# Development of Low Cost Radiator for Surface Fission Power - Final Stage

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**The paper reports on the final stage of development of a Low Cost Radiator to be integrated with Technology Demonstration Unit (TDU) at NASA Glenn Research Center (GRC). Fission power system technology is developed by NASA GRC for future Lunar and Martian surface power applications. The systems are envisioned in the 10 to 100kWe range and have an anticipated design life of 8 to 15 years with no maintenance. NASA GRC is currently setting up a 55 kWe non-nuclear system ground test in thermal-vacuum to validate technologies required to transfer reactor heat, convert the heat into electricity, reject waste heat, process the electrical output, and demonstrate overall system performance. The paper reports on the development of the heat pipe radiator to reject the waste heat from the Stirling convertors. Reducing the radiator mass, size, and cost is essential to the success of the program. To meet these goals, Advanced Cooling Technologies, Inc. (ACT) and Vanguard Space Technologies, Inc. (VST) are developing a single facesheet radiator with heat pipes directly bonded to the facesheet. The facesheet material is a graphite fiber reinforced composite (GFRC) and the heat pipes are titanium/water Variable Conductance Heat Pipes (VCHPs). By directly bonding a single facesheet to the heat pipes, several heavy and expensive components can be eliminated from the traditional radiator design such as, POCO™ foam saddles, aluminum honeycomb, and a second facesheet. As mentioned in previous papers by the authors, the final design of the waste heat radiator is described as being modular with independent GFRC panels for each heat pipe. Testing results on the radiator clusters are presented in the present paper. These tests were carried out in both ambient and vacuum conditions. While all the radiator clusters were tested in ambient, only the first radiator cluster was tested in vacuum in NASA GRC's vacuum chamber to accommodate the larger size of the cluster. Both rounds of vacuum testing are reported in this paper. The experimental results show good agreement with theoretical predictions. The ambient testing of the radiator clusters was also carried in two rounds: one round before pinching and a second round after pinching the fill tubes. Although a few heat pipes showed a slight gain of non-condensable gas (NCG) after pinching, the power rejecting capability did not change for any of the 8 radiator clusters. After a cost assessment was performed, the entire set of eight radiator clusters delivered to NASA GRC for integration with TDU.**

## Nomenclature

| | | |
|---|---|---|
| *ACT* | = | Advanced Cooling Technologies |
| *VST* | = | Vanguard Space Technologies |
| *GRC* | = | Glenn Research Center |
| *TDU* | = | Technology Demonstration Unit |
| *NCG* | = | Non-Condensable Gas |
| *GFRC* | = | Graphite Fiber Reinforced Composite |

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*VCHP* = Variable Conductance Heat Pipe
*RTD* = Resistance Temperature Detector

# I. INTRODUCTION

NASA Glenn Research Center (GRC) is developing fission power system technology for future Lunar surface power applications. The systems are envisioned in the 10 to 100kW$_e$ range and have an anticipated design life of 8 to 15 years with no maintenance. A nominal lunar fission surface power design has been developed and is shown in Figure 1[3]. The nuclear reactor supplies thermal energy to Brayton (or Stirling) convertors to produce electricity, and uses a heat pipe radiator to reject the waste heat generated by the convertors. The radiator panels must reject heat from both sides to achieve the highest efficiency; therefore, the optimum mounting position is vertical. The radiator panels contain embedded heat pipes to improve thermal transfer efficiency. Since the heat pipe evaporator is on the bottom, the heat pipes are gravity aided and can work as a thermosyphon. This is advantageous because the heat pipe is not required to pump the working fluid back to the evaporator against gravity. Heat is supplied to the heat pipes through a titanium/water heat exchanger that is coupled with the coolant loop in the radiator.

Currently, NASA GRC is developing a Fission Power System Technology Demonstration Unit (TDU)[2, 3, 4]. The TDU is a non-nuclear demonstration unit that will be tested in vacuum to demonstrate the performance of the integrated system. The primary goals for the early systems are low cost, high reliability and long life. To help achieve these goals, ACT, NASA GRC, and VST are developing a single facesheet direct-bond radiator; see Figure 2. The radiator will have VCHPs made from titanium that will use water as the working fluid and argon as non-condensable gas (NCG).

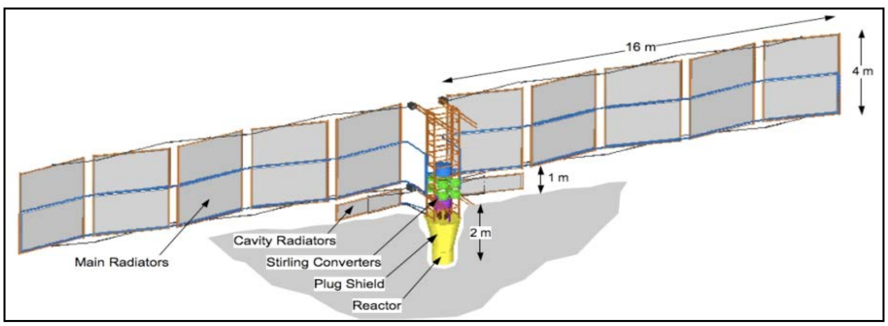



**Figure 1. Fission surface power system concept[2]**

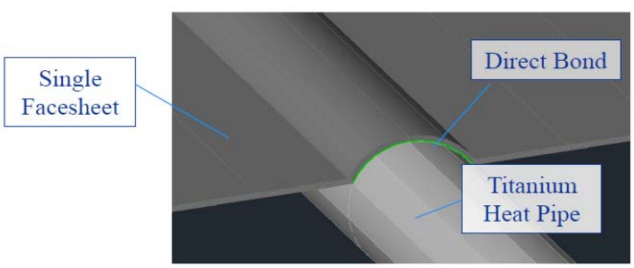



**Figure 2. Single facesheet radiator with direct bonding of the facesheet to the heat pipes[4]**

## A. Background

The single, direct-bond facesheet radiator has the advantages of reducing mass and cost of the system by eliminating the graphite foam saddles, aluminum honeycomb, and one of the graphite fiber reinforced composite (GFRC) facesheets, which are present in the previous ACT/VST heat pipe radiators[7].

ACT and VST have previously demonstrated the feasibility of the single facesheet radiator by fabricating and testing a small-scale, two heat pipe radiator panel[5]. Several papers related to this topic[1, 6, 7] and showing the current status of development of the Low Cost Radiator Development were presented where the final design was shown. It was decided that a 0.75 in. (1.91 cm) heat pipe condenser O.D. was more suitable for TDU integration, since it lowers the risk of composite fiber breakage during facesheet direct bonding. The larger diameter pipes also allow for more heat transfer area between the pipes and facesheet, thus lowering the thermal resistance and reducing the necessary number of heat pipes (radiator modules). Table 1 1 summarizes the geometry, predicted thermal performance and mass of the final radiator design.

Prior to the radiator cluster fabrication and testing, a significant amount of development was performed for the radiator module that consists of a heat pipe and the corresponding GFRC facesheet directly bonded to the condenser. The details of this development were presented in a previous paper[1]. In conclusion, the power rejected by the module in both ambient and vacuum were in agreement with the predictions. Also, it was decided that the evaporator length will be 5.5in (13.7 cm) for two of the radiator clusters and 7in (17.8 cm) for the rest of six radiator clusters. The current paper presents the development of the radiator clusters.

**Table 1. Summary of final radiator design**

| Geometry | 0.75" Cond. OD Design |
|---|---|
| Evaporator Length (cm) | 13 |
| Adiabatic Section Length (cm) | 7.62 |
| Condenser Length (cm) | 170 |
| NCG Reservoir Length (cm) | 7.62 |
| Fin Width Overhang (cm) | 12 |
| Total GFRC Area ($m^2$) | 42.36 |
| Total Number of Heat Pipe Modules | 96 |
| Total Number of Heat Pipe Clusters | 12 |
| Heat Pipe Redundancy Compared to Nominal Radiator (i.e. 36kW, 175K Sink, 400K inlet) | 23 |
| % Margin by Area Compared to Nominal Radiator | 24 |
| **Thermal Performance & Mass** | |
| Total Power Output (kW) | 40 |
| Specific Power (W/kg) | 609.0 |
| Dry Mass of Single Heat Pipe/Fin Module (kg) | 0.685 |
| Total Dry Mass of Radiator System (kg) | 65.74 |

## II. HEAT PIPE RADIATOR CLUSTER DEVELOPMENT

The plan in the beginning of the program was that only the first radiator cluster will be tested in vacuum at NASA GRC's vacuum chamber. Since this cluster was the first one, it has short (5.5in, 13.7.cm) evaporators, as shown in Figure 3 3. As soon as the cluster arrived at ACT valves were installed on the heat pipes and the heat pipes were charged with water. A flow meter was installed and RTDs were placed in the hot water supply stream before and after the cluster for calorimetric measurements.

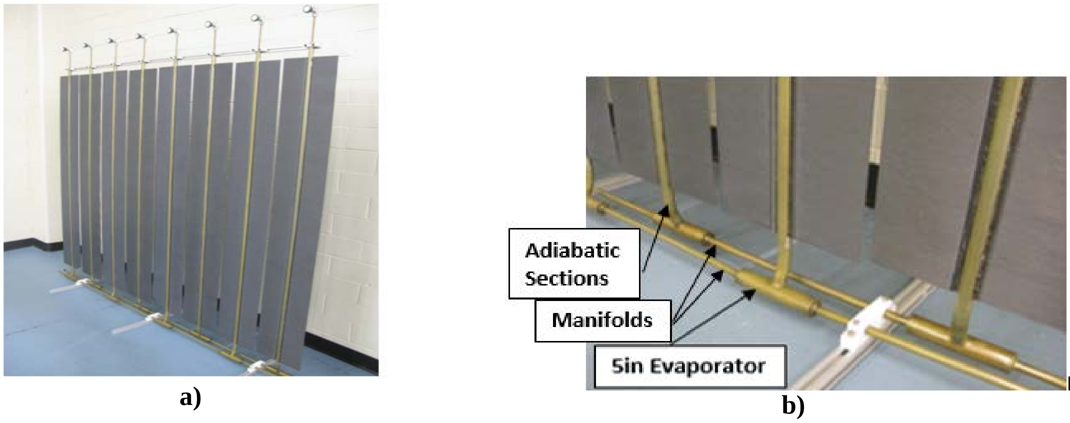



**Figure 3. First cluster a) Actual radiator cluster b) Detail showing the manifolds, the heat pipe evaporators and adiabatic sections**

### A. Full Testing in Ambient at ACT

After a preliminary testing the cluster was fully instrumented and also charged with NCG. Figure 4 shows the thermocouple map used for both full ambient testing at ACT and future vacuum testing at NASA GRC. As it can be seen, each condenser was provided with 6 TCs marked as P1C1, P1C2 …P1C6 …P8C1…P8C6. The condenser TCs were installed on GFRC and not on the titanium pipe. The reservoirs had one TC each marked as P1R …P8R. The adiabatic sections also have one TC each marked as P1A …P8A. In addition to the two fluid "in" and "out" RTDs, 6 other TCs were installed on the manifold surfaces between the evaporators. These thermocouples are marked as CC1 …CC6.

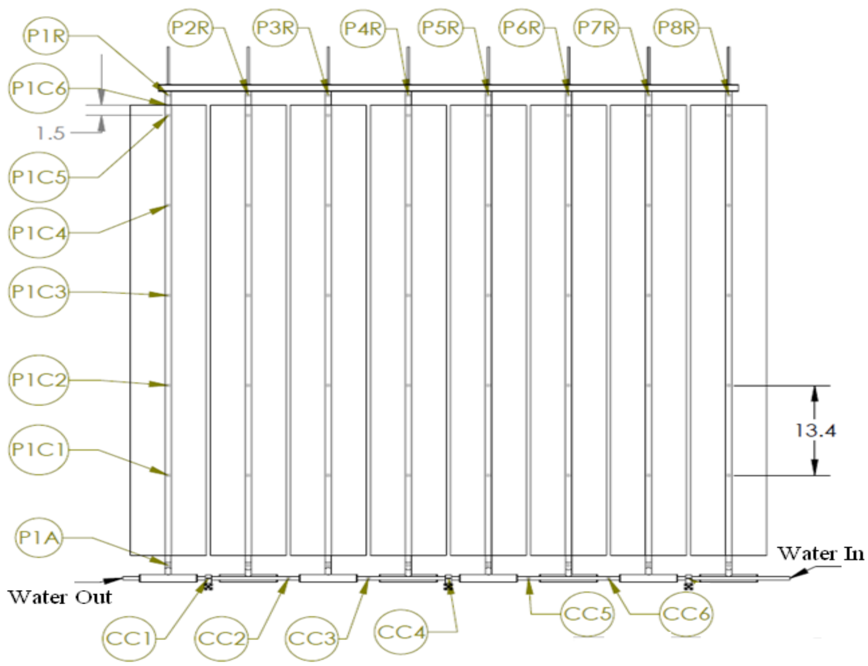



**Figure 4. Thermocouple map on the first cluster**

The actual testing consisted of a power test for various water inlet temperatures. The sink temperature was always ambient (21ºC) and the flow rate was always 6 GPM (22.7 L/min). Since the two manifolds are connected in parallel, it was assumed that the flow rate per manifold was approximately 3 GPM (11.35 L/min).

Figure 5 shows the power test results in ambient at ACT. As seen, the water inlet temperature was increased in steps from ambient all the way to the nominal value of 127°C. The intermediate steps were at 40°C, 70°C and 100°C. At each temperature step steady state was allowed to be reached. The maximum rejected power was again ~3.5 kW. However, there was conservative aspect of this test that is described in more detail below.

During this experiment the heat pipes worked as VCHPs and not as CCHPs. As the next plots will show, the NCG charge is slightly too large which prevented the heat pipe condensers to be fully active at nominal water inlet temperature. As a consequence, it is expected that the panel would reject more than 3.5 kW in ambient conditions at nominal water inlet temperature and flow rate if the NCG amount is properly adjusted.

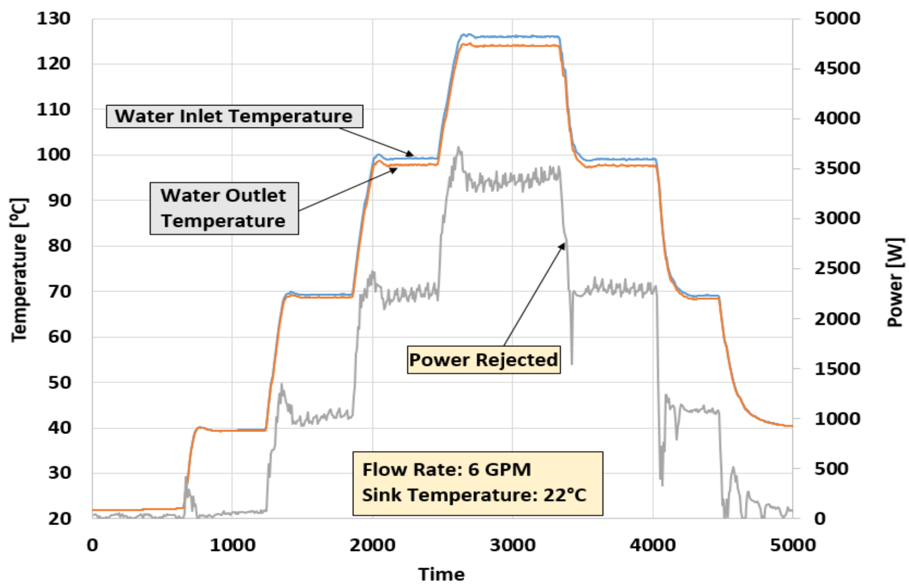



**Figure 5. Power test: heat rejected for various water inlet temperatures**

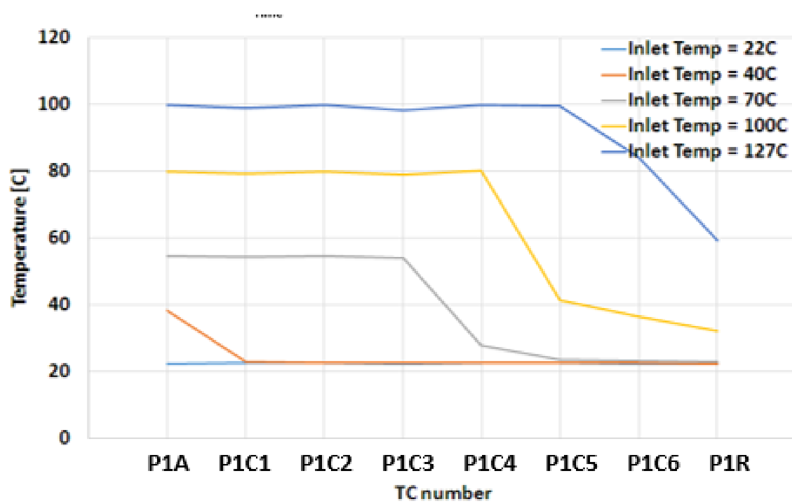



**Figure 6. Steady state temperature profiles along Pipe No 1 corresponding to each water inlet temperature**

Figure 6 shows temperature profiles along the heat pipe number 1 during steady states at each water inlet temperature. This representation was necessary to evaluate the active length of the condenser. Indeed, it can be observed the NCG is slightly oversized. This is shown mainly by the temperature profile at the nominal water inlet temperature of 127°C where TCs P1C6 and P1R show lower temperatures when compared to the rest of the thermocouples. More complete analysis (not shown here) revealed similar temperature distributions in each pipe.

The slight NCG apparent overcharge is due to the fact that the charge was calculated for a nominal sink temperature of -23°C rather than 22°C. As a consequence, the warmer reservoir caused a shorter active length of the condenser.

### B. First Round of Vacuum Testing at GRC: 100ºC Maximum Inlet Temperature

The first cluster was tested in vacuum in two rounds. During the first round the nominal parameters could not be used because of various reasons. In other words, sink temperature was 2ºC (compared to the nominal value of -23ºC), water inlet temperature and flow rate were 100ºC and 3.9 GPM (14.8 L/min) respectively compared to the nominal values of 127ºC and 6GPM (22.7 L/min), respectively. Therefore, a second round of testing where water inlet temperature was nominal was performed at a later time. This paper presents both sets of results.

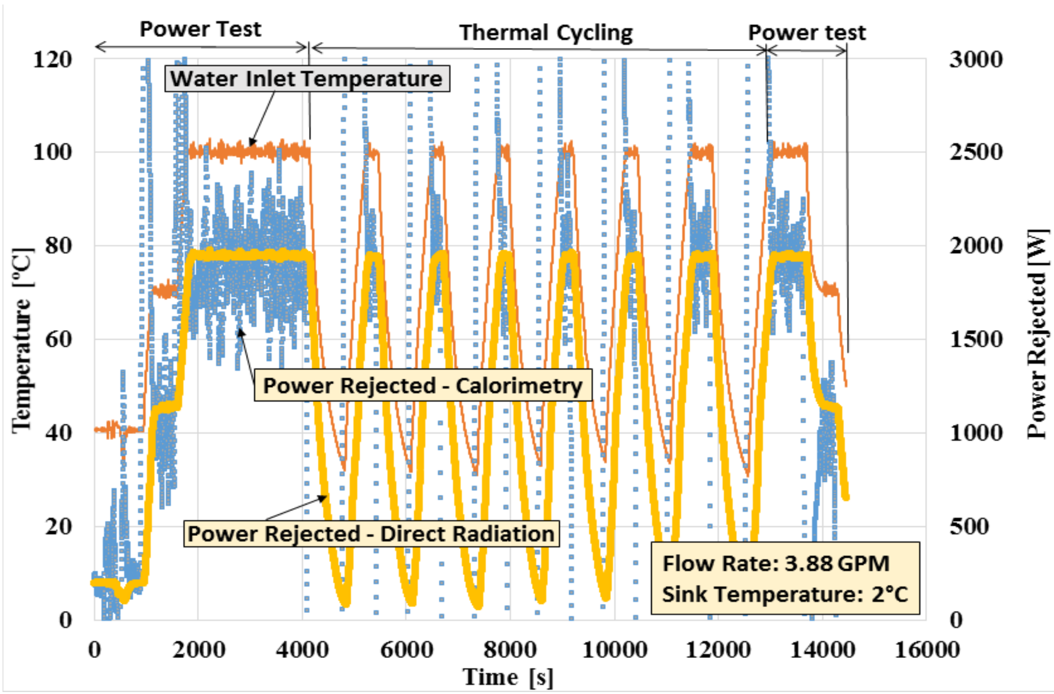



**Figure 7. Radiator cluster testing in vacuum – first round. Testing was carried as power test, thermocycling and power test again.**

The actual test consisted of a power test, followed by thermocycling and another power test to verify the status of the thermal resistance of the direct bond between GFRC and the titanium condenser. The water inlet temperatures during the two power tests were 40ºC, 70ºC and 100ºC.

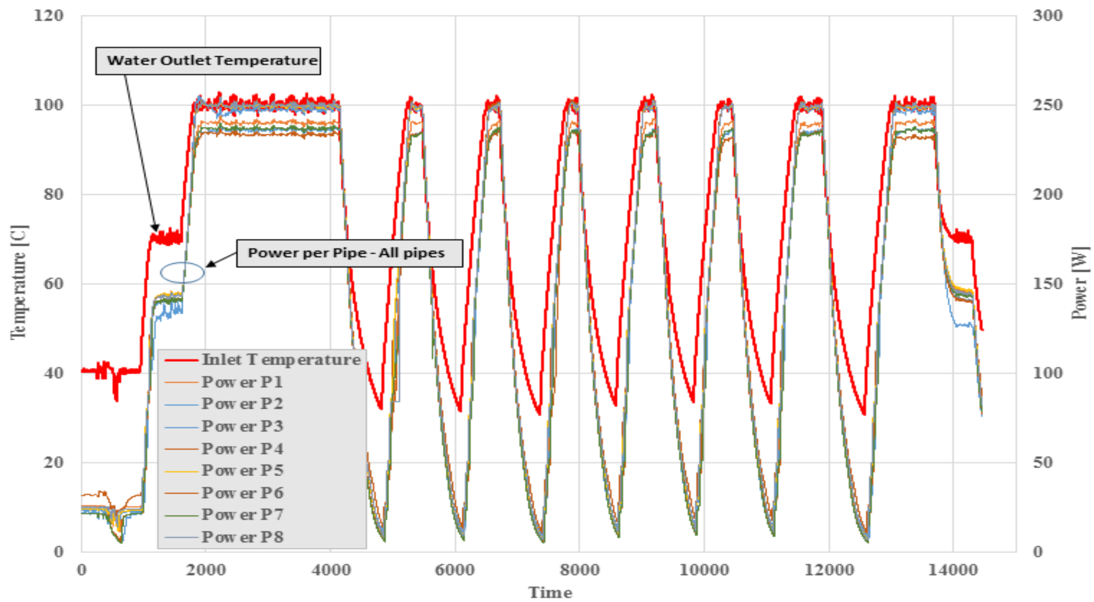



**Figure 8. Power rejected by each module to validate the calculation method that was used to evaluate the total power during the first round of vacuum testing (max outlet water temperature was 100ºC)**

During the thermal cycling sequence, the water inlet temperature was varied between 100ºC and ambient. Water flow rate and sink temperature were always 3.88 GPM (14.7 L/min) and 2ºC, respectively. As seen in Figure 7, two rejected powers are represented: one power resulted from calorimetric calculations and is represented by a highly scattered succession of data points, while the other power resulted from radiation calculations based on temperatures measured on each panel. As it can be observed, the agreement between the two power representations is good. It can be concluded that the power rejected by the radiator at 100ºC water inlet temperature is 1.94 kW. Moreover, the rejected power after thermocycling did not change for all three water inlet temperatures. This fact confirms the integrity of the bond. Other conservative factors are discussed below in the conclusion section.

Figure 8 shows the performance/power rejected by each module to validate the calculation method that was used to evaluate the total power. All eight pipes delivered maximum powers in a range between 230 and 250W. Again, the conservative factors are discussed in the end of this section.

## C. Second Round of Vacuum Testing at GRC: 127ºC Maximum Inlet Temperature

A second round of testing was completed at NASA GRC where the nominal water inlet temperature of 127°C was reached. The sink temperature remained at 2°C and the flow rate remained relatively the same. The power rejected through direct radiation along with the inlet water temperature can be observed in Figure 99. Three cycles were performed, consistently showing a max power of about 2.87 kW at 127°C. The flow rate was not recorded in the second round of testing. However through comparison of performance results from both rounds of testing it is shown that both conditions rejected 1.9 kW at 100°C water inlet temperature. In conclusion the flow rate was not nominal (~4 GPM or 15.12 L/min).

Figure  shows the performance/power rejected for each module. All 8 pipes delivered maximum powers in a range between 345 and 360W.

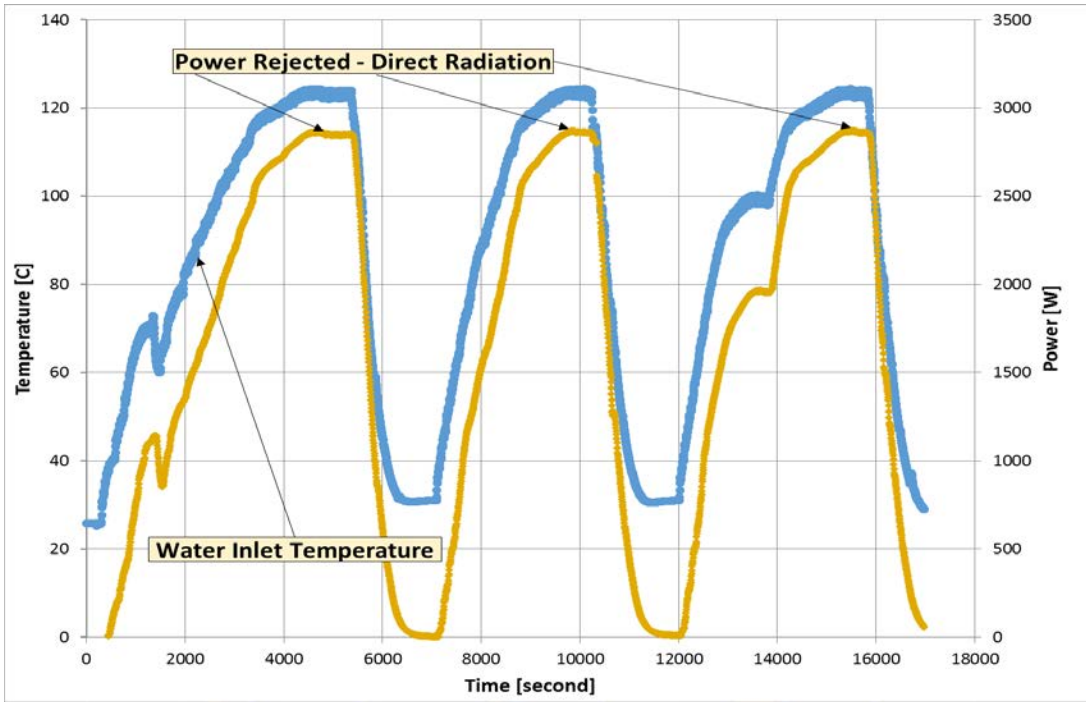



**Figure 9. Power rejected in vacuum during the second round of testing when maximum inlet water temperature was 127°C**

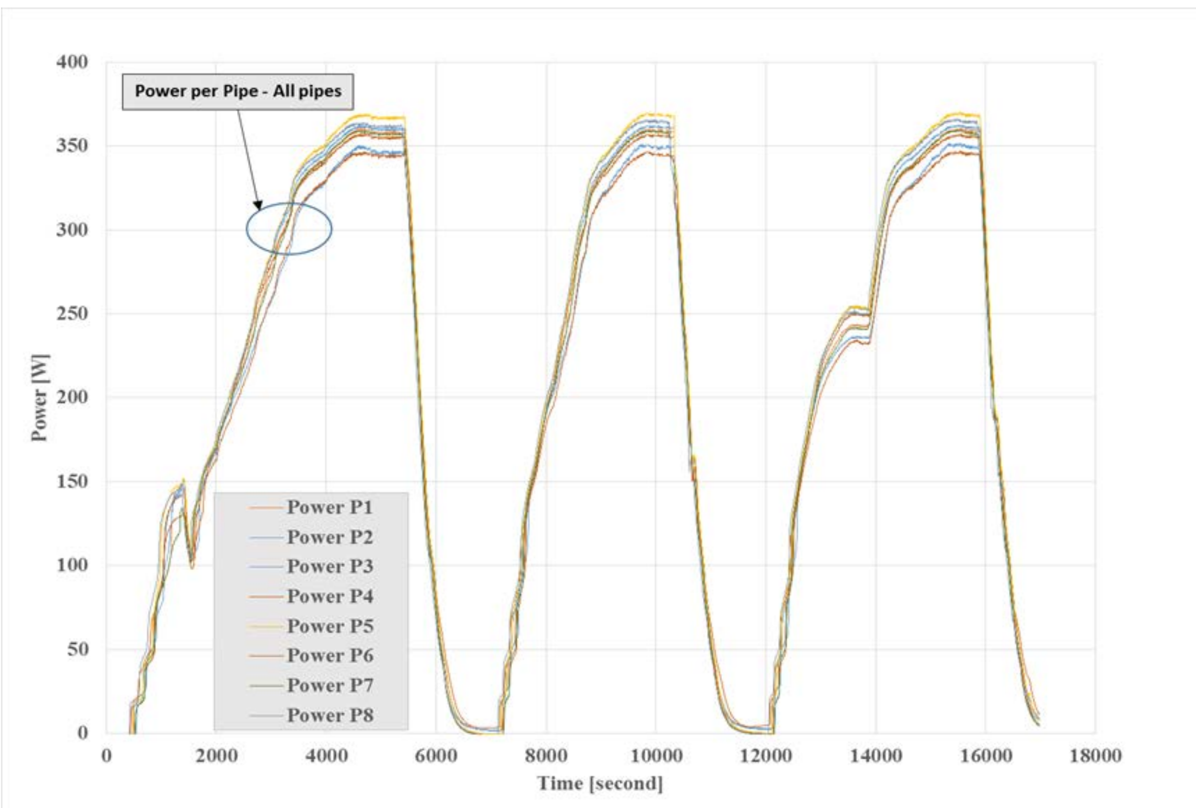
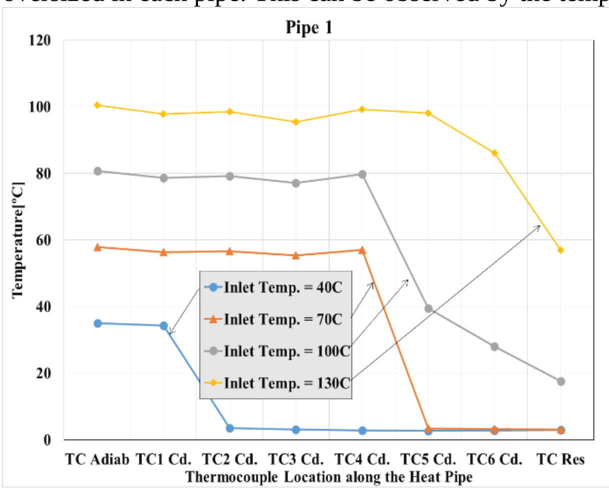
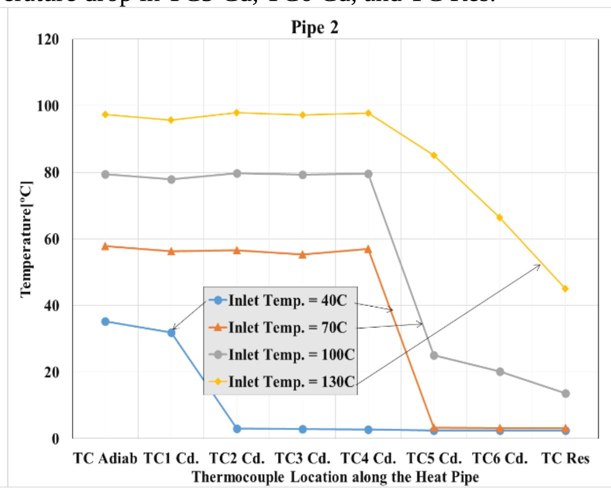



**Figure 10. Power dissipated by each individual module/condenser**

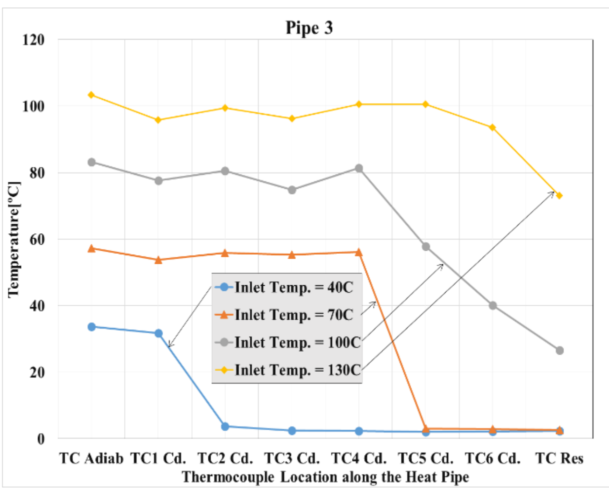
Figure  shows temperature profiles along each pipe during the steady states at each temperature. The representation was necessary to evaluate the active length of each condenser. Indeed, it can be observed the NCG is slightly oversized in each pipe. This can be observed by the temperature drop in TC5 Cd, TC6 Cd, and TC Res.



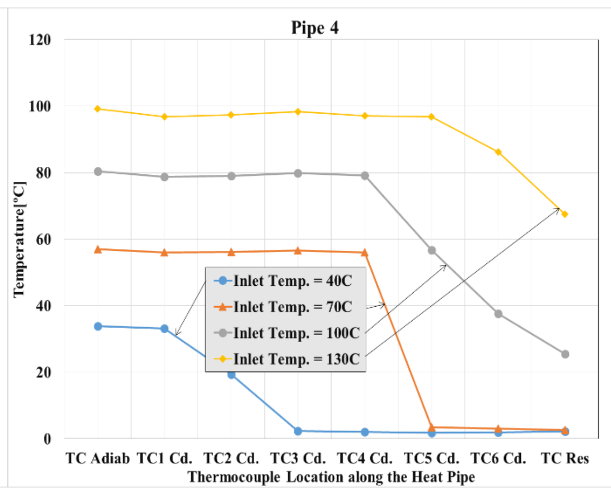

Pipe 1



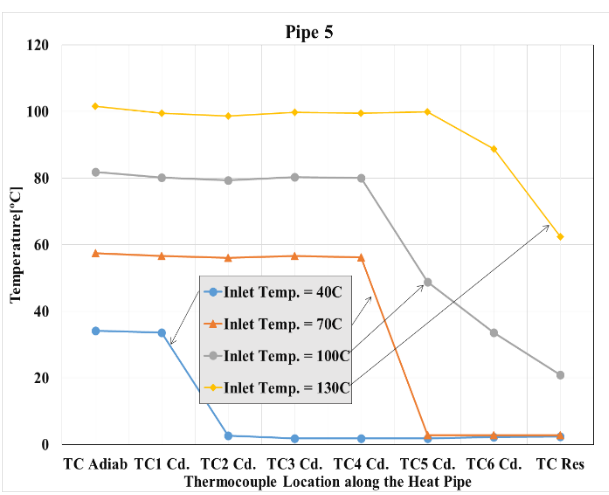

Pipe 2



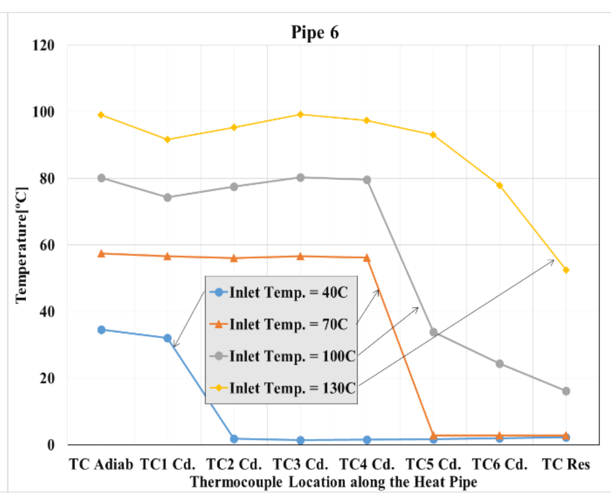

Pipe 3



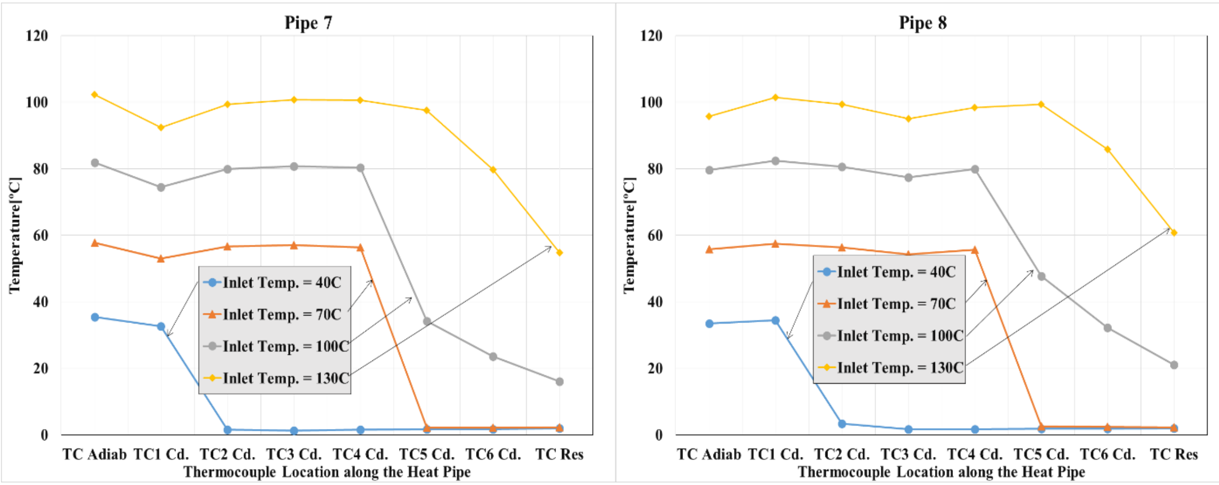

Pipe 4




Pipe 5




Pipe 6




**Pipe 7** **Pipe 8**

**Figure 11. Steady state temperature profiles along each of the eight heat pipes during the second round of vacuum testing at GRC when maximum outlet water temperature was 127°C**

In conclusion the first cluster, that has the short evaporator, was tested in both ambient (at ACT) and vacuum (at GRC). Ambient testing showed a performance of 3.5 kW at nominal water temperature and flow rate. However, the sink temperature was ambient. In addition, an oversized NCG charge was observed in all 8 heat pipes of the cluster. Several conservative factors influenced the performance of the radiator in ambient conditions.

Vacuum testing of the cluster was conducted in two rounds. The ***first round*** included an initial power test, thermos-cycling followed by another power test. None of the parameters were nominal. The power rejected by the radiator in vacuum was 1.94kW for the highest water inlet temperature (100°C). Again, the power test carried after thermos-cycling showed no degradation of the direct bond. During the ***second round*** of vacuum testing, the maximum temperature of the inlet water was nominal (127-130°C) while the other parameters were the similar to the first round. In these conditions the power delivered by the cluster was ~2.87kW. However, it is expected that the performance of the cluster in vacuum would be significantly higher if water flow rate and sink temperature were at nominal conditions. In addition, other conservative factors during vacuum testing were: the oversized amount of NCG, which at nominal temperature would not allow a fully active condenser and the length of the evaporator.

## III. CONCLUSION

The paper mainly presented testing results for the heat pipe radiator module and for the radiator cluster both in ambient and vacuum. The radiator module was tested in vacuum at nominal parameters where it rejected 380W, a power that is slightly less than the predicted 418W. However, the module initially had a short evaporator. After increasing the size of the evaporator, new ambient testing showed that the performance of the module increased by 25%. Also, thermal cycling in vacuum of the module showed that the direct bond was not affected by the repeated exposure to thermal stresses.

The cluster was also tested in both ambient (at ACT) and vacuum (at GRC). Ambient testing showed a performance of 3.5 kW at nominal water temperature and flow rate. However, the sink temperature was ambient. In addition, an oversized NCG charge was observed in all 8 heat pipes of the cluster. In conclusion, several conservative factors influenced the performance of the radiator in ambient conditions. Vacuum testing of the cluster included an initial power test, thermocycling, and a second power test. None of the parameters were nominal. The power rejected by the radiator in vacuum was 1.94kW for the highest water inlet temperature. Again, the power test carried after thermocycling showed no degradation of the direct bond.

In conclusion, it is expected that the performance of the cluster in vacuum would be significantly higher if all three parameters (water inlet temperature, flow rate and sink temperature) were at nominal conditions. In addition, other conservative factors during vacuum testing were: 1) the oversized amount of NCG, which even at nominal temperature would not allow a fully open condenser, 2) the fact that water inlet temperature was 27°C less than nominal, which further amplified the effects of the oversized amount of NCG, and lastly, the short evaporator. A second round of cluster testing was performed in vacuum where the water inlet temperature was raised to nominal values. These results will be presented in a future paper. Finally, it is also important to mention that all subsequent clusters will be fabricated with long evaporators.

## ACKNOWLEDGMENTS

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