Heat-Transfer Advances for Submerged Oceanographic Systems

Glenn McDonald, Matt Naiman, Applied Ocean Physics and Engineering

Woods Hole Oceanographic Institution
86 Water Street
Woods Hole, MA 02543
e-mail: gmcdonald@whoi.edu
mnaiman@whoi.edu

Abstract—This paper outlines various heat-transfer methods utilizing modern fabrication techniques in conjunction with computer modeling to provide low-risk alternatives for thermal management. It presents details of a particular heat pipe configuration capable of dissipating 400 watts through a 9 1/2-inch diameter, 2-inch-thick grade 5 titanium endcap. Traditional dry contact methods, liquid cooling, and improved geometry are also discussed.

The amount of power delivered to cabled systems is on the rise. As all-electric ROVs, manned submersibles, and high-powered cabled seafloor observatories come on line, inevitable inefficiencies mean that these systems must dissipate more heat.

The rationale for this effort is multifaceted. Excessive heat is the enemy of solid-state electronics. It affects component longevity and efficiency in addition to introducing undesired drift in instrumentation. Increased component density is creating more heat per volume. Additionally, power conversion modules and improved motor drives are decreasing in form factor and providing less area for heat dissipation.

New and improved heat-transfer methods will facilitate a greater selection of appropriate pressure case materials. Titanium, stainless steel, plastics, and ceramics should not be disallowed because they limit heat transfer. Trends in electronic components and material selection can continue to improve system design without compromising overall heat transfer. Thermal engineering needs to be part of the system integration at the onset of a project's design.

I. INTRODUCTION

Cooling and thermal issues of oceanographic systems need to be addressed at this time because of the greater cooling demands of power and telemetry electronics accompanying larger, more capable, all-electric ROVs and cabled sea-floor observatories. Efficiencies of power-conversion devices have improved along with their reduced space requirements; however, the overall heat load per unit volume has increased dramatically. In essence, much more is being asked of the same contained volume and available surface area—to remove the heat evolved from packages with markedly improved performance. Failing to remove sufficient heat reduces component longevity and efficiency in addition to creating undesired drift in instrumentation [1].

Although not directly pertinent to AUVs and other low-power battery-based instrument platforms, this heat-transfer topic may be relevant to their "on-deck" or in-the-lab pre-deployment servicing and testing. The heat generated during the charge cycle of battery-powered gear is one such instance.

The goal of this article is to discuss current heat-transfer methods—including technologies that have been applied to recently fielded systems. Attention will be given to analytic design tools and testing methods. Additionally, material considerations and fabrication will be briefly discussed.

II. METHODS AND GEOMETRIES

It is important to emphasize that for all methods being discussed, each has its own advantages and disadvantages. It is key to carefully choose and properly apply each of these techniques to address cooling needs of any given system.

A. Dry-Contract Methods

Using direct contact to achieve conduction through a vessel wall is often accomplished by planar attachment of the heat sources to an endcap. In moderate water flow, a coefficient of convection of $700 W/m^2 \cdot K$ can easily be reached.

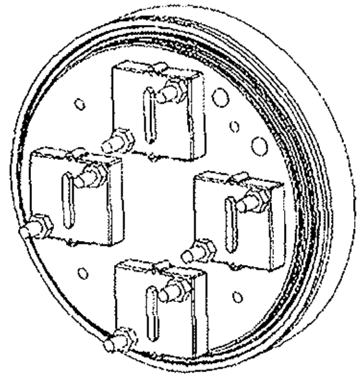

Figure 1: Endcap with mounted electronics

0-7803-7534-3/$10.00©2002 IEEE

Similarly, a shoe-type heat sink that mates with the interior cylinder wall is often used. The principal advantage of these dry-contact methods is their simplicity coupled with reasonable effectiveness under near ideal conditions. The shoe interface has served several systems: WHOI's Alvin and ABE, and MBARI's Tiburon, to name just a few.

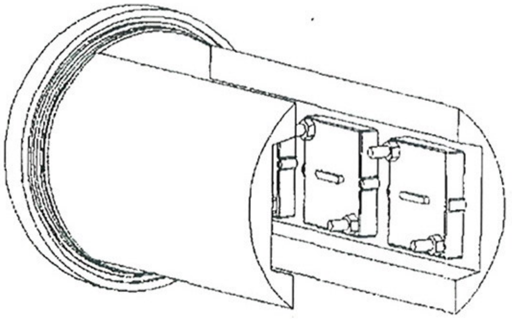

Figure 2: Shoe-type heat sink with mounted electronics

Disadvantages, however, also exist. Endcaps provide only limited surface area for heat-sink mounting. Often this space is needed for electrical penetrations. This competition for real estate is the prime challenge to utilizing this method. A drawback to using the shoe method is that it is machining intensive. Finally, both methods are adversely affected by distortion of the pressure housing due to extreme external pressure at depth. Because this uneven bowing of the vessel has an adverse effect on contact, heat transfer is reduced.

Similar to endcap mounting, cantilevering plates off the endcap also has its place. This arrangement will increase the effective surface area for heat transfer, but caution should be used with the endcap/cantilever interface due to potential heat bottlenecking.

B. Water Cooling

The thermal design of the motor controller housings for WHOI's ROV Jason II was based on calorimetric testing of components to be packaged. This testing clearly indicated that a water-feed-through midplate with domed endcaps design would be appropriate. The midplate minimizes pressure-induced distortion of the electronics-mounting surface. This is important for both the heat-transfer interface and safety of the electronics. Undue distortion of the vessel can damage electronics that are tightly mounted to the surface.

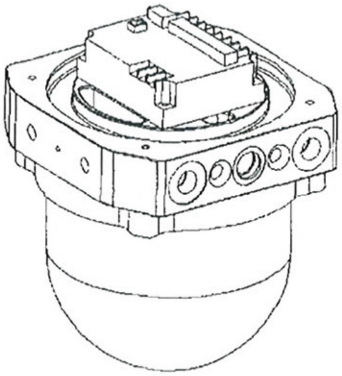

Figure 3: Water-cooled motor controller housing

C. Oil Immersion

Oil immersion as a method of heat transfer should be mentioned as a possible packaging solution for which detailed servicing is not required. Motor and transformer current ratings are significantly increased by immersion in oil. Gas or air bubbles at source-to-oil and sink-to-oil interfaces need to be removed to achieve maximum effectiveness. Preferred designs are based on adequate surface area of interfaces and geometries that favor convection. Increased mass and out-of-water weight impact overall system designs. Fusing and circuit protection in general require special attention in both one-atmosphere and pressure-compensated enclosures, but are beyond the scope of this article.

D. Fluorinert

The transformer case in the MBARI ROV Tiburon uses a closed-loop, liquid-vapor-state method of heat transport. In this case, the step-down transformer is bathed in liquid Fluorinert, which in turn boils off to condense on the case wall only to repeat the cycle. This was implemented to achieve acoustic isolation from the transformer while simultaneously cooling the unit [2].

Fluorinert is a product of 3M Industrial Chemicals Division, St. Paul, MN.

E. Heat Pipes

Before detailing the use of heat pipes in actual systems, some brief background information on these devices is provided.

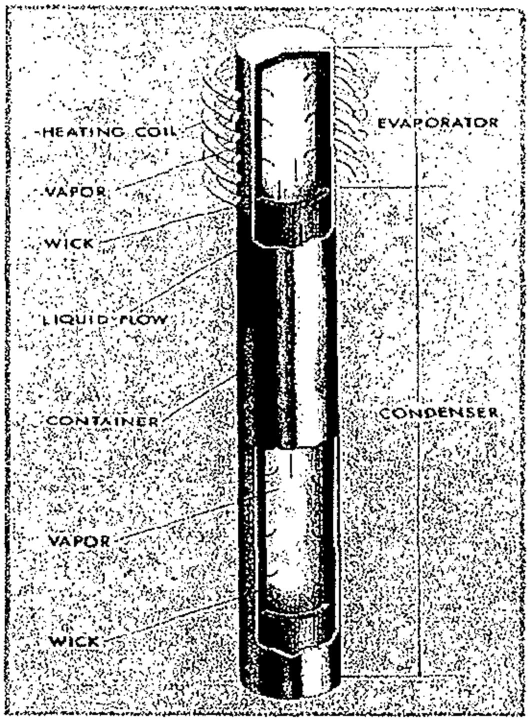

Figure 4: Heat pipe (used with permission from Los Alamos National Laboratory Heat Pipe Division)

Heat pipes were invented at Los Alamos National Laboratory in 1963 by George Grover [3]. Heat pipes provide a heat-transfer method in and of themselves: the heat pipe absorbs heat at one end and sheds it at the other. This works through a two-phase, continuous liquid-vapor cycle in which the latent heat of vaporization is utilized [3]. Heat pipes reduce mass and thermal inertia over conventional heat sinks because of their light weight and exceptional response time. Weight savings and volume gains could be seen in existing designs, and packaging size reduction in new designs.

III. HEAT PIPES IN RECENTLY FIELDED SYSTEMS

Heat pipes were effectively employed in the three primary titanium housings of the WHOI ROV JASON II. The power distribution and conversion topology used numerous DC/DC switching converters, which provided desired robustness and electrical isolation. However, this created a larger wiring harness and increased the mean distance from the available endcap. Additionally, space had to be allotted for fiber-optic penetrations and at the same time allow for fast and simple removal of the completed chassis in each pressure case. The primary advantage of this heat pipe installation is that it adequately removes a sufficient amount of heat and still allows the packaging geometry to address other design requirements. The chief concern is the same as that for electrical penetrations: the use of O-rings, which in this case are used to seal the conductive heat-exchanger plugs—dubbed "CoolPlugs."

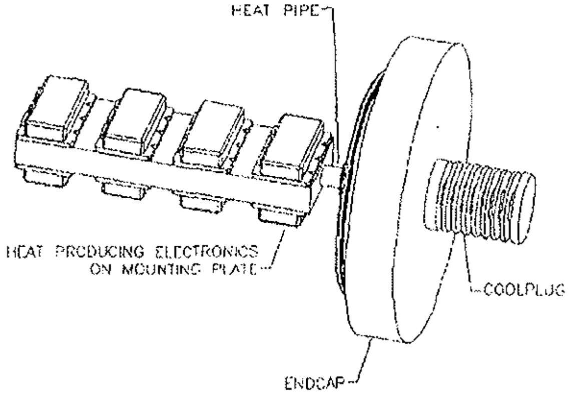

Figure 5: Endcap-mounted CoolPlug heat sink

Mounted to the exterior of the titanium endcap, each CoolPlug has a heat pipe inserted into its core. The blind hole and heat pipe are toleranced in construction to 0.001 inch of clearance. A silver-based thermal compound is used to fill this void between the copper heat pipe and the titanium CoolPlug. Heat-generating components are then attached to the heat pipe inside the vessel. Heat moves from the heat-producing component through the heat pipe to the CoolPlug and then to the water. The thick titanium endcap is no longer a thermal barrier. The CoolPlug material choice was based on long life, so it is made from the same material as the endcap/housing—grade 5 titanium. A CoolPlug made from a more conductive material would yield better heat-transfer results with the trade-off being a shorter life span. With a through-the-endcap heat-transfer capability, plastics and glass can be used without having concerns for their thermal resistance.

For similar reasons mentioned previously, heat pipes were used in the DSL-120-A. However, in this case, they were employed to distribute heat evenly in the vessel so that convection would take place over a larger, more distributed area. CoolPlugs were not employed. The heat pipes were placed along the band of highest heat generation of the power conversion modules. The cooling end was fitted with fins cut from an abrasive water jet. Fans were placed below the fins to both force convection and also mix the interior vessel volume of air. Again, this particular arrangement was used to deal with a difficult chassis layout, but without endcap penetrations. Because this installation is dependent upon internal recirculation of a fixed air volume to transfer the heat to the vessel walls, it is not nearly as effective as those that employ through-the-endcap CoolPlugs. Comparative results confirm this.

With the Jason II operating in a similar volume at similar DC/DC converter loads and two times the telemetry power load of the DSL-120-A, a 20°C difference in chassis temperatures is being observed.

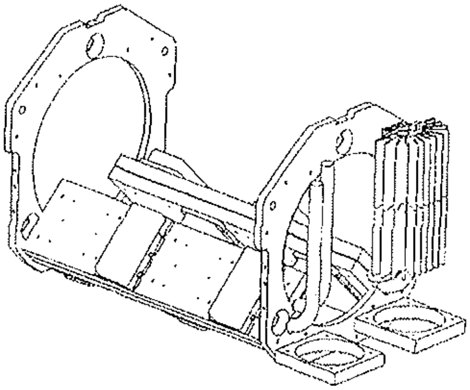

Figure 6: Chassis-mounted heat pipes assist convection.

IV. DESIGN TOOLS AND TESTING

Computer Aided Design (CAD) and Finite Element Analysis (FEA) are invaluable tools in the pursuit of the analytic solution. Each contributes to refining the model and understanding/resolving unknowns. Heat-transfer problems often force assumptions. FEA provides a deterministic method for eliminating unknowns. Coupled with empirical testing, thermal models built in CAD and FEA can sharply streamline the iterative design process.

For example, our testing consisted of loading mock-up power plates, heat pipes, and CoolPlugs at various power levels. The CoolPlugs were cooled with room temperature water flowing at a rate of 250cc/min with no observable ΔT. Temperatures on the baseplate were collected and recorded. Having these temperatures enabled us to return to the FEA model and compare our results with values we initially assumed. In our case, adjustments were made to determine a coefficient of heat transfer around 180W/(m^2·K).

The dual heat pipe configuration is capable of transferring 100W (electrically determined) out of the system. By placing four CoolPlugs through our 2-inch-thick titanium endcap, we achieved a 400W output. Dock testing and sea trials of the vehicle confirmed the ability of the CoolPlugs to cool our enclosed electronics with a 30°C ΔT.

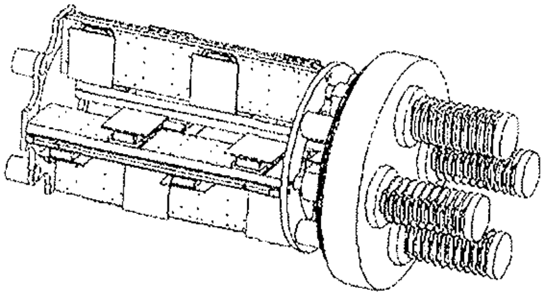

Figure 7: Four dual heat pipe CoolPlugs through a 2-inch-thick endcap

It can be deduced that lower water temperatures and attachment to the endcap, although not characterized, should increase the actual performance of the CoolPlug system.

A major caveat during the testing stage is to allow for steady-state thermal equilibration. Not allowing for thermal inertia can lead to erroneous results. Variation in effective thermal cross-sections of interfaces can impact results. Consideration should be given to surface finish and flatness.

V. MATERIAL CONSIDERATIONS AND FABRICATION

To achieve effective heat transfer regardless of method, it is important to provide a brief treatment on material selection and fabrication techniques. Additionally, the design and construction aspects of dealing with thermal issues are very tightly bound with respect to maintaining the effectiveness of the various conductive interfaces.

Material selection is limited and is driven by other design constraints such as attractive strength-to-weight ratio, minimized magnetic signature, and reduced susceptibility to corrosion. Interestingly, materials that conduct electricity well also conduct heat well and vice versa. It's difficult to find materials that are structurally sound, corrosion resistant, and transfer heat well. Stainless steel, titanium, plastic composites, ceramics, and glass are all good ocean-going materials, but none of them transfer heat well.

From this brief list of materials, titanium is gaining "common ground" as an oceanographic engineering material because of its strength-to-weight ratio and corrosion resistance, but, like stainless steel, titanium limits heat transfer. Still, all of these materials will probably enjoy wider use as liquid vapor state and liquid-enhanced cooling mechanisms can be integrated into the overall chassis and pressure case design.

For the sake of working with challenging geometries and materials, a brief list of modern machining and fabrication techniques is provided below:

- Wire electrodynamic machining (Wire EDM)
- Ram EDM
- Abrasive water-jet machining
- Electroplating and electroforming
- Modern bonding methods
  - Spin welding
  - Friction stir welding
  - Vacuum furnace brazing
  - Hydrogen furnace brazing

Water-jet and EDM methods lend themselves to working refractory metals and other hard-to-machine metals such as titanium and copper. EDM is appropriate when tight tolerances are required. Wire EDM is most often used with plate stock. Ram EDM is most often employed when blind holes are needed in refractory metal.

Water-jet also is excellent for hard-to-machine plate stock, but should be utilized when designs are not predicated on higher tolerances and exactness of fit that conventional lathe and mill operation are capable of performing.

In instances where limited cross-sectional areas are available in conductive interfaces, it is important to maximize the effective contact area. While being mindful of intermediate assembly requirements, modern bonding methods should be considered to ensure effective contact. Future applications of the CoolPlug and heat pipe interface can be improved by using modern bonding methods to join the two elements, thus eliminating the thermally conductive grease contact interface.

VI. CONCLUSION

The use of heat pipes and other liquid-enhanced topologies for oceanographic systems should be considered as mechanisms to complement and support existing methods.

The thermal aspects of the JASON II electronic packaging design show initial success. Equally important, this success was founded on a couple of iterations of modeling and real data collected on crude but representative test fixtures.

In closing, electronic packaging for oceanographic use requires a systems approach. It is not just a thermal-versus-space problem or strength-versus-weight problem. Over-optimizing about a single set of parameters is often just as damning as totally ignoring the same area of concern. Attention to cooling should be given equal billing, no more no less. Thermal issues should be considered early in the design and layout phase of any hardware that is expected to evolve significant amounts of heat.

ACKNOWLEDGMENTS

Funding has been provided by The Cecil H. and Ida M. Green Technology Innovation Program and The Alfred H. Zeien Endowed Fund for Innovative Ocean Research.

The authors would like to thank the following individuals for their input and contributions: Russ Wood of the University of Maryland, Department of Physics Instrument Machine Shop; Ed Mellinger of MBARI; Andy Bowen, Dana Yoerger, Albert Williams, Kenneth Doherty, Lane Abrams, Albert Bradley, and Don Peters of Woods Hole Oceanographic Institution; and Christopher Nicholson of DSSI, Inc. Thanks also go to Bill Byrne of Noren Products for providing technical support in the heat pipe applications. Special thanks to Sharon Wilkey and Valerie Thompson for editing and generation of this paper.

Woods Hole Oceanographic Institution contribution number 10777.

REFERENCES

[1] G.A. Mazur, T.E. Proctor, Troubleshooting Electrical/Electronic Systems, Home Wood, Ill, American Technical Publishers, 1994, pp 149, 153-154, 391-392.

[2] E. Mellinger, "Power system for new MBARI ROV," Proceedings Oceans, 1993 Victoria B.C., Canada.

[3] G.P. Peterson, An Introduction to Heat Pipes: Modeling, Testing, and Applications, New York, NY: J. Wiley and Sons, 1994, pp xi, 1-13.