The views expressed are those of the authors and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

Navy integrated Power and Energy Corridor (NiPEC)

ONR Grant N00014-21-1-2124
Electric Ship Research and Development Consortium

Julie Chalfant, Ph.D.
MIT Sea Grant College Program

National Shipbuilding Research Program
2025 All Panel Meeting
February 25-27, 2025
Charleston, SC

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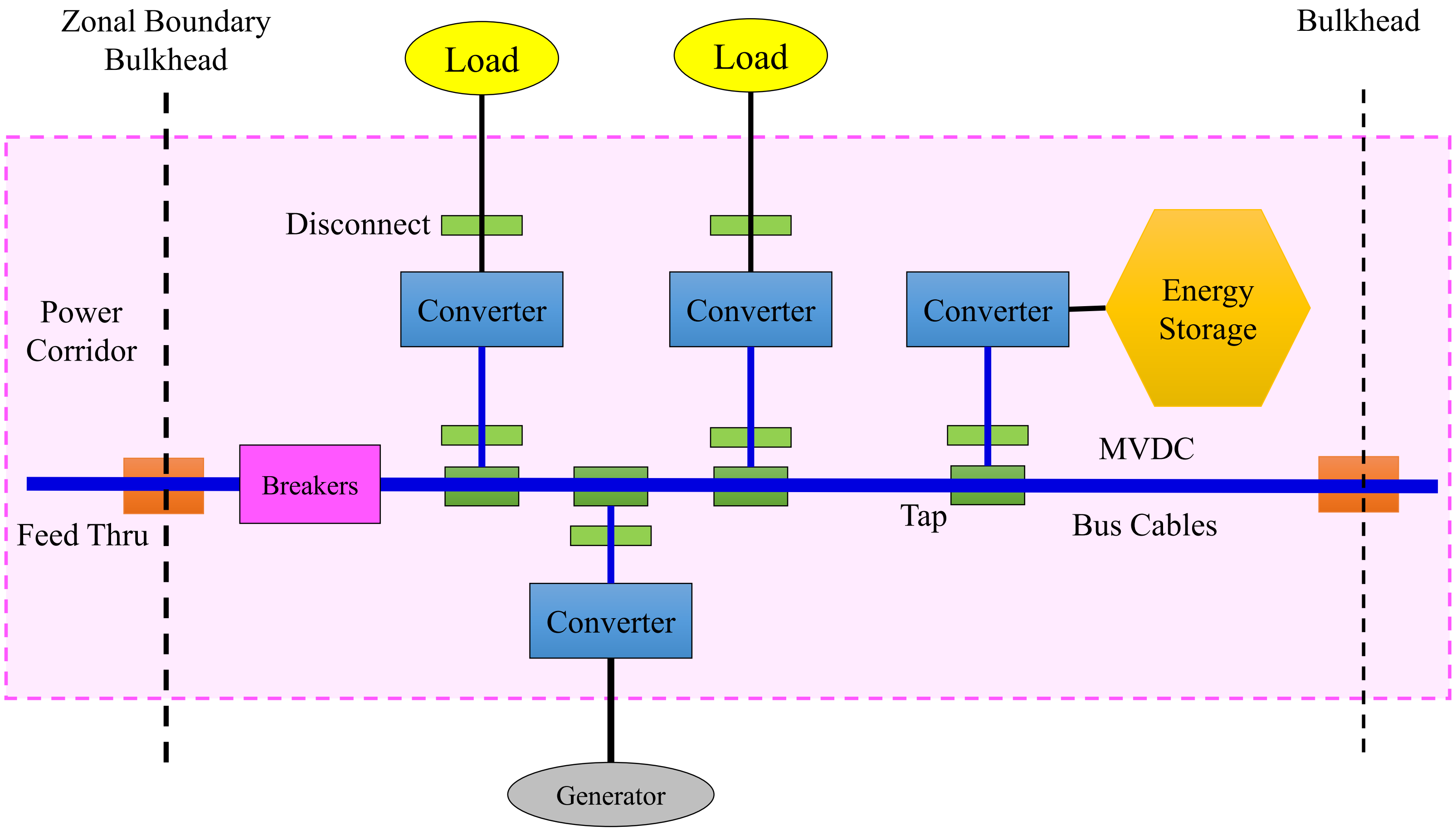


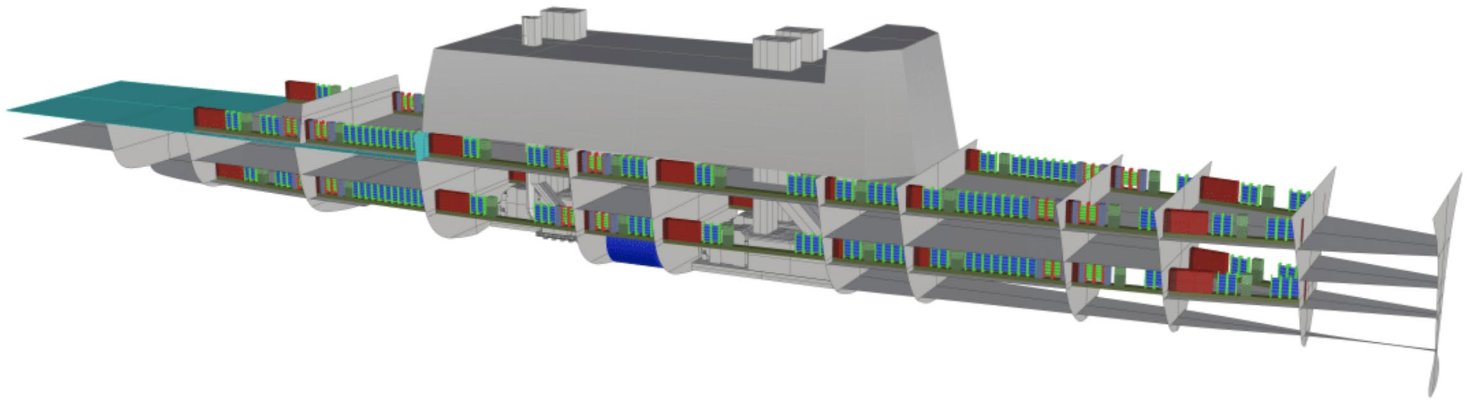
The concept:

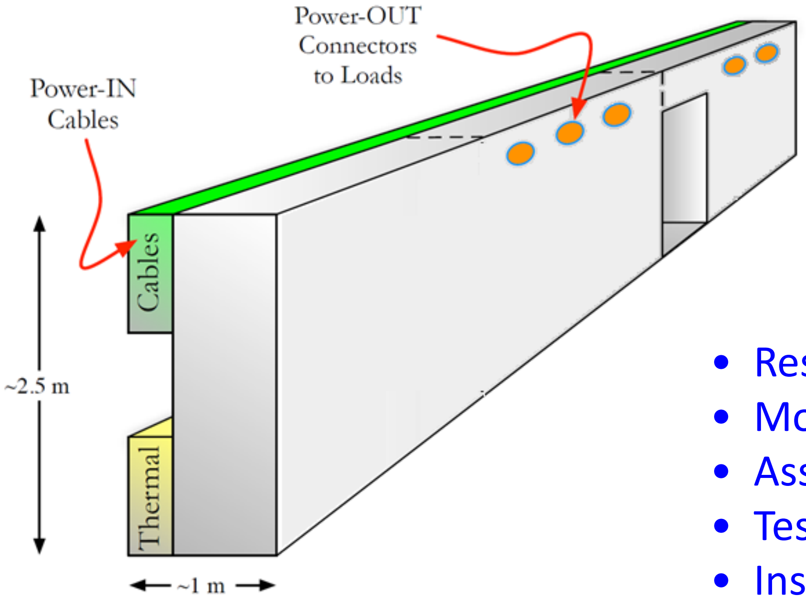
Incorporate in a single modular entity all the components of the electrical distribution system:

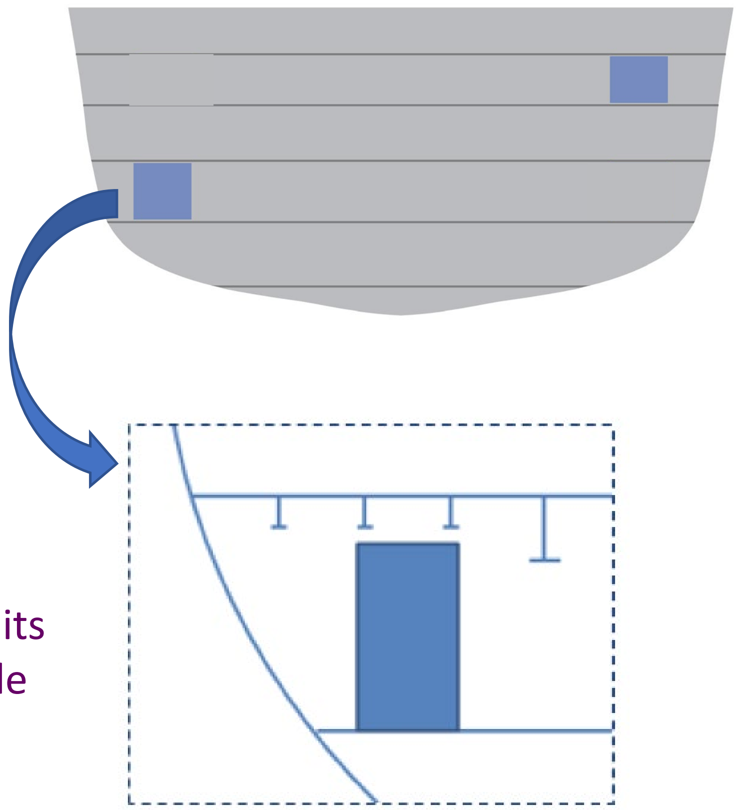
- Main bus cables
- Conversion
- Protection
- Isolation
- Control
- Energy Storage

for the main bus power throughout the ship.

NiPEC Concept

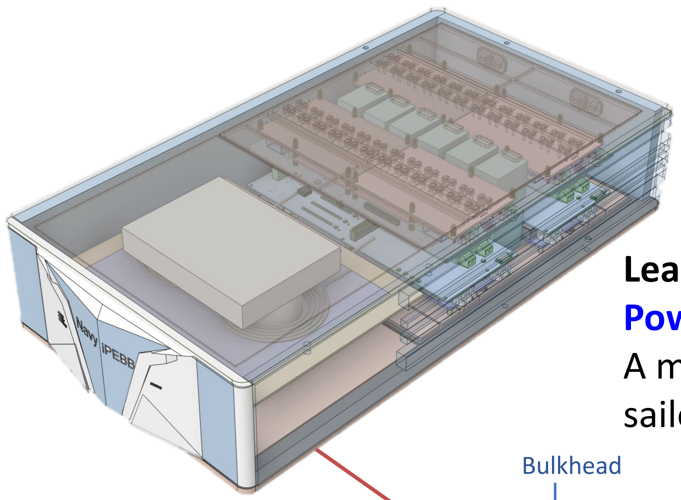


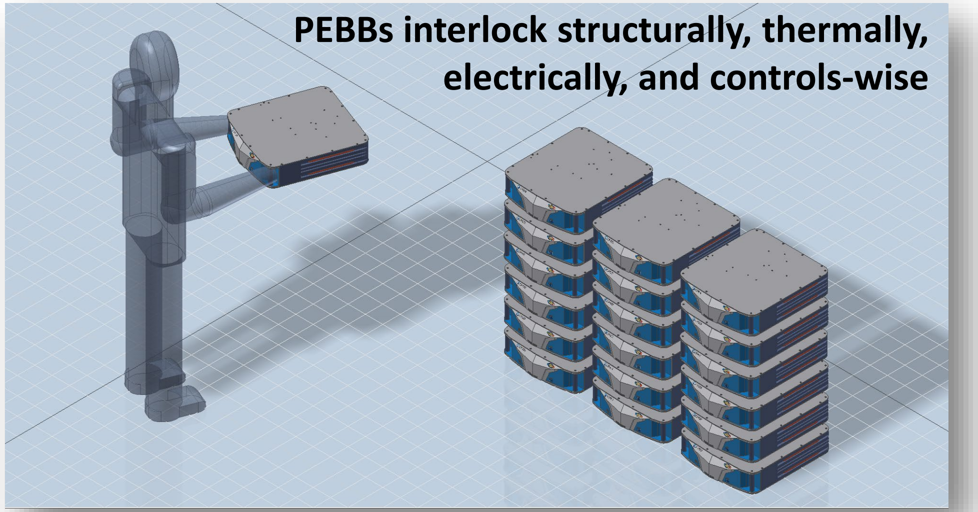




- Reserved space, early in design
- Modular construction, repeated units
- Assembled off-hull, clean, accessible
- Tested off-hull, sensitive, thorough
- Install into ship, as an assembly

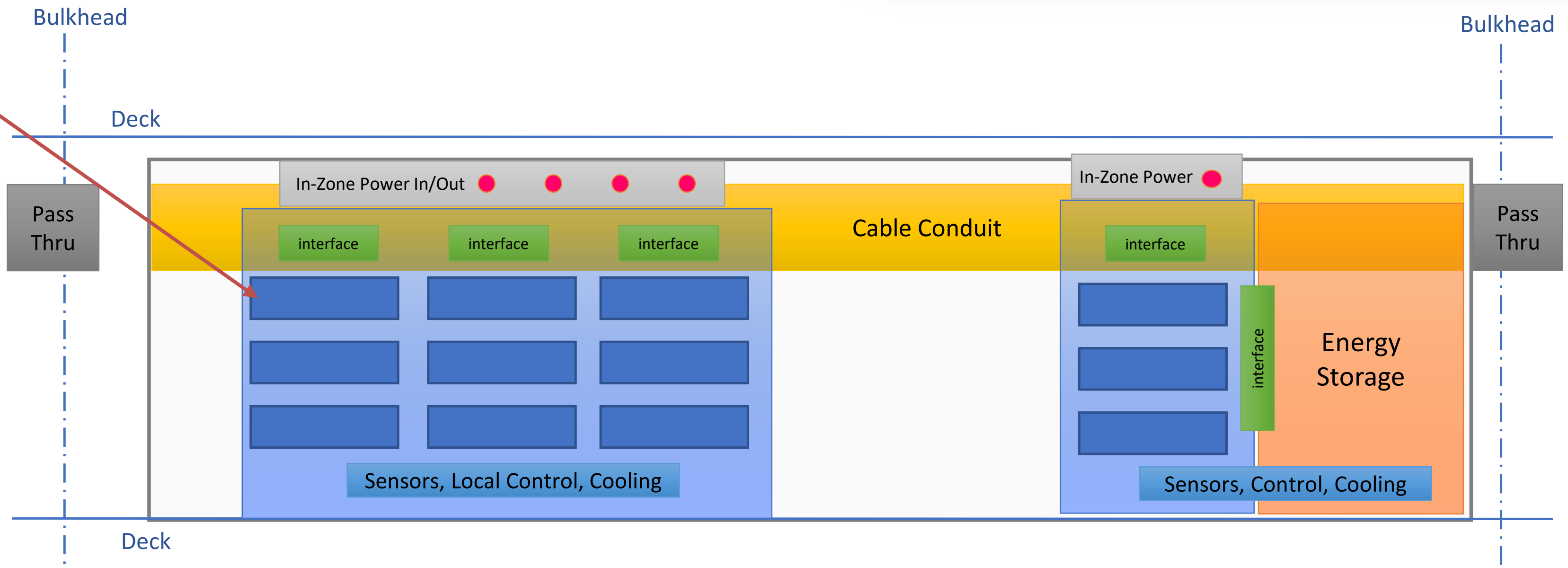
PEBB-Based NiPEC



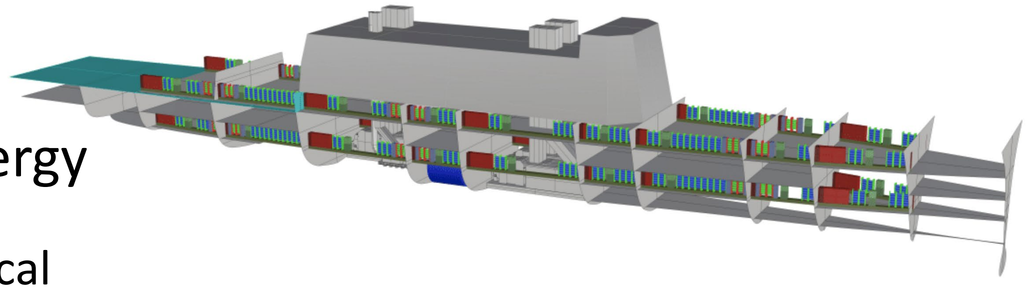


Least Replaceable Unit (LRU):

Power Electronics Building Block (PEBB) - A modular, repeatable, programmable, sailor-carriable universal converter



NiPEC brings … advantages and risks (knowledge gaps)



- A *new arrangement paradigm*
  - with ship design impacts in survivability, redundancy, interferences, stability, safety
- A *new construction paradigm* for power and energy systems based on modularity
  - in which the connections and interfaces become critical
- A *new technology concept* based on the plug-and-play iPEBB, for which we must handle
  - the interfaces
  - electrical isolation, contact resistance, EMI, creepage, clearance, control, cooling, …
- A *new level of power density*
  - which brings challenges in thermal management
- A *new energy storage paradigm* in which energy storage is grid-tied, and is both centralized and distributed
  - with concomitant design, arrangement and control challenges

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https://www.mainebiz.biz/article/decades-of-tide-changes-investments-help-bath-iron-works-maintain-its-shipbuilding-prowess

https://www.tesllc.us/marine-electrical-safety-what-every-boat-owner-should-know

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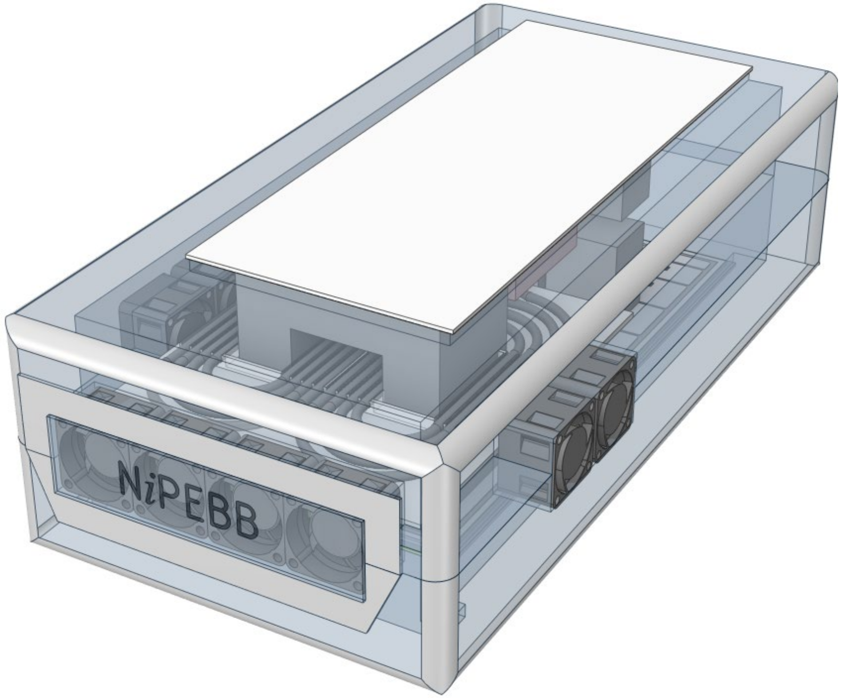

Image courtesy of VA Tech CPES

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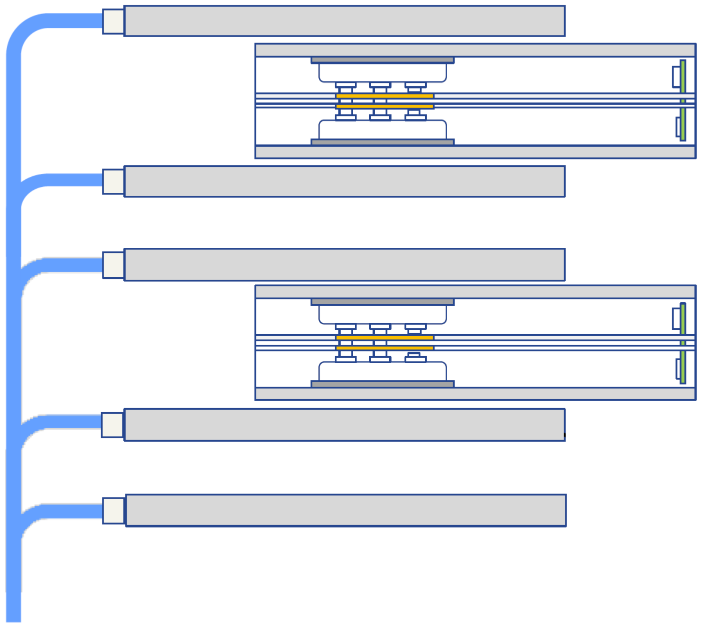

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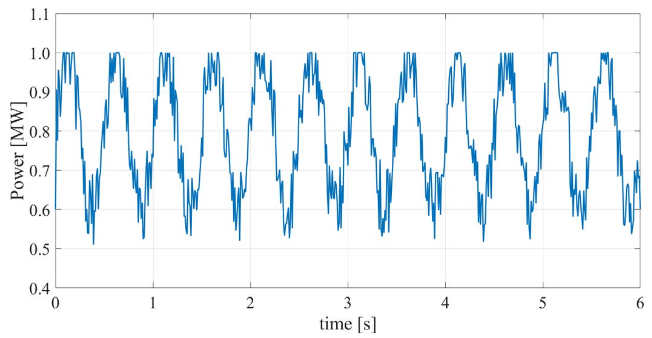
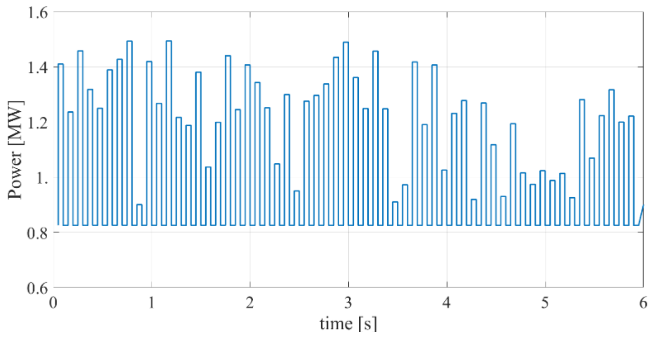
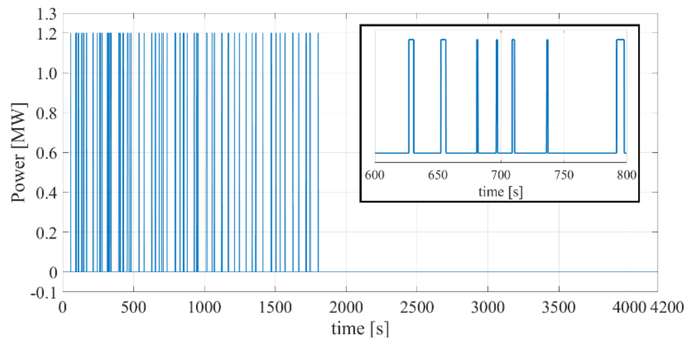






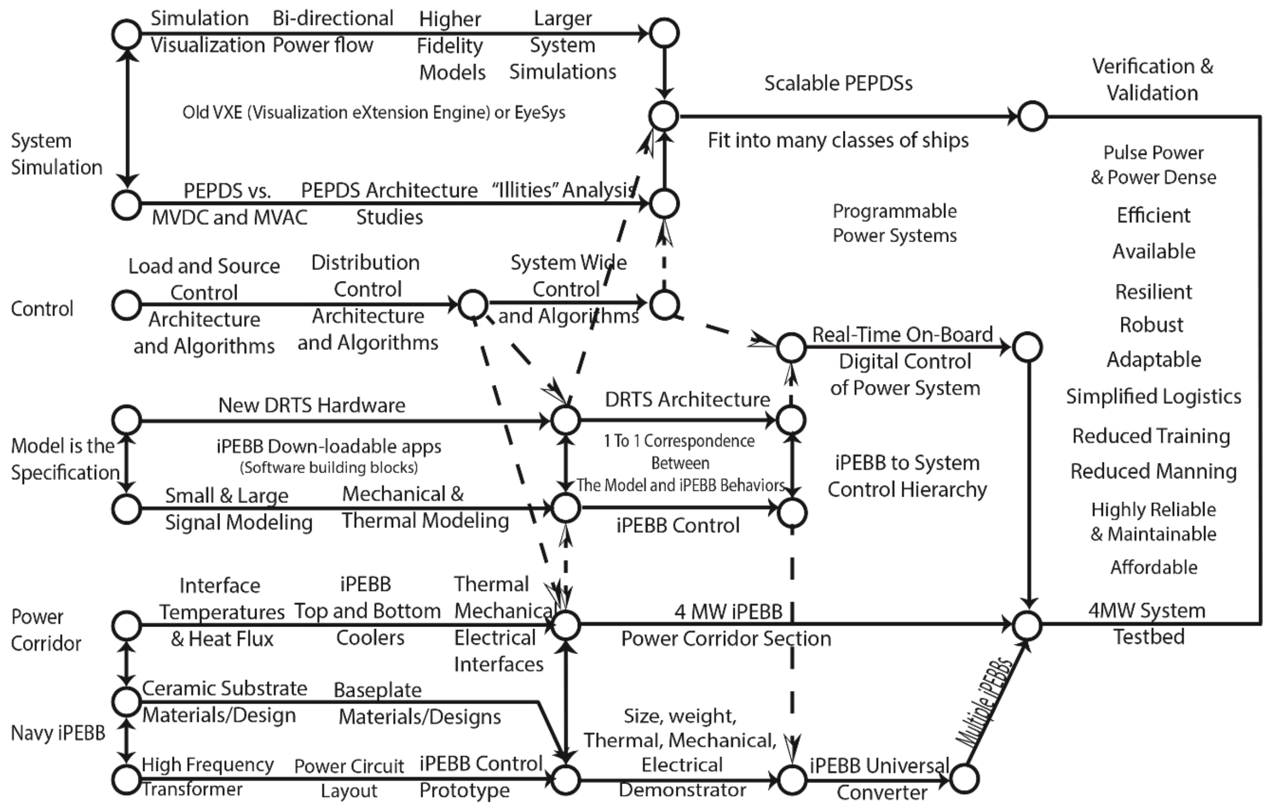
Ship Construction Advantages

A truly modular NiPEC provides power distribution, conversion, isolation, protection, and storage tailored to a ship compartment or watertight bulkhead section. Each tailored NiPEC segment will function independently, allowing:

- Off-hull assembly and testing of the NiPEC segment itself,
    - Allowing construction and test operations to be conducted in parallel which **shortens the ship construction timespan**
- followed by shipboard installation
    - Using a standard set of interfaces and mounting methods for electrical, cooling, structural, mechanical
    - For a given item, **construction cost decreases by an order of magnitude** for work done off-hull, compared to onboard
- and testing of all connected equipment within that ship section (e.g., single watertight bulkhead section),
    - Allowing ship (non-NiPEC) equipment to be tested **while it is still relatively accessible** for repair/replacement if it fails
    - Current methodology requires essentially full ship assembly before testing, and there are numerous examples of equipment buried in the center of the ship that required replacement (including removal/replacement of all interferences) at the late stages of the ship construction. This leads to unrecoverable delays (at the end of the project) and great expense.
- ship segment by ship segment.
    - Current electrical distribution systems contain main bus cables in excess of 200m that run the length of the ship;
    - Unwieldy cable is occasionally damaged while being pulled from one end of the ship to another, with very high replacement cost.

Team (to date)

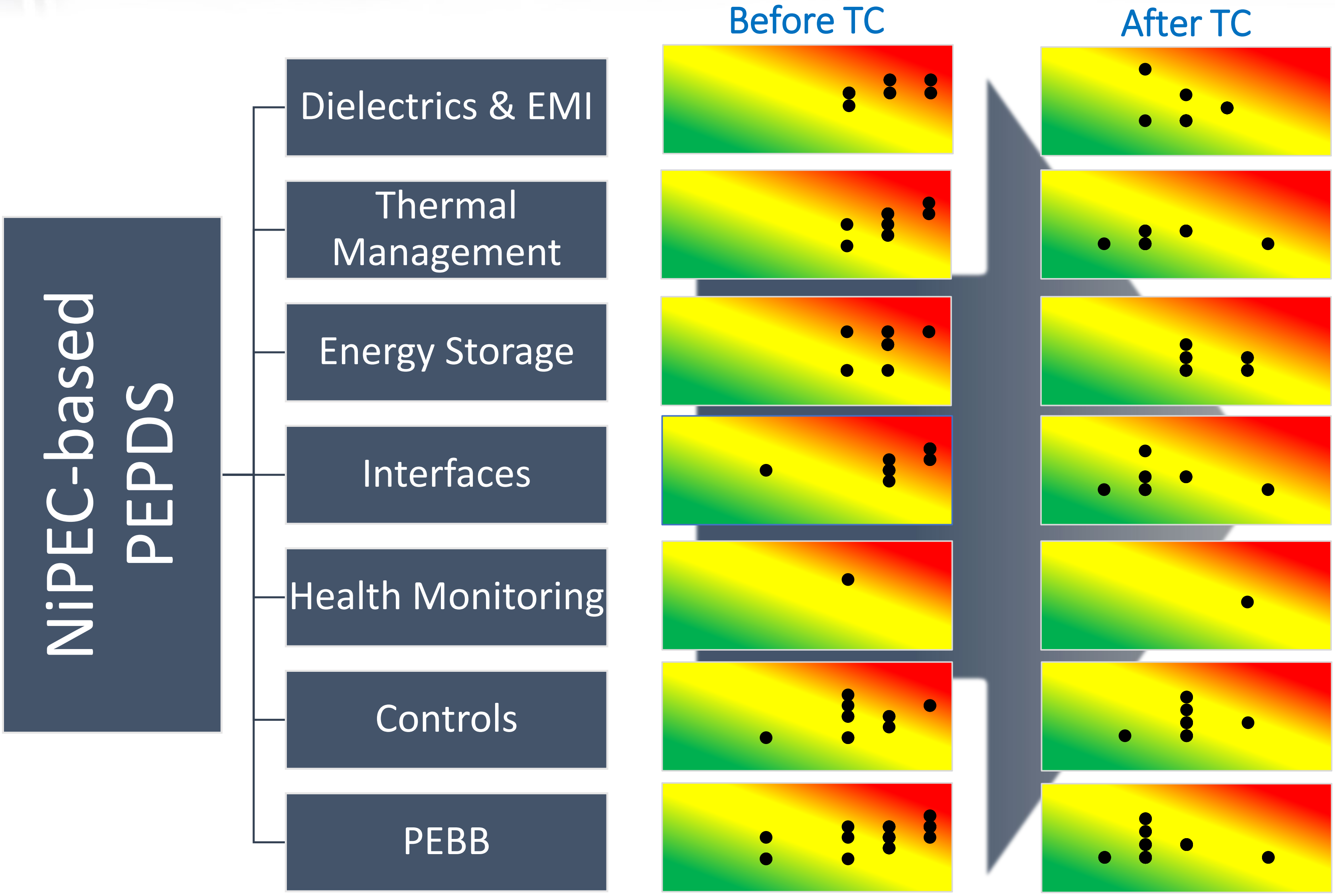
Multi-year Multi-university Research Program



Areas of study:

- Controls
- Energy Storage
- Dielectrics/EMI
- Thermal Management
- PEBB
- Electrical/Thermal/ Mechanical Interfaces
- Health Monitoring
- Ship Integration

Risks: Closing the S&T Gaps



Current Status: PEPDS Tech Candidate Demonstrations

1. **1 MW Power Corridor- like demonstration platform at NSWCPD utilizing legacy IFTP equipment**
2. **Physical comparison of legacy PEBBS to NiPEBB demonstrating SWAP improvements, connectivity and differences in installation**
3. **Demonstrate a prototype PEBB tray with locking mechanism and visualize the reduced footprint from legacy equipment** (*Note: Ideally this would be a physical demonstrations, but we may need to default to CAD drawings*)
4. **Show a "full-scale" demonstration of the use-cases in the legacy demo using NiPEBB in RT simulation (*electro-thermal model*).** *Note: Model design, requirements, documentation and V&V will leverage processes developed during RCPC FNC*
5. **Show a "full-scale" demonstration of the use-cases in the legacy demo using NiPEBB CHIL with RT simulation (*electro-thermal model*).** *Note: This would include at least two physical NiPEBB controllers.*
6. **Show a "reduced-scale" demonstration of the use-cases in the legacy demo using NiPEBB PHIL with RT simulation (*electro-thermal model*).**
7. **Demonstrate tools for design of PEPDS/NIPEB/PEBB**

Research areas are mapped directly to technical risks outlined in the TC proposal in order to be addressed/mitigated.

#	Baseline	Threshold	Objective
1	X	X	X
2	X	X	X
3	X	X	X
4	X	X	X
5		X	X
6			X

Ship Integration Research

Past and planned

Ship Integration

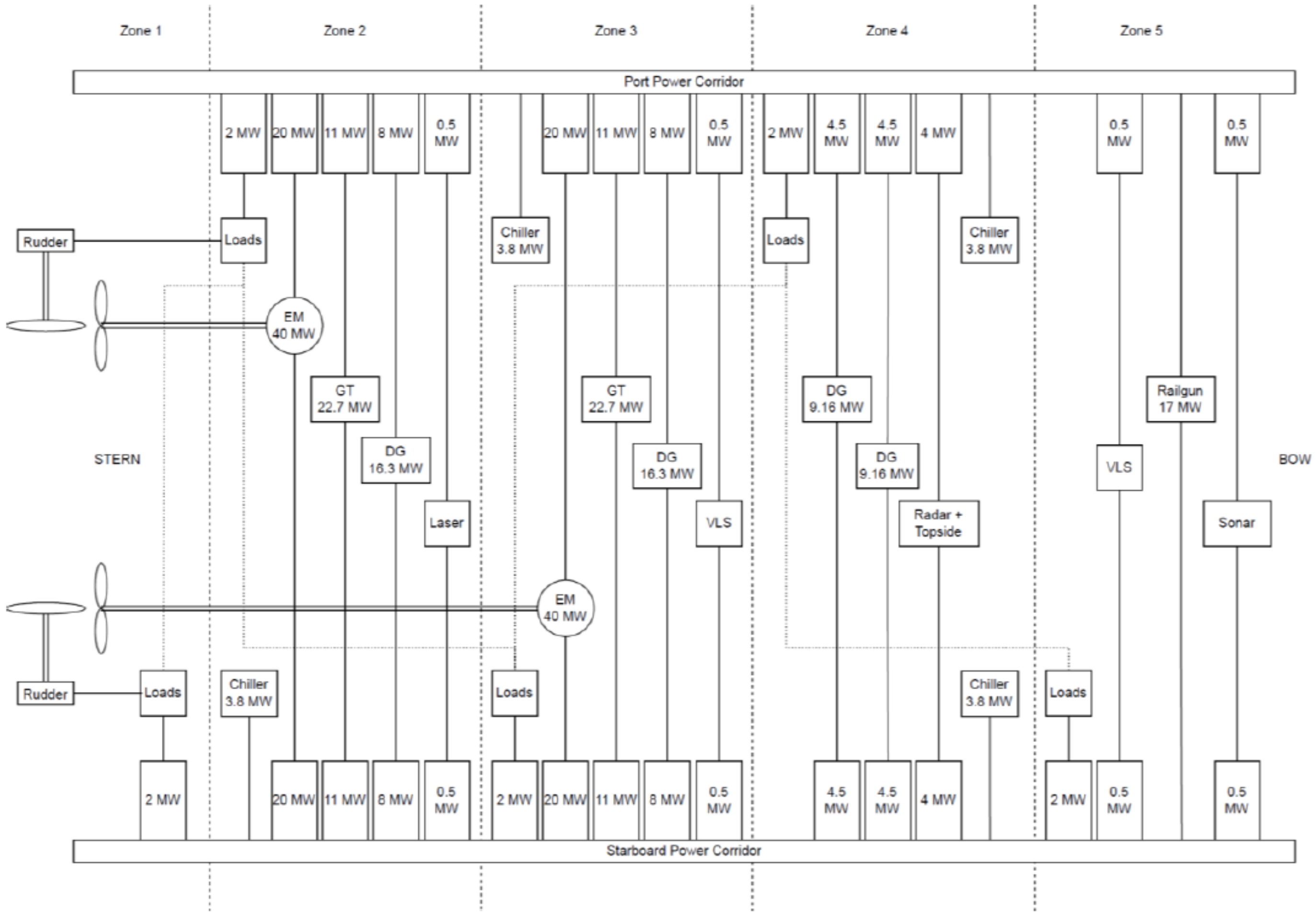
Risk Mitigation Actions

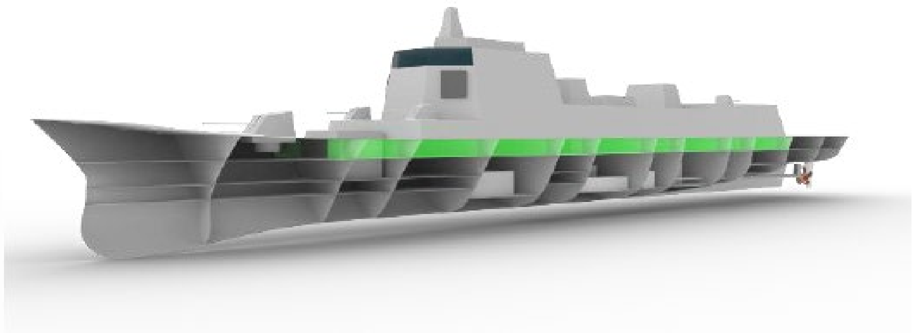
- Accomplish studies to address application of PEPDS to
  - different types of vessels
  - manning/maintenance levels (manned vs. unmanned)
  - retrofit
  - power/voltage levels
  - source/load mix
- Develop appropriate metrics for comparison of designs.
- S3D/RSDE will be used for the analysis, likely in conjunction with other tools. Appropriate S3D models must be developed.

Steps

- Develop RDSE models of various ships
  - Destroyer, Frigate, Amphib, Unmanned, etc.
- Develop PEPDS system arrangements
  - Converter design
  - Thermal Management
- Comparisons/analysis using metrics
- Develop S3D models of NiPEC segments
  - Assembly

Integration of the Power Corridor Concept in the Early-Phase Design of Electric Naval Ships



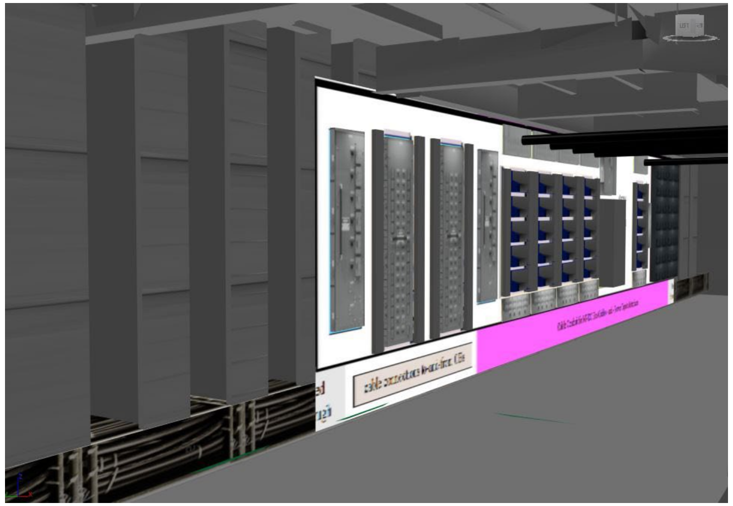


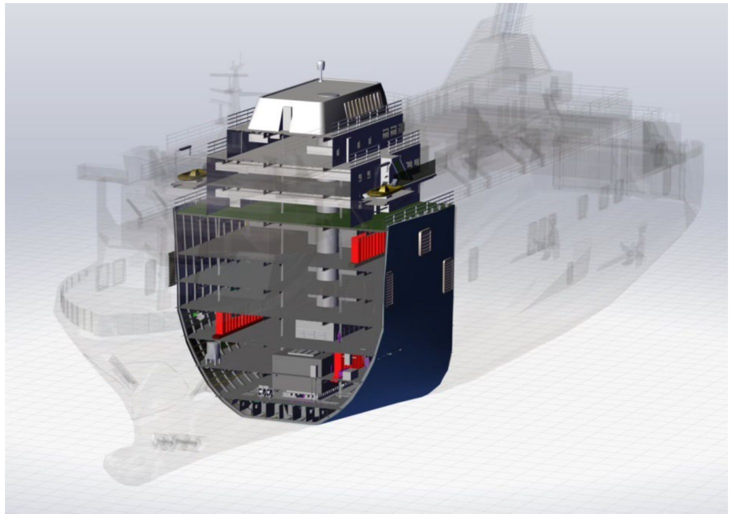
Trincas, Braidotti, Vicenzutti, Tavagnutti, Cooke, Chalfant, Bucci, Chryssostomidis, and Sulligoi. "Integration of the Power Corridor Concept in the Early-Phase Design of Electric Naval Ships using Mathematical Design Models." In *Proceedings of 15th International Marine Design Conference (IMDC-2024),* June 2-6, 2024, Amsterdam, the Netherlands. DOI: https://doi.org/10.59490/imdc.2024.753

Bath Iron Works

Images courtesy of GDBIW

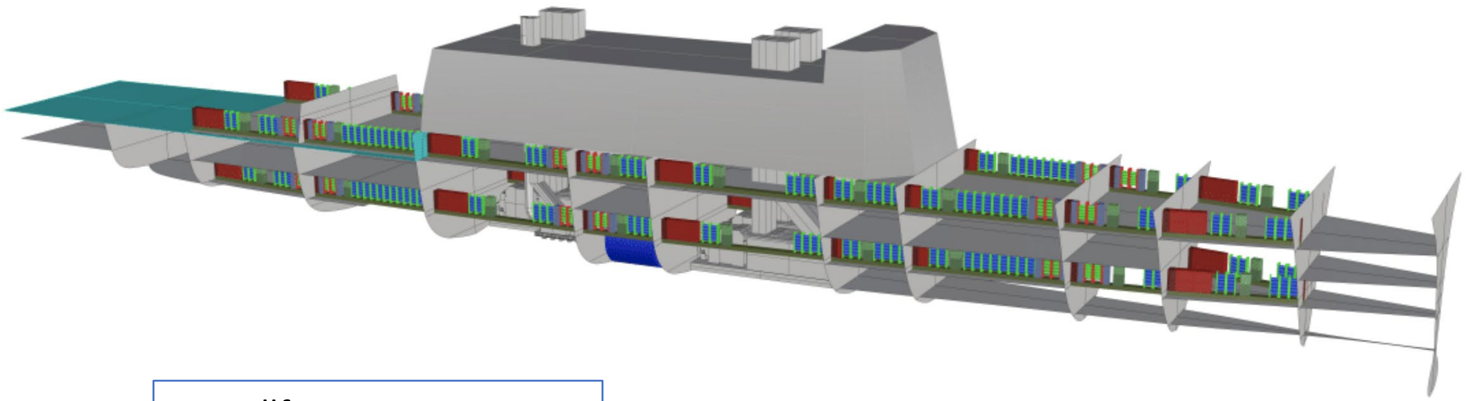
- Conceptual modeling views of integrating IPEC in notional ship (2018)
- Plug-in electrical connectors
- Insulated bus pipe



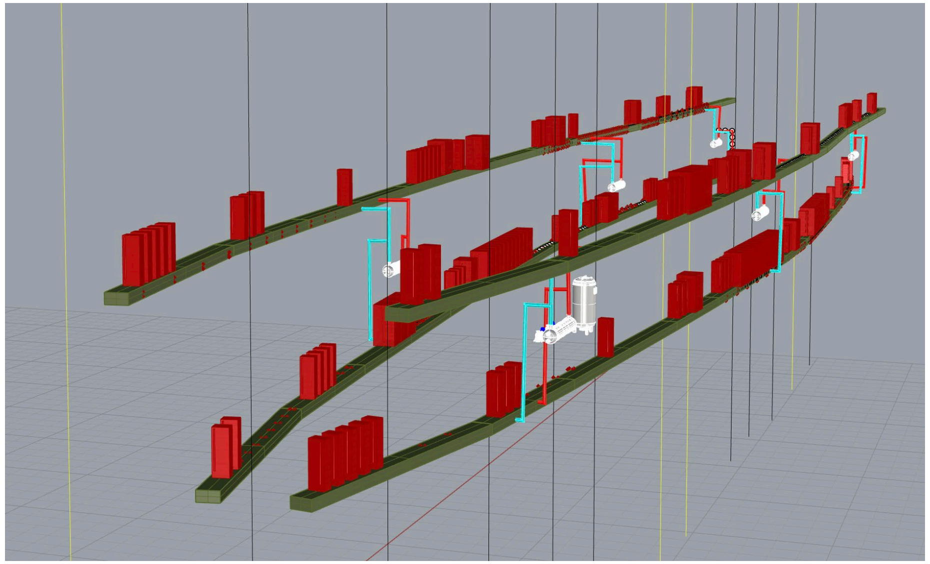


GENERAL DYNAMICS
Bath Iron Works

Notional Destroyer Model

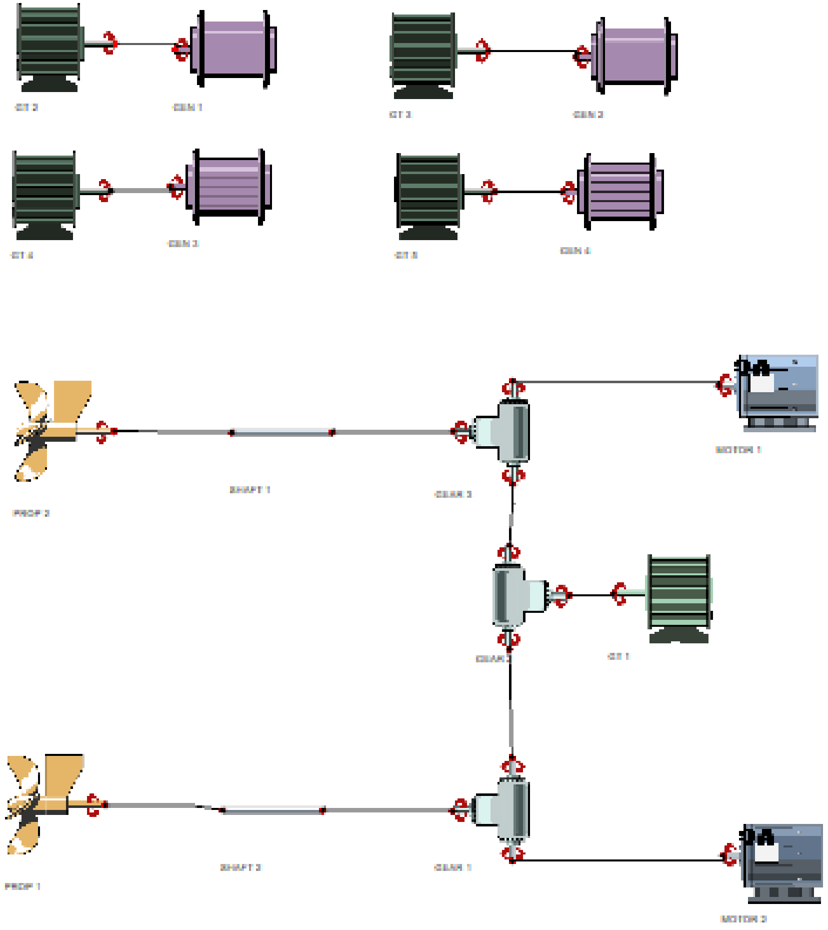


- Hullform
- Propulsion
- Mission equipment
- Power Generation
- Power Distribution
- Thermal System
- Mission Definition



https://www.esrdc.com/library/draft-esrdc-initial-notional-ship-data/

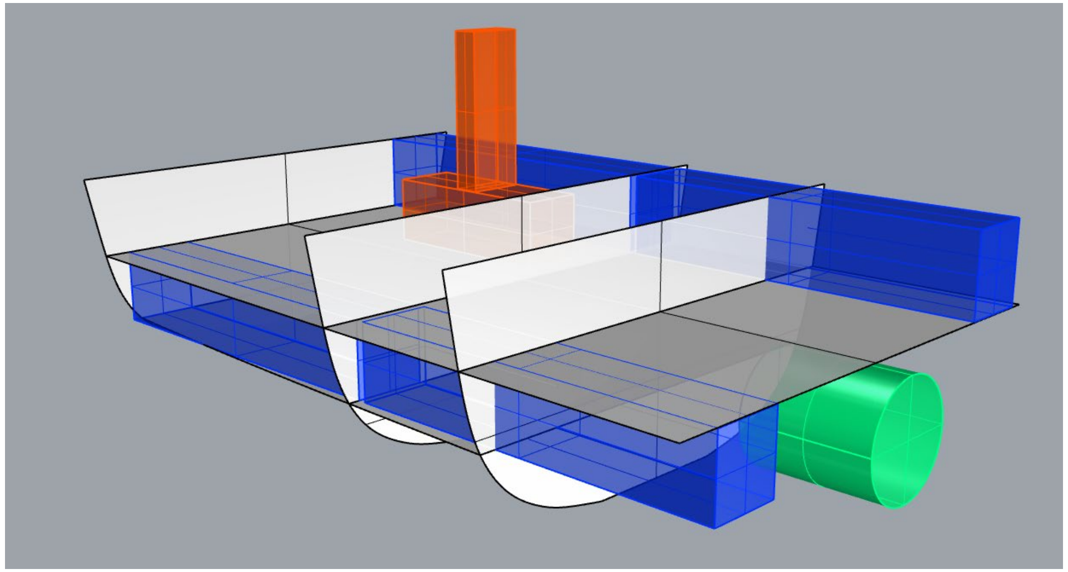
Notional Frigate Model



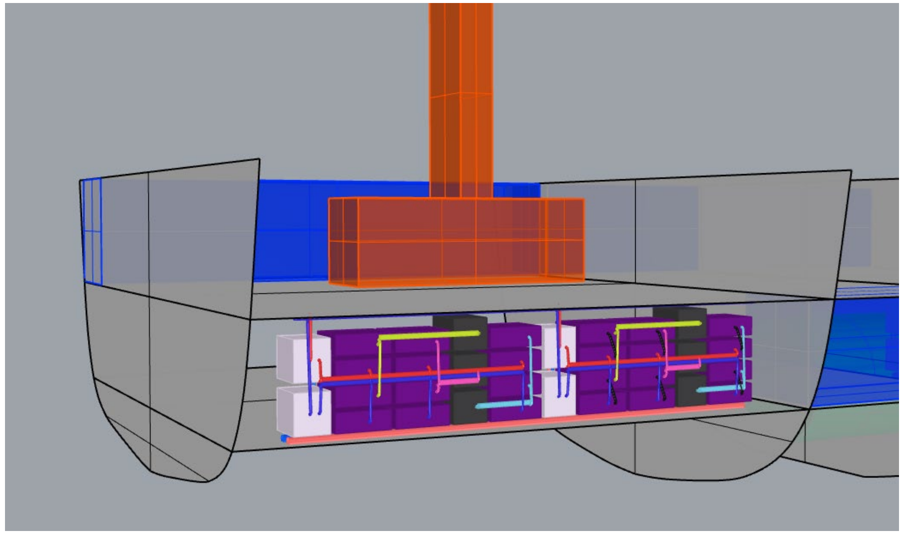
- Roughly based on Constellation Class
  - CODLAG
  - Propulsion equipment
  - Mission systems
- RSDE Model of generic frigate
  - Structure: Hullform, Decks, Bhds,
  - Resistance/Powering
  - Major mission loads
  - Electric load power and location
- S3D Model
  - Mechanical
  - Electrical (PEPDS)
  - Thermal

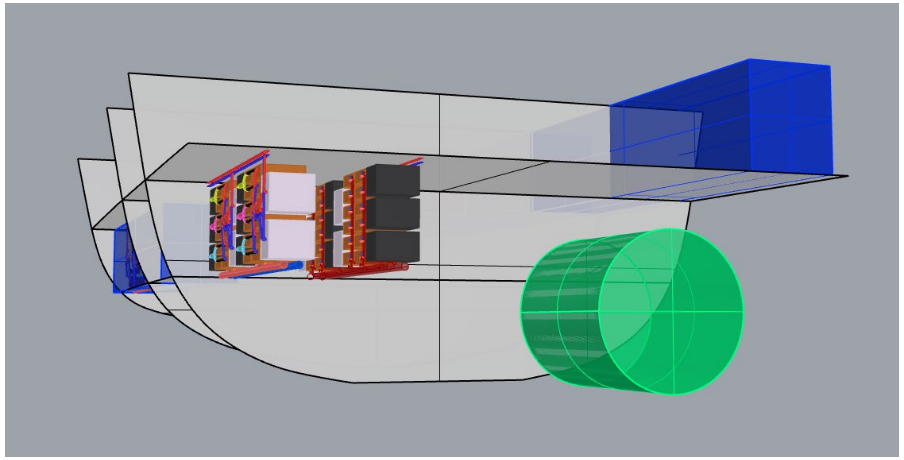
NiPEC Arrangements

NiPEC Reserved Space (Blue)



NiPEC Elements within ship structure



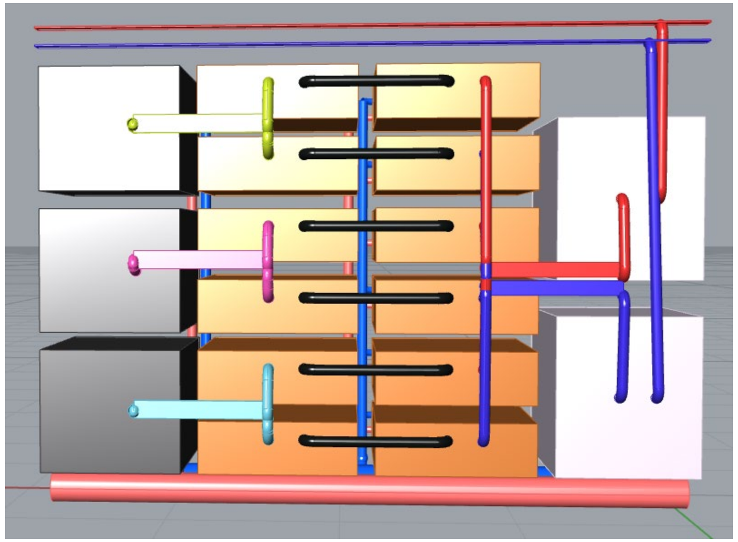


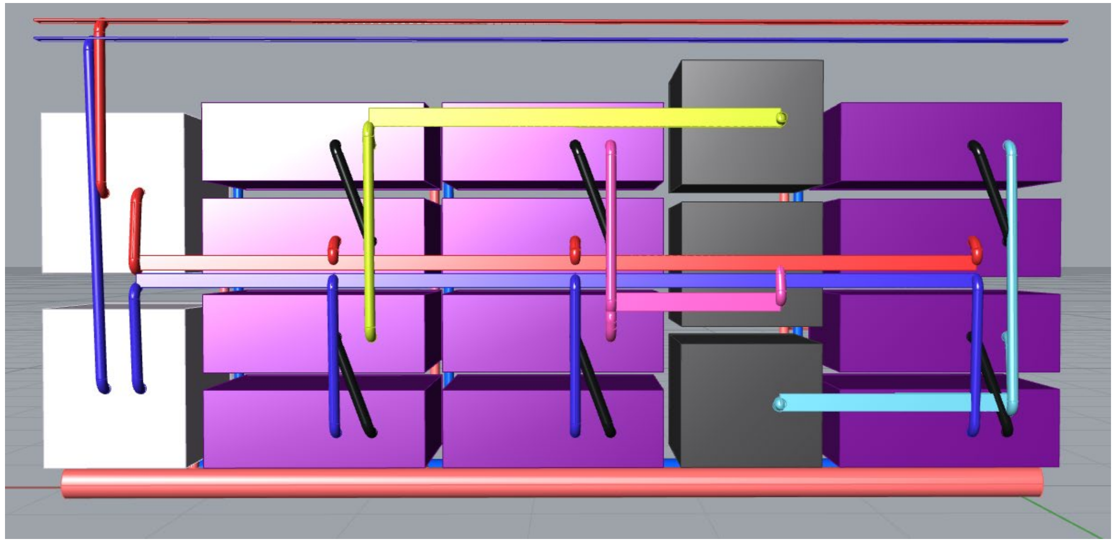
Example test case:

- Power train for
  - Single generator (MVAC)
  - Single propulsion motor (MVAC)
- Within notional destroyer

Robert M. Cuzner, David C. Gross, Hamed Shabani, Naqash Ali, Julie Chalfant and Mischa Steurer, "**Determining Parameter Objectives for MBSE Approach to Early Ship Design Exploration**", *IEEE Transactions on Transportation Electrification Special Issue on Electrified Ship Technologies*. Accepted.

NiPEC segments – metrics development



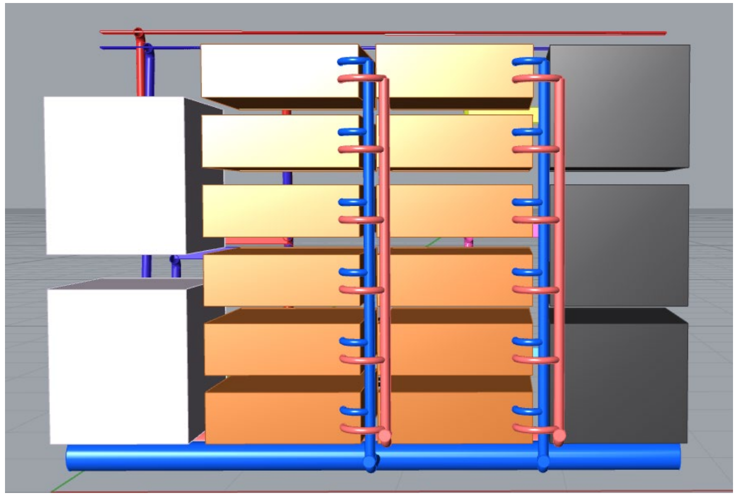


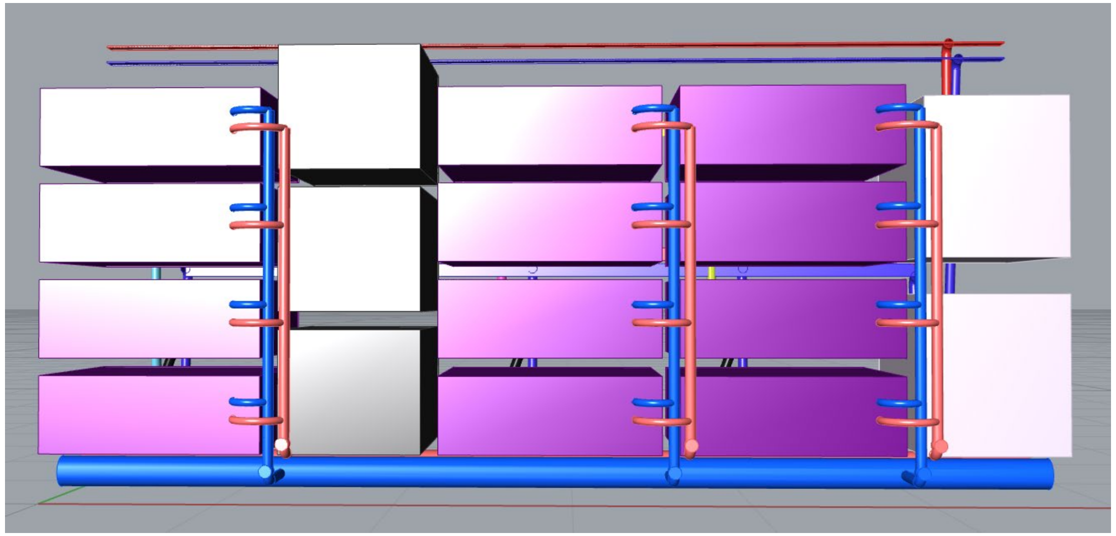
Drawer sizes provided by UWM, product of VPP process.

AC and DC switch (disconnect) sizes provided by UWM.

Stackup height and length limited by ship design specifications.

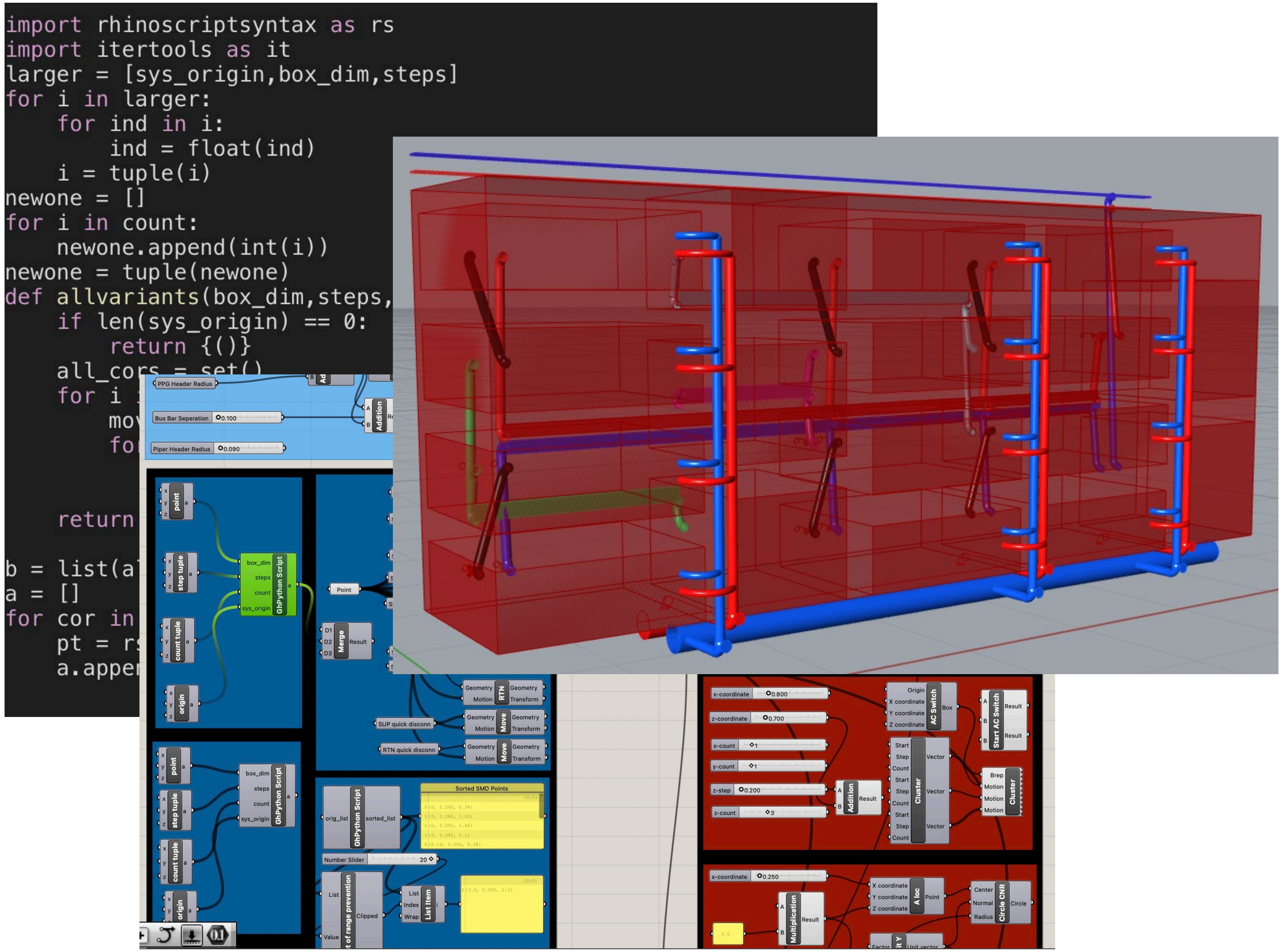
Cooling, electrical connections shown. Structure omitted for clarity of image.



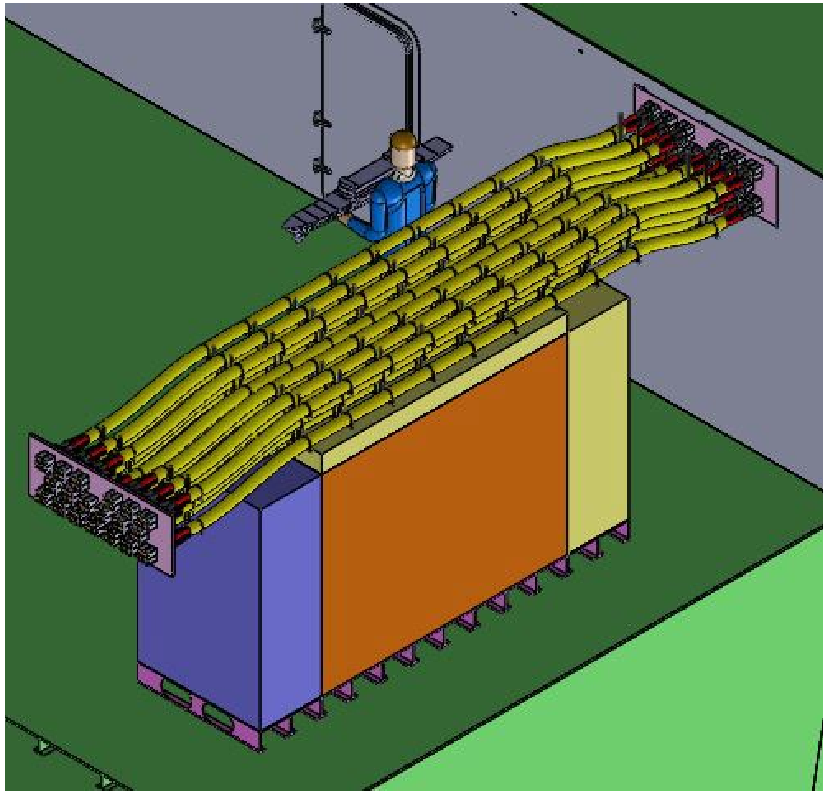


NiPEC Segment Sizing and CAD Model

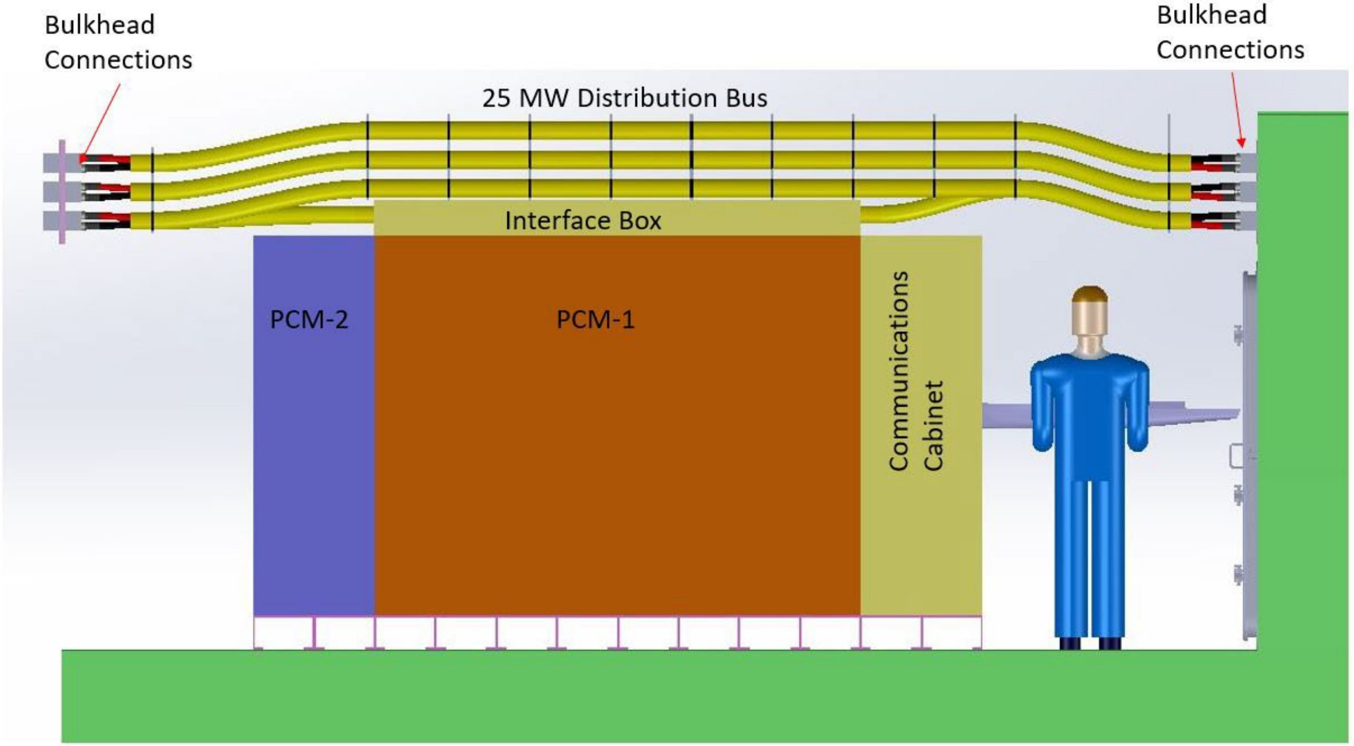
- Create a CAD model of a NiPEC section
  - PEBBs
  - Cooling
  - Cabling
  - Data/Controls Hardware
  - Switching
  - etc.
- Using Grasshopper and Rhino 3D
- Responsive to changes in assumptions and dimensions of basic building blocks.
- Form the basis for creating an S3D component model
- Develop metrics associated with NiPEC



NiPEC Arrangement Example – Legacy Equipment

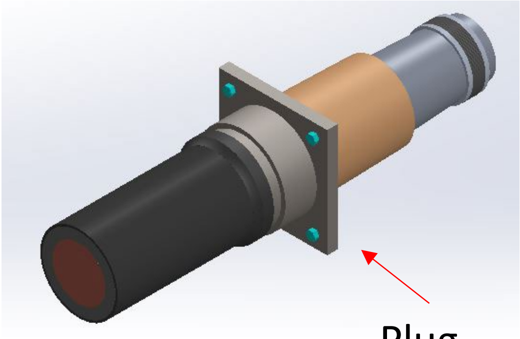


Arrangement example using legacy equipment

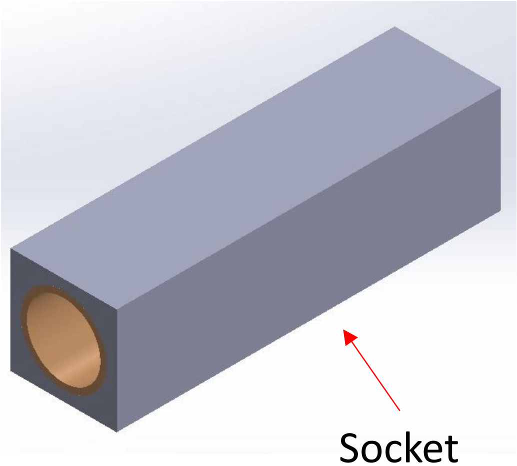


Kruse, Matthew, *Preliminary Shipboard Layout of Navy Integrated Power and Energy Corridor (NiPEC),* Master's Thesis, Massachusetts Institute of Technology, 2023.

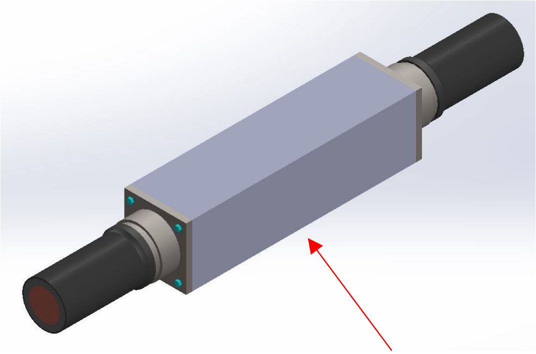
Example Plug-in Bulkhead Connections



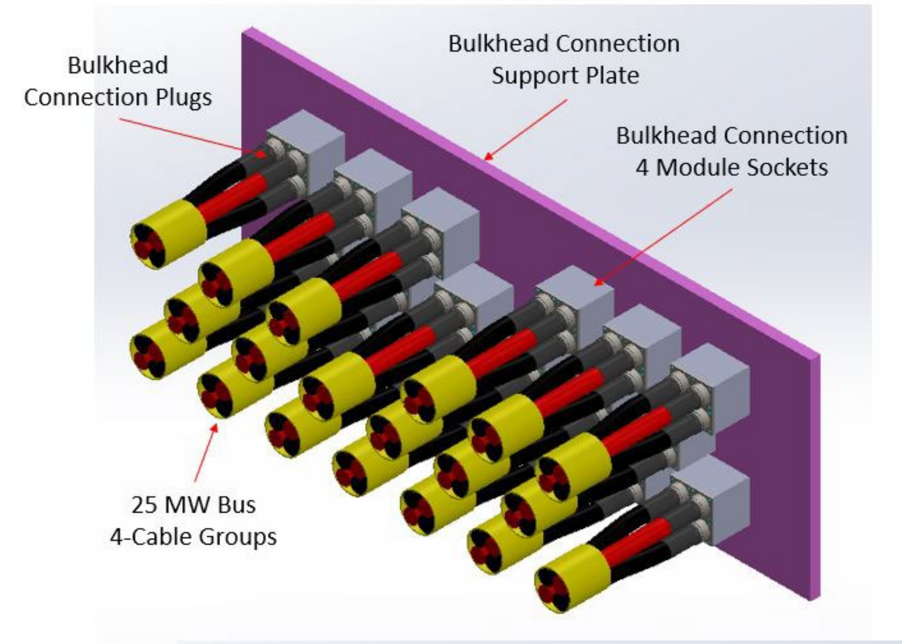
Plug

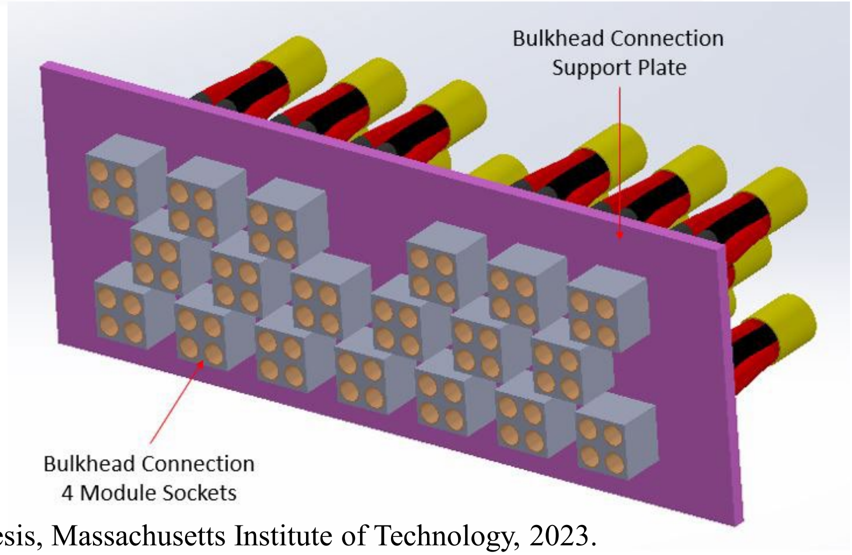


Socket



Assembled Plug and Socket

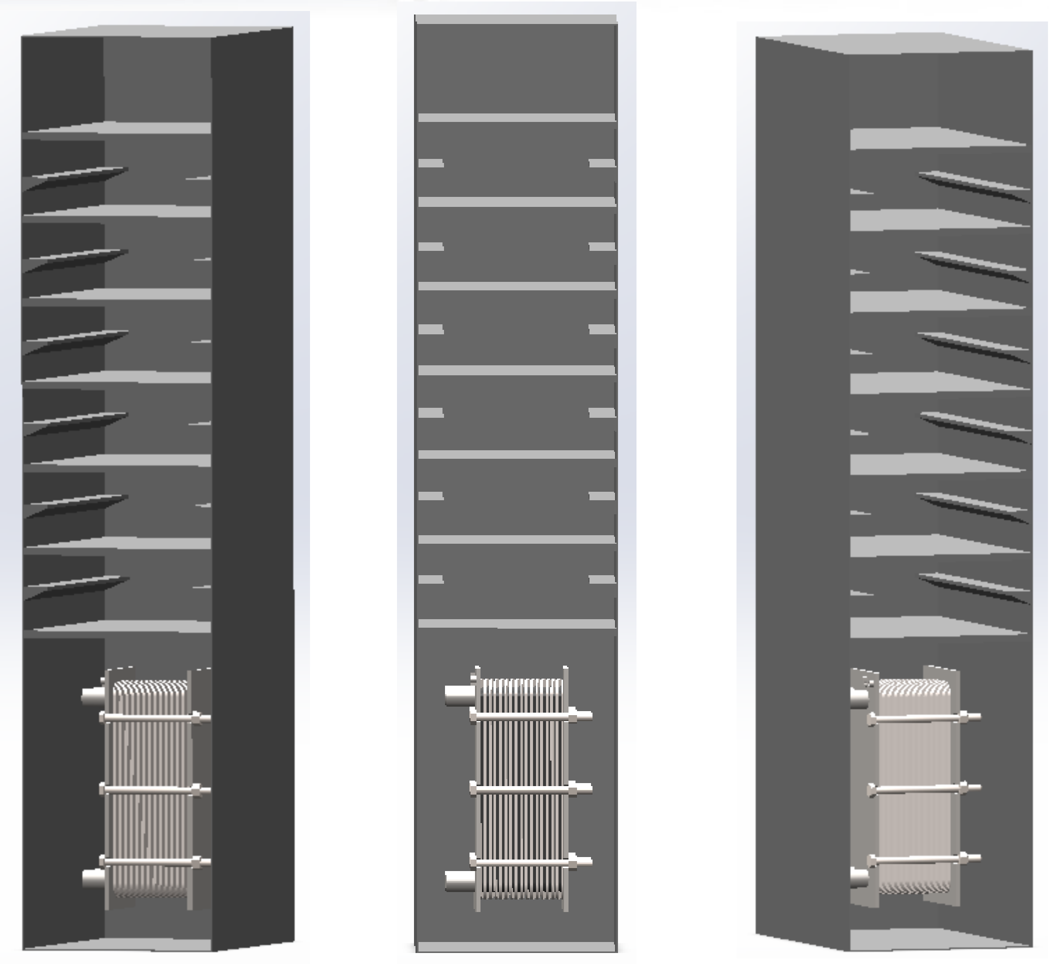




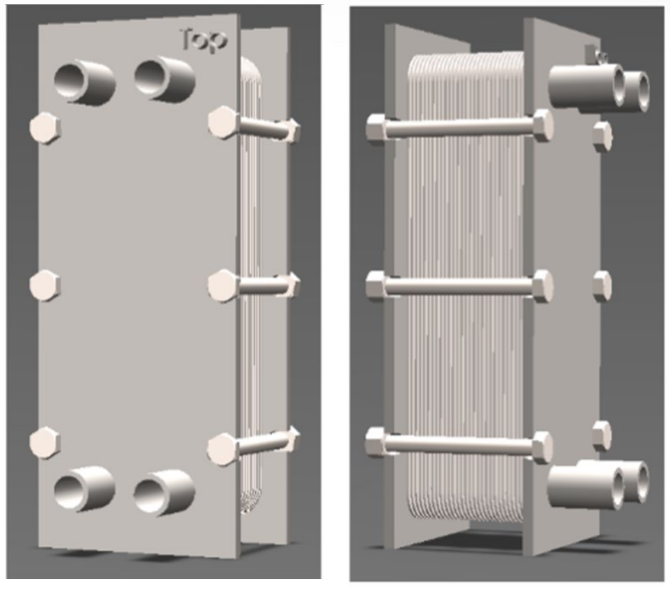
Source: TE Connectivity, Raychem Plug-In Terminations

Kruse, Matthew, *Preliminary Shipboard Layout of Navy Integrated Power and Energy Corridor (NiPEC),* Master's Thesis, Massachusetts Institute of Technology, 2023.

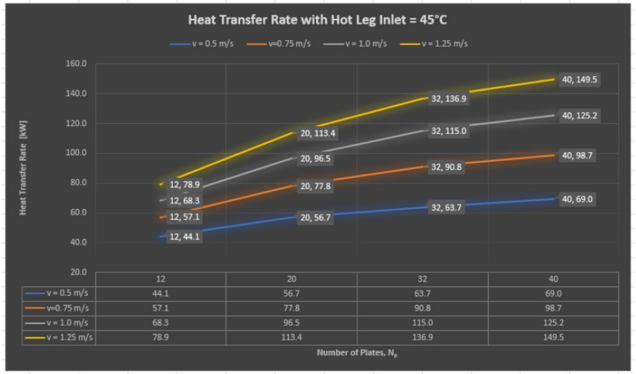
Modular plate heat exchanger example within NiPEC Segment

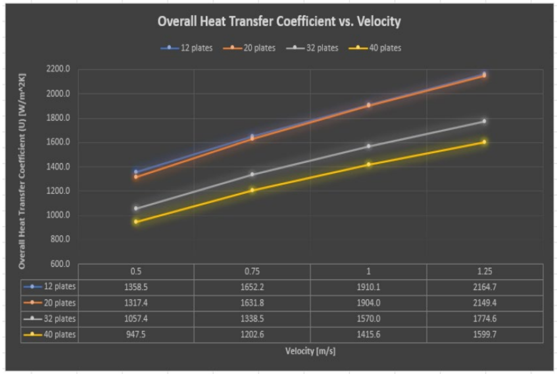


Modular PHE in NiPEC PEBB Stack



30-plate PHE





Meyers, Wade, Design, *Analysis and Modeling of a Modular Navy Integrated Power and Energy Corridor Cooling System,* Master's Thesis, Massachusetts Institute of Technology, 2024.

Conclusion: Key Changes with NiPEC

- Arrangement
  - defines the space for the corridor in the earliest stages of design
  - enables full customization at the bulkhead section level
  - co-location of vital distribution systems, e.g. passageways, CHW, data, etc.
- Energy storage
  - tied directly to distribution bus can be sized for in-port battery operations, single generator operations, energy-efficient management
- Control
  - enable autonomous segment control/diagnostics
- Manufacturing/Installation
  - modules are constructed and tested off-hull and assembled onboard
  - modularity enables access for maintenance and facilitates alteration/upgrade
- Survivability/Reconfiguration/Resilience
  - co-location of supporting (serial) and separation of redundant (parallel) components
  - soft power degradation; failure of one component does not take down entire load
  - plug-in casualty power
- Safety
  - essentially all electric connections, protection and power conditioning equipment are in a highly defined, enclosed space away from any chance for unintended exposures
- Flexibility
  - Adaptable to new technologies and upgrades
  - Scalable; applicable to many ship classes

Backup

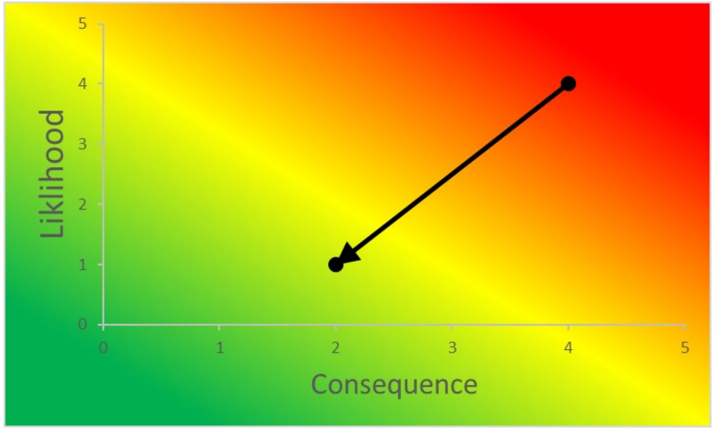
We would like to partner with you…

Collaborations and discussion regarding:

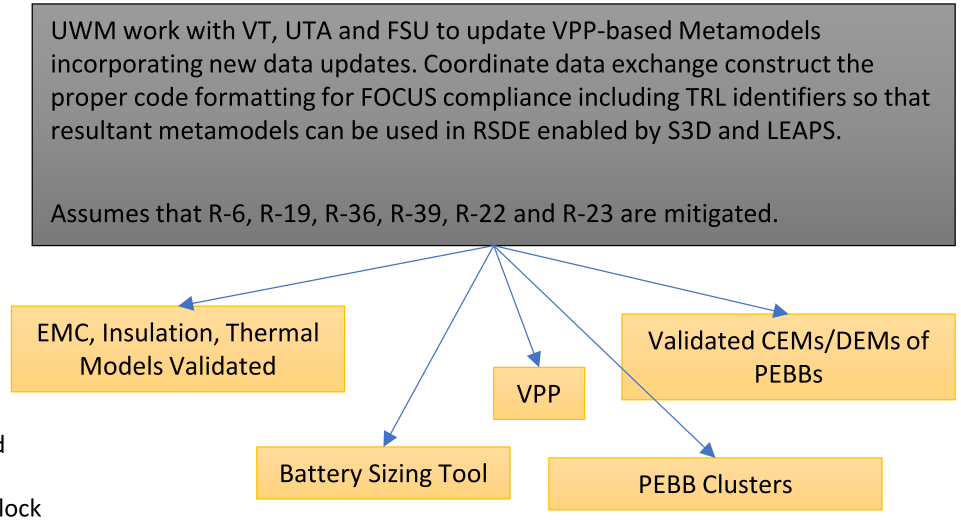
- Application of NiPEC to various Navy ship models
- Shipbuilding methods in various shipyards
  - Modularity
  - Testing protocols and support equipment
- Research into modularity of various aspects:
  - Main bus
  - Plug-in Power Connections at Power/Voltage
  - Thermal management

Mitigation: Risk ID-20

Research Area	Technology	IF	THEN	Comment
Dielectrics, Thermal, Interfaces, PEBB	Virtual Prototyping Process (VPP)	***the integration of data and surrogate models*** describing NiPEBBs thermal interfaces, field grading and EMI mitigations ***are not validated using NiPEBB hardware*** use cases in PEBB clusters	***traceability*** of unique NiPEBB identifiers (required for Metamodels of NiPEBB within RSDE) ***for trustworthy Solution Space Exploration of NiPEBB Types*** in RSDE results will not be achieved.	A representative section of ***NiPEC needs to be built with actively controlled PEBBs and NiPEBBs*** to understand impacts at the system level, derive compatibility requirements and test against those requirements. Tech Candidate effort bringing NiPEBBs to a higher TRL is necessary to complete this.



Mitigation



Acronyms:

CEM – Common Mode Equivalent Model
DEM – Differential Mode Equivalent Model
EMC – Electromagnetic Compatibility
EMI – Electromagnetic Interference
LEAPS – Leading-Edge Architecture for Prototyping Systems
NiPEBB – Navy Integrated PEBB
NiPEC – Navy Integrated Power and Energy Corridor
PEBB – Power Electronic Building Block
RSDE – Rapid Ship Design Environment
S3D – Smart Ship Systems Design
TRL – Technology Readiness Level
VPP – Virtual Prototyping Process

S&T: Closing Gaps

Energy Storage and Power Conversion:

- Develop ***NiPEC sections*** to capitalize on ***PEBB clusters*** within power trains.
- Establish and ***validate tools for integrating*** energy storage to maintain operability and power quality in normal and transient loading.
- Develop ship integration models and assess for ***reliability, stability, survivability,*** and ***operability.***

Ship Integration & Interfaces:

- Develop electrical, mechanical and thermal ***interface technology*** for NiPEC connections (e.g. latching mechanism, disconnect).
- Investigate NiPEC impact on ship ***construction, testing, and upgrade.***
- Coordinate and develop ***higher performing mission systems*** afforded by NiPEC.
- Develop ***scale-ability*** of LRU arrangements, thermal management, EMI mitigation and dielectrics within NiPEC and determine impacts on SWAP-C.

Control:

- Develop ***orchestration*** techniques for ***discretized power routing.***
- Integrate ***energy management*** concepts leveraged from past RCPC work.
- Develop ***stability process/control and protection algorithms*** for integrated clusters of PEBBs.
- Develop ***agile and secure*** programming processes for control code

S&T: Closing Gaps (2)

Thermal Management:

- Co-design ***scalable thermal management solutions*** that support PEBB operability, reliability and survivability.
- Develop advanced cooling strategies to accommodate power electronics and high-frequency transformer designs.
- Validate scalable LRU and NiPEC thermal models in relevant environments.

Electro-Magnetic Interference (EMI), and Dielectrics:

- Develop and demonstrate ***EMI cancellation and mitigation strategies.***
- Integrate outcomes of ***ESARCA*** concerning insulation material and partial discharge.
- Add isolation layers and PCB-embedded shielding for ***enhanced EMI immunity.***
- Develop and standardize effects of dielectrics on NiPEC composition.

Cyber-Physical Systems and Cyber-Security:

- Leverage outcomes from RCPC FNC and research between Clarkson, FSU, USC and FIU; with respect to analysis methods that differentiate between normal behaviors, natural degradations, and cyber-attacks.