the switching and control sections of the PCMs.

Given the ABB and SatCon PCMs have similar power conversion densities, but the SatCon PCM-1 was built for USN purposes and meets military shock and vibration specifications requirements, the SatCon PCM-1 was chosen as the baseline for implementation in a power corridor. The baseline values are listed in Table 3.2.

3.2 Power Conversion Module (PCM-2)

The PCM-2 is a power conversion module to convert 800 VDC to 3 phase 450 VAC. The SATCON Brochure in Appendix B lists the DC to AC inverter sections as having a conversion capacity of 112.5 kW and fitting the same modular layout as the DC to DC converters in the PCM-1. Table 3.4 summaries the data of the PCM-2.

In this power corridor concept the PCM-2 is assumed to be 24 inches wide and the AC power requirement is small. If additional AC power is needed, more conversion sections can be added.

Each PCM-2 conversion section requires an associated PCM-1 conversion section. The PCM-1 is required to step down the 25 MW Bus voltage of 1000 V to 800 V for use by the PCM-2. Refer to Figure 3-17 for a diagram of output electrical connections.

Dimensions	24" W, 48" D and 75" H
Input Voltage	800 V DC
Output Voltage	450 V AC
Power Conversion	1 section rated at 112.5 kW

Table 3.4: SATCON PCM-2 Data

3.3 Cabling

The sizing of the electrical cabling for the power corridor was calculated based on the thesis The Impact of Electrical Standards on MVDC Shipboard Power Cable Size by Joshua Malone [5]. The key information taken away from the thesis are cable conductor sizes, cable insulation thickness, number of conductors in a single cable, and spacing of cable groups.

3.3.1 Input Cabling

The input cabling is the main distribution cabling throughout the entire ship. Based on the power corridor concepts discussed in Section 1.1, there will be four power corridors running the length of the ship. Two power corridors will be located the second deck on port and starboard sides and two power corridors will be located on the forth deck on port and starboard sides. Each corridor is required to distribute 25 MW of power at 1000 VDC. This allows the ship to theoretically lose one whole corridor and still operate at 100 % electrical capacity.

The Malone Thesis focused on calculations of 4-cable groups (2 pairs of 2 cables of opposite polarities) as they will likely be used on future USN ships to minimize inductance and magnetic signatures [23]. Maximum current of individual conductors in a 4-cable group were calculated for a range of conductor sizes (8.25-25.4 mm). The maximum current value was based on heat dissipation analysis of the 4-cable group and ensuring the cable did not exceed an operating temperature of 90°C [5].

The maximum conductor size (25.4 mm) analyzed in the Malone Thesis was chosen to minimize the total number of the cables in the power corridor. As input cabling is the main distribution cabling, it will run the length of the corridor. The Malone Thesis calculated the maximum current allowed in a 25.4 mm (1000 All Wire Gage (AWG)) conductor within a 4 cable group operating at 12 kV is 654 Amps. The 654 Amp limit is also valid for an operating voltage of 1 kV base on equations 3.2. The heat produced within a conductor is based on the current and resistance of the cable and not the operating voltage of the cable [5].

$$\text{Heat Produced}_{\text{DC 4-Cable Group}}(\frac{W}{m}) = 4 * I^2_{\text{DC Single Cable}} * R_{DC} \tag{3.2}$$

$$I_{\text{DC Single Cable}} = \text{DC Current per Cable (Amp)}$$
$$R_{\text{DC}} = \text{Cable Resistance to Direct Current}(\frac{\Omega}{m})$$

The insulation thickness of a single conductor is based on the operating voltage of the cable. The Malone Thesis evaluated Crosslinked Polyethylene Insulation (XLPE) insulation thicknesses required at varying voltages on land-based and shipboard applications. This is seen in Figure 3-4. The shipboard application curves (100% and 133%) converge at approximately 2.25 mm at 1 kV.

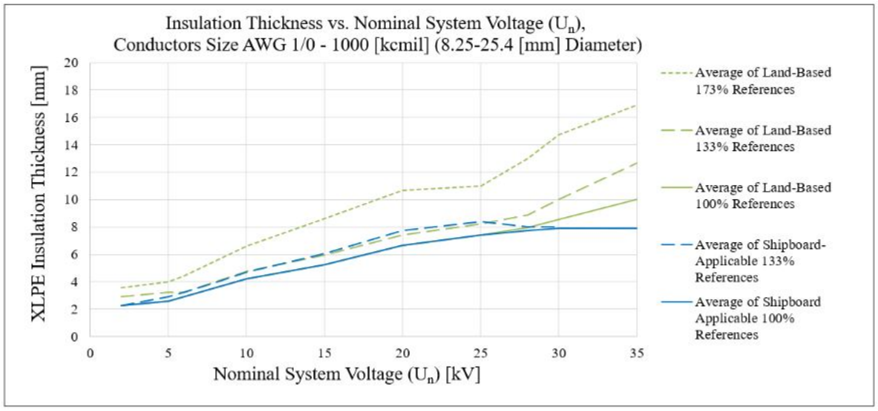


Figure 3-4: Comparison of Shipboard-Applicable and Land-Based Evaluated Reference's Average Insulation Thicknesses vs. U$_n$ [5]

Based on military specifications and research, several additional layers are required around the single conductor. All the concentric layers are summarized in Table 3.5. The total diameter of a single cable is calculated to be 34.726 mm and rounded up to 35 mm for ease of modeling as 34.726 mm is the minimum required thickness.

Conductor Diameter [5]	25.4 mm
Semi-Conducting Tape Thickness [23]	0.127 mm
Insulation Thickness [5]	2.25 mm
Silicone rubber or Fiberglass Tape Thickness [24]	2.032 mm
Two or More Cross-Lapped Semi-Conducting Tapes Thickness [24]	2.032 mm
Total Single Cable Diameter	34.726 mm ≈ **35 mm**

Table 3.5: Input Cable Single Cable Data

Four 35 mm cables can then be bundled together to create the 4-cable group. The 4-cable group is encased in several layers of material that are summarized in Table 3.6.

Single Cable Diameter	35 mm
Semi-Conducting Tape Thickness [23]	0.127 mm
Braided 34 AWG shielding [23]	0.4064 mm
Polyester Tapes [23]	0.127 mm
Cross-linked Polyolefin Jacket [24]	2.2.286 mm
Total 4-Cable Group Diameter	**90.4 mm**

Table 3.6: Input 4-Cable Group Data

A cross sectional view of the 4-cable group is show in Figure 3-5 (not to scale).

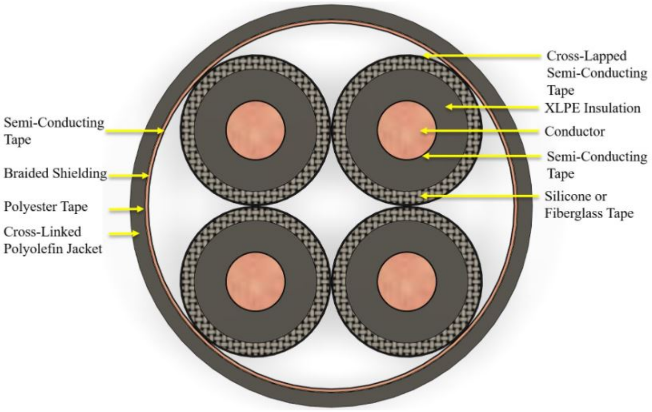


Figure 3-5: Input 4-Cable Group Cross Section (not to scale) [5]

The total amperage needed to distribute 25 MW at 1kV is show in Equation 3.3.

$$I(\text{Amps}) = \frac{P(\text{Watts})}{V(\text{Volts})} = \frac{25,000,000(\text{Watts})}{1000(\text{Volts})} = 25,000(\text{Amps}) \tag{3.3}$$

Utilizing the maximum current from Equation 3.3 and the maximum current per cable (654 Amps), the total number of conductors can be calculated (shown in Equation 3.4).

$$\begin{aligned} \text{Number of Conductors} &= \frac{\text{Total Current (Amps)}}{\text{Maximum Current Per Cable (Amps)}} \\ &= \frac{25,000(\text{Amps})}{654(\text{Amps})} \\ &= 38.2 \text{ Conductors} \end{aligned} \tag{3.4}$$

Finally, factoring in that DC cabling operates in pairs and the input cables will be bundled into groups of 4, the total number of input 4-cable groups is calculated (shown in Equation 3.5). The total number of 4-cable groups needed was 19.1 which was rounded down to 19 4-cable groups for an even multiple of 4. Rounding the number of 4-cable groups down to 19 was done due to spacing constraints which will be discussed further in Chapter 4 Section 4.3. Rounding the number of 4-cable groups down to 19 increased the maximum amperage per cable to 658 amps. This 4 amp increase from the 654 amp maximum discussed in the Malone thesis was deemed acceptable as the Malone thesis stated it's calculation appears to be conservative [5].

$$\begin{aligned}\text{Number of 4-Cable Groups} &= \text{Total Conductors} * \frac{\text{2 Cables Per Pair}}{\text{4 Cables Per Group}} \\ &= 38.2 * \frac{\text{2 Cables Per Pair}}{\text{4 Cables Per Group}} \\ &= 19.1 \text{ 4-Cable Groups} \\ &\approx 19 \text{ 4-Cable Groups}\end{aligned} \tag{3.5}$$

The spacing of the cabling needs to be accounted for to ensure proper heat dissipation. IEEE Std. 45.8 states the individual cable groups are to be spaced 2.15 times the diameter of a single cable [25]. The cables are are spaced 1.075 times a single cable diameter from any surface of the ship [5]. Table 3.7 lists the spacing required for the 4-cable group.

Spacing Between 4-Group Cables	75.25 mm
Spacing Between 4-Group Cable and Ship Surface	37.625 mm

Table 3.7: Input 4-Cable Group Spacing

Figure 3-6 shows the arrangement of the 19 4-cable groups. Further details on this arrangement are discussed in Section 4.3.1.

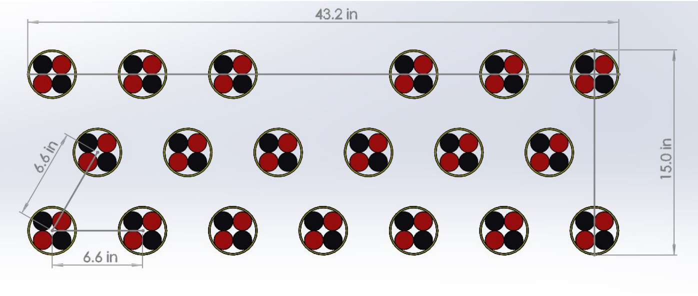


Figure 3-6: 25 MW Bus Arrangement

3.3.2 Output Cabling

The output cabling is the cabling that will connect the output of the PCM-1 to a load. Since the PCM-1 has nine individual power conversion sections rated at 125 kW, it can support nine individual loads each at their own voltage level. To design output wiring that can support all the possible voltage outputs from the PCM-1 a conservative output voltage of 1000 VDC was chosen. Distributing 125 kW at 1000 VDC requires the conductor to support 125 amps at seen in Equation 3.6. From the Malone Thesis, a single cable at 1/0 AWG (8.25 mm diameter) has a maximum ampacity of 187 amps [5].

$$I(\text{Amps}) = \frac{P(\text{Watts})}{V(\text{Volts})} = \frac{125,000(\text{Watts})}{1000(\text{Volts})} = 125(\text{Amps}) \tag{3.6}$$

The calculation of the total cable diameter is similar to that of the Input Cabling in Section 3.3.1 with the exception that this will be a 2-cable group. A 2-cable group is needed because DC wiring operates in pairs with positive and negative polarity. The concentric layers of a single conductor are summarized in Table 3.8. The total diameter of a single cable is calculated to be 17.576 mm and rounded up to 18 mm for ease of modeling as 17.576 mm is the minimum required thickness. The bundled 2-cable layers are summarized in Table 3.9. The final diameter of the 2-cable group was rounded up to 42 mm for ease of modeling as 41.89 is the minimum diameter.

Conductor Diameter [5]	8.25 mm
Semi-Conducting Tape Thickness [23]	0.127 mm
Insulation Thickness [5]	2.25 mm
Silicone rubber or Fiberglass Tape Thickness [24]	2.032 mm
Two or More Cross-Lapped Semi-Conducting Tapes Thickness [24]	2.032 mm
Total Single Cable Diameter	17.576 mm ≈ **18 mm**

Table 3.8: Output Cable Single Cable Data

As in Section 3.3.1, the minimum spacing between cabling needs to be calculated for heat dissipation. Table 3.9 lists the spacing required for the 2-cable group. Both of the distances listed were rounded for ease of modeling up as these were minimum distances required.

Single Cable Diameter	18 mm
Semi-Conducting Tape Thickness [23]	0.127 mm
Braided 34 AWG shielding [23]	0.4064 mm
Polyester Tapes [23]	0.127 mm
Cross-linked Polyolefin Jacket [24]	2.2.286 mm
Total 2-Cable Group Diameter	41.89 mm ≈ **42 mm**

Table 3.9: Output 2-Cable Group Data

Spacing Between 2-Group Cables	38.7 ≈ **40 mm mm**
Spacing Between 2-Group Cable and Ship Surface	19.35 ≈ **20 mm mm**

Table 3.10: Output 2-Cable Group Spacing

3.3.3 Cable Clamps

All the wiring aboard a USN vessel needs to be secured for the safety of crew and equipment and to maintain proper cable spacing for heat dissipation. Military Specification 21919 provides design requirements for cable clamps [26]. The cable clamps were designed using this specification based on the outer diameter of cables needing support. Three cable clamp models were created in Solidworks to support the input 4-cable group (outer diameter 90.4 mm), single input cable (outer diameter 35 mm), and output 2-cable group (outer diameter 42 mm). Figure 3-7 shows an example of a cable clamp modeled in Solidworks.

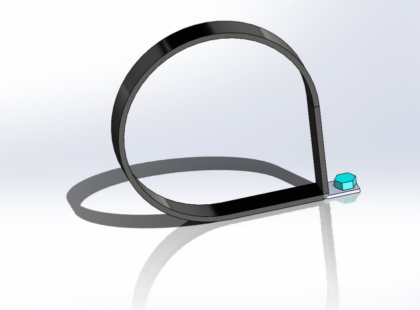


Figure 3-7: Solidworks Cable Clamp Example

3.3.4 Minimum Wiring Bending Radii

MIL-STD-2003-4B Electric Plant Installation Standard Methods for Surface Ships and Submarines (Cableways) specifies the "the conductor bend radius shall not be less than eight times the conductor outer diameter, as measured around the individual conductor jacketing" [27].

The cable bending radii of main concern is the input 4-cable group and the single input cable. Both of these cables needed to be route within the confined space of the power corridor. The input 4-cable group runs the length of the ship and requires bends to be routed into the Interface Box mounted on top of the PCM-1. The input single cable need to be routed within the Interface Box. The Interface Box will be discussed further in Section 3.4. The output 2-cable group bending radius will not have the space limitations of the input cable as it will not be routed within the power corridor, but it still important when developing the layout of the corridor. Table 3.11 shows the calculated minimum bending radius for each other cables of concern.

Input 4-Cable Group	723.2 mm
Input Single Cable	280 mm
Output 2-Cable Group	320 mm

Table 3.11: Minimum Cable Bending Radius

Using the known minimum radii in Table 3.11, a relationship was developed (Equation 3.7) to relate the vertical offset between two points and the minimum horizontal distance needed between the two points to not violate a minimum cable bending radius. The definition of offset and separations are shown in Figure 3-8.

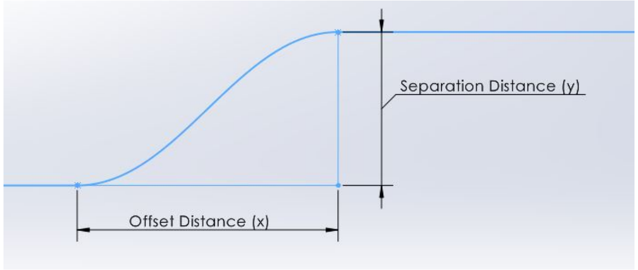


Figure 3-8: Offset and Separation Definition

In Equation 3.7, r is a constant minimum cable bending radius, x is the offset between two points, and y minimum distance needed between the two points to not violate a minimum radius. Equation 3.7 is valid for $0 \leq x \leq 2r$. As x become larger past $2r$, y stays constant.

$$y = \sqrt{-x^2 + 4\sqrt{r^2 x^2}} \tag{3.7}$$

for

$$0 \leq x \leq 2r$$

Figure 3-9 shows the relationship between a desired offset and the minimum separation needed to not violate a minimum cable bending radius.

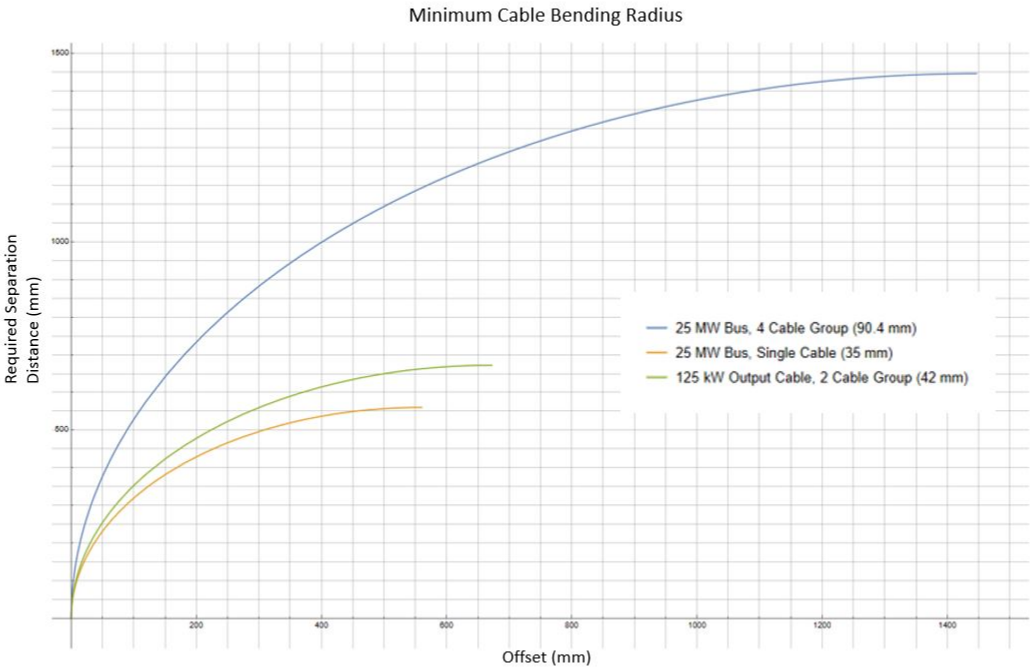


Figure 3-9: Minimum Cable Bending Radius

3.4 Interface Box

The interface box will provide the space for connecting and routing power from the 25 MW distribution bus, to the PCM-1, and the output 2-cable group. Inside the interface box will be DC isolation switches to isolate power from the 25 MW distribution bus to the PCM-1. The interface box will be physically mounted above the PCM-1 within the power corridor. Since there is little open source information on marine 1000 VDC switches, the next best option is to research industrial land based DC electrical equipment.

3.4.1 Isolation Switches

Electrical isolation switches could be needed in the interface box in order to be able to isolate the PCM-1 from the 25 MW distribution bus. Each PCM-1 could have two power sources for redundancy. The isolation switches will allow operators to select between the power sources. A power source will be a single input 4-cable group as each input 4-cable group has a power capacity of 1.3 MW based on the calculations in Section 3.3.1. This is greater than the PCM-1 power capacity of 1.125 MW. To establish redundancy to the PCM-1, two input 4-cable groups are routed into the interface box.

Marine DC isolation switches typically have a rating of 12-48 VDC which is well below the 1000 VDC of the power corridor. Shore based technology has isolation switch rated up to 1000 VDC. A system study is needed to determine whether these switches would be no-load or full-load disconnects.

The global company Siemens has a large open source database available with information on their products. Researching their online databases and product catalogs, a suitable DC isolation switch was found. A two pole, single throw isolation switch was selected as one switch could isolate a positive and negative cable pair. Additionally the isolation switches could operate with remote actuation to increase the reliability of the system. Operators will not need to be physically present in a power corridor section to re-align power for maintenance or casualty.

The Siemens model series 3KD Switch Disconnectors was selected as a surrogate and represents what can be achieved with off the shelf components today. These switches are rated up to 1000 VDC and 1600 amps. The 3KD Switch Disconnectors are manufactured in 3 to 6 pole variants [28]. Siemens has 3D models of their products available for download. Figure 3-10 shows a 3 Pole 3DK Switch Disconnector.

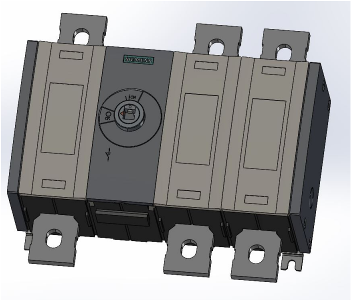


Figure 3-10: Siemens 3-Pole 3KD Switch Disconnector [6]

The model seen in Figure 3-10 was modified in Solidworks to be a 2 pole design which is shown in Figure 3-11. One pair of terminals on the isolation switch will be connected to tee connectors (discussed in Section 3.4.2). The other pair of terminals will be connected to riser connections from the interface box that connects the isolation switch to PCM-1 internal bus.

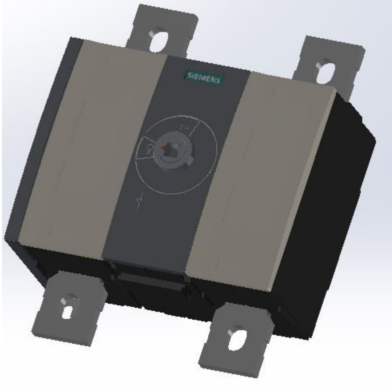


Figure 3-11: Siemens 2 Pole 3KD Series Switch Disconnector

3.4.2 Tee Connector

The connection between the 25 MW distribution bus and the isolation switches will be made with tee connectors. The tee connectors will allow for isolation switches to tap into the 25 MW distribution bus without termination of the cabling. Electrical insulation will be removed from an individual input cable conductor and the tee can be clamped onto the cable. The tee will be bolted to the DC isolation switch creating an electrical connection between the 25 MW distribution bus and the isolation switch.

The PT Connector Series from the Greaves Corporation was found as suitable basis for a tee connector design. The Greaves connector is shown in Figure 3-12.

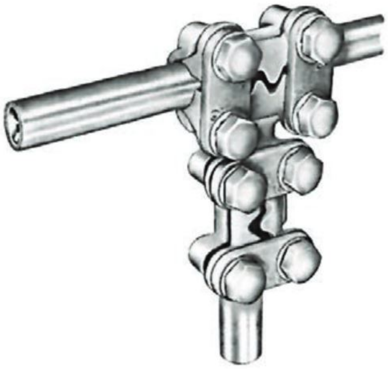


Figure 3-12: Greaves PT Series Tee Connector [7]

The Greaves tee connector design was modified so that it could fit within the confined space of the interface box and be bolted to the isolation switches. The Solidworks model of the tee is shown in Figure 3-13. The brown cylinder through the center represents a single uninsulated input cable conductor, and the yellow, green, and 4 bigger blue bolts are the clamping mechanism to the conductor. The smaller bolt on the bottom is the connection point to the isolation switch.

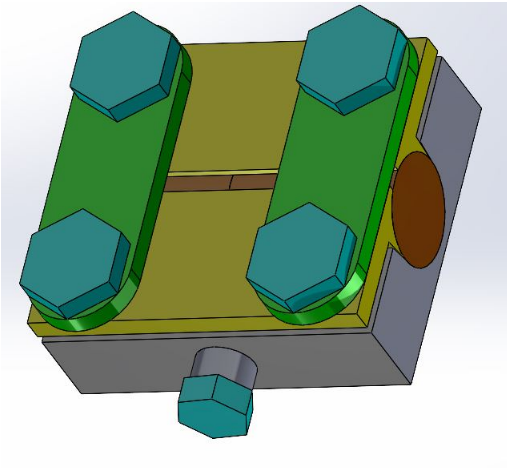


Figure 3-13: Solidworks Tee Model

Figures 3-14 and 3-15 shows two tee connectors bolted to the isolation switch and isolation switch electrical riser connections to the PCM-1.

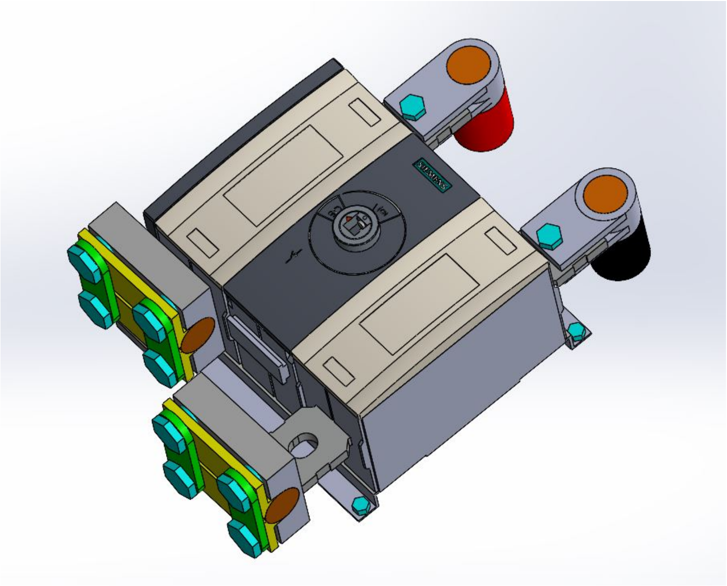


Figure 3-14: Solidworks Top View of Isolation Switch with Connections

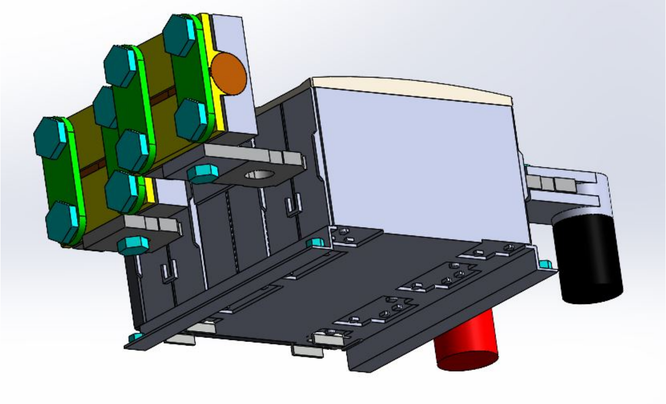


Figure 3-15: Solidworks Bottom View of Isolation Switch with Connections

3.4.3 Layout

The layout of the interface box was designed in such a way to minimize the bending of cables to insure the cables to do not violate USN cable minimum bending radius requirements (discussed further in Section 3.3.4), observe minimum electrical creepage lengths, and components placed for ease of access during maintenance. The overall dimensions of the interface box are 96" W, 48" D, and 7" H.

The USN requirements for electrical creepage in MIL-DTL-917 revision F (Detailed Specification Basic Requirements for Electrical Power Equipment) are based on operating voltage, operating volt-amperage, and whether the electrical components are enclosed [17]. A power corridor single conductor could be operating at 1 kV, 658000 volt-amps, and enclosed. Based on these factors the minimum electrical creepage length is 1.5 inches. The electrical creepage length is what drove the distance needed between exposed conductors at different potentials. This included distance needed between positive and negative terminals of cabling and distance from exposed conductors to a ground potential. Historically USN ships have used un-grounded systems with grounding used for safety. Therefore the zero potential of the ship is the ship's hull and anything electrically connected to it. In the case of the power corridor, the metal enclosures of the electrical components are considered at ground potential.

Figure 3-16 shows a diagram of the electrical connections within the interface box to the PCM-1 internal bus.

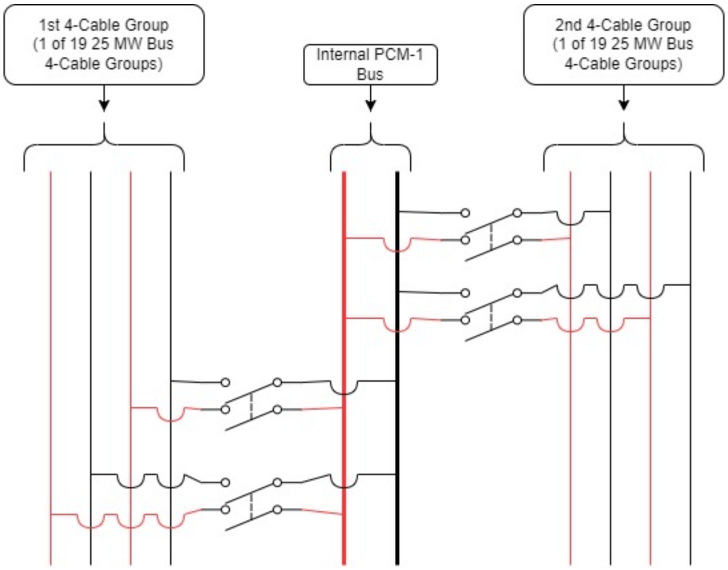


Figure 3-16: Interface Box Electrical Diagram

Figure 3-17 shows a concept of all the main connections within the PCM-1. Power is deliverer to the internal PCM-1 Bus from the 25 MW Bus (as seen in Figure 3-16) and distributed to the nine power conversion sections within the PCM-1. Each conversion section has its own associated output connection to a load.

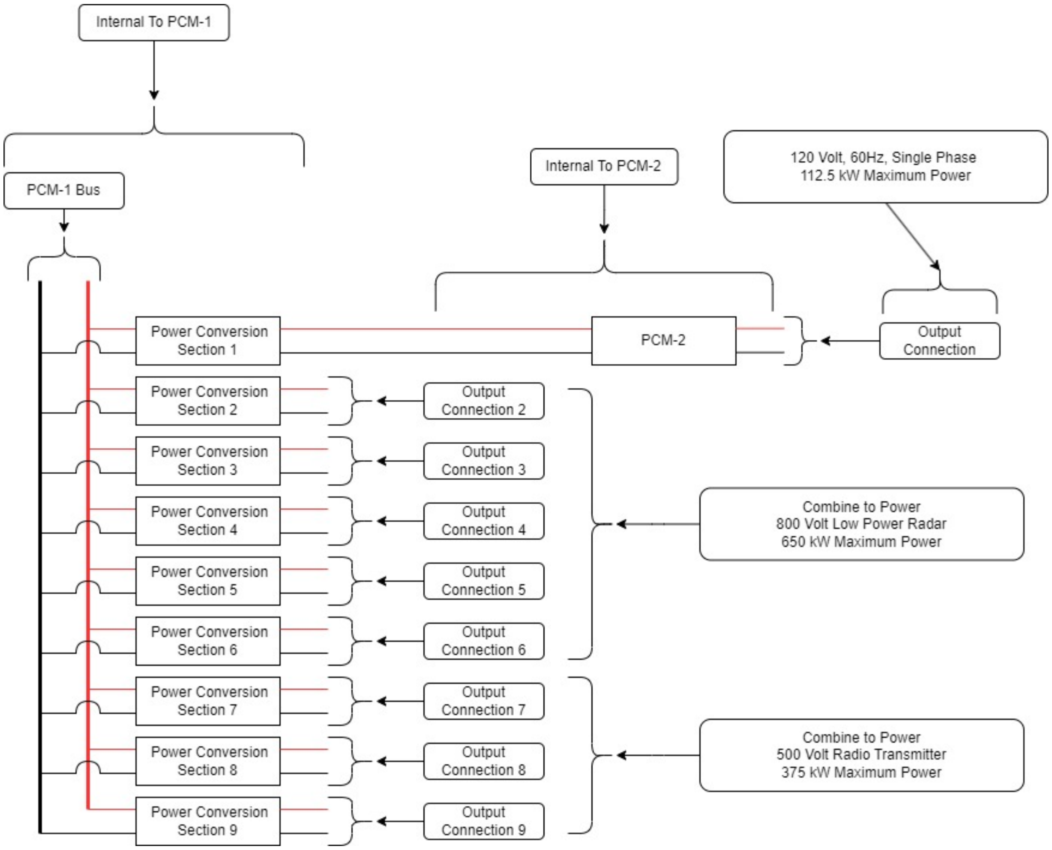


Figure 3-17: Output Connections Electrical Diagram

Figure 3-18 shows a top view of the Interface Box Solidworks model. The grid overlaid in Figure 3-18 is a 6 x 6 in. grid. Shown in Figure 3-18 from left to right are two yellow 25 MW 4-cable groups which split out into their respective positive and negative cables. One set of cables it shaded lighter than the other for ease of visually understanding the cable groups. Each cable pair (black and red) is connected to its isolation switch. On the bottom of Figure 3-18 is the nine output connections of the PCM-1.

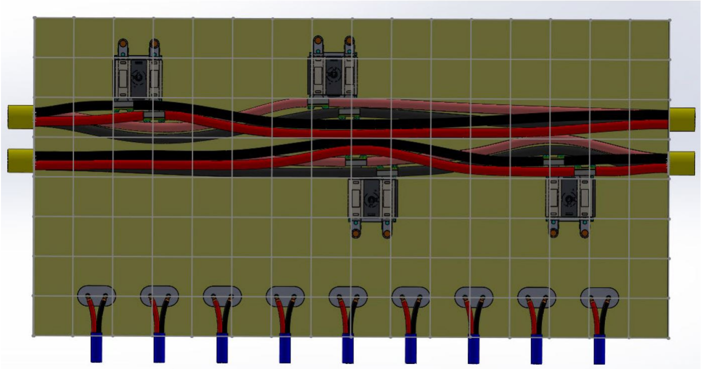


Figure 3-18: Solidworks Interface Box Top View (6 x 6 in grid)

Figures 3-19 and 3-20 shows a perspective view of the internal layout of the interface box.

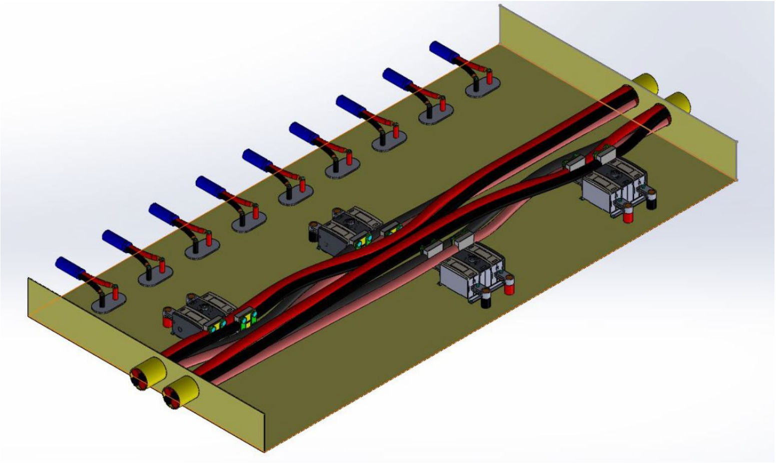


Figure 3-19: Solidworks Interface Box Perspective View

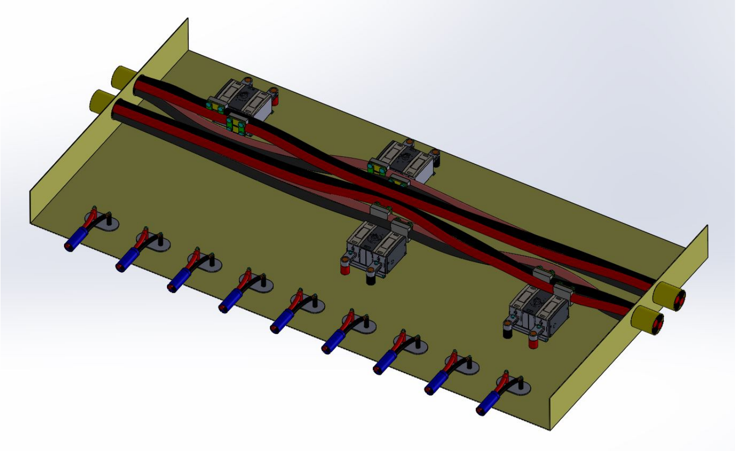


Figure 3-20: Solidworks Interface Box Perspective View 2

Figures 3-21 and 3-21 show different perspectives of the interface box with its cover installed. The cover is installed during operation of the power corridor and only removed for maintenance and inspection.

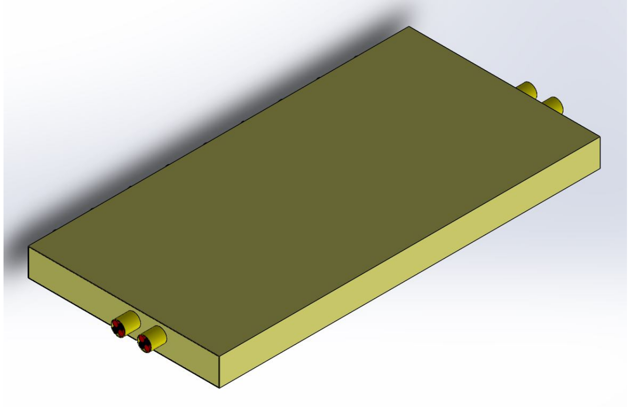


Figure 3-21: Solidworks Interface Box Perspective View Cover Installed

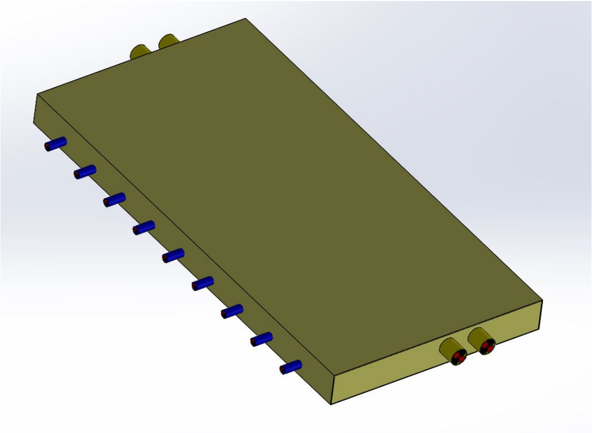


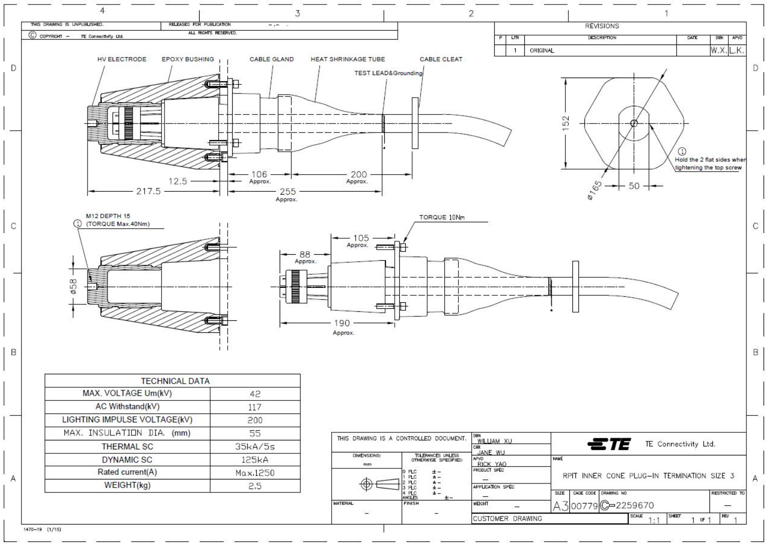
Figure 3-22: Solidworks Interface Box Perspective View Cover Installed 2

3.5 Bulkhead Connections

The bulkhead connections are the method of connecting the power corridor between compartments. These connections will be semi-permanent to allow for the installation of power corridor 25 MW Bus sections individually. This differs from how cable is traditionally installed on ships. Traditionally, cabling is installed by manually running each cable from its starting point to it's ending point. This can lead to long cable runs, potentially the length of the ship, passing through many compartments and bulkheads. Traditional cable installation methods require many hours of human labor. As discussed in Section 1.4, there are economic benefits to be gained by constructing the power corridor components off hull in a workshop. Semi-permanent 25 MW Bus connections allow for the bus to be constructed off hull with other power corridor components, then a power corridor section is rigged onto the ship and plugged in.

There are companies that specialize in high voltage and current connections. Pfisterer has developed medium voltage connection systems rated up to 52 kV and can operated in marine environments [29]. These connection systems were physically too large to be utilized in the power corridor, but did provide insight into connection systems developed to operate in marine environments.

TE Connectivity has developed connection system with a lower voltage rating of 12 kV [8]. There were no details provided on the use of this connection system in marine environments but it is reasonable to assume the connection system could work in marine environments due to its physical similarities to the Pfisterer system. Figure 3-23 shows a diagram of the TE Connectivity cable system which is used for reference in power corridor connection modeling. This connector model is rated at 12 kV and 1250 amps. Since the connector in the power corridor only needs to support approximately half this current, all the dimensions in Figure 3-23 where scaled by half to provide a good estimation of the space needed for the connector.



TECHNICAL DATA	
MAX. VOLTAGE Um(kV)	42
AC Withstand(kV)	117
LIGHTING IMPULSE VOLTAGE(kV)	200
MAX. INSULATION DIA. (mm)	55
THERMAL SC	35kA/5s
DYNAMIC SC	125kA
Rated current(A)	Max.1250
WEIGHT(kg)	2.5

THIS DRAWING IS A CONTROLLED DOCUMENT.
DIMENSIONS: mm
TOLERANCES UNLESS OTHERWISE SPECIFIED:
0 PLC ± –
1 PLC ± –
2 PLC ± –
3 PLC ± –
4 PLC ± –
ANGLES ± –
MATERIAL –
FINISH –
DWN WILLIAM XU
CHK JANE WU
APVD RICK YAO
PRODUCT SPEC –
APPLICATION SPEC –
WEIGHT –
CUSTOMER DRAWING
TE Connectivity Ltd.
NAME RPIT INNER CONE PLUG–IN TERMINATION SIZE 3
SIZE A3
CAGE CODE 00779
DRAWING NO C–2259670
RESTRICTED TO –
SCALE 1:1
SHEET 1 OF 1
REV 1

Figure 3-23: TE Connectivity Connection System Diagram [8]

Figures 3-24 show the Solidworks model of the plug. The plug will be installed as a termination to a single input 4-cable group conductor. The plug is approximately 4 inches long (not including the cable shown in the figures) and the mounting bracket is a 2 by 2 inch square. Figure 3-25 show a cross sectional view with labels of key components needed for the function of the plug.

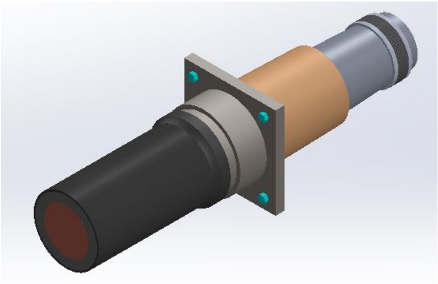


Figure 3-24: Plug Perspective

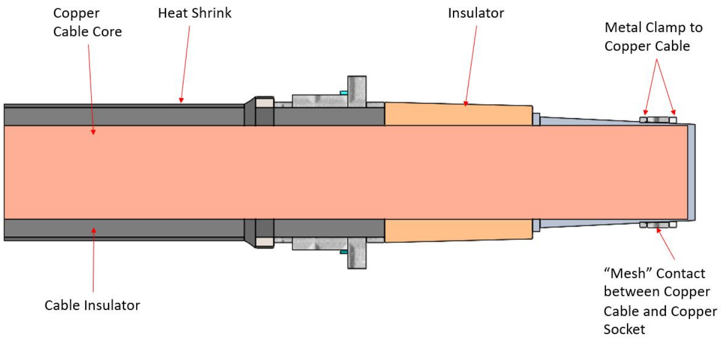


Figure 3-25: Plug Cross Section

Figures 3-25 shows a perspective view of the socket connection. The socket will connect two plugs together (one plug on each side). It will be is manufactured such that all the internal parts are continuous to reduces electrical resistance in the joint and outside of the socket is properly insulated from the operating bus voltage.

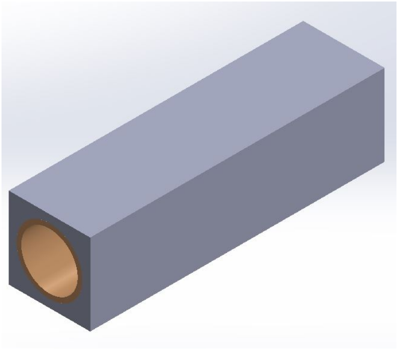


Figure 3-26: Socket Perspective

Figure 3-27 shows a cross sectional view with labels of key components needed for the function of the socket. The center copper plug is to prevent water from flowing from one compartment to another in a flooding casualty.

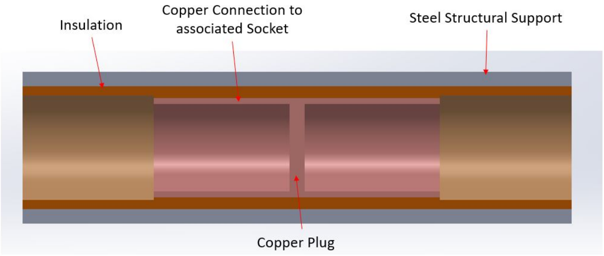


Figure 3-27: Socket Cross Section

Figures 3-29 and 3-28 show the mating of the plug and socket connections and the associated cross section. The plug will be held in place with four bolts. The socket connection will be installed in bulkheads to connect neighboring power corridor sections.

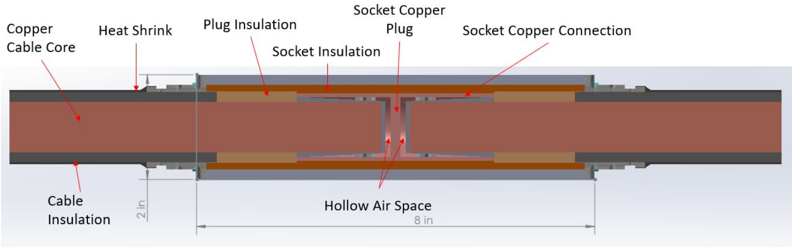


Figure 3-28: Plug and Socket Cross Section

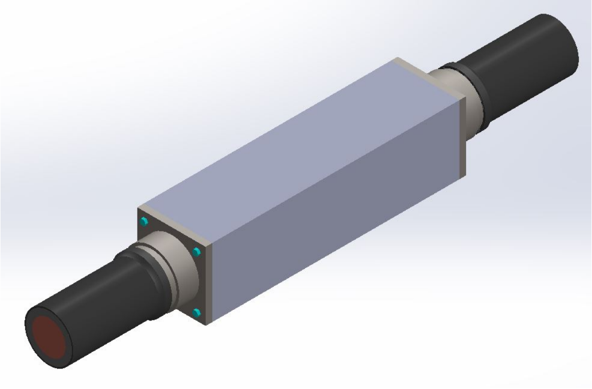


Figure 3-29: Plug and Socket Perspective

Plugs and sockets are joined together to form a module that corresponds to one 4-cable group. The modules are then formed into an assembly to be installed in the bulkhead as shown in Figures 3-30 and 3-31. The separation between the end of the yellow insulated 4-cable group and the beginning of the heat shrink is 6 inches to meet the minimum cable bending radius requirement (Section 3.3.4). The bulkhead assembly plate is 55.7 by 20.5 inch rectangle.

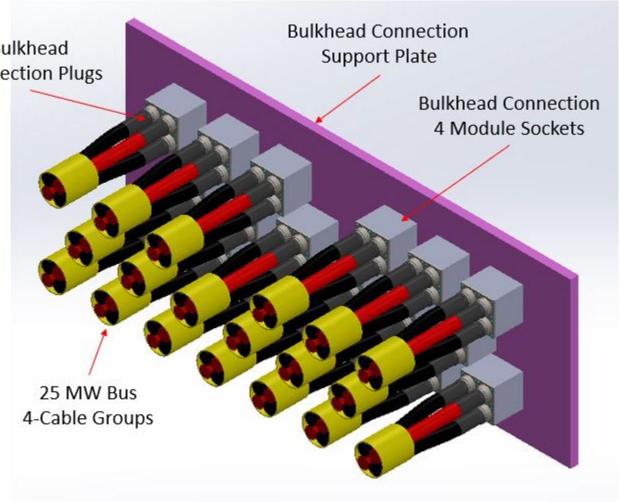


Figure 3-30: Full Bulkhead Connection View

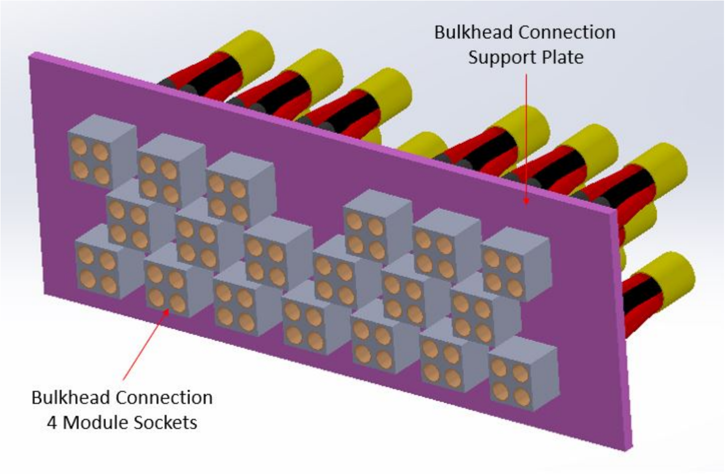


Figure 3-31: Full Bulkhead Connection View 2

3.6 Connected Loads

3.6.1 High Power Loads

Included in same compartment of the power corridor could be several potential representative loads for the PCM-1 to power. Table 3.12 lists several USN loads that have been used in previous research into the design of a notional ship for the power corridor. Operating voltages are not provided but for concept purposes, it is assumed the loads operate at differing voltages.

Load	Power
Active Denial System (ADS)	600 kW
Multi-Function Dual-Band Radar	5 MW
Integrated Radio-Frequency (RF) Suite	2 MW

Table 3.12: Notional Ship Loads [11]

3.6.2 Hotel Loads

It is reasonable to assume that internal to the PCM-1 there could be one or two auxiliary power electrical converters if there was no PCM-2 connected to provide AC power conversion. The auxiliary converters could be rated at approximately 5-10 kW. They could power PCM-1 control circuity, communications cabinet, and/or space and cabinet lighting. Figure 3-32 shows an example electric diagram of the auxiliary converter and potential connections.

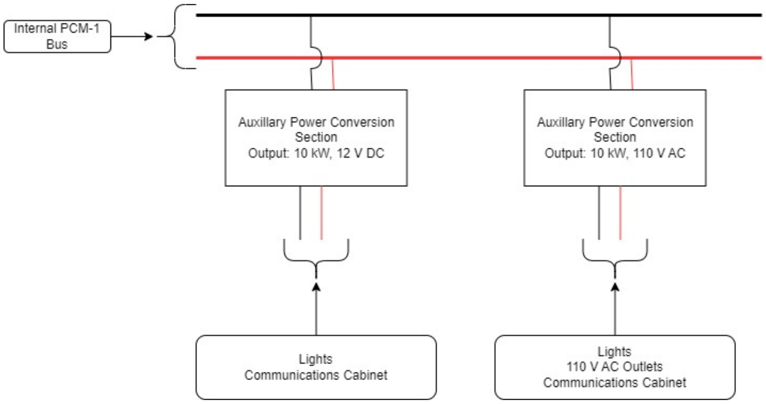


Figure 3-32: Hotel Loads Electrical Diagram

Chapter 4

Assembling Electrical Components into Corridor

Chapter 3 discussed the major components that will be included in the power corridor. This chapter will discuss the arrangement of all the components in the power corridor within available space.

To help with model orientation, there is a 6 foot person is facing the center line of the ship holding a scaled model of the ship. Figure 4-1 shows a whole model perspective view with the 6ft person and scaled ship. The deck above the person and the port hull are hidden in this figure. Figure 4-2 shows a zoomed in view of Figure 4-1.

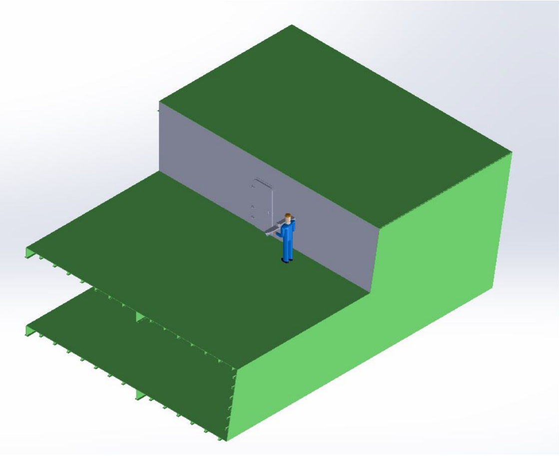


Figure 4-1: 6 ft Person Perspective View

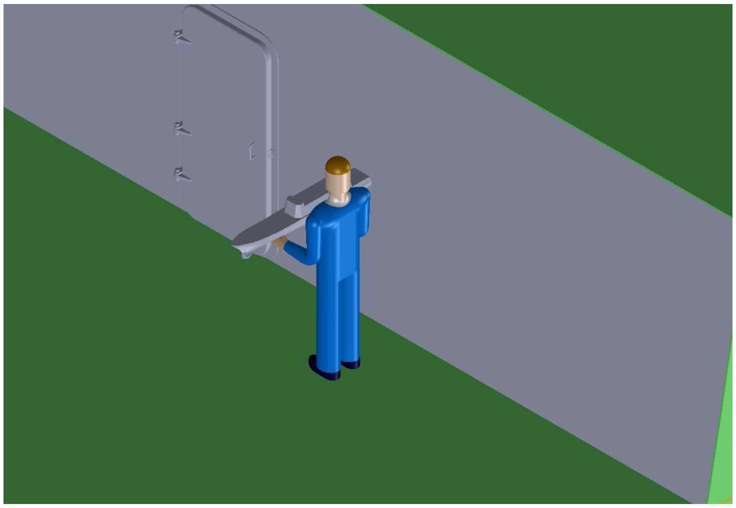


Figure 4-2: 6 ft Person Zoomed Perspective View

4.1 7 inch Foundation

Much of the arrangements in the power corridor centers around the placement of the PCM-1 within the power corridor. This is the largest component with many electrical and cooling water connections. An in depth design into the cooling system is outside the scope of this thesis but space is reserved for cooling water piping, valves, and connections.

In this concept, the cooling water piping is placed below the PCM-1. The space above the PCM-1 was designated for the 25 MW Bus (discussed in Section 4.3). The PCM-1 was raised 7 inches above the deck to allow for 6 inches for the cooling pipes and an addition 1 inch for support material in the foundation. The sizing of the cooling water piping is discussed in Section 4.4.

Figures 4-3 and 4-4 show the front and side view of the 7 inch foundation with dimensions. The foundation is 144 inches long to fit the 96 inch PCM-1 plus another 48 inches for a communications cabinet and a PCM-2 cabinet. The communications cabinet will be discussed more in Section 4.2.2 and the PCM-2 in Section 4.2.3. The foundation of is 48 inches deep to fit the cabinetry.

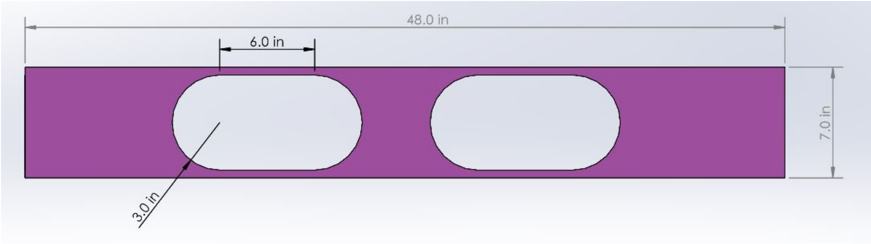


Figure 4-3: 7 in Foundation Side View

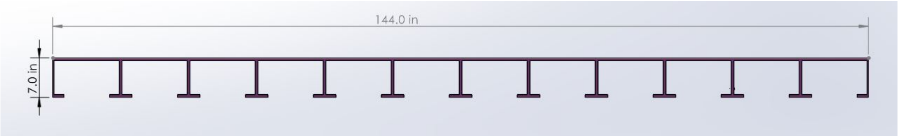


Figure 4-4: 7 in Foundation Front View

Figure 4-5 shows a perspective view of the whole 7 inch foundation. The foundation is colored to allow for easier viewing within the Solidworks model. Figure 4-6 shows the placement of the 7 inch foundation within the ship model. The distance of the 7 inch foundation from the hull corresponds to maintenance access space needed between the PCM-1 and hull (discussed further in Section 4.2.1) and placement of the 25 MW Bus (discussed further in Section 4.3).

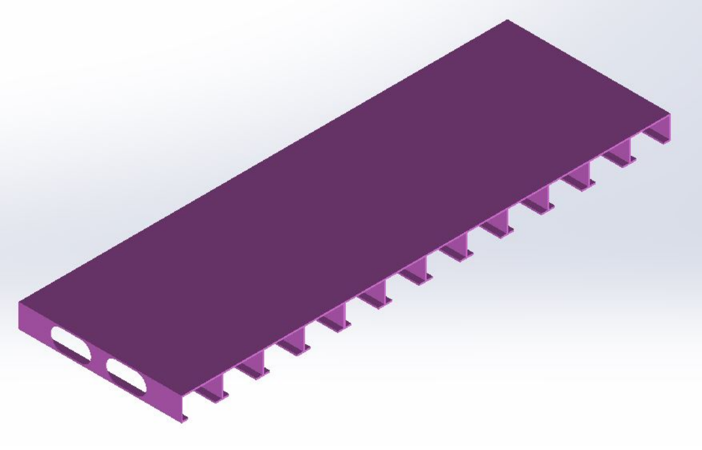


Figure 4-5: 7 in Foundation Perspective View

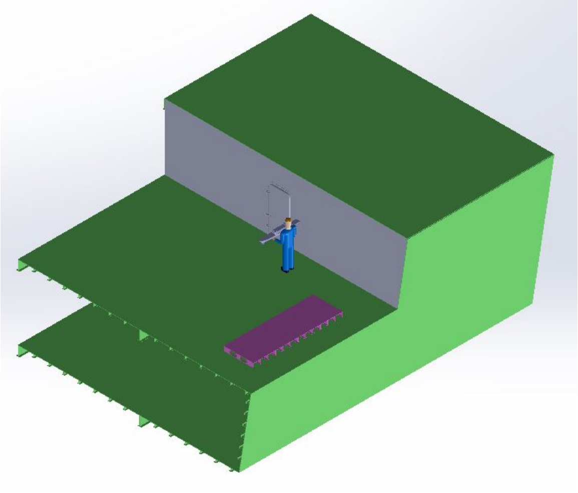


Figure 4-6: 7 in Foundation Ship Placement Perspective View

The 7 inch foundation was designed to place the structural members of the 7 inch foundation perpendicular to the structural members of the ship. This was done to evenly distribute the weight of the 7 inch foundation and the mounted cabinetry. The ship's structural members run from bow to stern and the 7 inch foundation's structural members run port to starboard.

4.2 Cabinetry

4.2.1 PCM-1

The PCM-1 was placed such that there was adequate room between the PCM-1 and the hull of the ship for access by maintenance personnel. MIL-STD-1472 (Human Engineering) identifies the minimum walking floor width for a person to walk on a catwalk and carrying tools or equipment as 18 inches [30]. While walkway between the PCM-1 and the hull is not located on a catwalk, it provides an good minimum of walk space needed. MIL-STD-1472 also specifies "Floor space of 0.4 square meters (m2) (4.0 square feet) minimum per person shall be provided for maintenance personnel and their clothing (including required personal protective equipment, tools, and equipment) as well as free space for the movements and activities required to perform maintenance tasks" [30].

Naval Sea Systems Command (NAVSEA) Technical Publication T9640-AC-DSP-010/HAB (Shipboard Habitability Design Criteria and Practice Manual) specifies secondary walkways shall be not less than 30 inches wide and main walkway width within a berthing area shall be not less than 36 inches [31]. While the walkway between the PCM-1 and the hull is not a berthing area, this provides a good basis for walkway width to ensure adequate personnel access to equipment.

The majority of maintenance is expected to be performed on the side of the PCM-1 facing the centerline of the ship. The hull side access of the PCM-1 is expected to by utilized mainly for periodic inspections of equipment. Any electronic equipment needing to be repaired or replaced is expected to happen from the ship centerline side of the PCM-1. This side is expected to have more room because it opens up to a larger personnel passageway or compartment.

Figure 4-7 shows the placement of the PCM-1 cabinet on the 7 inch foundation. The distance of the 7 inch foundation and the PCM-1 from the hull at deck level is 33 inches. The distance between the PCM-1 and the hull increase with height above the deck due to hull curving outward from the keel of the ship to the weather deck. The distance of 33 inches from the hull was chosen to maximize the volume above the PCM-1 for the 25 MW Bus (discussed in Section 4.3). 33 inches exceeds the 30 inches of a secondary walkway specified in NAVSEA Technical Publication T9640-AC-DSP-010/HAB Shipboard Habitability Design Criteria and Practice Manual. Due to the length of the walkway on the hull side of the PCM-1, there is space for several maintenance personnel (4.0 square feet) as specified in MIL-STD-1472 Human Engineering.

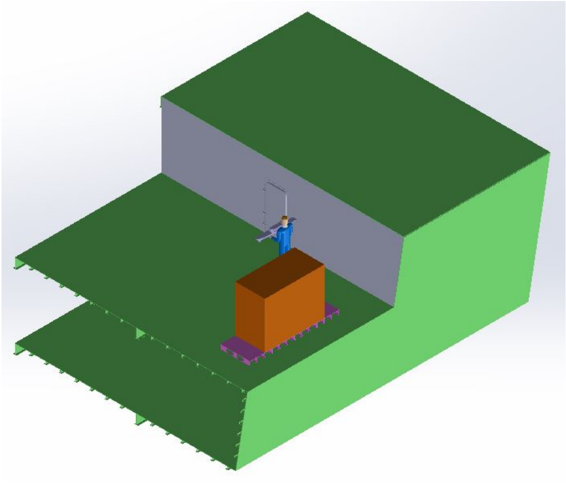


Figure 4-7: PCM-1 (Colored Orange) Perspective View

4.2.2 Communications and Control Cabinet

An additional cabinet was added to the power corridor model to represent space that could be needed to house communications and control equipment in this section of the power corridor. In maintaining the modular footprint of the power corridor, the communications and control cabinet was sized 24 inches wide by 48 inches deep by 75 inches tall. This allowed the cabinet to be placed next to the PCM-1. The communications and control cabinet is shown next to the PCM-1 in Figure 4-8.

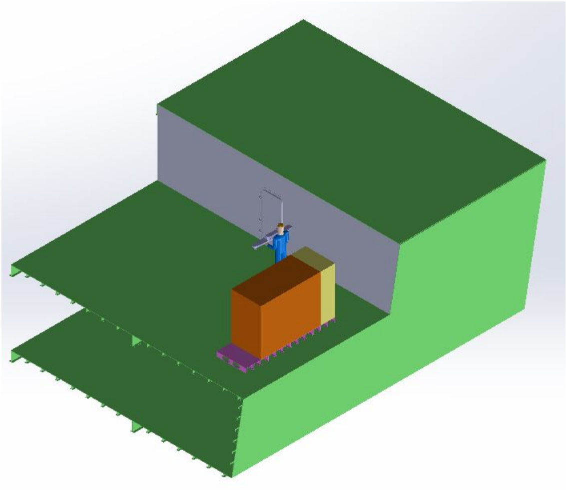


Figure 4-8: Communications and Control Cabinet (Colored Yellow) Perspective View

4.2.3 PCM-2 Cabinet

A third cabinet was added to the power corridor model to represent the space that could be to house a PCM-2 cabinet. In maintaining a modular footprint of the power corridor, the communications and control cabinet was sized 24 inches wide by 48 inches deep by 75 inches tall. This allowed the cabinet to be placed next to the PCM-1. The PCM-2 cabinet is shown next to the PCM-1 in Figure 4-9.

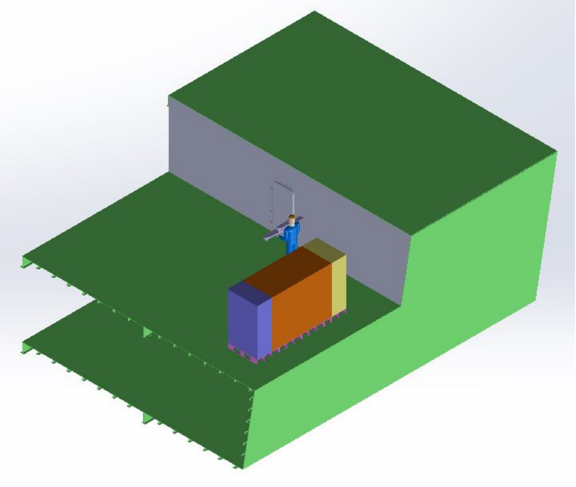


Figure 4-9: PCM-2 (Colored Purple) Perspective View

4.2.4 Interface Box

The interface box is mounted above the PCM-1. The design of the internal components of the interface box is discussed in Section 3.4. Figure 4-10 shows the interface box mounted on top of the PCM-1. Figure 4-11 shows the mounted interface box with its cover installed.

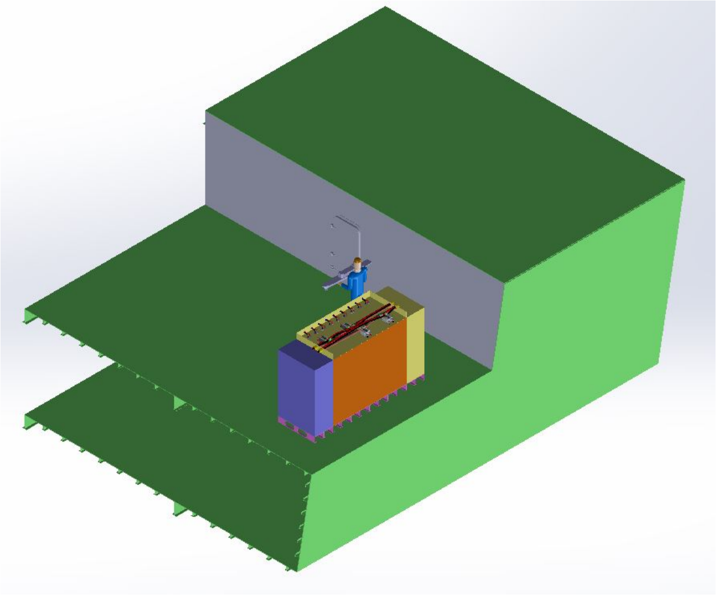


Figure 4-10: Interface Box Perspective View

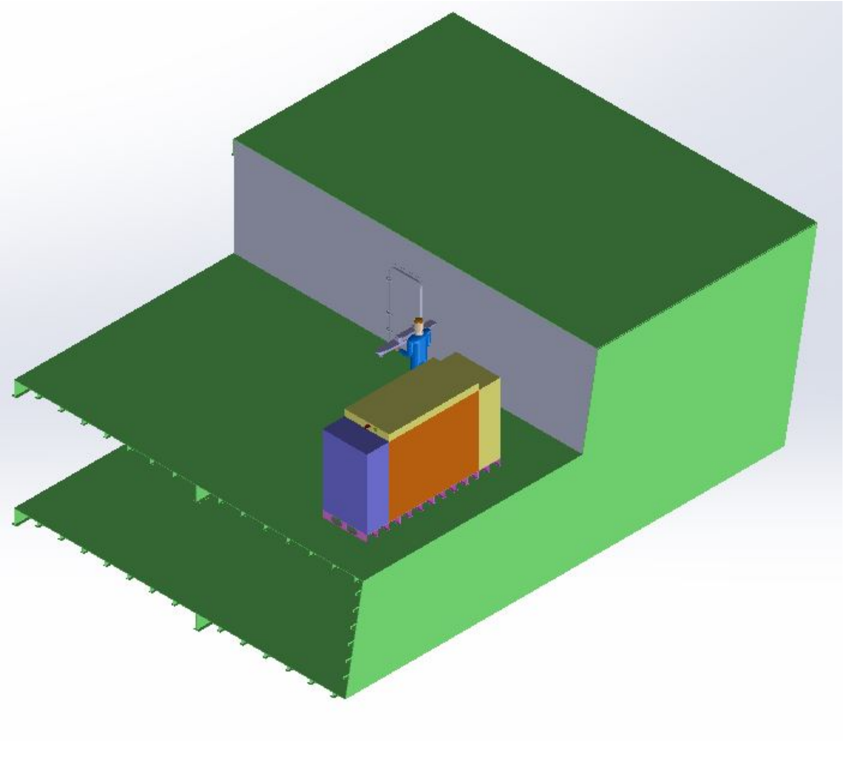


Figure 4-11: Interface Box Perspective View with Cover

4.3 25 MW Bus

4.3.1 Cable Configuration

The 25 MW Bus Cabling needed to fit above and within the footprint of the PCM-1 while also maintaining the required spacing of the 4-cable groups as discussed in Section 3.3.1. The most compact arrangement of the 25 MW Bus was determined to be a triangular packing arrangement.

Figure 4-12 show the 25 MW Bus arrangement. The cables are arranged in an equilateral triangular matrix. The distance of one 4-cable group from another group is 6.6 inches center to center. This maintains the cable to cable spacing calculated in Section 3.3.1 for heat dissipation.

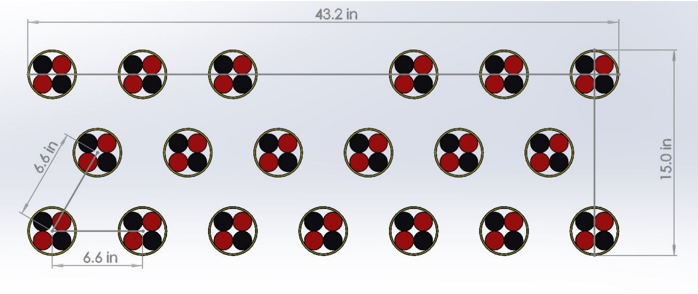


Figure 4-12: 25 MW Bus Arrangement End View

Figure 4-13 shows the constraints around the 25 MW Bus. There is no 4-cable group in the center of the top row because of the structural 'T' beam. This 'T' beam is the reason in Section 3.3.1 the number of 4-cable groups was rounded down to 19 cables instead of rounding up to 20 cables.

Due to space limitations, the current design of the 25 MW Bus does not meet the required distance between a 4-cable group and a ship surface (Table 3.7). The distance between the bottom 4-cable groups and the top of the Interface Box is 0.5 inches. The distance between the top row outer 4-cable groups and 'T' beams is 1.0 and 1.4 inches. The required distance is approximately 1.5 inches

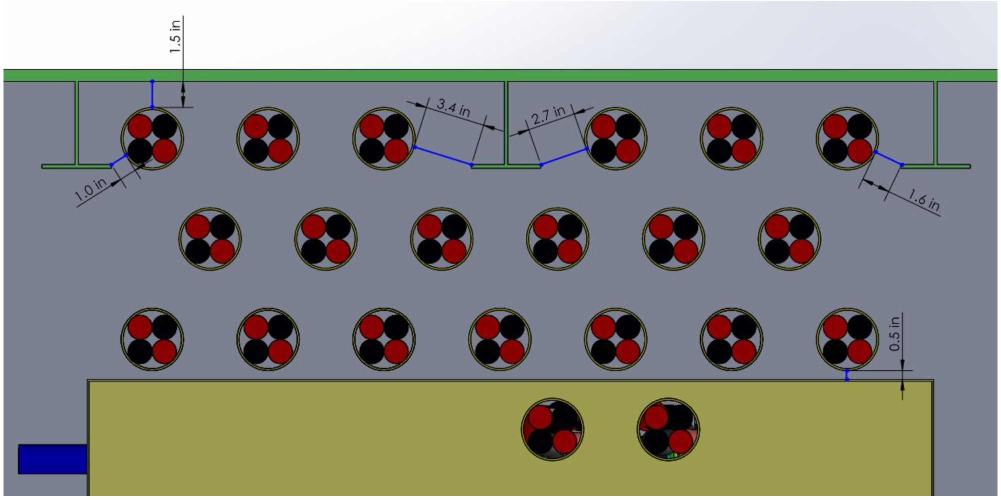


Figure 4-13: 25 MW Bus Clearance

4.3.2 Cable Support

Support for the 25 MW Bus was accomplished by building a metal support structure around the 4-cable groups and securing the cables with cable clamps (cable clamps discussed in Section 3.3.3). Figure 4-14 shows the arrangement of the 25 MW Bus with the metal support and cable clamps. The top and middle rows have 0.5 inch vertical thickness and the bottom row has a thickness of 0.25 inch to allow for a small gap between the bottom of the support and the top of the interface box. The entire support structure has a depth (into the page) of 0.5 inches. No structural or weight analysis was completed on the cabling and cable support.

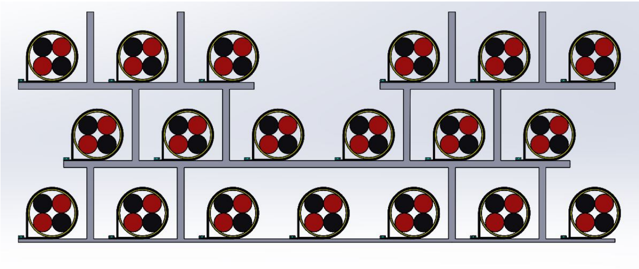


Figure 4-14: 25 MW Bus Support and Clamps End View

Figure 4-15 show a perspective view of a 25 MW Bus section with support and cable clamps. The length of the yellow 4-cable groups is 16 inches. This corresponds to the minimum allows distance between cable hangers specified in MIL-STD-2003-4B to avoid excessive number of cable hangers [27].

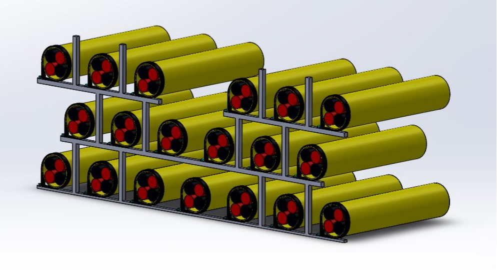


Figure 4-15: 25 MW Bus Perspective View

Portions of the 25 MW Bus will only have 17 4-cable groups because two of the 4-cable groups will be routed into the PCM-1. Figure 4-16 shows the installation of a straight section of the 25 MW Bus above the PCM-1. Figure 4-17 is a zoomed in version of Figure 4-16. 17 4-cable groups are in the cable support as two 4-cable groups are routed into and through the PCM-1. It can be seen how the 25 MW Bus fits around the green structure of the ship.

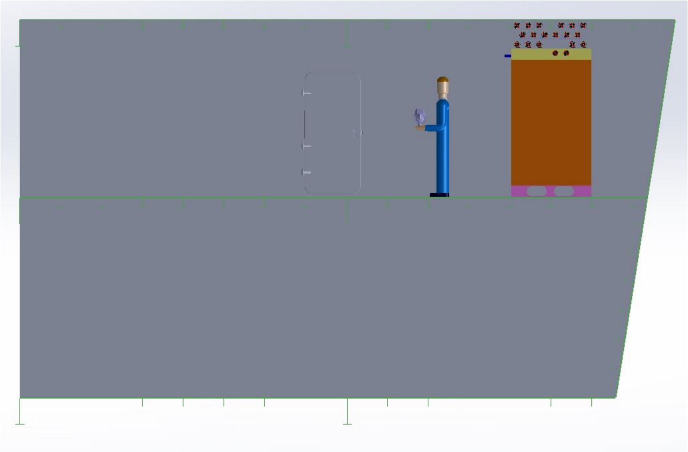


Figure 4-16: Power Corridor 25 MW Bus End View

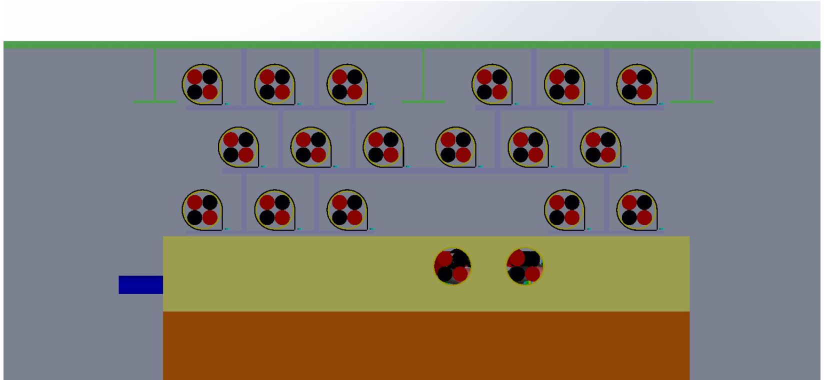


Figure 4-17: Power Corridor 25 MW Bus Zoomed End View

Figures 4-18 and 4-19 show perspective views of the straight section of the 25 MW Bus above the PCM-1.

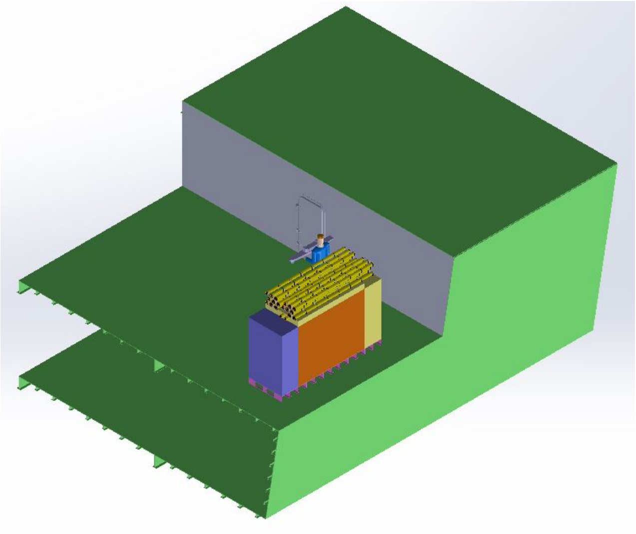


Figure 4-18: Power Corridor 25 MW Bus Perspective View

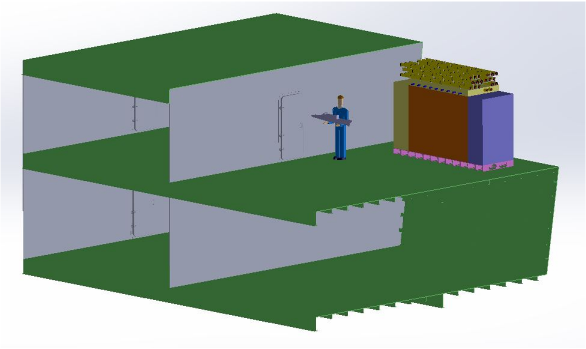


Figure 4-19: Power Corridor 25 MW Bus Perspective View 2

4.3.3 Bulkhead Connection

The bulkhead connections are installed on the bulkheads between ship compartments. As discussed in Section 3.5, the bulkhead connections are installed on a rectangular plate. A hole for the connection plate is made in the bulkhead and welded into place. In order to not interfere with the 'T' beams passing through the bulkhead, the placement of the bulkhead connection plate was located below the 'T' beams. Figure 4-20 shows the installation of the bulkhead connection plate with Figure 4-21 showing a zoomed in version. These figures show the bulkhead connection plate installed below the 'T' beam and installed cable supports to support the protruding cabling.

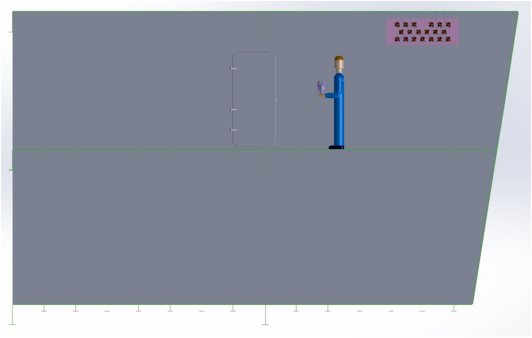


Figure 4-20: Power Corridor Ship Bulkhead Connection View Looking Aft

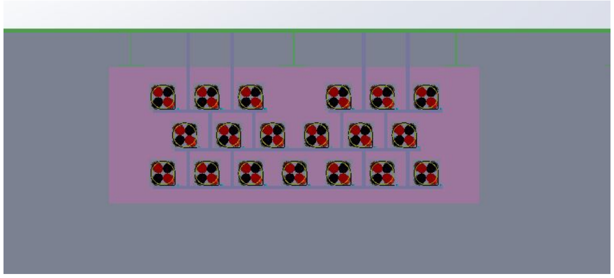


Figure 4-21: Power Corridor Ship Bulkhead Connection Zoomed View Looking Aft

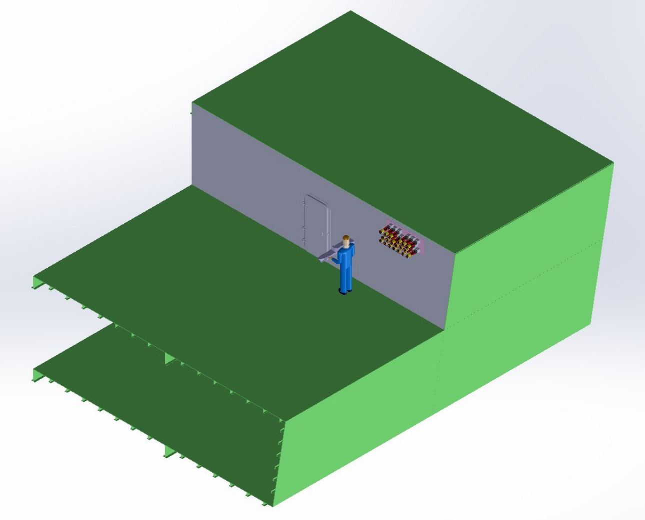


Figure 4-22: Power Corridor Ship Bulkhead Connection Perspective View

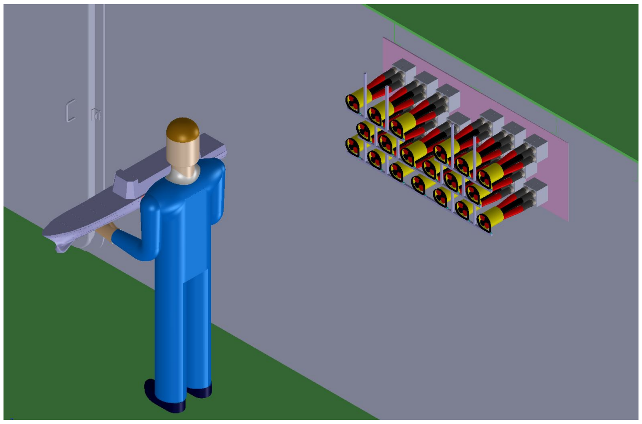


Figure 4-23: Power Corridor Ship Bulkhead Connection Zoomed Perspective View

A second bulkhead connection plate was added on the forward side of the compartment for connection to the adjacent compartment. This is shown in Figure 4-24. The bulkhead connections are at the same height above the deck and distance from ship's centerline.

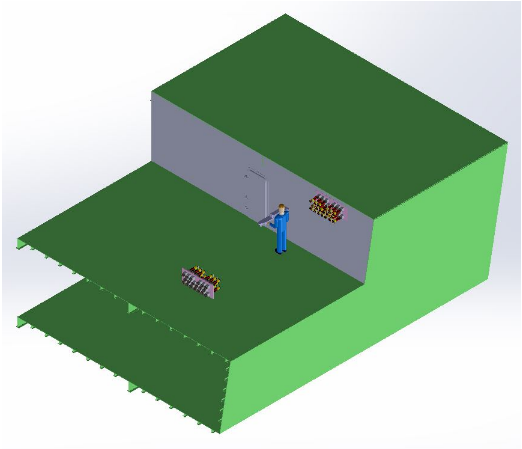


Figure 4-24: Power Corridor Two Ship Bulkhead Connections Perspective View

4.3.4 Curved Sections of Cabling

The straight section of 25 MW Bus, Interface Box, and Bulkhead Connections were all connected with curved 4-cable group sections. The cable curve distances were measured to ensure they do not violate the minimum bending radius requirement discussed in Section 3.3.4. Figures 4-25, 4-26, and 4-27 shows perspective views of the continuous 25 MW Bus.

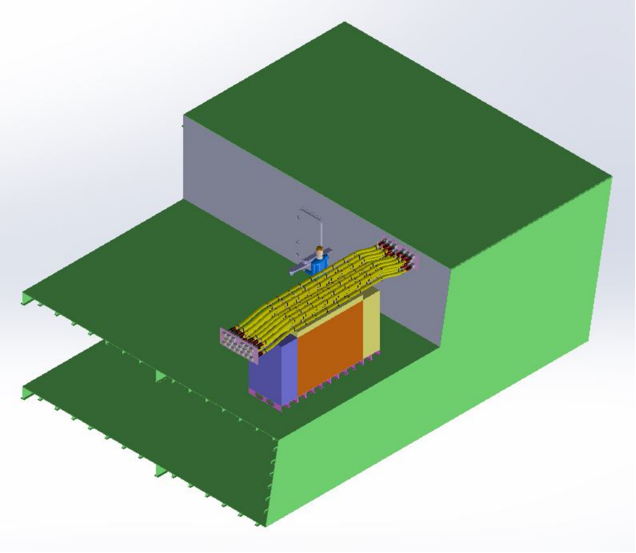


Figure 4-25: Continuous 25 MW Bus Perspective View

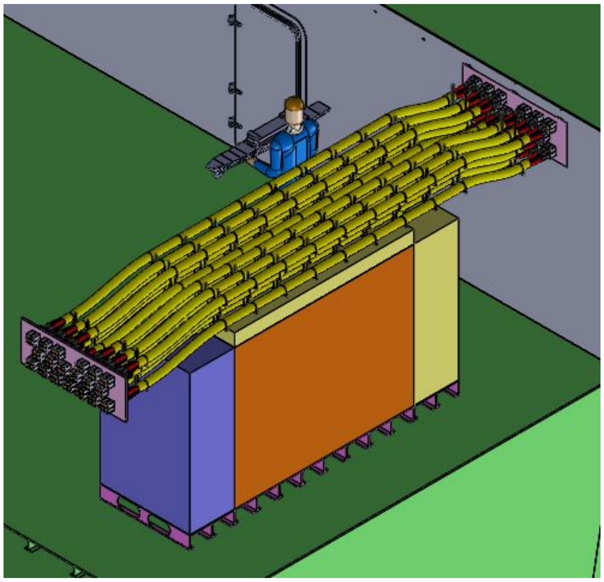


Figure 4-26: Continuous 25 MW Bus Perspective View 2

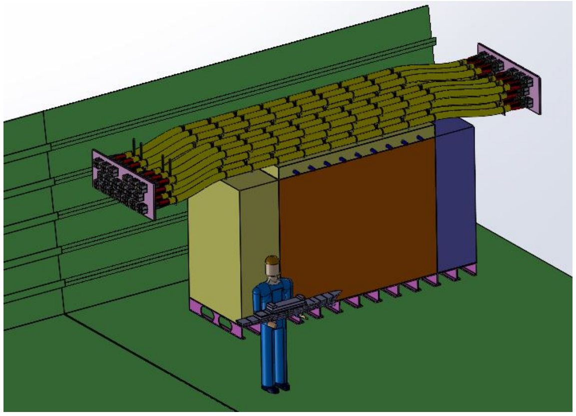


Figure 4-27: Continuous 25 MW Bus Perspective View 3

Figure 4-28 shows a view looking from port side towards ship centerline of the continuous 25 MW Bus. From this view, it can be seen the path of the 25 MW Bus cabling. Figures 4-29 and 4-30 show additional views from the port side.

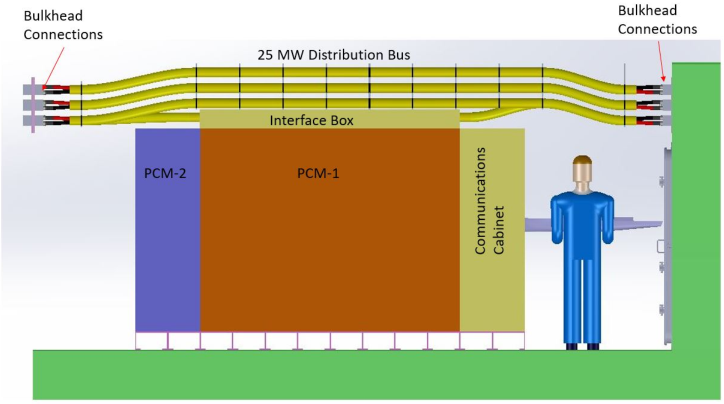


Figure 4-28: Continuous 25 MW Bus Port Side Looking Towards Ship Centerline

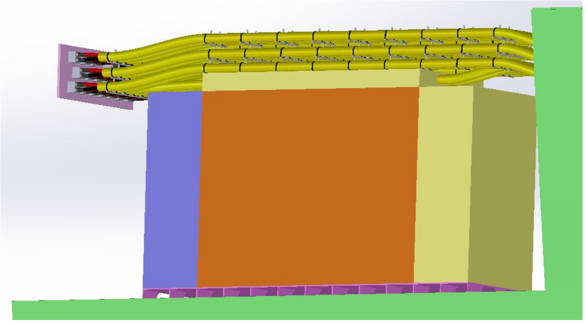


Figure 4-29: Continuous 25 MW Bus Port Side Looking Towards Ship Centerline 2

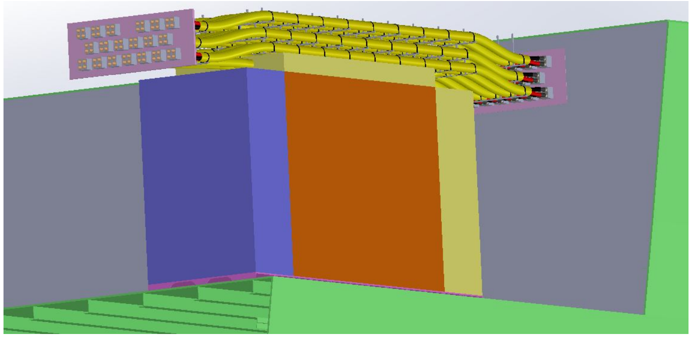
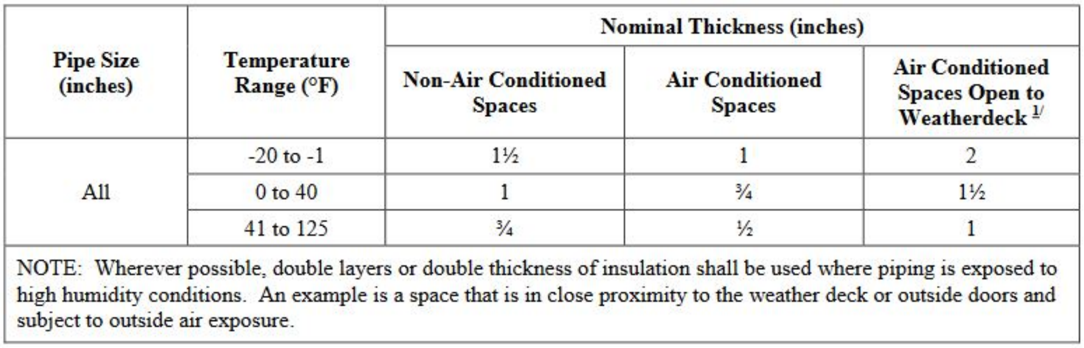


Figure 4-30: Continuous 25 MW Bus Port Side Looking Towards Ship Centerline 3

4.4 Cooling Water Piping

Current research into the cooling system needed for the power corridor has cooling water distribution piping outer diameter of approximately 5 inches and chill water plants located outside the corridor space [32]. The piping also needs to be insulated to maintain the cooling power temperature and to prevent condensation from forming on the outside of the piping and causing corrosion. Table 4.1 lists the insulation thicknesses required from MIL-STD-769 Insulation and Lagging. The power corridor could be housed within the hull of the ship and operate in an air conditioned space at temperatures from 41 to 125 degrees Fahrenheit. This assumption requires an insulation thickness of 0.5 inches. This means the cross sectional diameter of the cooling piping and its insulation to approximately 6 inches.



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.

Table 4.1: MIL-STD-769 Insulation Thickness

Figure 4-31 shows the concept location of supply and return cooling water piping. Figure 4-32 shows a zoomed in view of Figure 4-32. The interface between the piping and cooled components was not modeled. There is space within the corridor on either side of the cabinetry for valves and control manifolds for controlling the cooling water flow rate.

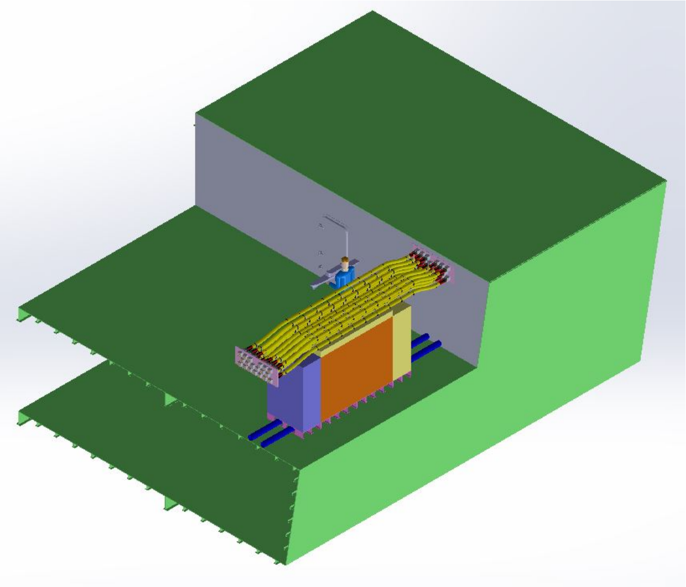


Figure 4-31: Cooling Piping (Colored Blue) Perspective View

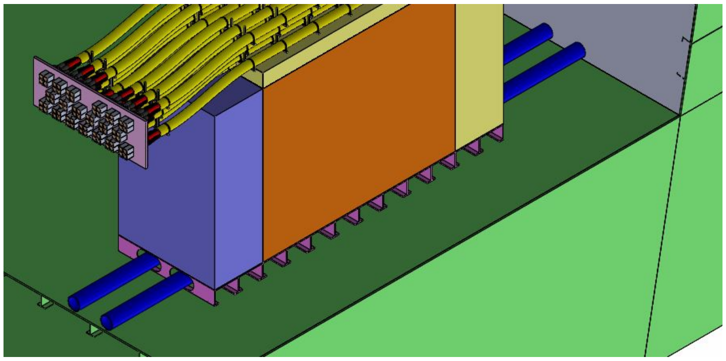


Figure 4-32: Zoomed Cooling (Colored Blue) Piping Perspective View

Chapter 5

Enclosing Power Corridor

The power corridor was enclosed to protect the equipment from dust and contaminants and a personnel safety barrier due to the high operating voltages. A military requirement in designing the enclosure is during normal operation personnel will only need to access the corridor from one side [33]. Another military requirement for the enclosure is all parts should be accessible for periodic inspection and maintenance [27].

5.1 Power Corridor Front Side

5.1.1 Cabinetry Access

The front side of the cabinetry (PCM-1, PCM-2, and Communications Cabinet) will have access doors. MIL-STD-1472 (Human Engineering) specifies "When hinged doors are adjacent, they shall open in opposite directions to maximize accessibility". Figures 5-1 and 5-2 show the placement of the equipment access doors on the front side of the cabinetry. Each door is 24 inches wide by 75 inches tall. The black rectangles in the middle of each door are door handles. The side opposite the door handles is the hinged side of the door. Each door would have a catch to hold it open while operating at sea [30].

Since there is high voltage operating behind the cabinet doors, each door requires a non-bypassable interlock. This interlock would prevent personnel from accessing the equipment inside while it is energized. Additionally there would be a mechanism to energize internal cabinetry lighting when the equipment doors are opened [30]. On the outside of each door, a hazardous marking will be installed to identify high voltage inside [33].

A status display was installed on the second door from the left in Figure 5-2. This would allow personnel to understand the general status and health of the components inside while performing frequent inspections around the ship.

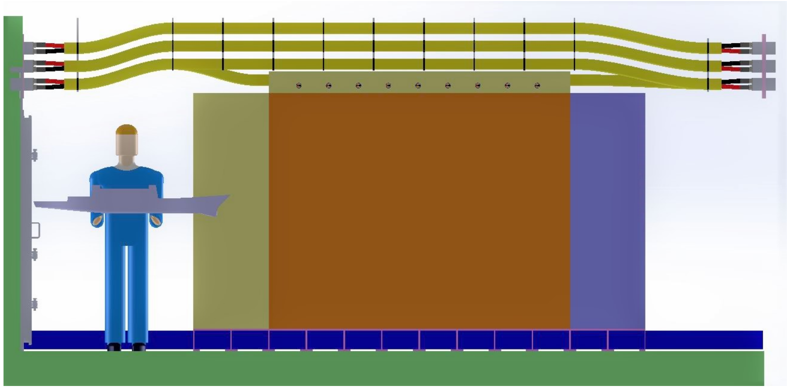


Figure 5-1: Cabinetry Looking Towards Port Hull

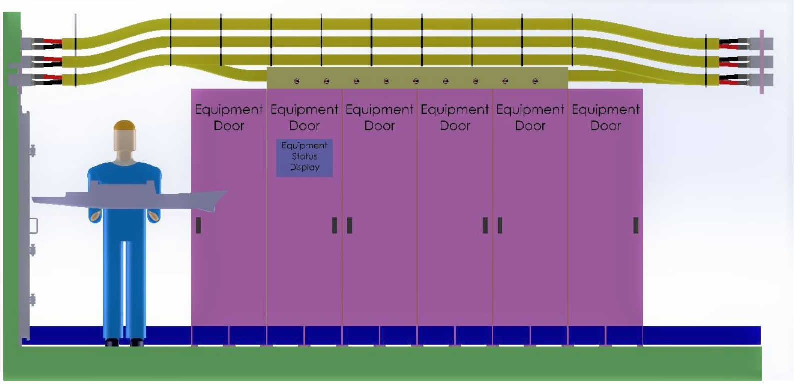


Figure 5-2: Cabinetry Equipment Doors Looking Towards Port Hull

5.1.2 Passage Door

A personnel passage door was installed on the front of the enclosure. This allows personnel to access the back side of the power corridor (area between the power corridor and the hull). Figure 5-3 shows the placement of the passage door. This door is 75 inches tall by 26 inches wide to correspond with ship habitability standards [31]. The door hinge is on the left side of the door when seen in Figure 5-3. The door swings inward (towards the ship's hull) to avoid interference with passage traffic [31]. The door is spaced 4 inches from the left bulkhead for human engineering requirements [33].

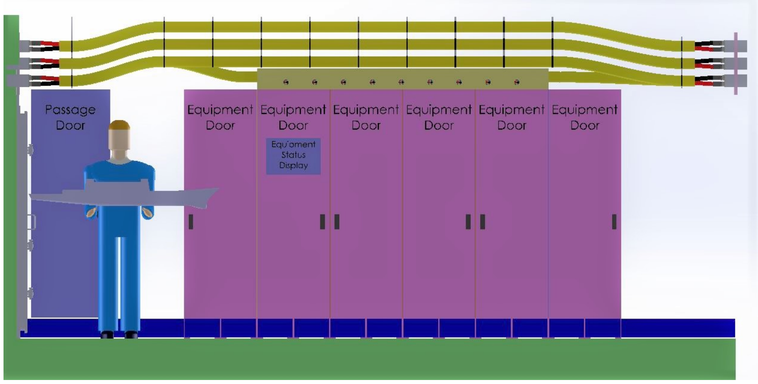


Figure 5-3: Passage Door Looking Towards Port Hull

5.1.3 25 MW Bus Covers

Bolted covers were installed over the 25 MW Bus to allow for periodic inspection and maintenance of the cableway [27]. Figure 5-4 shows the installation of the bolted covers over the 25 MW Bus. For concept purposes within this model, there is no structure behind the covers for the bolts to attach. Potential attachment points could use the 25 MW support behind the covers. A cover was not installed over the Interface box because the Interface Box has its own cover for the output connections.

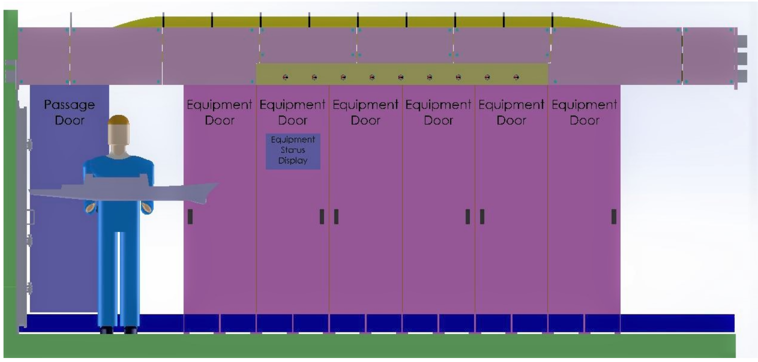


Figure 5-4: 25 MW Bus Bolted Covers Looking Towards Port Hull

The top of the 25 MW Bus can be seen in 5-4 because overhead ship structure is hidden in this view. Showing the ship's structure in Figure 5-5 shows how the covers extend to the 'T' Beam of the ship's structure.

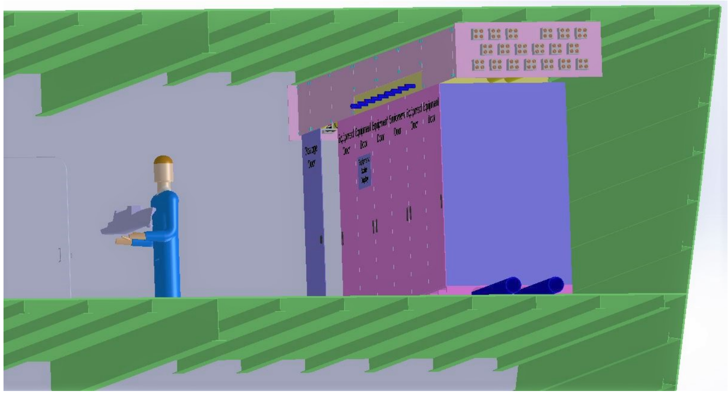


Figure 5-5: 25 MW Bus Bolted Covers Looking Aft

5.1.4 Welded Paneling

In sections of the power corridor where access was not needed or required, welded paneling was installed. Figures 5-6 and 5-7 show the installation of the welded paneling (dark green).

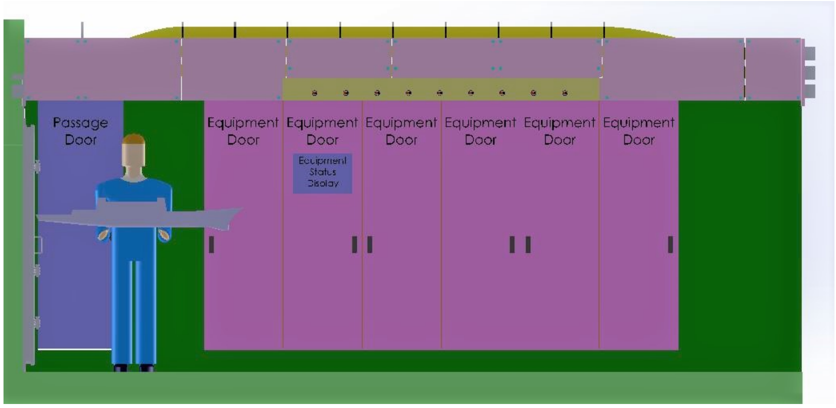


Figure 5-6: Welded Paneling (dark green) Looking Towards Port Hull

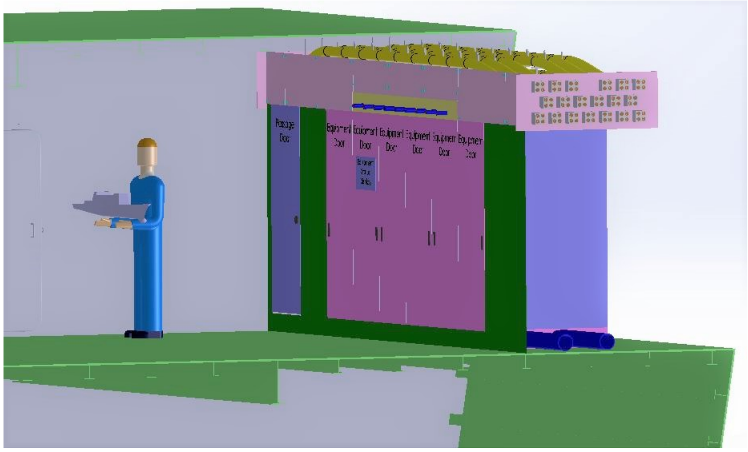


Figure 5-7: Welded Paneling Looking Aft

5.2 Power Corridor Back Side

In this concept, the back side of the power corridor is the side between the cabinetry and hull. The minimum space required for personnel access between the cabinetry and the ships hull is 30 inches by habitability standards [31]. The distance between the back side of the corridor and the ship's hull in the concept in 33 inches.

5.2.1 Bolted Covers

Bolted covers were install to cover all the cabinetry, 25 MW Bus, and portions of the cooling water piping. This allows for access to all the components for maintenance and inspection while still providing protection from foreign objects. Figure 5-8 shows the installation of the bolted covers on the back side. In this view the front parts of the enclosure are hidden. Similar to Section 5.1.3, the top of the 25 MW Bus can be seen because overhead ship structure is hidden in this view.

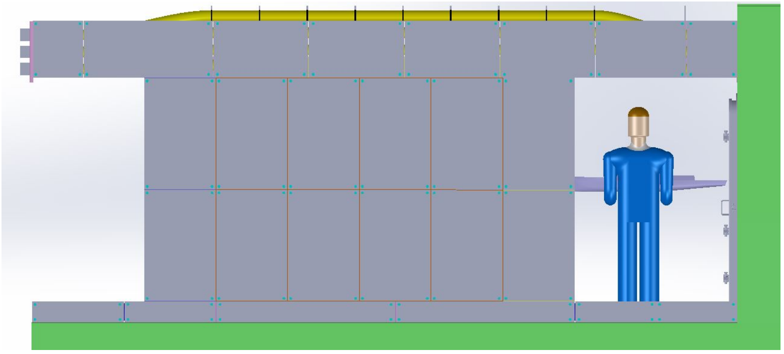


Figure 5-8: Back Side Bolted Covers Looking Towards Ship's Centerline

5.2.2 Walkways

Two walkways were installed to protect the cooling water piping from personnel stepping on them. The first walkway is aligned with the passage door and the only walkway required within the power corridor. The second walkway is optional and provides a working space for personnel if there is space on the opposite side of the corridor. Figure 5-9 shows the placement of the walkway.

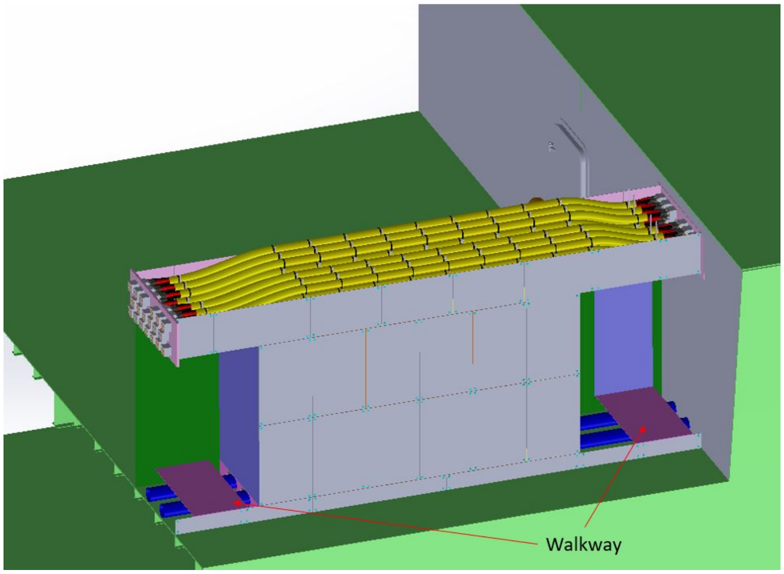


Figure 5-9: Walkways Looking Towards Ship's Centerline

5.3 Complete Enclosure

The following figures show the completed power corridor with enclosures and the ship's structure hidden.

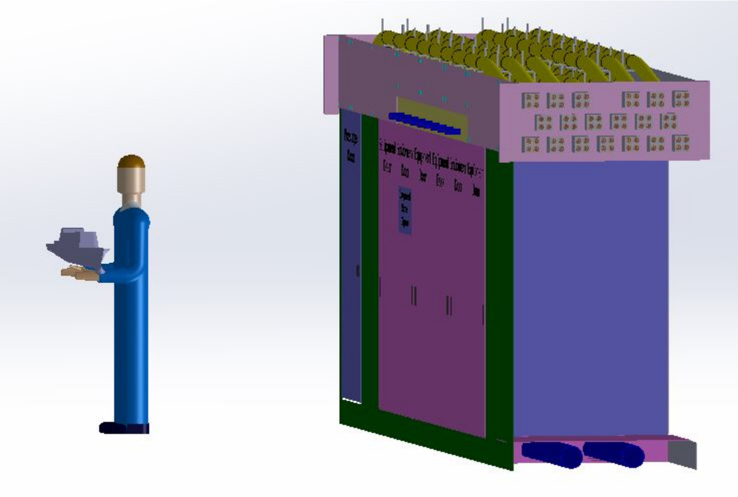


Figure 5-10: Completed Enclosure Looking Aft

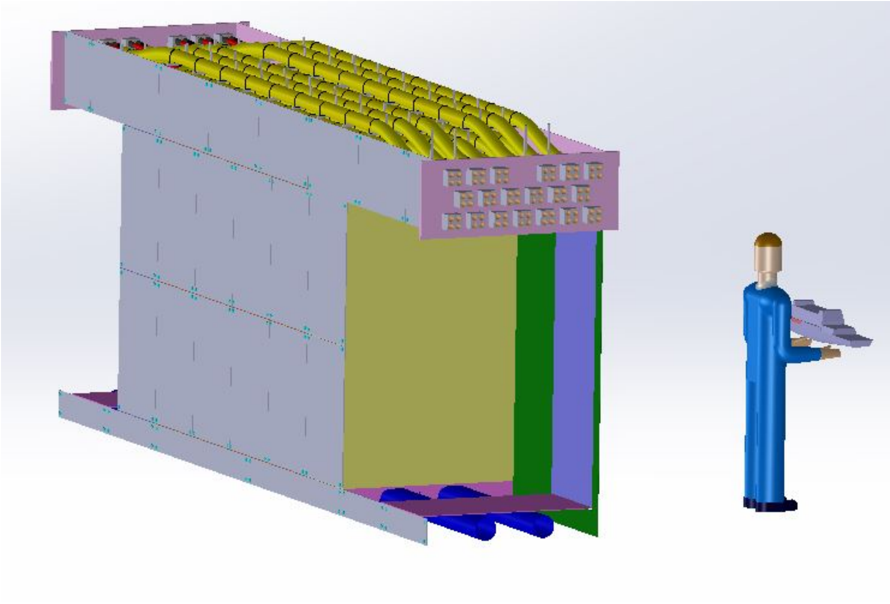


Figure 5-11: Completed Enclosure Looking Forward

Chapter 6

Integrating Corridor into Ship

The completed power corridor concept from Chapter 5 can be integrated throughout the ship. As discussed in Section 1.2 space will be reserved within the ship for the power corridor in the design phase of the ship. The space reserved for the power corridor will be maintained through out the life of the ship. This builds in margin for future electrical component upgrades.

6.1 Ship Section View

The corridor section modeled in Chapter 5 was located on the port side of the 2nd deck of the ship. In Figure 6-1, this would be the top right corridor. Integrating the complete power corridor section into the ship, adds a power corridor on the starboard side of the second deck, and port and starboard sides of the forth deck. This physical separation allows for different sections of the ship (and power corridor) to sustain damage and not affect the operation of the undamaged sections.

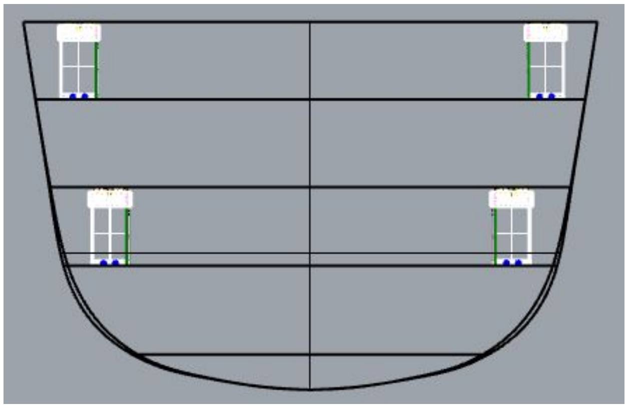


Figure 6-1: Power Corridor Section View Looking Aft

Figure 6-2 shows a perspective view of a ship section. This ship section is from the center (bow to stern) of the ship.

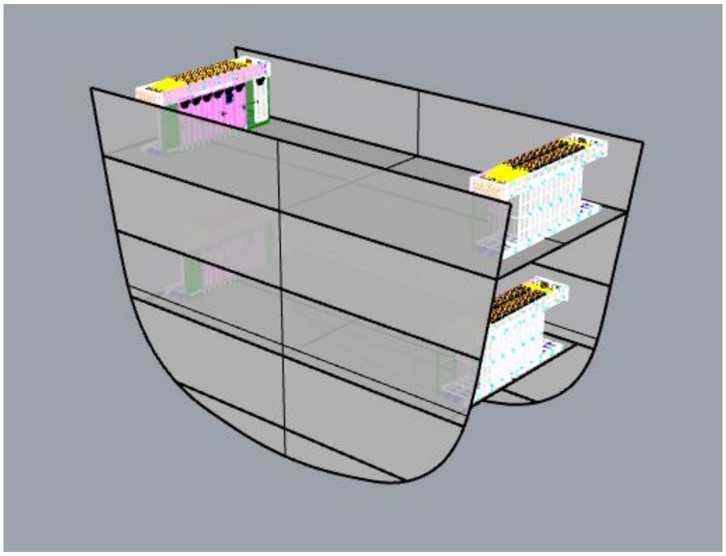


Figure 6-2: Power Corridor Section Perspective View Looking Aft

Figure 6-3 shows a side view of the ship section looking from the port to starboard side. This view shows decks 2 through 5.

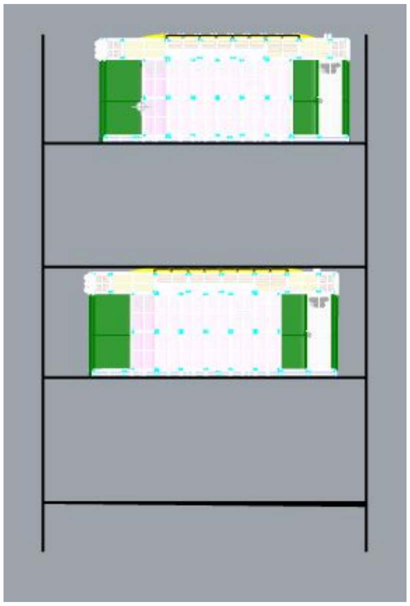


Figure 6-3: Power Corridor Section Side View Looking Port to Starboard

6.2 Whole Ship View

Figures 6-4 and 6-5 show the integration of the power corridor into the entire ship hull. Decks 2 and 4 are shows and decks 1 and 3 hidden in the model. For simplicity in this concept, the 25 MW Bus is not shown extended from bulkhead to bulkhead within each compartment. The length of the 25 MW Bus is the same length as described in Chapter 5. In a fully completed corridor, the 25 MW Bus and cooling water piping could run the length of the corridor in the overhead and deck level respectively. A power corridor section is not placed in every compartment to demonstrate the flexibility of PCM locations.

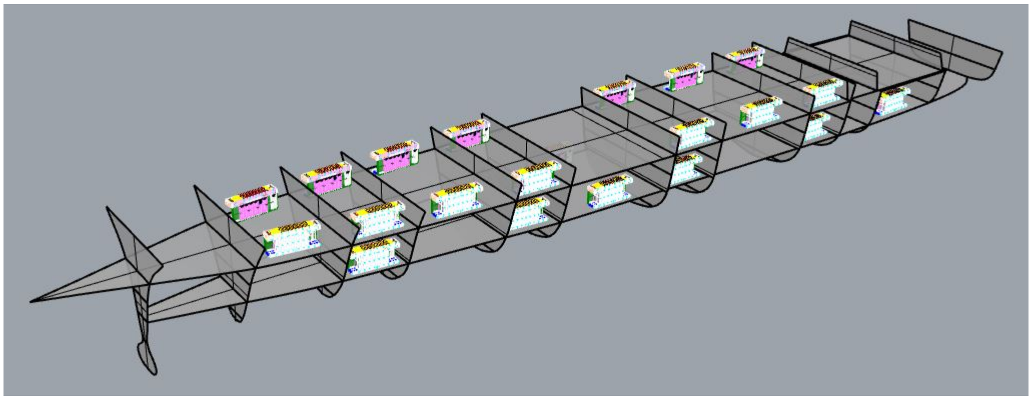


Figure 6-4: Ship Power Corridor Perspective View Looking Aft

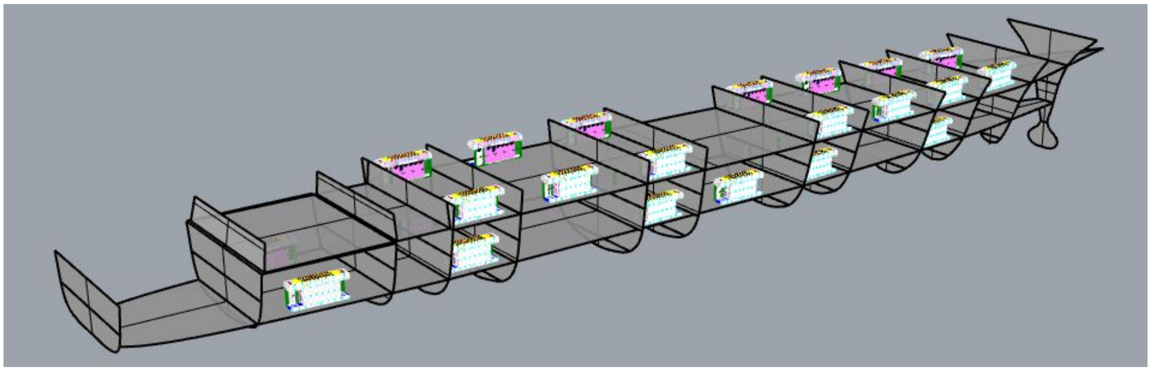


Figure 6-5: Ship Power Corridor Perspective View Looking Forward

Figure 6-3 shows a side view of the ship looking port to starboard. In this view the outline of the ship's hull and super structure are shown.

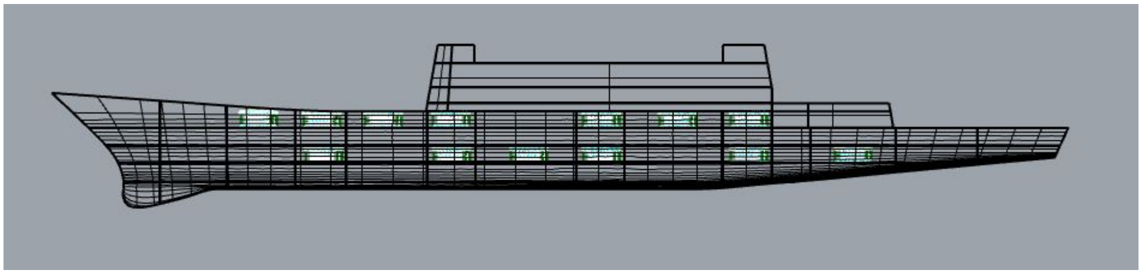


Figure 6-6: Ship Power Corridor Side View Looking Port to Starboard

Figure 6-7 shows a top down view of the power corridor within the ship. In this view the only the ship's hull and bulkheads are shown. The individual decks and superstructure are hidden.

Figure 6-7: Ship Power Corridor Top Down View

6.3 Modularity

The power corridor integration into that ship shown in Sections 6.1 and 6.2 show one concept of the layout of the power corridor with all the corridor sections having the same size PCM-1 and PCM-2. A more realistic concept could have different sized PCM-1 and PCM-2 cabinets depending on the power requirements in a ship section.

For example, the ship would have higher power demands near the larger loads described in Table 3.12. The power corridor sections that are closest to these loads would require more power conversion sections within a PCM-1 and/or power from multiple corridors in order to meet the power demands of these loads. Since the reserved space approach is used when designing the ship with the power corridor, more PCM-1s could be installed to meet the power demands of a ship section.

6.4 Redundancy

There are several ways redundancy is built into the power corridor. The first way is each power corridor section within a compartment has two power sources connected to it as described is Section 3.4. One 4-cable group from the 25 MW Bus is required to fully power the PCM-1. The Interface Box has two 4-cable groups from the 25 MW Bus.

Additionally within the Interface Box, each cable pair (positive and negative) from the 4-cable group has its own isolation switch into the PCM-1. The isolation switches at each cable pair offers and additional layer of redundancy as one faulty cable pair does not affect the other cable pair within the 4-cable group. The PCM-1 can still be fully powered from two 4-cable groups each with one functioning cable pair.

Another way redundancy is built into the power corridor is loads could be powered from multiple corridors. If an entire power corridor was out of service, the loads could be powered from another operating corridor. This is particularly important for vital loads such as Multi-Function Dual-Band Radar (5 MW) and Integrated Radio-Frequency (RF) Suite (2 MW). By powering these loads from more than one power corridor, it decreases the likelihood that a single failure within the power corridor will affect the operation of this equipment.

6.5 Reliability

Reliability is built into the power corridor both through the Redundancy discussed in Section 6.4 and the physical separation of the power corridors from one another. This physical separation decreases the likelyhood that an event that damaged one power corridor affects another power corridor.

6.6 Space Distribution

6.6.1 Corridor Space Distribution within Notional Ship

The total arrangeable floor area and total arrangeable volume of the notional ship were 48804 ft^2 and 574375 ft^3 respectively [11]. The floor area and volume required for one compartment of the notional power corridor was approximately 79 ft^2 and 701.3 ft^3 respectively. Table 6.1 shows a dimensions summary of the notional power corridor in one compartment.

Length (Bow to Stern)	19.7 Feet
Width (Port to Starboard)	4.0 Feet
Height	8.9 Feet
Floor Area	78.8 ft^2
Bulkhead Area	35.6 ft^2
Volume	701.3 ft^3

Table 6.1: Notional Power Corridor Dimensions, One Compartment

Assuming half of the ship's 75 MW electrical capacity is designated for non-propulsion electrical loads, approximately 33 notional power corridor compartment sections are needed. Table 6.2 shows the space distribution of 33 notional power corridor compartments to the notional ship.

	Notional Ship	33 notional power corridor compartments	Fraction of Ship Space
Floor Area (ft^2)	48804	2600	5.3 %
Volume (ft^3)	574375	23143	4.0 %

Table 6.2: Corridor Space Allocation within Notional Ship

6.6.2 Component Space Distribution within Notional Power Corridor

Using corridor floor and bulkhead areas and volume values in Table 6.1, Table 6.3 shows the fraction of space required in each corridor by each of six corridor components. The areas and volume for the cooling pipes assumed a 7 inch high by 48 inch wide floor area running at deck level the length of the corridor.

	Fraction of Corridor Bulkhead Area	Fraction of Corridor Floor Area	Fraction of Corridor Volume
25 MW Bus (including air gap for heat dissipation)	16.6 %	96.3 %	16.2 %
1.125 MW PCM-1	70.2 %	40.6 %	28.5 %
112.5 kW PCM-2	70.2 %	10.2 %	7.1 %
Interface Box	6.6 %	40.6 %	2.7 %
Communications and Control Cabinet	70.2 %	10.2 %	7.1 %
Cooling Pipes	6.6 %	100 %	6.6 %

Table 6.3: Component Space Distribution within Notional Power Corridor Compartment

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This thesis examined the initial physical layout of a power corridor section in a generic naval ship compartment using existing technology. By using technology available today, a benchmark was established on size and power conversion density of the power corridor components. This benchmark will help guide the design and sizing of future components such as the iPEBB that is presently under development.

The designed power corridor section included all the major components required for operation. This included cabling, DC and AC power conversion, connections, and space for corridor control equipment. The corridor section was sized to convert 1.125 MW of DC power to nine individual lower DC voltages using a PCM-1. The size of the PCM-1 is variable meaning that the cabinet size can be increased or decreased depending on available space, power, and voltage requirements of equipment connected to the corridor section. A PCM-2 was also introduced to enable power for AC loads.

The relative amounts of volume occupied by the different major power elements in the corridor section are shown in Table 7.1 .

Component	Fraction of Corridor Volume
25 MW Bus (including air gap for heat dissipation)	16.2 %
1.125 MW PCM-1	28.5 %
112.5 kW PCM-2	7.1 %
Interface Box	2.7 %
Communications and Control Cabinet	7.1 %
Cooling Pipes	6.6 %

Table 7.1: Fraction of Power Corridor Component Volumes

7.2 Future Work

One area of future research could be increasing the voltage of the 25 MW Bus. As an example, increasing the 25 MW Bus to 6000 VDC decreases total current by a factor 6. One 4-cable group operating at 6000 VDC could have approximately the same power capacity as six 4-cable groups operating at 1000 VDC. The Malone thesis showed, in general, higher operating voltages correlate to a lower required bus cross sectional area and volume [5].

Additionally, increasing the voltage could decrease the weight of copper wiring. For the design in this thesis, the 25 MW Bus cabling was assumed to run the 85 % the length of the ship or 436 feet. The conductor diameter was approximately 1.0 inch and there were 304 cables total in four notional power corridors. This gives a volume of 723 ft^3 of copper. The density of copper is approximately 558.2 lb/ft^3. The total copper weight in the bus cable is thus 403,565 pounds or 0.18 kilotonnes, and hence 0.0018 % of a 10 kilotonne ship. The six times increase in bus voltage would thus reduce the bus copper weight, for the same power, by a factor of 6 to just 0.03 kilotonnes.

A second area of future research could be concerned with the size and capability of future power conversion equipment. For example, the Navy iPEBB, presently under development, could lower the total volume and area of reserved space needed within the power corridor. The PCM-1 power conversion density was 5.6 $\frac{kW}{ft^3}$. The iPEBB presently has a power conversion density of approximately double the PCM-1. A power conversion density of 11.2 $\frac{kW}{ft^3}$ could decrease the number of notional power corridor compartments by half. Sixteen notional power corridor compartments in the notional ship could take 2.6 % of the ship's floor area and 2.0 % of the ship's total volume.

A final area of future research could be understanding the volume required within the power corridor for the cooling piping and associated connections to the PCMs. The pipe size was assumed to be 5 inches in diameter based on previous theses. Given the cooling system is actively being researched based on the PEBB 1000 and PEBB 6000 cooling requirements, the layout of a power corridor compartment needs to include this data.

Note that any opinions, findings, conclusions or recommendations expressed in this thesis are those of the author and do not necessarily reflect the views of the U.S. Navy.

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Appendix A

List of Acronyms

AC Alternating Current

AWG All Wire Gage

ASSET Advanced Ship and Submarine Evaluation Tool

DC Direct Current

ESRDC Electric Ship Research and Development Consortium

Hz Hertz

iPEBB Integrated Power Electronics Building Block

kV Kilovolts

kW Kilowatts

MIT Massachusetts Institute of Technology

MW Megawatt

NAVSEA Naval Sea Systems Command

NiPEC Navy Integrated Power and Energy Corridor

NSWCCD Naval Surface Warfare Center, Carderock Division

NSWCPD Naval Surface Warfare Center, Philadelphia Division

PCM Power Conversion Module

PEBB Power Electronics Building Block

PEPDS Power Electronic Power Distribution Systems

RSDE Rapid Ship Design Environment

USN United States Navy

V Volts

ONR Office Of Naval Research

XLPE Crosslinked Polyethylene Insulation

Appendix B

SATCON Technology Corp Brochure

Modular Expandable Power Converters for Redundant Zonal Distribution

- Modular 125kW DC-DC converters and 112.5kW DC-AC inverters in a common physical configuration
- Hot-swappable for fast non-intrusive maintenance
- Modules parallel to 3MW
- Designed to meet shipboard shock (901D) and vibration, EM1 (461-E)
- Load shared for fight through redundancy (IFTP)
- Power flow management (load shed and restore)

"INTEGRATED FIGHT THROUGH POWER" SYSTEMS (PCMs) FOR ADVANCED ELECTRIC SHIPS

SatCon's IFTP Power Control Modules (PCMs) are designed to provide ships with a reconfigurable power distribution system in cases of localized damage or turbine generator failures. Each electrical zone of a ship consists of several Power Converter Modules that distribute power to user AC and DC loads. If any zone encounters an outage the network can reconfigure itself to isolate the local problem and reroute power through the remaining distribution system. **The IFTP-PCM ensures that critical powered systems remain alive with redundant and re-configurable power sources.**

Providing solutions to power management challenges
for commercial, industrial and defense applications

SatCon
Applied Technology

DISTRIBUTED POWER SYSTEMS

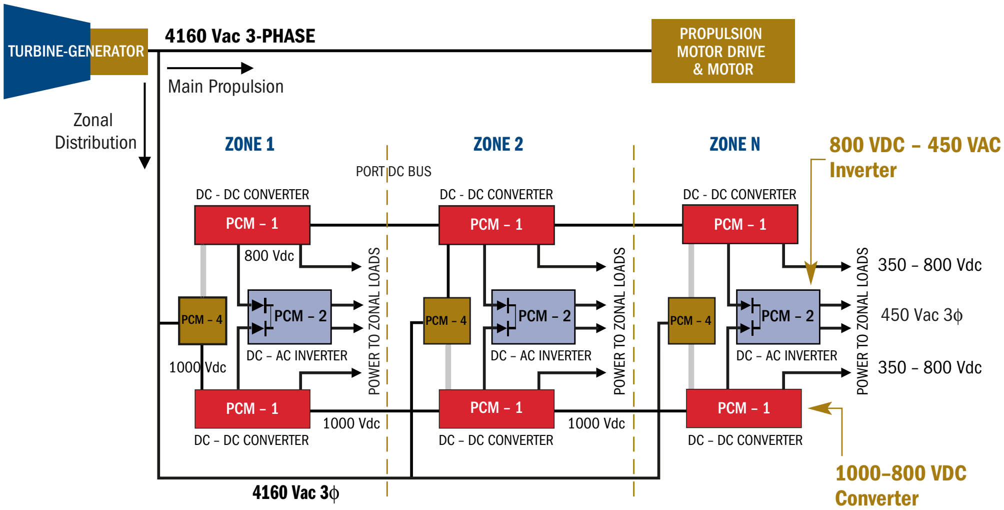
- Fault protection and isolation for fast fight through reconfiguration
- Integrated power flow management with supervisory control programmability

Modular building block cabinets and LRUs are expandable to meet varying power needs, and are hot-swappable for fast non-intrusive maintenance. Each cabinet is 24” W, 48” D and 75” H.

Common physical configuration for converter and inverter Line Replacement Units (LRUs)

Navy Integrated Power System (IPS)
Integrated Fight Through Power (IFTP)

SatCon’s Power Control Modules were developed as part of the Integrated Fight Through Power Program for the US Navy but can be applied to other land or sea based electric distribution systems.



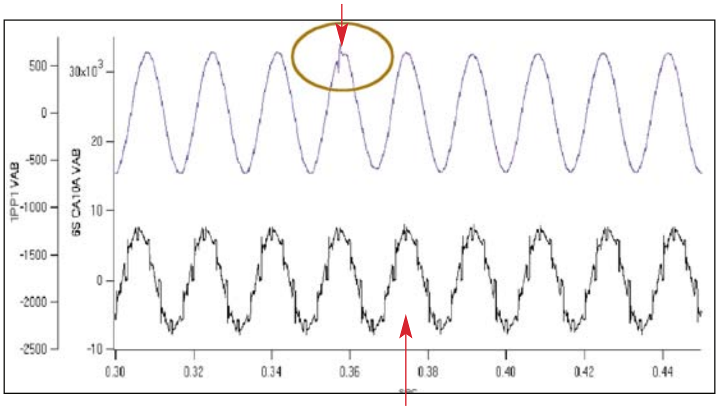
Zonal distribution allows automatic reconfiguration in response to battle damage or equipment failure

PCM-1 Power Quality

Description	Value
Nominal output, adjustble range	800, 350 – 800 VDC
Input range	925 – 1035 VDC
Output droop with load	4%
Voltage ripple	1% of nominal. 15kHz
Voltage transient, 0 to 100% step load	17%
Voltage transient recovery, 0 to 100% step load	0.1 sec
1.8 pu overload	5 sec
EMI	Mil-Std 461

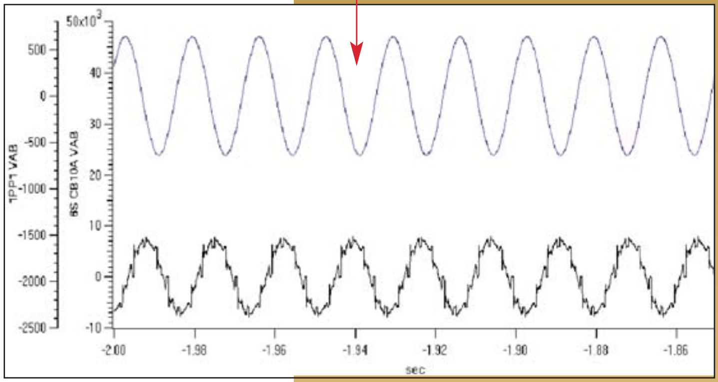
SatCon's IPS Provides Excellent Power Quality

PCM-2 450 Vac output 70% (350kW) step load applied.



NSWCCD propulsion power bus 4,160 Vac input to PCM-4 loaded at 2 MW. Ship's turbine generator with Alstom's 6-pulse motor converter propulsion load with harmonic filter at 80% load causing ~13% VTHD.

PCM-2 450 Vac output 70% (350kW) step load removed.

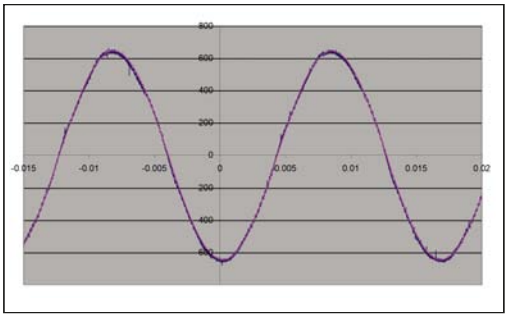


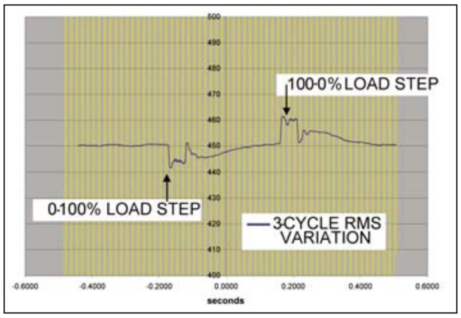
PCM-2 provides exceptionally clean 450 Vac even with 13% VTHD on the input propulsion bus feeding PCM-4.

PCM-2 Specifications

Description	Required Value	Measured Value
Allowable line voltage unbalance	1.0%	0.3%
Voltage transient excursion limit	+/- 5.0%	2.5%
Voltage transient recovery time	0.25 sec	0.3 sec
Total harmonic distortion	< 2.0%	1.2%, out to n=50
Individual harmonic distortion	< 1.0%	0.8%, 5th harmonic
Maximum waveform voltage deviation	2.0%	< 2.0%
Efficiency at full power	> 95.0%	95.7%

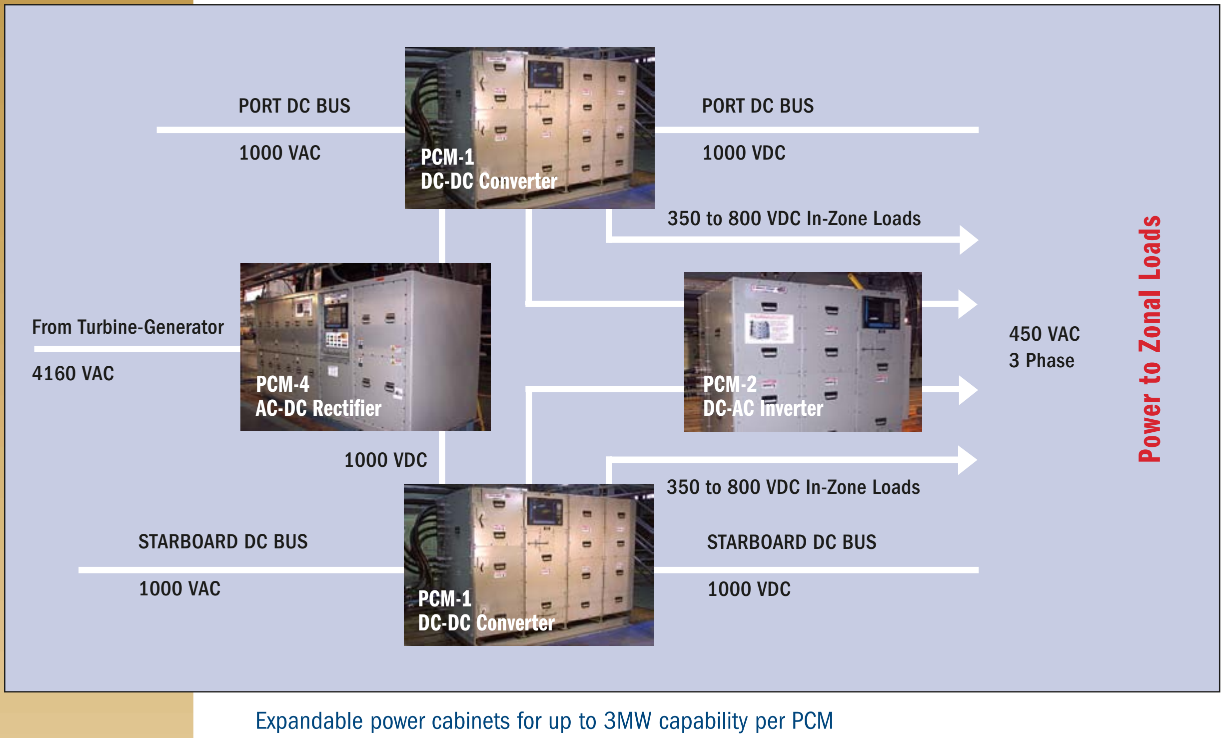
Output Power Quality Maintained





Test results show power quality requirements are met even under transients and with input voltages down to 654 Vdc.

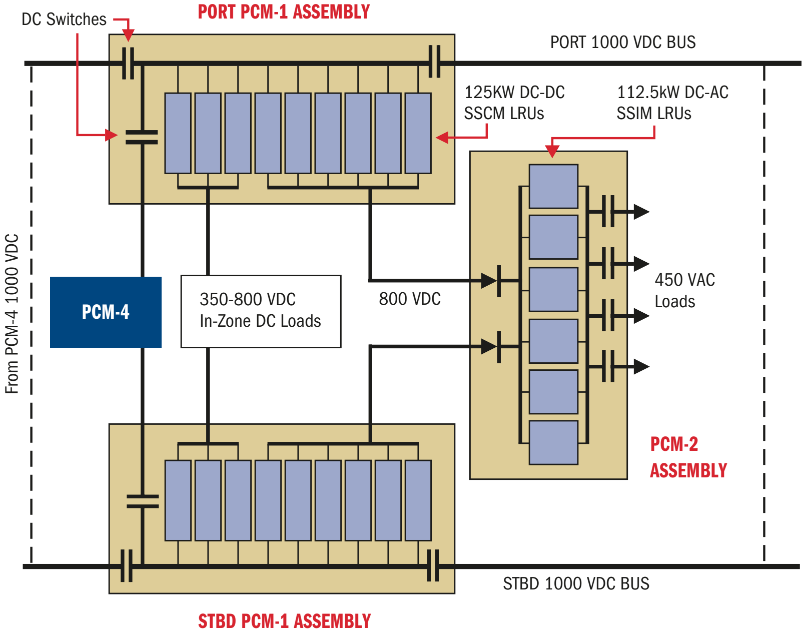
Typical IPS Zone



Expandable power cabinets for up to 3MW capability per PCM

The Integrated Power System (IPS), Integrated Fight Through Power (IFTP) Program is a development effort under the leadership of NAVSEA. SatCon is teamed with General Atomics and Gibbs & Cox to build and install several megawatts worth of IPS/IFTP distribution power at the Navy's Full Scale Test Facility in Philadelphia.

Zonal Power



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