High Thermal Conductivity Graphite Foams

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Lightweight Materials

FOR THE 21ST CENTURY

Background

A novel technique for fabricating high thermal conductivity pitch-based carbon foams has been developed and patented at Oak Ridge National Laboratory under the direction of the U.S. Department of Energy (DOE) Office of Transportation Technologies. This technique produces a graphitic foam with thermal conductivity equivalent to aluminum alloys at 1/5th their weight, see Figure to right. It also exhibits an open porous structure with more than 100 times greater surface area than typical heat exchangers (>20 m2/g). The cell walls are made of highly oriented graphite planes, similar to high performance carbon fibers, which have been estimated to exhibit a thermal conductivity greater than 1700 W/m·K (copper is 400 W/m·K).

Recently, many aerospace applications have identified improved thermal management as a leading research objective. Many heat sinks and heat exchangers are bulky and require large surface areas to dump waste heat to the environment. The use of graphite foams as an alternative to current materials is very attractive from the standpoint of reducing weight, volume, while improving heat transfer efficiencies. Moreover, the unique combination of material properties also result in excellent acoustic absorption, yielding a material which can be used for thermal, electromagnetic, and acoustic signature management.

The Technology

The open porosity yields a relatively large specific surface are (>20 m2/g), significantly improving heat transfer to a working fluid. This could lead to extremely efficient and lightweight heat exchangers. In fact, a finned heat sink made from graphitic foam can be up to 3 times more efficient than an aluminum heat sink, yet at 1/5 the weight (effectively 5 times more efficient per gram of heat sink).

The material is also an excellent electromagnetic shield as it reflects RF energy very well. In addition, the foam absorbs sound very well, even in the non-thermally conductive form.

The new material is a lightweight, very high thermal conductivity graphite foam and is drastically different from graphite foams developed by others. In the six short years since its invention, it has already demonstrated the ability to dramatically improve the transfer of unwanted heat. While optimization of the graphite foam and its incorporation into complex systems is still under development, it clearly has the potential to improve many commercial systems.

Applications Being Explored Currently

- **Power electronics cooling**
  - **demonstrated 10x cooling potential compared to traditional heat sinks**
- **Personal cooling**
  - **Firefighterers, soldiers, HAZMAT, etc.**
- **Transpiration/evaporative cooling**
  - **electronics and leading edges**
- **Radiators**
  - **heavy vehicles, racing vehicles, aircraft, fuel celled vehicles**
- **Nuclear reactor core**
- **Space Radiator (Lockheed Martin)**
  - **Flight qualified and being deployed**
- **Composite materials**
- **Brake and clutch cooling**
- **High temperature friction applications**
- **EMI shielding**
- **Thermal and Acoustic Signature Management**
- **Batteries and Battery Cooling**

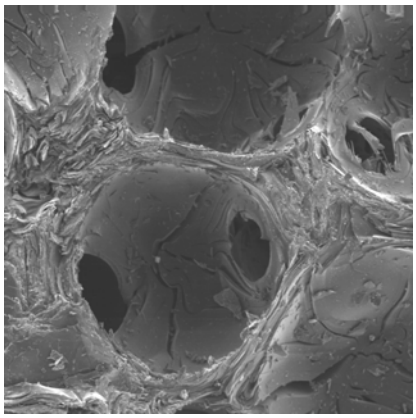
Current Licensees for Manufacturing

- **Poco Graphite, Inc.**
  www.pocofoam.com
  Lee Wiechmann: (940) 393-4324

- **Koppers Inc.**
  Tom Golubic: (412) 826-3955

Benefits

- **Low Density**
  - **0.2-0.7 g/cm^3**
- **Open Porosity**
- **Dimensionally Stable**
- **Very high bulk apparent thermal conductivity**
  - **Equivalent to aluminum at 1/5 the weight**
- **Acoustically Absorptive**
- **EMI Shield**



For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Richard Stouder
National Security Directorate
Ph: (865)-574-3053
stouderrl@ornl.gov

July 2005

2000 R&D 100 Award Winner

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History

FOR THE 21ST CENTURY

Background

Carbon foams were first developed by researchers in the late 60's as a reticulated vitreous (glassy) carbon foam. Ford (1) reported on carbon foams produced by carbonizing thermosetting organic polymer foams through a simple heat treatment. Then, Googin et al. (2) at the Oak Ridge Atomic Energy Commission Laboratory reported the first process dedicated to controlling the structure and material properties of carbon and graphitic foams by varying the precursor material (partially cured urethane polymer). In the several decades following these initial discoveries, many researchers explored a variety of applications for these materials (3-12) ranging from electrodes to insulating liners for temperatures up to 2500°C. In fact, reticulated carbon foams have been used as the template for many of the metal and ceramic foams currently used in industry. In the 1970's, research focused primarily on producing carbon foams from alternative precursors. For example, Klett, R. (6) at the Sandia National Laboratories produced the first carbon foams from cork, a natural cellular precursor. Others worked on various processing and precursor changes in an attempt to modify properties and reduce cost. The majority of these carbon foams were used for thermal insulation, although some structural applications were found.

In the early 1990's, researchers at the Wright Patterson Air Force Base Materials Lab pioneered mesophase-derived graphitic foams, specifically for replacing expensive 3-D woven fiber performs in polymer composites and as replacements for honeycomb materials (13-20). Their work was centered on developing a highly structural material that was lightweight, and to date, exhibits the highest specific strength of carbon foams. Concurrently, Ultramet Corp, performed research on RVC foam and used chemical vapor deposition (CVD) as a technique to place pyrolytic graphite on the glassy carbon ligaments of RVC, producing 3-D carbon structures with high-modulus ligaments.

With the goal of producing very inexpensive carbon foams, researchers at West Virginia University developed a method that used coal as a precursor for high strength foams with excellent thermal insulation properties (21-24).

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In 1997, Klett, J. (25-35) at the Oak Ridge National Laboratory (ORNL) reported the first graphitic foams with bulk thermal conductivities greater than 40 W/m·K (recently, conductivities up to 180 W/m·K have been measured (36)). By combining an open cellular structure with a thermal conductivity to weight ratio of greater than 200 (compared to 45 for copper), this material presents a unique opportunity to radically change the approach to solving many heat transfer problems. This graphite material has been examined for the core of heat transfer devices such as radiators and heat sinks, evaporative cooling and phase change devices. Furthermore, the ability of the graphite foam to intercalate lithium and absorb acoustic energy makes them candidates for several applications beyond thermal management.

For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Richard Stouder
National Security Directorate
Ph: (865)-574-3053
stouderrl@ornl.gov

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Graphite Foam Enables New Space Technologies

Materials Properties

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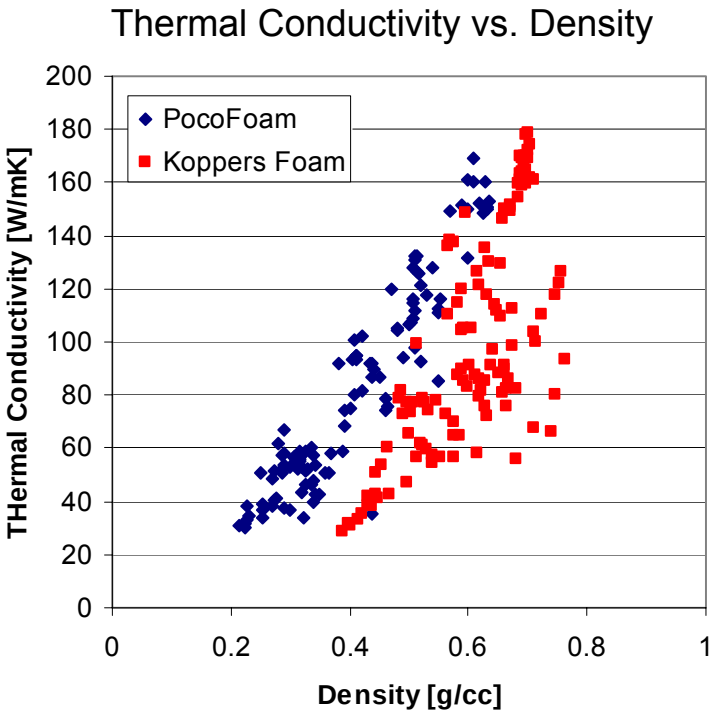
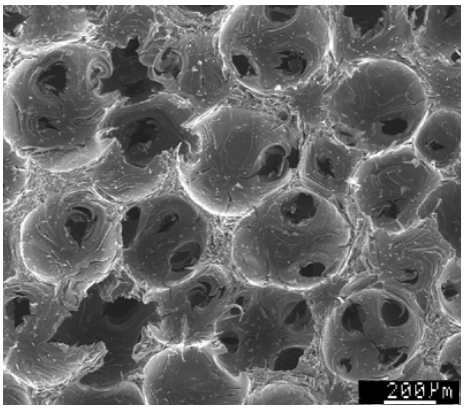
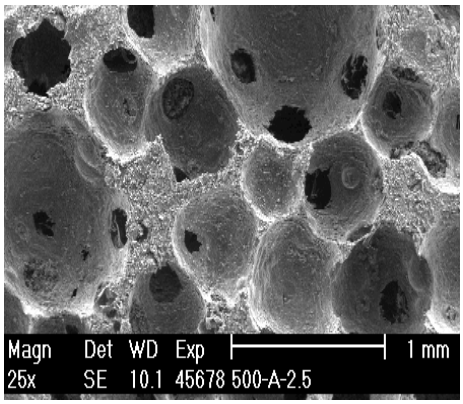
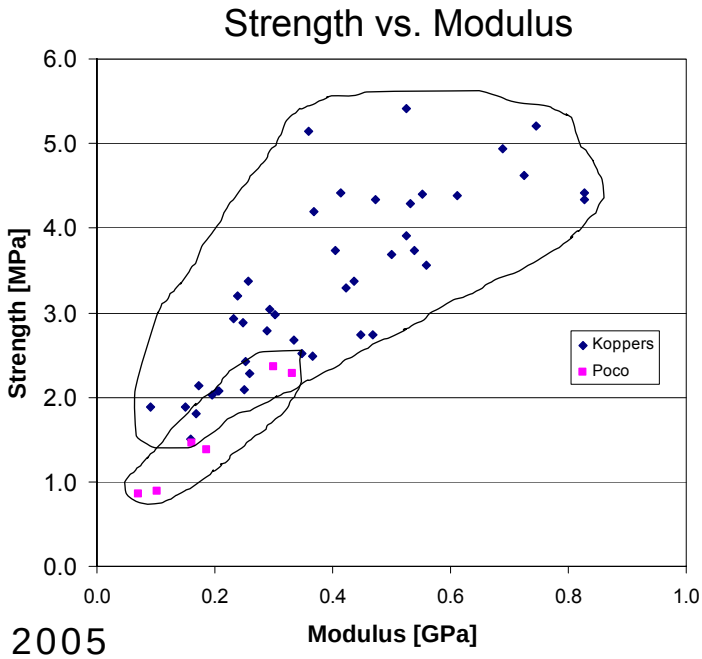




PocoFoam®



Koppers Foam



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Materials Properties

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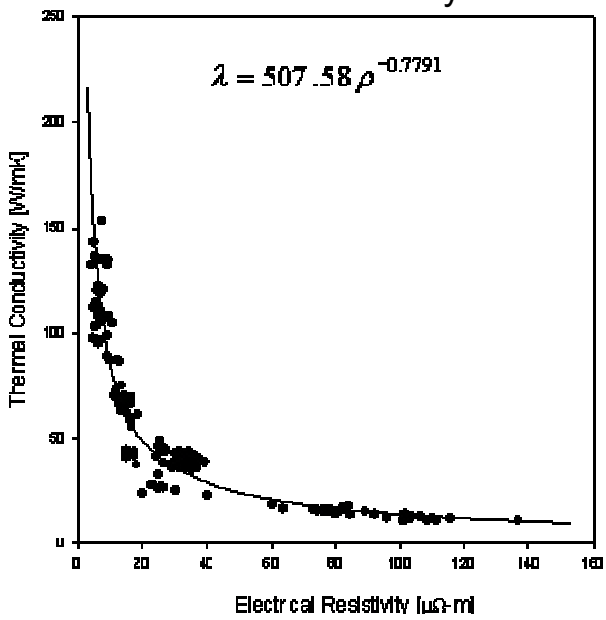
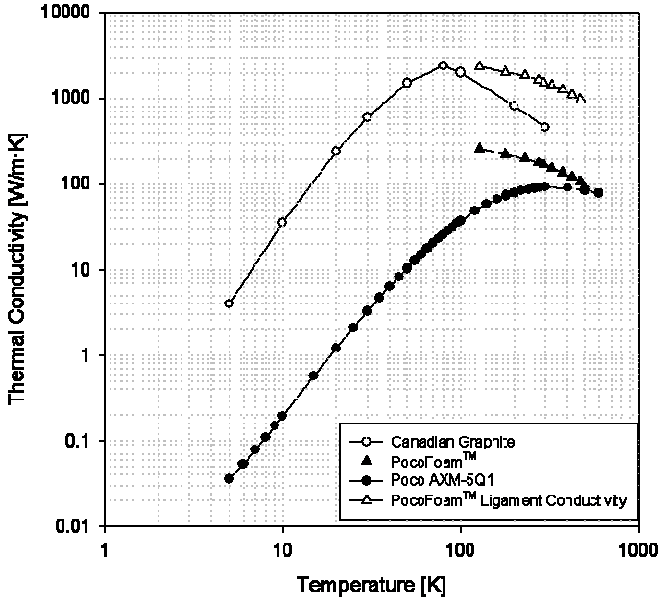
Thermal Conductivity vs. Electric Resistivity



Thermal Conductivity vs. Temperature



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Materials Properties

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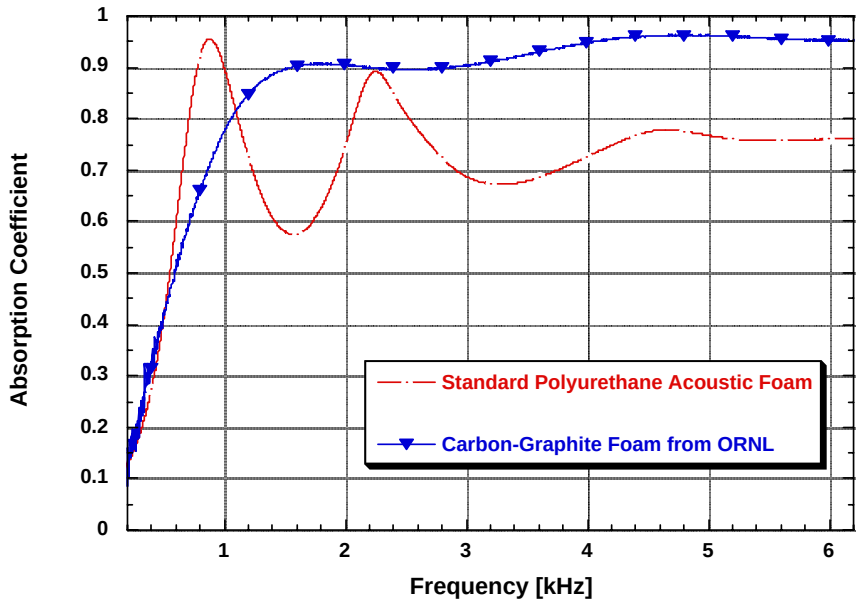
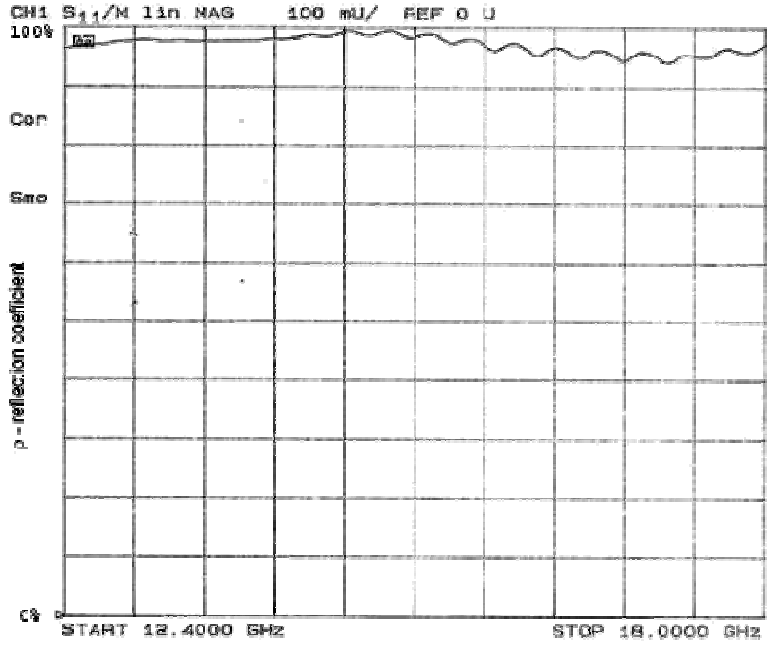
Acoustic Absorption of the Graphite Foam



EMI Shielding Effect of the Graphite Foam



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Graphite Foam Helps Computers Run Faster

Evaporative Cooling

FOR THE 21ST CENTURY

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Background

Current CMOS (complementary metal-oxide semiconductors) type microprocessors experience power densities up to 50 W/cm^2 and are cooled effectively with aluminum and copper heat sinks. However, as technology improves, high performance computer chips will likely experience power densities over 200 W/cm^2. The "flip-chip" design currently used in today's microprocessors has inherent problems. Here, the silicon die is inverted with the back of the printed chip oriented towards the top of the package. In this case, the integrated heat spreader (IHS) can be joined (typically with epoxy) directly to the silicon chip and cooled with a finned air cooled heat sink. Unfortunately, as the power increases above 100W, this can result in temperatures above design limits on the printed active layer in the chip, reducing reliability and shortening life.

The Technology

In cooperation between the National Security Agency (NSA) and the Laboratory for Physical Sciences (LPS), and the Oak Ridge National Laboratory, novel techniques involving alternative evaporators for cooling electronic chips with very high power densities have been demonstrated. A novel high thermal conductivity graphite foam developed and patented at Oak Ridge National Laboratory promises to overcome this limitation. This material is a graphitic foam with high bulk thermal conductivity (up to 180 W/m·K) and an open porous structure with more than 2 orders of magnitude greater surface area than the diamond wafers, see Figure 1. The cell walls are made of oriented graphitic planes and exhibit thermal conductivities in excess of 1640 W/m·K [klett]. Hence, we have a microporous heat spreader with significantly more surface area than the diamond spreaders/evaporators.

Figure 1 shows thermosyphon fabricated with the graphite foam bonded directly to the silicon die. Figure 2 shows a comparison of performance of the thermosyphon with the graphite foam compared to a thermosyphon without the graphite foam. As can be clearly seen, the graphite foam increases the heat flux significantly, while lowering the wall superheats.

These results are very impressive in that the CMOS chip was able to dissipate 150 W/cm^2 at a modest superheat of only 11C. What is more significant is that the actual temperature of the active layer on the chip, Figure 1, was less than 71C. Therefore, this demonstrated that a printed active layer temperature less than the limit of 85C can be attainable at powers as high as 150 W/cm^2 using the graphite foam. This is significantly better than any other previously reported literature data [ref. here].

Basically, a passive cooling device with no moving parts has been developed which can dissipate 150 W/cm^2 at silicon die temperatures less than 71C. There is no competition to this in that no other passive device has this heat dissipation capability.

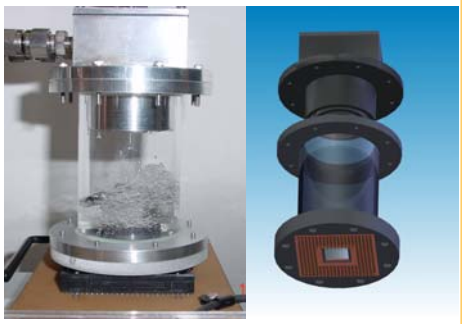


Figure 1. Thermosyphon with graphite foam evaporator

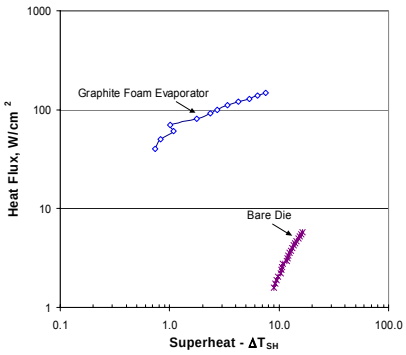
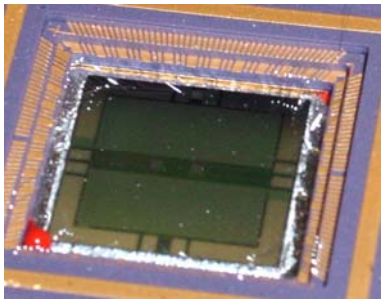


Figure 2. Performance of Graphite Foam Thermosyphon compared to traditional system with no evaporator.

Benefits

- **Totally passive design**
- **Devices utilizing ORNL graphite foam systems shown up to 150W/cm^2 heat dissipation at chip temperatures of 71°C.**
- **Represents >400% improvement in cooling power**
- **Further improvements are anticipated with design modifications**
- **The graphite foam's high ligament conductivity and very high specific surface area may lead to efficient wick, evaporator, and condenser materials for heat pipes**



Resistor Chip Wire Bonded in PGA Package

For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Bob Leicht
National Security Directorate
Ph: (865)-574-3032
stouderrl@ornl.gov

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Graphite Foam Aftermarket Heat Sinks

Evaporative Cooling

FOR THE 21ST CENTURY

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Background

Current sate-of-the-art heat sinks are finned aluminum with a copper spreader of some sort (see Figure 1). The copper spreads the heat as much as possible without sacrificing weight. The aluminum reduces mass, while maintaining heat transfer. Typical heat sinks, such as the TI-V707TN by Thermal-Integration™, are mounted to the top of the chip package and a standard commercial fan is used to force air over the fins at up to 5500 rpm. This speed is the limit due to noise problems, rather than the physical limits of the fan. At these speeds, the best thermal resistance reported for this heat sink is around 0.44 °C/W. In addition, weight of these heat sinks is a concern, as during shipping, the heat sink is creating a large moment arm that can vibrate and crack the mother board. Hence, if the evaporative cooling technique can be applied to this modular heat sink design and result in either a reduction in weight or thermal resistance (or both), the product would be useful.

The Technology

The design of the heat sink was simple (Figure 2), and comprised of an aluminum housing, foam bonded to base of housing, and a condenser lid. The Foam was bonded to the base of the aluminum housing with the MRi process. The condenser lid was then bonded to the housing creating an internal cavity. A heater was attached to the bottom surface of the base with thermal grease and held in place by small drops of epoxy at two corners. A flat micro thermocouple was also placed between the heater and the base, in the thermal grease. A commercial cooling fan, TR2-M2, used in an aftermarket heat sink by Thermaltake, was used to supply the air over the condenser lid at a fan speed of 5600 rpm. After assembly, the Fluroinert™ FC-87 was backfilled into the evacuated chamber, boiled to de-air the system, and then sealed. Tests were conducted by incrementally increasing power to the heater and recording the internal vapor temperature, the interface temperature, and the heater temperature.

Using the internal vapor temperature and the heater temperature, the thermal resistance to boiling and the overall thermal resistance can be calculated as a function of power input. As can be seen in Figure 3, the internal resistance decreases between 1 and 20 W input, most likely the point at which nucleate boiling is starting to occur, and then levels out to a uniform thermal resistance of nearly 0.08 °C/W. However, it can also be noted that the overall resistance is significantly larger, nearly 0.31 °C/W. Clearly, the thermal resistances other than the boiling are a large part of the overall resistance and optimization of the system can result in an excellent heat sink.

Figure 1. Thermosyphon with graphite foam evaporator

Figure 2. Thermosyphon with graphite foam evaporator

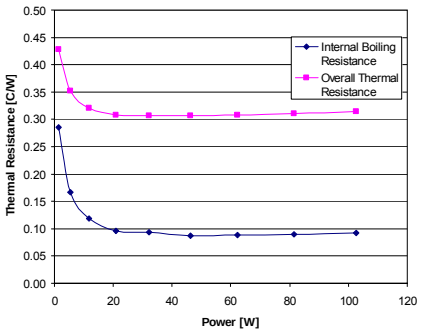
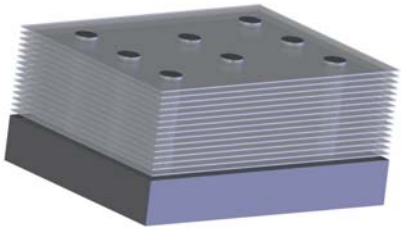


Figure 3. Performance of Graphite Foam Thermosyphon compared to traditional system with no evaporator.

Benefits

- **Totally passive design**
- **Thermal Resistances of an aftermarket type heat sink can be reduced substantially**
- **Models show a 50% reduction in thermal resistance**
- **Reduction of weight can be attained**



Potential Thermosyphon using aluminum fins and a vapor chamber with graphite foam evaporator

For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Rich Stouder
National Security Directorate
Ph: (865)-574-3053
stouderrl@ornl.gov

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Graphite Foam Helps Spray Cooling go to IRAQ

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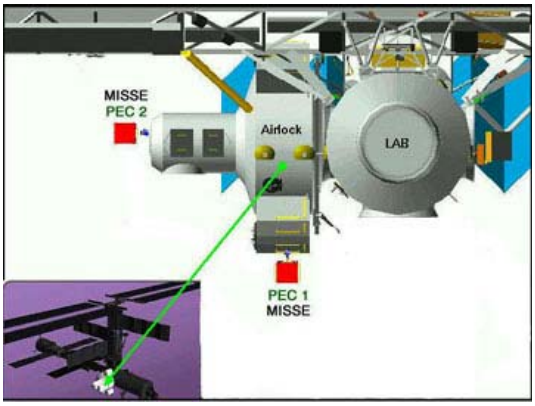
Space Applications

FOR THE 21ST CENTURY

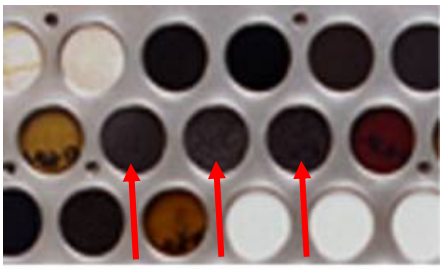
Background

The carbon foam experiment, developed by a team representing ORNL, Air Force, and West Virginia University (WVU) traveled recently on the shuttle Discovery to its destination aboard the International Space Station (ISS).

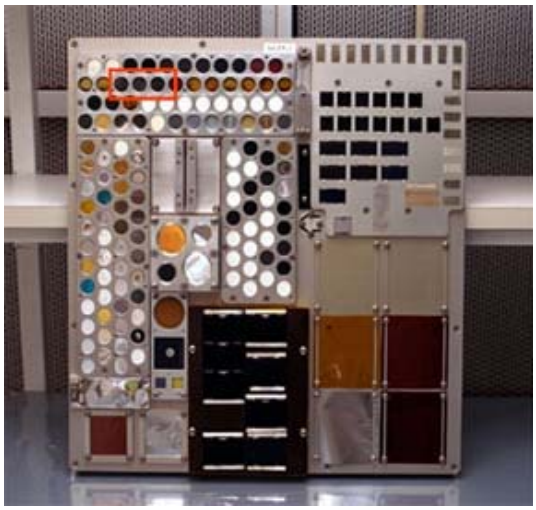
The Materials International Space Station Experiment or MISSE (pronounced 'Missy') consists of two suitcase-like containers, each holding hundreds of samples of advanced materials. The carbon foam experiment is packaged in one of these 'suitcases'. Foam produced by ORNL's James Klett under the DOE's Office of Transportation Technologies, along with foam produced by both the Air Force and WVU are part of the experiment. On August 16, shuttle crew members attached the suitcases to the outside of the space station and opened them, exposing the material samples to the harsh environment of space. MISSE is the first externally-mounted science experiment on the ISS. The suitcases will remain in place for one year, when they will be returned to Earth, where scientists will examine the materials and study the effects of their exposure.



An artist's rendering illustrates where the suitcase experiment will be located on the ISS.



WPAFB, ORNL, and WVU carbon graphite foams



The photo at left shows the exact location of the foams within the suitcase (outlined by the red rectangular box).

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Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Bob Leicht
National Security Directorate
Ph: (865)-574-3032
stouderrl@ornl.gov

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Graphite Foam Enables New Space Technologies

Space Radiators

FOR THE 21ST CENTURY

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Background

Lockheed Martin has flight qualified a radiator for Spacecraft applications made from graphite foam (PocoFoam®)

> One of the XSS-11 mission goals is to perform space flight demonstration of technologies needed for future space missions, but unclassified and classified.
>
> It Also will be flown on another classified spacecraft.

The Technology

Deploying tiny probes to inspect or service spacecraft in distress and flying satellites that can operate with limited human touch are the chief goals behind a state-of-the-art technology demonstration mission successfully launched into Earth orbit this morning.

The Air Force Research Laboratory's Experimental Satellite System-11 craft reached space aboard a four-stage, $18 million Orbital Sciences Minotaur rocket. Liftoff occurred at 1335 GMT (6:35 a.m. local time; 9:35 a.m. EDT) from the Space Launch Complex 8 pad on the southern edge of California's Vandenberg Air Force Base.

Officials confirm that the XSS-11 spacecraft separated from the launcher as planned and has begun its initial activities.

"Everything looks good," an Orbital spokesman said. "Early preliminary indications look like (the satellite) is healthy. It was an accurate launch, right in the middle of the box."

Over the coming weeks, controllers will conduct a fundamental checkout of the satellite's main systems.

The first real test of the XSS-11's rendezvous sensors and technology is expected sometime in the next three to six weeks when the craft revisits the Minotaur fourth stage.

"That is really where we get the basic performance parameters for the sensors," said Harold Baker, XSS-11 program manager at the Air Force Research Lab.

The mission will last 12 to 18 months as XSS-11 demonstrates new autonomous satellite features during encounters with six or seven spent rocket stages and dead U.S. satellites.

The microsatellite project is designed to test technologies that could allow quick visual examinations or maintenance of spacecraft in orbit.

"This satellite represents a significant advance of what's ever been done in space before," Baker said. "Proving these technologies could have considerable impact on the amount of money it takes to operate a satellite, to launch a satellite, to build a satellite."

At the heart of XSS-11 is a radiation-hardened Power PC 750 processor that serves as the master avionics box, enabling onboard autonomous operations and mission planning by the satellite itself.

"The real technology is in the autonomous planner onboard and the logic algorithms that are required to do that mission, as well as the ground tools," Baker said.

The U.S. military has spent $56 million creating the XSS-11 spacecraft. Another $6 million has gone into mission operations over the life of the program.

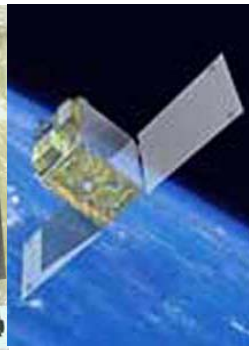
Ground controllers will be actively involved in the early rendezvous attempts, but hope to gradually wean XSS-11 from human intervention.

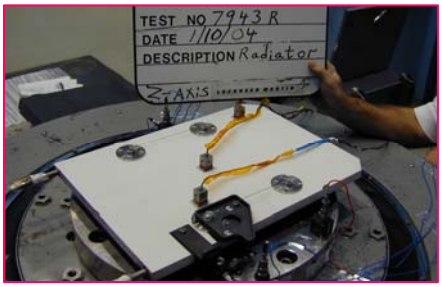
"From the beginning, safety has been foremost in our minds. If we collide with an object, we fail. So initially we let the planner plan, but it has many, many ground decision points that have to be reached before it can proceed on its own," Baker said.

"As we proceed through the mission, we take some of those points out as we get more confidence that the planner is doing the right thing and it's agreeing with what we are seeing on the tools on the ground. As we go through the mission, we will take more and more of those go/no go decision points out that are given from the ground. The objective by the end of the program is have as many of those, if not all those, out and tell it what you want it to do and have confidence it is going to succeed."

Benefits

- **The foam acts as heat spreader and reduces the size and weight of space radiators**
- **Mission life can be extended**
- **More satellites can be launched in one launch**





For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Bob Leicht
National Security Directorate
Ph: (865)-574-3032
stouderrl@ornl.gov

July 2005

http://www.skyrocket.de/space/doc_sdat/xss-11.htm

Graphite Foam Helps Keep Soldiers Cool

Microclimate Cooling

FOR THE 21ST CENTURY

U.S. Department of Energy

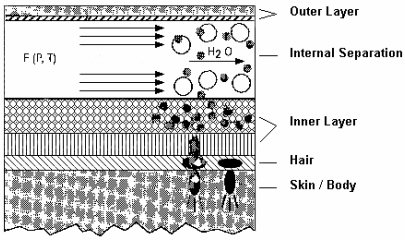
Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

Heat stress has been a problem for military personnel since armies first operated in hot environments. Greek and Roman soldiers suffered from the heat in addition to the physical burden imposed by the weight of body armor and weapons whenever they fought in the Middle East or Southwest Asia. During the 1967 War between Israel and Egypt, the Egyptian army sustained over 20,000 heat casualties. Today's warfighter faces the same problem; a combination of physical workload and lack of cooling diminish the performance of highly trained individuals.

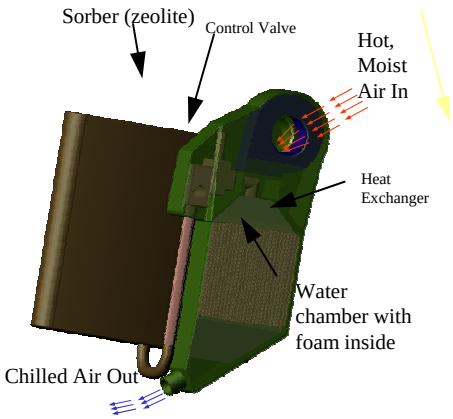


The Technology

Numerous military and civilian occupations expose workers to high thermal stress, impairing performance and increasing injury risk. This problem is exacerbated for workers using encapsulating clothing ensembles (e.g., chemical or fire protective clothing). This paper reports on an effort by the authors to develop a man-mounted air-based cooling system that permits sustained operations under thermal stress. Approach: A desiccant (zeolite)-based heat pipe is under development that utilizes water as the heat transfer medium which is adsorbed by a zeolite bed. The cooling system is designed to integrate with a ventilated garment to exploit the body's evaporative cooling capacity. Cooling efficiency is attained by blowing cool, relatively dry air over the user's body surface and evaporating sweat. The system is designed to provide 300 L/min ventilation with a sustained temperature change (ambient – cooler output) ≥10 degrees C at ambient conditions = 32.2 degrees C, 30% RH. Evaporative cooling greatly enhances a convective cooling capacity roughly = 60W, based on a change in enthalpy = -9.80 kJ/kg across the heat exchanger capacity, to approximately 365W (assuming maximal sweat evaporation). The system is sized (mass of zeolite and internal water, power supply) to operate up to 3 hours at full efficiency. Current total system weight is approximately 5.9 kg with a target weight ≤ 4.5 kg and is configured to fit on a U.S. Navy helicopter crewman vest. Results: The prototype system has performed up to specifications during benchtop testing (roughly 170 min at temperature change ≥ 10 degrees C).

Benefits

- **The foam acts as heat spreader and enhances the performance of the air side heat exchanger**
- **The high thermal conductivity of the foam allows very rapid control of temperature, thus allowing biometric feed back to control the system**



For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Jon Kaufman
NAVAIR PAXRIVER
Ph: (301)-342-8883
stouderrl@ornl.gov

July 2005

Graphite Foam Enables New Friction Applications

Bearing Applications

FOR THE 21ST CENTURY

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

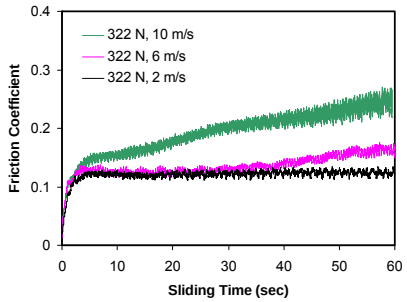
High thermal conductivity graphite foam, developed by researchers at Oak Ridge National Laboratory, has shown considerable promise for use in electronics cooling systems and vehicle radiators. With a thermal conductivity comparable to that for aluminum and one-fifth of that metal's density, this material has the potential to solve thermal management problems in a variety of industrial and military applications. Several forms of graphite have lubricating characteristics.

In order to overcome the limitations of the as-formed graphitic foam, a novel densification process has been developed at the US Air Force Research Lab Propulsion Directorate, Edwards AFB, CA and licensed to SMJ Carbon Technology. A hydrocarbon feedstock, such as naphthalene, is impregnated into raw graphitic foam. Then under pressure and elevated temperature, the naphthalene is converted to mesophase pitch, which at higher temperatures is eventually converted to a graphitic structure to form a foam-reinforced carbon-carbon composite. The structures of graphitic foams before and after densification are shown in Figs. 1(a) and 1(b), respectively. The density, thermal conductivity, and compressive strength increase significantly after densification. That process makes the densified foam suitable for a wider range of applications.

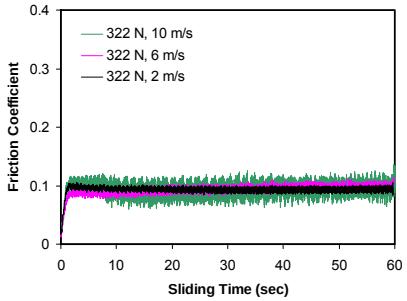
The Technology

While the use of ORNL developed high-thermal-conductivity graphitic foam materials has been focused on thermal management applications, recent experiments have revealed their potential as bearing surfaces as well. The three primary tribological advantages are (1) they can efficiently remove frictional heat, (2) their natural porosity can trap wear debris, and (3) their porosity can serve as a lubricant reservoir for the contact surface. A series of pin-on-disk experiments were conducted at both room temperature and 400 °C to compare the sliding friction and wear characteristics of the densified graphitic foam (mated against M-50 tool steel or against alumina) to those of conventional bearing materials like graphite, bearing bronze, poly-tetrafluoroethylene, bearing steel, and a Co-based superalloy. At room temperature and under low contact pressure, the tribological behavior of the densified graphitic foam material was comparable to that of graphite and better than that of other bearing materials. At 400 °C, traditional graphite exhibited a 'dusting' wear regime accompanied by a high friction coefficient. In contrast, the graphitic foam demonstrated an ability to maintain low friction and wear at that temperature.

Poco AXM-5Q

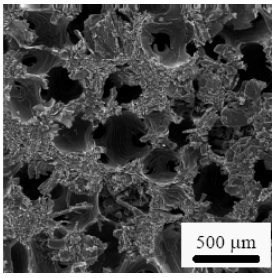


Densified Graphite Foam

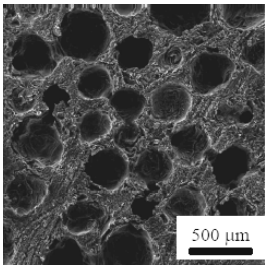


Benefits

- **Friction Coefficient remains constant during operation**
- **Friction Coefficient does not change with temperature**
- **Friction parts effectively remove heat while providing excellent friction**



Raw Graphite Foam



Densified Graphite Foam

For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Richard Stouder
National Security Directorate
Ph: (865)-574-3053
stouderrl@ornl.gov

July 2005

Graphite Foam Enables Lighter Cold Plates

Thermal Sinks

FOR THE 21ST CENTURY

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

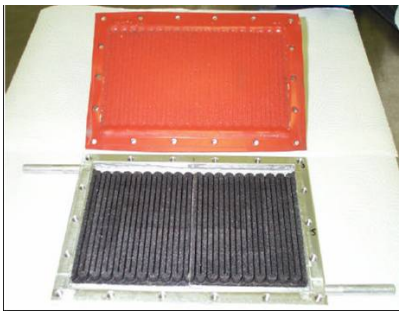
Background

Approximately two thirds of the world's energy consumption is wasted as heat (i.e. incandescent light bulbs, internal combustion engines, air conditioning, power plants, etc.). This will likely get worse as the power levels of computer processors and other electronic devices increase. Computer chips with power up to 1000 watts may be commonplace in less than 5 years, unfortunately, the cooling means is not available at an affordable rate. High efficiency heat exchangers are being incorporated into computers and electronics to recover some of the heat losses and increase efficiencies. The primary function of the heat exchanger in these applications is to reduce the temperature of the electronics, improving both life and reliability. The second task of the heat exchanger is to recover the energy and utilize it for other applications, thereby reducing the total energy consumed. Unfortunately, most heat exchangers dissipate captured heat from the electronics as low-quality heat (very low temperature compared to ambient). Subsequently, this recovered heat is simply dumped to ambient and wasted. A unique graphite foam developed at the Oak Ridge National Laboratory (ORNL) and licensed to Poco Graphite, Inc., promises to allow for novel, more efficient heat exchanger designs which can possibly dump high quality heat, allowing recovery of energy for other applications. This unique graphite foam, Figure 1, has a density between 0.2 and 0.6 g/cm3 and a bulk thermal conductivity between 40 and 187 W/m·K. The ligaments of the foam exhibit a thermal conductivity higher than artificial diamond and, in combination with a very accessible surface area (> 4 m2/g), the overall heat transfer coefficients of foam-based heat exchangers can be up to two orders of magnitude greater than conventional heat exchangers. As a result, foam-based heat exchangers could be dramatically smaller and lighter than conventional designs.

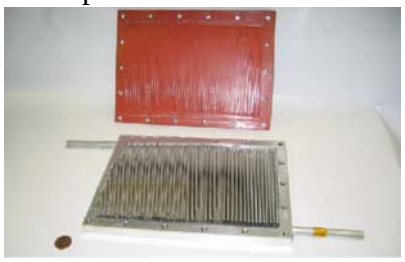
The Technology

By engineering a system, the large pressure drops found with foams can be minimized. As seen below, a corrugated (serpentine) design similar to the pleats in a standard filter, the pressure drop can be reduce by more than an order of magnitude. The fluid then flows down the channels and then across the webs (through) the small pores in the foam) and then out the channels. This process still exposes nearly 90% of the original mass of the foam ligaments to fluids for excellent heat transfer, but minimized pressure drop.

Due to the very high ligament conductivity, the heat from the source effectively travels to all the internal surfaces of the foam for transfer to the cooling fluid. To achieve the same thermal resistance, the graphite foam cold plate was shown to require 1/3 the amount of fluid (and 1/20th the pumping power) compared to a standard aluminum finned cold plate. Thus, cold plates can be made lighter, smaller and more efficient at the same time with graphite foam.



Graphite Foam Cold Plate

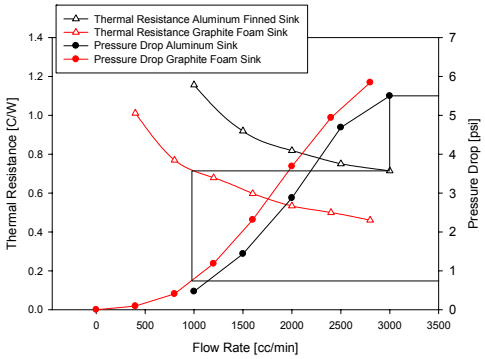


Aluminum Fin Cold Plate

Benefits

Graphite foam cold plates have several benefits.

- **Reduced Weight**
- **Reduced Size of cold plate**
- **Reduced volume of coolant required**
- **Reduced Pumping Power to achieve same thermal resistance**
- **Improved Designs**
- **Use of air instead of water**



For more information on how ORNL is helping America be secure in the 21st century, please contact:

James Klett
Oak Ridge National Laboratory
(865) 574-5220
klettjw@ornl.gov

Richard Stouder
National Security Directorate
Ph: (865)-574-3053
stouderrl@ornl.gov

July 2005