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Fiscal Year 1993 Annual Report for the Bubble Membrane Radiator Project

**R. J. Guenther
Z. I. Antoniak**

**K. A. Pauley
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February 1994

**Prepared for the
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas
under a Related Services Agreement
Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
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Summary and Conclusions

This report summarizes the activities conducted on the Bubble Membrane Radiator (BMR) Project during Fiscal Year (FY) 1993 at the Pacific Northwest Laboratory (PNL) in Richland, Washington. Funding for this work has been provided by the National Aeronautics and Space Administration (NASA), Lyndon B. Johnson Space Center (JSC), Crew and Thermal Sciences Division. The BMR Project was initiated at PNL in March 1988 to continue development of promising thermal management concepts for space applications. In FY 1992 work was refocused from the BMR to fabrication and testing of ultralight fabric reflux tubes (UFRT) because of progress in this area and the desire to incorporate this concept in thermal management for a lunar colony.

Development, optimization, and testing of UFRTs continued in FY 1993 under five tasks. Task B, Radiative Properties, and Task D, Development of Tough Metal UFRT Technology, were initiated in FY 1992 and completed this year. Three additional tasks were initiated: Task 1, Fabricate Tubes; Task 2, Heat Transfer Optimization; and Task 3, Analyses Follow-On. A summary of the activities under these tasks and conclusions are provided below.

The work remaining under Task B involved life testing of a UFRT and wicking tests on ceramic fabrics at Oregon State University (OSU). Vacuum chamber testing of a UFRT at moderately low vacuum and temperature included a "life test" at a steady-state power input of 78.1 W and two subsequent startup and shutdown tests. The condenser temperature during operation was nominally 87°C (188°F). These tests proceeded well and were terminated after over 800 hours of operation to make visual observations.

Results from the life tests indicated that the temperature difference between the evaporator and condenser surfaces was about 33° to 39°C (60° to 70°F). Such a difference has been observed in several other tests and is believed to be at least partly a result of the placement and effect of the installed thermocouples. Another phenomenon observed was cycling of the temperatures and pressure inside the reflux tube during steady-state operation. This cycling was observed during rapid data collection and involved a 20°C (36°F) rise on the evaporator end and a drop of about 2° to 3°C (3.6° to 5.4°F) on the condenser end. During a typical cycle, the UFRT interior temperature, condenser temperature, and pressure all dropped while the temperature in the evaporator section rose. The process reversed and returned to the original working conditions in less than 2 seconds. This is postulated to result from vapor condensing on the liner interior wall, forming a critical radius, and dropping down the UFRT where it quenches the liner under the thermocouple locations.

Nextel® 440, Nextel® 312, s-glass, Kevlar, and SiC were also tested at OSU to determine their wicking capacity, which is important in determining UFRT operating limits. The tests consisted of measuring the flow in saturated wicks connecting two trays at different elevations, the upper tray acting as a fluid reservoir. The flowrate decreased for tests involving greater differences in elevation, apparently because the added pressure from the larger drop is less than the added resistance to flow in longer

fabric samples. There were indications that stiffer materials, such as Nextel® 440 and SiC, may hold their shape better and permit better flow. These results are in review for potential application to selection and design of UFRT wicks.

Task D involved the design, fabrication, and testing of a new cluster mill for making liners out of tougher materials (tougher than the existing copper liner) with diameters as small as 1.27 cm (0.5 in.). The new cluster mill was designed in FY 1992 and fabricated offsite because of the extreme tolerances required. Upon receipt inspection, some of the roller dimensions were found to be out of tolerance. Independent measurement of the roller dimensions were made to accommodate these differences during setup. D. V. Archer assumed the role of principal fabricator for thin wall tubing and had two copper preforms made that will be used for testing of the new cluster mill in early FY 1994.

The primary goal of Task 1 is to fabricate new UFRTs with an improved design. A previous review of the material properties and fabrication requirements for stainless steel, Monel, and titanium was reevaluated to select a better liner material than the copper used in the first UFRTs. Titanium was selected because of past fabrication experience at PNL, titanium's greater strength, and the much lower weight expected with such a design. After several trial runs, D. V. Archer made a short thin-wall tube from copper. A titanium preform was then made and used to form a 0.45-m (18-in.) long tube with a 50- μ m (0.002 in.) thick wall. Work will continue on developing the parameters to make an acceptable thin-wall titanium tube and assembly of a new UFRT.

Task 2 involved evaluations of past UFRT tests to investigate the observed temperature differences in the UFRT components and to propose testing and design changes that would validate and/or improve UFRT performance. Several phenomenological tests have been identified for evaluating these issues. In addition, potential changes to the test setups and design of the UFRTs that will improve the quality of the tests have been identified based on common problems, including interruption of the pressure transducer diaphragm setting during fill operation, condensation on the internal probe, variable thermocouple contact resistance, and inadequate calibration/compensation of the thermocouples.

Potential changes to UFRT tests include 1) filling and sealing the UFRT before testing, because the current fill procedure is not prototypic of space flight operations; 2) immersing the evaporator in a working fluid to transfer the heat load (which should decrease aberrations), increasing the precision of thermocouple measurements, and more closely simulating prototypic coupling of the UFRT with a heat source; and 3) developing a standard thermocouple mounting technique. These improvements should enhance the evaluation of UFRT performance.

UFRT design changes that should improve heat transfer include thinner evaporator walls, thinner ceramic fabric, pre-treatment of the outer surface of the metal liner, and looser ceramic fabric over-braid. In combination or individually, each of these design changes would potentially offer better thermal properties. Other options may also warrant evaluation.

Additional analyses were started under Task 3 on data collected during the vacuum chamber tests of three UFRTs at NASA JSC in August 1992. A major concern after the initial examination of data

was the apparent large temperature drop between the evaporator and condenser outer surfaces. Preliminary evaluation of the data from the frozen startup test series indicates that the large temperature gradients may be an artifact of the experimental setup. Accounting for the different effects of the environment on each UFRT in the array, the radiated power seems to be consistent among UFRTs. Variations between the emissivity of the ceramic fabric and the thermocouple, as well as differences in absorptivity, may also cause the thermocouples to measure temperatures that are not prototypic of the UFRT. The result of these and future evaluations should help to understand the results of these tests.

The successful completion of the life testing at OSU and continued development of an improved UFRT design have brought this concept from a mere idea only a few years ago to a first generation prototype. Continued development and system testing should provide a sound basis for promoting this concept for thermal management systems when the need arises.

Acknowledgments

The authors would like to thank Patricia A. Petete and Kathryn M. Miller of the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Crew and Thermal Sciences Division, Houston, Texas, for their programmatic guidance and review of this effort. The authors would especially like to acknowledge the efforts of Dale V. Archer of Pacific Northwest Laboratory (PNL) for his contributions to the fabrication of thin wall tubing. One of us (T. M. Sambrook) gratefully acknowledges support from the U.S. Department of Energy, Division of University and Industry Programs, Office of Energy Research, as a Science and Engineering Research Semester program participant at PNL.

The contributions of Dr. A. C. Klein, R. D. Snuggerud, and S. Abdul-Hamid of Oregon State University are also gratefully appreciated. Sharon K. Loverne (PNL) also made an important contribution to this document as editor.

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1.0 Introduction

This report provides a summary of the activities conducted on the Bubble Membrane Radiator (BMR) Project (Project 13634) during Fiscal Year (FY) 1993 at the Pacific Northwest Laboratory^(a) (PNL) in Richland, Washington. Funding for this work was provided under National Aeronautics and Space Administration (NASA) Defense Purchase Agreement T-6762P. Program direction is provided through the Thermal Branch, Crew and Thermal Sciences Division of the Lyndon B. Johnson Space Center (JSC) located in Houston, Texas. Additional background information, a description of the tasks conducted, and progress on those tasks are provided in the following sections.

1.1 Background

The BMR Project was initiated at PNL in March 1988 to continue development of promising thermal management concepts for space applications. The initial concept studied was the BMR that was designed to reject heat by ejecting heated fluid from the central axis of a rotating bubble membrane toward the interior surface of the membrane made of layers of ceramic fabric and metallic or plastic sheets. Work on this concept was completed in FY 1992.

Work was refocused during FY 1992 toward fabrication and testing of ultralight fabric reflux tubes (UFRT) because of progress at PNL in this area and a desire to evaluate and develop this concept for thermal management of a lunar colony. Design of the UFRT is based on waste heat being removed from the habitat and equipment areas at 21°C (70°F) and transported to a heat pump where the working fluid temperature is increased to 87°C (188°F). A summary of the design assumptions are shown in Table 1.1.

The first generation of UFRTs made at PNL were completed in 1992 and consisted of a copper inner liner and a Nextel® overwrap. The UFRT design is 1.1 m (43.3 in.) in overall length and 0.03 m (1 in.) in nominal diameter.

Table 1.1. Assumed UFRT Environmental Conditions

Environment	Lunar
Gravity	1/6 g
Lunar-day Temperature	51°C (125°F)
Lunar-night Temperature	-157°C (-250°F)
Nominal Operating Temperature	87°C (188°F)
Operating Temperature Range	71-127°C (160-260°F)
Working Fluid	Water

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830.

Four features separate PNL's design from traditional reflux tubes: the thin metallic liner, ceramic fabric overwrap, water working fluid, and ceramic fabric evaporator wick structure. The various components used to make a UFRT with a copper liner and SiC overwrap are shown in Figure 1.1.

The copper liner acts as a permeation barrier to retain the working fluid in the reflux tube and is about 50- μm thick in the condenser region and 305- μm thick in the evaporator region. The thin metal liner is also used to transfer the stress associated with the operating pressures in the UFRT to the high strength ceramic fabric that provides the principal support along the 0.8-m long condenser region. The SiC ceramic fabric overwrap shown in Figure 1.1 was replaced with Nextel® because of more desirable thermal properties. Nextel® used as the wick and as the overwrap for the JSC reflux tubes is made of a 560- μm thick aluminoborosilicate, commercially produced by the 3M Company. Selection of this material was based primarily on its absorptance and emittance characteristics in the solar spectrum: an emittance measured at approximately 0.93 at 152°C (306°F) and an absorptance of 0.1 in solar wavelengths. Water was used for the working fluid because it is benign and a relatively good working fluid. It was possible to use water in the UFRTs because of the high strength of the ceramic fabric/thin-wall liner, even with the relatively high pressures at the temperatures of interest. The Nextel® wick is used to reduce the potential for reaching critical heat flux in the evaporator region, which would produce local dryout. These design attributes combine to provide a unique and potential cost-saving means of heat rejection.

Several successful tests have been conducted on this first generation of UFRTs. Ultralight fabric reflux tubes with either SiC or Nextel® overwraps were tested at PNL in 1992 to ensure proper startup behavior and to test maximum power capability in an ambient air atmosphere. The UFRTs were successfully tested to power levels of 200 W with an internal pressure of about 503 kPa (73 psia); however, this power did not appear to be limiting. Eight UFRTs were shipped to NASA JSC for thermal vacuum testing in August 1992. The test matrix included startup and shutdown, frozen startup, load/follow transients, lunar day and night performance, and maximum heat rejection capabilities. The thermal vacuum chamber tests have indicated that the UFRT design operates isothermally along the condenser region and performs as anticipated in nominal operation and load following. The UFRT design also began operation without incident from a full frozen initial condition. Due to instrumentation failures, the design was only tested to 90 W in a thermal vacuum environment of -129°C (-200°F) and 10^{-4} kPa (1.5×10^{-5} psia) or lower. In general, this design has met all expectations for short-term duration tests.

Several areas for improvement of the UFRT design became evident as a result of past testing and design evaluation. One major conclusion from the testing was that the liner material needed improvement to withstand handling operations as a number of UFRTs have failed during test setup. While some of these problems could be avoided by experience and improved procedures, it was decided that a tougher liner would be an important improvement to the design. Optimization studies indicated that the current UFRT mass of $<6 \text{ kg/m}^2$ (based on projected, one-sided condenser area) could be lowered, potentially to $<2 \text{ kg/m}^2$, without compromising performance by a number of design changes. The potential changes include smaller liner diameters (i.e., greater length to diameter ratios), thinner or smaller attachment components, materials with lower densities, and the use of fins. Results from the testing also indicated that improvements could be made in the method of monitoring the tests as well as the design of the reflux tubes. Several of these improvements are being addressed by activities initiated in FY 1993.

Figure 1.1. Stages of Fabrication of a Silicon Carbide UFRT

1.2 Activities Conducted During FY 1993

The carryover activities from FY 1992 and three new tasks for FY 1993 are listed in Table 1.2. Tasks B and D were activities initiated in FY 1992. The work remaining under Task B involved life testing of a UFRT and wicking tests on ceramic fabrics at Oregon State University (OSU). Under Task D, a new cluster mill was fabricated for use with materials with greater toughness than the copper used in previous UFRTs.

The three new technical activities started in FY 1993 were Task 1, Fabricate Tubes; Task 2, Heat Transfer Optimization; and Task 3, Analysis Follow On. A fourth task provides management and reporting for the project. Fabrication of one or more UFRTs using a new liner material that is expected to provide improved resistance to failure during handling was started under Task 1. Task 2 consists of reviewing past test information to determine ways of improving test results from both a testing and design perspective. Task 3 involves additional review of the vacuum chamber tests conducted last year at JSC.

Table 1.2. Tasks for BMR Project During FY 1993

Task	Title	Deliverable/Schedule
B	Radiative Properties (complete OSU subcontract work)	OSU to deliver final report by 2/93
D	Development of Tough Metal UFRT Technology	Fabricate Cluster mill and test, 6/93
1	Fabricate Tubes	Best effort to produce one or more new UFRTs, 8/93
2	Heat Transfer Optimization	Summarize results in annual report, 8/93
3	Analysis Follow On	None
4	Project Management and Reporting	Annual Report, 9/93

2.0 Progress On Tasks

As previously explained, work conducted in FY 1993 consisted of completing two remaining activities initiated in FY 1992 and starting three new tasks in FY 1993. Detailed results from the tests under Task B were provided in a separate report (Klein et al. 1993) but are summarized in Section 2.1 for completeness of this report. The progress on fabricating a new cluster mill and new UFRTs is described in Sections 2.2 and 2.3, respectively. Evaluation of options for improving the ability to test and collect data from UFRTs is reported in Section 2.4. A summary of the past thermal vacuum chamber tests were reported by Pauley et al. (1993), but further evaluation of these data has been initiated as explained in Section 2.5.

2.1 Radiative Properties (Task B)

As the final activity initiated under Task B, two types of experiments were performed at OSU to support the development of UFRTs. The first type of experiment was a series of life tests conducted with a PNL UFRT in an OSU vacuum chamber. The second series of tests involved wicking rate tests for PNL-supplied ceramic fabric samples. A summary of the test results are provided below.

2.1.1 UFRT Life Testing

The first type of experiment performed at OSU was a series of life tests conducted in their Fabric Composite Heat Pipe Test Facility (HPTF). The series of tests conducted included transient testing (startup and shutdown) of a PNL UFRT and a "lifetime" test of over 800 hours. Testing was initiated in October 1992 after a test stand was fabricated and after the test stand and thermal vacuum chamber were reconfigured to accommodate the PNL UFRT.

Apparatus Description

The vacuum chamber consisted of two mild steel concentric cylinders welded together to form an outer cooling jacket and an inner vacuum chamber. The vacuum chamber had an inner length of 1.02 m (40 in.) and a diameter 0.14 m (5.5 in.). A 0.15-m (6-in.) extension was added to the existing system and insulated to accommodate the UFRT. The chamber could be maintained at a moderate vacuum (about 0.00133 kPa, 10^{-2} torr) and an inner wall surface below 0°C (32°F). Pressure in the vacuum chamber was monitored manually using a standard bellows type gage. Cooling was provided by a recirculating bath chiller using a 50% aqueous ethylene-glycol coolant through the cooling jacket. The chiller was rated at 240 W at -20°C (-4°F); during this test an inlet temperature of approximately -10°C (14°F) was maintained. The system was designed to provide for the collection of temperature and pressure of the UFRT as well as charging of the UFRT prior to testing. System power was monitored manually. This facility is diagramed in Figure 2.1.

Heat was provided to the reflux tube evaporator end by a 0.076-m (3-in.) band heater. The temperatures generated in the test apparatus were measured by chromel-alumel (K-type) thermocouples. A single iron-constantan (J-type) sheathed thermocouple was used to monitor the

Figure 2.1. Schematic of OSU Vacuum Chamber Apparatus

internal temperature of the reflux tube. The thermocouples were attached at the locations shown in Figure 2.2 using small thermocouple adhesive tabs. Data from the reflux tube and HPTF were continuously monitored and logged using a 8088 personal computer and Omega DAS-8 analog/digital interface board. The reported data are based on the average of the collected data over the last recording interval.

Summary of Life Testing Results

Vacuum chamber testing of the UFRT included a "life test" at a steady-state total power input of 78.1 W and two subsequent startup and shutdown tests. The condenser temperature during operation was nominally 87°C (188°F). These tests were initiated in November 1992 and lasted for over 800 hours.

Figure 2.2. Location of Thermocouples for UFRT Vacuum Chamber Testing

The tests proceeded well and were terminated to make visual observations; there is no reason to believe that the reflux tube would not have continued to perform for a much longer period of time. Data from one of the startup tests were lost; however, the reflux tube operated as expected, and a second startup was conducted. Temperatures measured with Thermocouples 1 (condenser end cap), 4 (fabric surface at middle of UFRT), 8 (evaporator surface), and 15 (UFRT interior at condenser end) and the UFRT pressure are plotted in Figure 2.3 for the startup of the UFRT from November 17, 1992. For this set of data, information was collected at 5-minute intervals. Various lengths of collection intervals were used throughout these tests: long intervals (1 to 5 min.) for life tests to minimize data collection and short intervals (0.3 to 9.5 sec) to observe interesting test features. The overall difference in temperatures between the evaporator and condenser surfaces (ΔT) was in the 33.3° to 38.9°C (60° to 70°F) range. This higher than expected ΔT has been observed during several other tests and is believed to be a matter of the placement and effect of the installed thermocouples. More evaluation of this observation is provided in Section 2.4 below.

A plot of similar temperature and pressure data during steady-state operation from November 19 to 23, 1992 is shown in Figure 2.4. The very slow loss of vacuum in the chamber required occasional operation of the vacuum pump that is believed to have caused drops in the measured temperatures such as shown in Figure 2.4. It is speculated that the vibration from the operating pump caused drops of water in the condenser end to fall down causing the momentary decrease in temperatures. It was also noted that the evaporator temperature decreased by about 5°C (9°F) over the first several days of operation.

Figure 2.3. Selected Temperatures and Pressure in the UFRT During Startup from November 17, 1992 (4:03:07 p.m.) (5 min. sampling time)

Figure 2.4. Selected Temperatures and Pressure in the UFRT During Steady-State Operation from November 19, 1992 (11:45:12 a.m.) to November 23, 1992 (1:24:54 p.m.) (5 min. sampling time)

Another particularly interesting phenomena observed during the life test involved cycling of the temperatures and pressure inside the reflux tube during steady-state operation. The cycling of the temperature within the reflux tube can only be observed when the data cycle time is short, recalling that the data are averaged over the time interval. As demonstrated in Figure 2.5, this cycling involved a rise of about 20°C (36°F) on the evaporator end and a drop of about 2° to 3°C (3.6° to 5.4°F) on the condenser end. During the typical cycles shown in Figure 2.5, the UFRT interior temperature, condenser temperature, and pressure all start to drop while the temperature in the evaporator section begins to rise. After about 1 minute, the process reverses returning the UFRT to its original working conditions in less than 2 seconds. The periodic thermal cycling, on the order of 2 to 3 minutes, has been observed on each of the external thermocouples. This has been attributed to the drop-wise condensation mechanism, which allows a buildup of condensate in a location until it reaches a critical radius. The condensate then forms a rivulet and quenches the locations under the thermocouples.

2.1.2 Ceramic Fabric Wicking Tests

Five ceramic fabrics were tested to determine their wicking capacity: Nextel 440®, Nextel 312®, s-glass (a fiberglass fabric), Kevlar, and SiC. This information is of interest because the amount of liquid that a particular fabric is able to return to the evaporator is an important part in determining the maximum operating conditions.

Figure 2.5. Example of Temperature and Pressure Cycling in the UFRT During Steady-State Operation from December 6, 1993 (9:49:48 a.m. to 10:24:08 a.m.) (1.5 sec sampling time)

Test Description

The test apparatus is shown in Figure 2.6. It consisted of two trays separated vertically by a distance of 14 or 7 cm (5.5 or 2.75 in.) with a copper bridge joining them. The upper tray was made much larger than the bottom tray to minimize the effect of removed water on the flow rate. A copper bridge was used to obtain better wettability than found during initial testing with aluminum. The fabrics were heat treated to remove any sizing: 8 hr at 400°C (752°F) for the s-glass and SiC, and 12 hr at 550°C (1022°F) for Nextel 312 and 440. The Kevlar was soaked in deionized water (DIW) and detergent for 2 weeks to allow comparison of results with previous tests for this material. The fabrics were cut into 6.5-cm (2.56-in.) wide strips and sealed at the edges using silicon gel to prevent unraveling. The thickness of a single layer of fabric is 0.014 cm (0.0055 in.) for s-glass, 0.0254 cm (0.01 in.) for Kevlar, 0.028 cm (0.011 in.) for SiC, 0.036 cm (0.014 in.) for Nextel 312, and 0.043 cm (0.017 in.) for Nextel 440. For each test, the upper tray was partially filled with DIW, and the fabric was moistened and laid on the bridge, allowing time for a flow to be established. When about 100 to 150 mL of water was collected in the lower tray, it was removed and placed back in the upper tray for another run. Test times varied from 30 minutes to 4 hours. Each fabric was tested in four different setups: as single and double layers with either 14-cm (tall) or 7-cm (short) drops between the trays.

Summary of Wicking Test Results

The four runs for a given test setup (single or double layer of fabric with tall or short drop) were averaged and are plotted in Figure 2.7 for the five fabrics tested. While there is some inconsistency in the data, some of which may be due to differences in separate tests for a given setup, there are some

Figure 2.6. Schematic Diagram of the Wicking Rate Test Equipment

Figure 2.7. Fabric Wicking Rates in Four Setups

conclusions worth noting. The addition of a second layer of fabric did not significantly change the flow rate for s-glass, Nextel 312, and Kevlar in either the tall or short setup. This was also true for Nextel 440 on an aluminum bridge for the tall setup and for a copper bridge for the short setup. It was concluded that the decrease in flow rate going from short to tall setups for single layers indicates the added pressure from the larger drop is not greater than the added resistance from the increased flow length in longer fabric samples. Nextel 440 and SiC are much stiffer than the s-glass and Kevlar and may hold their shape better, permitting better flow. These results are in review for potential application to our selection and design of wicks in the UFRTs.

2.2 Development Of Tough Metal UFRT Technology (Task D)

This task involves the design, fabrication, and testing of a new cluster mill for use with materials that offer greater toughness than the existing copper liner. The new cluster mill was designed by L. L. King of PNL in FY 1992 and fabricated offsite because of the extreme tolerances required for the various components. Such requirements are desirable because uncertainties in the equipment dimensions or the dimensions of the preforms translate into significant errors when making reductions of 90% to 95% in a single pass for long tubes as is done with PNL's process.

Fabrication was initiated in late 1992 on the new cluster mill and completed by a machine shop in Idaho in early 1993. The mill was shipped to PNL where on-site examinations indicated that some of the roller dimensions were out of tolerance. The rollers for the new cluster mill were sent off site for independent measurements and were confirmed to be out of tolerance. The actual dimensions will be used to adjust for these differences; adjustments are typically made to the mill during setup and are not expected to be a problem.

Last year's studies indicated that a slightly smaller liner diameter, among other changes, would help optimize the UFRT design. Thus, the new mill was designed to make liners with diameters as small as 1.27 cm (0.5 in.) compared with 2.54 cm (1 in.) for the original mill. It was concluded that an initial test with the 2.54-cm (1-in.) mandrel used for previous UFRTs would facilitate this comparison. However, assembly and testing of the cluster mill was impacted because of L. L. King's absence on short-term disability. Because of L. L. King's continued absence, D. V. Archer has assumed the role of principal fabricator for the thin wall tubing at PNL. He has had two copper preforms made that will be used for testing of the new cluster mill and comparison with results from the original mill. The cluster mill is scheduled to be assembled and tested in early FY 1994.

2.3 Fabricate Tubes (FY 1993 Task 1)

The goal of this task is to fabricate new UFRTs with an improved design. Testing last year at PNL and JSC indicated a need for improved durability. Testing of the reflux tubes made with copper liners and Nextel® ceramic fabric overwrap indicated good thermal performance under startup and steady-state operation, but a number of UFRTs failed during handling and/or setup. An initial evaluation of potential new liner materials made last year was reviewed, and a selection was made as explained below. The status of fabrication of new UFRTs is also discussed; fabrication of one or two new UFRTs with an improved design is on a best-effort basis because of limited funding this year.

2.3.1 Selection of Next Generation Liner Material

Based on the review conducted last year, the material properties and fabrication requirements for three candidate liner materials were reevaluated: stainless steel, Monel, and titanium. Any one of these materials should provide improved durability during testing and operation. Experience at PNL with fabricating liners from stainless steel and titanium indicated that there was a greater potential for success with titanium. The stainless steel has proven difficult to work, but several short titanium thin wall tubes have been made. While Monel might be an ideal liner material for some applications, PNL had never worked with this material. Another fabrication issue was the potential cost to attach the end caps. Monel could be soldered, as was the case for the copper liners used previously, but there would be development costs associated with either soldering Monel or electron-beam-welding titanium. Both the titanium and Monel liners might require some heat treatment depending on the effect of cold forming on the liner; thus the cost of heat treatment was eliminated as a selection criteria. Titanium was selected as the new liner material because of past fabrication experience at PNL, its greater strength, and the much lower weight expected with such a design.

Selection of this material will present some challenges, but fabrication of new reflux tubes with this material has a higher probability of success than with other materials considered.

A brief review was conducted on options for annealing the titanium liners and setting them into the ceramic fabric. Limited tests will be conducted to evaluate the annealing options once liners are available.

2.3.2 Progress on Fabrication of Titanium Heat Pipes

D. V. Archer reviewed L. L. King's records and test procedures for making UFRTs and obtained titanium pipe stock for preparation of new liners. An available copper preform was used by D. V. Archer to make a short thin wall tube after several trial runs. Subsequently, two copper and four titanium preforms were made for further fabrication testing. To date, a titanium preform has been used to make a 0.45-m (18 in.) long tube with a 50- μ m (0.002-in.) thick wall. An example of the thick/thin regions of the copper and titanium tubes are shown in Figures 2.8a and 2.8b, respectively. While a fairly smooth thin wall region was made with the copper, additional work will be necessary to produce an acceptable thin wall tube from the titanium.

2.4 Heat Transfer Optimization (Task 2)

The observed temperature gradients along the UFRTs have been unacceptably large during recent experiments. In several cases, the temperature gradient has been as high as 38.8°C (70°F), which is at least twice as large as would be predicted analytically. As a result, the design of tests for the UFRTs, as well as the design of the UFRTs, have been reviewed to determine what improvements could or should be made.

This information is important because the temperature gradients from the exterior of the evaporator to the exterior of the condenser are of primary importance to adequate operation of the UFRTs. This information is also relevant to the safe and efficient operation of primary thermal management systems to which the UFRTs are integrated. In order for a specified amount of heat to be rejected from a system with a fixed surface area, the radiators must be maintained at a certain temperature. The thermal management system working fluid, which flows past the evaporator portion of the UFRT, controls the temperature at which heat is transferred into the UFRT. With a large thermal gradient across the radiator, two options may be employed to maintain the capability of the radiator. First, additional surface area, i.e., additional UFRTs, may be utilized in the radiator design. This creates a non-optimal use of mass and volume for space system component launches. Second, the temperature of the thermal management system working fluid may be increased. Increases in working fluid temperatures dramatically impact the operation and efficiency of the primary system. Thus, there is a need to evaluate and minimize the temperature gradient along the UFRT.

The tests conducted to date on the current UFRT design are not considered optimal for two primary reasons. First, the current UFRT design is a proof-of-principle test article. A number of possibilities for optimizing the current design were summarized in last year's annual report, some of which are being incorporated into the second generation UFRT. Second, the tests were not configured optimally. Instrumentation selection and placement did not consistently yield high quality data. Therefore, improvements in the operation and evaluation of future UFRT tests will benefit from stricter controls on instrumentation and configuration.

a) Copper Thin Wall Tubing

b) Titanium Thin Wall Tubing

Figure 2.8. Example of Copper and Titanium Thin Wall Tubes Made with Uniscan Process

The results of earlier tests conducted on UFRTs were reviewed to determine ways in which the temperature gradient could be evaluated and minimized for future UFRTs. A review of the thermal resistance paths and issues that arose from the various test configurations is summarized in Section 2.4.1. Several phenomenological tests are outlined for evaluating these issues. Potential changes to the test setups and design of the UFRTs that will improve the quality of the tests are described in Section 2.4.2.

2.4.1 Evaluation of UFRT Heat Transfer and Past Test Issues

Prior to evaluating the test results, it is useful to consider the paths for heat transfer in the UFRTs using a thermal resistance model. Each heat transfer mode, i.e., conduction, convection, or radiation, can be described using a circuit analogy. The thermal resistance paths in the evaporator and condenser sections of the UFRT design are shown in Figure 2.9. From this diagram, the specific resistances that require further investigation may be identified. For instance, since conduction through copper is well understood, this resistance requires no further analysis. However, for the evaporator section, the heat contact resistance and the resistances associated with convection and phase change in the wick are not easily quantified and require further study. With the exception of conduction through the copper inner liner, the complex phenomena associated with both condensation and radiation heat transfer through bundled pseudo-arrays of filaments (ceramic fabric) have not been adequately studied in the past and require substantial study in order to understand the importance of each resistance path. Reference to these heat transfer paths can facilitate evaluating potential areas for improvement in UFRT tests and designs.

Summary of Past Test Issues

Three series of tests were conducted on the UFRT designs during 1992. Two of these tests were performed for the BMR program at the NASA JSC and OSU. A separate set of tests were conducted at PNL for the U.S. Department of Energy (DOE), using a heat pipe design similar to those developed for the BMR program. Review of these tests provides insight into common issues with testing the UFRTs.

The UFRT tests conducted at the NASA JSC employed Nextel®/Cu reflux tubes in an ultra-low-pressure thermal vacuum chamber. The test consisted of an array of five UFRTs placed along side each other and was the first vacuum chamber test for the UFRTs. The instrumentation used and its placement are shown in Figure 2.10. Potential problems using each instrument are also tabulated in Figure 2.10 to assist in adequately assessing the quality of the data produced during the experiment.

The OSU tests were conducted in a low-pressure, low-temperature vacuum chamber using the Nextel®/Cu UFRT design. The purpose of these tests was to document the lifetime operational characteristics of the current UFRT design. A single UFRT was instrumented as shown in Figure 2.11. Problem areas identified for this set of tests are also shown.

A SiC/Cu heat pipe was designed, constructed, and tested for DOE, Office of Space. This heat pipe was tested at PNL in an ambient laboratory environment to demonstrate its capabilities in both reflux (oriented parallel to gravity) and heat pipe (oriented perpendicular to gravity) modes. This test is included in this analysis due to its similarity to previous UFRT experiments. The test configuration, instrumentation, and problem areas for this test set are shown in Figure 2.12.

Evaporator Section

- R1 -- Contact resistance between the heater surface and the evaporator wall
- R2 -- Conductive resistance through the evaporator wall
- R3 -- Conductive/convective resistance through fluid film under wick (may contain vapor bubbles)
- R4 -- Conductive resistance through the wick/fluid
- R5 -- Phase change resistance from "in-depth" surface of wick

Condenser Section

- R1 -- Conductive/convective resistance through condensate film
- R2 -- Conductive resistance through the condenser wall
- R3 -- Emissive resistance from the surface of the metal liner
- R4 -- Emissive/transmissive resistance from the surface of the metal liner through the fabric
- R5 -- Transmissive/re-emissive resistance from the fibers in the ceramic fabric
- R6 -- Conductive resistance through the ceramic fabric
- R7 -- Emissive resistance from the surface of the ceramic fabric

Figure 2.9. UFRT Heat Resistance Paths

Figure 2.10. NASA Johnson Chamber E UFRT Test

Instrument	Attachment Method	Potential Problems
Pressure Transducer	T-fitting off of fill tube	<ul style="list-style-type: none"> • Interruption of diaphragm seating during fill operation • Inadequate calibration
Thermocouple # 1	Sheathed probe extending through a Swagelok seal	<ul style="list-style-type: none"> • Thermocouple in contact with wall • Condensation on probe • Sheath penetrated by Swagelok
Thermocouple #2, #3	Attached to end-cap with adhesive-backed thermocouple	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • adhesive may not adhere to surface • Inadequate calibration
Thermocouple #4, #5, #6, #7, #8	Attached to fabric with adhesive-backed thermocouple (see inset to left)	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • Adhesive may not adhere to surface • Inadequate calibration
Thermocouple #9, #10	Attached to end-cap with adhesive-backed thermocouple	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • adhesive may not adhere to surface • Inadequate calibration

Figure 2.11. Oregon State University UFRT Test

Instrument	Attachment Method	Potential Problems
Pressure Transducer	T-fitting off of fill tube	<ul style="list-style-type: none"> • Interruption of diaphragm seating during fill operation • Inadequate calibration
Thermocouple # 1	Sheathed probe extending through a Swagelok seal	<ul style="list-style-type: none"> • Thermocouple in contact with wall • Condensation on probe • Sheath penetrated by Swagelok
Thermocouple # 2	Attached to end-cap with adhesive-backed thermocouple and taped over with silver tape	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • adhesive may not adhere to surface • Inadequate calibration
Thermocouple #3, #4, #5	Attached to fabric with adhesive-backed thermocouple and the backing was taped to the fabric with glass tape (see inset to left)	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • Adhesive may not adhere to surface • Inadequate calibration
Thermocouple # 6	Attached to end-cap with adhesive-backed thermocouple and taped over with silver tape	<ul style="list-style-type: none"> • Variable contact resistance of adhesive • adhesive may not adhere to surface • Inadequate calibration

Figure 2.12. DOE/PNL UFRT Test

Review of these results indicates some of the principle problem areas were common to all of the tests. The more important potential problems include the following:

- interruption of the pressure transducer diaphragm setting during fill operation
- condensation on the internal probe
- variable thermocouple contact resistance
- inadequate calibration/compensation of the thermocouples.

Potential Phenomenological Tests

Based on the issues that have arisen during testing, two principle causes of the observed thermal gradients are suspected: 1) larger heat transfer resistances than anticipated, and 2) instrumentation errors. While larger and more complex tests might be conducted in the future, simple and inexpensive tests have been suggested.

Three tests are proposed for the isolation and investigation of the phenomena. The first two tests would seek to understand the effects of contact resistance and materials properties on heat transfer. The last test would explore the ability of various instruments to accurately measure the temperature of a given surface.

The first test would utilize a band heater to investigate the heat transfer through the evaporator wall in an arrangement shown in Figure 2.13. An evaporator would be sectioned from an existing UFRT and thermocouples placed on the endcap and interior surface. The contact resistance would be varied by tightening and loosening the band heater clamp. An alternative configuration would include water filling the evaporator section.

A second test would use an adhesive band heater in an experimental arrangement of copper foil and ultralight fabric material similar to that shown in Figure 2.14, but without the block of metal and insulation. The test would be designed to measure total heat throughput and temperature drop across the condenser wall.

The third test for studying heat transfer phenomena would include the copper foil, ultralight fabric, and a heated block of metal shown in Figure 2.14 to investigate the effects of temperature on thermocouple adhesive, contact resistance, and variations in the surface properties of the fabric. Thermocouples would be attached to the metal block, which would be heated by a hand held heater from the reverse side, using various adhesives and potting materials. The effects of increasing the temperature of the metal block would be observed. A variation of this test would also be conducted with ultralight fabric over the heated metal block. The fabric would be instrumented with thermocouples using various methods to observe the effect of temperature variations. An effort could also be made to move the thermocouples along the irregular surface of the fabric to qualitatively observe the effects of fabric weave on thermocouple response. These tests should offer relatively inexpensive methods for evaluating the effect of instrumentation and heat paths on test results for the UFRTs.

Figure 2.13. Evaporator Thermocouple Test Arrangement (Test 1)

Figure 2.14. Heat Conduction Test Arrangement (Tests 2 and 3)

2.4.2 Future Test and Design Changes

Depending on the results of the above phenomenological tests and follow-on analyses of past tests, several changes may be made to the test arrangements. A number of changes to the UFRT design are also anticipated as explained below.

Test Design Changes

The changes that can be incorporated in future UFRT tests should enhance the data collection capability and quality, in addition to moving the UFRT design toward prototypic flight hardware. One design change involves filling and sealing the UFRT before testing because the fill procedure commonly used in the laboratory is not prototypic of space flight operations. Eliminating the use of charge lines and unoptimized fill amounts is expected to significantly improve the heat transfer of the UFRT because the charge lines allow heat loss by conduction, adding uncertainty to the overall operation of the test. The use of unoptimized quantities of working fluid 1) increases the mass of the device and 2) exaggerates the performance capabilities of the device.

Another improvement would involve immersing the evaporator in a working fluid. The use of band or clamp heaters has been found to introduce significant aberrations to the system. These variations include variable contact resistances and out-right failure of the UFRT due to crushing the evaporator or creasing the metal liner. The immersion of the evaporator region into a single phase flow loop would have the advantages of decreasing aberrations, increasing the precision of thermocouple measurements on the evaporator surface, and more closely simulating prototypic coupling of the UFRT with a heat source.

A standard thermocouple mounting technique needs to be developed for the ceramic fabric surface. Potential methods, such as direct mounting on the metal liner and using micro-meter-sized thermocouple junctions, should be evaluated. This improvement, as well as those suggested above, should significantly enhance the evaluation of UFRT performance.

UFRT Design Changes

The current UFRT design has not been optimized, and further design iteration may yield improved heat transfer results. These design improvements include thinner evaporator walls, thinner ceramic fabric, pre-treatment of the outer surface of the metal liner, and looser ceramic fabric overbraid. In combination or individually, each of these design changes would potentially offer better thermal properties.

Pressure vessel calculations have indicated that the 0.030-cm (0.012 in.) evaporator wall may be reduced. This wall thickness may be reduced to roughly 0.018 cm (0.007 in.) and still contain the UFRT working fluid with a reasonable safety factor. This reduction in the conduction path, and associated reduction in stored energy, will increase the thermal responsiveness of the UFRTs, although it is not expected to produce significant unilateral heat transfer gains.

The Nextel® ceramic fabric used on the current UFRT design may be reduced in thickness. The relatively low thermal conductivity of the ceramic fabric indicates that a smaller thermal gradient should be obtained with thinner fabrics. The current fabric has a thickness of 0.056 cm (0.022 in.). The structural requirements of containing the inner pressure would allow considerably thinner fabric, especially if the liner material was tougher.

By pre-treating the outer surface of the metal liner with a high emissivity coating, the thermal radiation heat transfer directly from this surface may be improved. Metals have notoriously poor thermal emissivities and treatment may offer an improvement. A number of high emissivity paints and coatings have been developed and may be used on these components. Of course, the significance of this design change is directly related to the transmissivity and weave of the ceramic fabric overbraid.

Other options should also be explored to enhance heat transfer, including the use of liners that do not set into the fabric, improved ceramic fabric attachment mechanisms, and incorporation of fins. As testing of the UFRTs continues in the laboratory, improvements for their use in space are expected to become more obvious.

2.5 Analysis Follow On

Additional analyses were started for the data collected during the vacuum chamber tests conducted at NASA JSC in August 1992. During that five-test series, three UFRTs were successfully tested in the Chamber E, thermal vacuum chamber. Because of the large amount of data generated during these tests, only limited evaluation has been completed. A detailed analysis of these data began recently because of the availability of James Sambrook, a senior in Aeronautical/Nuclear Engineering at Worcester Polytechnical Institute. Mr. Sambrook is conducting this evaluation for the BMR program as a participant in the DOE Science and Engineering Research Semester (SERS) program.

One major concern that arose from the initial examination of the data from the vacuum chamber tests was the apparent measurement of a large temperature drop between the evaporator and the condenser outer surfaces. A large ΔT between the primary system working fluid and the radiating surface would necessarily require a higher working fluid temperature. In most systems, this would be difficult or impossible to introduce. Furthermore, heat rejection devices, other than UFRTs, offer smaller ΔT s and would prove to be more attractive to the system designer. Thus, it was desired to further evaluate the data to determine whether the results were interpreted correctly.

Preliminary evaluation of the data from the frozen startup test series indicates that the large temperature gradients may be an artifact of the experimental setup. Two possible explanations are postulated based on this early review. First, the view factor of each of the UFRTs tested was different. Upon accounting for the effects of the environment seen by each UFRT in the array, the radiated power seems to be consistent between UFRTs. Second, the thermocouples drastically perturb the local radiation of heat from the UFRT surface. Variations between the emissivity of the ceramic fabric and the thermocouple, as well as differences in absorptivity, may cause the thermocouples to measure temperatures that are not prototypic of the UFRT.

These results are preliminary in nature and are presented to illustrate possible physical interpretations of the August 1992 test data. Plots of the data and a description of the methods for determining the power emitted are provided in the appendix.

3.0 References

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Appendix

Results of the August 1992 Vacuum Chamber Test

Appendix

Results of the August 1992 Vacuum Chamber Test

The first vacuum chamber tests for the ultralight fabric reflux tubes (UFRT) were conducted in the Chamber E thermal vacuum chamber at the National Aeronautics and Space Administration (NASA), Lyndon B. Johnson Space Center (JSC), Houston, Texas, during August 1992. The original series of tests was expected to include five tests at one or more of four thermal environments. Because of technical difficulties with the test apparatus and instrumentation, only three environmental temperatures were evaluated and not all of the tests were completed. The maximum heat transport test did not test the UFRTs to their limit because the heating element failed. Only three of the five UFRTs installed in the vacuum chamber were tested. The actual tests conducted for the three UFRTs tested are indicated in Table A.1.

The calculated power emitted from a UFRT was compared to the actual power in a UFRT and is plotted along with the power input in several of the figures in this appendix. The calculated power was determined by assuming radiation heat transfer to the environment and the other UFRTs. The calculated power for this design can be partially determined using the following equation:

$$Q = \epsilon \sigma L D (T^4 - T_{ENV}^4)$$

Table A.1. Actual Thermal Vacuum Tests and Conditions

Test Series		Effective Vacuum Environmental Temperatures, K			
		116K (-250°F)	144K (-200°F)	255K (0°F)	325K (125°F)
1	Warm Startup			XX	XX
2	Nominal Operations		XX	XX	XX
3	Load/Follow Transients				XX
4	Frozen Startup	XX			
5	Maximum Heat Transport		XX		

where Q = Heat transfer limit of previous UFRT design

e = Emissivity of the UFRT (assumed to be 0.93)

σ = Stefan-Boltzmann constant ($5.669 \times 10^{-9} \text{ W}/(\text{m}^2\text{K}^4)$)

L = Length of heat pipe (0.9 m)

D = Outer diameter of heat pipe (0.0266 m)

T = Measured UFRT temperature in Kelvin.

T_{ENV} = Measured environmental temperature in Kelvin.

The above equation does not include the effects of one UFRT on another, but it should account for heat transfer between the UFRTs in the vacuum chamber to determine the correct heat transfer. This can be accomplished by determining a view factor that accounts for the amount of heat transferred between the UFRTs. Assuming that the UFRTs are infinitely long parallel cylinders, the view factor between two cylinders can be found using the equations shown in Figure A.1. The spacing (s) between the UFRTs was 2.54 cm (1 in.) during the test of these UFRTs that had an outer radius (r) of 1.33096 cm (1.024 in.). Using these values in the equations shown in Figure A.1, the view factor between two adjacent UFRTs in this test is 0.0834. The view factor was doubled for the fourth UFRT because UFRT No. 3 and No. 5 were on either side of it. The environmental temperature was taken to be the average of the two readings measured during the test. This information was used to calculate the power emitted from each UFRT during the tests.

Figure A.1. View Factor Calculations for Heat Pipes
(Seigel and Howel 1981)

Using the above equation and the view factor results in the following equation for calculating the emitted power in UFRTs 3 and 5:

$$Q_{\text{CALC}} = F_{\text{PIPE-ENV}} * e\sigma LD(T^4 - T_{\text{ENV}}^4) + F_{\text{PIPE-PIPE}} * e\sigma LD(T^4 - T_{\text{PIPE}}^4)$$

where Q_{CALC} = Calculated Heat Transfer for the UFRT

$F_{\text{PIPE-ENV}}$ = View Factor between the UFRT and environment (0.9166)

e = Emissivity of the UFRT (assumed to be 0.93)

σ = Stefan-Boltzmann constant ($5.669 \times 10^{-9} \text{ W}/(\text{m}^2\text{K}^4)$)

L = Length of UFRT (0.9 m)

D = Outer diameter of UFRT (0.0266 m)

T = Measured temperature of UFRT in Kelvin

T_{ENV} = Environmental Temperature measured in Kelvin

$F_{\text{PIPE-PIPE}}$ = View Factor between the two UFRTs (0.0834)

T_{PIPE} = Temperature of other UFRT in Kelvin

The thermocouple used for the calculation of power for UFRT 3 was located on the condenser about one third the distance up from the bottom of the UFRT and is designated RT3-C-2TH in the graphs of this appendix. This temperature data was chosen because the data from RT3-C-1TH located at about two thirds the distance up from the bottom of the UFRT was unreliable. Temperature data for UFRT 5 was obtained from a thermocouple designated RT5-C-2QTR that was placed on the condenser in the middle of UFRT 5.

Because UFRT 4 was located midway between UFRTs 3 and 5, it emitted heat to both the environment and the other two UFRTs in the test. Therefore the equation to find the power for UFRT 4 is slightly more complex, as shown below.

$$Q_4 = F_{4-\text{ENV}} * e\sigma LD(T^4 - T_{\text{ENV}}^4) + F_{4-3} * e\sigma LD(T^4 - T_3^4) + F_{4-5} * e\sigma LD(T^4 - T_5^4)$$

where Q_4 = Calculated Heat Transfer for UFRT 4

$F_{4-\text{ENV}}$ = View Factor between the UFRT and environment (0.8332)

e = Emissivity of the UFRT (assumed to be 0.93)

σ = Stefan-Boltzmann constant ($5.669 \times 10^{-9} \text{ W}/(\text{m}^2\text{K}^4)$)

L = Length of UFRT (0.9 m)

D = Outer diameter of UFRT (0.0266 m)

T = Measured temperature of UFRT in Kelvin

T_{ENV} = Environmental Temperature measured in Kelvin

F_{4-3} = View Factor between UFRTs 3 and 4 (0.0834)

T_3 = Temperature of UFRT 3 in Kelvin

F_{4-5} = View Factor between UFRTs 4 and 5 (0.0834)

T_5 = Temperature of UFRT 5 in Kelvin.

The temperature used in calculating the power for UFRT 4 was RT4-C-2QTR, located on the exterior of the condenser in the middle of the UFRT.

All of the above equations assume a steady state system. The assumption about the heat pipe system is that it is in a quasi-steady state. The steady state equations hold true at each instant in time, but the system itself is changing. The values calculated from the above equations are plotted along with data obtained from the tests and are shown in the figures that follow in the remainder of the appendix. Thermocouple nomenclature is shown in Table A.2. Results of the tests are provided in this appendix in the order in which the tests were conducted.

Table A.2. Location and Nomenclature for Thermocouples Used in Tests

Thermocouple Location	Nomenclature for UFRT 3	Nomenclature for UFRT 4	Nomenclature for UFRT 5
On condenser top end	RT3-C-TC1	RT4-C-TC1	RT5-C-TC1
Probe inside UFRT at top end	RT3-C-PROB	RT4-C-PROB	RT5-C-PROB
On condenser, 1/4 distance from top		RT4-C-1QTR	RT5-C-1QTR
On condenser, 1/3 distance from top	RT3-C-1TH		
On condenser, 1/2 distance from top		RT4-C-2QTR	RT5-C-2QTR
On condenser, 2/3 distance from top	RT3-C-2TH		
On condenser, 3/4 distance from top		RT4-C-3QTR	RT5-C-3QTR
Evaporator	RT3-E-TC2	RT4-E-TC2	RT5-E-TC2
Evaporator end	RT3-E-TC1	RT5-E-TC1	RT5-E-TC1

A.1 Test Results

A limited amount of high quality data was generated for the performance characteristics of the UFRT design during the thermal vacuum chamber tests. Qualification of the operational capabilities of the UFRT design was achieved for a range of powers from 0 to 90 W in environments from 116 to 325K (-250°F to 125°F). Several specific results were confirmed by these tests:

- The performance of the UFRT design is limited by the surface area available to radiate the heat from the condenser region. The design was not limited by evaporator heat flux, condensate return flow, entrainment, or sonic flow.
- The condenser region of the UFRT design was essentially isothermal over the exterior length, varying by as little as 2K (4°F) and as much as 35K (63°F). However, some of these variations appear to result from the position of the UFRT in the array. For example, UFRT 4, located between UFRTs 3 and 5, typically had temperatures vary by 2 to 10K (4° to 18°F) between the three thermocouples. The design operated at saturated internal conditions and did not display appreciable anomalies in conductive contact resistance between the ceramic fabric overwrap and copper thin-walled inner liner.
- The ability of the UFRT design to respond to load/follow transients was masked by the time constant of the heat elements used in the tests. However, the design adequately followed the actual heat input, and each reflux tube temperature tracked well with heater power.
- The UFRT design responded well to an instantaneous addition of full power from a fully frozen condition, as shown in Figures A.53 to A.56. This condition did not stress the capabilities of the design.
- Maximum heat rejection capabilities were not demonstrated due to the failure of several instruments, including the heating elements, at 90 W and an environmental temperature of 144K (-200°F). Since this was the last test series, the experiment was terminated without defining the heat and fluid transport limits of the UFRT design.

Several limits were found in the UFRT design and the experimental arrangement:

- The copper thin-walled tubing was found to be extremely delicate during handling and setup. Failures of the copper thin-walled tubing from this handling resulted in five of the eight UFRTs shipped to NASA-JSC for testing.
- The charging system for the UFRT tests unnecessarily complicated the evaluation of the thermodynamics of the UFRTs' operation. A pre-charged test article would be preferred.
- The UFRTs were not actually allowed to come to steady state during any of the test series. The temperature measurements and calculated powers did not come to an asymptotic value before a new test was initiated. This complicated the interpretation of the test data.

- The heat reflected from both of the vertical aluminized mylar sheets, and the floor surface was not accounted for in the heat transfer calculations. These effects were not observable in the environmental thermocouple configuration.

Since follow-on tests to this set of thermal vacuum tests are planned for the next generation UFRT, some consideration has been given to further improving the testing of UFRTs at this facility. The list of improvements are divided into equipment-oriented and planning-related changes and are shown in Tables A.3 and A.4.

A.2 Conclusions

The performance of the current UFRT design met all expectations for short duration tests. Startup was accomplished with no flaws, and performance limits were tested to 90 W. Results of the thermal vacuum tests have indicated that the UFRT design performs as anticipated in nominal operation and load following. A thermal gradient along the condenser region has been observed but may be partially an artifact of the thermocouple placement as well as the position of the UFRT in the array. The UFRT design also began operations without incident from a completely frozen initial condition. Due to instrumentation failures, the design was only tested to 90 W in a thermal vacuum environment. These tests are useful for providing confidence in the performance of the UFRT design over an anticipated mission lifetime. With continued and consistent development, the UFRT technology offers a dependable and inexpensive thermal management system for the lunar colony.

Table A.3. Recommended Equipment Modifications

- Heat the reflux tubes with higher rated power strips, or possibly heat the reflux tubes with a single-phase flow loop, with bypass heatup of the fluid.
- Fabricate end ports on each end of the UFRTs for the insertion of thermocouple probes.
- Fill/charge the reflux tubes outside the thermal vacuum chamber.
- Develop and install all instrumentation, with appropriate blue-dot connectors, on the reflux tubes prior to arrival at NASA-JSC.
- Mount the infrared lamps in a vertical orientation.
- Install an infrared camera on the interior of the thermal vacuum chamber.
- Install a VHS camera on the interior of the thermal vacuum chamber.
- Utilize the solar simulation capabilities of the thermal vacuum chamber.
- Place some thermocouples exterior to the chamber in a reference temperature configuration.
- Configure the data acquisition system on the Macintosh for additional channels.
- Configure the data acquisition software to calculate the theoretical rejected power and surface temperature from data input of thermocouple temperatures and heater power.
- Select higher quality brands of instrumentation, such as pressure transducers.
- Use PNL-supplied Variac power controllers.
- Use true watt transducers instead of voltage and current measurements.

Table A.4. Recommended Planning/Personnel Interface Improvement

- Increase contact with the NASA Testing Section throughout the planning phase.
- Define channels and interfaces well in advance.
- All schematics should be in final form prior to testing.
- Plan a depressurization of the chamber for reconfiguration of the test article into the schedule.
- Do not hesitate to depressurize the chamber if malfunctions or spurious interactions occur.
- Plan well in advance for facility utilization: Chamber E "free week" requires 6 months of planning in advance, and Chamber A "piggy-back" requires 1 year of planning.
- Train additional NASA/Lockheed staff to perform duties of the Test Article Manager.
- Conduct IR calculations at PNL to verify the spatial flux profile.

Figure A.2. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Warm Startup Test (1) with 325K (125°F) Environmental Temperature Beginning on August 13, 1992 at 5:10:26 hours

Figure A.3. Temperatures for UFRT 3 During Warm Startup Test (1) with 325K (125°F) Environmental Temperature Beginning on August 13, 1992 at 5:10:26 hours

Figure A.4. Temperatures for UFRT 4 During Warm Startup Test (I) with 325K (125°F) Environmental Temperature Beginning on August 13, 1992 at 5:10:26 hours

Figure A.5. Temperatures for UFRT 5 During Warm Startup Test (1) with 325K (125°F) Environmental Temperature Beginning on August 13, 1992 at 5:10:26 hours

Figure A.6. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) with 355K (125°F) Environmental Temperature Beginning on August 13, 1992 at 8:03:07 hours

Figure A.7. Temperatures for UFRT 3 During Nominal Operations (2) with 355K (125°F) Environmental Temperature Beginning on August 13, 1992 at 8:03:07 hours

Figure A.8. Temperatures for UFRT 4 During Nominal Operations (2) with 355K (125°F) Environmental Temperature Beginning on August 13, 1992 at 8:03:07 hours

Figure A.9. Temperatures for UFRT 5 During Nominal Operations (2) with 355K (125°F) Environmental Temperature Beginning on August 13, 1992 at 8:03:07 hours

Figure A.10. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Warm Startup Test (1) with 255K (0°F) Environmental Temperature

Figure A.11. Temperatures for UFRT 3 During Warm Startup Test (1) with 255K (0°F) Environmental Temperature

Figure A.12. Temperatures for UFRT 4 During Warm Startup Test (1) with 255K (0°F) Environmental Temperature

Figure A.13. Temperatures for UFRT 5 During Warm Startup Test (1) with 255K (0°F) Environmental Temperature

Figure A.14. Powers for Warm Startup Test (1) to 15 Watts Power Beginning on August 13, 1992 at 14:02:19 hours

Figure A.15. Powers for Warm Startup Test (1) to 20 Watts Power Beginning on August 13, 1992 at 14:17:41 hours

Figure A.16. Powers for Warm Startup Test (1) to 25 Watts Power Beginning on August 13, 1992 at 14:44:13 hours

Figure A.17. Powers for Warm Startup Test (1) to 30 Watts Power Beginning on August 13, 1992 at 15:05:04 hours

Figure A.18. Powers for Warm Startup Test (1) to 40 Watts Power Beginning on August 13, 1992 at 15:42:04 hours

Figure A.19. Powers for Warm Startup Test (1) to 50 Watts Power Beginning on August 13, 1992 at 16:03:44 hours

Figure A.20. Powers for Warm Startup Test (1) to 55 Watts Power Beginning on August 13, 1992 at 16:29:00 hours

Figure A.21. Powers for Warm Startup Test (1) to 60 Watts Power Beginning on August 13, 1992 at 16:43:05 hours

Figure A.22. Powers for Warm Startup Test (2) to 70 Watts Power Beginning on August 13, 1992 at 17:08:28 hours

Figure A.23. Powers for Warm Startup Test (2) to 80 Watts Power Beginning on August 13, 1992 at 17:44:01 hours

Figure A.24. Powers for Warm Startup Test (2) to 90 Watts Power Beginning on August 13, 1992 at 18:32:05 hours

Figure A.25. Temperatures for UFRT 3 During Warm Startup Test (1) 15 Watts Power Beginning on August 13, 1992 at 14:02:19 hours

Figure A.26. Temperatures for UFRT 3 During Warm Startup Test (1) 20 Watts Power Beginning on August 13, 1992 at 14:17:41 hours

Figure A.27. Temperatures for UFRT 3 During Warm Startup Test (1) 25 Watts Power Beginning on August 13, 1992 at 14:44:13 hours

Figure A.28. Temperatures for UFRT 3 During Warm Startup Test (1) 30 Watts Power Beginning on August 13, 1992 at 15:05:04 hours

Figure A.29. Temperatures for UFRT 3 During Warm Startup Test (1) 40 Watts Power Beginning on August 13, 1992 at 15:42:04 hours

Figure A.30. Temperatures for UFRT 3 During Warm Startup Test (1) 50 Watts Power Beginning on August 13, 1992 at 16:03:44 hours

Figure A.31. Temperatures for UFR3 3 During Warm Startup Test (1) 55 Watts Power Beginning on August 13, 1992 at 16:29:00 hours

Figure A.32. Temperatures for UFRT 3 During Warm Startup Test (1) 60 Watts Power Beginning on August 13, 1992 at 16:43:05 hours

Figure A.33. Temperatures for UFRT 4 During Warm Startup Test (1) 15 Watts Power Beginning on August 13, 1992 at 14:02:19 hours

Figure A.34. Temperatures for UFRT 4 During Warm Startup Test (1) 20 Watts Power Beginning on August 13, 1992 at 14:17:41 hours

Figure A.35. Temperatures for UFRT 4 During Warm Startup Test (1) 25 Watts Power Beginning on August 13, 1992 at 14:44:13 hours

Figure A.36. Temperatures for UFRT 4 During Warm Startup Test (1) 30 Watts Power Beginning on August 13, 1992 at 15:05:04 hours

Figure A.37. Temperatures for UFRT 4 During Warm Startup Test (1) 40 Watts Power Beginning on August 13, 1992 at 15:42:04 hours

Figure A.38. Temperatures for UFRT 4 During Warm Startup Test (1) 50 Watts Power Beginning on August 13, 1992 at 16:03:44 hours

Figure A.39. Temperatures for UFRT 4 During Warm Startup Test (1) 55 Watts Power Beginning on August 13, 1992 at 16:29:00 hours

Figure A.40. Temperatures for UFRT 4 During Warm Startup Test (1) 60 Watts Power Beginning on August 13, 1992 at 16:43:05 hours

Figure A.41. Temperatures for UFRT 5 During Warm Startup Test (1) 15 Watts Power Beginning on August 13, 1992 at 14:02:19 hours

Figure A.42. Temperatures for UFRT 5 During Warm Startup Test (1) 20 Watts Power Beginning on August 13, 1992 at 14:17:41 hours

Figure A.43. Temperatures for UFRT 5 During Warm Startup Test (1) 25 Watts Power Beginning on August 13, 1992 at 14:44:13 hours

Figure A.44. Temperatures for UFRT 5 During Warm Startup Test (1) 30 Watts Power Beginning on August 13, 1992 at 15:05:04 hours

Figure A.45. Temperatures for UFRT 5 During Warm Startup Test (1) 40 Watts Power Beginning on August 13, 1992 at 15:42:04 hours

Figure A.46. Temperatures for UFRT 5 During Warm Startup Test (1) 50 Watts Power Beginning on August 13, 1992 at 16:03:44 hours

Figure A.47. Temperatures for UFRT 5 During Warm Startup Test (1) 55 Watts Power Beginning on August 13, 1992 at 16:29:00 hours

Figure A.48. Temperatures for UFRT 5 During Warm Startup Test (1) 60 Watts Power Beginning on August 13, 1992 at 16:43:05 hours

Figure A.49. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) with 255K (0°F) Environmental Temperature Beginning on August 13, 1992 at 17:08:28 hours

Figure A.50. Temperatures for UFRT 3 During Nominal Operations (2) with 255K (0°F) Environmental Temperature Beginning on August 13, 1992 at 17:08:28 hours

Figure A.51. Temperatures for UFRT 4 During Nominal Operations (2) with 255K (0°F) Environmental Temperature Beginning on August 13, 1992 at 17:08:28 hours

Figure A.52. Temperatures for UFRT 5 During Nominal Operations (2) with 255K (0°F) Environmental Temperature Beginning on August 13, 1992 at 17:08:28 hours

Figure A.53. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Frozen Startup to Full Power with 116K (-250°F) Environmental Temperature Beginning on August 14, 1992 at 2:53:14 hours

Figure A.54. Temperatures for UFR3 During Frozen Startup to Full Power with 116K (-250°F) Environmental Temperature Beginning on August 14, 1992 at 2:53:14 hours

Figure A.55. Temperatures for UFRT 4 During Frozen Startup to Full Power with 116K (-250°F) Environmental Temperature Beginning on August 14, 1992 at 2:53:14 hours

Figure A.56. Temperatures for UFRT 5 During Frozen Startup to Full Power with 116K (-250°F) Environmental Temperature Beginning on August 14, 1992 at 2:53:14 hours

Figure A.57. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) with 144K (-200°F) Environmental Temperature

Figure A.58. Temperatures for UFRT 3 During Nominal Operations (2) with 144K (-200°F) Environmental Temperature

Figure A.59. Temperatures for UFRT 4 During Nominal Operations (2) with 144K (-200°F) Environmental Temperature

Figure A.60. Temperatures for UFRT 5 During Nominal Operations (2) with 144K (-200°F) Environmental Temperature

Figure A.61. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) at About 75 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 4:36:03 hours

Figure A.62. Temperatures for UFRT 3 During Nominal Operations (2) at About 75 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 4:36:03 hours

Figure A.63. Temperatures for UFRT 4 During Nominal Operations (2) at About 75 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 4:36:03 hours

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Figure A.64. Temperatures for UFRT 5 During Nominal Operations (2) at About 75 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 4:36:03 hours

Figure A.65. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) at About 80 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 5:38:32 hours

Figure A.66. Temperatures for UFRT 3 During Nominal Operations (2) at About 80 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 5:38:32 hours

Figure A.67. Temperatures for UFRT 4 During Nominal Operations (2) at About 80 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 5:38:32 hours

Figure A.68. Temperatures for UFRT 5 During Nominal Operations (2) at About 80 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 5:38:32 hours

Figure A.69. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) at About 85 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 6:25:30 hours

Figure A.70. Temperatures for UFRT 3 During Nominal Operations (2) at About 85 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 6:25:30 hours

Figure A.71. Temperatures for UFRT 4 During Nominal Operations (2) at About 85 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 6:25:30 hours

Figure A.72. Temperatures for UFRT 5 During Nominal Operations (2) at About 85 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 6:25:30 hours

Figure A.73. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Nominal Operations (2) at About 90 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 7:32:50 hours

Figure A.74. Temperatures for UFRT 3 During Nominal Operations (2) at About 90 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 7:32:50 hours

Figure A.75. Temperatures for UFRT 4 During Nominal Operations (2) at About 90 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 7:32:50 hours

Figure A.76. Temperatures for UFRT 5 During Nominal Operations (2) at About 90 Watts and 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 7:32:50 hours

Figure A.77. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Load/Follow Transients at 25% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.78. Temperatures for UFRT 3 During Load/Follow Transients at 25% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.79. Temperatures for UFRT 4 During Load/Follow Transients at 25% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.80. Temperatures for UFRT 5 During Load/Follow Transients at 25% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.81. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Load/Follow Transients at 50% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.82. Temperatures for UFRT 3 During Load/Follow Transients at 50% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.83. Temperatures for UFRT 4 During Load/Follow Transients at 50% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

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Figure A.84. Temperatures for UFRT 5 During Load/Follow Transients at 50% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.85. Actual and Calculated Powers for UFRTs 3, 4, and 5 During Load/Follow Transients at 100% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.86. Temperatures for UFRT 3 During Load/Follow Transients at 100% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.87. Temperatures for UFRT 4 During Load/Follow Transients at 100% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.88. Temperatures for UFRT 5 During Load/Follow Transients at 100% Increments to 35 W Steady State with 325K (125°F) Environmental Temperature

Figure A.89. Actual and Calculated Powers for UFR T 3 During Maximum Heat Transport Test (5) with 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 9:58:14 hours

Figure A.90. Temperatures for UFRT 3 During Maximum Heat Transport Test (5) with 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 9:58:14 hours

Figure A.91. Temperatures for UFR1 4 During Maximum Heat Transport Test (5) with 144K (-200°F)
Environmental Temperature Beginning on August 14, 1992 at 9:58:14 hours

Figure A.92. Temperatures for UFRT 4 During Maximum Heat Transport Test (5) with 144K (-200°F) Environmental Temperature Beginning on August 14, 1992 at 9:58:14 hours

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