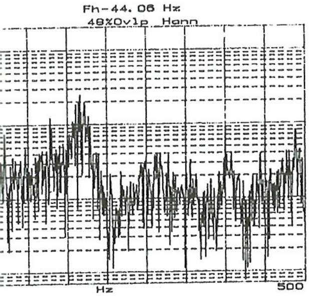

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Design and Test of the NIST/Lockheed Martin Miniature Pulse Tube Flight Cryocooler

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ABSTRACT

A two-stage miniature pulse tube (PT) cryocooler, designed for a Space Shuttle flight demonstration, was built and tested at Lockheed Martin Astronautics (LMA) at Denver, CO and the NIST Boulder Laboratory. The Miniature PT Flight Cryocooler (MPTFC) was designed to provide 0.15 W of cooling at 80 K with heat rejection at 275 K. It was developed as the smallest cryocooler of its kind for the purpose of demonstrating launch survivability and thermal performance in a zero-g environment. A prototype laboratory version was first built and tested to provide information on component sizing and flow rates for comparison to numerical models. The flight version was then fabricated as a Getaway Special (GAS) Payload. Cost containment and manned flight safety constraints limited the extent of the MPTFC development to achieve performance optimization. Nonetheless, it reached 87 K driven by a commercially available tactical compressor with a swept volume of 0.75 cc. The on-orbit cooling performance was not demonstrated because of low battery voltage resulting from failed primary batteries. The first off-state PT thermal conductance measurements were successful, however, and the MPTFC also demonstrated the robustness of PT cryocoolers by surviving pre-launch vibration testing, shipping, and the launch and landing of STS-90 with no measurable performance degradation.

The design and performance optimization approach for miniature two-stage PT coolers are discussed. Some factors that may limit performance in small-scale PT coolers are identified also. Laboratory pre-launch and post flight performance data of the MPTFC are presented, including cooling performance as a function of heat load and rejection temperature. Off-state conductance results are discussed in a related but separate presentation.

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Kluwer Academic/Plenum Publishers, 2001

INTRODUCTION

The Miniature Pulse Tube Flight Cryocooler (MPTFC) flew as a NASA shuttle payload (GAS-197) in April 1998 aboard STS-90 (Shuttle Transportation System-90) as a technology demonstration experiment. The primary objectives of this experiment were to demonstrate pulse tube (PT) cryocooler performance and "off-state" thermal conductance in a micro-gravity environment and to verify launch survivability of miniature coolers having limited vibration mitigation features. This project was a collaboration between Lockheed Martin Astronautics (LMA) and the National Institute of Standards and Technology (NIST). Because of the STS schedule and the safety issues associated with manned space missions, the experiment was subject to a number of design constraints. The tight development schedule was based on limited flight opportunities preceding the construction of the International Space Station (ISS) and on a low project budget. These two constraints dictated the extensive use of commercially available components, including a tactical compressor and drive electronics (to obviate a long-life flight compressor development effort), an inexpensive electromagnetic latching valve, a commercial data acquisition system, and numerous commercial electronics components. Attention to flight safety issues directly impacted the MPTFC design in terms of operating pressure, sizing for limited battery-powered operation in a cold environment, and limited design opportunity for performance optimization. The overall flight experiment design also had to address various flight hazard issues, such as mechanical and electrical integrity, EMI, redundant fusing, diode isolation, mitigation for high temperatures, etc. The experiment design had to accommodate operation over a range of STS bay temperatures from -50 to +40°C. In addition, the experiment timeline had to conform to limited STS crew operations.

The approach for completing the project on schedule was to design and test a prototype cryocooler in parallel with the overall flight hardware system definition and parts procurement. Subsequently, the flight hardware and flight cryocooler development and testing were also accomplished as parallel efforts. Lockheed Martin had primary responsibility for the flight and GSE hardware and electronics, systems engineering, and for payload management, while NIST had primary responsibility for the cryocooler development, assembly, and testing. In practice each organization contributed to all of these tasks.

DESIGN

Coldheads

The cryocooler coldhead design selected was a two-stage U-tube geometry orifice pulse tube (PT) system based upon the double inlet concept first introduced by Zhu, Wu, and Chen.[1] The system is schematically represented in Figure 1. This two-stage approach was arrived at based on the design goal of reaching 80K and the miniaturization requirement in which the compressor and coldhead are separate components. The compressor and coldhead were separated to reduce vibration at the coldhead and to balance the thermal operating loads at the compressor. This approach, commonly referred to as multi-inlet when two or more stages are present, reduces the regenerator loss by using a secondary orifice which diverts a small percentage (approximately 10%) of the gas to travel directly from the compressor to the warm end of the pulse tube. This small flow bypasses the regenerator and then compresses and expands the gas that remains at the warm end of the pulse tube. This reduces the flow through the regenerator thus reducing the regenerator loss accordingly. For optimal performance this configuration relies on optimized and stable flow division (provided by the three orifice impedances), minimum void volume, maximum pressure ratio, and minimization of any DC flows or turbulence. Analytical and numerical models such as REGEN3.1 developed by NIST[2,3,4] and a thermoacoustic model developed by Xiao[5,6,7,8] were employed to design both the prototype and flight coldheads.

The prototype cooler is shown in Figure 2. The test fixture for the prototype coldhead allowed the flow division between the primary and secondary orifices to be adjusted during operation using external metering valves, which were modified to minimize void volume. The approximate flow rates were easily determined for the primary and secondary orifices based on the metering valve settings. However, the intermediate flow path distribution between the first and second stages

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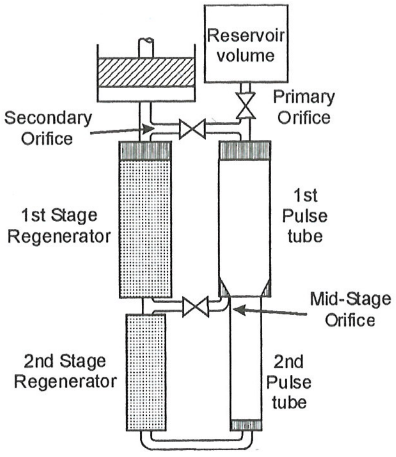

Figure 1. Schematic of double inlet configuration.

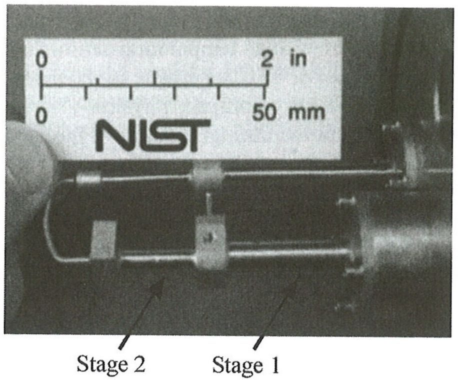

Figure 2. NIST/LMA pulse tube prototype.

required manual adjustment. Therefore partial disassembly of the coldhead was necessary during several iterations to optimize the intermediate orifice. Calculations provided the approximate final flow impedance for this orifice. The fabrication, characterization, and best thermal performance were accomplished within only 3 months of the initial design phase. The prototype unit used a larger 2.5 cc laboratory compressor operated at reduced power to simulate the expected power of the smaller 0.75 cc flight unit. Instrumentation of the prototype coldhead provided temperatures, heat loading, and pressure data for evaluating pressure ratios and phase angles. The relatively long transfer line and small but unavoidable void volumes in the valves limited the efficiency of the prototype coldhead, but its low temperature performance proved the design feasibility of such a small system. A low temperature of 84 K with a pressure ratio of about 1.23 was achieved. For a pressure ratio of 1.26 however, 76 K was achieved. When the 0.75 cc flight compressor was attached to the optimized prototype coldhead with its attendant void volume a temperature of only 127 K was achieved. This resulted from the much lower pressure ratio of 1.13, indicating that the PV work was lower with the flight compressor. A pressure ratio of 1.2 to 1.25 was the design value for the MPTFC. Steps were taken in the fabrication of the flight coldhead to minimize any void volume in the system in order to deliver the PV work associated with the design pressure ratio.

The flight cooler (MPTFC) coldhead shown in Figure 3 has a PT volume of nearly 0.54 cc (see Table 1 for other important coldhead dimensions). The figure provides an exploded view of the two stages but several components are not shown. The cold end and aftercooler are made using OFHC copper; the regenerator and pulse tubes are thin wall 304 stainless steel. The reservoir, which is also made from 304 stainless steel, has a bracket for attaching the flight pressure transducer. Two smaller diagnostic pressure transducers communicate with the compressor and primary orifice spaces of the coldhead. The transfer line is shown prior to final flight modification,

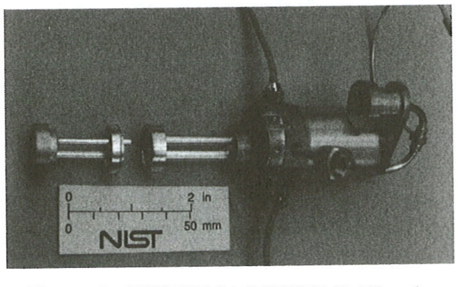

Figure 3. NIST/LMA MPTFC Coldhead.

Table 1. MPTFC Dimensions

	Stage 1	Stage 2
Regenerator OD	6.35 mm (0.25in.)	3.97 mm (0.156 in.)
ID	6.05 mm (0.238 in.)	3.66 mm (0.144 in.)
Length	34.8 mm (1.37 in.)	29.21 mm (1.15 in.)
Screen Type	400 Mesh S.S.	500 Mesh S.S.
Porosity	69 %	61 %
Pulse Tube ID	3.97 mm (0.156 in.)	2.79 mm (0.11 in.)
OD	3.66 mm (0.144 in.)	2.57 mm (0.101 in.)
Length	36.07 mm (1.42 in.)	30.48 mm (1.20 in.)
Volume	0.38 cc (0.023 $in.^3$)	0.158 cc (0.0096 in^3)

and the pressure relief capillary is also visible. The primary and secondary orifices (not shown) are integrated into the aftercooler. Clamps and seal rings to connect the two stages and the fixed radiation shield / MLI are not shown. Also not shown are two thin plates that provide impedances to form the secondary and intermediate orifices. Many other flight-related elements including other instrumentation such as temperature sensors and a film heater on the cold end are also omitted in this figure. The MPTFC schematic is shown in Figure 4. Some important features of the MPTFC design are 1) a very compact physical arrangement; 2) the aftercooler and the compressor are conductively cooled through contact to the experiment mounting plate (EMP); 3) nylon displacement stops are located at both the coldhead inter-stage and cold end. The development and test phases for the flight coldhead required about 11 months to complete concluding with final preparations for vibration testing just prior to integration.

Coldhead Instrumentation

The MPTFC was extensively instrumented for temperature, pressure, and vibration measurements. In fact there were double and triple redundancies built into the system. All of the sensors employed were commercial off the shelf (COTS) items. Specifically, thin film platinum RTDs, piezoresistive and piezoelectric pressure transducers, thin film heaters, and tri-axial accelerometers were used. Schedule constraints required two diagnostic piezoresistive_pressure transducers to be epoxied in place for flight to mitigate the risk of GHe leakage. The electronics system was designed and built in-house and made extensive use of COTS hardware. The DAS was configured at a 5 minute scan rate in a "fill and hold" mode.

G-197 Design Features

Figure 5 shows the G-197 Payload minus the GAS canister enclosure. This assembly can be referred to as a cantilevered frame support. The upper third of G-197 consists of the MPTFC experiment itself, a commercial latching vacuum valve to expose the experiment to space vacuum,

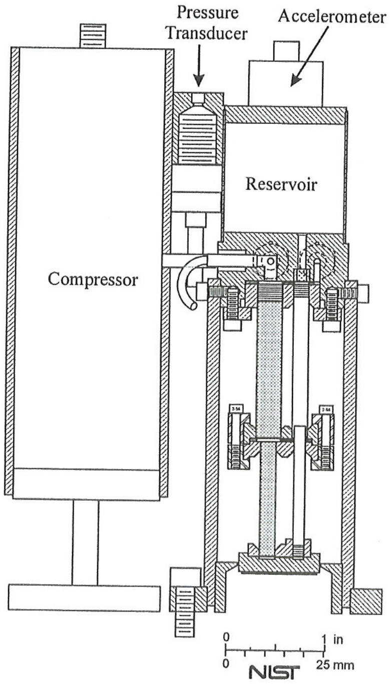

Figure 4. Exploded schematic of the flight cooler arrangement.

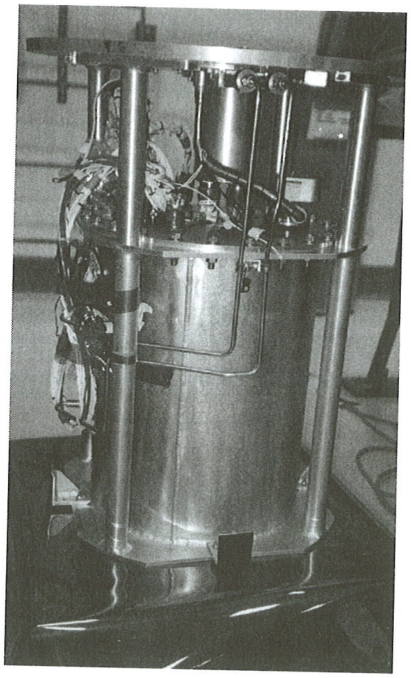

Figure 5. The G-197 payload minus GAS canister.

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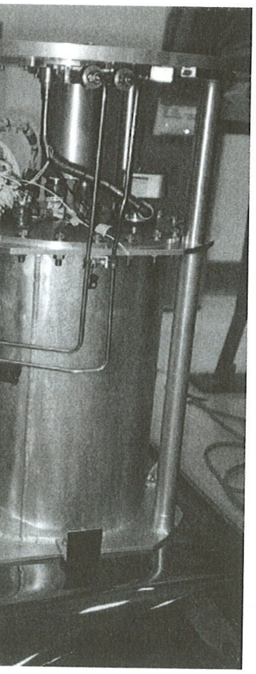


197 payload minus GAS canister.

and other electrical and battery venting connecting hardware. The lower two thirds (the "battery box") contains the battery modules and the flight electronics module — the DAS, computer, signal conditioners, and drive electronics for the experiment. This entire assembly, i.e., G-197, integrates with the NASA GAS canister, which is a 5 cubic ft. cylindrical containment vessel that is capped at both ends and evacuated during integration. There are four supports at the cantilevered end, known as bumpers, that lock the bottom of G-197 radially into the canister by preloading against the canister walls. This must be done in order to restrict the movement of the lower end of the battery box during launch and landing, thereby reducing the bending loads applied at the opposite end where the experiment attaches to the EMP with only 12 Ti alloy screws. The completed GAS canister then encloses the experiment with all electronic connections accomplished via feedthroughs at the canister bottom plate which holds the NASA GAS electronics. The bottom plate is the electronic interface between G-197, the GAS relay system, and the shuttle GAS computer which is operated by astronauts.

Special features of the G-197 GAS payload are: 1) the EMP is uninsulated and coated with silverized Teflon tape for maximum heat rejection to a space environment, 2) the GAS canister is evacuated to simulate a flight instrument environment, 3) The primary battery system consisted of thirty-three 2V batteries in a 3 string redundant arrangement to power the MPTFC and its compressor drive electronics at a nominal 22V. The secondary battery system consisted of four 4V batteries in series to maintain a nominal 16V supply to power the EM valve, DAS, and computer electronics. All batteries are polyurethane foamed into the BB and are vented to EMP relief valves, 4) "low voltage" and "high temperature" cutoff circuits are employed (no longer required by NASA), and 5) battery voltages and GAS canister temperatures are measured for the uninsulated EMP for comparison to NASA numerical models developed in 1987.

Flight Safety Features

The MPTFC design employed several voluntary safety features as well as those required by NASA to safeguard the STS and astronauts during flight. Although not all of the required safety features were practical for mission success, they had to be accommodated in order to fly MPTFC on the shuttle. NASA vacillated on certain requirements, but the following were final. Although the sealed lead acid primary batteries were vented external to the GAS canister to safeguard against the buildup of explosive gases, both low voltage and high temperature cutoff circuitry were also required. Proof pressure testing was required for the MPTFC vacuum housing to more than ten times the maximum pressure that would exist if the cooler developed a leak or the compressor pressure exceeded the limits of its housing. Thermal cutoff switches were employed in the drive electronics to prevent an overheat condition within the compressor. Furthermore, a pressure relief mode, consisting of a capillary that was sealed using an indium soldered cap connected to the warmest location on the MPTFC, was required in case the MPTFC overheated. The compressor drive power was set conservatively to eliminate excessive initial vibration. Polyswitch fusing and redundant wiring were also required to complete the electronics package. The 3.6 V Li cell used to retain memory was double-diode isolated and fused.

PREFLIGHT TESTS

All optimizations of both the prototype and the flight cooler (MPTFC) systems were conducted in the laboratory in a bench test environment. All instrumentation and drive electronics were installed in the best configuration for optimization and therefore were not configured (i.e., wired or attached) for flight. This meant that upon completion of optimization the sensors were removed and reworked for the flight configuration, including rewiring, reattachment, and functional tests.

Experiment Functional Testing

After reworking the MPTFC for the flight environment and integration with the flight electronics and the flight support structure, a complete functional verification of all sensors and a performance verification of the G-197 system were made. This of course included a final pump-out and

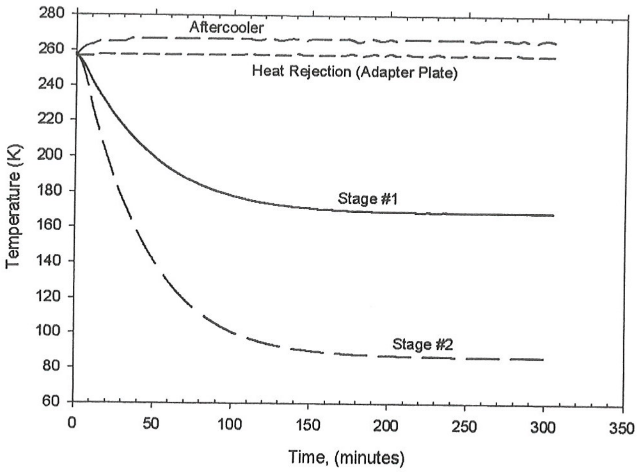


Figure 6. Cool down for flight system rejecting to 258 K.

gas helium pressure charge of the cooler system to 2.6 MPa. These tests included verifying that minimum temperatures and maximum refrigeration loads were maintained, as well as the cool-down performance. Figure 6 shows a representative cool-down for the flight system as measured during thermal vacuum testing conducted at the LMA facility. Figure 7 shows the MPTFC performance for a nominal rejection temperature of 273 K. This data was consistent with data measured before the flight configuration and integration with the DAS and flight electronics rework.

EMI Testing

Although G-197 was a GAS payload, which is considered to be a very low risk to the shuttle operations / communications when fully sealed, NASA required that the radiated EMI of the payload be measured. This requirement for G-197 was due to the vacuum line, which runs from the cooler housing via the EM valve to an EMP port for the on-orbit evacuation of the housing. The

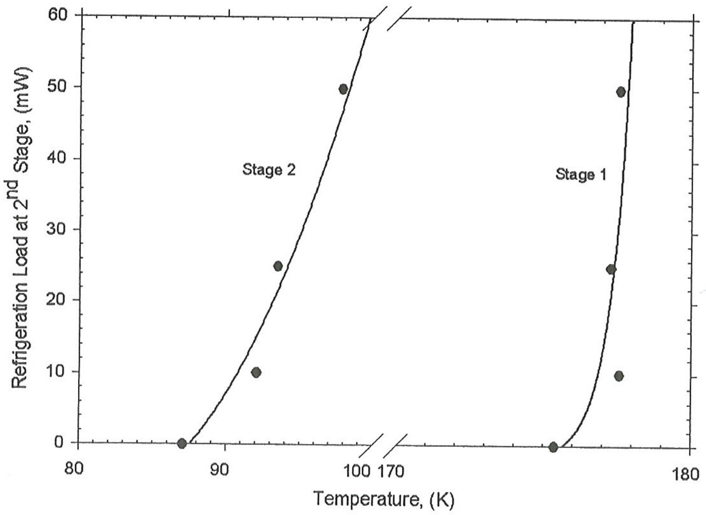
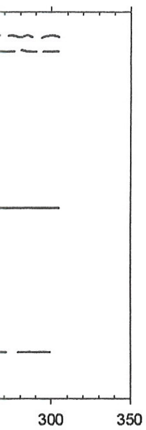


Figure 7. Nominal cooler performance for a 273 K rejection temperature.



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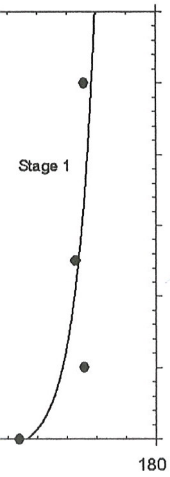

ction temperature.

MPTFC and flight electronics subsystem were tested at the LMA facilities. Testing included low frequency to GHz radiated emissions for both narrow and broad band. The G-197 radiated EMI easily passed within the acceptable limits imposed by NASA.

Vibration Testing

Complete vibration testing was required for the G-197 payload because it slightly exceeded the nominal limit of 91 kg (200 lb.). Both a low-level sine sweep and random vibration at qualification and protoflight acceptance levels were performed in lateral and axial modes. These tests were accomplished at the NASA/ARC. It is of note to the reader that these vibration levels are rather severe and often are conservative compared to the actual launch environment. They represent a safety concern by NASA for the structural integrity of the system. However, NASA requires this conservative level of testing because of the uncertainty of both location of the payload and flight vibration loads within the STS bay. G-197 was calculated to have a lowest lateral mode resonance of 58 Hz when installed in the GAS flight canister. A measured resonant frequency of 40 Hz was obtained using the shipping canister, still above the required 35 Hz minimum. An unexpected result of this test was that some of the Pb-acid batteries failed in the axial mode. This was recognized by a decrease in the primary string voltage from a nominal 22 V to ~20 V. However, due to schedule constraints, coupled with the knowledge that the MPTFC experiment can be operated effectively at 16 V, no changes or modification to the batteries were undertaken. It was believed that there was sufficient margin to continue with the scheduled integration and launch, anticipating that there would be no further degradation.

INTEGRATION AT NASA/KSC

Upon completion of the vibration testing and subsequent pre-integration functional checkouts, the G-197 payload was packaged and shipped to NASA Kennedy Space Center (KSC) for integration with the GAS flight electronics and flight canister. The integration is typically a three-day process that takes place about 3 months prior to launch. Upon completion and sign-off of the integration, there is no opportunity for further contact with the payload by the experiment investigators. Therefore the MPTFC experiment had to be able to retain its 2.6 MPa gas helium charge and an adequate battery charge over a three-month period. This requirement and STS safety considerations effectively eliminate many types of batteries used for unmanned missions.

The integration process is a very challenging exercise for a complicated powered experiment such as MPTFC. First the payload is unloaded from the shipping canister, which is quite similar to the GAS flight canister except that it has no NASA electronics and acts only as a protection vessel for shipping. However, because the support bumpers must be positioned to safeguard the experiment during transit, disassembly is required at NASA/KSC. Next, a very thorough visual safety inspection of the battery box (BB), electronics / fuse box, and experiment itself is conducted by NASA/KSC personnel to ensure that the payload is in full compliance with all safety paperwork. After the safety inspection is signed off, the real work to prepare the experiment for flight begins. The battery systems must be top-charged and the BB and vent plumbing subjected to a pressure proof test prior to a GN_2 purge. The experiment housing must be evacuated and valved off before a preliminary system functional check is made. After a final visual inspection, all fasteners are secured for flight which involves epoxying and/or lock-wiring external screws and securing wiring / cables. A weigh-in of the completed experiment verifies that it is within approved limits before NASA will proceed. Finally, the payload is installed into the flight canister, the bumpers are preloaded for flight, and the end plate with NASA electronics / interface cable is integrated to the payload. A final functional test is then made to ensure that the NASA electronics and payload are compatible. This test also serves to verify EM valve operation, MPTFC cooling, and adequate battery margin. The EM valve is reset to a closed position and a removable manual valve (which maintains a guard vacuum in the line connecting the EM valve to the EMP port) is closed and tagged for removal prior to flight. The GAS canister is evacuated and the payload is officially handed off to NASA/KSC for STS integration.

FLIGHT DATA

Minimal Cooling

The cooling data collected during the STS-90 mission was unfortunately of minimal content. After initial confirmation of primary power, the first data set consisted of 20 hrs, powered mostly by the secondary system, which operates the coldhead heater and the DAS in the absence of primary power. Attempts to operate the cooler on-orbit were apparently foiled by a fluctuating primary voltage, which dipped below 16 V causing a designed malfunction indication at the GAS control computer. Specifically, this led to periodic cutouts of relay 'A', eliminating power to the MPTFC compressor drive electronics. This relay supposedly resets automatically at 40 minute intervals by a NASA timer, but there was no indication of this operation in the data set. The relay was switched off and reset manually later in the mission, again with positive initial indication but little evidence of cooling in the data. This was unfortunate since the MPTFC can operate safely below 16 V, thereby making the NASA-mandated cutout level for battery protection unnecessary. It should be noted that NASA has recently eliminated malfunction circuitry requirements for GAS payloads. Measures to perform a re-flight of this experiment (as G-785) to demonstrate the on-orbit cooling have already been performed. The robustness of the MPTFC and its survivability without performance degradation have already been proven.

"Off-state" Thermal Conductance Test

The on-orbit data collected from the second data set of 15 hrs included continuous cold stage heater operation. This data comprises the on-orbit conductance test for a pulse tube cooler in an off-state passive mode. To date there has been little if any published data of this type. In fact, less than a handful of PT coolers have been operated in space. This conductance data and its analysis are presented in a related paper at this conference.[9]

POST-FLIGHT TESTS

Battery testing

One month after STS-90 touched down at KSC the G-197 payload was de-integrated and delivered to LMA personnel. A post-flight functional test determined that the primary battery system exhibited random voltage fluctuations that varied from ~15 to 21V. Later it was determined that at least 7 of the 33 cells were either intermittent or completely defective. At least two cells on each redundant string were affected. This condition explained the relay cutouts during flight. The low voltage condition was attributable to the vibration tests, the launch, and the -6°C STS bay temperature during initial MPTFC activation.

Accelerometer data and model results

Analysis of post-flight data from a miniature tri-axial accelerometer mounted at the reservoir of the cooler during operation was evaluated using a finite element model. It predicts a lateral displacement of 1.14 μm at 164 Hz for the as-built u-tube configuration. However, if a third thin wall support member were used to stiffen each stage, the model predicts the displacement would decrease to 0.21 μm at a frequency of 391 Hz. This result indicates improvement may be made to further reduce induced vibration at the cold tip for vibration sensitive sensor packages.

Cold environment testing

Subsequent to post-flight battery refurbishment (see below), cold environment testing was performed at rejection temperatures below the nominal 273 K. The performance as a function of the heat rejection temperature was conducted and the results are shown in Figure 8. The heat rejection temperature affects both stages consistently. The first stage temperature ranges from 161 K to 204 K for both a no load and a 45 mW load at the second stage based upon a rejection temperature ranging from 244 K to 300 K. For the same rejection temperature range the second

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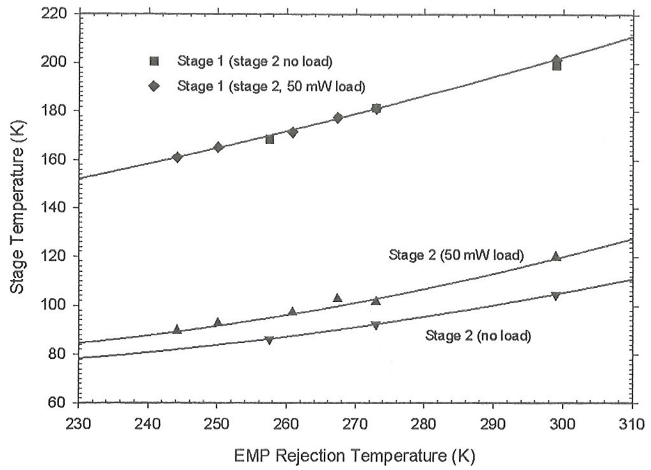

Figure 8. MPTFC cooler performance as a function of heat rejection temperature.

stage temperature ranges from 82 K to 105 K for no load, while it ranges from 90 K to 121 K with a 45 mW load. The cold testing also served to confirm the nominal operation of heaters located on the flight electronics and compressor.

PERFORMANCE DATA

This system as currently configured is certainly not very efficient, having a Carnot efficiency of only 2%. However, because of its very small size it represents an important step toward miniaturizing PT systems. As most readers of this paper are aware, extensive experimental optimization is required to achieve the best performance for PT cryocoolers after thorough modeling has been completed. Often the first iteration in the system design based on the numerical model falls short of the intended goal. This is especially true when pushing the predicting capabilities of the model into a new scaling arena, as for the MPTFC. Although the schedule allowed for only one design iteration, much has been learned about scaling miniature PT coolers, e.g., the complexities associated with the flow distribution and optimization for a two-stage multi-inlet design. For best efficiency the importance of minimizing parasitic heat leaks can not be overlooked.

Immediately after flight the MPTFC demonstrated no reduction in performance and there was no detectable change in the system pressure. In fact, it has held pressure for 2.5 yrs with only a 5% loss, but even this loss has degraded thermal performance from a no-load temperature of 111 K to 123 K at ambient rejection. A loss of only 5 % in the pressure nonetheless represents significant seal performance for a system designed for modification flexibility.

RE-FLIGHT

At present a re-flight of the MPTFC experiment is in progress as G-785. A re-flight provides a potential opportunity for MPTFC improvements, depending on the manifest date set by NASA. A new battery system is always required for a GAS re-flight. Failure of the NASA-recommended primary system batteries used in G-197 resulted in the selection of new batteries of the successful secondary system type, but even these batteries revealed a sourcing issue. Specifically, while the original 4V batteries and their new replacements were of the same model from the same vendor, they were not from the same *factory*. A different internal design in the newer version resulted in failure during sample vibration tests; G-785 uses older version cells.

Other improvements include a high resolution voltmeter, improved frequency diagnostics, and an increased DAS scan rate. All paperwork and refurbishment are complete for a re-flight and we are anticipating an opportunity in early 2001. If it becomes necessary to re-pressurize the MPTFC to 2.6 MPa, more diagnostic sensors and some radiation baffles will be installed.

FUTURE MPTFC COLDHEAD DESIGN AND TEST

Future efforts in MPTFC research will concentrate on improving the current 2-stage coldhead, including evaluation of DC flow, further reduction of the parasitic heat loads[9], modification of stage geometry, and performance evaluation at higher operating pressures. Furthermore, a new one-stage design effort will be undertaken for comparison with the two-stage approach. Extending existing numerical models with innovations will streamline the design and test of miniature systems, thereby advancing their predicting capabilities and accuracy.

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