Power Electronic Building Block Cooling Using Two-Phase, Non-Conducting Fluid for Medium Voltage Solid State Transformers

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Abstract — Power electronic building block (PEBB) based solid state transformers (SSTs) are attractive for shipboard applications due to their power density, controllability, and modularity. However, cooling of these PEBBs presents significant technical challenges including, but not limited to, electrical isolation, low thermal resistance, and high heat flux. These issues are amplified when the SSTs reach medium voltage (MV) and mega-watt (MW) scale power levels due to the increased power losses, increased creepage and clearance distances, and module isolation ratings in the single kilovolt (kV) range.

This paper presents application specific cold plate (CP) solutions that are part of a larger, system-level, two-phase cooling system with pumped refrigerant as the working fluid. The CPs are designed to fit within a MV MW scale input-series output-parallel (ISOP) SST design where a single PEBB includes multiple, MV, high power, Silicon Carbide (SiC) MOSFET modules with varying heat loads per module, and varying isolation voltage requirements by location within the full SST. Experimental results show CP designs meet or exceed design requirements, enabling higher power building blocks to be applied to future shipboard systems.

Keywords—Medium Voltage, power electronic building blocks, cold plate, SiC MOSFET, two-phase cooling, pumped loop, non-conducting, dielectric fluid.

I. Introduction

There is increasing interest in integrating SSTs into shipboard power systems due to their high-power density, enhanced controllability, and modularity. Fig. 1 shows a representative SST configuration where the input is a medium voltage (MV) three phase AC source and the output can serve dedicated DC loads or a DC distribution bus.

The overall structure of the SST is modular, built from power electronic building blocks (PEBBs), each containing an AC/DC stage and a galvanically isolated DC/DC stage. The overall architecture considered here represents a generic input-series output-parallel (ISOP) configuration. The AC/DC stages of the PEBBs are connected in series to achieve the necessary voltage rating while the DC/DC stages are connected in parallel to achieve the required output current ratings.

A high efficiency MW scale SST has been developed that accepts a 13.8 kV, 60 Hz alternating current (AC) three-phase input, and produces a regulated 1kV direct current (DC) output. As shown in Fig. 1, the primary components of the SST are the PEBBs, which are composed of individual MV and low voltage (LV) sub-building blocks, each with isolated and independent cold plates (CPs). The custom MV and LV PEBB CPs, specifically designed for the SiC device packages being used, support multiple modules per cold plate and maintain junction temperatures below derated limits throughout all the operating states, even when heat load distribution between the modules varies significantly. The CPs are tied into the overall SST Thermal Management System (TMS), which manages system heat with a pumped two-phase (P2P), refrigerant-based cooling system. This type of system utilizes the latent heat of vaporization of the fluid to provide efficient cooling.

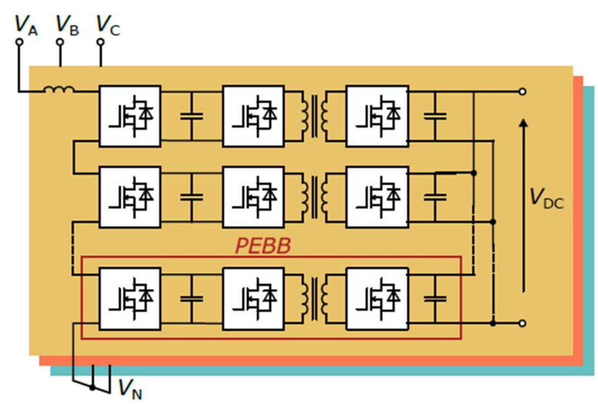

Fig. 1: ISOP SST configuration with PEBBs

II. Application Overview

A. SST System

The MV MW scale SST power conversion system accepts a 13.8 kV, 60 Hz AC three-phase input, and produces a regulated 1kVDC output. This system can be used on current and future marine platforms as either a dedicated load source converter or a generalized distribution unit providing power to low voltage direct current (LVDC) distribution buses. As shown in Fig. 1, the primary components of the SST are the PEBBs. A total of nine PEBBs are used in the example SST to meet system level interface voltage and load power requirements. The main multi-stage PEBB is composed of sub-MV and sub-LV PEBBs, as well as a medium voltage, medium frequency (MVMF) transformer (XFMR). The sub-MV PEBB utilizes 3.3 kV SiC modules, and the sub-LV PEBB utilizes 1.7 kV SiC modules. As the MV and LV PEBB CPs are designed to similar requirements, only the MV PEBB CP is discussed in this paper.

The MV PEBB can be utilized in two modes of operation within the SST, depending on its location within the SST and the multi-stage PEBB depicted in Fig. 1. The first mode is an active rectifier (AR), which is required on the 13.8 kV interface to convert the incoming AC voltage to an intermediate voltage. The second mode is operating as the primary side converter in a DC/DC dual active bridge (DAB) converter, which converts the intermediate medium voltage direct current (MVDC) bus to the regulated 1kVDC output required by the application. A photo of the MV PEBB assembly is provided in Fig. 2.

Fig. 2: MV PEBB Assembly

B. Thermal Management System

Historically, marine applications have relied on LV distribution with single phase, water-glycol liquid cooling used to good effect [1]. With increasing power demands on the ship, the current generation and next generation ships have moved to MVAC distribution at either 4160V or 13.8 kV. The PEBBs discussed herein can be utilized in either application, with the initial requirements targeting a 13.8 kV system.

One major technical challenge with MV power electronics is the ability to stay within component electrical isolation ratings and meet system level creepage and clearance requirements, while also providing a high-performance thermal system. Because of this, MV SSTs and power converters in general have target cooling systems that either eliminate cooling fluids or adopt non-conductive cooling fluids such as de-ionized water (DI water). Multiple factors including, freeze point, corrosivity limits on materials and the infrastructure needed to remove and maintain ions [1,5] preclude the use of DI water in this application. A number of viable working fluids exist [2][3][4][5][6], but for this P2P TMS, R134a refrigerant was selected due to its ready availability and prior approval for marine applications. A primary feature of the working fluid is the dielectric nature of the refrigerant, which, when coupled with the use of non-conductive hoses, provides over 30 kV of electrical isolation. Given 13.8 kV electrical creepage requirements dictate a minimum 9-inch hose length, non-conducting hoses will have less than 13 microamps of leakage current in all cases.

The CPs are electrically insulated from ground to enable the module voltage rating to meet operational requirements. Numerous protective features, including PEBB redundancy, aid in avoiding catastrophic failure modes. The dielectric fluid precludes a parallel path to ground through the TMS, and the induction of high frequency current noise via capacitive coupling of the switching devices between PEBBs and ground is also eliminated. The choice of a dielectric refrigerant provides a critical benefit to the overall design of the SST.

A P2P TMS utilizes both the liquid and vapor phases of the working fluid in the CP. When heat from the SiC components is transferred to the refrigerant, that energy causes some of the liquid to evaporate. By utilizing this latent heat of vaporization, the working fluid can hold large amounts of thermal energy in a relatively small quantity of fluid. Unlike single phase liquid-cooling, where the thermal energy increases the temperature of the fluid, the boiling refrigerant maintains a uniform temperature throughout the heat input area. The life and reliability benefit to reduced junction temperature variation is an added benefit. Additionally, convective heat transfer coefficients for an evaporative flow can be an order of magnitude higher than those of liquid cooling with a similar mass flow. These three qualities of two-phase cooling (high heat capacity, isothermal heat transfer, and high heat transfer coefficients), all contribute to P2P's ability to provide the required cooling with greatly reduced flow rates as compared to single-phase cooling. The fluid mass flow rate within a P2P system is typically less than half of that with water cooling, yielding smaller pumps and reduced plumbing sizes [2][3][4].

The TMS (Fig. 3) is designed not only to cool the PEBBs but also to manage heat dissipated by all the components in the SST. These heat sources include many different types (e.g., magnetics, resistors, semiconductor modules, power supplies, control electronics, etc.) each with different thermal requirements. Heat is absorbed by cold plates in direct contact with components or through liquid-to-air heat exchangers that keep the air within the cabinet cool. With more than forty-six parallel flow paths, flow management is an important design feature of the TMS, ensuring proper distribution of coolant flow to each of the heat loads.

The two-phase flow leaving the CPs and liquid-to-air heat exchangers is condensed back to liquid in the condensing heat exchanger, which is cooled by facility chilled water (CW). CW serves as the ultimate heat sink of the P2P system and provides a lower limit to the temperatures which the P2P can achieve. Despite using refrigerant as a working fluid, P2P is not a refrigeration cycle and therefore moves heat only in the natural direction of hot to cold. The first law of thermodynamics indicates that moving heat from a colder source to a hotter sink is possible only when doing work on the fluid, typically in the form of compression, which requires a large energy input. The pump in the P2P simply provides a motive force to overcome losses, thus requiring significantly less energy input to manage waste heat.

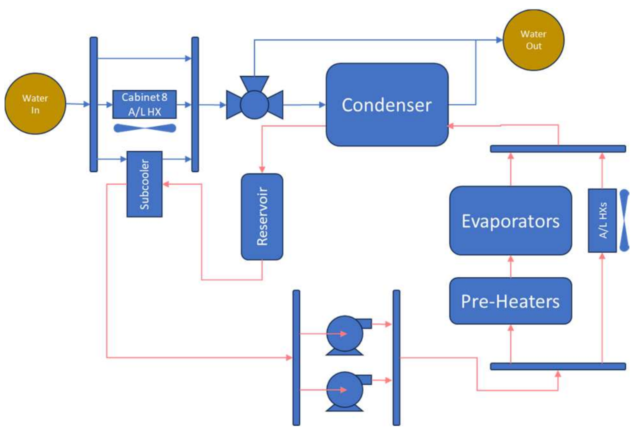

Fig. 3: SST System TMS Fluid Flow Schematic

A variety of other components are included in the balance-of-plant of the P2P TMS including redundant pumps, a reservoir and sub-cooler to protect the pumps from cavitation, a control valve on the facility water, and various sensors throughout for dynamic control and health monitoring. With all of the components and controls of the TMS in place, the working fluid is continually circulated and the heat collected in the evaporators is rejected to the CW in the condenser and sub-cooling heat exchanger. The temperature and pressure of the refrigerant being supplied to CPs is regulated and the CPs are electrically isolated from any shorts to ground.

III. Cold Plate Design and Test

A. MV PEBB Cold Plate Design

The custom MV CPs (Fig. 4), specifically designed for the LV100 industry standard device package, supports multiple packages per cold plate.

The power modules are the key component of this SST architecture, and they dissipate the highest heat loads. CPs are, therefore, specifically designed for these components. Similar to the cooling system as a whole, the CPs contain a significant number of parallel paths to ensure flow is distributed evenly across the whole heat input area. Parallel paths reduce the pressure loss as compared to a single serpentine path. Compared to a simply wide-open flow channel, parallel paths provide internal structures that conduct heat to a larger surface area of fluid as well as mechanically support the CP against the internal pressure of the fluid pushing outwards.

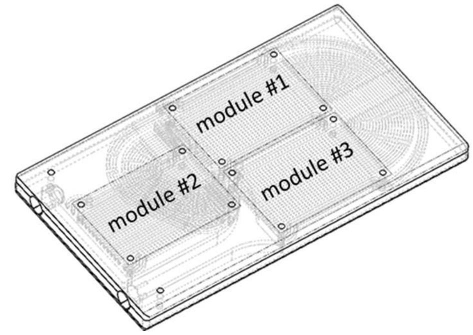

Fig. 4: MV PEBB SiC MOSFET Layout

The heat load from each module on an MV CP is not the same, and furthermore it may vary in different modes, where in one mode module #1 has a larger heat load, while in another mode module #2 or module #3 may have the larger heat load. Heat loads are calculated based on detailed numerical electro-thermal device models, based on double pulse testing of the SiC modules themselves. Worst case heat loads under worst care operating conditions are used. Table 1 shows the power dissipation from each module for four such modes, High Power (450 kW per PEBB) and Low Power (200 kW per PEBB), AR and DAB. If each module had its own flow channels in parallel with the other modules, then more flow would be needed for the channels cooling the modules with higher heat dissipations. To accommodate these different modes within the same parallel cooling design would require active modulation of the flow distribution. To avoid such complexities, the channels are instead arranged to traverse each module in series thereby picking up nearly identical heat loads in each channel. The spacing of the SiC modules is set by electrical performance constraints including creepage and clearance, minimizing overall loop inductance, and system level packaging, so achieving series flow for every channel requires utilizing three dimensions and looping some channels below others.

Table 1*:* STEADY STATE COLD PLATE PERFORMACE OVER VARIOUS OPERATIONAL MODES

Case Name	Module #1 Power (W)	Module #2 Power (W)	Module #3 Power (W)	Mass Flow Rate (kg/min)
Low Power AR	55	652	55	0.508
Low Power DAB	649	462	450	1.042
High Power AR	804	1641	803	2.166
High Power DAB	1060	782	490	1.554

To uniformly distribute flow between the channels, the effective pressure drop, or flow resistance, of each path must be matched as closely as possible. One primary driver of pressure drop is the velocity of the fluid. Even though conservation of mass dictates that the mass flow rate is constant from the inlet to outlet of a channel, the working fluid accelerates as heat is added to it because of the density change from liquid to vapor. The first objective in uniformly distributing flow is already accomplished by ensuring that each parallel channel receives a similar amount of heat input and thereby accelerates to similar velocities, causing similar pressure drops. Many other geometric factors affect pressure losses, including flow length, channel cross-sectional profile, and the radius and number of bends and turns. These cannot all be exactly matched, but creative design effort is applied to approximate them, so that differences are small relative to the total flow resistance of the channels. To further minimize the relative differences between channels, the total flow resistance of each channel is artificially increased by means of a static flow restriction at the inlet. Computational Fluid Dynamics (CFD) simulations accounting for accelerational pressure drop (Fig. 5 and Fig. 6) provide a means for verifying adequate flow balancing. These analyses are performed using Autodesk CFD software, which while it does not provide a means for modeling the interactions between liquid and vapor, it does allow for the effective density of the fluid to be varied along the flow path. Standard k-ε turbulence models are applied, while the mesh contains five rows of boundary layer elements along every solid wall interface.

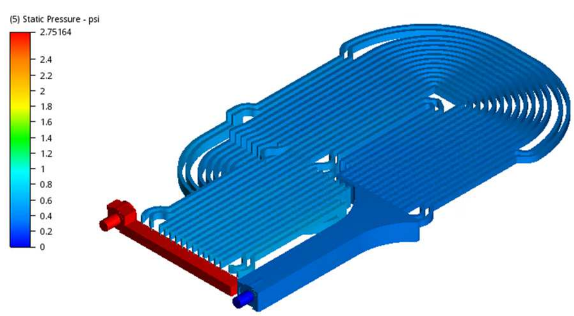

Fig. 5: MV PEBB Cold Plate Cooling Channel Pressure Drop at Rated Flow

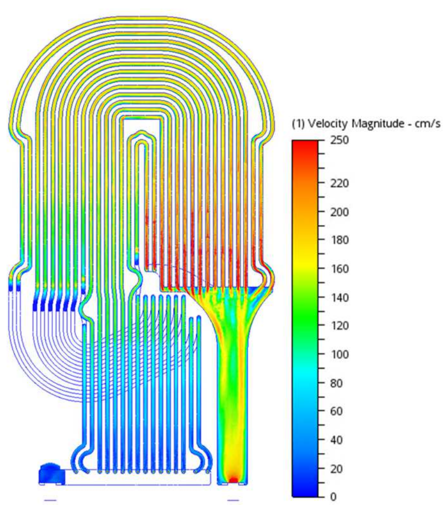

Fig. 6: Fluid Velocity Contours in the MV PEBB Coldplate, Illustrating Acceleration in the Channels

The channel profiles are designed for increasing surface area to aid in heat transfer, but also to achieve particular two-phase flow regimes. A stratified flow regime is to be avoided, as this leads to liquid separating from the vapor within the cold plate and when the heat input is on the top of the plate, thermal energy will have to conduct through the low-density vapor in order to reach the liquid which readily absorbs the heat in the form of phase change. One metric for ensuring stratification does not occur is the Froude number, a non-dimensional number which represents the ratio of momentum forces to body forces in the fluid. When the Froude number is above a critical threshold, the momentum of the fluid dominates the gravitational forces that would cause stratification.

Proprietary analytical correlations are utilized during the design process to predict cold plate surface temperatures based on refrigerant flow, channel geometry, and applied heat flux. These predictions are compared to experimental results in the next section.

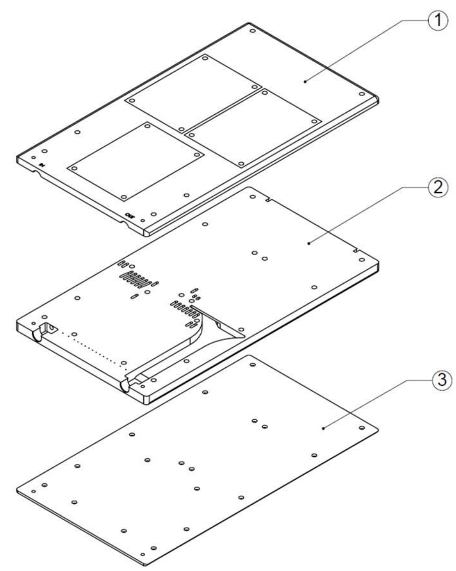

Fig. 7: Exploded View of MV Cold Plate Brazement

Fig. 8: Finished MV CP Hardware

The CPs were fabricated by vacuum brazing three aluminum plates (Fig. 7). Each plate is machined with the appropriate internal geometry prior to brazing. A sheet of braze foil over each of the interfaces ensures that the cold plate is not only hermetically sealed, but also that the internal walls are securely attached to the next plate and are providing structural support to withstand the relatively high internal pressures. The CPs, shown in Fig. 8, are proof-pressure tested to contain up to 500 psi and maintain 0.001-inch flatness across the areas where the modules are mounted.

B. *MV PEBB Cold Plate Testing*

Five of the MV PEBB CPs were selected from the first fabrication run and were subjected to thermal testing. These five units are identified by their serial numbers (SN) 13 through 17 in the results shown in Fig. 11 through Fig. 15. Advanced Cooling Technologies (ACT)'s P2P testing facility served as the balance-of-plant of the TMS, cooling the R134a to the correct temperature and pumping the liquid to a single cold plate at the appropriate flow rate.

Heater blocks fabricated from aluminum and containing embedded resistive cartridge heaters are utilized to simulate the heat loads from the modules. A thermocouple is also embedded on the bottom surface of the heater block which measures the interface surface temperature, representing the case temperature of the module. Module manufacturers publish junction-to-case thermal resistances, allowing junction temperatures to be calculated from case temperature measurements if the thermal dissipation is known.

Four power loading cases were tested. In all four cases the refrigerant was supplied to the cold plates at 25°C with the pressure controlling the saturation pressure at 27.5°C. Flow rate was set differently for each case such that the outlet quality should be 50% vapor by mass. The nominal conditions of the four cases are detailed in Table 1.

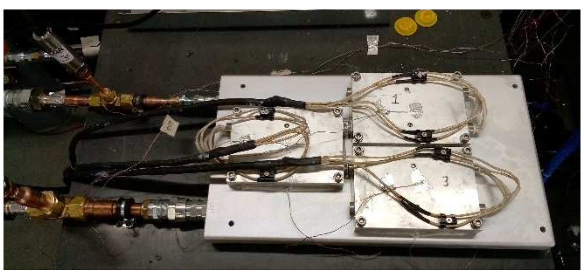

Fig. 9: Assembled MV Cold Plate Test Setup with Heater Blocks

Fig. 10: Insulated MV Cold Plate Test Setup

The heater blocks are attached to cold plates with four M6 bolts torqued to 70 in-lbs (Fig. 9). A layer of AOS 340 LR, non-silicone thermal grease (1.3 W/m*K thermal conductivity) is applied between the heater blocks and the CP with a bondline thickness less than 0.0003 inches.

To prevent significant heat loss to ambient the MV CP was insulated with standard 1-inch, black polyethylene, closed-cell foam insulation (Fig. 10). The insulation has a melting temperature of 120°C and thermal conductivity of only 0.04 W/m*K.

A total of twelve data channels were recorded during the testing. Three watt transducers measured the power being applied to each heater module. A Coriolis flow meter measured refrigerant mass flow rate. Three T-type thermocouples measured the case temperature of each module. Two pressure transducers measured the static fluid pressure at the inlet and outlet of the cold plate. Three more T-type thermocouples measured the inlet and outlet fluid temperatures as well as the ambient air temperature.

For each of the five cold plates, the module heater powers and refrigerant flow rate was adjusted to match the first case and the system was allowed to come to steady state, where temperatures and pressures were not changing. Data was recorded from all 12 data channels every 2.5 seconds. A five minute sample during the steady-state operation was averaged in order to obtain the results presented here. Variations in module temperatures follow the trends expected, with higher power modules showing higher case temperatures. All five MV CPs tested show similar performance, with variations between MV CPs being less than 2.5°C even in the highest heat flux case.

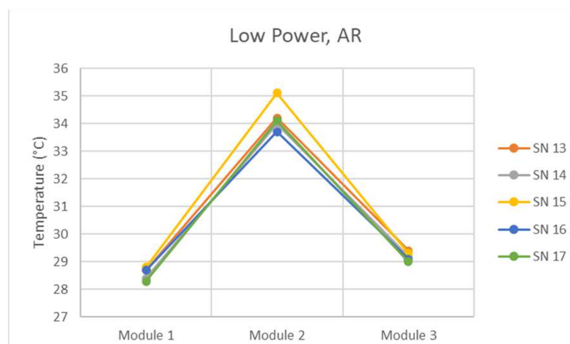

Fig. 11: SiC Module Case Temperature Results for Low Power AR

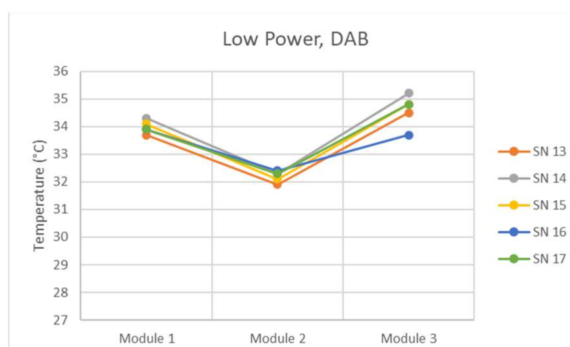

Fig. 12: SiC Module Case Temperature Results for Low Power DAB

Analytical predictions were calculated only for the High Power cases (Fig. 13 & Fig. 14), since these were the cases driving the MV CP design. Those predictions are plotted with the testing results and demonstrate that ACT's models are conservative, overpredicting the temperatures of the modules. The thermal performance of the cold plates was better than expected.

Fig. 13: SiC Module Case Temperature Results for High Power AR

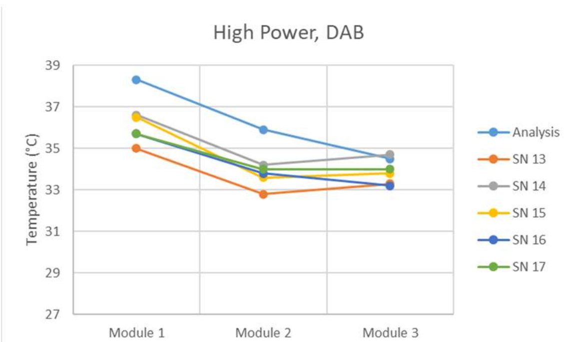

Fig. 14: SiC Module Case Temperature Results for High Power DAB

The difference between the inlet pressure to the outlet pressure gives the total pressure drop of the MV CP. As expected, the pressure drop increases exponentially with the flow rate. The analytical pressure drop was calculated only for the highest flow rate case and included only the channels and manifolding within the MV CP. The pressure transducers were located beyond the dry-break quick-disconnect fittings and a few inches of copper tubing as can be seen on the left side of Fig. 9 and Fig. 10. The added pressure drops of those fittings likely accounts for the underprediction of the analysis (Fig. 15). It is hypothesized that the extra high pressure drop of SN 15 is may be due to one of these dry-break fittings not being fully engaged and causing excess pressure loss. It should be noted that the higher pressure drop of SN 15 did not noticeably affect the thermal performance of that CP, and the pressure drop did not exceed any limits of the system.

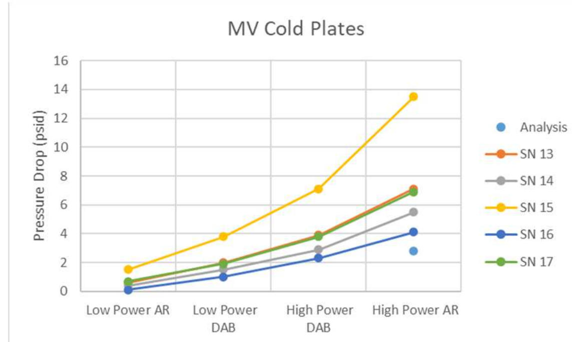

Fig. 15: MV Cold Plate Pressure Drop Results for All Cases

IV. Conclusion

This paper presented the design, build, and test of a custom high performance CP for a MV PEBB. This PEBB is utilized in a MV SST application requiring a combination of high thermal performance and superior electrical isolating properties. Multiple CPs were built and tested using simulated heat sources. Details of CP performance at multiple test cases compared favorably with design goals and successfully met all requirements.

Future work includes integrating the MV and LV PEBBs with the high performance CPs into production hardware for in-application testing.

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