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Thermal Management for Ship Electrification - Approaches for Power Electronic Building Blocks and Power Corridors

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***Abstract*—This paper presents an overview of thermal management solutions, in support of ship electrification, that are being investigated for power electronic building blocks and their integration into power corridors, both of which are seen as enablers of flexible and reconfigurable power distribution systems in the next generation Navy ships. Air, liquid, two-phase, and indirect cooling approaches are discussed in the context of specific building block configurations built and designed at CPES (Virginia Tech). The paper presents an overview of ongoing efforts towards the design, construction, and testing of cooling technology prototypes.**

***Index Terms*—thermal management, cooling, power electronics, PEBB, NiPEC, Power Corridor, LRU**

I. Introduction

Several arguments can be made in support of ship electrification. A major one, that applies to other modes of transportation, is that electrification provides an essential step towards decarbonization, as electrified systems can, in principle, be integrated to renewable and carbon-free energy sources. Another important argument, is that electrical power trains provide more flexibility than the traditional mechanical ones.

Ambitious target goals for greenhouse gas (GHG) reduction have been set by the International Maritime Organization (IMO). The IMO, as part of its 2023 GHG strategy, set goals to reduce by at least 40% by 2030 the average CO_2 emissions per transport work across international shipping [1].

In a navy context, the primary reason behind ship electrification has been the expected added flexibility to divert power from, for example, propulsion to critical loads in response to specific mission requirements. While this continues to be the primary driver, the potential for emissions reduction has gained traction as countries that are key players in navy shipbuilding advance in their commitments to support global decarbonization efforts.

The concept of electric ships dates back to the late 19$^{\text{th}}$ century. Prior to WWI there were examples like the diesel-electric river tanker Vandal and the naval ship Juniper that used electric propulsion [2], [3]. The initial designs of electric ships resulted from coupling steam engines that drove generators with propulsion motor-propellers in which speed control came from regulating the generator speed [3]. A major trigger for the current approaches to ship electrification started in the 1980s when power electronic technology for motor speed control began to be incorporated into prototypes.

In the late 1990s and early 2000s, electric navy ship designs started incorporating approaches to increase flexibility and reduce production cost through similarity [4]. A salient idea that emerged was that of Integrated Power Systems (IPS), which involves architectural concepts to configure modules to serve multiple ship electrical needs [4].

Current navy electric ship concepts rely on a variety of electric power distribution architectures and maintain prime movers (e.g., gas turbines) operating on fossil fuels, which, in principle, can substituted with sustainable transportation fuels, like those conceived for aviation (e.g., SAF), by developing turbomachinery that can burn renewable hydrogen, by replacing the turbomachinery with fuel cells, or through breakthroughs in energy storage that enable storing on board renewable energy that can meet the price, power and energy densities currently provided by liquid fuels.

Within the navy design paradigm that aims to enable

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reconfigurability, modularity and off-hull fabrication, Power Electronics Building Blocks (PEBBs) and Navy integrated Power and Energy Corridors (NiPECs) are central ideas in the development of future Navy electric ships. The former are least replaceable units that provide power conversion flexibility, and the latter are space reservation corridors allocated to power conversion, transmission and storage.

Due in large part to their modularity and flexibility, PEBBs are envisioned to support reductions in production and installation costs, facilitate maintenance [5], and support ship resiliency. The majority of existing PEBB concepts [6]–[9] are drawer-type hexahedrons with faces dedicated to specific purposes. Typically, one face is used for sailor interactions, two for thermal management, one or two for power and communication interfaces, and two provide mechanical connection to a rack-type structure.

The Navy integrated Power and Energy Corridor (NiPEC) incorporates into a single modular entity all the components of the electrical distribution system for the main bus power throughout the ship, including main bus cabling, conversion, protection, isolation, control and energy storage. The corridor runs almost the full length of the ship, penetrating into the forward- and aft-most zones, with redundant corridors separated horizontally and vertically for survivability purposes. Space for the corridor is reserved at the earliest stages of the ship design process, recognizing the importance of these vital systems to the operational performance of the ship. The NiPEC may use one or more varieties of PEBBs as the least replaceable units (LRU) to perform conversion, protection and possibly isolation functionality; these PEBBs are designed to be easily swapped out onboard the ship. In addition to the LRU modularity, it is expected that the NiPEC sections themselves will be modular; they will be constructed and tested off-hull and installed in the ship as a single component. Since the cabling is built into the NiPEC sections, this reduces the labor associated with routing the main bus cables. A graphic illustrating a sample NiPEC section is provided in Fig. 1. A related ongoing development for navy ship electrification is that of a Power Electronic Power Distribution System (PEPDS). The PEPDS vision seeks to design future power distribution systems based on PEBBs and NiPEC that, beyond the interfaces to the rest of the ship, rely solely on power electronics for electric power conversion and distribution (Figure 2).

One area of intensive research under the NiPEC and PEBB umbrella is the resolution of the cooling challenge posed by individual PEBBs and ensembles of them within sections of a NiPEC. Fig. 3 illustrates a range of heat spreading methods, heat sinks, and cooling media that are part of the design space that is being considered. The design space for cooling solutions of power electronic components is relatively wide if we consider the potential combinations of cooling media, the potential to incorporate single or two-phase flow, the different heat sink configurations, the arrangements of the fluid with respect to the heat sink structures, the interface materials, and the heat spreading strategies.

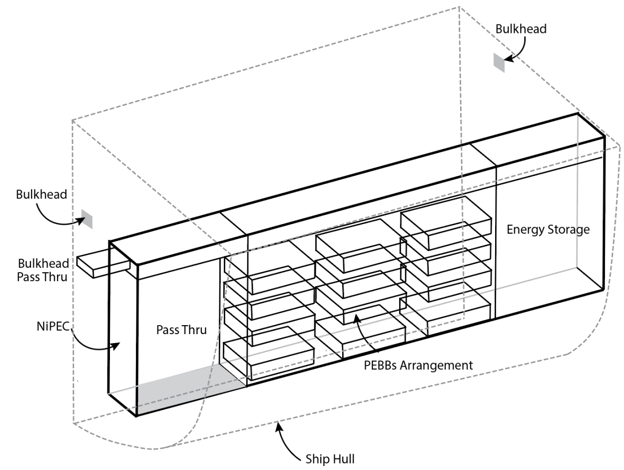

Fig. 1. Schematic of Navy Integrated Power and Energy Corridor (NiPEC) segment. Arrangements of multiple PEBB enable multiple power distribution and conversion functions.

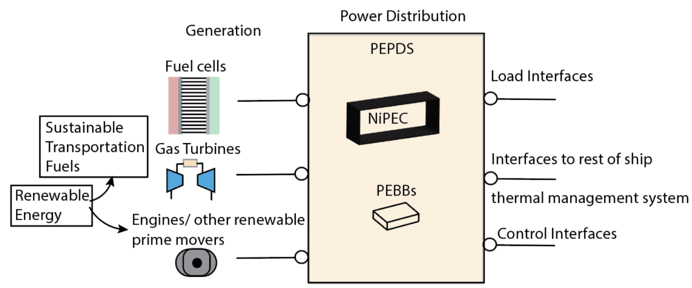

Fig. 2. Concept of ship electrification using Power Electronic Power Distribution Systems (PEPDS). Renewable energy and sustainable transportation fuels can be used for power generation. The power conversion and distribution is done with power electronics.

In the heat transfer literature there is a significant number of studies addressing the benefits and limitations of single and two-phase cooling solutions. For single-phase cooling, high heat fluxes can be removed with flow configurations that employ microchannels and impinging jets [10]. For microchannels, the small geometrical features (hydraulic diameters) are conducive to large convective heat transfer coefficients but, at the same time, these small hydraulic diameters contribute to high pressure drops. A benefit of the large convective heat transfer coefficient is that lower flow rates are needed (reducing overall system weight and aiding in reducing pumping power). Nevertheless, low coolant flow rate operation under single phase cooling is of limited use by applications that require uniform temperature control (as it is typical of electronic components) because the low flow rates and high heat fluxes result in large temperature gradients in the flow direction. Impinging jets can lead to very high local convection coefficients near the impingement zone but when the areas to cool are large in comparison to the jet, it is necessary to use multiple jets which adds complexity to the coolant supply and collection systems.

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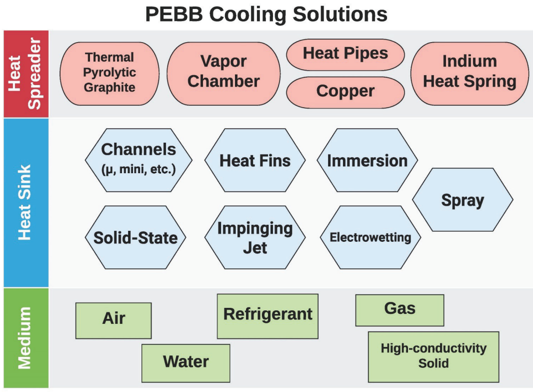

Fig. 3. PEBB cooling solution design space.

Finned heat sinks are of widespread use in cooling of electronics for natural and forced convection in connection with multiple flow configurations, including impinging jets. From a PEBB perspective, weight limitations constrain the additional surface area that can be used giving more relevance to fin geometry optimization efforts. A study of fin arrays under natural convection by Bar-Cohen et al. [11] reports finned arrays with optimized fin spacing in the range of 6 to 8 mm and fin thickness in the range of 8 to 10 mm that exhibit natural convective heat transfer coefficients of 198 $\mathrm{W/(m^2 \cdot K)}$. In that study, the thermal conductivity of the base case array was 200 $\mathrm{W/(m \cdot K)}$, the base-to-ambient temperature difference 25K and the baseplate a 10 cm $\times$ 10 cm area. Consistent with the efforts to reduce weight and space contributions of the thermal management systems, they explore mass-specific and volume-specific heat transfer coefficients for the finned array. A mass-specific natural convection heat transfer coefficient of $2.5\ \mathrm{W/(kg \cdot K)}$, for the array described above, was obtained for the cases with the maximum spacing (15 mm) and the smallest fin thickness considered (1 mm). The exploration of the geometry that leads to highest convection coefficient with respect to space claimed by the array resulted in a maximum natural convection space claim heat transfer coefficient of $566\ \mathrm{W/(m^3 \cdot K)}$ (at a fin thickness of 1 mm and a lateral spacing of 9 mm). Interestingly, the study finds that aspect ratios identified as optimal are in ranges that, at that moment, require specialised manufacturing techniques and, when comparing among copper, aluminum and magnesium, identifies the latter to be the most efficient in material utilization.

Similar explorations have been conducted to identify operational limits of finned arrays that employ forced convection [12], [13].

In this paper, single-phase air and liquid, two-phase liquid, and indirect cooling approaches for PEBBs are summarized. The paper is structured as follows: Section II provides an overview of the thermal management needs, the geometry, and the levels of heat dissipation; Section III-A covers forced convection air cooling; Section III-B forced liquid cooling; Section III-C air and liquid cooled combined; Section IV presents approaches to use two-phase cooling directly integrated into power modules and vapor chambers for heat spreading; Section V presents ideas to implement indirect cooling; Section VI refers to integration with ship-level thermal management; and Section VII covers some future work and concluding remarks.

II. Characterization of the Thermal Problem

This paper will cover thermal studies and efforts in relation to three PEBB versions: PEBB 1000, PEBB 6000, and the Navy integrated PEBB (iPEBB).

Design guidelines and Navy's preferences bring constraints to the thermal solutions, including:

1) Air cooling is preferred over liquid cooling in the vicinity of electrical elements.
2) Thermal approaches should not interfere with the envisioned single-sailor, simple replaceability of the PEBB. In this sense, quick connect/disconnect functionality should be maintained.
3) A ground potential may be present in the PEBB cover. Therefore, the cooling system path should be electrically isolated from high-voltage components.

A. PEBB-1000 Thermal Problem

The PEBB 1000, developed and tested at Virginia Tech Center for Power Electronics Systems (VT-CPES), is a 1 kVdc bus, 100 kW, 100 kHz H-bridge based converter with dual-sided cooling [8]. Fig. 4 illustrates the PEBB 1000 prototype with a power density of 5 kW/L and its principal heat loads. PEBB 1000 uses two 1.7 kV SiC MOSFET power modules to form an H-bridge building block along with intelligent gate drivers, sensors, and passive components. The power modules are mounted to an aluminum cover plate which serves as the the main interface to the external cooling system.

In the absence of internal fans, the enclosure becomes a cavity in which the primary heat transfer mechanisms are natural convection and conduction. Under these conditions, it becomes essential to establish thermal conduction paths from the heat loads to the cover plates while maintaining the electrical grounding requirements. These thermally conductive cover plates — upper and bottom covers (not shown) — can be interfaced with an external or embedded cooling system.

If appropriate thermal contact between the internal components and the covers is achieved, and the heat load is effectively diffused in the covers, then the expected heat flux is manageable with air cooling. Localized heat fluxes at cover level, if power module heat loads are fully diffused to their cases, are of order $\sim 18\ \mathrm{W/cm^2}$. At the die level, these fluxes are an order of magnitude larger.

B. PEBB-6000 Thermal Problem

The PEBB 6000 utilizes two 10 kV, 240 A XHV-6 half-bridge SiC MOSFET modules to form an H-bridge topology. It has intelligent circuitry, insulation coordination for >30kV, and a PCB-based busbar [15].

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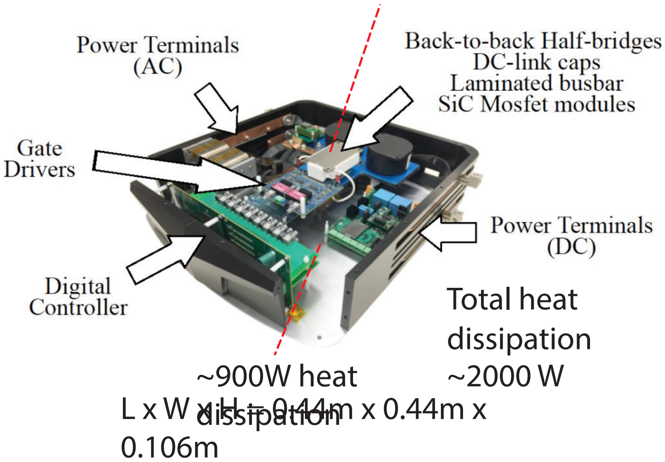

Fig. 4. PEBB 1000 prototype with dimensions of 49 cm x 44 cm x 100 cm and the main heat dissipating components [14].

The ratings of the PEBB 6000 make the thermal issues of the converter a critical topic [15]. Each 500 kW PEBB-6000 operates at 6 kV. The larger converter assembly can operate with up to four PEBBs in series to provide a bus voltage of 24 kV. Due to the large power requirement to supply such a cooling system, all PEBBs are powered from an external, earth-grounded supply. The heat sink of each PEBB is referenced to its own bus midpoint to create a local ground. Therefore, under the most severe operating conditions, the heatsink-to-cooling system voltage can be up to 27 kV.

To simplify PEBB- and converter- level insulation design, a forced air cooling system was selected. This allows the heatsink-to-fan clearances to be carefully designed to improve power density while ensuring reliability [7]. The PEBB 6000 uses an aluminum heat sink and 12 fans for the thermal management system. A thermal study of the PEBB 6000 was previously completed in [16] and additional simulations are shown in Fig. 5. Additional hardware validation of the cooling system is discussed in Section III-A.

C. *iPEBB Thermal Problem*

The Navy iPEBB is a 1 kV, 250 kW, 500 kHz building block currently under development at VT-CPES. This new generation of PEBB aims to achieve lighter weight (35 lbs), improved manufacturability, and higher power density (12 kW/L) than previous PEBB designs [17]. While the PEBB 1000 and PEBB 6000 are H-bridge-based building blocks, the iPEBB is a galvanically-isolated, bidirectional power converter with a 500 kHz transformer and four H-bridges. The PEBB 1000 and PEBB 6000 employed discrete power modules or discrete packaged devices to form the topology. In the iPEBB, the topology is realized by bonding and interconnecting 1.7 kV SiC MOSFET bare dies and passive components to a common substrate [17]. The common substrate provides a unified cooling platform, mechanical support, and a reduction in thermal interface layers. The common substrate is formed using organic direct-bonded copper (ODBC) polyimide-based material [18]. The ambitious ratings and integration goals of the iPEBB require advanced cooling methods.

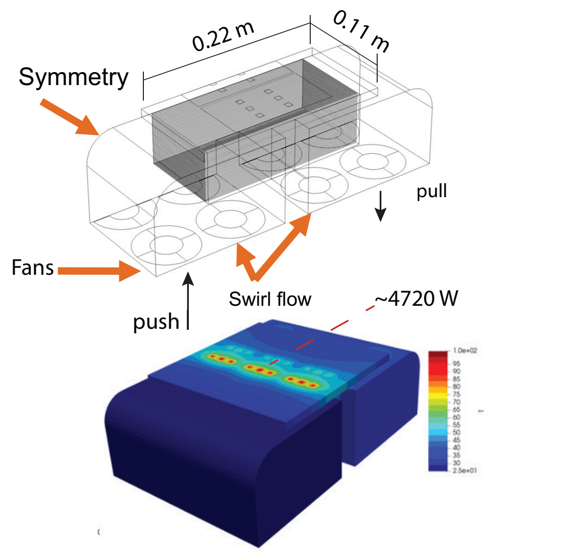

Fig. 5. PEBB 6000. (Top) Dimensions and fan arrangement, and (bottom) temperature field with an air-cooled heat sink using a push-pull arrangement with 12 fans.

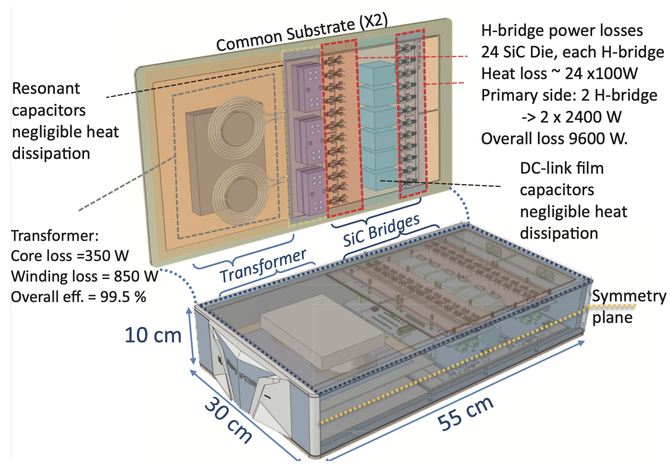

Fig. 6. Dimensions and main heat dissipating components of the iPEBB [9].

Fig. 6 illustrates the main heat-dissipating components for this PEBB. Initial worst-case studies of the iPEBB show the converter dissipates approximately 5400 W on each cover ($\sim$ 4800 W on the common substrates plus $\sim$ 1200/2 W from transformer losses). In the current version of iPEBB, all devices (SiC power modules, capacitors, transformer, etc.) are on the common substrate and enclosed inside of the converter housing. The copper top and bottom covers, part of the common substrate, are electrically insulated from internal components and can be used to interface to external or embedded thermal management solutions. 1.7 kV SiC MOSFETs are used and have a worst-case heat flux of $\sim$ 300 W/cm^2 in their hot spot locations.

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III. SINGLE PHASE COOLING

A. Forced Air Cooling

It is well understood that, from a heat transfer perspective, air cooling solutions are restricted to lower heat flux levels than liquid and two-phase ones. Nevertheless, forced air cooling is of common practice for cooling of electronics due in part to simplicity and safety advantages (e.g., [19], [20]). As in liquid cooling, the limits of heat removal in forced convection with air come mostly from limitations in available flow rates. For air, these limitations are related both to acceptable noise levels and to the matching of the system pressure losses to the fan curve that supplies the pressure head to overcome losses.

Air cooling approaches for all three PEBB versions being discussed have been studied. For PEBB 6000, a computational and preliminary experimental tests using 12 fans arranged in a push-pull configuration has been conducted. Fig. 5 illustrates the computed temperature field. The darker blue region towards the front of the image is the housing used for the incoming air. The hot spots in the base plate occur directly under the power modules and are kept under 100 °C ensuring junction temperatures (T_j) are below their limit. Heat sink fins with approximate dimensions L x W x H = 0.195m x 0.184m x 0.060m, were used. Loss equations derived from device characterization were used to estimate the expected power losses for each switch position, including both conduction and switching losses. The model was first calibrated experimentally to validate the thermal simulation results. Measurements using a Fluke airflow meter provided an operating point that was used to match the calibrated model within 3%. The converters were run for two hours in the dc-dc pump-back configuration to ensure thermal equilibrium was reached. In the worst-case switch position, a maximum T_j of approximately 108 °C was observed, which was within 5% of the temperature calculated through simulation and analysis.

For PEBB-1000-like and iPEBB-like configurations, a parametric exploration of air cooling solutions was conducted [16]. That study explored different fin arrangements (parallel-plates, pin-fins, rectangular fins) and different angles for the incoming air (from transversal flow to direct impingement).

In [21] the authors explore a PEBB1000-like configuration cooled by an impinging jet. Computational results indicated internal air temperatures and overall peak temperatures to be within the design limits.

B. Liquid Cooling

Cooling solutions in which the cold plate or cooling channels are directly attached or embedded into the PEBB covers (as opposed to indirect solutions considered in Section V) have been generated for PEBBs in a wide range of flow configurations. Fig. 7 illustrates serpentine arrangements. These can be modified to accommodate the terminals to the coolant connections and the number of passes and their spacing to better irrigate the cold plate near hot spots.

When the cold plate is attached to the PEBB cover, careful attention needs to be paid to the selection of a thermal interface material and the proper pressure distribution to ensure good thermal contact. This problem is eliminated if the cold plate channels are embedded within the PEBB covers.

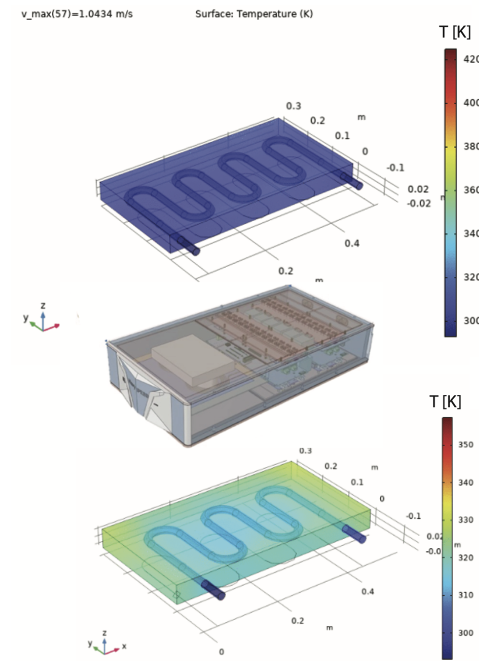

Fig. 7. Serpentine-shaped flow structure for liquid cooled iPEBB.

From a heat transfer perspective, the problem of collecting the heat dissipation distributed over the cover area becomes one of identifying the proper flow network that balances the pressure drop penalties that result from added complexity in the network with the gains in thermal performance that result from having better coverage (irrigation) of the area. Figure 8 illustrates this balance for a serpentine configuration. The added features of flow distribution network represented here simply by the added turns lead, as expected, to more uniform temperature distributions and larger pressure drops. Just as in living organisms, the heat dissipation benefits from enhanced vascularization. Nevertheless, complex networks bring added manufacturing complexity.

C. Air and Liquid Cooling

Efforts to link the PEBB heat dissipation structures to a rack-mounted liquid cooling system can open the design space to options that combine forced air cooling and liquid cooling. With proper filtration systems to remove suspended particles, it should be possible to integrate forced air cooling systems into a PEBB's built-in ducts. When operating conditions prevent air exchanges between the PEBB interior and the surrounding compartments, forced air cooling systems can still play an important role internally by enhancing the internal convection and therefore providing better contact to external cooling systems. Having multiple thermal management resources opens up the possibility of implementing control strategies that are better equipped to address thermal transients, in part, because

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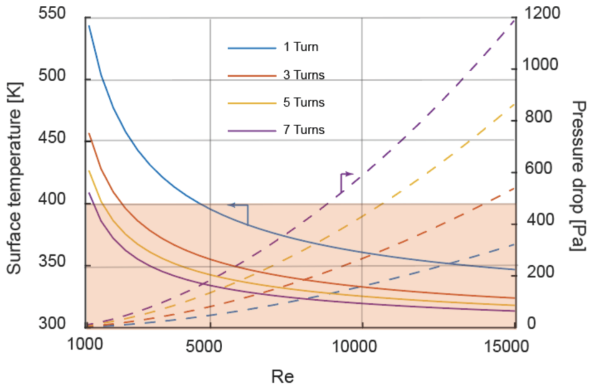

Fig. 8. Effect of number of turns and Reynolds number on peak surface temperature and pressure drop for a serpentine covering 35 cm × 35 cm on an aluminum plate. Shaded region is representative of typical temperature limits.

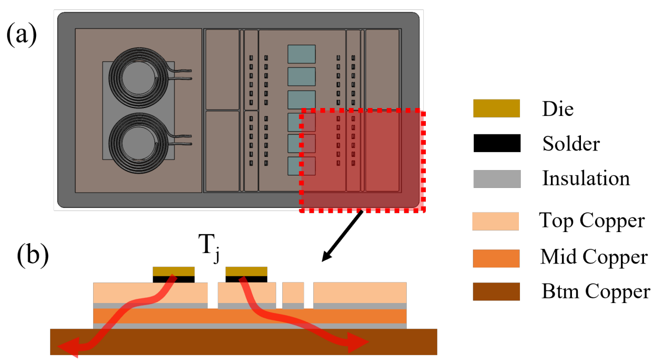

Fig. 9. iPEBB substrate (a) Top view of iPEBB cover, and (b) Cross-section of SiC bridges section.

of the different response times associated with air cooling and other (liquid, two-phase) cooling options.

IV. Two-Phase Cooling

Fig. 9 shows the structure of the iPEBB substrate. The power converter substrate consists of three copper layers and two layers of electrical insulation between them. The bottom copper serves as the iPEBB cover and is expected to be electrically isolated. The heat dissipation density on the iPEBB hot spot (1.7 kV SiC MOSFET die) is up to $\approx 300\ \mathrm{W/cm^2}$. One of the main challenges for iPEBB cooling is caused by the very low thermal conductivity of the electrical insulation layer (e.g., ODBC $\approx 0.7\ \mathrm{W/m \cdot K}$). To keep the junction temperature (T_j) under the operation limit and meet the weight limit requirement, two-phase cooling is extremely promising due to its high heat transfer rates and compact features compared to single-phase cold plates. This section focuses on reducing the through-plane (heat sink) and in-plane (heat spreading) thermal resistances of the iPEBB by implementing advanced two-phase cooling solutions.

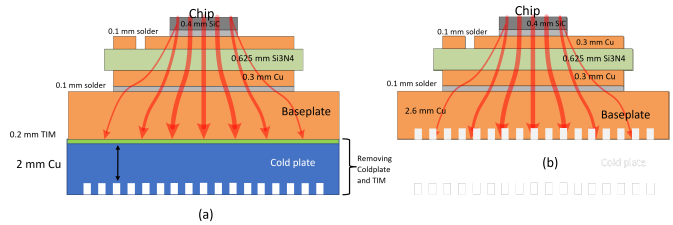

Fig. 10. (a) Power module cooling using two-phase minichannel coldplate and TIM, and (b) Proposed power module cooling using two-phase minichannels integrated in the module baseplate.

A. Direct Integration of Two-phase Cold Plate with Substrate

This method aims to enable a high-performance power module by directly integrating two-phase mini-channel cooling in the power module substrate. Three decades ago, single-phase microchannels were proposed to cool electronics. However, single-phase microchannel cooling brings prohibitive pumping power and considerable inlet-outlet temperature differences. In contrast, two-phase microchannels come with high power density cooling capability, spatially uniform temperature and drastically reduced coolant flow rate, which would reduce pumping power and the overall size and weight of the cooling system.

A power module with an integrated two-phase mini-channel on the baseplate significantly reduces thermal resistance by removing the cold plate and thermal interface material (TIM). Fig. 10(a) shows the structure of a commercial power module (Wolfspeed CAB450M12XM3) with a separate two-phase minichannel coldplate interfaced to the baseplate using a TIM layer. Fig. 10(b) shows the same power module with two-phase minichannels integrated in the module baseplate, eliminating coldplate and TIM. Note that this would not be possible for conventional single-phase coooling, given the large coolant flow rate required.

The power module's dimensions and geometry make it feasible to integrate the two-phase mini-channel into the baseplate using a conventional milling technique. Our experimental results show that the integrated two-phase cooling module's cold plate only contributes 11% of thermal resistance, which is down from 18% in conventional cooling; combined with the removal of the TIM achieves an overall reduction of 38.1%.

Major advantages of two-phase flow boiling for this application are:

1) Reduction of thermal resistance: The suggested module minimizes thermal resistance by removing the cold plate and thermal interface material. Integrated mini channel (IMC) thermal resistance $R_{th(j-in)}$ is 38.1% lower than conventional mini channel (CMC) cooling.
2) Increased lifetime of innovative power module: Power module reliability depends on thermal cycling during operation and on thermal gradients within the module structure. Two-phase cooling results in increased heat flux, lower peak temperatures and more uniform ther-

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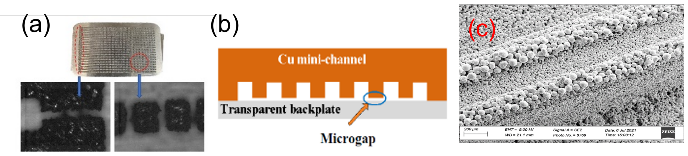

Fig. 11. a) Slot structure Micro-gap structure, b) Schematic of mini-channel with micro-gap, c) Porous structure by sintering copper powder.

mal distribution, reducing thermal stress and increasing module lifetime.

3) Reduced parasitics and increased electrical performance. Two-phase cooling reduces module size and switching loop inductance. Low parasitic inductance results in mitigation of device stress and EMI.
4) Decreased cooling fluid flow: The two-phase cooling flow rate ($\approx$ 11.2 μL/s) is lowered by 4 orders of magnitude compared to a traditional cold plate, which requires 8 L/min (133, 333 μL/s), as reported in [22].
5) Reduced system size and weight: Two-phase microchannel structure and baseplate elimination reduces system size and weight.
6) Uniform temperature distribution: Heat spreading using vapor chambers is effective in improving the uniformity of power module thermal distribution.

However, some technical challenges have to be addressed such as liquid supply dryout in long channel two-phase flow and optimal operation parameters. Three solutions have been explored to address the aforementioned challenges, namely slot structure, porous structure, and micro-gap as shown in Fig. 11.

1) The **slot structure** introduces a lateral flow path to avoid the formation of large vapor slugs by sustainable nucleate boiling, and enhances boiling and critical heat flux [23].
2) The **micro-gap structure** facilitates rewetting flow and vapor expansion over the micro-gap, preventing blockage of vapor slugs. An optimum micro-gap thickness of $60\mu m$ was experimentally determined.
3) The **porous structure in mini-channel** utilizes capillary force to supply and spread liquid on the heating surface [24]. Typically, the porous layers on the microchannel surfaces are created by spray painting, diffusion-brazing, or sintering [4].

Experimental Validation and Analysis:

De-ionized (DI) water was used to test integrated micro-gap mini-channel (IMGMC) and CMC cooling. Both cold plates are first tested at 25 ml/min. The cooling system operates in single-phase mode when water temperature is below 100 °C and in two-phase mode above 100 °C since water boils at 100 °C at 1 atmosphere of pressure.

Junction temperature T_j and thermal resistance from junction to coolant at inlet $R_{th(j-in)}$ were measured and estimated to indicate thermal performance of two-phase cooling. Fig. 12(a) shows that IMGMC's maximum power dissipation

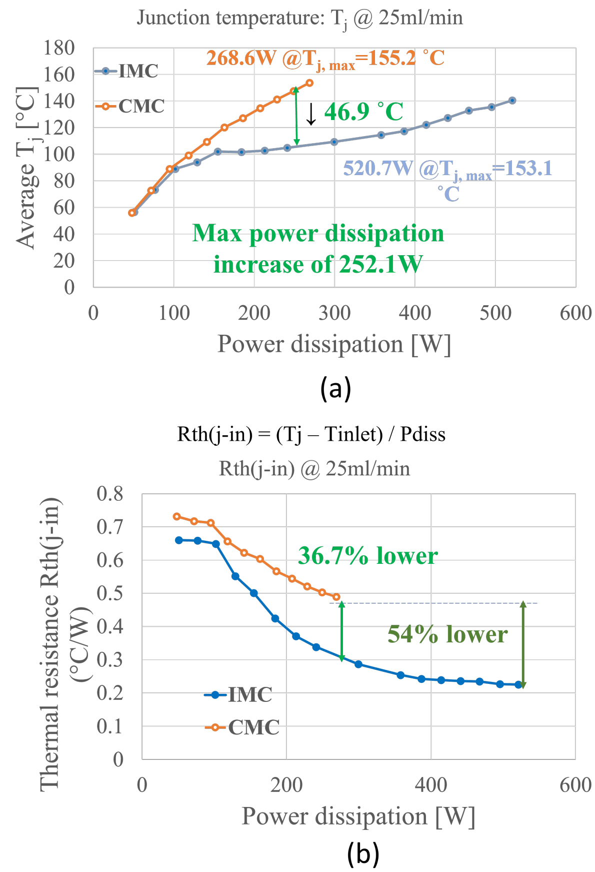

Fig. 12. IMC and CMC Junction temperature T_j and thermal resistance $R_{th(j-in)}$. (a) Junction temperature T_j comparison, and (b) $R_{th(j-in)}$.

is 520.7 W which is twice as high as the CMC's value of 268.6 W. Using the CMC with 268.6 W maximum power dissipation, T_j is 46.9 °C. The thermal resistance from junction to coolant at inlet $R_{th(j-in)}$ is determined by $R_{th(j-in)} = (T_j - T_{in})/P_{diss}$.

Fig. 12(b) shows that the IMGMC structure results in a large drop in thermal resistance $R_{th(j-in)}$: thermal resistance $R_{th(j-in)}$ of IMGMC at power dissipation of 268.6 W is 0.314 °C/W, which is 36.7% lower than CMC at 0.489 °C/W. The thermal resistance then saturates at a low value until dryout at 520 W. IMGMC $R_{th(j-in)}$ drops to 0.225 °C/W, 54% lower than CMC at maximum power dissipation achieved in this experimental study.

B. Two-phase Heat Spreader (Vapor Chamber)

Heat spreading is critical for iPEBB thermal management because it helps to effectively spread heat to available cooling areas. Materials like copper and graphite are limited by their thermal conductivity ($\approx$ 1000 W/mK), therefore often sacrifice the compatibility and weight to meet thermal requirements. Vapor chamber is one of the most efficient heat-spreading technologies and can achieve over $10X$ better performance compared with graphite [25]. Moreover, vapor

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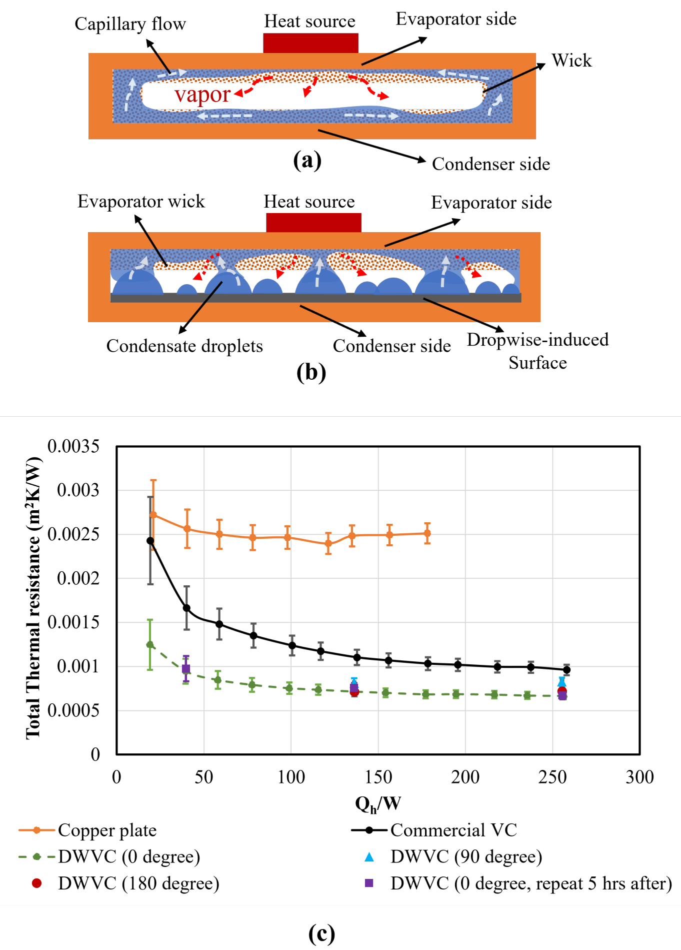

Fig. 13. Comparison of vapor chamber mechanism (a) conventional vapor chamber, (b) dropwise vapor chamber. (c) Experimental result comparison between DWVC, commercial VC, and copper plate.

chambers are generally light weight because they are essentially hollow structures charged with a small amount of working fluid. They can also be made into thin (≈ 1 mm) and customized shapes [26].

Conventional vapor chambers (CVC) have wicking structures on both the evaporator and the condenser in order to circulate the working fluid. In contrast, dropwise vapor chambers (DWVC) do not require a condenser wick because the working fluid circulates through rapid growth of condensate droplets, which further improves the heat spreading performance [27]. Fig. 13 shows the comparison of different mechanisms between conventional and dropwise vapor chambers.

Experimental Validation and Analysis:

A highly sustainable graphene surface [28] was applied inside a vapor chamber to induce dropwise condensation. The evaporator consists of 4 layers of copper mesh, and the condenser surface (Cu-Ni-Gr) is a multi-layer graphene structure grown on a nickel-plated copper plate via chemical vapor deposition. Our visualization study demonstrated that the working fluid rapidly condensed in diverse droplets and circulated back to the evaporator via direct contact.

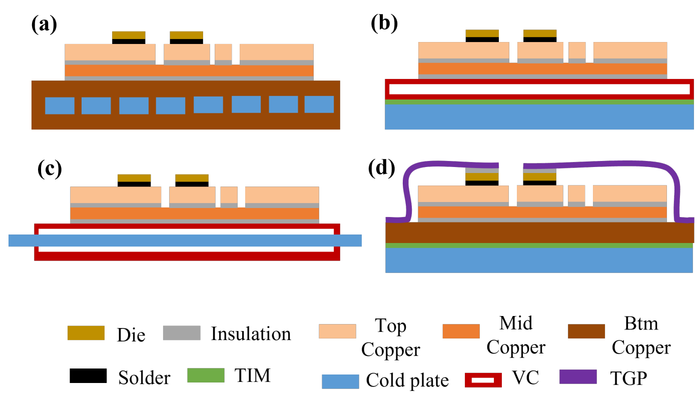

Fig. 14. Two-phase cooling solutions (a)-(d).

A prototype DWVC with an overall size of $104\times36\times3$ mm^3 was built and tested. The lowest total thermal resistance (on the condenser surface) achieved in the experiment was $\approx 6.7\cdot10^{-4}$ $\mathrm{m^2K/W}$. The experiment also showed a significant reduction in thermal resistance ($30\% - 50\%$) compared with a commercial vapor chamber (VC-106-70-3 Wakefield-Vette). That is, only half of the condenser (cold plate) surface area is needed for the proposed DWVC to achieve the same heat spreading performance as a commercial vapor chamber. Despite the lack of a condenser wick in the DWVC, the experiment showed little performance dependence on the orientation angle due to the small size of the droplets. Moreover, the overall density of the prototype DWVC is about 5.2 $\mathrm{g/cm^3}$, 42% lighter than pure copper.

C. Application of Two-phase Solutions to PEBB and NiPEC

Four two-phase cooling solutions are discussed for the iPEBB structure, as shown in Fig. 14 (a)-(d). Advantages and disadvantages are summarized in Table I. Solution (a) integrates mini-channels in the bottom copper layer, which eliminates thermal interface materials (TIM) and further reduces the in-plane thermal resistance by implementing two-phase flow boiling. Solution (b) replaces the bottom copper layer with a two-phase heat spreader (vapor chamber), and a cold plate (single-phase or two-phase) is attached to the vapor chamber with a TIM. Solution (c) eliminates the TIM by integrating the heat spreader and the cold plate; this internally cooled vapor chamber [29] has a compact structure that can achieve heat spreading and cooling at once. Solution (d) applies a thermal ground plane (TGP) such as thin heat pipe [30] to directly transfer heat from the top of the die to the cover; this cooling strategy can be combined with other strategies. An electrically insulated layer and good bonding are required between the TGP and dies [31].

Conventional wire bond techniques, shown in Fig. 15(a), on the top of the chip could impose challenges in implementing solution (d) and may make it difficult to produce a strong thermal contact; however, new wire bond techniques such as ribbon bonding, shown in Fig. 15(b), offer an alternative to wire bonding. Ribbon bonding is well organized and neat and,

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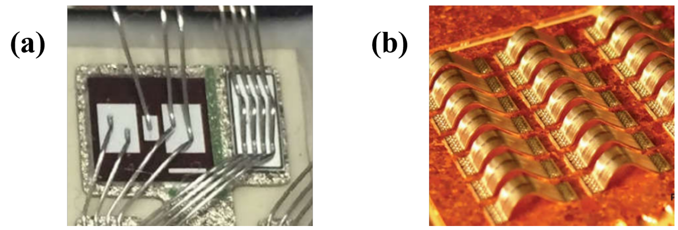

Fig. 15. Conventional wire bonds (a) and ribbon wire bonds (b).

hence, leaves space for TGP installation and enables a better thermal contact [32].

D. Hybrid heat sinks with integrated vapor chamber

Figure 16 (top) illustrates a vapor chamber used to spread a localized heat. The chamber is mounted on a heat sink with a TIM layer in between. In an effort to reduce the total thermal resistance through integration the concept illustrated in Fig. 16 (bottom) is being explored. It integrates the heat sink and a vapor chamber.

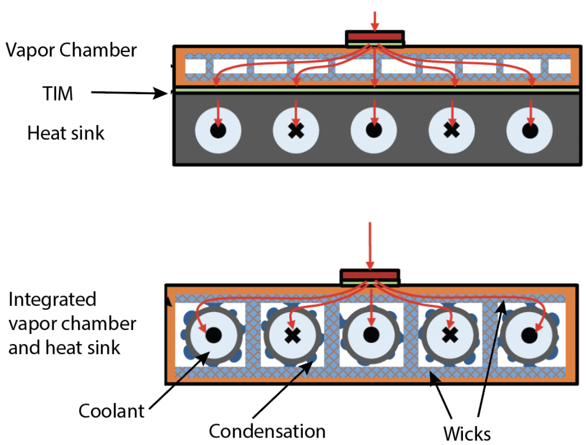

Fig. 16. (top) Vapor chamber and heat sink. (bottom) Integrated heat sink with vapor chamber

A pin fin array serves as evaporator while the outer surface of the serpentine with a non-wetting graphene coating serves as a condenser (Fig. 17). The upper middle portion of Fig. 17 illustrates schematically the basic elements of the experimental setup. A controllable heat source is used to heat the evaporator side which is integrated with the condenser and sealed to form a vapor chamber. The experimental comparison resulted in total thermal resistance reductions of 48% at 700 W.

The exploration of the hybrid heat sink with integrated vapor chamber is ongoing and it expected to offer good scalability and provide a common compact structure for heat spreading and rejection.

V. Indirect Cooling

At first blush the iPEBB cooling problem does not seem very challenging. The iPEBB produces approximately 10.8 kW of heat, with two large surfaces (300 x 550 mm each)

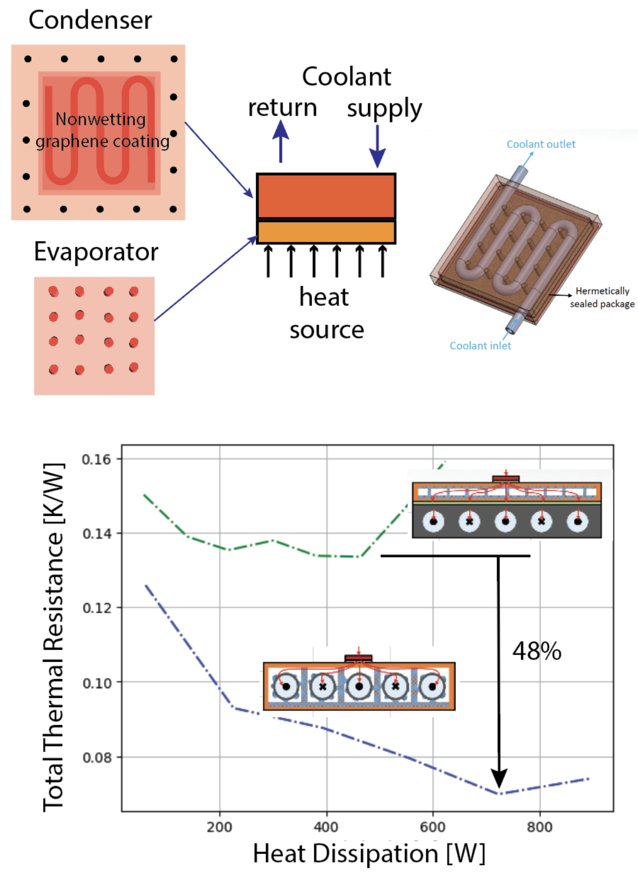

Fig. 17. Hybrid heat sink integrated with vapor chamber.

available for heat transfer, yielding an overall heat flux of $3.3\ \mathrm{W/cm^2}$. This heat flux is entirely manageable using very conventional methods of heat transfer. What makes this specific thermal management problem interesting is the other constraints: namely, the weight restriction on the iPEBB and requirement for easy insertion/removal of the iPEBB into and out of the NiPEC.

Since the use case for the iPEBB includes the requirement that it can be replaced underway by the ship's crew, the iPEBB must meet Navy standards for size and weight of individual portable components; this places a weight limit of 35 lbs. on the iPEBB. The current iPEBB design uses almost the entire available weight allocation for the electrical components and casing, making the integration of a traditional cold plate for liquid cooling or a heat sink for air cooling problematic.

Ease of insertion has been taken to mean that all connections required for the iPEBB are made up as part of the insertion and latching process; thus, cooling connections such as liquid quick-disconnects are prohibited and direct liquid cooling is eliminated as a possible solution. If this prohibition were lifted or a permanently installed leak-free quick-disconnect that is made up as part of the latching process were designed, the weight restriction on the iPEBB still remains to be solved.

One possible solution to this challenge is indirect liquid cooling. In this scenario, cold plates using de-ionized water

TABLE I
COMPARISON OF TWO-PHASE COOLING SOLUTIONS FOR IPEBB

Two-phase cooling solutions	**Advantage**	**Disadvantage/concern**
(a) Flow boiling mini channels integrated in the bottom copper layer (iPEBB cover).	No TIM, low in-plane thermal resistance, and compact coolant system.	No heat spreading (potential hot spot), two-phase instabilities.
(b) Vapor chamber replaces the bottom copper layer and cold plate is attached using TIM.	Weight reduction in the bottom copper, efficient heat spreading, and good compatibility with single-phase or two-phase cold plates.	Cooling performance dependent on the temperature distribution on the bottom copper layer and cold plate efficiency.
(c) Internally cooled vapor chamber replaces the bottom copper layer.	No TIM, both heat spreading and cooling in a compact structure.	Cooling performance limited by the through-plane thermal resistance of iPEBB substrate (ultra-low thermal conductivity of insulation).
(d) Thermal ground plane (such as thin heat pipe) directly transfers heat from the top of dies to the base layer.	Efficient heat dissipation, supplementary solution which can be applied together with other solutions.	Possible interference with electrical components (e.g., wire bonds), which requires careful design of heat pipe and electronics.

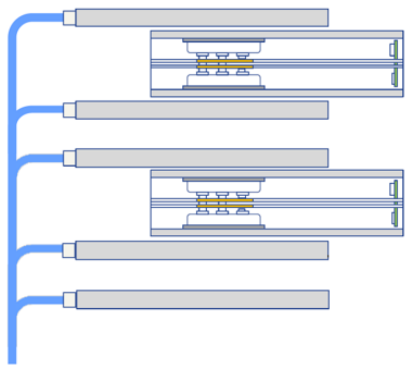

Fig. 18. In indirect cooling, the cold plates are mounted in the NiPEC structure, and the iPEBB cooling surfaces come into contact with the cold plates upon insertion of the iPEBB into the NiPEC. Thermal interface material inserted between the iPEBB and the cold plate improves heat transfer across this contact surface.

as a cooling medium are installed in the cabinet such that they contact the full top and bottom surfaces of the iPEBB. Fig. 18 conveys the concept.

The contact resistance between the iPEBB and the cold plate must be overcome. To mitigate this issue, placing a thermal interface material between the iPEBB and the cold plate improves heat transfer across the contact surface. If the thermal interface material is part of the PEBB package, it will not have to be separately installed by the sailor replacing the unit, thus keeping the training and skills required to complete maintenance minimal.

Thermal interface materials are generally employed in cases such as connecting computer chips to a heat sink; they are installed in a clean environment such as a factory, are used for relatively small-surface-area applications, and remain in place as installed for the life of the component. This application is somewhat out of the ordinary in that the thermal interface materials will be installed shipboard, are used over a large surface area, and must be amenable to installation and especially removal without disintegrating. Therefore, the desired traits of a thermal interface material for this application include high thermal conductivity under low pressure, ease of installation and removal, structural robustness, light weight, and acceptable performance under uneven loading or intrusion of small-scale grit. An investigation into thermal interface materials identified materials that fit these specifications is presented in [33].

The performance of thermal interface materials improves with increased pressure; therefore, exploration of a latching mechanism that provides pressure across the full heat transfer surface is needed.

The current assumption is that the NiPEC will operate at medium voltage, somewhere in the range of 6-18 kV. The PEBB is expected to connect to the NiPEC backplane via connectors embedded in the back surface of the PEBB. These connectors will not be bolted or welded; they will, instead, be made up as part of the PEBB insertion process and held in place by the PEBB latching mechanism. Since these connections are at a fairly high voltage and power, we assume that no flexibility is permitted in the electrical connection once the PEBB is inserted. Therefore, in order to place pressure across the thermal contact surface, the flexibility must occur in the cooling system; i.e., the cold plates will be moved away from the PEBB to allow the PEBB removal, and they will be pushed into contact with the PEBB upon insertion with sufficient pressure to promote heat transfer. Electrical contact design details can be found in [34].

One solution to the latching mechanism is a hinge-type design, shown in Fig. 19. The iPEBB is inserted horizontally and the electrical contacts, shown as round connections in the back of the iPEBB and latch, are made up as part of the insertion process. Once the electrical contacts are made up, the cold plates are rotated into contact with the iPEBB and the latch is secured. Cooling water supply and return lines are axially aligned with the hinge via a swivel joint, thus avoiding flexible hoses with their attendant inspection and maintenance burdens. A sample NiPEC section consisting of four iPEBBs inserted using the proposed latching mechanism is shown in Fig. 20. Details of the latching mechanism design are available in [35]. Significant clearance is required between iPEBBs to accommodate the swing path of the cold plates as they open and close; the latching mechanism is under re-investigation to improve power density.

VI. INTEGRATION WITH SHIP-WIDE COOLING SYSTEMS

All PEBB-level thermal management solutions discussed so far require integration with the ship-level thermal management

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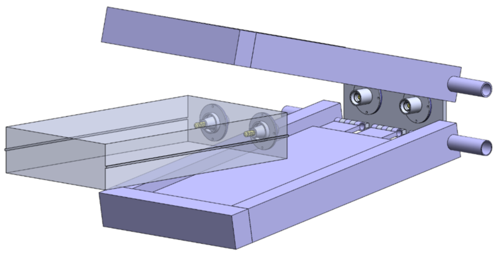

Fig. 19. Latching mechanism [35].

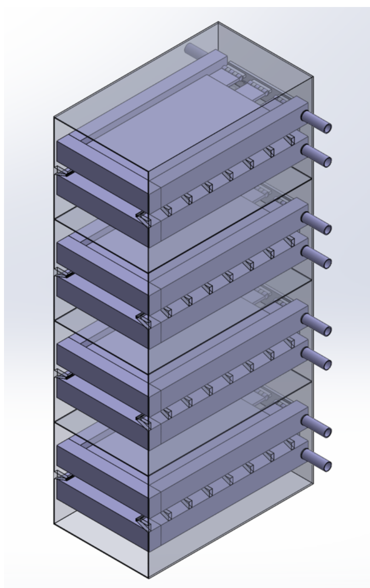

Fig. 20. A stack of four iPEBBs inserted into a NiPEC section using the proposed latching mechanism.

system. Taking advantage of the space reservations and collocation that results from the NiPEC architecture, groups of nearby PEBBs can be served by a common cooling network that can the be integrated with ship-level cooling systems.

For NiPEC arrangements, a zonal cooling scheme coinciding with ship zones is desirable. Cooling skids serving each zone will be separated by at least one watertight compartment and redundancy at the zonal level can be implemented following the same practices used for other zonal systems (e.g., dual sourcing) and provisions to enable the routing of cooling power to other two zones on same side of ship in case of loss of cooling (Figure 21). Investigations into ship-wide cooling systems providing chilled de-ionized water to NiPEC systems can be found in [36], [37]. The same considerations of space reservation that are at the core of the NiPEC concept should be applied to the cooling systems supporting the NiPEC. Enclosed dedicated spaces for NiPEC cooling skids can be reserved early in the design.

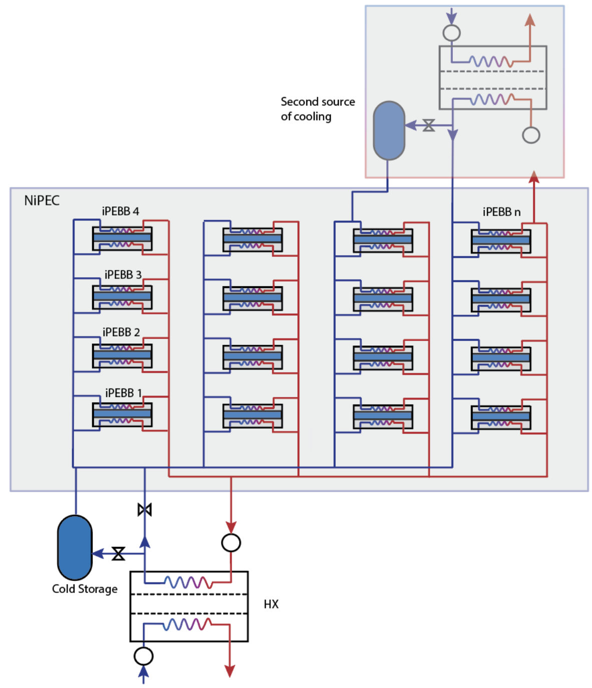

Fig. 21. Cooling network for a PEBB arrangement within NiPEC.

VII. Concluding Remarks and Future Work

Four potential methods of cooling PEBBs in a NiPEC application have been addressed: direct air cooling, single-phase direct liquid cooling, two-phase direct liquid cooling, and indirect liquid cooling; each has advantages and disadvantages. Air cooling is much more amenable to managing electrical isolation stand-off distances, but is unlikely to be able to remove sufficient heat for the application as the heat load increases, and requires significant air flow with accompanying noise and fan power. Direct single-phase liquid cooling is a well-established technology that can definitely meet the cooling needs, but a traditional serpentine-style cold plate is likely to add too much weight to the PEBB and carries the risk of placing water in close proximity to electronics. Single-phase liquid cooling using mini- or micro-channels would likely reduce the amount of water and the weight of the heat exchanger, but there may be significant pressure resistance to overcome. Single-phase liquid cooling applications with small channels embedded in the cover and targeted at the hot spots have the potential to meet the cooling requirements with acceptable weight and pressure. Two-phase cooling has the advantage of being able to remove large amounts of heat with very small amounts of liquid and with a lighter-weight heat exchanger than single-phase cooling, but this relatively new technology still needs to overcome challenges such as dry-out that bring potential reliability problems. Indirect liquid cooling can be achieved with no additional weight to the PEBB itself, but is less efficient thermally and adds significant complexity to the NiPEC cabinet structure.

Given the above scenarios, future work includes continuing the exploration of the different possibilities to mitigate the challenges inherent in them and the application of these methodologies to specific case studies to allow a direct comparison of operational, performance and other relevant metrics.

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