Vapor-Venting Thermal Management System for Sample Return Missions

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Sample return missions allow for in-depth scientific studies that are not possible in-situ but maintaining sample integrity is critical to maximizing the scientific value. In this paper, ACT will present a novel, consumable-based thermal management system for sample return missions that utilizes the latent heat of vaporization of a working fluid to absorb the external heat load and removes thermal energy by venting vapor the environment. The thermal management system is lightweight, scalable, requires minimal energy input and is applicable to a range of mission requirements. This paper will discuss the design, fabrication and testing of a vapor-venting thermal management system prototype for sample return missions.

Nomenclature

ACT	=	Advanced Cooling Technologies
FEP	=	Fluorinated Ethylene Propylene
LHV	=	Latent Heat of Vaporization
NCG	=	Non-Condensable Gas
PCM	=	Phase Change Material
TC	=	Thermocouples
TMS	=	Thermal Management System
VVTMS	=	Vapor Venting Thermal Management System

I. Introduction

Sample return missions represent some of the most challenging but scientifically promising missions under consideration.[1] Returning samples to Earth allows for in-depth scientific studies that are not possible in-situ. The scientific community is interested in studying samples from a variety of bodies including, Mars,[2] the Lunar surface[3] and comets/asteroids.[1,4] In order to maximize the scientific value of any returned sample, it is critical that the sample not be mechanically or thermally altered. For samples originating from extreme cold environments, such as comets[1,4] and permanently shadowed regions on the Lunar surface,[3] this may require maintaining the temperature of the sample at or below temperatures ranging from -60°C to -180°C, depending on the particular sample. The temperature of the sample must be maintained throughout all phases of the mission including transit, re-entry and recovery on the ground.

Veverka[4] conducted an analysis of thermal requirements for cryogenic comet sample return missions, Table 1 shows a breakdown of the different phases of the mission with estimates of the duration and thermal loads for each phase. During the Return Cruise phase, the sample temperature can be maintained passively via radiation to deep space and/or actively with a cryocooler. Earth Approach and Re-Entry/Recovery represent the most thermally challenging phases of the mission. During Re-entry in particular, solar panels cannot be utilized and battery power would be required for an active cryocooler system. Veverka's analysis determined that the mass of batteries required to power a cryocooler system would be prohibitive. The use of a solid-to-liquid phase change material (PCM) is an obvious approach to absorb the heat generated during re-entry but such systems tend to be bulky and heavy.

As part of a NASA Phase I SBIR program, Advanced Cooling Technologies, Inc. (ACT) developed a novel, consumable-based thermal management system (TMS) for sample-return missions that utilizes the latent heat of vaporization of a working fluid to absorb heat leaks from the environment. The vapor is then vented into the environment, preventing thermal energy from reaching the sample. The TMS is lightweight, scalable, requires minimal

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energy input and is applicable to a range of mission requirements. This paper will discuss the design, fabrication and testing of a vapor-venting TMS prototype for sample return missions.

Table 1. The various phases of a comet sample return mission, duration, heat sources and estimated heat loads during each phase. Adapted from Veverka.[4]

Pre-Encounter	Encounter	Return Cruise	Earth Approach	Re-Entry/Recovery
Years	Days	Years	Days	Hours
-	Pre-cooling sample chamber	Heat leaks from spacecraft and radiation ~0.5 – 4.0W	Additional heating due to spacecraft orientation ~2.0 – 6.0W	Heat generated during re-entry, heating while awaiting recover +10.0W

II. Vapor-Venting Thermal Management System

The Vapor-Venting Thermal Management System (VVTMS) developed for sample-return missions is illustrated in Figure 1. Incoming thermal energy is absorbed via the latent heat of vaporization of a working fluid and the vapor is vented from the system to maintain the temperature of the sample. The collected sample is contained in the centrally located sample chamber which is surrounded by several annular regions. The first annular region is the bladder chamber where the working fluid is stored, as subcooled liquid, in a positive expulsion bladder. A high pressure non-condensable gas (NCG) surrounds the bladder to provide passive pumping. Surrounding the bladder chamber is the vapor jacket where the working fluid absorbs heat via vaporization. Working fluid within the vapor jacket is in a two-phase saturated state with liquid contained in a porous wick lining the walls. Liquid is supplied to the wick, from the bladder, via a solenoid valve that opens when liquid is required. Incoming thermal energy vaporizes liquid contained within the wick generating vapor raising the temperature and pressure of the vapor jacket. At a pre-determined setpoint, a second solenoid valve is opened and vapor flows to the final annular space, the heat guarding chamber where superheated vapor absorbs additional heat through sensible heating before finally venting to the environment.
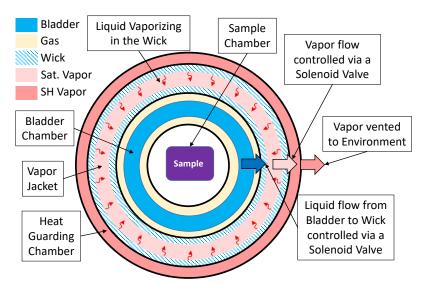

Figure 1. Illustration of Vapor-Venting Thermal Management System. Working fluid within a Vapor Jacket absorbs heat through vaporization and vapor is vented from the system. The wick is supplied with liquid from a positive expulsion bladder.

The VVTMS has several advantages:
- Lightweight – Latent heat of vaporization is highly mass efficient. It can be fabricated from lightweight materials and components
- Continuous set point adjustability – The temperature of the system is set by the choice of working fluid and operating pressure within the vapor jacket. The pressure inside the vapor jacket is controlled by opening the valve at the desired setpoint. By properly selecting the working fluid and the control setpoint pressure a continuous range of temperatures can be selected. The setpoint can also be adjusted remotely by changing the pressure or temperature at which the valves open.
- Remote setpoint change – the setpoint can be changed as needed during the mission throughout its phases.
  - The system could be driven into significant pre-cooling before Earth Entry, impact, and recovery.
- Relatively Simple and no moving parts

o   Except for the valves
- Passive – the system works autonomously
- No energy requirements
  - o   Except for sensors and valve actuation
- Relatively low cost

III.   Proof-of-Concept Prototype

A. Proof-of-Concept Setpoint Temperature

The first step to designing the Phase I proof-of-concept prototype was to select the target temperature at which the sample must be maintained, known as the setpoint temperature. For a particular sample-return mission this temperature would be dictated by the sample to be collected and scientific requirements. Comet and Lunar sample-return missions generally require cryogenic temperatures which would be challenging to accomplish in a Phase I program. When selecting the design setpoint it was decided to select a value only slightly below the ambient room temperature. This choice was made so that heat transfer would occur from the ambient environment into the VVTMS simulating generic environmental heat leaks the actual sample return chamber may experience. Based on these considerations a nominal setpoint of 15°C was selected for the Phase I prototype. Note that because the setpoint is controlled by selecting the pressure at which the vapor jacket solenoid valves open, the setpoint is adjustable

B. Working Fluid Selection

After selecting a setpoint temperature it was necessary to select a working fluid. There are a variety of factors that must be considered when selecting a working fluid including:
- The setpoint must be above the triple point but below the critical point of the fluid.
- Vapor pressure at the setpoint must be above atmospheric pressure for venting during the Recovery Phase of the mission (sample capsule on the ground).
- High latent heat of vaporization (LHV) to minimize the required mass of fluid.
- High surface tension so that the liquid can distribute throughout the wick in the vapor jacket.
- High liquid density to minimize storage volume.
- Compatibility of the fluid with the material of the bladder, wick and container.

The setpoint temperature selected for the Phase I prototype was 15°C. Table 2 lists several fluids that could be considered for this setpoint temperature and compares the vapor pressure, latent heat of vaporization and surface tension. Based on the fluid requirements listed above, the only suitable fluid is ammonia because the vapor pressure is higher than atmospheric pressure at the selected setpoint. This requirement is necessary for the Recovery Phase of the mission. Ammonia also has a very high LHV. ACT decided against using ammonia for the Phase I proof-of-concept demonstration due to safety concerns. The other possible choices listed in Table 2 are not able to vent to the atmospheric pressure requiring a specialized experimental setup for the Phase I proof-of-concept. The experimental setup will be discussed below. Based solely on the LHV, water represents the best possible choice; however, water has been eliminated based on the very low vapor pressure and lack of compatibility between water and potential envelope materials such as stainless steel and aluminum. Ultimately it was decided to used acetone for the Phase I proof-of-concept prototype. Acetone provides reasonable fluid properties, is compatible with relevant materials and is relatively safe and easy to work with. It should be stressed that while acetone represents a reasonable choice for the proof-of-concept demonstration it would not likely be selected for an actual mission due to other superior options. Section IV discusses potential working fluids for cryogenic sample-return missions.

Table 2. Comparison of different potential fluids for the Phase I prototype. Properties evaluated at 15°C.

Fluid	Vapor Pressure (kPa)	LHV (kJ/kg)	Surface Tension (N/m)
Water	1.7	2466	0.074
Ammonia	724.9	1200	0.028
Acetone	19.5	544	0.024
Pentane	46.2	373	0.017
Methanol	9.8	1184	0.023

C. VVTMS Prototype Design

A 3D model of the Phase I proof-of-concept prototype for the VVTMS is shown in Figure 2. The different chambers and fluid lines are color-coded. The outer diameter of the prototype was 208.28mm and the height of the cylinder was 152.4mm. The sample chamber was located in the center of the prototype and was surrounded by the bladder chamber. As shown in Figure 2, the bladder chamber had two connections, the NCG line (non-condensable gas) and the liquid line. The liquid line into the bladder chamber connected directly to the bladder. By opening and closing the corresponding valves, the liquid line was used for charging the bladder or for transporting liquid from the bladder to the vapor jacket. The NCG line was for charging the bladder chamber, external to the bladder, with NCG which was used to pressurize the bladder and provide passive pumping of the working fluid. A pressure transducer was used to measure the amount of NCG added to the chamber. Liquid flow from the bladder to the vapor jacket was controlled by a solenoid valve. Within the vapor jacket, the working fluid
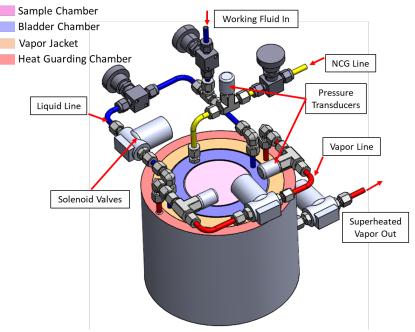

Figure 2. 3D model of the Phase I prototype showing the valve and plumbing system for fluid distribution and control.

vaporized as heat was absorbed and the vapor was vented from the vapor jacket to the heat guarding chamber by opening the solenoid valve located on the vapor line. A pressure transducer located in-between the vapor jacket and the vapor line solenoid valve was used to determine when to vent the vapor jacket. Finally, the heat guarding chamber can be vented to the environment by a final solenoid valve located on the side of the model in Figure 2. The pressure within the heat guarding chamber was monitored by a pressure transducer located on the vapor line upstream of the solenoid valve. The final solenoid could also be replaced with a needle valve to provide flow resistance or a relief valve so that electronic control was not necessary.

Figure 3a shows a cross-sectional view of the internal structure of the prototype. A flexible bladder was wrapped around the sample chamber. The bladder was connected to the liquid line that carried liquid to the vapor jacket. Screen wick was placed on the inner surfaces of the vapor jacket. The liquid header system, shown in Figure 3b, interfaced with the screen wick of the vapor jacket through screen arteries.

a) Cross-Section of Phase I Prototype   b) 3D Model of Liquid Header System
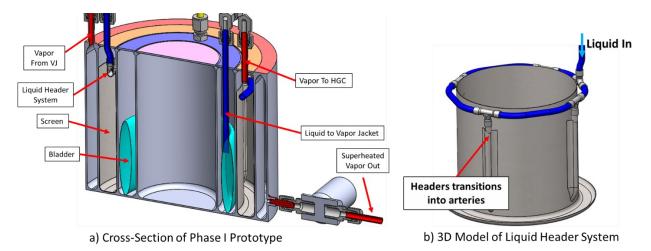
Figure 3. a) Cross-section showing the internal structure of the Phase I VVTMS Prototype design. b) 3D model of the liquid header system that fed liquid into the screen within the vapor jacket.

The concentric cylinders and the bottom surface of the prototype were additively manufactured as a single part. Stainless steel was selected as the material for the Phase I prototype. This selection was based on compatibility with the working fluid acetone and the relative ease of additively manufacturing a stainless-steel part as opposed to a lighter material such as aluminum. The additively manufactured envelope, shown in Figure 4, contained the entire structure except the end caps used to close the top of the prototype. The top of the 3D printed walls contained a small lip used for placing the end caps. The end caps were water jet cut and eventually welded into place.
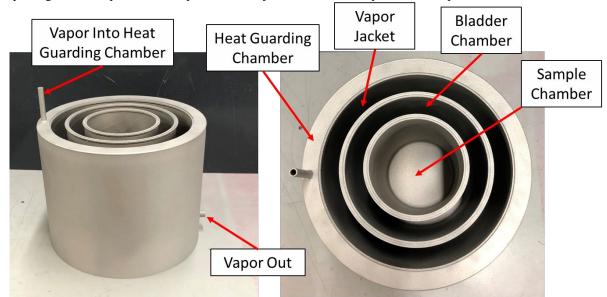

Figure 4. Images of the stainless-steel additively manufactured envelope of the Phase I prototype. Annular end caps (not shown) were used to close the vapor and bladder chambers. A circular disk end cap (not shown) was used to close the sample chamber.

For the Phase I prototype, the flexible bladder was a polymer bag made from fluorinated ethylene propylene (FEP). FEP was chosen due to its compatibility with a wide range of chemicals including acetone. Figure 5 shows an example of the bladder used on the prototype. The bag was manufactured with two ports, one of which was plugged with a stainless-steel rod while a tube was attached to the other port. A single tube was used for charging and discharging the bladder. The tube was bent 90° so that it could exit the top of the bladder chamber and interface with valves shown in Figure 2.
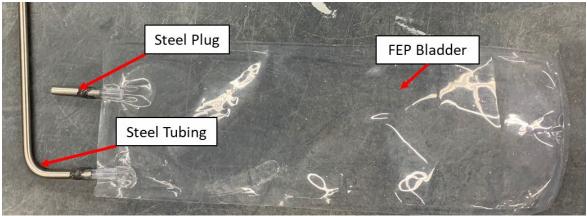
Figure 5. Image of FEP bladder used in Phase I Prototype. The bag was manufactured with two ports. One port was plugged with a stainless-steel rod. A stainless-steel tube was connected to the other port for charging and discharging the bladder.

D. VVTMS Prototype Experimental Setup

The final prototype is shown in Figure 6. The prototype was placed within a frame to support the external plumbing and so that the prototype could be easily transported. Three pressure transducers are seen in Figure 6 for measuring the pressure of the gas surrounding the bladder in bladder chamber, the vapor jacket and the heat guarding chamber. Solenoid 1 was used for controlling liquid flow from the bladder to the vapor jacket and Solenoid 2 was used for controlling vapor venting from the vapor jacket into the heat guarding chamber. Note that no valve was connected to the exit of the heat guarding chamber. When Solenoid 2 was opened, vapor exited the vapor jacket, flowed through the heat guarding chamber and exited the system via the vapor out port indicated in Figure 4.
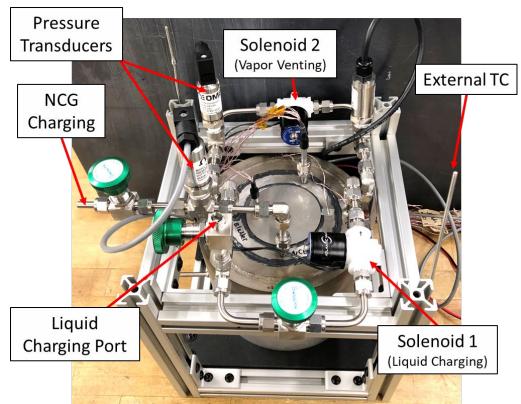

Figure 6. Image of the Phase I prototype. Various components for liquid distribution and control are labeled.

At the selected setpoint temperature of 15°C, the vapor pressure of acetone is approximately 19.5kPa. In order for the prototype to vent vapor into the environment it was necessary to place the prototype inside a bell jar where the environmental pressure could be lowered. Figure 7a shows an image of the Phase I prototype placed inside the bell jar. Figure 7b shows a closeup of the same image. The external plumbing was covered with insulation. A rope heater was wrapped around the prototype near the bottom. This heater was used to increase heat loads on the system and was placed near the bottom to shorten the heat transfer path from the outer wall of the prototype to the end caps and towards the sample chamber. Thermocouples (TCs) were placed at several locations on the prototype, including the outer wall, the upper and lower end caps, on the inside walls of the bladder chamber (wall shared with vapor jacket) and on the inner walls of the sample chamber. External TCs were also mounted inside the bell jar to measure the environmental temperature. A tube connected the gas in the bladder chamber to atmospheric pressure outside of the bell jar so that the bladder was always compressed by atmospheric pressure.

Acetone was charged into the bladder via a syringe (not shown), prior to placing the bell jar over the prototype. It was determined that when the bladder was installed in the bladder chamber it was capable of holding 370cm^3 of acetone, corresponding to 0.294 kg of working fluid.
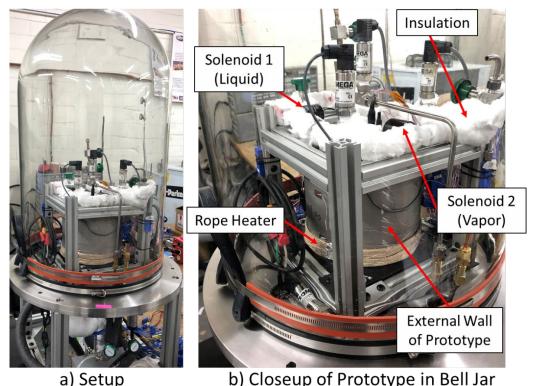

Figure 7. a) Image of the entire experimental setup, b) closeup of the prototype in the bell jar. The external plumbing was covered with insulation. A rope heater was wrapped around the prototype.

The VVTMS is designed to operate autonomously, the solenoid valves controlling liquid into the vapor jacket and vapor venting were opened in response to temperature and pressure measurements. During the Phase I program a simple control scheme was implemented based on experimental observations.

- The vapor venting valve (Solenoid 2 in Figure 6) was controlled by a TC mounted to the wall of the vapor jacket. When this temperature exceeded the setpoint of 15°, Solenoid 2 was briefly opened to vent vapor.
- As vapor was vented from the vapor jacket the liquid inventory in the wick was eventually depleted. This resulted in a rapid decrease in pressure within the vapor jacket. When the vapor jacket pressure fell below a predetermined value, Solenoid 1 was opened allowing liquid flow from the bladder to the vapor jacket.
- Each valve was opened for a predetermined amount of time based on experimental observations.

Prior to starting the experiment, the prototype was precooled to near the setpoint temperature. Before placing the bell jar over the prototype, the vacuum pump was connected directly to the prototype via a hose. The vapor jacket was charged with an arbitrary amount of acetone and the vapor venting valve was opened to allow acetone to continuously

vaporize and flow out of the system. This resulted in continuous cooling until the prototype was near the setpoint temperature. The bladder was then fully charged and the bell jar was set in place.

E. VVTMS Prototype Experimental Results

Test scenario # 1: Long-Term Steady-State Operation of Phase I prototype

Figure 8 shows experimental results for the Phase I prototype. The plot includes several temperatures (Vapor Jacket, Sample Chamber, Outer Wall and Environmental), the Vapor Pressure, the Environmental Pressure and an Estimated Mass of Fluid remaining in the bladder. The Estimated Mass is calculated based on the initial mass (0.294 kg) and the observation that each opening of Solenoid 1 (Liquid Charging Valve) added 5cm^3 from the bladder to the vapor jacket. Note that in Figure 8, the Estimated Mass of Fluid is multiplied by 100 in order to more favorably scale it on the plot.

The experiment began with a brief period during which the Environmental Pressure within the bell jar was being reduced and this was followed by a short period when the system vented frequently to cool itself to the setpoint temperature. After the cooldown period, the Environmental pressure slowly decreased to a steady value of approximately 8.3 kPa, which was reached approximately 6,000 seconds into the test. This pressure was largely dictated by what the pump was capable of achieving. For approximately 40,000 seconds (11.1 hours) the system was at a near steady-state condition; the Sample Chamber temperature was approximately 14.5°C and the Environmental Temperature was 24.3°C. The control inputs, opening of the solenoid valves, was controlled by the Vapor Jacket temperature. Periodic spikes in the Vapor Jacket temperature can be observed in Figure 8. These spikes were due to slightly warmer liquid being added into the Vapor Jacket from the bladder when Solenoid 1 was opened. During the time in-between the spikes the Vapor Jacket temperature oscillated at a higher frequency corresponding to the opening of the vapor venting valve, Solenoid 2. The higher frequency oscillations are not clearly visible at the time scale of Figure 8.
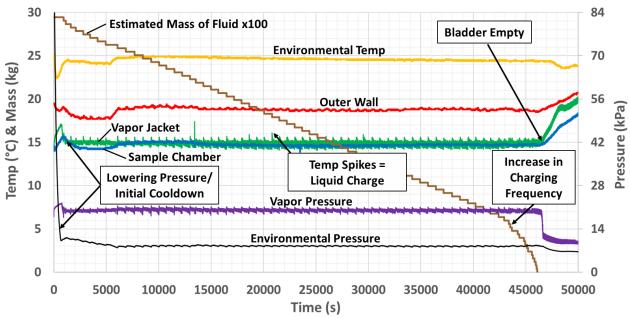

Figure 8. Time history of temperature measurements on the Phase I prototype during testing. The setpoint temperature was controlled by a TC on the wall separating the vapor jacket and bladder chamber, labelled "Vapor Jacket" in the plot. Temperatures and "Estimated Mass of Fluid×100" are read on the left axis and pressure is read on the right axis. Dividing "Estimated Mass of Fluid×100" by 100 gives the mass of fluid in kg. The initial mass of acetone was 0.294 kg.

The plot of "Estimated Mass of Fluid x100" shows a very steady decrease from 10,000 seconds to 40,000 seconds. This indicates that the charging of liquid and venting of vapor were both occurring at regular intervals. At approximately 43,000 seconds the slope of "Estimated Mass of Fluid x100" began to decrease due to an increase in frequency of opening the liquid charging valve. This suggests that as the bladder was nearing empty, each charge no

longer consistently added 5cm³ of acetone to the vapor jacket. Despite this, the system maintained a steady temperature until approximately 46,500 seconds at which point the temperature began to rise and the pressure within the vapor jacket rapidly dropped. The drop in pressure was due to the system attempting to vent vapor but being unable to replenish liquid. The ability of the system to fully empty the bladder was verified by refilling the bladder after testing. Before and after the test a total 370cm³ was able to be added to the bladder.

By examining the steady-state operating condition between 10,000 seconds and 40,000 seconds it was possible to estimate the average heat load absorbed by the VVTMS during the experiment. During that 30,000 second internal, the system added liquid to the vapor jacket 41 times. Assuming a consistent charge of 5cm³, a total of 0.163kg of acetone was consumed during that period of time. Based on the latent heat of vaporization of acetone at the setpoint temperature (544kJ/kg) a total of 88.8kJ was removed by venting. Over a 30,000 second internal this equates to an average heat load of 2.96W.

For a setpoint temperature of 15°C, most commercially available solid-to-liquid PCMs have a latent heat around 200kJ/kg and would require a total mass of approximately 0.444 kg to absorb 2.96W for 30,000 seconds. This is an increase in mass by a factor of 2.7 compared to mass of acetone required.

Test scenario # 2: Demonstration of VVTMS Response to Variable Environmental Conditions

A second test of the prototype VVTMS was conducted to demonstrate the ability of the system to maintain the setpoint temperature as the environmental conditions changed. Figure 9 plots the time history of several temperatures (Vapor Jacket, Sample Chamber, Outer Wall and Environmental), the Vapor Pressure, the Environmental Pressure and an "Estimated Mass of Fluid x100" remaining in the bladder during the second test of the VVTMS prototype. The experimental process was similar to that described above. The prototype was precooled to near the setpoint prior to setting the bell jar in place. During the first 1,600 seconds the pressure within the bell jar was reduced from atmospheric to approximately 3.4kPa, note that this is lower than the Environmental Pressure shown in Figure 8 due to using a superior pump for the data shown in Figure 9. Between approximately 1,700 seconds and 6,000 seconds, the system operated at a steady state with a Sample Chamber temperature of 14.5°C and an Environmental Temperature of 24.0°C. During this time period, there were 7 liquid charges into the vapor jacket and the system consumed 0.028kg of acetone. This equates to an average heat load of 3.5W.
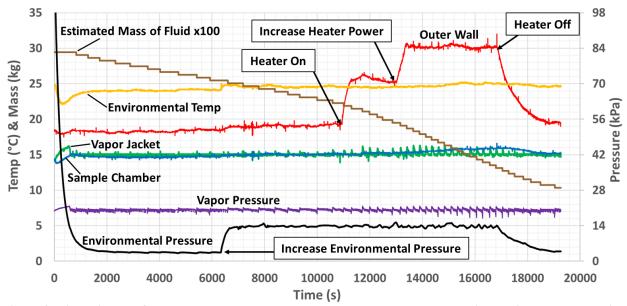

Figure 9. Time history of temperature measurements on the Phase I prototype during testing. Demonstrating system response to changes in environmental conditions. The setpoint temperature was controlled by a TC on the wall separating the vapor jacket and bladder chamber, labelled "Vapor Jacket" in the plot. Temperatures and "Estimated Mass of Fluid×100" are read on the left axis and pressure is read on the right axis. Dividing "Estimated Mass of Fluid×100" by 100 gives the mass of fluid in kg. The initial mass of acetone was 0.294 kg.

After approximately 6,300 seconds the pressure within the bell jar was increased to approximately 13.8kPa. This was accomplished by adjusting a valve to allow airflow into the bell jar. In an actual application, this increase in pressure would represent the transition from operation in space to operation on the ground. After the pressure within the bell jar was increased there was a slight increase in temperature of the Sample Chamber, to 15.0°C, and the Environmental Temperature, to 24.5°C. These temperature increases were due to warm air flowing into the bell jar. The sample chamber was not perfectly sealed so some warm air was able to enter the sample chamber resulting in the slight increase. The system operated at a steady state between approximately 6,600 seconds and 10,500 seconds. Based on the number of liquid charges it was estimated that the average heat load was 3.8W.

At approximately 11,000 seconds the rope heater (see Figure 7b) was turned on. The effect of the heater was most clearly seen in the Outer Wall temperature (where the heater was located). The initial heater setting resulted in the Outer Wall temperature rising from 19.0°C to approximately 25°C. Then at 13,000 seconds the heater power was increased until the Outer Wall temperature reached a steady value of 30°C. When applying heater power, the VVTMS must vent and charge liquid at an increased rate. An increase in liquid charging frequency can be observed by the increased frequency of Vapor Jacket temperature spikes, which resulted from slightly warmer liquid entering the Vapor Jacket. The increased liquid consumption can also be noted by the change in slope of the "Estimated Mass of Fluid x100" line. During the period of high heater power, approximately 13,400 seconds to 16,800 seconds, there were 13 liquid charges, consuming 0.052kg of acetone. This equates to an average heat load of 8.4W, 2.5 times higher than without the heater. There was a slight increase in the Sample Chamber temperature, from 15.0°C to 16.0°C during this time period despite the Vapor Jacket temperature remaining at the setpoint of 15°C. The reason for this slight increase in Sample Chamber temperature was heat conduction through the endcaps. A more effective realization of the VVTMS concept will have the vapor jacket completely surround the sample chamber.

IV. Preliminary Investigation of a VVTMS for Cryogenic Comet Sample Return Missions

A. Overview of Cryogenic Comet Sample Return Mission Thermal Requirements

Veverka[4] provides a detailed overview of cryogenic comet sample return missions that require sample temperature setpoints between 90K (-183°C) and 125K (-148°C). During the transit phase of the mission, from the comet to Earth, it is likely that some combination of active and passive cooling would be required. This could include an active cryocooler system and/or a passive radiator. The active cryocooler would be powered by solar energy. When the system begins preparing for reentry it is expected that heat loads will increase and it will be necessary to break the thermal link between the system and a radiator. When the system begins reentry, and while awaiting recovery on the ground, the options for thermal management include an active cryocooler powered by batteries, a solid-to-liquid PCM system and the vapor-venting system developed in this program. Veverka[4] estimates heat leaks through insulation to the sample ranging from 1W to 9W for several hours throughout the reentry and recovery phases of the mission. Due to the low efficiency of cryocoolers, Veverka[4] estimates that a cryocooler powered by 40 D-cell batteries would be capable of lifting approximately 5W at 125K (-148°C). The mass of a D-cell battery is in the range of 100 to 160 grams/cell. Therefore 40 D-cell batteries would have a mass ranging from 4kg to 6kg. Note that this does not include the mass of the cryocooler itself. A battery powered cryocooler would likely require additional thermal capacity through the use of a PCM.

B. Comparison of Solid-to-Liquid PCM and Vapor Venting Working Fluids

Yang et al.[5] conducted a survey of cold temperature phase change materials. Figure 10 plots the latent heat of fusion for solid-to-liquid PCM's, identified in the survey, as a function of temperature. Cryogenic comet sample return missions are likely to have a temperature requirement below 125K (-148°C) and it can be seen in Figure 10 that for this temperature range the maximum latent heat of fusion was approximately 75kJ/kg.

ACT conducted a survey of potential fluids that could be used in a vapor-venting TMS for cryogenic comet sample return missions. Table 3 lists several potential fluids and relevant properties. In order to be considered, the triple point of the substance must be below at least
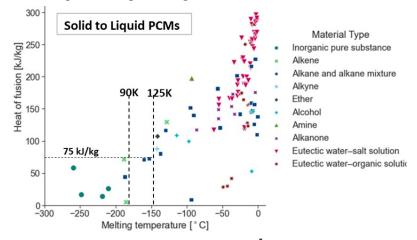

Figure 10. Results of a survey by Yang et al.[5] providing an overview of latent heats of fusion at low temperatures for a large number of potential solid-to-liquid phase change materials. Marks added to indicated the temperature range most relevant to comet sample return missions (90K to 125K).

125K (-148°C). For each fluid, Table 3 lists the vapor pressure and the latent heat of vaporization (LHV) at setpoint temperatures of 90K (-183°C) and 125K (-148°C), the most likely temperature requirements for comet sample return missions according to Veverka.[4] Ethane, krypton and ethylene cannot be used at 90K because that temperature is below the triple point. Oxygen and methane cannot be used at 90K because the vapor pressure is too low to vent into atmospheric pressure. Nitrogen, argon, carbon monoxide (CO) and fluorine are all capable of venting to atmospheric pressure at 90K. All four fluids have LHV greater than 75kJ/kg, which was the highest latent heat of fusion for solid-to-liquid PCMs identified by Yang et al.[5], see Figure 10. The fluid with the highest LHV at 90K was carbon monoxide with a value of 202kJ/kg. The vapor pressure of CO at this temperature is only 238.6 kPa which low enough to not require heavy structural mass.

At 125K, ethane and ethylene cannot be used because of the low vapor pressure. At this temperature, methane represents the best choice based on the high LHV and relatively low pressure. Nitrogen is very near the critical temperature and has high vapor pressure and low LHV. Argon, oxygen, CO and fluorine all have LHV's higher than 75kJ/kg but relatively high pressures resulting in larger structural mass compared to methane.

Table 3. Properties of various fluids with the potential to be used in a cryogenic vapor-venting system. Vapor pressure and latent heat of vaporization (LHV) shown for setpoints of 90K and 125K. Red text indicates that the vapor pressure is too low to vent to atmospheric pressure on the ground. Green text indicates the fluid has the highest LHV for that setpoint.

Fluid	Triple Point (K)	Crit T (K)	Setpoint = 90K (-183C)		Setpoint = 125K (-148C)	
			Pressure (kPa)	LHV (kJ/kg)	Pressure (kPa)	LHV (kJ/kg)
Ethane	91	305	-----	-----	0.697	557.4
Nitrogen	63.18	126	360.5	180.487	3200.5	51.7
Argon	83.8	151	133.5	159.06	1582.3	118.756
Oxygen	54.4	154.4	99.3	213.2	1350.7	164.08
Methane	90.68	190.4	10.5	545.252	268.8	483.79
CO	68	133	238.6	202.223	2415.7	106.2
Fluorine	53.38	144	172.9	110.38	2138.8	176.26
Krypton	115.64	209	-----	-----	150	105.17
Ethylene	104	282	-----	-----	2.5	432.12

Based on this preliminary analysis, the latent heat of vaporization of various potential working fluids at cryogenic temperatures is significantly higher than the latent heat of fusion of solid-to-liquid PCMs for similar temperatures. An interesting additional advantage of the VVTMS concept is that the system can be designed for any specific setpoint temperature as opposed to solid-to-liquid PCM systems where the PCMs only provide discrete setpoint options. Using methane as the working fluid, the VVTMS setpoint can be adjusted to 115K by simply adjusting the temperature at which vapor is vented. Lowering the setpoint provides two advantages. First, there is a slight increase in the latent heat of vaporization, 483 kJ/kg to 505 kJ/kg. Second, the vapor pressure is reduced from 268.8 kPa to 132.4 kPa allowing for a lighter structure to contain the pressure but the system can still vent to the atmosphere.

C. Preliminary Mass Comparison of PCM-Based and Vapor Venting-Based TMS

A mass analysis comparing a traditional solid-to-liquid PCM and the VVTMS was performed for a hypothetical cryogenic mission using the thermal requirements listed in Table 4 (based on the trade studies of Veverka[4]).

Table 4. Thermal requirements for a hypothetical cryogenic comet sample return mission based on the report by Veverka.[4]

Max Sample Temperature	Heat Load to Sample from Insulation	Duration
125K (-148°C)	10W	12 hours

According to Figure 10, a traditional solid-to-liquid PCM system designed for a maximum of 125K may have a latent heat of fusion of 75 kJ/kg and would require a PCM mass of 5.76kg. The mass of the structure, including the PCM container, fins to enhance conduction into the PCM and a container for storing the cryogenic sample were assumed to be 50% of the mass of PCM or an additional 2.88 kg. The total mass of the solid-to-liquid PCM for the requirements in Table 4 was estimated to be 8.64 kg.

Based on Table 3, methane is the best working fluid for a VVTMS with a maximum sample temperature of 125K. As explained above, the setpoint of the VVTMS can be adjusted by controlling when the system vents. By setting the control temperature to 115K the vapor pressure is reduced by half, reducing structural requirements. The vapor pressure at this temperature is still above atmospheric pressure. At 115K the LHV of methane is 505 kJ/kg. Based on the thermal requirements in Table 4, 0.856 kg of methane would be required. The mass of a hypothetical VVTMS using methane as the working fluid for a setpoint of 115K was estimated based on the following assumptions:

- The system was assumed to be cylindrical with hemispherical endcaps.
- The sample storage chamber and bladder chamber were contained within the cylindrical portion but the vapor jacket extended into the hemispherical endcaps. In other words, the sample chamber and bladder chamber were fully surrounded by the vapor jacket.
- Any impact of the heat guarding chamber on the thermal performance and mass was not considered.
- The volume of the bladder chamber, not occupied by the liquid inventory was filled with a fixed amount of NCG.
- The amount of NCG in the bladder chamber was selected such that when the bladder is nearly empty, the NCG pressure will be 10% greater than the vapor pressure within the vapor jacket. This ensures that fluid can always be pumped from the bladder to the vapor jacket.
- The walls were constructed from aluminum.
- The wall thickness was determined by calculating the maximum stress of the outer wall, based on the vapor pressure at the setpoint temperature and a factor of safety of 8.
- 2kg of mass were added to account for various additional features such as valves, tubing and additional structural support.

Table 5 lists the chamber diameters, height of the cylindrical section and the wall thickness used in the mass calculations.

Table 5. Various geometric parameters and other relevant quantities used in the mass calculation of hypothetical vapor-venting thermal management system structure. The heat guarding chamber was excluded from this analysis.

Material	Aluminum
Shape of VVTMS	Cylindrical with hemispherical end caps
Sample Chamber Outer Radius	50.8 mm (2.0 in.)
Bladder Chamber Outer Radius	101.6 mm (4.0 in.)
Vapor Jacket Outer Radius	127 mm (5.0 in.)
Chamber Wall Thickness	0.508 mm (0.02 in.)
Height of Cylindrical Section	203.2 mm (8.0 in.)
Total Height of VVTMS (Cylindrical + Hemispherical Endcaps)	330.2 mm (13.0 in.)
Miscellaneous Mass (Valves, tubing…)	2 kg

Based on the above assumptions and parameters in Table 5, the total mass of the hypothetical VVTMS, including working fluid, designed for a setpoint of 115K was estimated to be 3.78kg. The total mass of the VVTMS is 34.4% less than mass of the PCM alone (5.76 kg). When accounting for the structural mass of the PCM-based system this preliminary analysis indicates that the VVTMS can provide a mass saving of over 50%. The VVTMS design also has potential for optimization and further mass reduction.

If the VVTMS was designed for a setpoint of 125K the total mass would increase to 4.76 kg, a 26% increase compared to the setpoint of 115K. At the higher setpoint temperature, the primary contributor to the increase in mass was thicker walls required to contain the higher vapor pressure.

V. Conclusion

Under a Phase I SBIR program, ACT successfully developed a Vapor-Venting Thermal Management System that can provide temperature control of samples during sample return missions. The system is capable of operating during all phases of the mission (transit, reentry and recovery on the ground) and provides several advantages compared to traditional solid-to-liquid PCM systems.

- Lightweight due to high latent heat of vaporization of working fluids.
- Broadly applicable to many mission scenarios and setpoint temperature.

A proof-of-concept prototype was fabricated and tested within a bell jar to provide control over the environmental conditions. Testing successfully demonstrated:

- Successful control over the vapor venting and liquid charging to maintain a constant setpoint temperature.
- The system's ability to maintain the setpoint temperature for extended periods of time until the entire working fluid inventory is utilized.
- The ability of the system to maintain the setpoint temperature despite changes in the environmental conditions and heat loads.

Finally, a preliminary investigation into a design for cryogenic comet sample return missions indicates a significant potential for mass savings compared to traditional solid-to-liquid PCMs.

Acknowledgments

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