BOYD CORPORATION

Additive Manufactured Heat Pipes

INTRODUCTION TO ADDITIVE MANUFACTURED HEAT PIPES AND NEW, INNOVATIVE THERMAL SOLUTIONS COMING TO MARKET

Boyd Additive Manufactured Heat Pipe Technology

Introduction to Additive Manufactured Heat Pipes and New Thermal Solutions Coming to Market.

Ryan J. M^{c}Glen
Advanced Technology Manager
Aavid, Thermal Division of Boyd Corporation,
Boyd UK Design Center, 12 Wansbeck Business Park,
Ashington, Northumberland NE63 8QW, United Kingdom

Overview

This paper introduces additive manufactured (AM) heat pipes and other advanced thermal management technologies, previously presented as a Keynote Lecture at the 16th UK Heat Transfer Conference at the University of Nottingham.

Boyd and its research partners developed additive manufactured heat pipes utilizing laser powder bed fusion (LPBF) techniques to form titanium heat pipe vessels with integrated miniaturized lattice capillary wick structures. The article covers an overview of this technology, its development through the European Space Agency (ESA), and an Innovate UK project., The technology includes a titanium-ammonia space mini-heat pipe assembly and a titanium-water two-phase heat pipe vapor chamber. Additionally, the paper addresses various other custom thermal management solutions and technologies for next-generation electronic applications in the Space, Aerospace, high-end Automotive, and eMobility markets. Commercial examples of heat pipe technology, ultra-thin vapor chambers, vacuum brazed liquid cold plate technology, and encapsulated graphite technology are also included in this overview.

INTRODUCTION

Boyd Corporation is a world-leading innovator, developer, and manufacturer of thermal management systems and engineered material solutions for most major industries, including heat pipes and two-phase cooling technologies for Aerospace, Defense, 5G, and Cloud Computing. Boyd customers benefit from agile global manufacturing capabilities, rapid prototyping and scalable volume production, decades of engineering expertise in thermal technology development, and high quality and reliability standards. In addition to heat pipe and two-phase innovation, Aavid, Thermal Division of Boyd Corporation maintains the largest global portfolio of thermal management technologies and integrated systems ranging from heat spreaders for mobile and wearable devices to liquid systems and loop heat pipes (LHP) for high heat load applications.

The Boyd Ashington UK facility includes one of several global Boyd Design Centers focused on thermal technology innovation and testing. With the support of world-leading academic and industrial partners, the UK design center is pioneering patented additive manufactured heat pipe technology [1], developed through European Space Agency (ESA) and Innovate UK funded collaborative R&D projects. Other advanced two-phase technologies currently in development include titanium-ammonia heat pipes, titanium-water heat pipes and vapor chambers, and integrated lattice capillary wick structures.

EARLY STAGES: DEVELOPING ADDITIVE MANUFACTURED HEAT PIPE TECHNOLOGY

In collaboration with the University of Liverpool (UoL), who pioneered laser powder bed fusion (LPBF) technology, Boyd UK Design Center engineers are focused on developing additive manufactured heat pipe technology with integrated microscale lattice capillary wick structure. Boyd's UK Design Center has been granted European Patent No. 2,715,265 [1], which is believed to be the first patent in this field. Aavid, Thermal Division of Boyd has identified this technology as an ideal solution for future generations of customers' high-performance applications.

Early use of this technology is expected to be in high-tech, low volume applications in the aerospace sector, where both mass and thermal performance are critical specifications. As the additive manufacturing process advances, the technology will start to scale into high-end medium volume products and then to high volume solutions in consumer applications [3].

The LPBF process constructs 3D metal components by laser fusion of 2D patterns in multiple-subsequent layers of powder material [4]. The most significant challenge in technology development was miniaturization of the lattice wick structure to enable functionality as a heat pipe capillary wick. Boyd optimized laser parameters utilizing various titanium powder grades to miniaturize capillary pore size. Refer to the published description of the optimization process [5] for more details. To illustrate the process, examples of a lattice structure construction model and achievable lattice size at development activity initiation are shown in Fig. 2. An example of a miniaturized characterization test piece used for porosity and permeability testing is shown in Fig. 3. In a functional heat pipe, a vapor space would go through the center of the wick structure.

Fig. 1: An example of a titanium AM vapor chamber heat pipe being built vertically on a Renishaw AM 250

The figure shows a cross-section (40mm x 6mm) through the vapor chamber shown. The solidified material shows the perimeter of the vapor chamber vessel and the internal lattice wick structure around the perimeter of the internal surface.

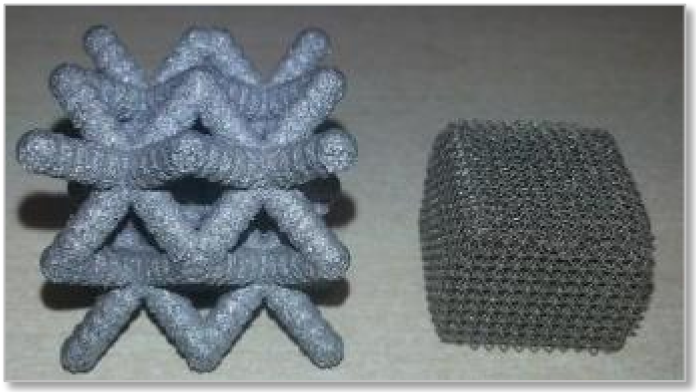

Fig.2: 25mm Lattice structure example & 20mm lattice cube (UoL).

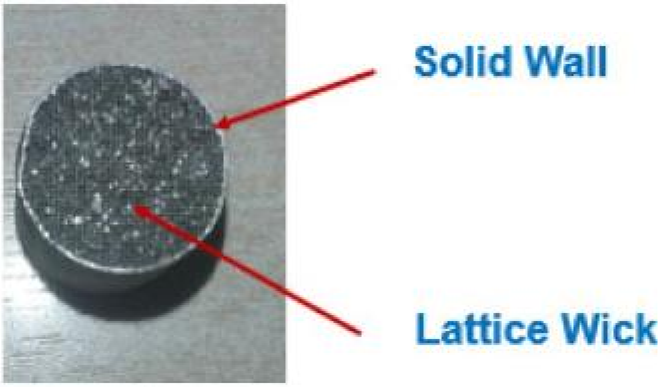

Fig.3: Ø12.7mm characterization test piece with integrated solid tube wall (pore size < 700 µm).
(UoL & Aavid, Thermal Division of Boyd Corporation).

FURTHER DEVELOPMENT WITH THE EUROPEAN SPACE AGENCY (ESA)

The preliminary research and testing prompted a European Space Agency (ESA) ARTES 5.1 activity [6] to investigate novel, 'gravity friendly' heat pipes that enable functionality on ground test and direct thermal management of the electronics. Current aluminum-ammonia constant conduction heat pipes with extruded grooved wicks do not allow for this, so an alternative is required.

Engineers conducted Laser Parameter Optimization during the ESA project to identify laser build parameters to construct lattice structures with minimized cell sizes achievable within the limits of the process, where the structure transitions from open cell to closed cell. They completed several hundred laser parameter sets, examining two titanium material grades and a series of seven lattice cell sizes. Lattice cell sizes were selected based on calculated capillary lift heights for candidate working fluids at minimum temperature values of 0° and - 35 °C. Ultimately the ESA selected ammonia as the preferred working fluid for charging the heat pipe test pieces. Characterization testing (porosity, permeability, and pore size measurement) enabled the identification of optimized laser parameters for each lattice cell size that were utilized to additive manufacture a series of representative pieces (half-pipes) (Fig. 4) to test capillary lift height against gravity and mass flow rate of the fluid.

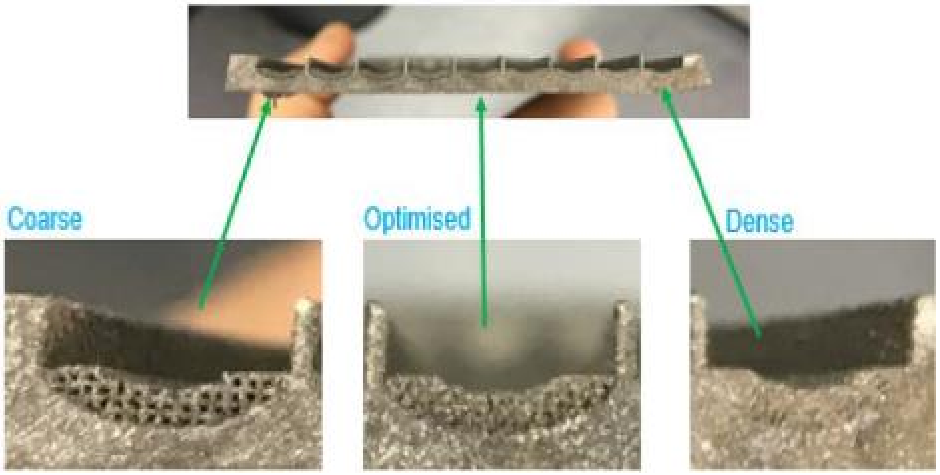

Fig.4: Example of lift height and mass flow rate test pieces with coarse, optimized and closed cell lattice structures.

Determining characterization:

- Porosity
    - Measured by mass balance of dry and saturated test pieces.
- Pore Size
    - Analyzed by photogrammetry, following a method described by Evans et.al (2017) [7].
- Permeability Testing
    - Conducted on porous samples with dimensions of 30mm x 20mm x 5mm
    - Permeability was calculated using Forchheimer's equation.
- Capillary Lift Height
    - Determined experimentally utilizing an infrared camera to observe transition of the progression through the test piece.
    - In parallel, engineers completed a mass balance, enabling the measurement of the mass flow rate of the fluid (water) through the test piece.
- Decreasing pore size increases capillary lift height / capillary pressure, however it also reduces mass flow rate of liquid phase condensate to the evaporator. This limits maximum transport power of the heat pipe. Therefore, suitable pore sizes were selected to achieve required transport power to manufacture the ESA heat pipe test pieces.

During the ESA project, the teams constructed, charged, and tested a series of additive manufactured titanium heat pipe test pieces utilizing Boyd's UK Facility ammonia heat pipe capabilities (Fig. 5). Preliminary development and testing activities were completed in alignment with the specific test requirements of the ESA, and were aligned with ESA standard ECSS-E-ST-31-02C.

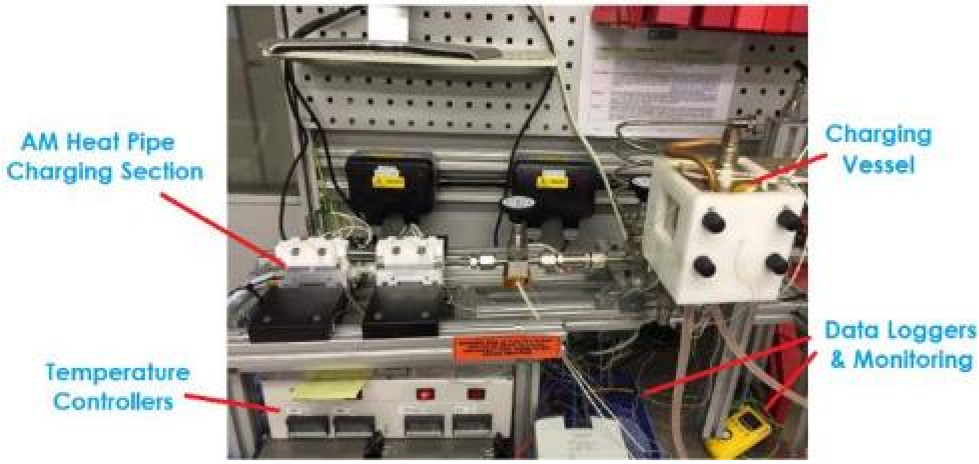

Fig.5: Lab-scale ammonia charging facility in the Boyd UK Design Center

Tests included:

- Pneumatic proof pressure test (nitrogen) at 79.5 Bar
- Ammonia charge mass optimization
- Helium leak detection
- Welding and sealing development
- Thermal performance testing
    - ($T_{adiabatic}$ = 60 °C; Test Angles: +90°, - 0.3° and increasing negative angles until dry-out occurred; transport power, 2W to 11W).

Completing these tests enabled successful functional titanium-ammonia heat pipes with circular design (08mm × 200mm long) to be manufactured. The heat pipes were then integrated by epoxy bonding with two aluminum saddles to form the final heat pipe assembly test piece (Fig. 6).

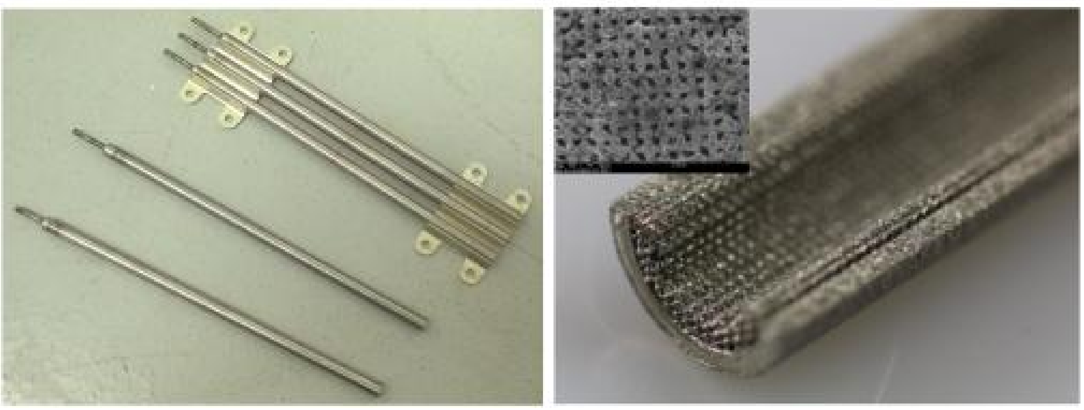

Fig.6: ESA activity titanium-ammonia additive manufactured heat pipes and heat pipe assembly (Aavid, Thermal Division of Boyd Corp. / UoL).

The individual heat pipes and heat pipe assembly successfully completed a series of qualification tests to the ESA project test specification, including:

- Ageing and non-condensable gas tests (T = -35 ◦C)
- Proof pressure at temperature testing
- Preliminary accelerated life test (burn-in) at temperature test (300 h at 100 ◦C to 105 ◦C, equivalent to 2 years accelerated lifetime, full test = 8000 h)
- Thermal cycle test
- Vibration testing to simulate launch conditions

Thermal characterization testing was completed at pre-test stage and after significant qualification tests to observe any variations in performance. The heat pipe assembly achieved required transport power of 30W and was functional at an angle of - 20° against gravity versus a maximum functional angle of - 2° for screen-mesh wicked ammonia heat pipe reference test pieces.

INNOVATE UK DEVELOPMENTS AND REAL WORLD UTILIZATION

Boyd has designed and manufactured various demonstrators, including one for loop heat pipes, to highlight the potential benefits of additive manufacturing heat pipe technology. Loop heat pipes enable thermal transport against high gravitational acceleration loads and over long distances by deploying a primary and secondary wick arrangement that is challenging to manufacture [8]. An innovative loop heat pipe evaporator with integrated primary wick is shown in Fig. 7. The component dimensions are 020mm × 45mm long and it incorporates a solid outer vessel with integrated primary wick and vapor passage network, secondary wick representation, and solid bulkhead seal. This loop heat pipe component is a good example of innovation in two-phase technology, however, further work on minimization of wick pore size is required to realize this technology.

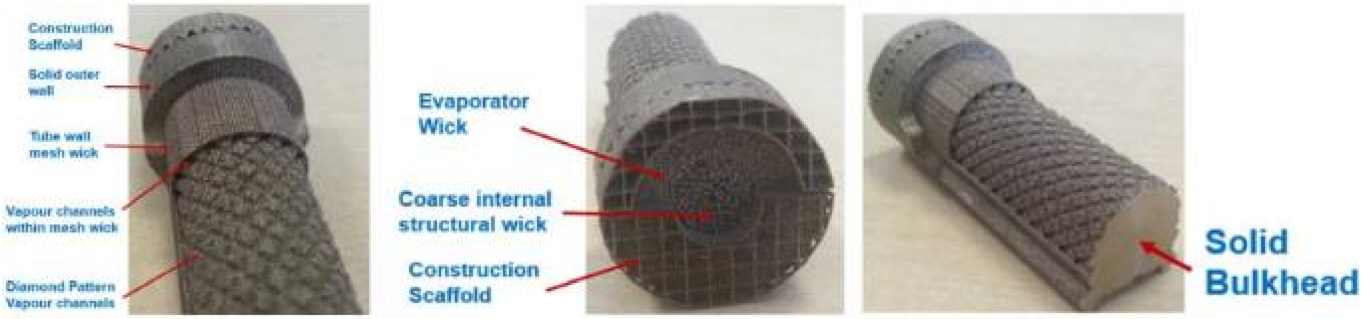

Fig.7: Additive Manufactured Loop Heat Pipe Evaporator Demonstrator, Incorporating Various Innovative Features

An additive manufactured titanium-water vapor chamber heat pipe example, developed in an Innovate UK collaborative R&D 'CLASS' project [9], is shown in Fig. 8. Lift height testing demonstrated capillary pumping, vertically against gravity, up to a lift height of 100mm (top of the component) for the Additive Manufactured wick. An example of how a vapor chamber can be integrated into a lightweight aerospace electronics chassis (≈20% mass reduction) is shown in Fig. 9. Three discrete heat sources with heat dissipation requirements of 50W to 100W each can potentially be thermally managed by this vapor chamber technology.

Fig 8: Titanium-Water Additive Manufactured Vapor Chamber Heat Pipe Capillary Wick Test Piece with Integrated Lattice Structure

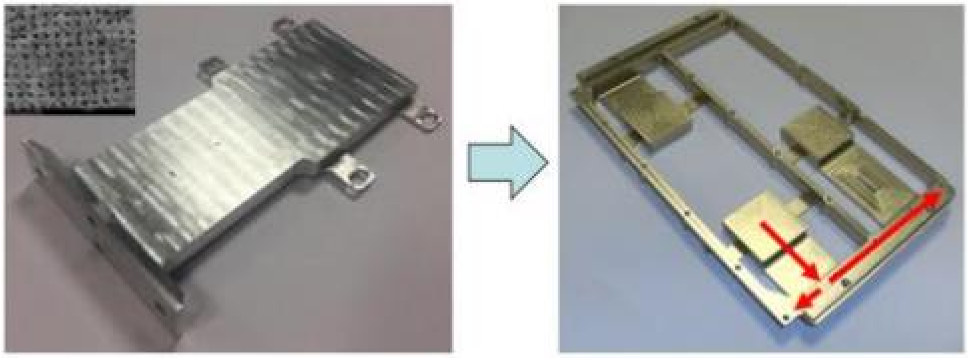

Fig 9: Integration of Additive Manufactured Vapor Chamber Heat Pipe Technology into Aerospace Electronics Chassis Example

Aavid, Thermal Division of Boyd Corporation's patented additive manufactured heat pipe technology has achieved technology readiness level (TRL 4) and is ready for demonstration in commercial applications. Boyd has demonstrated functionality against gravity and high power transport that can be deployed in commercial applications. To advance towards commercialization, collaborations with early adopters are progressing from lab-scale to a pilot production capability. Further modifications can be made in capillary wick construction techniques and processes to convert additive manufactured vessels into functional heat pipes. Processes and products to end user specifications must be qualified as well.

RADIO TELESCOPE HEAT PIPE APPLICATION EXAMPLE

Radio telescopes are often deployed in remote low population regions to minimize the impact of human activity on telescope functionality. The Australian Square Kilometer Array Pathfinder (ASKAP) radio-telescope constructed by the Commonwealth Science and Industrial Research Organization (CSIRO) [10] has 36 twelve-meter reflector antennas, located in an extremely harsh environment with low nighttime temperatures and daytime ambient temperatures up to 55°C.

Fig 10: Photographs of an ASKAP radio-telescope with and close-up view of the PAF receiver module with integrated Aavid UK heat pipe receiver disc (CSIRO).

Each radio telescope has an advanced phased array feed (PAF) receiver module (Fig. 10) that incorporates a Ø1.2m heat pipe chassis disc (Fig. 11) [11], designed and manufactured by Boyd Corporation. The disc [12] incorporates 117 customized heat pipes to transport heat from 188 individual receiver components to the disc perimeter. Heat is dissipated by eight secondary cooling systems consisting of perpendicular heat pipe thermal links and heat pipe forced convection fin stacks (Fig. 12) at the disc perimeter.

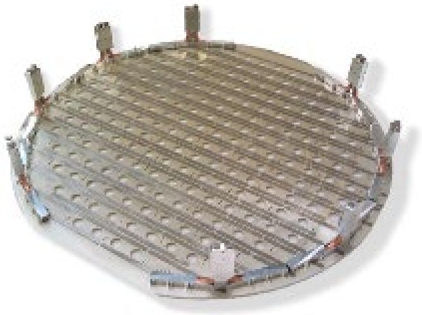

Fig 11: Heat pipe receiver disc (Ø1.2 m) developed for ASKAP radio telescope.

The secondary cooling system incorporates thermo-electric coolers (TEC) that sub-cool the disc perimeter to 20 °C, enable functionality in a 55°C ambient temperature environment, and prevent thermal failure of electronics. The TEC's add an additional heat dissipation requirement of 560W to the system.

Fig 12: Secondary cooling system: heat pipe assembly and forced convection heat pipe fin stack for ASKAP radio telescope

UTILIZING BOYD ADVANCED THERMAL TECHNOLOGIES

Boyd has made technological advancements targeted at high-end electronics and more disruptive applications that pose new thermal management challenges in addition to additive manufactured heat pipes. This includes applications that require a high level of engineering development, qualification testing, and integration.

HEAT PIPE INTEGRATIONS

Boyd was an integral developer of traditional heat pipes and has utilized and improved the technology since the 1970's. Combining this rich history in two phase cooling technology with Boyd's wide breadth of additional cooling and engineered material solutions enables Boyd to provide customer solutions that are smaller, lighter, more reliable, and higher performing in almost any known environment.

Copper-water heat pipes with sintered wick structures are a low-cost, high-volume solution often deployed in consumer and industrial electronics applications such as computers, gaming consoles, and telecom server applications. The function of the heat pipe is to transport heat from the high heat flux source to a region where it is more easily dissipated, such as a forced air convection fin stack or a heat sink. Heat pipes can also be integrated into a heat sink base for more uniform heat spreading and faster heat transfer.

Equivalent thermal conductivity is application-specific, but typically ranges from 8,000 to 30,000 W/mK. Progressing to high-tech applications may require considering sub-zero operation, varying or high gravitational acceleration loads, and operating angles such as in fast jet applications. To achieve low temperature functionality, replace water with methanol or ethanol in copper heat pipes. Aluminum-ammonia heat pipes are heavily used to achieve this in space applications. Customized capillary wicks can help achieve functionality against gravity and high gravitational acceleration loads. Loop heat pipes can be developed for highly specific conditions.

UTRA-THIN VAPOR CHAMBER TECHNOLOGY

Ultra-thin vapor chambers are a newer technology entering into volume production. Applications that will benefit from this technology include future high performance mobile electronics, eMobility applications, 5G, and Cloud Computing. Wearable electronics, such as smart watches and Virtual Reality (VR)/Augmented Reality (AR), where lightweight, compact design and touch temperature are key performance requirements may also benefit from ultra-thin heat spreading.

Fig 13: Ultra-Thin Vapor Chamber Examples for Miniaturized Electronics Applications.

Transporting and spreading waste heat from discrete electronic components within confined spaces or narrow gaps over a larger surface area was conventionally achieved by flattening circular heat pipes to thicknesses of 1.0 to

1.5mm or by similar thickness two-phase vapor chamber heat pipes. Rapid evolution of smaller, thinner, lightweight mobile electronic devices required higher performance thermal solutions that manage higher heat fluxes generated by these smaller, more powerful electronic components.

Ultra-thin vapor chambers [13] reduce solution thickness, offer high thermal performance, and can manage high heat flux bursts and high-performance modes of mobile and display devices (Fig. 13). Titanium ultra-thin vapor chambers offer a thickness range of 0.3mm to 0.5mm with a mass reduction of > 50% versus equivalent copper (0.4mm) and stainless-steel (approaching 0.3mm) ultra-thin vapor chamber variants.

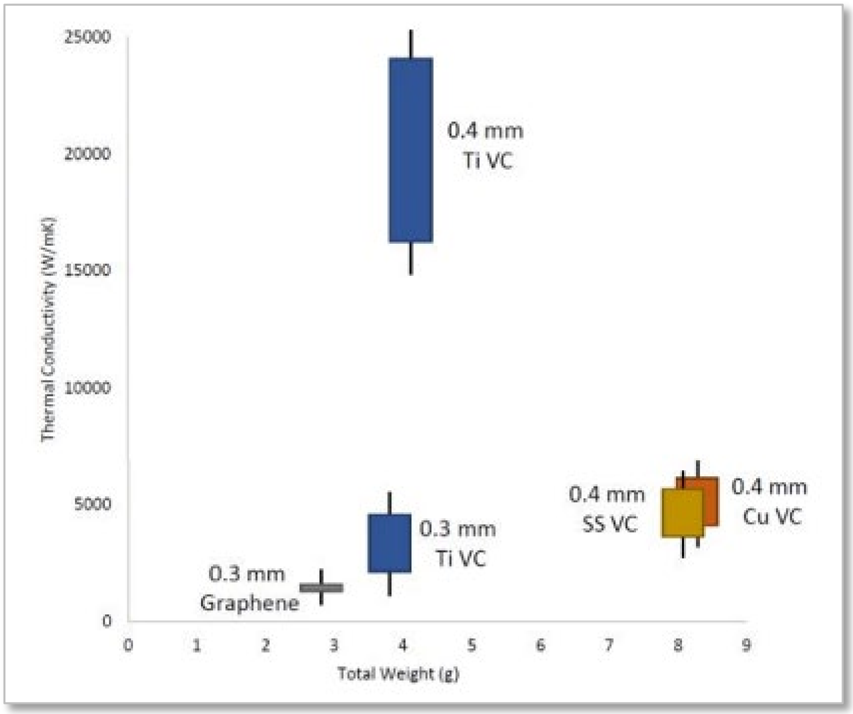

Fig 14: Thermal Conductance and Mass Comparison of Various Ultra-Thin Vapor Chambers vs. Graphene, for a representative vapor chamber temperature typical in mobile phones at 60°C.

This advanced technology incorporates customized wick structures that are performance-matched to the application. Fig. 14 compares the thermal conductance of various ultra-thin vapor chambers against 0.3mm thick graphene (1300 W/mK), for a typical mobile phone heat spreading application (100mm - 50mm; at 60°C). 0.4mm thickness stainless steel and copper vapor chambers have similar thermal conductance up to 5700 W/mK and 6000 W/mK respectively. The 0.3mm thick titanium ultra-thin vapor chamber is comparable, with thermal conductance in the range of ≈2000 to 4500 W/mK. The 0.4mm thickness titanium ultra-thin vapor chamber offers up to five times higher thermal conductance, ranging from ≈16,000 up to 24,000 W/mK in the mobile phone application.

Ultra-thin vapor chambers increase end device reliability and lifetime, reduce volume, thickness, and weight, and enhance handling short burst, high power usage modes with greater responsiveness. The technology also enables reduced touch temperatures, an important factor in wearable and display electronics. The high strength of titanium and stainless-steel ultrathin vapor chambers allows them to be incorporated as a structural component, doubling both as a thermal and mechanical solution, to further reduce size and mass of the electronic device. Titanium has a further benefit of low coefficient of thermal expansion, potentially enabling an increased level of integration with the electronics (CTETi = 4.8x10-6 m/ m.°C; CTESS = 8.8 x10-6 m/m.°C; CTECu = 9.8 x10-6 m/m.°C).

VACUUM BRAZED LIQUID COLD PLATE TECHNOLOGY

Vacuum brazed liquid cold plates are often utilized within an electronics chassis to provide direct thermal management for heat dissipating components and are mounted to specific locations across the chassis surface.

Vacuum brazed liquid cold plate construction allows larger, low pressure drop, CNC-machined coolant supply passages to improve thermal performance of heat sources and hot spots. Cold plates may also include integrated close-packed folded fin or machined channels that increase heat transfer surface area and are tailored to maximize thermal performance. For example, fin design can be optimized to break-up the boundary layer (wavy fin, louvered fin, etc.), enhancing thermal performance over alternative cold plate technology like CAB Brazing and extrusions.

Unlike two-phase technologies, liquid cold plates are part of an active pumped liquid loop system that requires electricity supply to function. Active systems require maintenance to preserve reliability of the overall system. Vacuum brazed liquid cold plates transport heat loads in the region of 500W to 10kW, where commercial heat pipes and k-Core® applications typically transport between 1W and 500W.

Boyd's vacuum brazing is completed in a high purity atmosphere that enables the breakdown of oxide layers, resulting in high quality braze joints with enhanced corrosion and vibration resistance over conventional brazing techniques. Older brazing techniques often retain fluxes within the braze joint, causing a reduction in joint quality. This may lead to corrosion and porosity in the joint after a period of operation in the end application.

Fig 15: Labyrinth Style Flow Passage Example

Vacuum brazing's clean, high quality braze joints enable a step-increase in the complexity and thermal performance of liquid cold plate technology as compared to conventional volume manufacturing techniques, such as controlled atmosphere brazing (CAB). Boyd excels at the design and manufacture of complex cold plates including those with labyrinth-style flow passages and customized fin inserts that target individual heat sources. Cold plates are optimized utilizing CFD analysis to minimize pressure drop and maximize thermal performance. Applications include optimized high-end motorsport and eMobility applications, aerospace chassis thermal management, and ruggedized transmitter applications. Examples of a labyrinth-style flow passage (280mm × 40mm × 6mm) and a vacuum brazed folded fin insert (≈ 45mm × 4mm) are shown in Fig. 15 & Fig. 16.

Fig 16: Vacuum Brazed Folded Fin Insert Example

An Air Transport Rack (ATR) avionics electronics chassis with integrated vacuum brazed liquid cold plate sidewalls example is shown in Fig. 17 [14]. External mechanical design is simplistic, with a flat chassis wall surface and internal CNC machined castellations to house multiple electronics cards. The component is internally optimized to thermally manage selected high heat dissipation electronics cards positioned in specific card slots. Low pressure drop channels are deployed across low heat dissipation slots to maximize coolant flowrate through the cold plate.

Fig 17: ATR electronics chassis with optimized vacuum brazed liquid cold plate sidewalls

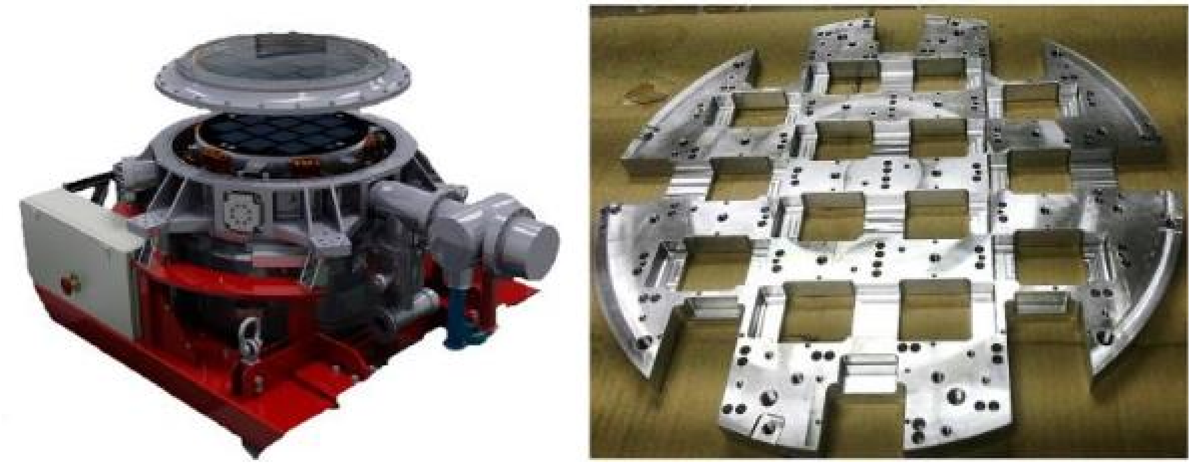

Fig 18: Complex Vacuum Brazed Liquid Cold Plate for Terrestrial Radio Telescope Applications

ENCAPSULATED GRAPHITE TECHNOLOGY (k-Core®)

Aavid, Thermal Division of Boyd Corporation develops and manufactures advanced solid conduction technology solutions including encapsulated annealed pyrolytic graphite (APG) for high performance applications. Known as k-Core®, this family of solutions incorporates various encapsulating materials like Kapton film, aluminum and copper foils, carbon fiber, or solid bulk machined aluminum, around the APG to create a functional electronics chassis and fixed or flexible thermal spreaders (Fig. 19).

APG is characterized by high in-plane thermal conductivity (1450 W/mK at 100°C) and low through-plane thermal conductivity (6–10 W/mK). Through-plane thermal conductivity is bolstered by integrating strategically placed metal thermal vias or bridges. Encapsulating aluminum thickness is optimized most typically 0.75mm to negate the impact of lower thermal conductivity of aluminum (180 W/mK). APG inserts are 3D CAD designed to fully integrate within the application and provide ports to accommodate thermal vias and machined features (e.g. tapped fixing points) in the aluminum body. The function of a thermal via is to introduce a higher thermal conductivity conduction path that overcomes the low through-plane thermal conductivity of the APG.

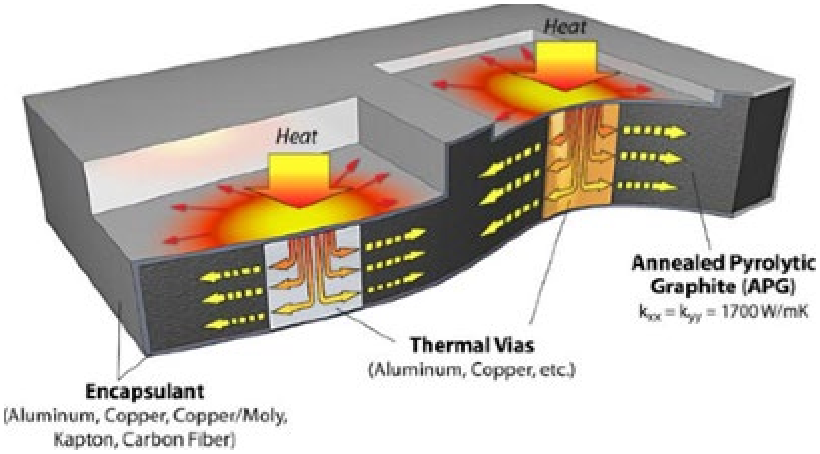

Fig 19: Encapsulated graphite thermal spreader construction

Fig 20: Encapsulated graphite thermal spreader construction

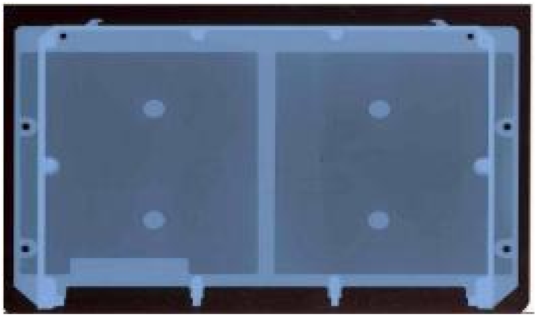

Fig 21: X-Ray revealing APG internal location within avionics electronics chassis

The ‘equivalent’ thermal conductivity of the integrated k-Core® component typically ranges from 600 to 1000 W/mK (3X to 5X higher than solid aluminum) with a mass reduction of ~5% achievable over solid aluminum due to the slightly lower density of APG. An example of a sectioned k-Core thermal spreader chassis, sectioned to reveal the internal APG core, is shown in Fig. 20.

An X-ray showing the location of APG within an avionics electronics chassis is shown in Fig. 21. A central aluminum spline within the component acts as a thermal via located centrally on the external surface of the component. The heat is transferred by conduction to the card guides that interface with the electronics chassis (e.g. similar to Fig. 17). By incorporating customized APG inserts within the chassis, the maximum temperature difference between the heat input surfaces and card guides was reduced from ≈ 56.9°C for a solid aluminum chassis to ≈ 17.5°C for a k-Core advanced conduction chassis (Fig. 22).

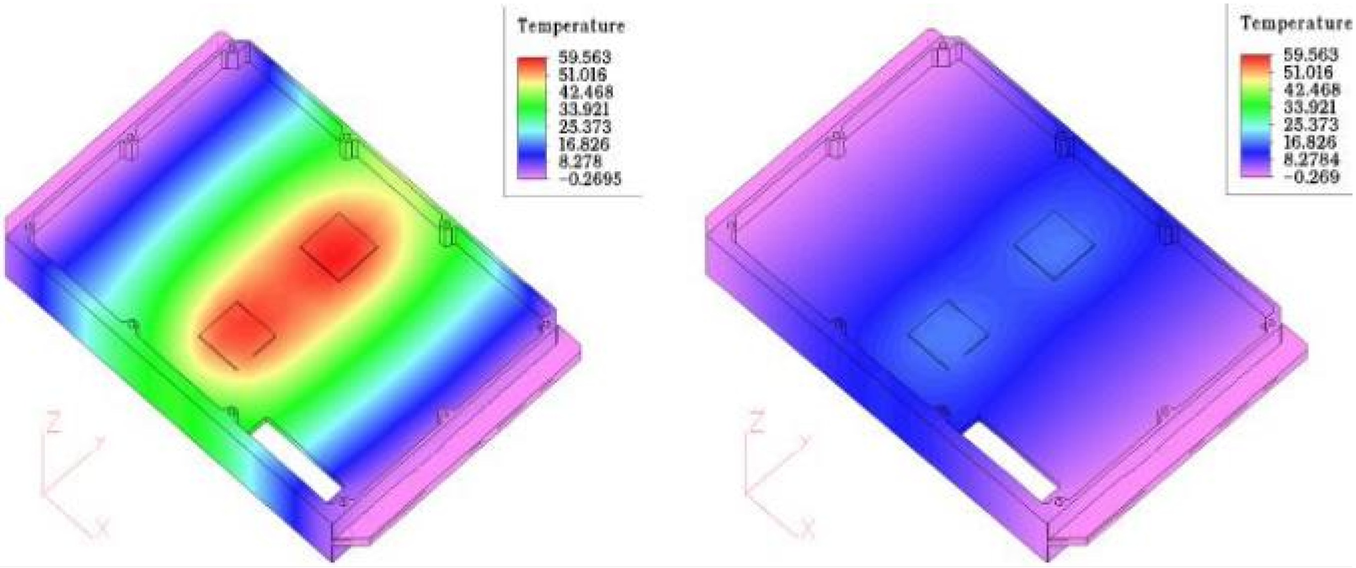

Fig 22 CFD simulation comparing a solid aluminum chassis with a k-Core chassis, with a 250W input power

Aluminum encapsulated graphite thermal management components are currently utilized in applications that require optimized weight, volume, and thermal performance, such as enhanced electronics chassis or space radiator panels. Boyd encapsulated graphite solutions are most often utilized in space and aerospace applications where size and weight are a premium consideration. The technology has lower thermal performance than heat pipes, as the conductive heat transfer is through solid material, however its performance is not affected by operating angle or gravitational acceleration.

WHAT IS NEXT?

Boyd Corporation’s decades of innovation expertise, experience, resources and unique approach to integrating multiple technologies into a streamlined product will continue to keep the company on the forefront of innovation and improved manufacturing. If you are ready to improve or retrofit your cooling solutions or are looking to tackle new challenges for the next generation, start by contacting Boyd Corporation to learn more about two phase solutions, customizations, and other possibilities for better optimized cooling.

To receive more information regarding Boyd Two-Phase Solutions, please visit www.boydcorp.com.

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