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Impact of SprayCool® Cooling Technology Applied to Power Electronics on Shipboard Cooling System Infrastructure

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Abstract:

The application of SprayCool® technology to the Next Generation Integrated Power System (NGIPS) is expected to demonstrate significant savings in SWaP and power throughput enabling the technology necessary to achieve the NGIPS. Preliminary test results have shown a 30% reduction in space, 70% reduction in weight and a 4X increase in power throughput. Removing the dissipated heat directly from the surface of the power electronics module by means of 2-phase SprayCool latent heat of evaporation increases the efficiency of cooling, reduces surface temperature gradients, and reduces system temperatures below that of other cooling methods. The increased cooling efficiencies will enable new ship design paradigms, reducing life cycle costs, and enabling new technology insertion.

Keywords: SprayCool, thermal management, ship cooling infrastructure, power electronics

Background: The Next Generation Integrated Power System (NGIPS) Technology Development Roadmap, Doerry (2007) cites an Open Architecture business model as the enterprise approach to enabling designated System Integrators and small business developers to provide the best technical solution at reduced cost to the navy. The ability to enable the use of commercially available power electronic module systems off the shelf and easily insert them into the shipboard environment without added ruggedization costs is an objective of the open architecture approach. SprayCool technology enables commercial grade systems of higher power density in harsh operating environments.

The NGIPS Technology Development Roadmap sites three power architectures, Doerry (2007):

- Medium Voltage AC Power (Emphasize Affordability) - 6.9 KVAC, 13.8 KVAC
- High Frequency AC Power (Near Term - Emphasize Power Density)

- Medium Voltage DC Power (Goal - Emphasize Power Density) - up to 10 KVDC

SprayCool technology can enable developers in all three of these areas to achieve increased power density and more efficient thermal management at the component and system level.

For Ship Service electrical loads, zonal distribution is also added and SprayCool can enable advances in this area as well. Traditional transformers are used to convert MVAC to 450VAC distributions.

The high power density solutions are targeting small combatant, service ships, and submarines where power density has a large impact on ship design.

The benefits of Integrated Power Systems are cited by Ashton et al. (2005) as:

- Improved ship layouts
- shorter engine rooms
- redundancy
- lower installed power
- improved control
- reduced fuel consumption
- lower construction costs

To achieve these improvements and afford the new systems from the NGIPS spiral design, Ashton et al. (2005), state that "the infra-structure needs to be modular and allow easy technology insertions"

The DDG1000 is in the first stages of the transition to an all electric ship. It will be the first to be challenged to integrate electric drive (~80 MW) with other installed shipboard electric loads. The efficiency, power density, and thermal management of these systems will have a large impact on the infra-structure design and cost of the ship systems. Ashton et al. (2005), state that "An increase in efficiency as small as 1% can save over 1MW of increased thermal, acoustic, and electromagnetic signature. Moreover, improved efficiency decreases the thermal and mechanical stresses of the equipment, resulting in increased equipment up-time and decreased maintenance."

Money et al. (2000) in a study of lessons learned from the commercial market states "It is a fact that for many of the technologies that are critical to military systems, the commercial marketplace - and not the DoD (Department of Defense) - now drives the pace of innovation and development..... Simply put, if the DOD intends to field state-of-the-art systems in a cost-effective manner, then it must incorporate commercial items into these systems."

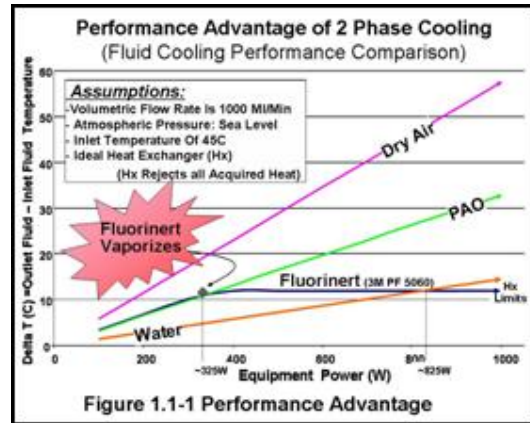
Ashton et al. (2005) predict a commercial market trend towards COTS High Power Electronic Modules, and evaluates a given HPEM configuration for

shipboard application. There are many benefits that can be gained by the Navy leveraging commercial power electronic building blocks in ship design.

SprayCool technology enables an improvement in the efficiency, reliability, and ease of fielding commercial HPEM in shipboard design when compared to conventional cooling technology.

Brief description of technology:

Removing the dissipated heat directly from the surface of the power electronics module by means of 2-phase SprayCool latent heat of evaporation increases the efficiency of cooling, reduces surface temperature gradients, and reduces system temperatures below that of other cooling methods. (Figure 1.1-1)



SprayCool technology utilizes evaporative, or spray cooling, in which liquid droplets are sprayed directly onto the hot electronic components, then evaporates to remove excess heat. The hot vapor is transported to a remote heat exchanger where the waste heat is rejected and the vapor condensed back into a liquid. Thus, the fluid is continuously recycled for reuse within a closed cycle system. The heat exchanger can reject to any medium, but it is assumed for this paper that the heat exchanger is liquid to liquid with the heat rejected to the ships cooling water or sea water systems. (Figure 1.1-2)

SprayCool uses Fluorinert® by 3M as the primary working fluid. Fluorinert is an electrically insulating, inert perfluorocarbon fluid which is used mainly for cooling electronics. Other fluids including water mixtures can also be used in indirect spray applications.

SprayCool technology enables all surfaces exposed to the dielectric liquid/vapor environment to remain very close to the saturation temperature of the fluid, resulting in an “isothermal” environment around the electronics. This isothermal environment effectively reduces hot spots and thermal cycling, as well as providing increased cooling efficiency.

The result of reduced thermal mechanical stresses and lower operating temperatures, compared to other cooling methodologies, is increased reliability and higher achievable power density. SprayCool therefore plays a pivotal role in the design of high reliability, high performance power electronics systems.

In other applications of SprayCool technology significant Space Weight, and Power (SWaP) improvements have been demonstrated. The paper will demonstrate the basis of these claims and show that SprayCool can provide

benefits to the ship design process by improved thermal performance, higher power throughput, and reduced cooling infrastructure.

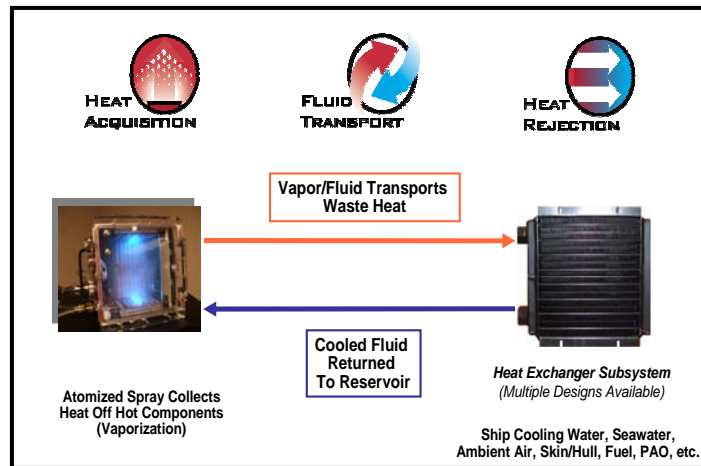


Figure 1.1-2 SprayCool Process

Fluid Testing for approval: Testing was done at the University of Idaho by SprayCool to test for decomposition products at elevated temperatures in Submarine Burners with the Carulite catalyst material. The catalyst material was provided by Mr. Alan McCarrick at NAVSEA Philadelphia. The test plan was coordinated with and reviewed by Mr. Alan McCarrick, NAVSEA Philadelphia Division and Mr. Rich Hagar NAVSEA 05Z. The test results were presented to NAVSEA 05 and approval was requested for use of FC-72 Fluorinert on ships and submarines. Fluorinert has received approval from NAVSEA 05Z, Mr. Rich Hagar, for utilization in surface ship applications. Approval for use on submarines is awaiting the setting of exposure limits by the Navy Environmental Health Lab.

The report provided to NAVSEA was accompanied by spectra demonstrating the accuracy of the findings of the report. Difference spectra between before entering the catalyst and after the catalyst were used to search for PFIB bands and other decomposition products.

The test was conducted to assess the impact of Fluorinert gases passing through the atmospheric burner on submarine classes. This was the major concern for approval of the fluids on submarines.

Stainless steel was used for all components in the test setup, and the following conditions were met:

- All tests were conducted in the absence and presence of FC-72 vapor
- The following residence times were used.
 - Residence time of 0.18s used for dry air and humid air

density semiconductor components and can be a limiting factor in many high density system packages.

2. Liquid Cooling - A coldplate designed for a single phase fluid is attached to the base plate of the module. A mixture of Ethylene Glycol and water is the most common fluid used for liquid cooling. The excess heat from the module is transferred to the fluid in the coldplate and ultimately transferred to the ambient environment. Liquid cooling offers a reduced package size, acoustically quieter and increased semiconductor life over air cooling.

Depending on the application either approach to cooling is effective to a degree. Both approaches have been proven in military conditions; however, both are large and heavy.

How SprayCool technology can be applied to power electronics cooling:

There are three ways to SprayCool power electronics modules:

1. Baseplate Direct Spray Cooling - A spray plate designed for Fluorinert fluid is attached to the base plate of the power electronics module. The excess heat from the module is transferred to the Fluorinert from the base plate and ultimately transferred to the cooling water or ambient environment. Cooling with Fluorinert offers the advantages of liquid cooling with the additional benefit of smaller system components and the safety of using a nonconductive fluid in the event of a leak.

2. Encasement of a Standard IGBT Module - An enclosure is designed around a "standard" IGBT or power electronics module (no encapsulant or cover) and SprayCool technology is applied to both the top and baseplate of the module. The excess heat from the module is transferred to the Fluorinert fluid in the enclosure and transferred to the ships cooling water via a heat exchanger or the ambient environment via a condenser. This method of cooling power electronics is more effective, smaller and lighter than current cooling methods.

3. SprayCool Custom Package - A custom package designed to allow both sides of a bare IGBT or power electronics device to be sprayed with Fluorinert fluid using SprayCool technology. The excess heat from the both sides of the die is transferred to the Fluorinert in a sealed enclosure and transferred to the ambient environment via a condenser. This is the best method of cooling power electronics; it is the most effective, smallest and lightest of all cooling methods.

SprayCool technology is smaller and lighter than conventional cooling methods, and offers additional benefits of rejecting to higher temperature water. It also allows the elimination or reduction of air handlers and chill water systems. Advanced methods of SprayCool cooling of power electronics have also been

shown to improve electrical performance, while reducing temperature cycling -
 - resulting in substantial improvements in reliability.

Space Weight and Power (SWaP) comparison between cooling methodologies: A comparison was done utilizing a Semikron SEMIX 553GB128D with it's standard air cooling and liquid cooling cold plate options compared to the SprayCool encapsulated Global solution with the same IGBT. The results are showing in Table 2.

mm/in = 25.4		IGBT Cooling Volume and Weight Comparison												
Date	1-Aug-08													
Item	Device	Cooling	Function	Applications	Number of IGBT circuits	Volts (V)	Current (Amps)	Power (W)	Length (Inch)	Width (inch)	Height (inch)	Volume (cuin)	Weight (lbs)	Power/Volume (W/cuin)
1	Semikron SEMIX 553GB128D	Air	Power Module	AC Inverter Drives UPS Electronic Welders	2 IGBT 1 diode	1200	540	648000	5.89	2.40	0.67	9.46	0.64	
	P16 Heatsink	Air							8.46	4.72	3.03	121.23	10.30	
	Fan part1	Air							7.01	5.91	7.19	297.35		
	Fan part 2	Air							2.36	8.50	2.99	60.11	7.94	
	Total SEMIX Air											486.15	18.88	1327
2	Semikron SEMIX 553GB128D	Liquid	Power Module	AC Inverter Drives UPS Electronic Welders	2 IGBT 1 diode	1200	540	648000	5.89	2.40	0.67	9.46	0.64	
	WP16 Cold Plate	Liquid							8.46	2.62	0.79	17.49	4.85	
	Total SEMIX Cold Plate										1.46	26.95	5.49	24041
3	Semikron SEMIX 553GB128D	SprayCool	Power Module	AC Inverter Drives UPS Electronic Welders	2 IGBT 1 diode	1200	540	648000	*inside enclosure	*	*	*	0.46	
	SprayCool	SprayCool	Enclosure						5.30	2.50	1.20	15.90	1.00	
	Total SEMIX SprayCool											15.90	1.46	40755
SprayCool vs Air Cooled											% Reduction over Air	96.74	92.27	
SprayCool vs Liquid Cold Plate											% Reduction over cold plate	41.01	73.41	

Table 2: SWaP Comparison SprayCool to Air/Liquid

The comparison shows a space and weight reduction of 41% and 73% compared to the liquid cooled cold plate solution. The power density is doubled. When compared to the air cooled case the space and weight reduction is over 90% and the power density is increased by a factor of 40.

A comparison has not been done at the cooling system level since adequate data was not available. However, it is expected that the savings at the system level will be much larger due to SprayCool technology enabling the elimination of air handlers and reduction in size requirements on the chill water system.

Range and limitations of specific NGIPS applications: SprayCool technology is applicable over a wide range of voltages and power conditions. The 3M published dielectric breakdown for the PF5060 Fluorinert fluid is 30 to 40 KV at a 0.1 inch gap. The fluid should be suitable for the projected 13 KV for NGIPS projected applications.

SprayCool has been demonstrated for low power UPS applications and low power electronics to medium power IGBTs. The technology can theoretically be applied to high power motor drives, but has not been demonstrated in this area.

Report of previous and ongoing testing:

Previous IGBT testing - A proof of concept SprayCool three phase demonstration IGBT was developed and tested.(Figure 1.1-3) The SprayCool three phase IGBT had all three phases on a single board compared to the air cooled version which required three boards, a board for each phase. The SprayCool technology enables minimization of power electronics foot print for greater performance. The solution utilized a Global Spray Solution where heat is exchanged with a dielectric liquid sprayed directly onto the hot surfaces. This is more efficient than air cooling and has less thermal resistance boundaries. With the improved efficiency of 2 phase SprayCool technology the component surfaces are kept in isothermal conditions.


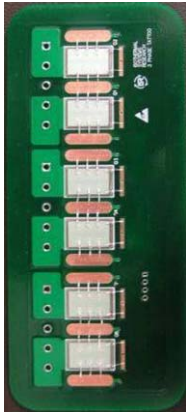
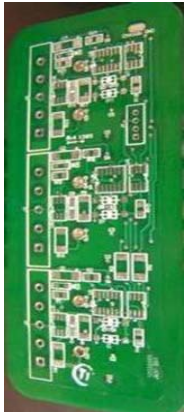
Air vs. SprayCool Comparison		
<ul style="list-style-type: none"> Air-Cooled Single Phase Board 	<ul style="list-style-type: none"> SprayCool Three Phase PCB Board 	
		
<ul style="list-style-type: none"> Requires Three Boards for a Three Phase Circuit Area for Three Phase = 16.4 in² Weight for Three Phase = 6.3oz Thermal Limit at 10 amps 	<ul style="list-style-type: none"> Area = 11.6 in², 30 % Reduction Weight = 2.1oz, 67 % Reduction Thermal Limit at 40 amps, 4 X Increase in Throughput Power 	

Figure 1.1-3 Air vs. SprayCool IGBT comparison

The isothermal conditions keep the components at a near constant temperature eliminating thermal cycling and the associated thermal stresses. As a result the component junction temperature is lower with SprayCool than air cooling. The power handled in this demonstration was 1250 W. The power that could be demonstrated is expected to be 2KW in a single IGBT.

The following benefits were demonstrated:

- Deliver 4 X Power Throughput
- Acquires 100% of the power switching node heat directly to liquid
- reduces shipboard air flow demands
- Improves energy efficiency
- Reduces size and weight (30%, 67%)

Transformer testing - In another power electronics demonstration, two 600 W transformers in a 3U UPS chassis were cooled utilizing SprayCool technology. The transformers were not optimized for SprayCool, but were sprayed in an off-the-shelf configuration. Further improvements could be achieved if the transformer was designed to take advantage of the SprayCool efficiencies. In the air cooled case the heat was rejected to 25C air and reached a maximum temperature of 70 C before the test was secured due to concern for the transformer. In the SprayCool case the heat was rejected to two different temperatures of fluid 43 C and 53 C. Both kept the temperature of the transformers at lower temperature than air out to 1800 W. See the plot in figure 1.1-4.

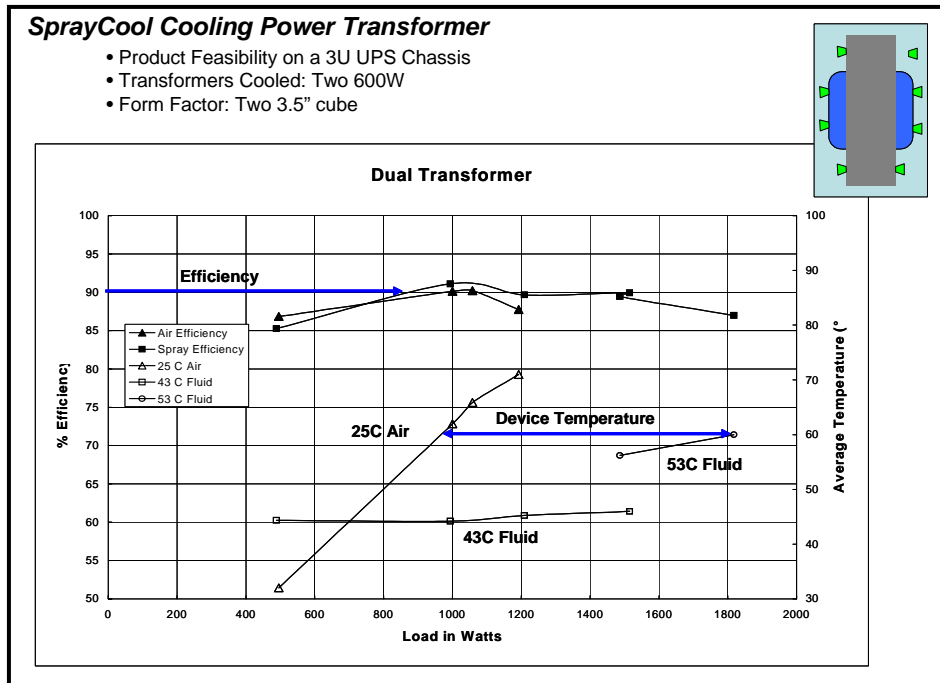


Figure 1.1-4 SprayCool Power Transformers

The following benefits were demonstrated:

- Increased power delivered from 1200 W air cooled to 1800 W SprayCool
- Maintained efficiency to higher power load
- Reduced temperature compared to air cooled

Current work - SprayCool is currently exploring a couple of potential applications of SprayCool technology to power electronics. The target applications include shipboard as well as ground vehicle applications. Thermal imaging is used to determine the hot spots on the IGBT or power electronic module which is then used to determine the spray pattern density needed.

Each IGBT is sprayed in multiple locations targeting the hot spots, and using vapor entrainment techniques to maximize the heat transfer coefficients while minimizing flow.

Future work includes complete characterization of the SprayModule and the development of an attitude-independent thermal management unit (TMU) that



is size-appropriate to the applications. The TMU contains a reservoir, pumps, liquid to liquid heat exchanger, and controller. Current testing uses a TMU designed for higher heat loads and lower vapor qualities.

The current TMU is shown in figure 1.1-5. The results of this testing is ongoing and will be reported in the future.

Figure 1.1-5 Thermal Management Unit (TMU) used for Testing

Impact on shipboard cooling infrastructure: The benefit of SprayCool efficiencies applied to shipboard cooling infrastructure design has set the stage for a shift in design paradigm. SprayCool has demonstrated in shore based high performance data centers the ability to bypass air handlers and chillers and reject the heat directly to the cooling tower at water temperatures of 35 - 50 C. This can be applied to the shipboard application by enabling the bypass of air handlers and chillers. SprayCool can reject either directly to salt water or to a non chilled fresh water loop. Studies done for the application of SprayCool to topside radar arrays has shown that with the replacement of ethylene-glycol water loops topside by Fluorinert loops, the piping and pumping size can be reduced by a factor of four (4).

An analysis done for the Electronic Module Enclosure on the DDG1000 estimated that with spot cooled SprayCool solutions in the computing equipment from 35 - 50 % of the heat could be removed directly to SprayCool and rejected

downstream of the air handlers significantly reducing the demand on the HVAC system and thus restoring margin to the system for other applications. If globally sprayed solutions were adopted, all of the heat could be rejected to non-chill water systems. This would reduce demand on chillers freeing them up for more critical applications.

A similar study has not been done for power electronics, but is needed. In principal these same gains can be achieved on these systems as well.

Conclusions and Recommendations: The application of SprayCool technology to the Next Generation Integrated Power System (NGIPS) is expected to demonstrate significant savings in SWaP and power throughput enabling the technology necessary to achieve the NGIPS. Preliminary test results have shown a 30% reduction in space, 70% reduction in weight and a 4X increase in power throughput. The increased cooling efficiencies will enable new ship design paradigms, reducing life cycle costs, and enabling new technology insertion.

SprayCool technology has demonstrated the ability to reject heat to 35 - 45 C water. This will eliminate the need for the utilization of chill water systems for electronics liquid cooling. Additionally, replacing air cooling with liquid cooling reduces the load on air handling systems. These benefits will allow the elimination of air handlers and chillers or an increase in margin on cooling systems. Utilizing Fluorinert for cooling of topside locations will remove the need for ethylene-glycol cooling loops and reduce the size of pipes and pumps utilized for this purpose.

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