3D Printed Thermal Management System for the Next Generation of Gallium Nitride-Based Solid State Power Amplifiers

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Current spacecraft thermal control systems often use aluminum/ammonia Constant Conductance Heat Pipes (CCHPs) to remove waste heat from electronics on spacecraft, which has been proven to be reliable over the last fifty years. One drawback of ammonia CCHPs is that they are only designed to work at temperatures up to about 80°C, with relatively low heat fluxes. Gallium Nitride (GaN) based solid state power amplifiers (SSPAs) are desirable for satellite communications due to their superior linearity, built-in redundancy, reliability, power density and energy efficiency as compared to current technologies such as traveling wave tube amplifiers (TWTAs). A thermal management system was developed to handle the higher heat fluxes and temperatures of GaN power amplifiers, which can operate at temperatures up to 150°C. Note that higher temperature operation allows significant reduction in radiator size and mass. The thermal management system uses a titanium/water vapor chamber to reduce the heat flux, and a 3D-printed hybrid wick (screen/grooved) titanium/water heat pipe to transport the waste heat. The heat pipe has features that allow multiple freeze/thaw cycles in space, and a small number of freeze/thaw cycles in any orientation during storage on the ground.

Nomenclature

GA	=	Gallium Nitride
CCHP	=	Constant Conductance Heat Pipe
CTE	=	Coefficient of Thermal Expansion
DMLS	=	Direct Metal Laser Sintering
EDM	=	Electrical Discharge Machining
GaN	=	Gallium Nitride
GFRC	=	Graphite Fiber Reinforced Composite
HEMT	=	High Electron Mobility Transistor
ISS	=	International Space Station
LHP	=	Loop Heat Pipe
LM	=	Lockheed Martin
LN	=	Liquid Nitrogen
NCG	=	Non-Condensable Gas
SSPA	=	Solid State Power Amplifier
T/R	=	Transmit/Receive
TIM	=	Thermal Interface Material
TWTA	=	Traveling Wave Tube Amplifiers

I. Introduction

Gallium Nitride (GaN) based solid state power amplifiers (SSPAs) are desirable for satellite communications due to their superior linearity, built-in redundancy, reliability, power density and energy efficiency as compared to

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current technologies. GaN SSPAs can offer up to a 60% reduction in volume and a 12% reduction in energy consumption as compared to Traveling Wave Tube Amplifiers (TWTAs). (Damien and Gelerman, 2012, Wertz and Larson, 1999) In addition, they can operate at higher temperatures (potentially up to 250ºC), reducing radiator size and mass.

Current spacecraft thermal control systems typically use aluminum/ammonia Constant Conductance Heat Pipes (CCHPs), or aluminum/stainless steel/ammonia Loop Heat Pipes (LHPs). Typically, the CCHP or LHP condensers are embedded in an aluminum honeycomb radiator, with aluminum facesheets. Since the maximum operating temperature for ammonia-based CCHPs and LHPs is roughly 80ºC, a different working fluid with compatible envelope/wick materials must be developed for GaN electronics thermal management.

II. Material and Wick Selection

Water is the ideal working fluid for thermal management in terrestrial electronics. It is typically used with copper envelopes and wicks at temperatures up to about 150ºC. At higher temperatures, the envelope becomes too thick to be practical, so other materials must be used. For spacecraft applications, a lower mass, thinner envelope material is desirable even at lower temperatures. In order to use water heat pipes in space, the following is required:

1. Identify suitable envelope and wick materials
2. Verify the compatibility of water with these materials through long term life tests
3. Develop a suitable radiator for the heat pipes
4. Develop methods for accommodating multiple freeze-thaw cycles.

Compatible Materials: Over the past 15 years, Anderson, Tarau, and co-workers have been identifying compatible working fluids and materials for the Intermediate Temperature Range, defined as the range between 150ºC (upper practical limit of copper/water heat pipes) and 400ºC (lower practical limit for alkali metal heat pipes). (Anderson et al., 2018, ACT, 2019). For water heat pipes, they identified CP (Commercially Pure) titanium, several titanium alloys, Monel 400, and Monel K500 as potentially compatible. This was verified by life tests at elevated temperatures (230ºC and 270ºC) for roughly 8 years, depending on the alloy. Some of the heat pipes were then sectioned, and shown to be compatible. Titanium was identified as the best envelope material for spacecraft heat pipes, because it allows a lower mass envelope than the Monel alloys.

Radiators for Titanium Heat Pipes: In conventional heat pipe radiators, the aluminum heat pipes are bonded to the aluminum radiator facesheets, with no CTE (Coefficient of Thermal Expansion) mismatch. Aluminum has a high CTE, ~ 24 10^{-6} m/(m K), while titanium's CTE is ~ 8.5 10^{-6} m/(m K). This CTE mismatch will cause wrinkling of an aluminum facesheet bonded to a titanium heat pipe.

The solution, proposed by Ted Stern, was to use Graphite Fiber Reinforced Composite (GFRC) Facesheets (Stern and Anderson, 2005). The layup of the GFRC can be controlled to match the titanium CTE along the heat pipe access. As shown Figure 1, POCO foam saddles were initially used to accommodate the CTE mismatch perpendicular to the heat pipe axis. (Anderson et al., 2006a)

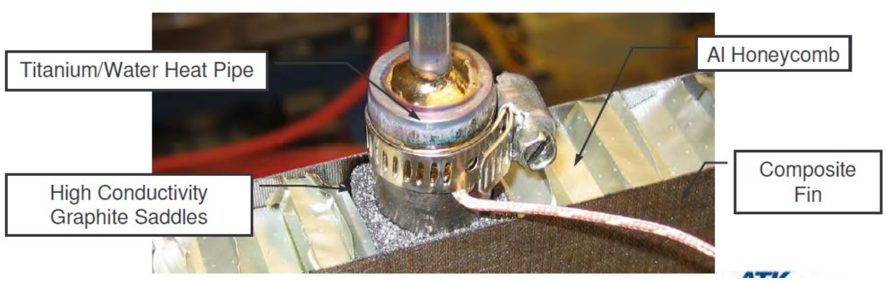
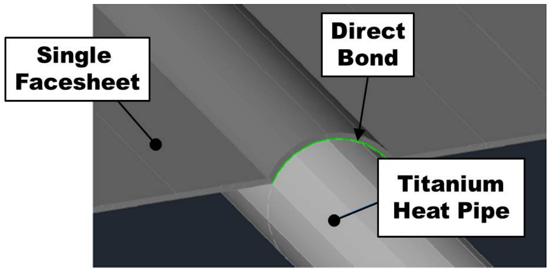


Figure 1. Initial titanium heat pipe/POCO Foam Saddle/GFRC radiator design (Anderson et al., 2006a)

During the radiator panel development, a small test panel with two tubes (simulating heat pipes) was fabricated and further exposed to a tensile test by pulling the bottoms of the heat pipes apart. Surprisingly, the tubes failed in bending and the panel was unaffected. This result led to the conclusion that a direct bond of GFRC panels to the heat pipe is feasible; see Figure 2a. The resultant single facesheet titanium heat pipe radiator is shown in Figure 2b. (Tarau et al., 2016)



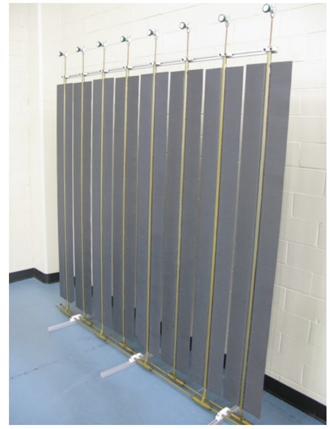


Figure 2. a. Direct bond concept. b. Single face-sheet titanium heat pipe radiator direct bonded to GFRC facesheets. (Tarau et al., 2016)

A. Design for Multiple Freeze/Thaw Cycles

Anyone who has had their pipes freeze in the winter knows that when a solid slug of water freezes, it can deform and even split tubes. The same thing can happen in heat pipes if water bridges the heat pipe vapor space. The basic method of preventing freeze/thaw damage in water heat pipes is to prevent formation of a slug of water during the freezing process. For sintered and screen wick heat pipes, this can be accomplished by carefully controlling the water charge, so that all of the water is contained in the heat pipe wick at any temperature. Freeze/thaw tolerant heat pipes with screen or sintered wicks have been used for many years in spacecraft thermal control. More recently, this has also been demonstrated by screened copper/water heat pipes in microgravity testing on the ISS. (Ababneh et al., 2017)

Due to the relatively large pressure drop in the screen or sintered wick, standard copper/water heat pipes are limited to about 25 cm in length. This is suitable for heat pipes embedded in electronics chasses, but is too short to transport heat from a GaN SSPA to a radiator panel. For longer lengths, either grooved heat pipes, or hybrid wick pipes with a grooved condenser section must be used. There are three design features that a freeze-tolerant grooved heat pipe must have:

1. A small amount of Non-Condensable Gas (NCG), to allow the heat pipe to freeze/unfreeze gradually, without freezing water in the condenser
2. A supplemental wick near the evaporator, to hold excess water, and prevent it freezing in the condenser.
3. A buffer in the condenser for storage on the ground to prevent freezing related problems if the condenser is down.

NCG: The heat pipe radiator panel shown in Figure 2b is designed to cool a Fission Surface Power system on the Lunar surface. Each of the heat pipes is roughly 2m long, and functions as a thermosyphon. Consider attempting to start up the system during the Lunar night, when the radiator and thermosyphon condensers are below the freezing point. With no condensable gas, the vapor will condense and freeze along the length of the entire condenser, and the heat pipe evaporator will dry out, with no way to recover. By adding a small amount of NCG, it will block most of the condenser, forcing all the vapor to condense near the evaporator, without further freezing (Ellis and Anderson, 2009).

Supplemental Wick Near the Evaporator: If the heat pipe will always be frozen with the evaporator lower than the condenser, damage can be prevented by adding a supplemental wick structure near the evaporator. Lee et al. (2018) developed titanium/water heat pipes for Kilopower. They had three separate wicks: 1. A grooved wick in the condenser, a screen wick on the evaporator walls, and a coarser wick filling part of the vapor space in the evaporator. The system acts like a heat pipe in micro-gravity, and as a thermosyphon on the Earth, Moon, or Mars. The coarser wick is designed to hold all of the excess water when in thermosyphon mode, allowing the heat pipe to be frozen without damage. Theoretically, it should also work in microgravity, but this has not yet been verified.

Condenser Buffer: One of the design requirements in the current program was that the heat pipe should be able to withstand a few (<10 freeze/thaw cycles) when stored on Earth, with the condenser down, allowing water to pool in the condenser. This is discussed in more detail below.

III. Thermal Management System Design

Design requirements for the thermal management system are shown in Table 1.The thermal management concept is shown in Figure 3 and includes:

- The heat source for the future GaN power amplifier, which can operate at temperatures in excess of 150°C and may in the future exceed power densities of 1400 W/cm^2 (600W over 0.635 cm x 0.635 cm).
- The vapor chamber heat spreader. This transforms the heat flux to a lower flux that can be handled by a grooved evaporator.
- The titanium-water heat pipes that will be attached to the heat spreader by an aluminum flange at one end and to a Graphite Fiber Reinforced Composite (GFRC) facesheet at the other end as shown in Figure 3-b.

Designing the system for freeze/thaw tolerance is discussed in the next section.

Table 1. Design requirements for the SSPA thermal management system.

Heat dissipated	600 W
Vapor Chamber Heat Flux In	Up to 1400 W/cm^2
Vapor Chamber Heat Flux Out	10-15 W/cm^2
Operating Temperature	25 °C – 150 °C
Survival Temperature	-60 °C – 150 °C
Space Compatible	Yes
Freeze/Thaw Cycles in Microgravity	Thousands
Freeze/Thaw Cycles during Ground Testing	<10

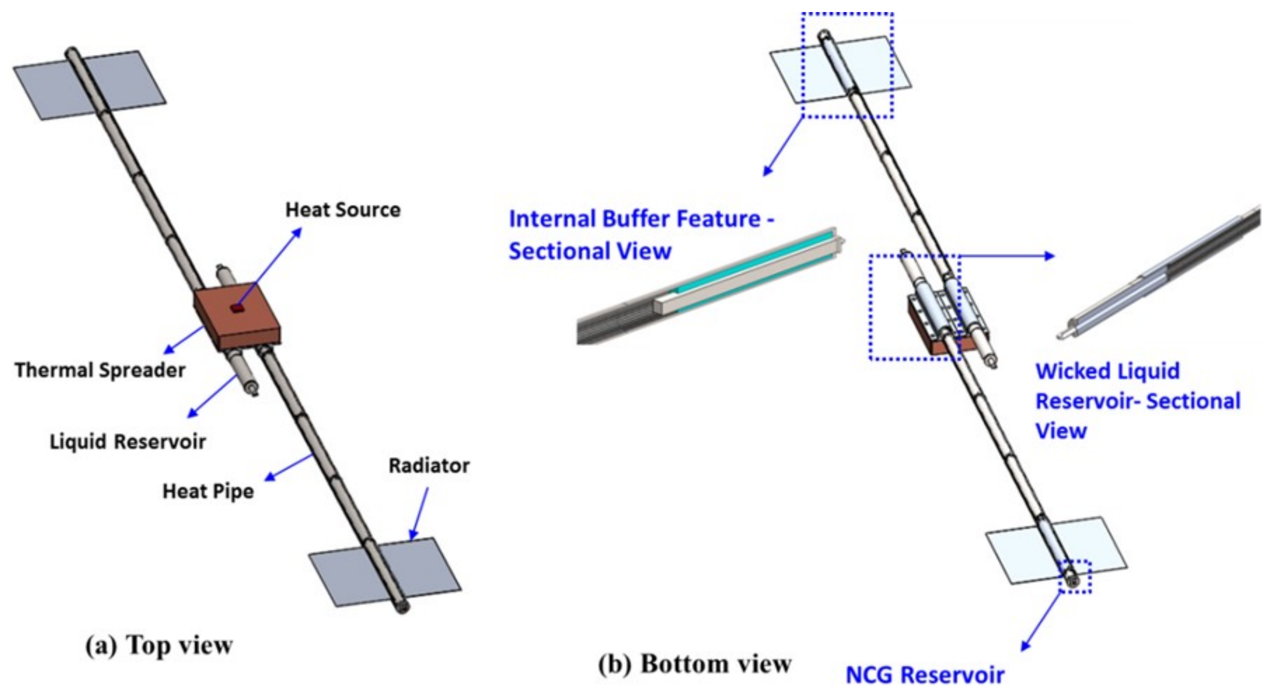


Figure 3. Thermal Management System Schematic for Future GaN SSPA Devices (a) Top view. (b) Bottom view.

IV. Prototype Fabrication

For freeze/thaw tolerance, the groove base width must be greater than or equal to top groove width so that the geometry cannot "lock in" the ice, i.e., grooves with parallel or inverted trapezoid sides. A cross-section of the selected heat pipe geometry is shown below in Figure 4, and the heat pipe parameters are shown in Table 2.

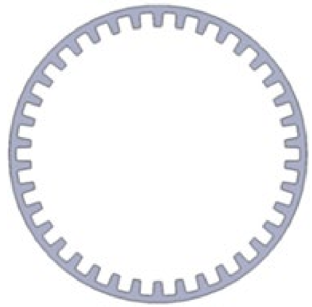


Figure 4. The grooves in the selected heat pipe geometry are square, allowing water to expand into the vapor space. Inverted trapezoidal wicks, wider at the I.D., have also been used successfully in the past.

Table 2. Heat Pipe Parameters.

Envelope	Grade 5 Ti (6% Al 4% V)
Pipe OD	1.59 cm (0.625 in.)
Wall thickness	0.38 mm (0.015 in)
Number of grooves	38
Condenser length	27.9 cm (11 in.)
Adiabatic length	20.3 cm (8 in.)
Evaporator length	12.7 cm (5 in.)
Total Mass w. Flange	153 g

Aluminum has two advantages over titanium, the ability to be extruded, and higher thermal conductivity (~200 W/m K for aluminum, versus ~20 W/m K for titanium). As shown in Figure 5, aluminum CCHP bores can be extruded with fine grooves and with integral saddles. The saddles allow the heat pipes to accept heat from flat plates with electronics.

In contrast, titanium is too hard to be extruded, so the grooves must be formed by some other process. Initial heat pipes used a grooved wick formed from sintered titanium (Anderson et al., 2005). Grooved heat pipes were also formed by milling grooves in a flat plate, and then bending the plate into a cylinder. (Anderson et al., 2006b) Both of these methods worked well, but had relatively thick walls. More recently, Lee et al. (2017) demonstrated the ability to EDM grooved titanium heat pipes. Due to EDM machine limitations, the heat pipe was fabricated in sections, and then welded together.

Figure 5. The ductility and high thermal conductivity of aluminum allow the extrusion of fine-featured grooves, as well as integral saddles.

Since minimizing mass is very important for space systems, the current program used a 3D printing process that allowed fabrication of envelopes with 0.38 mm (0.015 in) thick walls, and still achieve a hermetic seal. The heat pipe was 3D printed in short sections (15.2 cm, 6 in.), due to the limitations of the 3D printer. Laser-beam welding was used to join multiple short 3D grooved sections as shown in Figure 6.

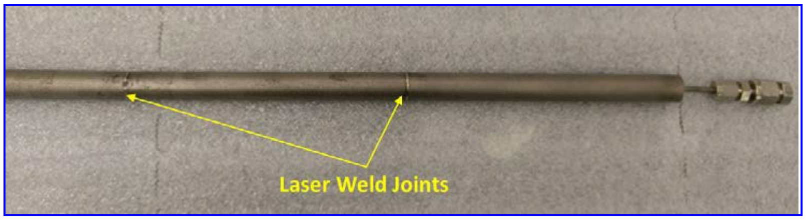


Figure 6. Laser-Beam Welding was used to join the 3D printed grooved sections.

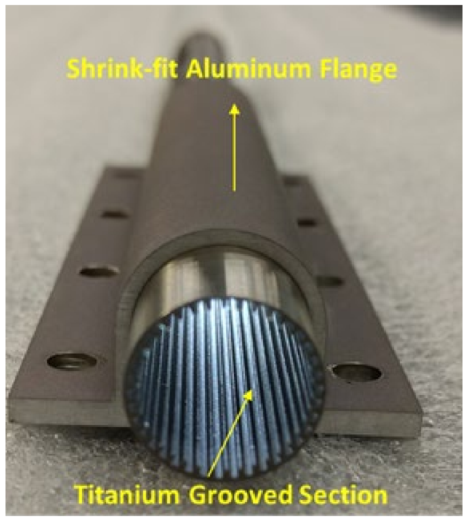


Figure 7. The aluminum flange was joined to the titanium heat pipe via shrink-fit.

Since the titanium thermal conductivity is so low, fabricated titanium saddles would not perform well. Instead, an aluminum flange was shrink-fit around the titanium heat pipe evaporator, as shown in Figure 7.

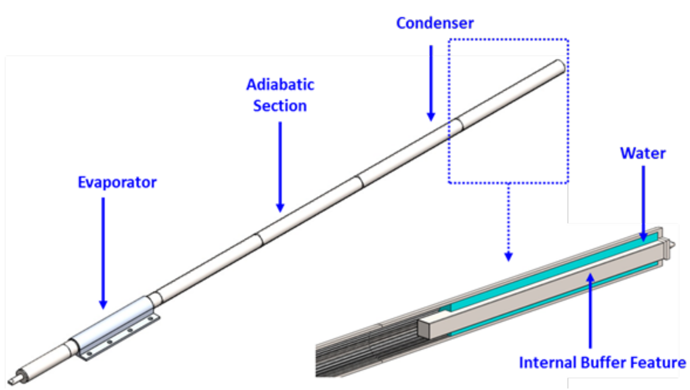


Figure 8. CAD model of grooved heat pipe with internal buffer for freeze/thaw control in the condenser section.

V. Design for Freeze/Thaw Tolerance

The following features were used in the titanium-water heat pipes, to make the heat pipes freeze/thaw tolerant in both space and on the ground in any orientation:

- Inverted trapezoidal grooves (or rectangular grooves), so that water in the grooves would expand out into the vapor space without damage.
- Microgravity operation, or evaporator down on the ground: a wicked, liquid reservoir connected to the evaporator allows water in the heat pipe to freeze in a controlled fashion as the heat pipe is shut down. The liquid reservoir will prevent forming a bridge of solid ice inside the heat pipe.

- Microgravity operation, or evaporator down on the ground: an NCG reservoir connected to the condenser is filled with a controlled amount of NCGs. The NCG will assist the freezing of the pipe and startup operation by not allowing water to freeze in the condenser.
- Condenser down on the ground: an internal buffer attached to the condenser section deforms to damp the forces induced by the frozen water.

A. Freeze-Thaw Tolerance with Water in the Condenser

During ground storage, the heat pipe could be stored with the condenser down. Since the wick in the condenser is grooved, all of the water in the grooves will drain into the bottom of the heat pipe. This slug of water would damage the heat pipe when the water freezes and expands. As shown in Figures 8 and 9, a hermetically sealed, hollow internal buffer was added at the bottom of the condenser.

Figure 9. Internal buffer feature that was used inside condenser of the grooved heat pipe.

The freeze/thaw test thermal cycling is shown in Figure 10 where the temperature is representative for the entire pipe. Measurements showed that the maximum OD of the pipe before and after each cycle was kept constant at 0.62”. The pipe was then opened for internal visual inspection. Figure 11 below shows how the internal buffer deformed after 10 freeze/thaw cycles. In case that the entire liquid inventory ended up frozen in the condenser section (i.e. if the heat pipe transported from ground to space vertically), this feature would protect the pipe from damage. Thus, this feature can protect the pipe for at least 10 freeze/thaw cycles which is sufficient for the current application. If additional freeze/thaw cycles are required, the buffer would need to be redesigned to deform only elastically.

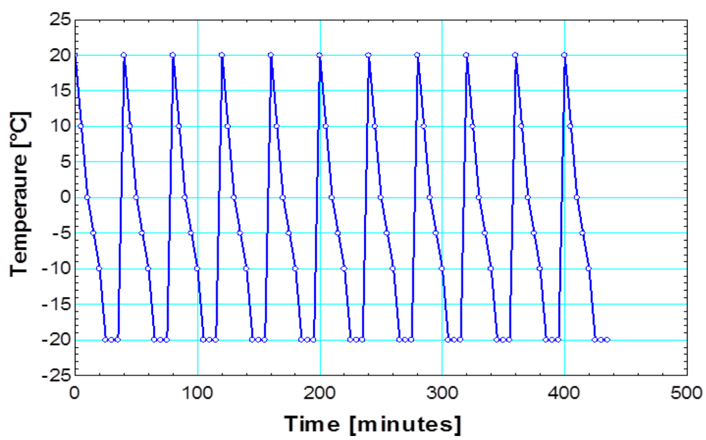


Figure 10. Freeze/Thaw cycle data for the internal buffer prototype.

Figure 11. The full-scale internal buffer before and after 10 Freeze/Thaw cycles.

B. Freeze/Thaw Tolerance with Water in the Evaporator

Figure 12. 3D Printed grooved heat pipe with the Liquid Wicked Reservoir in the evaporator section for freeze protection.

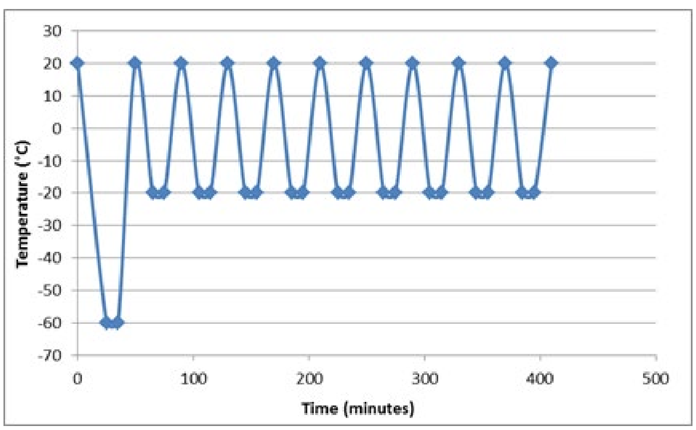


Figure 13. Freeze/Thaw cycle data for the Liquid Wicked Reservoir.

The evaporator design is shown in Figure 12. Multiple freeze/thaw cycles were run, as shown in Figure 13. Again, no damage was observed.

C. NCG Reservoir

As discussed above, adding a small amount of NCG aids in start-up and shut-down, by preventing the water from freezing in the long condenser. As shown in Figure 3, the condenser extends past the heat pipe radiator, to accommodate the NCG. During normal operation, the NCG is kept in the reservoir by the moving vapor. As the heat pipe temperature (and vapor pressure) drops, the NCG will expand first into the condenser, and then into the adiabatic section and evaporator, suppressing vapor flow.

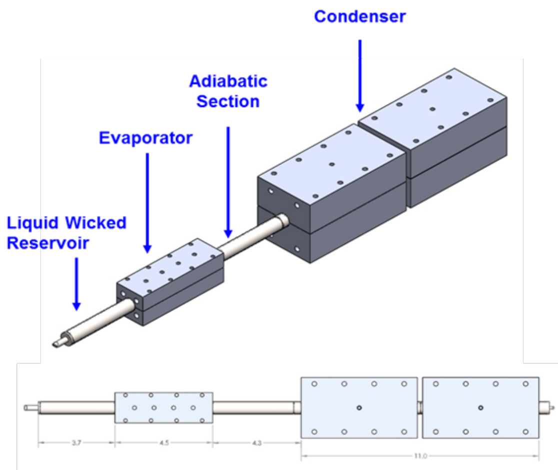


Figure 14. Test setup for the un-flanged titanium/water heat pipe.

VI. Heat Pipe Performance

The test setup for the unflanged titanium/water heat pipe is shown in Figure 14. Heat was applied to the evaporator using aluminum heater blocks with four cartridge heaters. The condenser sink condition was established using an aluminum block cooled by Liquid Nitrogen (LN). The LN flow was adjusted with a temperature controller to set the condenser temperature. The testing conditions were as follows:

- Heat pipe was insulated and oriented at 0.1” (2.5mm) adverse elevation between the evaporator and the condenser
- Sink temperature was adjusted to maintain a 145 °C vapor temperature.
- Power was varied (increased) incrementally until a dry out condition was observed. Dry out is signaled by a pronounced spike in temperatures within the evaporator section as vapor bubbles begin to interfere with liquid return in the wick.

Figure 15 shows the thermal performance as a function of time. The pipe transported a heat load of ~ 350 W before the complete dry-out. This power was higher than the design requirement of 300 W.

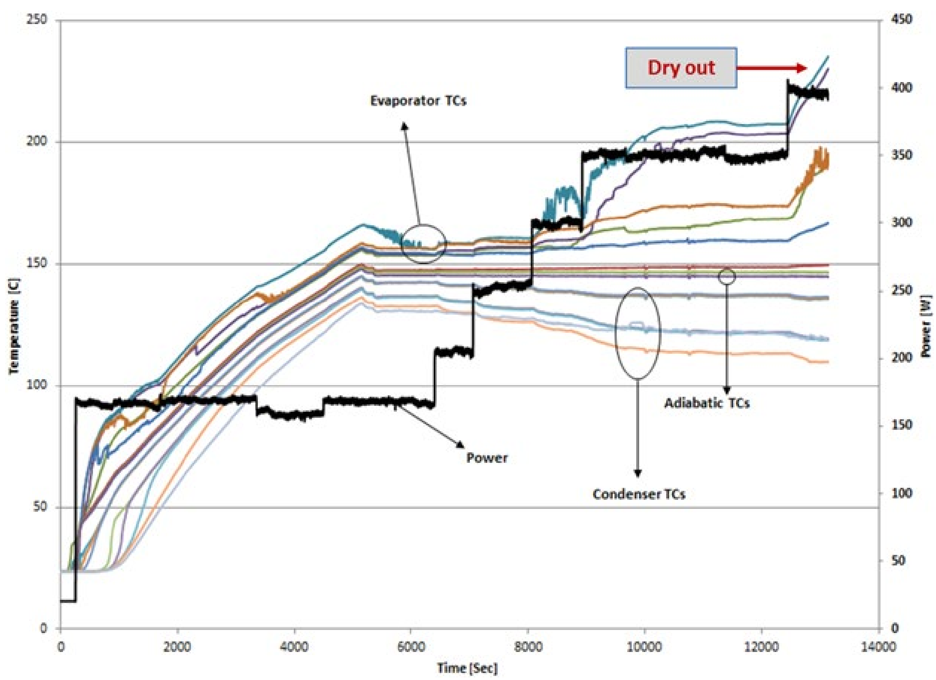


Figure 15. Thermal performance for the un-flanged 3D Printed grooved titanium-water heat pipe.

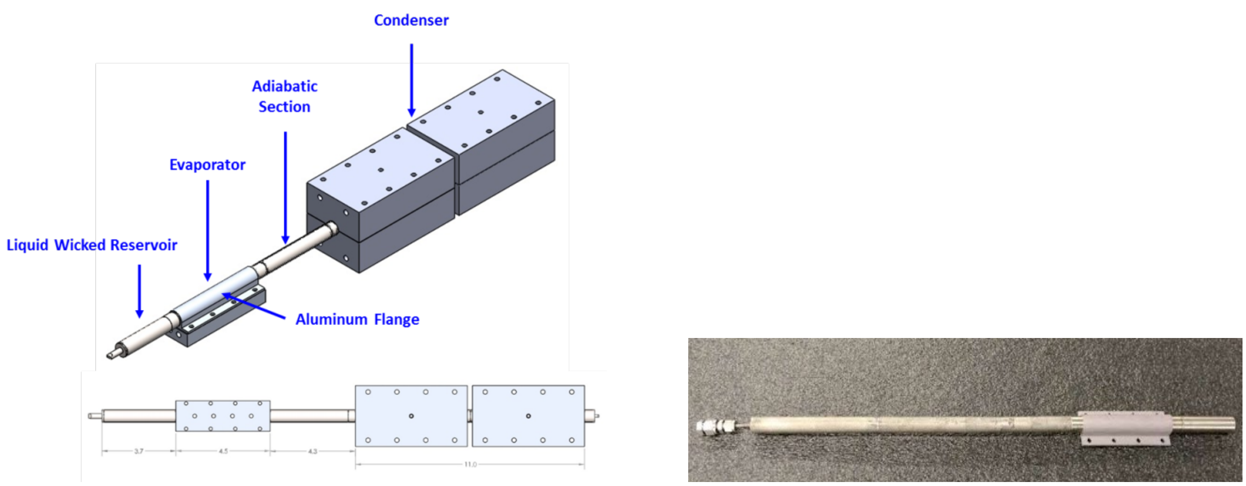


Figure 16. The flanged titanium/water heat pipe.

The flanged heat pipe was heated by applying the power to the evaporator aluminum flange using aluminum heater block with two cartridge heaters as shown in Figure 16. This heat pipe was able to transport more than 600 W before dryout. It is the author's belief that the better performance is due to the improved circumferential conduction in the flange.

Figure 17 shows a start-up after the heat pipe was frozen. After running at 300 W and ~145ºC of vapor temperature, the heater power was shutoff and the condenser of the pipe was cooled down to -45ºC. Cooling was relatively slow, due the NCG that expanded into the adiabatic section, preventing vapor from condensing and freezing in the condenser. As soon as the power was resumed the pipe warmed up sending vapor to the condenser and pushing the NCG front into the condenser. Figure 18 shows three critical instants of this freeze/thaw experiment: initial steady state at full power, temperature distribution at the end of the freezing sequence and finally, steady state after the restart of pipe. The two steady states (first and third sequences) show similar temperature distributions that demonstrate successful startup from the frozen condition.

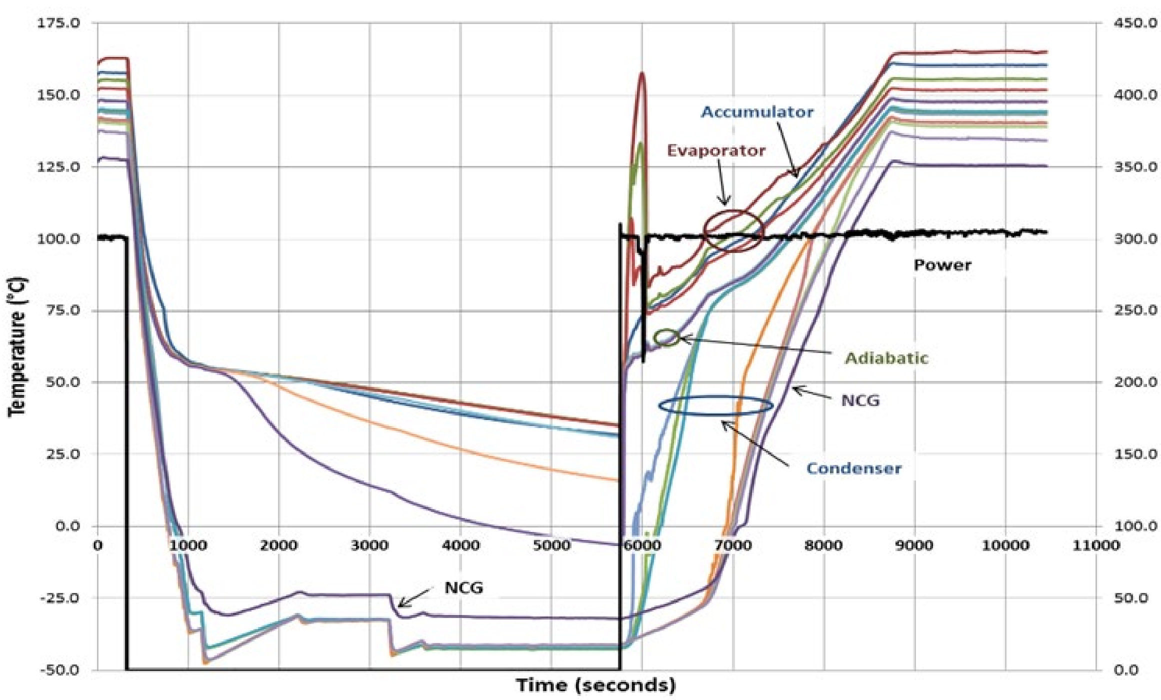


Figure 17. Grooved heat pipe start-up transient temperature profile from a frozen state.

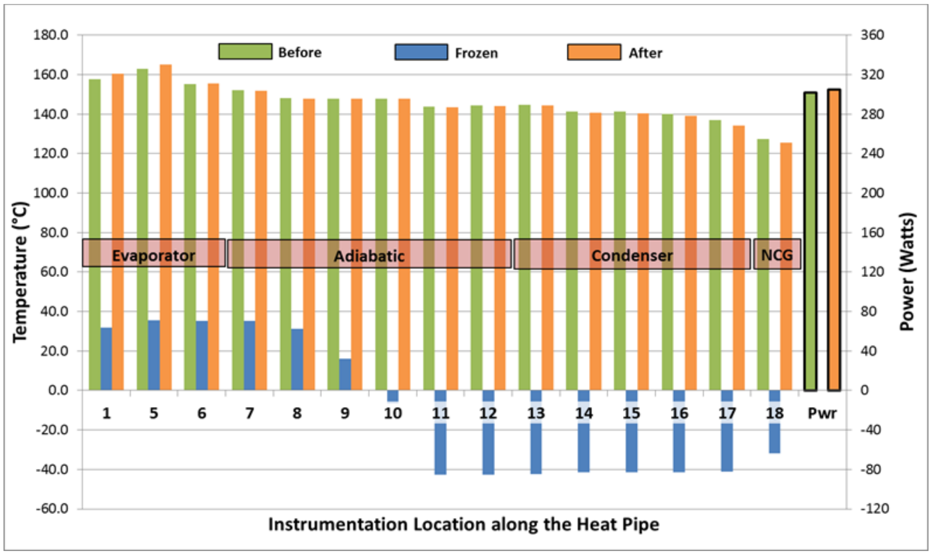


Figure 18. Grooved heat pipe instantaneous temperature profiles before, during, and after start-up from a frozen state.

VII. Design of a Vapor Chamber and Heat Pipe for Thermal Management of a GaN HEMT SSPA

Under the Dragonfly program, Lockheed Martin (LM) is developing a next generation high-power Transmit/Receive (T/R) module that implements Gallium-Nitride (GaN) high electron mobility transistor (HEMT) high power SSPAs in a highly-efficient, low loss package that is smaller than traditional T/R modules. On a Phase IIE program with NASA Glenn, the authors designed, fabricated and tested a subscale thermal management system for cooling these systems.

As shown in Figure 3, the thermal management system has three components:

1. A vapor chamber that acts as a heat flux transformer, transforming the high heat flux from the heat source (i.e. solid-state power amplifiers), into a lower heat flux that can be removed by the titanium-water heat pipe.
2. A 3D-printed grooved titanium-water heat pipe that accepts the low heat flux from the vapor chamber at the evaporator section and transfers the heat to the chiller block that, in this experimental case, replaces the radiator (this was not considered as part of the development since, as discussed above, suitable GFRC radiators have already been developed).
3. Radiators to reject the waste heat.

These GaN amplifiers have high power densities that lead to challenging thermal management. Each T/R module has more than 250 GaN amplifiers (as shown in Figure 19) and each single power amplifier dissipates 30 to 45 W of waste heat. The maximum GaN junction temperature is (Tj) < 175ºC. Design requirements are given in Table 3.

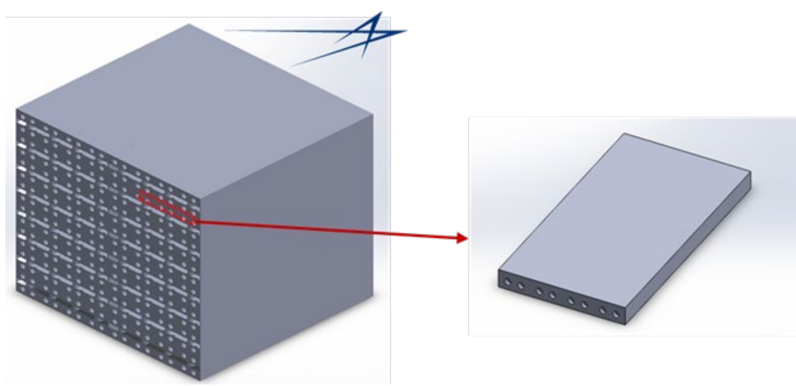


Figure 19. The Dragonfly high-power T/R module (Left), single quad pack unit with 8 SSPAs (Right).

Table 3. Design Requirements, based on a single quad pack with 8 SSPAs.

Total heat dissipated	~ 360 W
Long term goal for operating temperature	-55 °C to 125 °C
ΔT ($T_{Evaporator} - T_{Condenser}$)	10 °C
Space Compatible	Yes
Geometry of Quad Pack	11.8 x 5.8 cm

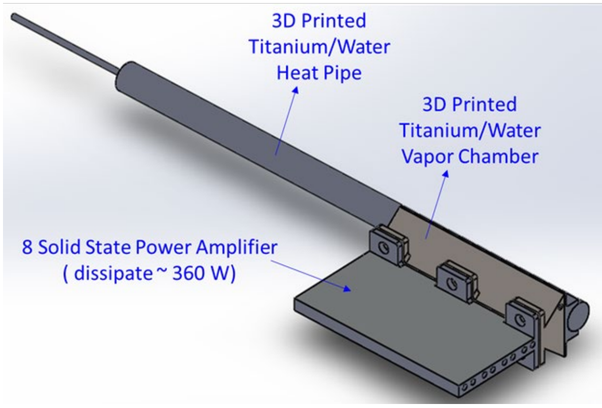


Figure 20. Thermal management design for the subscale (i.e. quad pack) Dragonfly high-power T/R module.

Table 4. Geometric parameters for the 3D printed grooved titanium/water heat pipe.

Pipe OD	1.9 cm (0.75 in.)”
Wall thickness	0.38 mm (0.015 in.)
Number of grooves	57
Condenser length	25.4 cm (10 in.)
Adiabatic length	5.1 cm (2 in.)
Evaporator length	10.2 cm (4 in.)

The design schematic for the sub-scale (~ 360 W) T/R module (i.e. for a single quad pack) as shown in Figure 20. The geometric parameters are shown in Table 4, and the optimized groove pattern is shown in Figure 21.

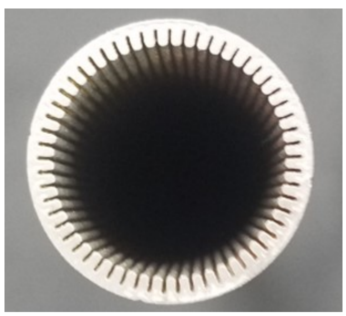


Figure 21. Cross sectional view of the 3D printed titanium heat pipe with 57 grooves.

Similar to the heat pipes discussed above, this heat pipe was fabricated in segments by Direct Metal Laser Sintering (DMLS), otherwise known as 3D printing. The segments were welded together to produce a low-cost lightweight heat pipe to be used for cooling of SSPAs in space. The resultant lightweight 3D printed heat pipe passed the helium leak test. For better heat collection from the source, an aluminum flange was attached to the 3D printed grooved titanium heat pipe via shrink-fit as shown in Figure 22.

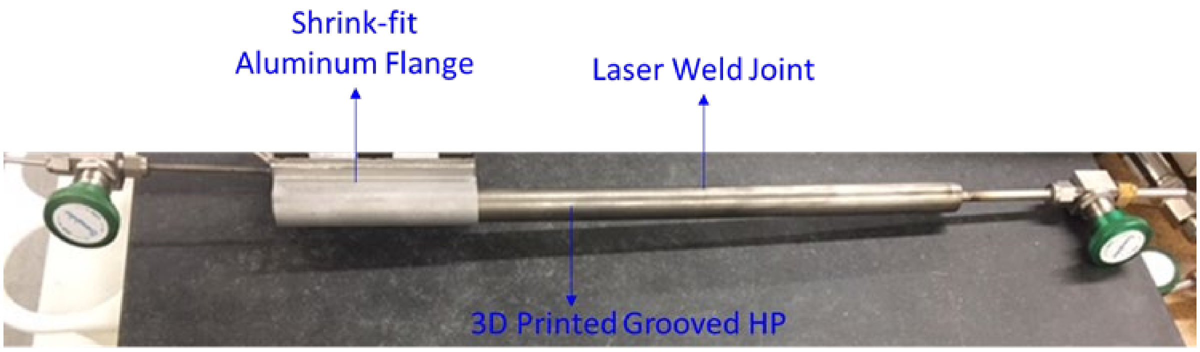


Figure 22. Heat pipe for SSPA cooling with a shrink-fit aluminum flange.

A titanium vapor chamber was also fabricated, as shown in Figure 23. Since this was a proof of concept setup, the vapor chamber was designed to bolt to the heaters, with no attempt made to minimize the temperature drop across the interface.

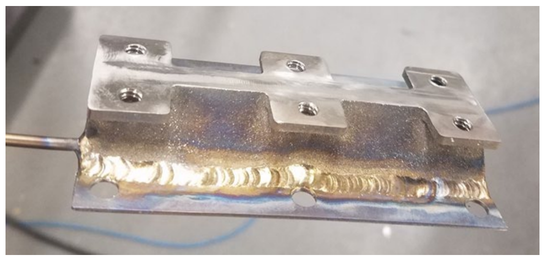


Figure 23. Titanium vapor chamber for SSPA cooling, with bolts to connect to the simulated GaN amplifier plate.

Figure 24. Thermal management system, with the vapor chamber attached to the titanium-water heat pipe and to the heater block.

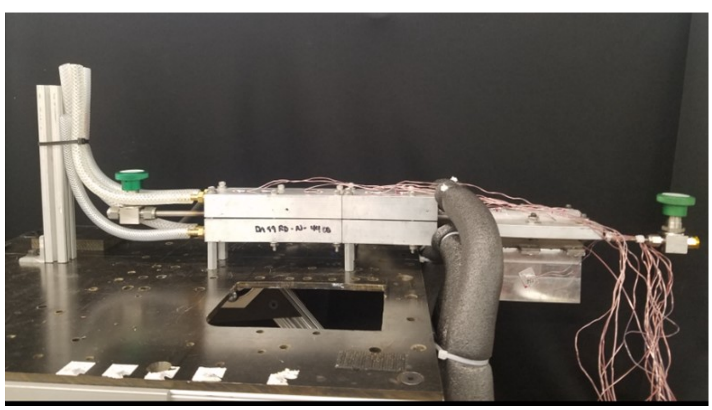


Figure 25. Thermal management system under testing for the subscale (i.e. quad pack) Dragonfly high-power T/R module.

Figure 24 shows the heater block/vapor chamber/heat pipe assembly, while Figure 25 shows the test setup. A typical test is shown in Figure 26 at 0.1” adverse elevation as a function of time with s-bond as Thermal Interface Material (TIM) and C-clamp. The system (i.e. heat pipe and vapor chamber) transported ~ 350 W. Since no dry-out condition was reached, it may be reasonable to assume that the heat pipe capillary limit is higher. The figure also shows the iso-thermality of the vapor chamber and acceptable temperature difference between the evaporator and the condenser of the heat pipe. On the negative side but not surprising, the temperature drop across the vapor chamber-evaporator interface is large, Further development of the interface is required.

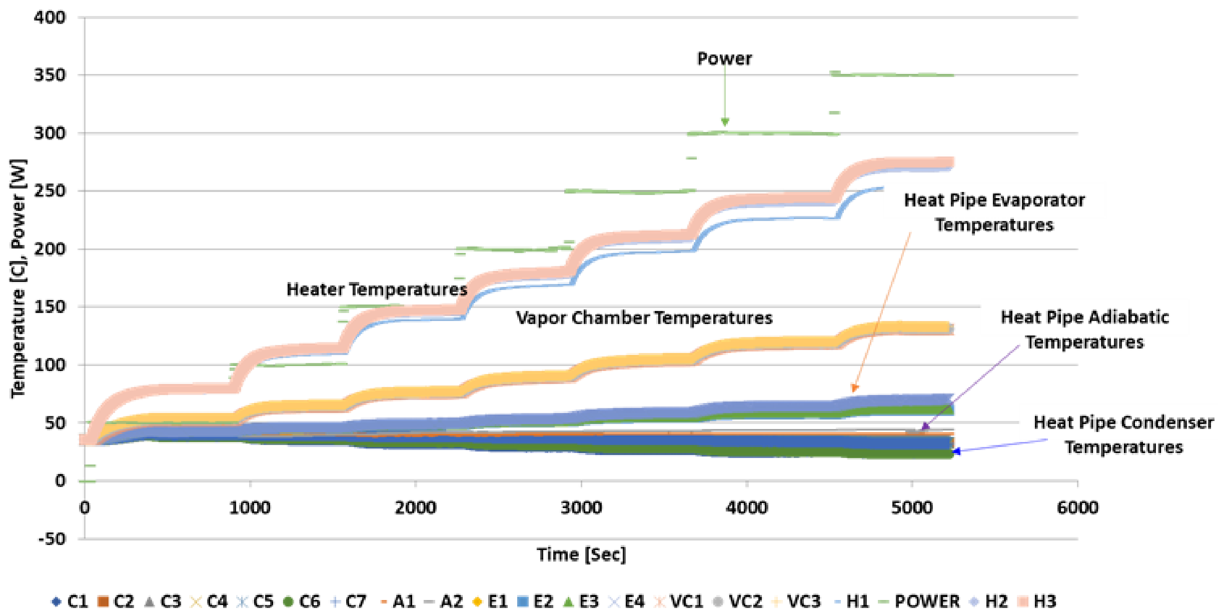


Figure 26. Thermal performance for the 3D printed thermal management system for the subscale (i.e. quad pack) Dragonfly high-power T/R module with s-bond as TIM.

VIII. Conclusion

GaN based solid state power amplifiers (SSPAs) are desirable for satellite communications, offering up to a 60% reduction in volume and a 12% reduction in energy consumption as compared to TWTAs. In addition, they can operate at higher temperatures (potentially up to 250ºC), reducing radiator size and mass. However, aluminum/ammonia thermal control systems can only operate up to about 80ºC; Therefore, a different working fluid with compatible envelope/wick materials must be developed for GaN electronics thermal management. Titanium/water vapor chambers and heat pipes, as well as GFRC radiator facesheets have been developed for these higher temperature and heat flux applications.

A titanium/water heat pipe was fabricated and tested with several novel features that allow multiple freeze/thaw cycles in any orientation on earth, start-up from frozen condition, and operation in both micro-gravity and terrestrial environments. The design innovations and resulting performance benefits can be summarized as below:

- Freeze tolerant grooves, that are either rectangular (parallel sides) or widen toward the interior.
- Internal buffer to provide freeze/thaw tolerance of the heat pipe and enable multiple freeze/thaw cycles without bursting the pipe during storage on the ground.
- 3D printing lightweight, 0.015” wall-thickness titanium heat pipe, with very low mass.
- Operation at temperatures above 150°C, allowing a smaller radiator size.
- NCG reservoir to facilitate startup from a frozen condition.

A titanium/water vapor chamber and a titanium/water heat pipe were designed and fabricated to test a quad pack Dragonfly high-power T/R module. Both the heat pipe and the vapor chamber met the power (more than 350W) and heat flux (more than 15W/cm^2) requirements. In fact, the vapor chamber handles more than 48W/cm^2. The word “more” is used due to the fact that no dry out was produced during all the testing leading to the conclusion that higher powers and fluxes could be achieved.

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