HIGH-TEMPERATURE CARBON FIBER RADIATOR FOR NUCLEAR ELECTRIC POWER AND PROPULSION: PROJECT OVERVIEW AND UPDATE. B. N. Tomboulian and R. W. Hyers, University of Massachusetts, Amherst, 160 Governors Drive, Amherst, MA 01003, btomboul@engin.umass.edu.

Introduction: This is an update on the paper presented at NETS 2013 on the development of a high-temperature carbon fiber radiator for nuclear electric power and propulsion applications. NASA has stated that advanced, lightweight radiators will be enabling technologies for next-generation in-space power and propulsion systems [1]. In an effort to both decrease the radiator areal density and increase the maximum operating temperature, this work investigates the use of carbon fiber fins as an alternative to metal and composite fin materials. In addition to high-temperature static power generators, advanced dynamic power generators may be designed with high-temperature (>500°C) heat rejection in order to gain radiative efficiencies. At elevated temperatures, the state-of-the-art polymer-carbon fiber composite radiators cannot be used [2]. With low density, high thermal conductivity, high heat tolerance, and intrinsically high surface emissivity, pitch carbon fiber possesses many unique characteristics that are extremely desirable for space-based radiator fins. This overview covers recent work on design and testing efforts.

Design Concept: The radiator temperature design point is 600°C based on the potential for advanced power converters. The radiator concept is to braze bare carbon fiber weave to sodium heat pipes, as shown in Figure 1, which interface with the pumped coolant loop on the cold side of a power conversion cycle. By using bare fiber weave (i.e., no matrix), the mass and overall thermal resistance of the fin are reduced. In addition, issues with thermal expansion mismatch when brazing fin material to heat pipes, as often encountered with brazing solid sheet fins to heat pipes [3], are eliminated because each fiber acts independently. First-generation test articles use simulated heat pipes with resistance heaters, while second-generation test articles will use sodium heat pipes.

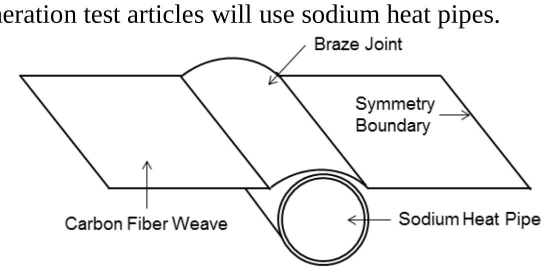

Figure 1. Fin-heat pipe design concept

Carbon Fiber Fins: The pitch carbon fiber (Mitsubishi K13D2U) selected for this study has an advertised axial thermal conductivity of 800 W/m-K, the highest thermal conductivity fiber currently available in continuous form. The pitch fiber microstructure consists of long graphite sheets, which give it the high thermal conductivity and also results in high stiffness. With a critical bend radius of about ¾-in, standard industrial weaving techniques are not possible and thus it is not available commercially. Therefore, weaving procedures were developed for this work. Figure 2 shows three test articles with fiber fins that were: 1) not woven (this was attempted first to determine if weaving was necessary), 2) woven using a preliminary weaving method, and 3) woven using the most current method that functions well.

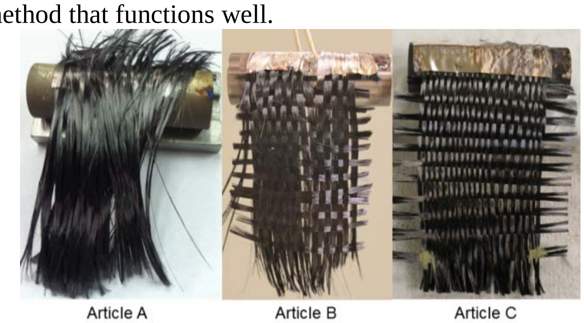

Figure 2. Evolution of carbon fiber fin test article.

Developing this more organized and robust weave has enabled us to build test articles and study the thermal properties of the fin. Since this is a critical manufacturing aspect of the design, an industrial weaving company (T.E.A.M. Inc.) has been commissioned to design a process to weave this fiber and produce samples for testing (this is in collaboration with a NASA Marshall Space Flight Center, Center Innovation Fund project).

Brazing Considerations: Of the common high-temperature chemical bonding mechanisms, brazing is the only mechanism suitable for joining bare carbon fiber with metal heat pipes. In essence, the braze joint becomes a matrix material to encapsulate the fibers, secure them to the pipe, and provide a direct heat conduction path to each fiber. Titanium-copper-silver (Ticusil) braze was selected because it contains titanium, which is necessary for bonding with carbon, melts at about 900°C (well above the target operating temperature), and has a relatively high thermal conductivity (219 W/m-K). The pre-braze assembly consists of a layer of Ticusil foil adjacent to the pipe, the fiber weave layer, and an outer Ticusil foil strip over the weave. The layers are secured with stainless steel wire until the brazing process is complete.

Brazing requires a vacuum or inert gas environment. To date, test articles have been brazed in a vacuum chamber with resistance heaters inside the simulated heat pipe. This technique has proven to be challenging because the braze joint does not reach isothermal conditions due to radiative heat dissipation from the fibers and tube, which leads to non-uniformity in the braze melt process (as shown in Figure 2 Article C). Figure 3 shows the most successful braze joint achieved by insulating the fibers to minimize heat loss and adding an IR heating lamp above the joint. Using a vacuum or inert gas furnace would ameliorate this problem and we are working to build such a facility.

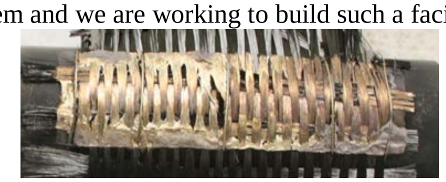

Figure 3. Test article braze joint

Test Results: Once the test articles are built, thermal performance tests are conducted. The bulk thermal conductivity of the fiber weave is an important property to estimate since it strongly influences the fin power rejection. To estimate the fin thermal conductivity, a temperature profile of the fin during operation, obtained from an IR image, is matched to a thermal model of the fin where thermal conductivity is the only free parameter. The thermal conductivity value in the model that minimizes the error between the IR data and the thermal model is the predicted property value. The surface emissivity and effective fin thickness are also not known precisely, however estimates are used in the model to bound the thermal conductivity. The surface emissivity, measured at NASA Glenn Research Center (GRC) at room temperature, is estimated to be 0.75±0.05 at 600°C. The effective fin thickness (i.e., assuming no void space between fibers) is taken as 0.12±0.01 mm as calculated by the number of fibers and actual fin thickness and width. At the extremes of thickness and emissivity, the thermal conductivity results ranged from 790-918 W/m-K and were much more sensitive to thickness.

Figure 4 gives an IR image of the test article during operation showing the location (black line) from which the temperature data was extracted. The largest uncertainty in the temperature measurement is in the user-defined surface emissivity. Figure 5 shows the temperature profiles from the IR data and corresponding thermal model for an emissivity of 0.75 and thickness of 0.12 mm. The thermal conductivity for this case was predicted to be 848 W/m-K, and the power rejected per meter width of fin when operated at 600°C is approximately 1.2 kW, corresponding to a fin specific power of about 50 kW/kg.

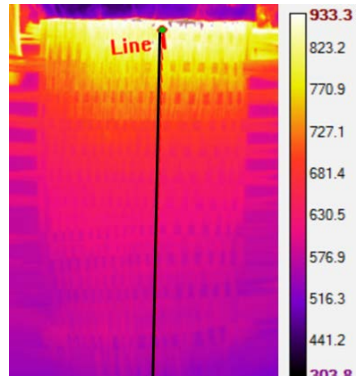

Figure 4. IR image of fin during operation

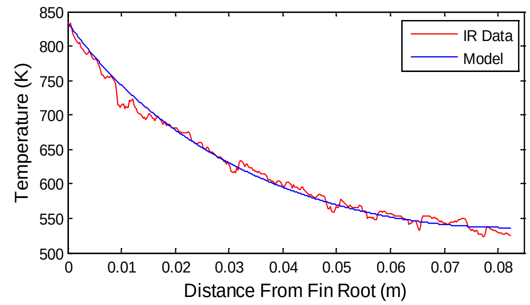

Figure 5. Fin surface temperature profiles

Heat Pipe Test Article: The next major improvement of the test articles and design TRL is to use real sodium heat pipes. Sodium is the optimal working fluid for high temperature radiators operating in the range of 500 to 1200°C. Three 6-in. long by ¾-in. diameter sodium heat pipes were fabricated at NASA GRC for this project. The heat pipes are designed to heat the fin root uniformly which will improve brazing consistency and fin power rejection measurements.

Future Work: Continued work on building heat pipe test articles and measuring power rejection is underway. Additional work on predicting the mass savings at the heat rejection sub-system level by using carbon fiber fins as compared with other high temperature fin options is ongoing and is an important part of demonstrating the game-changing potential of this technology.

References: [1] S.A. Hill, et. al. Office of the Chief Technologist (2010). [2] J. Siamidis. IECEC Conf. Proc. 4196 (2006). [3] H.B. Denham, *et. al.* AIP Conf. Proc. 301,1119 (1994).

Acknowledgments: The authors acknowledge Mr. Lee S. Mason for his guidance, Dr. Donald Jawarske for his assistance with the emissivity measurements, Mr. James L. Sanzi for fabricating the sodium heat pipes, the NASA MSFC team that provided the vacuum facility and imaging equipment, and the NASA Office of the Chief Technologist's Space Technology Research Fellowship for supporting this work.