# Development of a Mixed-Refrigerant Joule-Thomson Microcryocooler

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## ABSTRACT

We discuss in this paper the development of a mixed-refrigerant Joule-Thomson microcryocooler (MCC) to support on-chip cooling of high temperature superconducting electronics that require less than 5 mW of net refrigeration at about 80 K. Some applications include the cooling of infrared and terahertz imaging sensors that operate at about 77 K. Terahertz sensors can be used for the imaging of concealed nonmetallic weapons as well as the spectroscopic identification of chemical and biological material. The MCC is designed to deliver approximately 9 mW gross refrigeration, which yields about 3 mW of net refrigeration once losses due to the heat exchanger, conduction, radiation, and pressure drop are subtracted. The cryocooler utilizes a multicomponent gas mixture that is precooled to 240 K by a thermoelectric cooler. Precooling the gas mixture significantly increases the minimum isothermal enthalpy difference, which is the gross refrigeration power per unit flow. For a pressure ratio of 16:1 this enthalpy difference is about 1.43 kJ/mol for the mixed refrigerant compared with 0.15 kJ/mol for pure nitrogen. The MCC has been designed to operate at pressure ratios of 16:1 to 25:1 for a flow rate of about 6 mmol/s (~ 0.15 std. $cm^3/s$).

## INTRODUCTION

As electronics (e.g. low-noise amplifiers) and sensors (e.g. infrared detectors) evolve becoming ever smaller with more compact arrangements there exists a need to provide near to on-chip cooling of the devices to reduce overall system size while improving thermal performance and reducing cooler input powers for less than 100 K operation. Some applications employ superconducting devices whereupon it is essential that they are cooled well below their critical/transition temperature to operate properly. The small size of these devices and their attendant low power consumption lend themselves for accompanying small near-to or on-chip cryocoolers that reduce cooling requirements by sufficiently managing low parasitic and device loads. The goal of this micro-cryocooler (MCC) development effort is to develop an MCC to demonstrate cooling of a superconducting hot-electron bolometer operating as a THz detector. The MCC is designed to deliver about 9 mW gross refrigeration, yielding ~ 3 mW of net refrigeration for device cooling at/near 80K with less than 270 mW of input power to the compressor.

## MCC-DEVELOPMENT

### MCC Requirements

The MCC envisioned for this development is shown schematically in Figure 1 while Figure 2 shows the J-T cooling cycle employed. Cooling takes place via isenthalpic expansion across a

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pressure drop element also known as micro-valve after the incoming high pressure gas has been precooled by cold low pressure expansion gas. The notable difference for the MCC here is that the gas is precooled to 240 K by a thermoelectric cooler after exiting the compressor before it enters the heat exchanger. This precooling takes place as the gas flows from the compressor across the TE and proceeds into the cold head heat exchanger. From here the high pressure gas cools from 240 K at the warm end to the expected 80 K at the cold end. The high pressure gas expands across the micro-valve to 1 atm. whereupon about 9 mW of gross refrigeration intercepts losses and delivers about 3 mW refrigeration to the detector. This low pressure cold gas now proceeds to warm back to 240 K as it cools the incoming high pressure gas and proceeds to the compressor inlet.

The MCC is comprised of 5 primary elements, sensor/detector, cold head, heat exchanger, thermoelectric pre-cooler, and compressor. The THz sensor/device attaches to the cold head of a Joule-Thomson cryocooler and is shown at the bottom of the Figure 1. The total volume of this arrangement should be < 4 $cm^3$ (cold head volume including heat exchanger and manifold a small fraction of this) with a goal to decrease the volume further yet. The J-T cryocooler is intended to operate employing a gas mixture comprised of 5 to 7 or even 8 components for operating pressure ratios of 16:1 to 25:1 for a high pressure of not greater than 25 atm. (25 bar).

The MCC development is a high risk effort to achieve advances in all of the focus elements namely the micro-valve cold head, the heat exchanger, the compressor, and the superconducting HEB/THz detector. The system must meet the stringent volume and power requirements imposed by DARPA. The cooling requirements for the detector are quite low, about 3 mW. By miniaturizing the cryocooler a low system and parasitic loss approach can be realized. Miniaturizing cold head and heat exchanger conduction, radiation, and pressure drop losses can be significantly reduced to very low levels as lengths, cross-section areas and external surface areas are shrunk. Once this has been accomplished only 6 mW out of the 9 mW of gross refrigeration are required to intercept system parasitic losses.

## Mixed-Gas J-T – How to Select Refrigerants

Much of recent efforts to develop micro-cryocoolers have focused on J-T systems employing high pressure pure gases such as $N_2$ operating from 80 bar, or higher expanded down to about 6 bar with little or no precooling of the high pressure gas from ambient.[1,2] For pure gases such as nitrogen high pressures are needed to achieve sufficient refrigeration even for micro-cryocoolers that have lower parasitic losses due to their small size. Mixed or multicomponent gas approach has been discussed previously by Little[3] and successfully employed by Marquardt et al.[4] for small cryocoolers for sensors and medical applications. Little[5] also discussed opportunities for small J-T cryocoolers to provide refrigeration for CMOS, NMOS and other electronics including high tem-

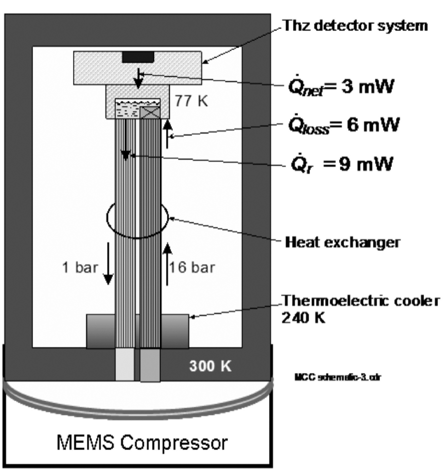


**Figure 1.** Schematic of MCC.

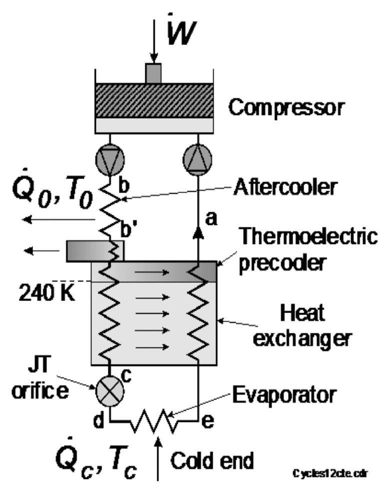


**Figure 2.** The MCC J-T cooling cycle.

perature superconducting devices which has lead to expectations for further developments of micro-cryocoolers to meet such needs. However it has not been demonstrated for on-chip applications such as the one we discuss here until recently. New fabrication techniques borrowed from MEMS technology were introduced by Little, Lerou, and others to pave the way for this effort.

While introducing mixed-gas approach for medical applications (cryogenic catheter) with precooling Marquardt et al. presented a novel method to design the gas mixture appropriate for specific temperatures, efficiencies, and/or COP. This approach forms the basis of component selection within the gas mixture. They found that by combining different components based upon their normal boiling points (nbp) and optimizing for appropriate vapor and phase equilibriums utilizing standard reference data from NIST[6,7] combined with equations of state developed by Peng et al[8]: a mixture can be designed that achieves significant increase in the maximum minimum enthalpy, $\Delta h_{min}$, compared with pure gases such as $N_2$. It is clear from Figures 3 and 4 that gas mixture can result in great improvements in minimum enthalpy differences over a pure fluid such as Nitrogen for similar operating conditions. The nbp's of Figure 4 present an interesting view toward making component selections for a mixture. By selecting components with increased $\Delta h_{min}$ at key temperatures we can maximize the $\Delta h_{min}$ for the mixture. The key is to pick just the right amount of each component (mol % of mixture) to arrive at a mixture that gives good $\Delta h_{min}$ over the temperature range of interest while remaining soluble in both vapor and liquid states for desired operating conditions (pressures, temperature, flow rates, pressure drops, etc.) without separating or freezing out individual components. We observe from Figure 5 the relationship between the solubility and normal boiling point of some candidate mixture constituents at 75 K. It is readily apparent from this that developing a fully soluble mixture is a delicate balancing process.

**Reducing MCC Volume, aka Reducing Losses by Miniaturizing the Cryocooler**

To effect a significant reduction of cryocooler size we need to look at three important aspects for J-T cryocoolers. First of course is to consider a manner in which we may achieve higher refrigeration for a given volume, flow rate, and/or input power. To accomplish this we need only look at the maximum $\Delta h_{min}$. Second we must consider methods for reducing the amount of refrigeration required just to cool the cryocooler itself (the gross refrigeration) thereby leading to lower input powers and improved net cooling.

For a higher $\Delta h_{min}$ the mixed gas J-T approach produces less parasitic losses. For example consider the minimum enthalpy differences, $Dh_{min}$ for a pure gas such as $N_2$ (Figure 3) and a mixed gas (Figure 4) for a $P_{high}$=16 atm. and a $P_{low}$ =1 Atm. The $\Delta h_{min}$ (= 0.155 kJ/mol) is nearly flat at 240 K above which it approaches nearly zero at 300 K. Whereas, the $\Delta h$ for the 7 component gas mixture becomes flat or near zero at about 265 K up to 300 K. The $\Delta h_{min}$ = 1.43 kJ/mol over the range of 240 down to 77 K for the gas mixture which is nearly a 10 fold increase over the pure nitrogen gas. Thus for a given flow rate the mixture will result in gross refrigeration that is nearly 10 times greater than the pure nitrogen. For the MCC however this means that very low flow rates are required to meet ~ 3 mW of net refrigeration required for the HEB/Thz detector. We desire low

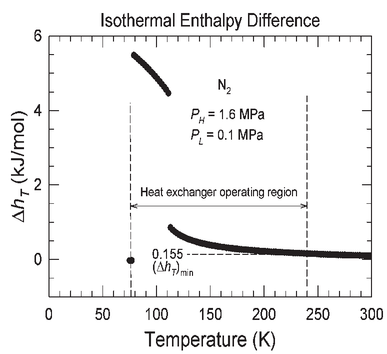


**Figure 3**. Minimum enthalpy difference for nitrogen

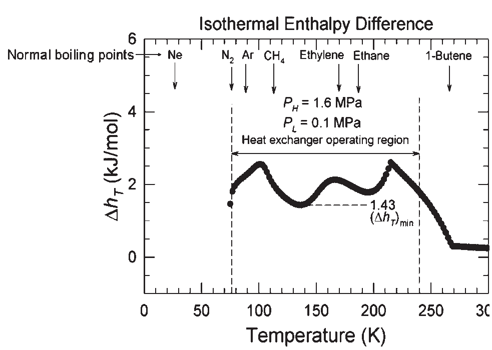


**Figure 4** Minimum enthalpy difference for 7 component mixed gas

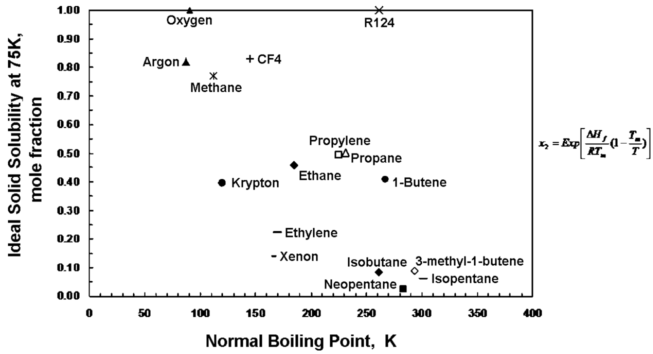


**Figure 5**. Relationship between normal boiling point and solubility for candidate mixture components.

flow rates to achieve small low power compressors while needing high $\Delta h_{min}$ to meet the gross refrigeration requirement of ~9 mW. This is determined from:

$$\dot{Q} = \dot{n}\Delta h_{min} \quad (1)$$

where $\dot{n}$ is the molar flow rate and of course $\Delta h_{min}$ is the minimum enthalpy difference for the mixture. Thus we arrive at a needed flow rate of ~ 6 mmol/s (~ 0.15 std. cm$^3$/s). From this we can determine appropriate compressor size and flow areas for the heat exchanger, and micro-valve cold head. Low flow rates result in small compressors with low input powers. A discussion on the MCC compressor development is presented in an adjoining paper.[9]

Reducing the gross refrigeration of any cryocooler is desirable. However, for this effort it is paramount for achieving the desired net refrigeration of 3 mW. Probably the single greatest advantage to miniaturizing the MCC is in reducing losses associated with volume and area in both the cold head and the heat exchanger. Once volume becomes low enough (on the order of less than a 1 cm$^3$) the dominant losses become conduction and radiation. As size decreases real gains are made to the structural aspects of the heat exchanger and cold head. Reduced size equates to increased strength for less volume or cross-section area so we are now open to use entirely different (even untraditional) materials than previously needed. There is of course heat exchanger ineffectiveness and pressure drop to consider but these can be managed as they scale with size for the most part.

The HEB/Thz detector is quite small so it requires a footprint of less than 4 mm$^2$ mostly for leads (not the detector itself). The micro-valve cold head is sized to meet this and thus it too is quite small. The heat exchanger, on the other hand, is somewhat larger than these and longer so it presents fairly large section-area for both conduction and radiation. We must find a balance between the conduction and radiation losses which also does not compromise pressure drop and heat exchanger effectiveness too much. For low conduction we need long and thin while for low radiation we need short and thin. For moderate flow with low pressure drop we need short, fat plus many channels while for high effectiveness we need long with many channels. We must consider these factors and look into the important aspect we now have moderate control over to define the appropriately small geometries and choice of material. While MEMS fabrication techniques work very well for silicon they do not perform nearly as well for glass or stainless steel. It becomes quite clear from Figure 6 that silicon is a very poor choice for the heat exchanger. Glass and stainless steel due to their low conductance on the other hand are very good candidates although fabrication issues have to be resolved. Glass is better yet as its conductance is about a factor of ~10 lower than of stainless steel over the 300 to 75 K temperature range of interest. It turns out that glass fibers are manufactured in a wide range of size and geometries small enough to be suitable for the MCC heat exchanger and provides for low conduction loss and reduced radiation loss from the small section and perimeter area.

## On-Chip Cooling — Limiting Propositions

One of the greatest limiting factors to microcryocoolers delivering on-chip cooling is the need for high thermal isolation of the sensor/detector during operation and in quiescent modes of opera-

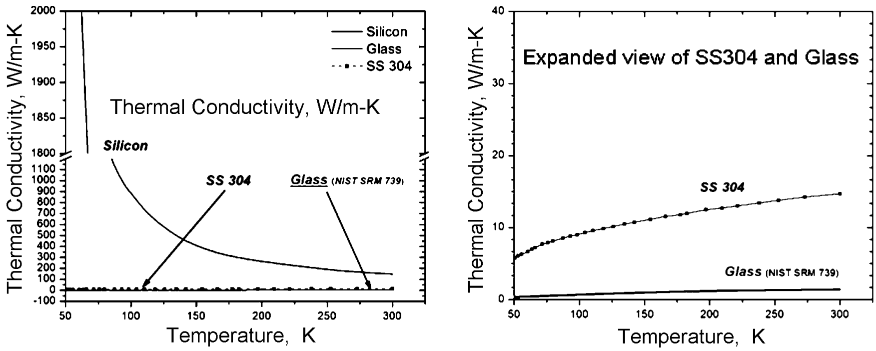


**Figure 6** a and b. Thermal conductivity for heat exchanger materials.

tion. For the MCC to provide the 3 mW of net cooling at 77 K efficiently for the HEB/Thz detector requires a high thermal isolation to reduce background losses. Thus, it is paramount that the detector be isolated from the entire cold head including micro-valve and heat exchanger by more than 30,000 K/W. This is more than a factor of 2 greater than the 13,000 K/W previously reported by S.-H. Lee et al.[10] While analyses show this to be the case for the MCC envisioned, it is important to demonstrate this in practice as unknowns for losses particularly from radiation and conduction are quite sensitive to actual geometries and surface finishes. Figures 7 and 8 show a test set up to demonstrate and measure thermal isolation of a test vehicle to simulate the cold head including micro-valve and heat exchanger. Step 1 consists of transferring the parasitic heat radiated and conducted from the a radiation shield (at 300 K) to the test chip (at 77 K) to the first stage of a G-M cryocooler through an 80 *u*m copper wire (Figure 7). Step 2 consists of calibrating the heat flow through the copper wire by applying heat to a Nb on silicon resistance heater/thermometer on the test chip maintained at 77 K when radiation and conduction from the shield are made zero by maintaining the shield at 77 K also (Figure 8). Measurements were made on a test vehicle such as the one shown in Figure 9 and found 5.1 mW of heat leak from the shield (300 K) to the chip (77 K) for a thermal isolation (thermal resistance) of 43,700 K/W. Figures 10 and 11 show the thermal isolation measurements and the separation of conduction and radiation losses as a function of shield temperature. These separate into an equitable split between radiation, 2.55 mW and conduction 2.55 mW (2.41 mW through glass fiber and 0.14 mW through 25 *u*m Pt-W leads).

As real properties such as viscosity, specific heat, enthalpy, and enthalpy difference can only be estimated from theoretical predications, design of the heat exchanger and micro-valve for pressure drops can only be estimated. While this is not too problematic for the heat exchanger, it certainly is for the micro-valve. We simply cannot predict well what the flow rates for given pres-

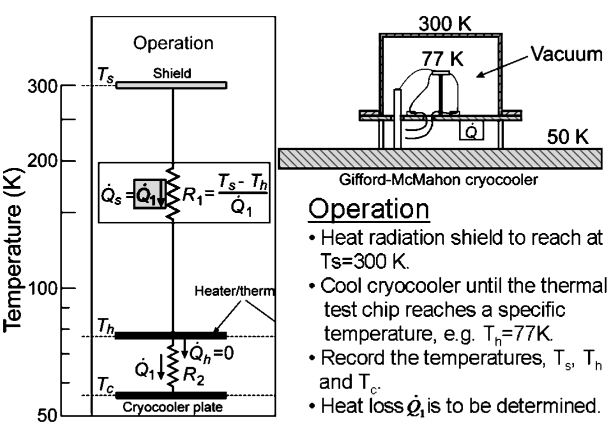


**Figure 7** Thermal isolation measurement set up

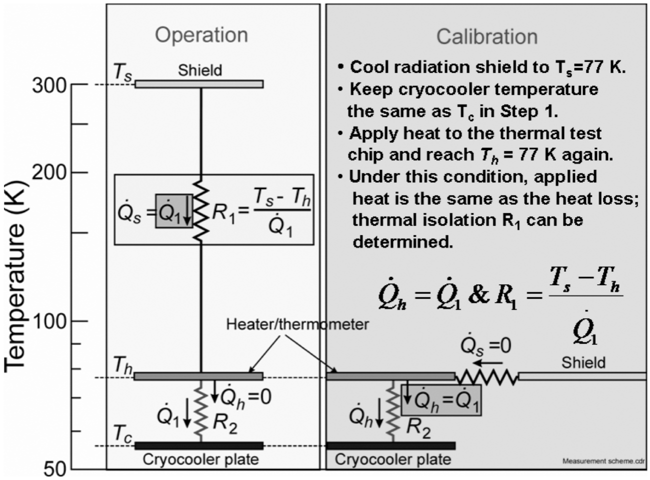


**Figure 8** Calibration of the thermal isolation measurement

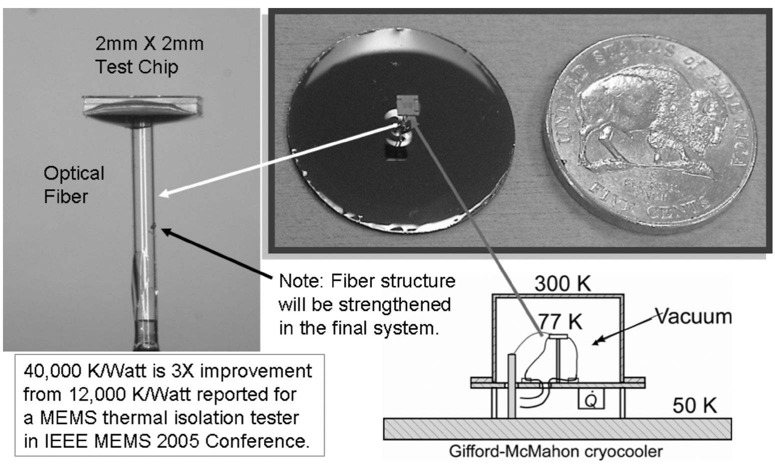


**Figure 9** Thermal isolation test vehicle

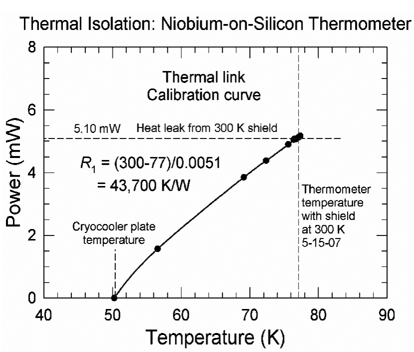


**Figure 10** Thermal isolation measurement

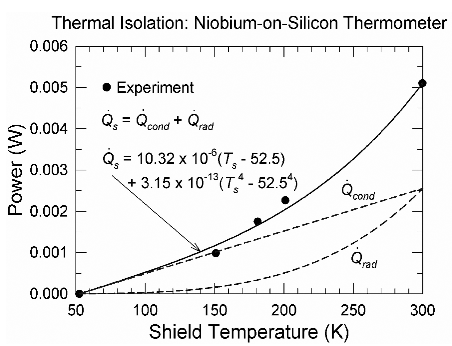


**Figure 11** Conduction and radiation losses

sure drops during operation will be. As such we decided the best approach would be to determine this in-situ as it were.

**MCC – Cold Head Testing — Evaluating performance**

To evaluate and measure performance for the MCC we have constructed a measurement apparatus as shown by the schematic in Figure 12. We use a dual stage non-lubricated linear compressor to provide the pressure ratios desired (16:1 to 25:1 for pressures up to about 25 atm.) and flow to the MCC while utilizing a G-M cryocooler to provide precooling of the MCC and gas mixture. The system is instrumented to provide temperature, pressure, and flow measurements as indicated, particularly across the cold head. This system was also used to perform the thermal isolation measurements as well but with some configuration differences.

To facilitate integration of the cold head into the measurement system it is mated to a copper coupler manifold which in turn thermally anchors to the G-M cold plate. The gas passes through the copper coupler en-route to the cold head after passing through a precooling line affixed along the underside of the G-M plate. The G-M cold plate and copper coupler thus perform the function of pre-cooler for the mixed gas thereby taking the place of the intended thermoelectric cooler to be integrated later.

Numerous sample cold heads (lower manifold, heat exchanger, and micro-valve) have been fabricated and tested to develop the fabrication process and to determine design and fabrication weaknesses. An example of the cold head is shown in Figure 13 while undergoing pressure test in the measurement apparatus at ambient conditions with Nitrogen as the test gas. This cold head has proven capable of sustaining high pressures (>20 atm.) without leakage both at ambient and 240 K conditions. The cold head has demonstrated flow through/across the micro-valve while sustaining from 16 to 20 atm. at the inlet and about 1 atm. at the low pressure outlet of resulting in 16:1 to 21:1 ratios with $N_2$ gas. A Nb on silicon resistance temperature/heat sensor is attached to the tip of the cold head similarly to the thermal isolation test vehicle. The leads are the same Pt-W variety as those used for the thermal isolation test. While the measurement system operates with both supply and catch tanks to fully recycle the gas mixture, $N_2$ gas is used for all pressure tests and to reduce losses of the mixture during installation and removal of a cold head.

**CONCLUSIONS AND FUTURE WORK**

We present a mixed-gas microcryocooler for on-chip cooling of high temperature superconducting HEB/Thz detectors. This microcryocooler incorporates novel fabrication techniques within the design of the cold head heat exchanger and micro-valve which enable it to operate at lower pressures and pressure ratios. The cold head has passed pressure and flow tests in preparation for mixed-

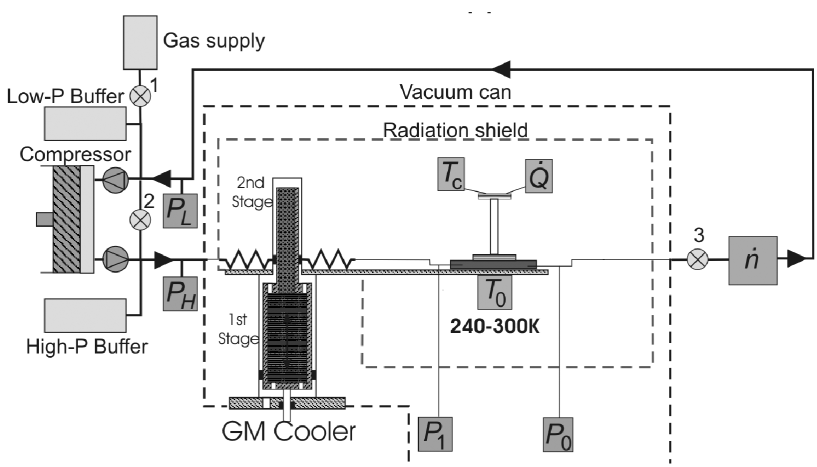


**Figure 12** Schematic of MCC measurement system

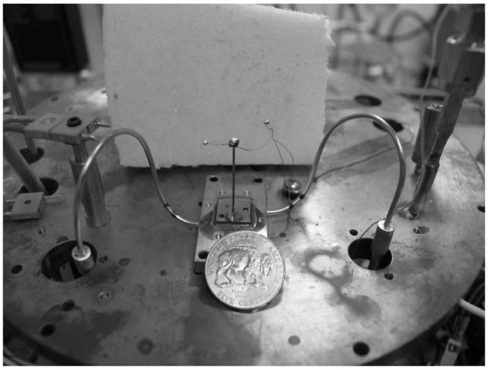

**Figure 13** MCC cold head assembly undergoing pressure test

gas operation. Evaluation of the cold head with mixture gas has been undertaken. However, results are not mature at this time to present regarding mixture composition and/or cooling performance with the mixture or details in fabrication techniques. We expect to present thorough details regarding cold head performance with a 5 to 7 component gas mixture at the CEC-ICMC in Tucson in 2009.

## ACKNOWLEDGMENT

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