MSL/CheMin Cryocooler System Requirements and Characterization Tests

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ABSTRACT

The Chemistry Mineralogy (CheMin) instrument is being built for use on the Mars Science Laboratory (MSL) to make precision measurements of mineral constituents of Mars rocks and soil. The instrument uses a commercially available Ricor K508 Stirling cycle cryocooler to cool a CCD to 173K to make X-ray diffraction spectroscopy measurements.

The Mars surface environment provides a unique and challenging thermal environment for the instrument and the cooler. The primary atmospheric constituent is carbon dioxide, which adds a conductive/convective load on the cooler, and which will freeze out on the cooler and detector if operating too cold. The MSL rover provides a thermal surround for the payload instruments that maintains the thermal environment between -40^{o}C and +50^{o}C. The CheMin instrument will operate during the Mars evening when the ambient temperatures are minimum; and for a limited number of hours each evening due to the energy limits on the science instruments. The cooler therefore will be subjected to many power cycles during the mission.

The Ricor K508 cooler has been flown on several space flight missions in the past, however the present CheMin version of the cooler drive electronics has not. CheMin plans to fly the cooler and its electronics as built; it therefore requires ample testing of the cooler to verify the robustness of the mechanical cooler and the electronics.

This paper presents the CheMin instrument cryogenic configuration and the extensive cryocooler characterization and qualification test program to validate the cooler capability to satisfy the instrument and MSL reliability requirements.

INTRODUCTION

The objective of the Chemistry and Mineralogy (CheMin) X-ray diffraction instrument is to investigate the chemical and mineralogical composition of rocks, sediments and soils of the Martian surface to assess the involvement of water in their formation, deposition or alteration, and to search for potential mineral biosignatures, energy sources for life or indicators of past habitable environments. It is part of an analytical suite of instruments that will be integrated in to the Mars Science Laboratory (MSL) rover that will be launched in 2009 and operated on Mars for a period of 670 sols, or one Mars year, to explore and quantitatively assess the geology and geochemistry of the regions visited by MSL as potential habitat for life, past or present. Figure 1

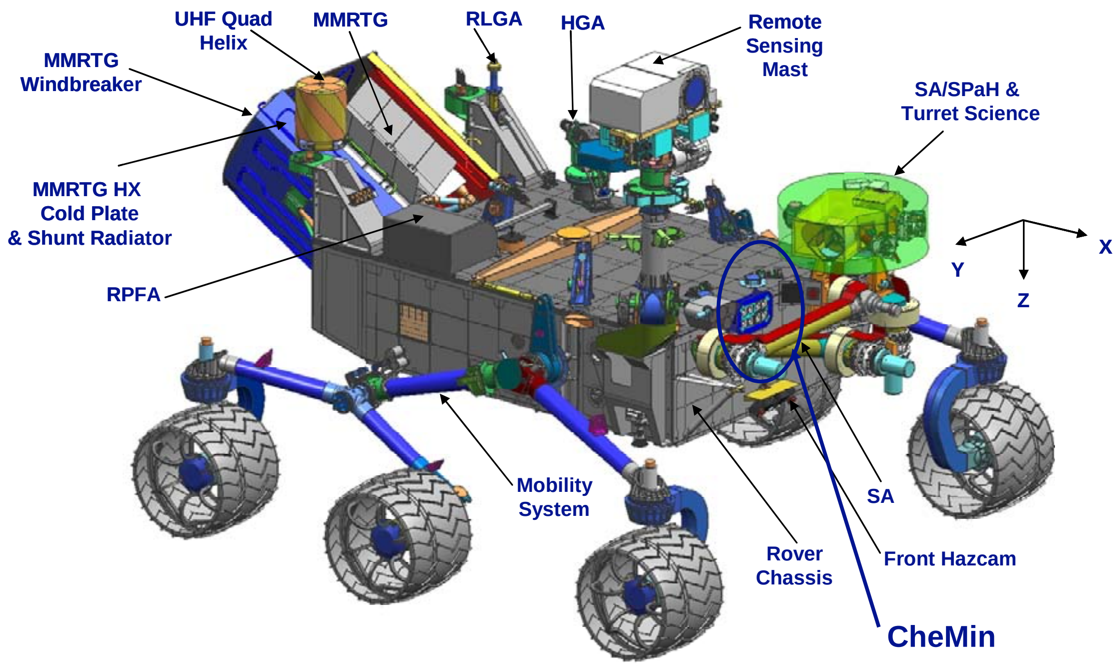

Figure 1. The Mars Science Laboratory rover.

shows the layout of the MSL rover and the location of the CheMin instrument and highlights the key rover assemblies and several of the payload instruments.

The CheMin instrument determines the mineralogy and elemental composition of crushed or powdered samples through the combined application of x-ray diffraction (mineral structure analysis) and energy dispersive histogram spectra (chemical analysis). In operation, a collimated X-ray beam from an X-ray source is directed through crushed and powdered sample material. An X-ray sensitive CCD imager is positioned on the opposite side of the sample from the source and directly detects X-rays diffracted by the sample. The cooled CCD has the ability to measure both location and energy of each X-ray photon it detects. The CCD is cooled to -60^{o}C or colder by a Ricor K508 Stirling cryocooler.

MSL ROVER ENVIRONMENTS

The Mars Science Laboratory will be operating in a hostile Mars environment where surface temperatures can range between -130^{o}C and +50^{o}C. The thin Mars atmosphere is primarily CO_2 that has seasonal variations ranging from 2-12 torr, and where wild storms with sustaining winds as high as 15 m/s can last for months and produce a wind chill to lower the rover internal temperature by another 30^{o}C. The Mars gravitational pull is 3.72 m/s^2, approximately 0.38 times that of earth's gravity.

Fortunately, the CheMin Instrument is nestled within the MSL rover where its temperature is controlled by the MSL Rover Avionics Mounting Plate (RAMP) during the course of the Mars mission. The RAMP uses a mechanically pumped single phase fluid loop to extract waste heat from the RTGs, and then serpentine throughout the RAMP to provide the temperature control for the payload instruments within the rover. The RAMP will limit the CheMin diurnal temperature variations to 30^{o}C. During the winter, the diurnal temperature variation will be -40^{o}C to -10^{o}C, and in the summertime from +20^{o}C to +50^{o}C. These temperature extremes will vary depending on the final landing location selected. The primary operating period for CheMin is during the Martian night when the RAMP will maintain the CheMin instrument temperature to between -40^{o}C and +20^{o}C, however the cooler will be turned on during ATLO, the cruise phase, and potentially during the Martian daytime when the ambient temperature may be +50^{o}C.

The predominant constituent of the Martian atmosphere is CO_2 (CO_2 is 95.5% mass fraction - 0.955 mole fraction). The absolute amount of CO_2, however, is very small. (the seasonal

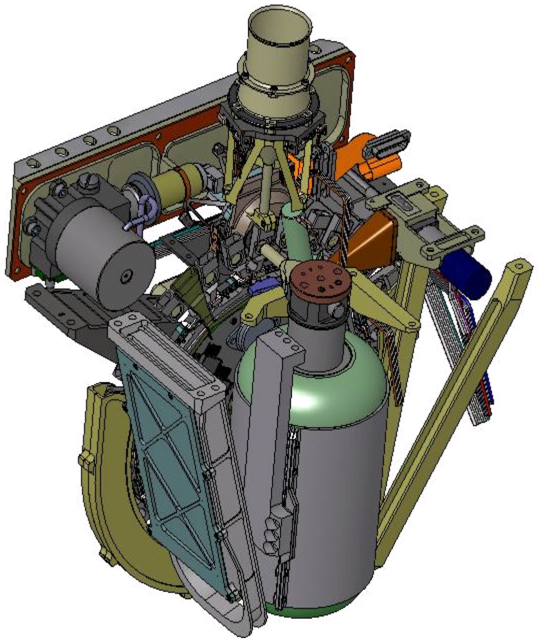

Figure 2. CheMin Instrument, shown here without its external housing.

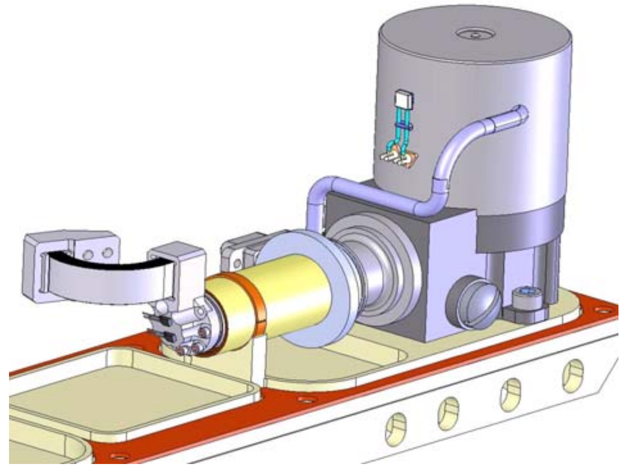

Figure 3. Cryocooler assembly mounted to the side plate of the instrument.

variations range from a of low 2 Torr to a high of 12 Torr, with an average of 8 Torr. The CO_2 is subject to frosting/sublimation at the lower Mars ambient temperatures. As the Martian atmosphere goes through the daily (diurnal) temperature cycle, a phase change of the CO2 gas can occur, depending on the season and the latitude of the location. This phase change will be from gas to solid directly and vice versa (i.e., a frosting/sublimation process).

There is also a small fraction of water vapor in the Mars atmosphere. An average column density of atmospheric water vapor on Martian surface is 6 ± 4 precipitated microns (pr μm), corresponding to a density of about $4x10^{-6}$ kg/m^3 and a pressure of about 0.00415 Torr at 300K[1]. This implies that the water will freeze out below 205 K (-68°C). Depending on the MSL landing site and seasonal cycle, the water vapor pressure can climb above 0.02 Torr.

CHEMIN THERMAL CONFIGURATION

Description of CheMin Instrument. The CheMin instrument is bolted directly to the MSL RAMP and is conductively cooled. The cryocooler is mounted on an aluminum side plate of the CheMin instrument that also bolts directly to the RAMP to help minimize the temperature gradient to the operating cooler. The CCD is mounted onto CE-7, a light-weight, silicon/aluminum composite material having relatively high thermal conductance and low thermal expansion properties. The CCD mounting structure is thermally isolated from the CheMin alignment bench using a titanium bipod support structure. The CCD is conductively cooled by the cooler through a flexible aluminum foil thermal strap. The CCD operating temperature will be selectable to either -60°C (213 K) or -100°C (173 K) by the cooler drive electronics. The temperature stability requirement for the CCD is 5°C/30 minutes during science operations.

CheMin operating scenario: CheMin has been given an energy allocation of 250W-hr per evening analysis period, and it will be the only instrument operating during this period. With a peak analysis power usage of 46 watts during science operations, CheMin is limited to approximately 4 hours of analysis per evening of operation, with the remaining energy allocated for pre-analysis warm-up of the X-ray source, and post analysis data processing and transfer. The cooldown period for the cooler is expected to take approximately one hour to get the CCD to stabilize at -60°C, leaving three hours of operation per night for the X-ray analysis with the cold

Figure 4. Ricor K508 cooler.

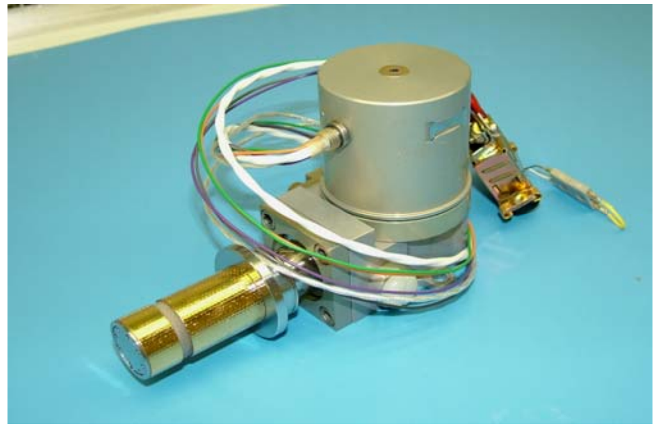

Figure 5. Coldfinger bumper attached to cooler.

CCD. The complete analysis of any one sample can take up to 10 hours, thus requiring multiple evenings to analyze a sample. There is an expected UHF pass each evening during the analysis period for which the cryocooler may need to be powered off for a short period. Thus the cryocooler is assumed to be power cycled twice during each evening of analysis.

CheMin Cryocooler. CheMin selected the Ricor K508 rotary Stirling cryocooler (see Fig. 2) to cool the CCD based on its small size, relatively high refrigeration capacity and its past flight experience. CheMin will use the Ricor Hybrid 18 electronics to drive the cooler, and will be powered with a regulated 15 Vdc input (1.1 A max) from a DC-DC converter. The cooler has been charged with 40 bar helium to produce a 1.8 W @ 163 K refrigeration capacity to cool the CCD, ensuring adequate performance margin over the anticipated thermal load. The CCD operating temperature will be selectable to either -60°C or -100°C using the Ricor electronics. The coldfinger coldtip flange provides the mechanical interface with the flexible thermal strap that provides the cooling for the CCD. A G-10 glass epoxy bumper tube (see Fig. 3) has been incorporated into the cooler coldfinger design to limit the coldtip deflection to 25 µm.

The thermal load on the cooler is predominantly parasitics, with the primary contribution due to the gaseous conduction/convection with the CO_2 atmosphere. The active load from the CCD is small (~28mW). The anticipated load on the cooler is 1.1 W for the CCD operating at -60°C, and 1.5 W when the CCD is operating at -100°C. The combined thermal resistance of the thermal strap, the CE-7 CCD support structure and all interfaces is 12.3°C/W, requiring the cooler to operate 13K-18K colder than the desired CCD temperature.

Operational requirements for the CheMin cooler have been summarized in Table 1. The cooler is expected to operate for 1600 hours on Mars over a period of 1 Mars year (2 earth years). During this time the cooler will experience ~700 diurnal temperature cycles of 30°C and be power cycled 480 times. Prior to launch the cooler will be subjected to an estimated 500 additional hours of operation and 100 power cycles.

CRYOCOOLER TEST PLAN

The cryocooler test plan included a comprehensive thermal characterization of six coolers over a range of heat sink temperatures, coldtip temperatures and applied thermal loads; the conduct of qualification-level dynamics and thermal tests on a dedicated qualification model cooler; and the long term endurance testing of two coolers. From the characterization tests a

Table 1. Operational requirements for the CheMin cryocooler.

	Mission	**Pre-launch testing**	**Total**
Operating hours	1600	500	2100
Power cycles	480	100	580
Diurnal thermal cycles of 30°C	670	10	680

Table 2. Ambient temperature requirements for the CheMin cooler.

Allowable Flight Temperature, °C Science		Allowable Flight Temperature, °C Functional		Flight Acceptance (AFT -5/+5), °C		Qualification/Protoflight (AFT -15/+20), °C	
Non-Op	Op	Non-Op	Op	Non-Op	Op	Non-Op	Op
-40/+50	-38/+33*	-40/+50	-38/+57*	-45/+55	-43/+62*	-55/+70	-53†/+77*

* Mission operating temperature AFTs were constrained to +20°C RAMP temperature, but not until after the cooler characterization testing had been completed.

† Temperature requirement is lower than Ricor's in-house qualification temperature of -45°C. The qualification cold temperature will be limited to -45°C.

flight and flight spare cooler would be selected, with other coolers being indentified as the EM instrument cooler, the qualification unit, and the two life test coolers. Six additional K508 coolers were purchased on a separate purchase order and had been expected to be included in the original test plan, but the late procurement cycle kept them from being part of the selection process.

Table 2 shows the flight allowable temperature range for the CheMin cryocooler and the required acceptance and qualification test temperatures. The thermal performance characterization of the cryocoolers was conducted over the heat sink temperature range of -40°C and +57°C to encompass the Allowable Flight Temperatures (AFT). The cryocoolers were also subjected to Flight Acceptance (FA)-level testing between -43°C and +62°C per the CheMin design requirements and the MSL environmental test requirements as part of the screening and ranking of the coolers. The qualification cold operating temperature extreme of -53°C was not attempted since Ricor had not qualified the K508 cryocooler to less than -45°C; the Ricor temperature limit became the CheMin qualification low temperature limit as well.

Thermal Characterization

Thermal Performance Load Lines. The cryocoolers were first placed into a thermal vacuum chamber to measure and compare their thermal performance. The heat sink plate accommodated two coolers. The plate included an aluminum wall which isolated the two coolers, and an aluminum lid to provide an isothermal environment for the coolers. Finally the entire heat sink box was wrapped with MLI blankets to maintain an isothermal ambient temperature for the coolers. The coolers were tested in vacuum only, and not in a CO_2 environment such as will be experienced on Mars, to simplify performance comparison. The CO_2 gaseous convection/conduction is simply a contribution to the overall thermal load, and is very dependent on the geometry of the cryogenically cooled hardware. The flight cryogenic subassembly hardware was not available for these characterization tests.

Six-gram copper heater blocks were directly attached to the coldtip flange of the coolers, using indium foil at the coldtip/heater block interface to ensure good thermal conductance. The heater block contained a 1000-ohm resistive heater, redundant diode temperature readout sensors and an additional diode temperature sensor for the voltage feedback to the cooler's PI temperature control loop.

Extensive thermal characterization testing of the cryocoolers was conducted according to the conditions shown in Table 3. Four different load lines were produced at each of the three heat sink temperatures. The open loop mode allowed the cooler to operate at its maximum drive frequency and input power to yield the maximum cooling capacity of the cooler as a function of coldtip temperature. The three closed loop control isotherms provided load lines showing the sensitivity of the input power as a function of applied thermal load at the three coldtip temperatures. The cooler coldtip temperatures were biased 15°C colder in these tests than the planned CCD operating temperature to compensate for the thermal impedance of the flex strap and CCD mounting structure. The cooler characterization testing attempted to include a wide range of operating temperatures to ensure that test results would cover the desired operating temperature of the flight CCDs, which had not completed fabrication and performance testing.

Table 3. The various test conditions for the cryocooler thermal characterization.

Heat Sink Temperatures, Celcius	Operating Mode	Coldtip Temperature, kelvin (Celcius)	Applied Thermal Load, Watts
+57, +20, -40	Open Loop	Variable	0.5 to 2.4
	Closed Loop	158 (-115)	
	Closed Loop	173 (-100)	
	Closed Loop	193 (-80)	
Variable, -43 to +62	Closed Loop	173 (-100)	1.5
+62	8-hour non-op soak	N/A	N/A
-45	8-hour non-op soak	N/A	N/A
+62	50-hour dwell	173 (-100)	1.5
-43	24-hour dwell	173 (-100)	1.5

The measured cooler set point temperature stability as a function of applied thermal load for the coolers was nominally 130 mK per watt, well within the required stability of 5°C/30minutes for the CCD. At the near maximum load for an isotherm, the cooler's PI controller would have a hard time maintaining closed loop control stability, but the resulting temperature oscillation would never vary more than 0.5°C_{p-p} (while the input power oscillated by 1 watt or less).

Figures 6 and 7 show the input power and input current sensitivity as a function of heat sink temperature and applied load for the one of the coolers (S/N 34548). For all coolers, the maximum input power and input current for 158 K operation was below the limit of 12.2 W and 1.1 A. The thermal performance results from the six coolers showed that they were quite well matched. Thermal performance comparisons for the six coolers operating in open loop mode are shown in Figs.8-10 for the three heat sink temperatures. All coolers were able to provide the 1.8 W at 163 K at the nominal 20°C reject temperature.

Flight Acceptance Tests. Each of the coolers was operated continuously in closed loop control mode at a coldtip temperature of 158 K and with a constant applied load of 1.5 W while the reject temperature was varied slowly (2°C/min) over the Flight Acceptance (FA) temperature range of -43°C to +62°C to determine the coldtip stability over the wide temperature span and to monitor for helium leaks from the coolers. Among the six coolers, the coldtip temperature stability varied between 1.1 K and 1.86 K over the 105°C sink temperature variation. While trying to maintain the 158-K coldtip temperature during the heat sink temperature variation, the input power to the compressor would vary by as much as 3.5 W, which represents as much as a 50% variation in input power. Each of the six coolers was then subjected to FA-level duration tests at the FA temperatures of -43°C (24 hours cold) and +62°C (50 hours hot), plus additional

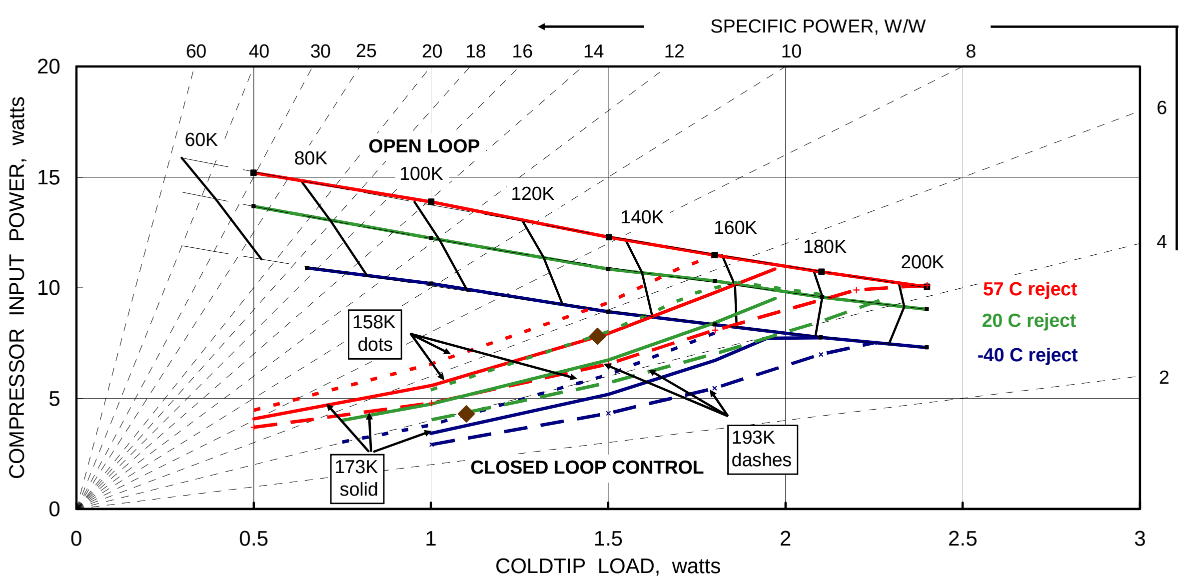

Figure 6. Input power sensitivity for Cooler S/N 34548 as a function of heat sink temperature and applied load.

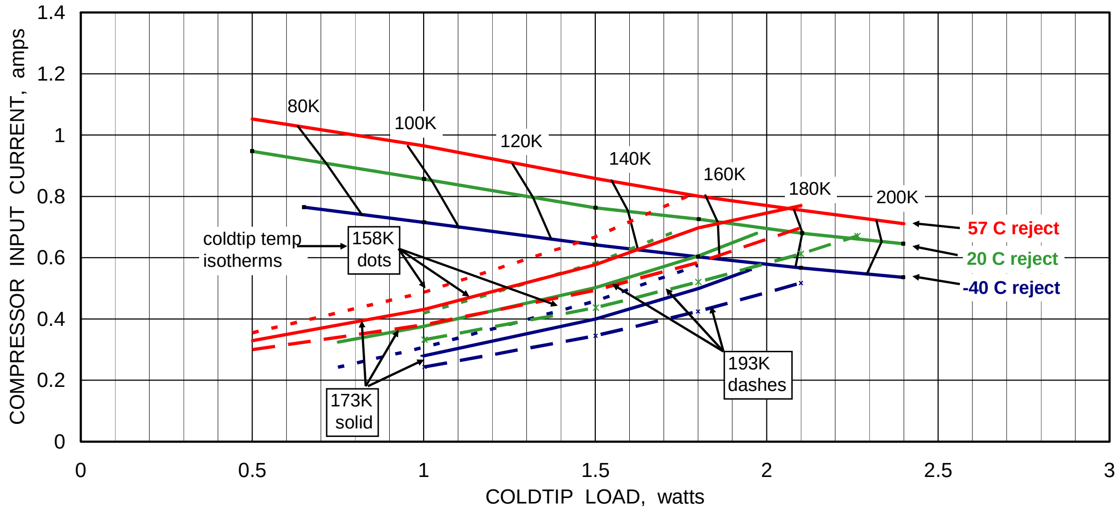

Figure 7. Input current sensitivity for cooler S/N 34548 as a function of applied load and heat sink temperature.

8-hour non-operational exposures at -45°C and +62°C.

Helium leak tests were performed on each operating cooler during the variable heat sink test between -45°C and +62°C. Only one of the six coolers showed a detectable leak, which was observed when the ambient temperature dropped below ~12°C, with the leak rate increasing with decreasing temperature. As the ambient temperature was raised, the cooler the leak again diminished, and became undetectable for ambient temperatures above ~-10°C and up to +62°C. This cooler was eliminated from flight, life test or qualification consideration. Additional helium leak tests performed have shown no indications of helium leaks between -55°C and +77°C with the EQM cooler, and no indications of leaks with the two life test coolers after more than 30 thermal cycles to -40°C.

Qualification thermal tests. Qualification level dynamics and thermal tests then followed using the cooler selected as the Qualification Model cooler. Following random vibration testing, cooler was subjected to the qualification thermal-vacuum tests. The thermal test calls for three thermal cycles between the hot and cold temperature extremes, with functional tests at each extreme. The third thermal cycle includes the long duration soaks with the operating cooler: 144 hours at the hot extreme, followed by 24 hours at the cold extreme.

The first two thermal cycles were carried out between the heat sink temperature extremes of 73°C and -48°C (corresponding to +77°C and -45°C compressor body temperatures). Functional tests at each extreme included a hot (or cold) power cycle and a 3-point load line (1W, 1.25W

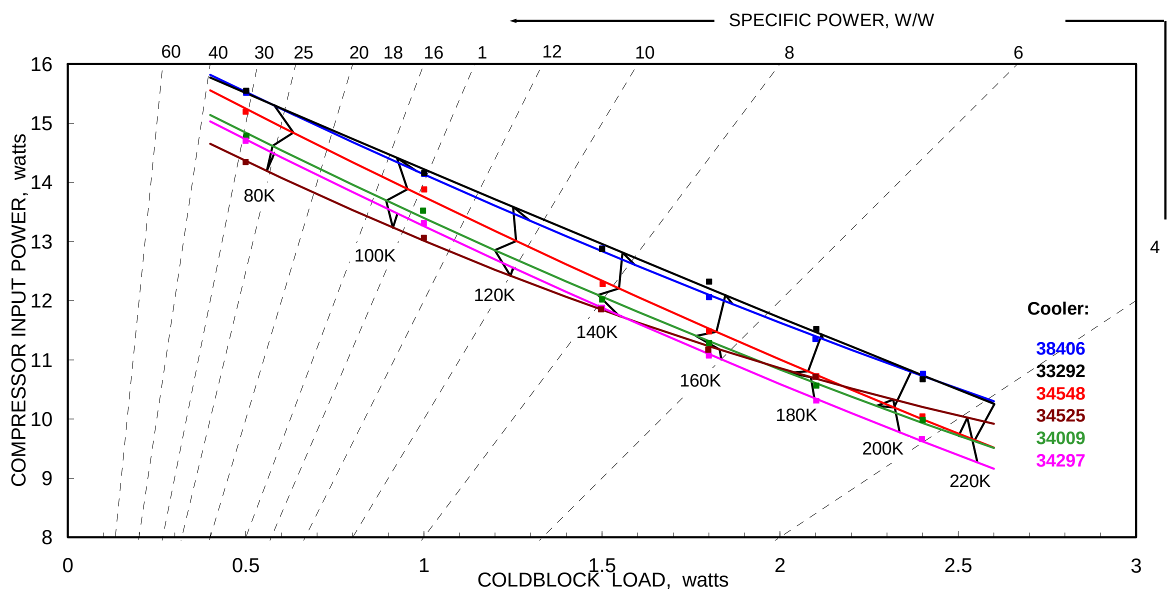

Figure 8. Comparison of the thermal performance at 57°C for the 6 cryocoolers operating in open loop.

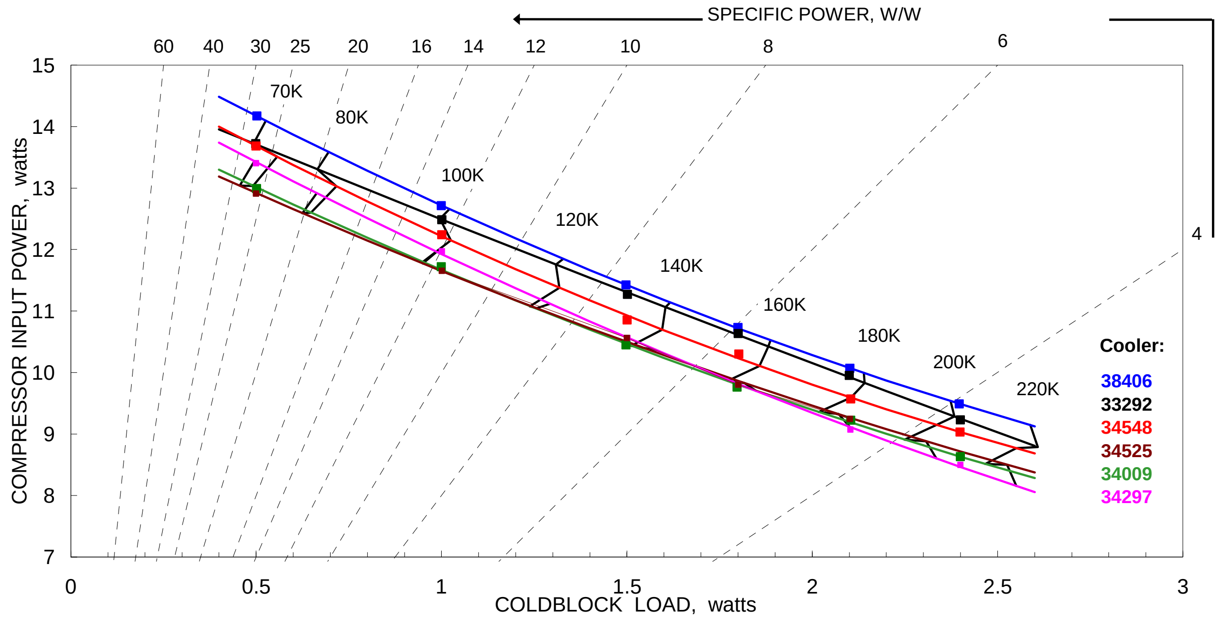

Figure 9. Comparison of the thermal performance at 20°C for the 6 cryocoolers operating in open loop.

and 1.5W) at the coldtip set point temperature of 158 K. Eight hour soaks at +77°C and -55°C while the cooler was not powered were included with the first thermal cycle.

At the hot extreme the compressor body was held at +77°C, a thermocouple mounted to the side of the motor housing indicated the housing temperature had reached +91°C. The cooler drive electronics located within the motor housing would be operating at an even higher temperature, but there was no way to monitor the temperature. During the 4 hour hot functional tests the cooler exhibited stable operation.

The third thermal cycle was to conduct the long term duration testing of the cooler: 144 hour hot and 24 hour cold with a constant applied coldtip load of 1.25W. Nineteen hours into the hot duration test the cooler electronics became unstable. The cooler could no longer maintain constant coldtip temperature, which in turn caused the cooler input power to oscillate. Reducing the applied load had no effect on the cooler operation so the cooler was shut down and the duration test run was aborted.

A review of the mission operating temperatures revealed that the cooler temperature AFTs had not been revised to reflect the constraint that the CheMin X-ray source would not be operated if the RAMP temperature was above 20°C. This temperature limitation also applies to the cooler since the cooler and x-ray source operate in concert to perform the X-ray analysis.

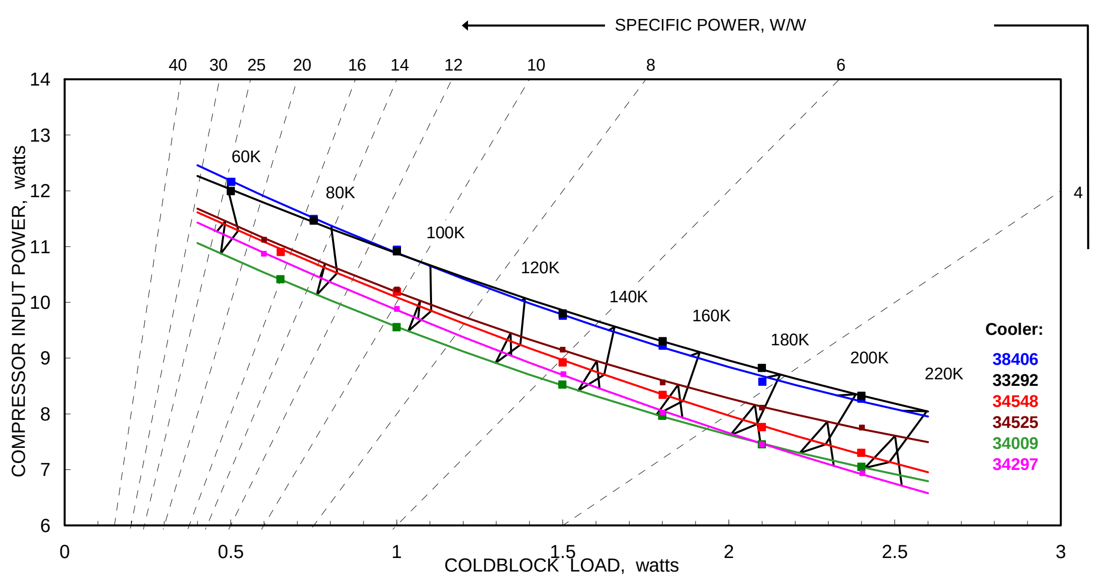

Figure 10. Comparison of the thermal performance at -40°C for the 6 coolers operating in open loop.

Two decisions were made: 1) the cooler qualification hot temperature heat sink would be 40°C, allowing the cooler compressor body to warm a few degrees above this temperature during operation, and 2) the 24 hour cold duration test at -45°C would not be performed since this test was already conducted during the earlier FA level tests on the cooler.

The 144-hour cooler qualification hot duration test at 40°C heat sink proceeded with the cooler applied thermal load of 1.25 W at 158 K. The cooler performed stably with an input power of 7.9 +/- 0.1 W throughout the 144 hour test.

A final post thermal functional test was performed at 20°C, and showed that the cooler performance had remained unchanged throughout the random vibration and qualification thermal tests.

LIFE TEST

Two coolers have been placed into endurance tests over the AFT temperature range of -40°C to +20°C to demonstrate 3X mission operating life (3X 2100 hrs = 6300 hours) plus 3X mission On/Off power cycles (~1740 On/Off power cycles) and more than 1X the thermal cycles (780). The heat sink plate on which the coolers are mounted is vertical so that the coolers are positioned on their sides, representative of the cooler orientation in the rover on Mars.

The cooler heat sink plate is stepped between +20°C, -10°C and -40°C in 5 hour steps, with the coolers powered on and operated for 4 hours at each ambient temperature, and powered off for one hour during the ambient temperature transition period. This power profile enables the coolers to operate for an 80% duty cycle, with 12 complete thermal cycles over a 5 day period that includes 24 power cycles. The cryocoolers are operated with a constant 1.5-watt applied load on the coldfinger during cooldown and under stable operation; this applied thermal load is representative of the anticipated load during the mission when the cooler is cooling the CCD to -100°C. At 20°C the life test coolers take ~15 minutes to cool to 157K with the 1.5-W load (one cooler ~13 minutes, the other cooler takes ~15 minutes). In these life tests the cooldown period during which the coolers are operating at the maximum 70-Hz drive frequency represents only 6% of the operating time of the coolers, where as in flight the cooldown is expected to encompass ~20-25% of the operating time of the cooler.

Cooldown times are compared only at the +20C cooldown using a 15 second data collection rate. To date, there have been no observed changes in the cooldown times for the coolers.

As of June 6, 2008, the coolers have been operated in life test for 1075 hours, with 272 power cycles and 65 thermal cycles of 60°Cp-p, representing roughly 50% of the required 2100 hour operating life of the cooler. This represents roughly 2.24 x 10^8 revolutions on the bearing. The input power and input current measured during each 4-hour operating period of the coolers

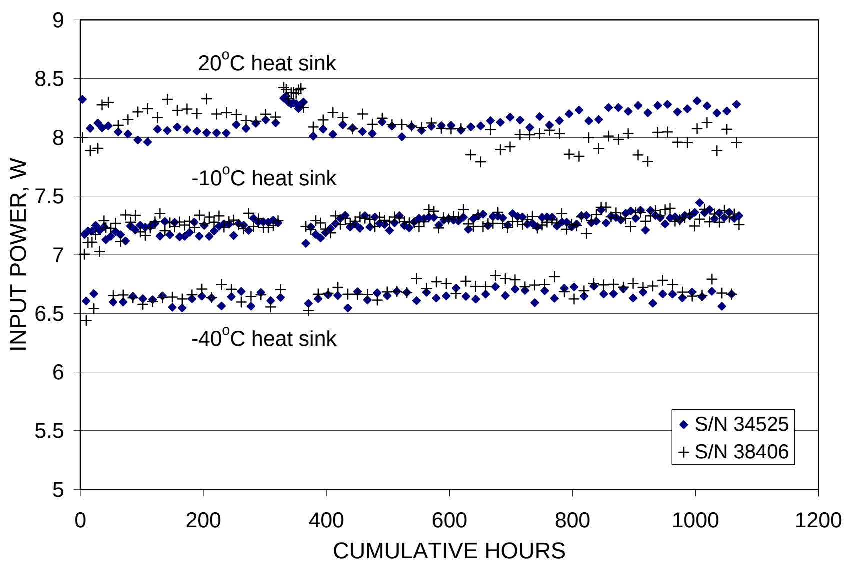

Figure 11. Input power for coolers operating with 1.5W @ 158K applied load at the three heat sink temperatures.

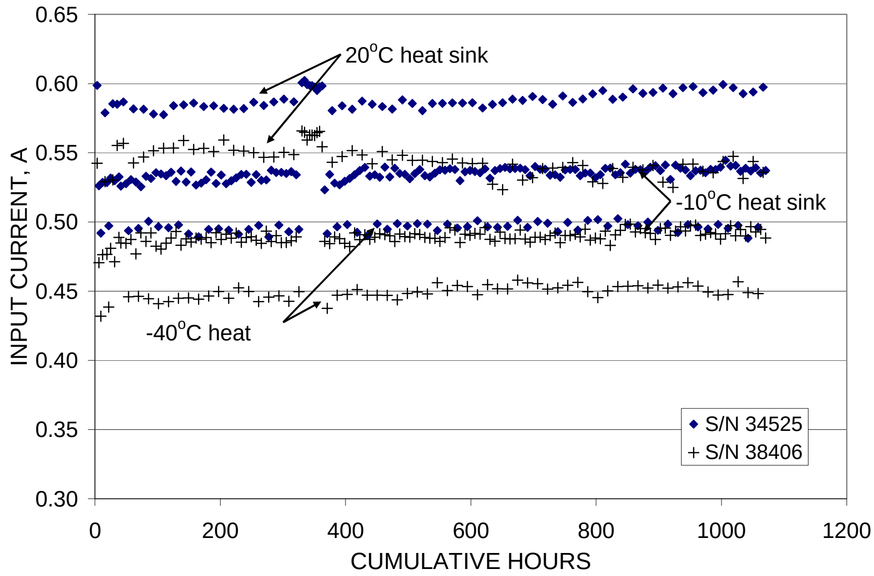

Figure 12. Input current for coolers operating with 1.5W @ 158K applied load at the three heat sink temperatures.

at each of the heat sink temperatures are shown in Figs. 11 and 12. The data show no significant changes in the input power levels to date. The data shown around the 350 hour period was due to operator error when the recirculating refrigerator was operated in "local" mode and maintained in constant temperature set point, instead of being operated in "remote" mode to receive remote commands to change set point temperatures.

SUMMARY

CheMin is one of a suite of instruments on board the Mars Science Laboratory rover that will be conducting chemistry and mineralogy studies on Mars. The Chemin instrument will use the Ricor K508 cooler, with the Hybrid 18 drive electronics, to cool the CheMin CCD. The cooler was selected for its small volume and mass, high cooling capacity, low cost, previous flight history and the fact that no other cooler of its size had any flight heritage (mechanical cooler). CheMin has conducted a comprehensive test program to qualify the cooler for the MSL mission. The coolers have been subjected to lengthy characterization tests, including FA level thermal tests; the qualification model cooler has been subjected to qualification level random vibration and qualification level thermal tests; and two coolers are presently undergoing life testing.

ACKNOWLEGEMENTS

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