FREEZE-THAW TOLERANT DIRECT CONDENSATION RADIATOR CONCEPT FOR TWO-PHASE HEAT TRANSPORT SYSTEMS

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ABSTRACT

The ever-increasing processing power of spacecraft and satellites puts a tremendous demand on the thermal control subsystem (TCS) to acquire, transport, and reject large amounts of heat to space normally via a space radiator. Due to the efficient heat transfer characteristics, two-phase loops are commonly utilized in the applications. If a Direct Condensation Radiator (DCR) is chosen for the system, it can get very cold in the extreme cold spacecraft survival mode and/or part-load operations. Conceivably, freezing of the working fluid happens which, in turn, risks bursting the condenser tubes. Electrical heater power is often expended to maintain the payloads above the temperature limit, potentially overwhelming the power subsystem. The existing DCR technology does not allow the fluid to freeze, precluding the best available refrigerant – Ammonia – to be used when the temperatures drop below the Ammonia freezing point of -77^{o}C. Propylene is usually an alternate fluid to be considered in situations like this for it does not solidify until the temperature decreases below -173^{o}C. While utilizing Propylene as the working fluid sidesteps the freezing issue, a reduction of 75-80% of the loop heat transport capacity and up to 30% of the overall thermal conductance – that an equivalent Ammonia LHP would deliver – shall ensue. The proposed concept of Freeze-Tolerant Direct Condensation Radiator (DCR) presented herein allows the working fluid of a two-phase heat transport system to freeze solid in the radiator but gracefully thaws it out without damaging the hardware. In addition, the DCR concept offers many more operational benefits relevant to space applications: (i) auto-regulating the amount of heat rejection, just enough to condense the vapor load back to saturated liquid under any operating condition, (ii) allowing the heat transport loop to operate under loads while the radiator fluid is partially frozen, and (iii) waste heat from the attached payloads (not electrical heaters) is used to thaw out the radiator. The research was proposed to and subsequently received a NASA SBIR Phase I award in 2021 to demonstrate the proof-of-concept/feasibility by constructing/testing a bread-board unit. The Phase I results shall be presented in the paper.

INTRODUCTION

<u>Issues with Freeze-Thaw of Radiator Fluid in Two-Phase Heat Transport Loops</u>

The insistence for Size, Weight, and Power (SWaP) optimization in the spacecraft design compels the thermal control system (TCS) engineers to move on from traditional *tried-and-true* methods and venture into more advanced technologies. Specifically, in regard to the transport of large amounts of heat over long distances, fluid systems of some kind (e.g. single-phase or two-phase) are becoming routine in space-based TCS designs as depicted Figure 1. Simply put, a working fluid is circulated in a closed sealed loop by a pumping mechanism to quickly collect and move heat from one location to another for rejection. Due to the ability of fluid to absorb a significant amount of heat per unit mass (latent heat of vaporization/condensation) when it changes phase from liquid to vapor and vice versa, the fluid mass flow rate in a two-phase system is considerably less than that of a liquid-phase counterpart carrying the same heat load. In addition, the two-phase heat transfer processes (both evaporation and condensation) are highly efficient enabling the design of the evaporator/condenser to be lightweight and compact. *Liquid/vapor phase-change* or two-phase fluid loops are the systems of choice for space use. Heat pipes[1], Loop Heat Pipes[2] (LHPs), and Capillary-Pumped Loops[3] (CPLs) are examples of the two-phase heat transport technology. They all are "semi-passive" devices having no mechanical moving parts to wear out or break down. However, because of the limited capillary pumping head, the TCS in the future shall need to consider a mechanical pump to enhance the system heat transport capability – either by itself or in a hybrid mechanical/ capillary mode. Regardless of what technology to be utilized (single/ two-phase or mechanical/capillary-pumped), the most challenging aspect of the system design is to mitigate the probability of the working fluid to freeze anywhere in the loop for two main reasons. First, a solidly formed plug of ice blocks the fluid circulation, literally ending the heat transport. Secondly, improperly thawing out the ice plug risks rupturing the condenser line if the melting liquid is trapped in-between frozen region (depicted in Figure 2), because almost all liquids contracts when they are solidified but expands when melted.

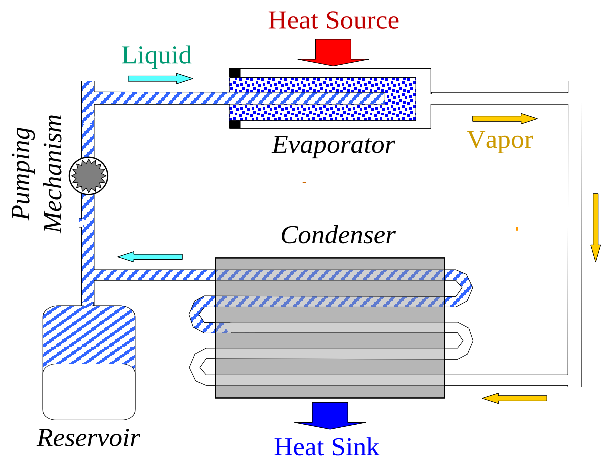

Figure 1. Two-Phase Heat Transport Loop.

Operational Challenges of Two-Phase Heat Transports with Current Space TCS Design Practice

The very nature of the radiative heat transfer in space undoubtedly puts undue difficulties on the design of a two-phase heat transport system, i.e. inadvertently promoting the possibility of fluid freezing in the radiator. First off, heat rejection per unit area from the radiator to space is rather poor, forcing the radiator surface to be sized large enough to jettison the maximum anticipated heat load in the potentially warmest environment. However, this worst-hot case scenario usually takes place only for a brief portion of the orbit or during the mission lifetime. In other words, the radiator area is unnecessarily oversized for the TCS operations in other times resulting in much colder condenser temperature. If nothing is done, the returning fluid will be too cold in the cold cases (e.g. reduced heat load and/or cold attitude) for the TCS to keep the payload temperatures above their temperature limit. Make-up heaters are often employed to remedy this situation but they would put stress on the power subsystem particularly in the less-than-perfect conditions for

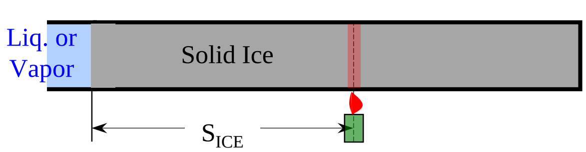

Figure 2. Failure Due to Volume Expansion.

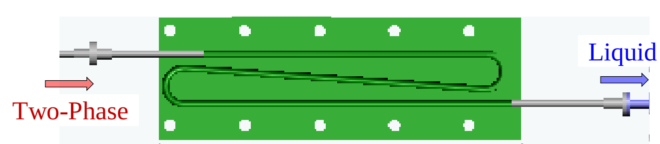

Figure 3. Single-Pass DCR.

the solar arrays to generate electricity. Moreover, the heat-dissipating sources may need to shut down in the cold survival mode, the radiator temperatures likely drop below the fluid freezing point as a consequence. A Direct Condensation Radiator (DCR) – usually made of metal smooth-wall tubing bonded directly to a panel as shown in Figure 3 – is the simplest and least expensive to construct while providing the lowest thermal impedance compared to non-direct *methods*, for heat rejection to space. It may have one through pass or multiple parallel passes. Nonetheless, DCR-type condensers are susceptible to the freeze-thaw cycling. As a matter of fact, Ammonia – despite having the best Figure of Merit[4] (FOM) among working fluids for room-temperature two-phase systems – was not utilized whenever the possibility of freezing cannot be ruled out (either by survival heaters or by other operational stipulations). Notice that the Ammonia freezing point is -77C. An alternate fluid is Propylene which does not solidify until -173C. A room-temperature Propylene loop would have less than 25% of the transport capacity of the Ammonia counterpart[5].

PROPOSED FREEZE-THAW TOLERANT DCR CONCEPT

The premise of the present concept for thawing a solidly frozen DCR is to heat up the solid (ice) plug at or close to its *free end* and to allow the applied heat to advance lengthwise gradually into the frozen ice. For lack of a better word, the "free end" implies the locations at which that the heated fluid volume expands unrestricted by the wall as illustrated in Figure 4. The ice adjacent to the free surface thaws first (encountering no/little stress resistance). Due to the low combined effective thermal conductivity of ice/tube, the heat propagation by conduction is a slow process, hence, the risk of a downstream temperature excursion is non-existent. Hence, heating at the free end of the ice plug is a safe and consistent technique to thaw/melt frozen ice in a long slender tube. Unfortunately, with the melted liquid trapped between the heating source and the solid ice downstream, the thawing/melting process slows down tremendously. It is impractical to wait for hours or days for the condenser/radiator to completely thaw out to operate the heat transport system again. A better method is therefore needed, which is the main feature of the following proposed design.

Figure 5 depicts schematically the refined DCR concept revealing a design enhancement over the one in Figure 4. Just like a traditional DCR, the condenser line is also made of smooth-wall metal

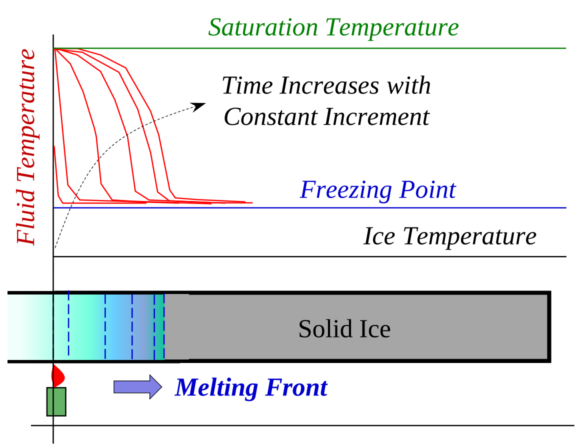

Figure 4. Safe Melting Long Slender Ice Plug.

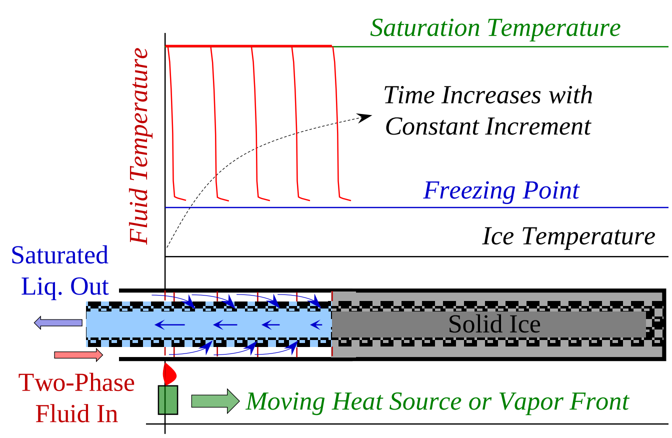

Figure 5. Freeze-Thaw Tolerant DCR Concept.

tubing which is, in turn, bonded to a flat panel to serve as the radiating surface. A flexible porous tube (e.g. porous Teflon or made of wire cloths) is loosely inserted into and encapsulated inside the condenser line. The annular gap between the metal tubing inner wall and the porous tube outer surface forms a flow path for vapor from the loop to penetrate quickly into the condenser for heating the solid ice. Due to the large latent heat, the vapor coming from the loop melts a portion of the ice plug swiftly (as soon as contact between the two occurs). The melted liquid percolates through the porous tube wall to enter its interior and exits out of the condenser (in the reverse vapor direction) into the liquid line. In effect, the proposed condenser line functions like an arterial constant conductance heat pipe, allowing vapor energy to advance rapidly to thaw out the frozen condenser from one end.

As introduced above and verified by a proof-of-concept test program (to be presented in the subsequent sections), the freeze-thaw tolerant DCR concept has proven to be a safe method of thawing out a frozen-solid DCR reliably and quickly, even subjected to severe adverse conditions. To top it off, various operational advantages of the two-phase heat transport system are realized as a consequence – partially listed below:

Loop Always Fully Functional: Excluding the radiator, if the rest of the loop components are well insulated and sufficiently isolated from the thermal environment such that solid ice plugs never form in them (even in extremely cold cases). The loop itself is always fully functional albeit the DCR is frozen solid. In other words, during the thawing process, the heat-dissipating payloads (e.g. housekeeping electronics) can be activated and the waste energy is utilized to thaw out the DCR, i.e. no electrical heaters is needed.

Auto-Regulated Variable Heat Rejection: the amount of heat rejection to space is regulated autonomously to reject just enough heat to condense vapor to saturated liquid at the condenser exit, i.e. a dedicated subcooler may be needed for LHPs. But this feature mitigates the makeup (electrical) heater power to prevent the payloads to get too cold (e.g. low power operations).

Self-Balancing of Fluid Flow Among Parallel DCR Arrangement: to speed up the thawing process, it is strongly recommended that the DCR contain multiple parallel legs joined together by a vapor manifold(s) and a liquid manifold(s) as portrayed in Figure 6. As such, each porous tube inside a condenser leg naturally serves the exact function of one flow regulator that currently in use in the two-phase capillary pumped technology[6].

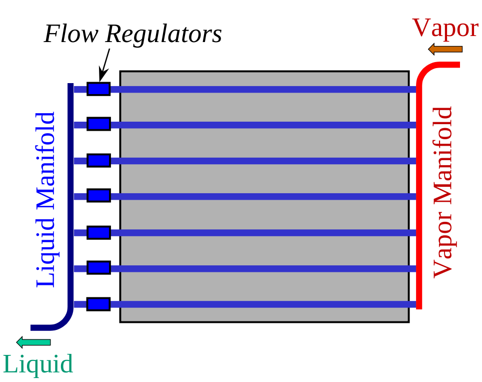

Figure 6. Multiple Parallel Pass DCR.

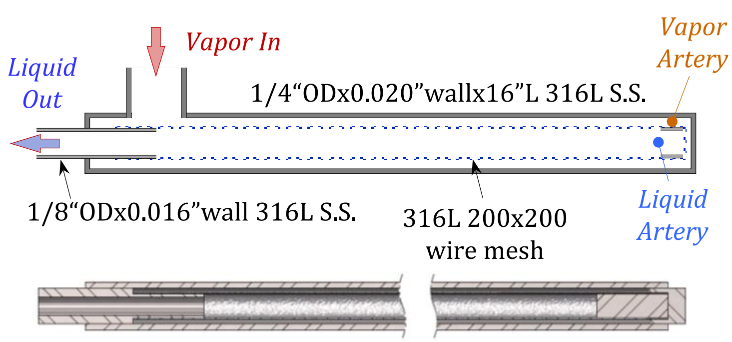

Figure 7. Phase I As-Built DCR.

PROOF-OF-CONCEPT DEMONSTRATION TEST PROGRAM

A technical proposal was submitted and subsequently funded by NASA SBIR Office in 2021 to demonstrate the viability of the Freeze-Thaw tolerant DCR concept for space use. Due to the cost and schedule constraints, a test demonstration program was carried out with a limited goal – to verify the hypothesis that a frozen-solid long and slender tube can be thawed out safely and effortlessly. As such, a small-scale LHP (mini-LHP) – constructed several years ago as a backup for a previous research project – was re-purposed to serve as the DCR freeze-thaw proof-of-concept (POC) testbed. The original condenser was cut out of the mini-LHP and replaced by a newly built single-pass DCR based on the freeze-thaw tolerant concept as illustrated in Figure 7. The testbed layout is depicted in Figure 8 while the as-built demonstration unit is pictured in Figure 9. The unit components' physical dimensions and wick properties are listed in Table 1.

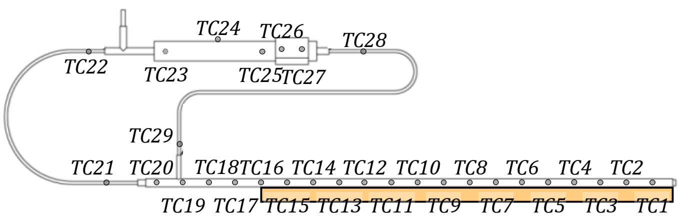

Figure 8. TC Locations of POC DCR Test Unit.

Figure 9. As-Built POC DCR Test Unit.

<u>Proof-of-Concept DCR Design and Analysis, Component Layout, and Testbed Setup</u>

As stated previously, the DCR fabricated for the POC testbed was a simplistic but fully functional unit, so to accommodate the aggressive test schedule. It contained one stainless steel smooth-wall tube measuring 0.24"OD x 0.016"wall x 16"L, of which 12" was thermally coupled to a copper plate to simulate the "active" condenser while the remaining 4" mimicked the vapor manifold of a multiple-leg condenser. The internal DCR structure is made of two full-length but separate axial arteries – one for vapor flow and the other for liquid flow in the opposite direction. So, it is constructed quite like a conventional arterial heat pipe or a LHP secondary wick with respect to

Table 1. Volume Breakdown of Phase I LHP DCR Test Unit

		Volume (cc)		
Components	Description	Vapor	2-f	Liquid
Capillary Pumps				
- Primary Wick	0.5"ODx0.2"IDx1.25"L 45% porosity			1.52
- Liquid Core	0.2"ODx0.125"IDx0.9"L		0.28	
- Vapor Grooves + Channels	Two 0.02"x0.08"x1" Axial Channels	0.05		
- Bayonet Tube	3/32"ODx0.016"wallx3.95"L			0.19
- Reservoir	0.5"IDx3"L		9.65	
Vapor Line	1/8"ODx0.068ID"x24.2"L	1.44		
Two (2) Uniton Sqagelok Fittings	0.095"IDx0.5"L	0.06		
Condenser Line	1/4"ODx0.194"IDx16"L	2.48		
- Screen Tube	0.16"ODx0.125"IDx16"L			5.27
Liquid Line	3/32"ODx0.056"IDx5"L			0.20
Pressure Gauge Tube	1/4"ODx0.194"IDx3"L			1.45
Total		**4.03**	**9.94**	**8.64**

the materials and fabrication methods (in fact, it functions like one, too). In other words, the thin porous *membrane* that keeps vapor/liquid segregated by capillary action (refer to Figure 7) was fashioned by rolling up a piece of a 316L stainless steel cloth to form a one- or two-layer porous tube, which was in turn spot-welded along the seam and pinched off one end. However, vapor was still able to flow through the artery wall if the pressure difference ΔP_{VL} between the vapor and liquid exceeded the capillary limit ΔP_{MAX} generated by the wire mesh. The porous tube made of 200x200 wire mesh was inserted into and welded at one end onto the inner wall of the solid condenser tube to establish a liquid-vapor seal. A bubble test were carried out revealing the effective pore radius of 150μm. Note that the 200x200 mesh porous tube had a sufficient capillary head with Ammonia for the current POC demonstration in which the DCR was adversely tilted no more than 0.8”. The adverse tilt was a precaution against the earth gravity assisting the DCR performance. Hence, the condenser internal wick must generate sufficient capillary action to overcome not only the vapor frictional pressure drop but also to the liquid hydrostatic pressure due to the adverse tilt. The model predictions showed that the mini-LHP heat transport capacity almost reached 300W if the DCR was capable of rejecting the same amount. However, the model also revealed that the fully open POC DCR would reject 85W flat, 70W (-0.5” tilt), 60W (-0.8” tilt) and 50W (-1” tilt). So, all POC demonstration tests were carried out with the DCR tilted -0.8” and the power input was kept at 50W or less.

A ¼” thick copper bar measuring 1.5”Wx12”L had the 12”L *active* section of the condenser tube clamped to one side and a copper tubing clamped to the other side allowing a stream of gaseous Nitrogen (GN2) to flow through and to bring/maintain the GN2 supply temperature below –80°C for a sufficient amount of time to ensure that the entire active DCR volume filled with Ammonia ice prior to each thawing test. Thirty-one (31) Type-T thermocouples were taped to the LHP components (including two on the GN2 coolant line) at various locations but twenty (20) of them were reserved for the DCR outer wall. The active portion of the condenser tube and its cold plate were placed inside a well-insulated Armaflex *cocoon* to minimize the environmental heating/ cooling. A (water) ice pack was placed on the liquid return line to simulate the functionality of a dedicated subcooler.

<u>Results of Proof-of-Concept Demonstration of Freeze-Thaw Tolerant DCR</u>

The primary focus of the Phase I proof-of-concept testing was to demonstrate, verify, and assess the ability of the proposed DCR concept to thaw out – without inducing structural damages to the hardware – from a frozen-solid situation and to full capacity operation even while remained partially frozen. Another operational attribute of the freeze-tolerant DCR design was that the liquid exiting the condenser was almost always at the loop saturation temperature regardless of the heat input applied to the evaporator or what the condenser sink temperature is. This feature of the design – intended to keep the required LHP temperature control heater power reasonably low during cold operating cases – was verified/quantified by running the system for a day or two to produce the “natural curve.” Hence, it was performed following the initial system shakedown/ checkout with the GN2 sink temperature maintained at -20°C and -50°C. Once the natural curve was obtained, the freeze-thaw test demonstration began. For lack of a better word, the level of “frozenness” was defined as how far the initial ice temperature was below the fluid freezing point. To put it in perspective, -78°C to -80°C is slightly frozen for Ammonia ice and, by the same token, -80°C to -90°C is medium and below -90°C is hard. The first few tests were dedicated to the operational characterization of the POC testbed to establish the baseline performance. The remaining effort focused solely on the freeze-thaw cycles mostly under initially hard frozen conditions. Dimensional checks of the condenser tube were made at room temperature at three (3) axial locations before anything was done to the testbed. The procedures described below would be followed for each of the freeze-thaw cycle demonstration tests:

(i) Adjust the GN2 supply bottle regulator valve to maintain the DCR temperatures (TC1–TC16) at a desired frozenness (i.e. -80°C, -90°C, -100°C, -120°C, -130°C, -140°C) prior to the thawing demonstration
(ii) Wait for at least 30 minutes after TC1–TC16 on the DCR cold plate are stabilized at the target temperature
(iii) Apply 25W to the evaporator
(iv) Wait 60 minutes or until the condenser temperatures reach steady state whichever takes place first
(v) Repeat Steps (iii) – (iv) but with a different power input in Step (iii) set to 50W and 75W

Regarding the test result presentation below, the thermocouple (TC) locations are indicated in Figure 8. Figures 10a plot the recorded the loop temperatures from the 10/14/21 test, in which the DCR line temperatures (TC1–TC16) were initially cooled down to about -90°C (slightly frozen)

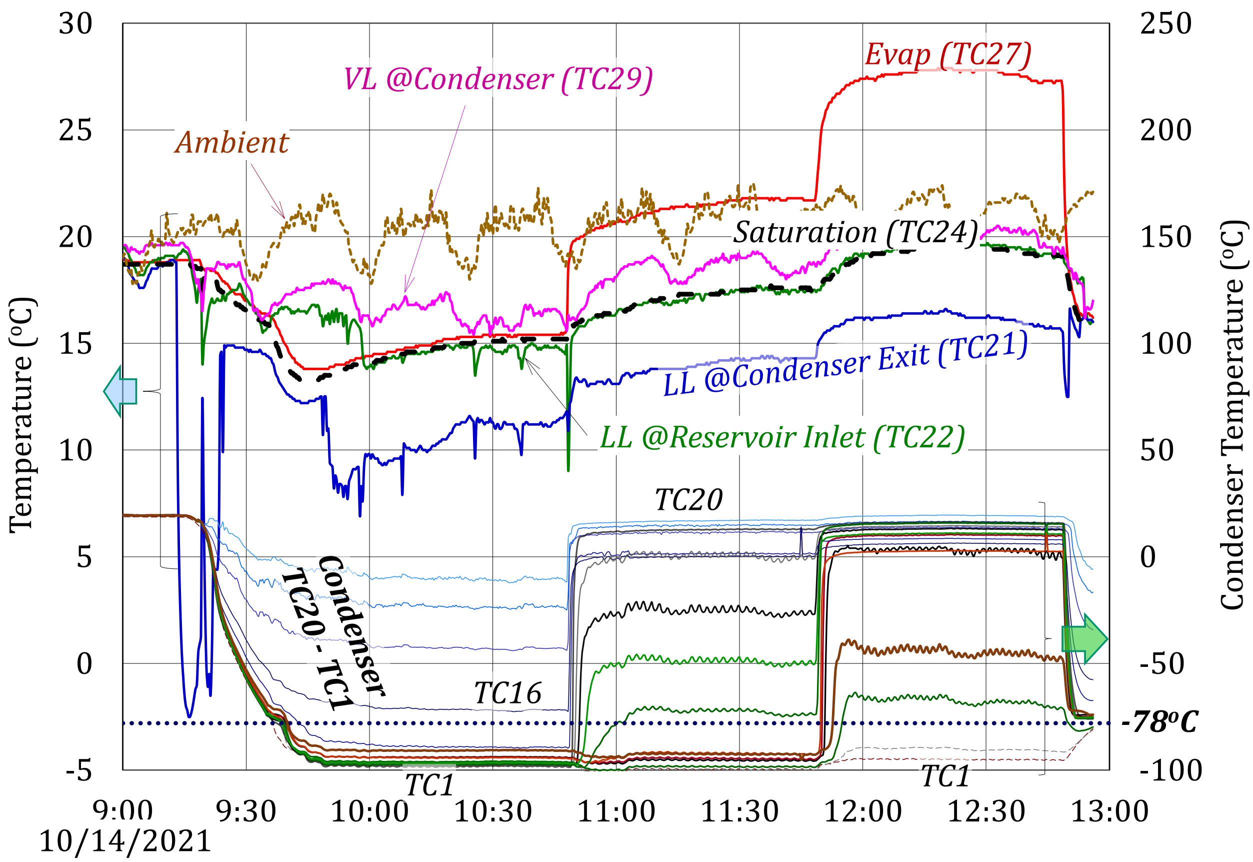

Figure 10a. POC DCR Test Demonstration with Sink –90°C.

prior to the test. Note that the DCR was positioned with the liquid outlet end being 0.5" above the other (i.e. dead-end) such that the melted liquid had to work against gravity (75Pa) to exit out of the condenser (i.e. an adverse tilt). In fact, the very first test of a slightly frozen condenser went so smoothly that the tilt was increased to 0.8" (or 120Pa of hydrostatic head to overcome) and kept at this level for the remaining demonstrations. The test began at 9:00 after the DCR temperatures became stable. All TCs on the active condenser section except TC16 indeed stayed colder than -90°C for 1 hour until the evaporator heater was turned on with a 25W input at 10:48 to commence the operation. The loop started right away and its subsequent transient response was representative of a typical LHP startup. With only 25W to reject, the vapor front in the DCR stopped advancing at the location of TC12. Indeed, from the location of TC9 to that of TC1, the fluid remained frozen even after the system reached steady state at 11:00 (as the time-lapsed temperature distribution of the DCR alluded to in Figure 10b). At 11:48, the evaporator heater power was stepped up to 50W, the DCR temperature response was not different from the 25W start-up. At steady state, the vapor front advanced to the location of TC8 (doubled the length of the 25W operation) and the still-frozen section covered the last 3 TC locations (one third of that of 25W test). It was decided not to increase the power input beyond 50W because the analysis had indicated that the DCR 200x200-mesh porous tube could not support more than 75W heat

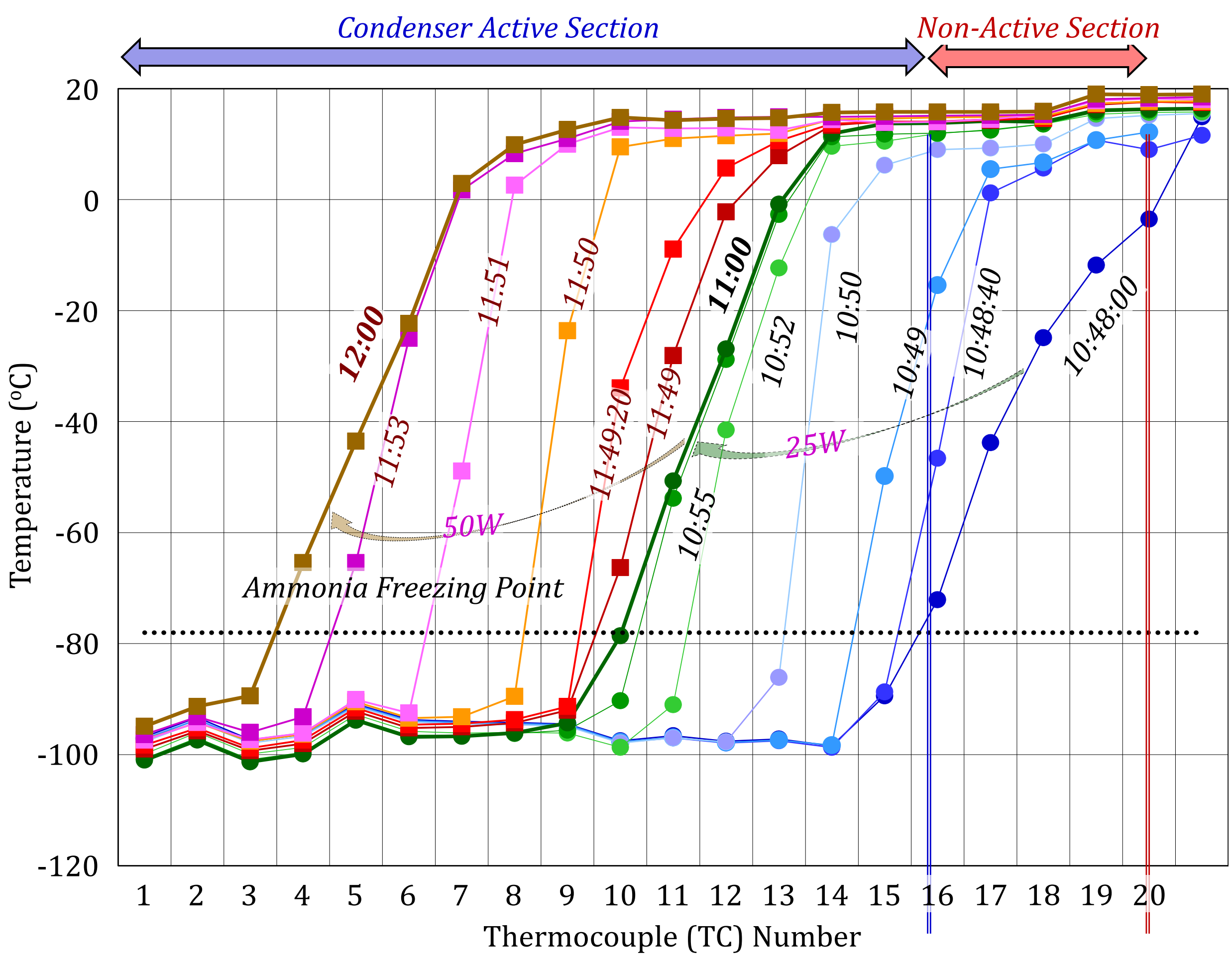

Figure 10b. POC DCR Freeze-Thaw Test with Sink - -90°C on 10/14/2021.

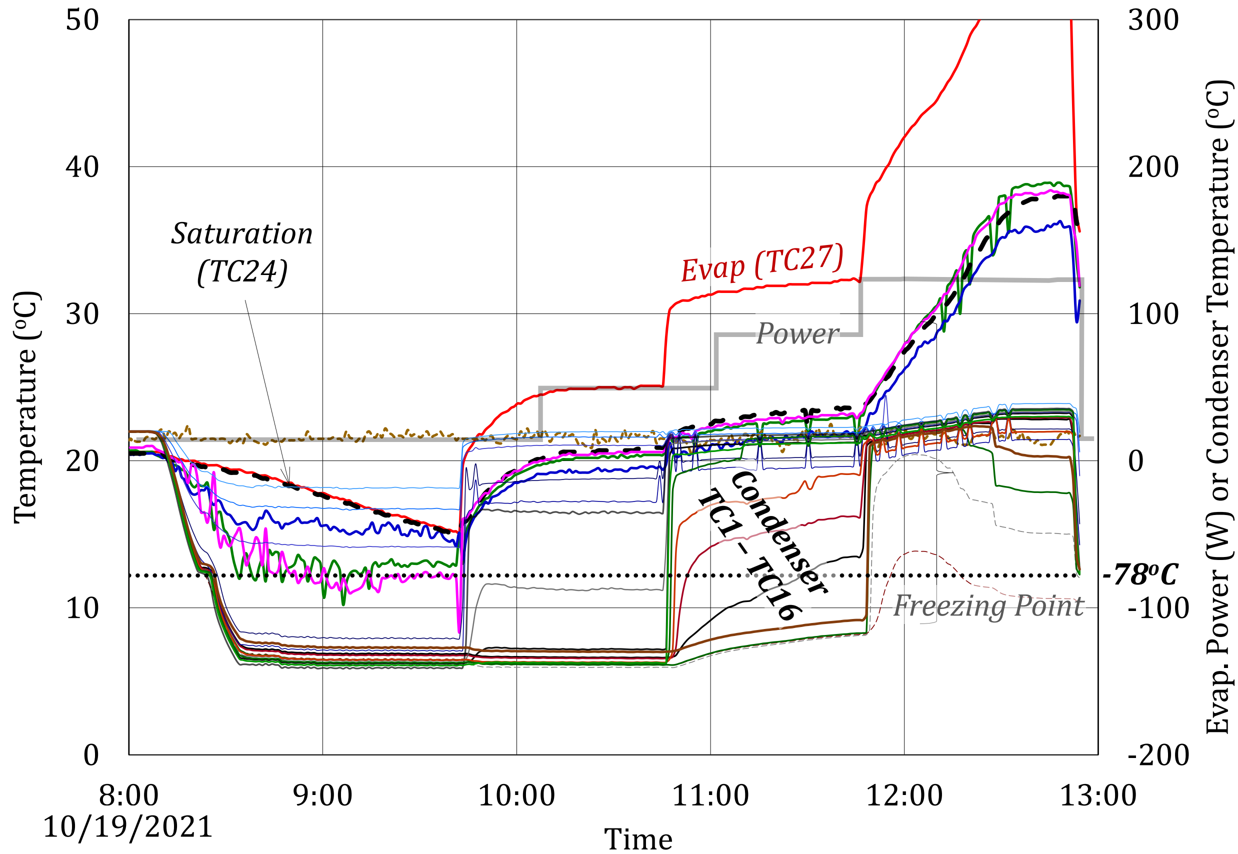

Figure 11a. POC DCR Test Demonstration with Sink –140°C.

rejection while operating with the adverse tilt of 0.8" in the current test setup. Had it been tested "flat" (horizontal) or in 0-g, the POC DCR heat rejection capacity would have been at least 170W. In other words, the DCR functionality is limited by its porous tube ability to segregate liquid and vapor within the condenser line (much like a heat pipe wick). To improve the DCR capability, the porous tube could have been formed with a finer wire mesh (200x800 Dutch Weave). Multiple DCRs arranged in parallel would have also achieved the same objective. The thawing operation in this test, nonetheless, was declared a success (ii) achieving the system steady state operation with an initially hard-frozen condenser line, (ii) advancing of the waste (vapor) energy from the evaporator into in the DCR quickly for the ice melting process, and (iii) to top it all off, the system was fully functional even with a partial frozen DCR.

Not convinced that -90°C test was hard enough for the DCR, the test program continued with the initial temperatures of the DCR line (TC1–TC16) were lowered to -100°C, -120°C, -140°C in the follow-on demonstrations. Note that -140°C was the coldest temperature that the GN2 supply (wide open throttle valve) could provide in the current test setup. Figures 11a and 11b present the results of the -140°C freeze-thaw demonstration performed on 10/19/21. Unlike the -90°C thawing tests, the DCR liquid appeared to be frozen beyond the active section. Nevertheless, the 25W startup was successful achieving steady operation at 10:15 (TC24 or saturation was around 21.5°C) albeit the 2/3 of the active condenser was still under the freezing point and almost 1/3

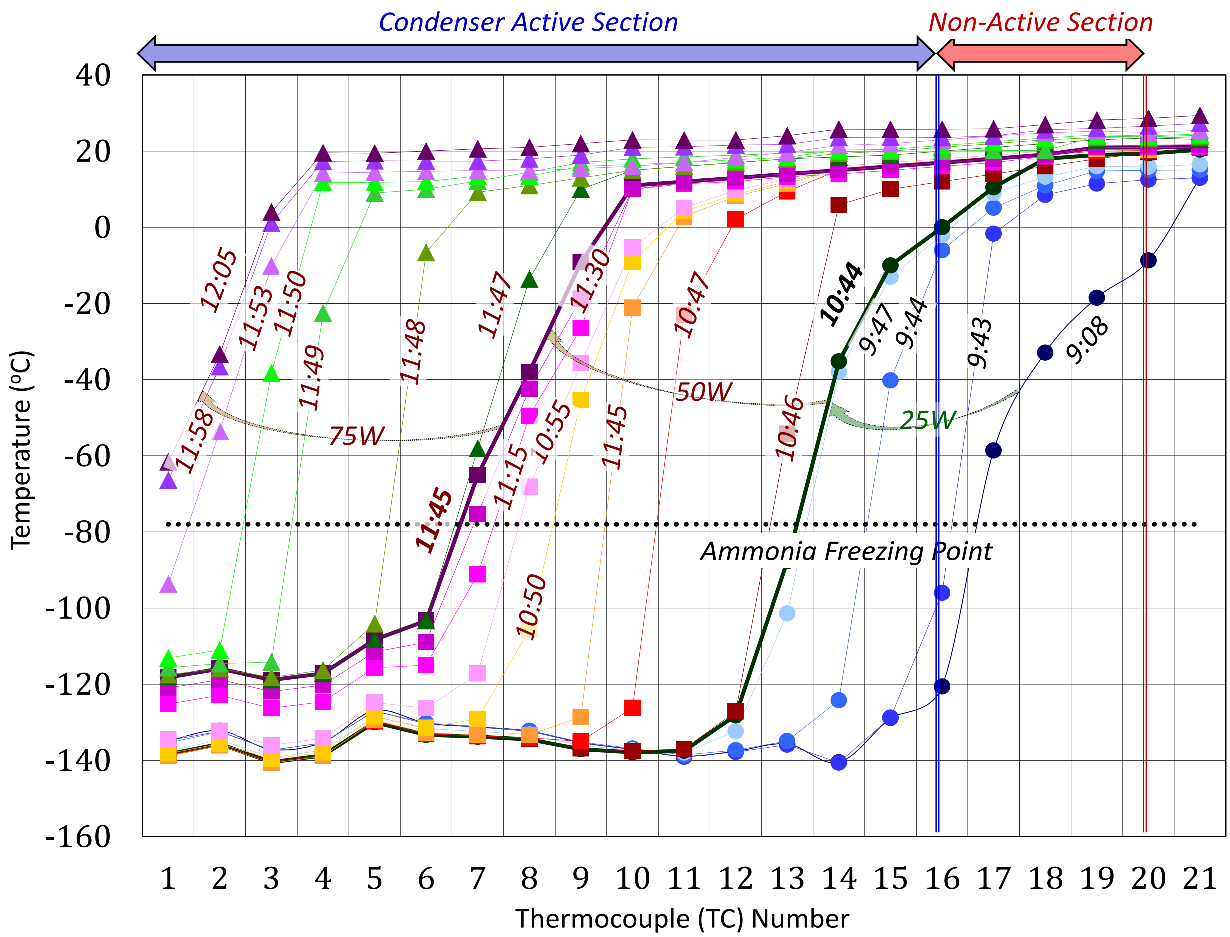

Figure 11b. POC DCR Freeze-Thaw Test with Sink - -140ºC on 10/19/2021.

was filled with subcooled liquid as portrayed by the DCR temperature distribution in Figure 11b. At 10:45, the evaporator heat input was doubled to 50W resulting in a higher vapor mass flow into the DCR melting more ice, displacing more liquid, and raising the DCR average temperature. But, despite all that, the vapor only advanced to the location of TC13 (20% of the condenser active length) while 40% of the condenser volume was occupied by solid Ammonia ice. The LHP reservoir (TC24) reached steady state temperature of 23.6ºC at 11:45. At this time, the test would have been stopped to declare a success but the desire to discover the system ultimate capacity compelled the testing to soldier on. The power input was stepped up to 75W. The vapor front advanced quickly along the condenser length and, in 5 minutes after the power change at 11:50, reached a location between TC3 & TC4 and melted all remaining ice in the condenser (evidenced by TC1 being above the freezing point at 11:56). The temperatures of the reservoir (TC24), evaporator (TC27), liquid line (TC21 & TC22), and vapor line (TC28), however, continued to climb at the rate of 5ºC over a 20-minute period from 11:50 to 12:10. The time rate of temperature change was doubled from 12:10 to 12:20, suggesting that some amount of vapor penetrated the condenser porous tube wall to flow into the liquid line along with subcooled liquid, resulting in low-quality liquid/vapor mixture return to the reservoir via the liquid line. A combination of saturation temperature increase and vapor bypass through the porous tube allowed the vapor front to recede back toward the vapor inlet as illustrated and validated by the time evolution of the condenser temperatures. The vapor recession reduced both frictional and hydrostatic pressure difference in the DCR, “repriming” the porous tube wall in the process. The saturation temperature would increase to a minimum level (38°C in this case) at which the LHP system was able to achieve a thermal equilibrium to reach steady state at 12:45. To remove any doubt about the validity of the -140°C thawing of a hard-frozen DCR, two (2) more tests were repeated the ensuing days with the same conditions. Both tests yielded the identical results.

Upon completion of the freeze-thaw demonstration, the DCR was allowed to warm up to room temperature and dimension checks on the DCR at three (3) axial locations was conducted the next day to determine if the freeze-thaw operations damaged the DCR metal casing. The result, given in Table 2, clearly suggested no detectable structural damage to the DCR. Notice that a 316L stainless steel tube was used for the POC DCR unit due to the short schedule of the research project. For space systems, aerospace-grade Titanium alloys are the alternate materials for their structural strength, fatigue resistance, and weight saving. Titanium is chemically compatible with Ammonia, water and host of other two-phase refrigerants.

Table 2. Pre-/Post-Test Diameter Measurements

Location / Date	3”	7.5”	10.75”	7.5”
10/12/21	0.2505 / 0.2505	0.2500 / 0.2500	0.2500 / 0.2500	0.2500 / 0.2500
10/13/21	0.2500 / 0.2500	0.2505 / 0.2500	0.2500 / 0.2505	0.2500 / 0.2505
10/19/21	0.2505 / 0.2505	0.2500 / 0.2500	0.2505 / 0.2505	0.2505 / 0.2505
11/08/21	0.2505 / 0.2505	0.2500 / 0.2500	0.2500 / 0.2500	0.2500 / 0.2500

0.2500 top-bottom 0.2500 front-back

CONCLUSION AND PATH FORWARD

The research effort was an unqualified success, validating all aspects of operation envisioned by the inventor and supported by analysis. The DCR demonstration test results, without a doubt, validate the principal assertion that thawing a hard-frozen DCR can be done easily/safely/quickly and, above all else, reliably leveraging the true-and-tried heat transfer/transport mechanism of a conventional heat pipe. The freeze-thaw tolerant DCR is, in fact, capable of gracefully melting an initially frozen DCR with the waste heat from the heat sources acquired by and conveyed to the DCR by its own two-phase heat transport system. In addition, the POC test program clearly demonstrates the ability of a two-phase loop with the freeze-thaw tolerant CDR to retain its full operability when the DCR is completely/partially frozen. Other DCR performance benefits – such as heat rejection by condensation only – added icing on the cake.

As much as the current POC test program accomplished, the research has just taken “baby steps” toward the technology ultimate goal of flight qualification for space applications. Since the proposed freeze-thaw tolerant DCR is deemed crucial for the future space programs such as the human habitation of the Moon/Mars and the exploration of the outer planets, the research and development must continue. The present Technology Readiness Level (TRL) is 3. The next logical step is to raise the TRL to 4-5 by constructing a breadboard two-phase heat transport loop with a representative freeze-tolerant DCR design (likely a multiple parallel pass DCR as portrayed in Figure 6). The breadboard test unit shall be tested in both air and thermal vacuum chamber.

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