The Ricor K508 Cryocooler Operational Experience on Mars

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Abstract. The Mars Science Laboratory (Curiosity) landed successfully on Mars on August 5, 2012, eight months after launch. The chosen landing site of Gale Crater, located at 4.5 degrees south latitude, 137.4 degrees east longitude, has provided a much more benign environment than was originally planned for during the critical design and integration phases of the MSL Project when all possible landing sites were still being considered. The expected near-surface atmospheric temperatures at the Gale Crater landing site during Curiosity's primary mission (1 Martian year or 687 Earth days) are from -90^{o}C to 0^{o}C. However, enclosed within Curiosity's thermal control fluid loops the Chemistry and Mineralogy (CheMin) instrument is maintained at approximately +20^{o}C. The CheMin instrument uses X-ray diffraction spectroscopy to make precise measurements of mineral constituents of Mars rocks and soil. The instrument incorporated the commercially available Ricor K508 Stirling cycle cryocooler to cool the CCD detector.

After several months of brushing itself off, stretching and testing out its subsystems, Curiosity began the exploration of the Mars surface in October 2012. The CheMin instrument on the Mars Science Laboratory (MSL) received its first soil sample from Curiosity on October 24, and successfully analyzed its first soil sample.

After a brief review of the rigorous Ricor K508 cooler qualification tests and life tests based on the original MSL environmental requirements this paper presents final pre-launch I&T instrument testing, and details the operational data of the CheMin cryocooler, providing a snapshot of the resulting CheMin instrument analytical data.

Keywords: Ricor K508, Stirling cooler, CheMin, X-Ray Diffraction, X-Ray Fluorescence
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INTRODUCTION

The Chemistry and Mineralogy (CheMin) X-ray diffraction instrument is one of an analytical suite of ten science instruments that were integrated in the Mars Science Laboratory (MSL) rover (see FIGURE 1) that landed on Mars on August 6, 2013 (Universal Time). The 900 kg MSL rover, named Curiosity, is scheduled to operate 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 a potential habitat for life, past or present. The objective of the CheMin instrument is to investigate the chemical and mineralogical composition of rocks, sediments and soil 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.

The CheMin instrument determines the mineralogy and elemental composition of fine-grained 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 a Cobalt-anode X-ray source is directed through the sample material. A piezoelectric actuator on the sample holder vigorously agitates the sample to ensure that grains in the sample are analyzed in random orientations over time. An X-ray sensitive CCD imager is positioned on the opposite side of the sample from the source and directly detects the 2-dimensional distribution of both fluoresced and diffracted X-rays from the sample. The cooled CCD has the ability to measure both location and energy of each X-ray photon it detects, providing both mineralogy (X-ray diffraction) and chemical (X-ray fluorescence) information, but the CCD performance is strongly dependent on its operating temperature. The CCD is cooled to about -50^{o}C by a Ricor K508 Stirling cryocooler during nighttime operation of the CheMin instrument.

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MARS ROVER ENVIRONMENTS

The Gale Crater landing site is located at 4.5 degrees south latitude, 137.4 degrees east longitude, at the foot of a layered mountain inside Gale Crater. Gale Crater was chosen as the landing site for Curiosity because of the many signs that water was present over the course of its history. Layering of sediments that contain clays and sulfate minerals deposits in Mount Sharp, which lies in the center of the crater, is suggestive that they were formed in water under a range of conditions.

Gale Crater also happens to have the mildest average climate of all the landing sites considered for Curiosity. The expected near-surface atmospheric temperatures at the Gale Crater landing site during Curiosity's primary mission (1 Martian year or 687 Earth days) vary diurnally from -90^{o}C to 0^{o}C. FIGURE 2 shows the measured surface and air temperatures as measured by Curiosity over the course of one Mars day. The MSL Rover Avionics Mounting Plate (RAMP), on which most of the payload instruments are mounted, has its temperature maintained using a mechanically pumped single phase fluid loop that extracts heat from the rover's RTG power source. The fluid loop serpentines throughout the RAMP and provides thermal control for the payload instruments. As a result, the CheMin diurnal temperature varies by no more than 20^{o}C (winter) to 40^{o}C (summer) throughout the Mars year. The primary operating period for CheMin is during the nighttime when the RAMP temperatures are the coolest. FIGURE 3 shows the predicted RAMP temperatures over the course of the Mars year, and assumes the horizontal top deck has 40% dust coverage. Conservative rover thermal designs have kept the RAMP temperatures above 0^{o}C. Measured temperatures at the RAMP interface to the CheMin instrument validate the RAMP thermal model predictions (FIGURE 4).

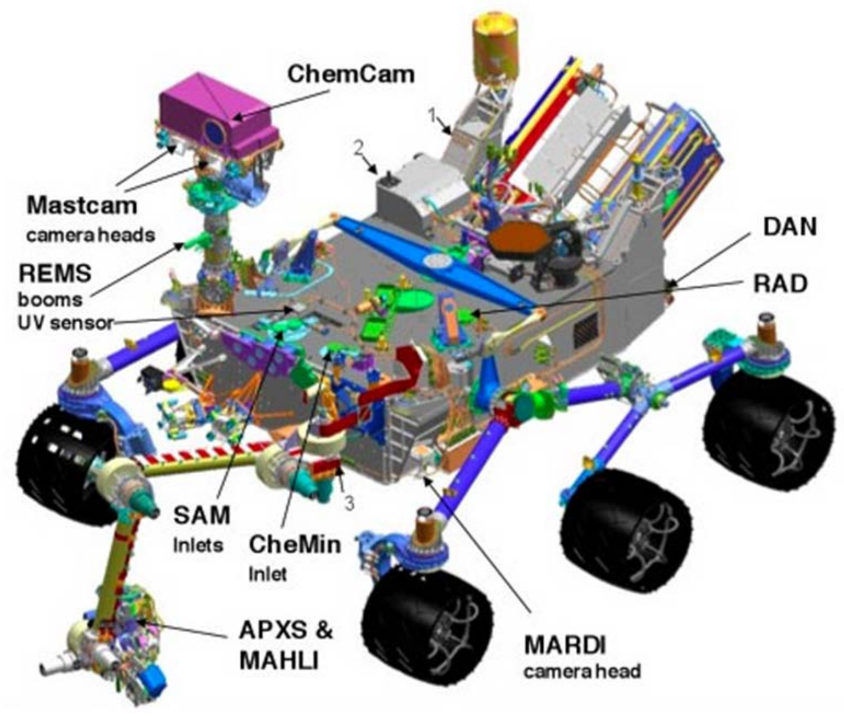

FIGURE 1. The Mars Science Laboratory. The CheMin Instrument is within the rover body at the front. Just the inlet for the soil samples, with its cover plate, is exposed at the top of the rover deck.

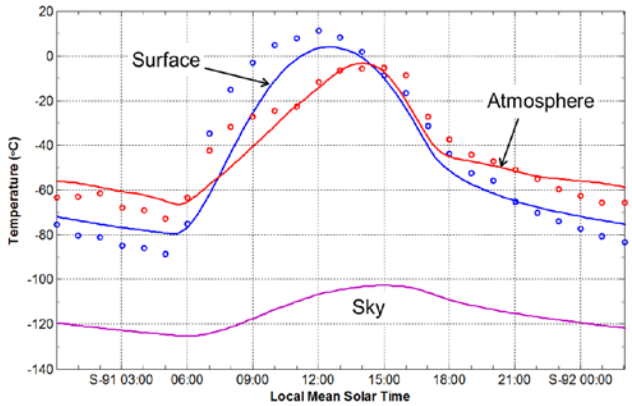

FIGURE 2. The predicted (solid curves) and measured (dots) Mars surface, atmosphere and sky temperatures during Sol 91.

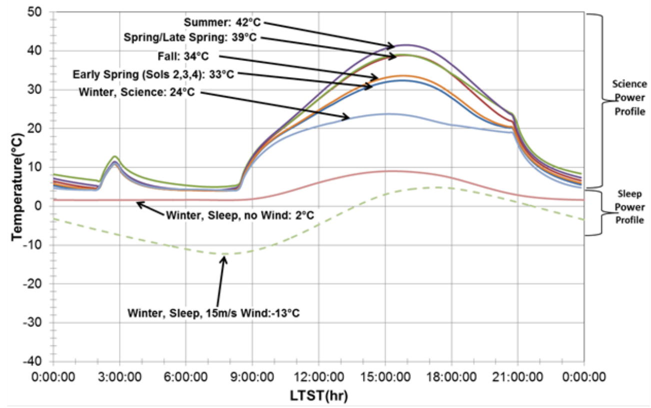

FIGURE 3. Predicted diurnal RAMP temperature at Gale Crater for all seasons.

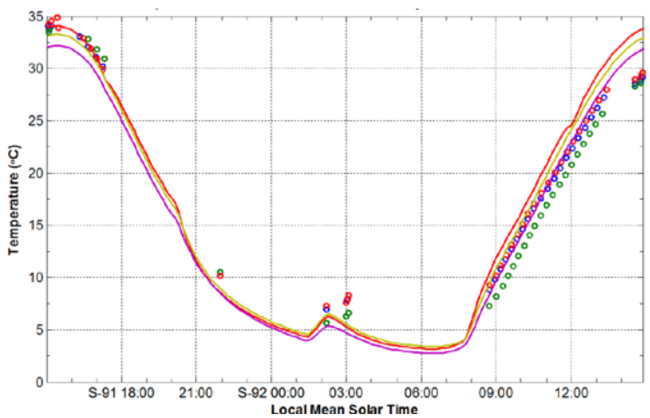

FIGURE 4. The RAMP/CheMin interface temperature predictions (solid curves) and telemetry (dots) from Sol 91 to Sol 92.

FIGURE 5. The CheMin K508 cooler with a G-10 coldfinger bumper tube attached.

CHEMIN CRYOCOOLER

The Ricor K508 rotary Stirling cryocooler (FIGURE 5) was selected to cool the CheMin CCD based on its small size, relatively high refrigeration capacity and its past flight experience. The CheMin cooler uses standard Ricor Hybrid 18 electronics to drive the cooler, and is powered with a regulated 15 Vdc input (1.1 A max) from a DC-DC converter. Temperature control of the cooler is based on feedback from a Lakeshore diode located at the coldtip. The cooler was required to cool the CCD to -100^{o}C (173K). Based on results of the pre-launch I&T testing, the CCD operating temperature was made selectable to either -60^{o}C (213 K) or -100^{o}C (173 K) using the Ricor electronics. The cooler was charged with 40 bar helium to provide the maximum possible refrigeration capacity to cool the CCD. A G-10 glass epoxy bumper tube was bonded to the inside of the KF flange at the base of the coldfinger and extended out to the coldtip flange. The gap at the coldtip between the coldtip flange and the bumper tube was less than 25 microns to ensure the coldfinger deflection did not exceed the gap dimension during launch. The coldfinger coldtip flange provides the mechanical interface with the flexible aluminum foil thermal strap that provides the cooling for the CCD.

The CCD is mounted in a thermally conductive CE-7 housing with a CE-7 cold finger protrusion to which the aluminum thermal strap attaches. The CCD and its housing are structurally supported off the CheMin instrument wall using a thin titanium bipod structure to provide thermal isolation.

There is no provision on the flight instrument for a temperature sensor on the cooler coldtip to provide engineering information. Temperature sensors on the CCD and the RAMP interface were used to give an indication of how well the cooler was operating. Comparison of the CCD operating temperature to the cryocooler characterization test data [1] indicated the thermal load on the cooler is on the order of 2.6W. The thermal load on the cooler is predominantly parasitic, with the primary contribution due to gaseous conduction/convection with the CO_2 atmosphere. The active load from the CCD is quite small (~23mW). The G-10 bumper tube contributed an approximate 150-mW thermal load due to convective losses in the gas at the coldtip. The thermal loads proved much higher than originally estimated, with the bulk of the load (2.2W) due to the CO_2 conductive/convective parasitic losses on the CCD. The high heat load limits the CCD operating temperature to roughly 60^{o}C below the ambient RAMP temperature.

Cooler operational requirements

In initial planning, the cooler was originally required to cool the CCD to -100^{o}C (173K) over a -40^{o}C to +20^{o}C heat reject temperature range, but upon further CCD investigation it was determined that a CCD operating temperature of -60^{o}C would suffice. During the course of the 1 Mars year (2 Earth years) Mars mission the CheMin cooler is expected to operate for 1600 hours. During this time the cooler will experience ~700 diurnal temperature cycles of 30^{o}C and be power cycled 480 times. Prior to launch the cooler was subjected to 500 additional hours of operation and 100 power cycles during characterization testing and instrument and spacecraft level I&T testing.

Cooler Life Test

Two Ricor K508 coolers were put on life test to demonstrate a 3X life over the operational requirements set forth for the coolers. These coolers had first gone through the characterization testing of approximately 150 hours, each. The life test consisted of stepping through heat reject temperatures of -10^{o}C, +20^{o}C, -10^{o}C, -40^{o}C, -10^{o}C, in 5 hour steps, where the cooler was powered on at each temperature and operated for 4 hours with an applied load of 1.5 W, followed by a power-off and a 1 hour non-operating temperature transition to the next reject temperature level. Over the course of the life test the first cooler experienced a mechanical failure after 3200 hours of operation and 800 power cycles. The second life test cooler showed no apparent degradation in thermal performance after 4500 hours of operation and 1134 power cycles when the life test was stopped. A helium leak test after the life test ended did show the second cooler would leak gas when the reject temperature was reduced below -10^{o}C. It should be noted that the life test reject temperature limits were imposed, and the cooler life tests conducted, before the final selection of the landing spot for Curiosity was made, such that all potential landing site environments would be covered.

THERMAL MODEL

The CheMin system level thermal model developed by ATK (Pasadena, CA) was used to support design activities and demonstrate requirements compliance. All instrument subsystems were represented in this model including the cryocooler/detector, X-ray source, alignment bench, electronics, sample wheel and the sample loading chimney. Three separate models were developed to model the Mars surface operational, hot functional, and cruise phases of the mission. The thermal scenarios included simulation of the instrument power modes expected during operation. A separate Microsoft Excel model of the detector and cryocooler assembly was also constructed for faster thermal model correlation.

The instrument cooler was required to cool the CCD to -100^{o}C within 60 minutes. The CCD decontamination heater was required to heat the detector to 50^{o}C within 60 minutes and maintain temperature for an extended time. The thermal model was used by ATK to size the CCD thermal straps and the CCD decontamination heater. Sensitivity studies were completed to estimate the thermal model uncertainty, and to quantify various inputs to the total system parasitic heat load to the cryocooler. The model was also used to study anomalous conditions such as stuck-on or disabled heaters.

In the SINDA v4.8 model of Mars surface operation, conduction and convection losses dominate. Therefore thermal radiation is excluded from the overall instrument system model except for radiation terms around the detector and cryocooler. Because the instrument would be in vacuum during the cruise phase, radiation was also included in the cruise phase model. Conductance for internal heat flow within individual components was calculated using TMG-Thermal and input manually into the SINDA model. For example, a 98,000 element TMG model was used to generate the conductance between the instrument alignment bench nodes. The model used conservative estimates for beginning of life and end of life material properties including emissivity and thermal conductivity. The model included a FORTRAN subroutine based on test data to describe the cryocooler performance in the SINDA model.

A much simplified heat map for the cooler is shown in FIGURE 6. It compares model predictions with measured thermal test data. In 7-torr Argon, and with a bench (RAMP) temperature of 26°C, the CCD was cooled to -23.5°C (-23.1°C prediction), for a net cooling of 49°C below the RAMP temperature. The predicted thermal load/temperature at the coldfinger coldtip was 2.708W at -52.1°C coldtip temperature. No operational thermometry is available on the cooler coldtip to provide a comparison.

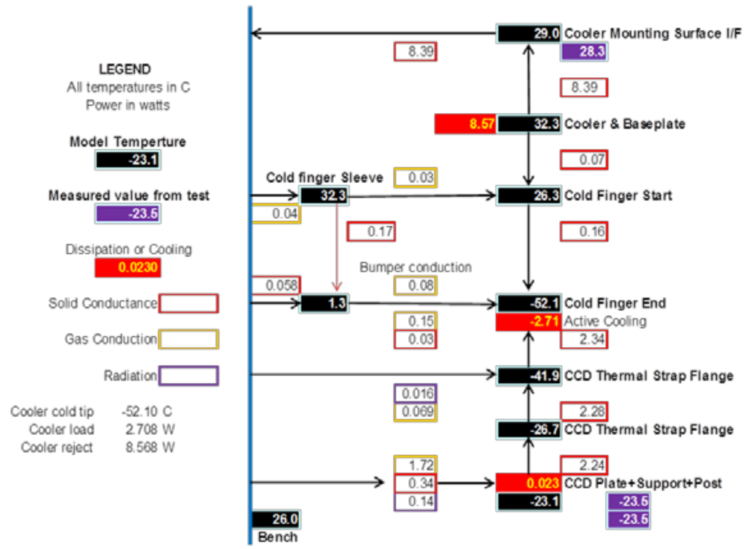

FIGURE 6. Simple heat flow map for thermal loads on the cryocooler, showing predicted and measured temperatures for comparison.

CHEMIN INSTRUMENT INTEGRATION AND TEST

The full CheMin Flight Model instrument was subjected to several thermal vacuum tests during 2009 and 2010 to proto-flight qualify the integrated flight instrument and to conduct steady state thermal balance tests under both high vacuum and 7-torr Argon (to model the Mars atmosphere), and at worst case cold and hot operational conditions. Argon represented the nearest thermodynamic properties to CO_2, the primary constituent in the Mars atmosphere. CO_2 could not be used in the tests because it would condense on the LN_2-cooled plumbing in the chamber. The thermal vacuum testing concluded in 2010 before learning of the selection of the Gale Crater landing site and its milder climate, and before learning how conservatively the MSL rover was thermally designed.

The instrument was tested under high vacuum conditions during the first thermal test to simulate the cruise phase conditions, and also to provide a baseline performance. Ambient heat reject (RAMP) temperatures were varied between -40°C and +26°C. The vacuum tests demonstrated that the CCD could be cooled to -100°C, and could be regulated at the planned -60°C (213 K) operating temperature for all RAMP temperatures. However, in the simulated Mars atmosphere the cooler's capability to cool the CCD was severely restricted. In the 7-torr Argon atmosphere the cooler was unable to cool the CCD to -60°C or below unless the RAMP temperature was less than -10°C. Thus the milder Gale Crater climate and the conservative rover thermal design did not work in the CCD's favor. It was noted during the tests that in the Argon atmosphere the operating CCD temperature was a nearly fixed temperature difference from the cooler reject (rover RAMP) temperature.

Examination of the problem lead to be discovery that several components, including the cooler coldfinger bumper tube and the CCD baffle, had unexpectedly thick copper plating under the gold vapor deposited surfaces, which led to large conduction losses. Additionally, the small gap distances at the cooler coldtip and at the CCD also played a significant role in increasing the gas conduction losses. The only physical modification allowed by the project schedule was a change in the coldfinger bumper tube design. The vapor-deposited gold G-10 bumper tube was replaced with a G-10 tube wrapped with a single layer of aluminized mylar inside and out. This resulted in a 6°C drop in CCD temperature. The final result was that in the 7-torr Argon environment the CCD could be cooled at best to 52°C below the RAMP temperature. In the thermal model, the CCD parasitic heating depends on two unknown parameters related to the gas gap in front of the CCD baffle and around the cryocooler bumper tube. After adjusting these parameters to fit all the test data in Argon and Nitrogen, the model predicts that the CCD temperature in the Mars CO_2 atmosphere is 60C below the RAMP temperature.

MISSION PHASE-CHEMIN CRYOCOOLER OPERATION

Settling of the lubricant used in the Ricor cooler was identified as a mechanism for loss of performance and possible failure. For this reason, all phases of mission operation were designed to accommodate periodic "cryocooler stirs", in which the cryocooler was briefly energized in order to redistribute the lubricant, whenever the cooler would not be otherwise operated for 3 months or longer. Integration of the instrument to the rover, and subsequent testing, was conducted in an earth laboratory ambient environment. Operation of the cooler during this phase of the mission was limited to about 3 minutes or to a 2°C drop in CCD temperature in order to prevent moisture in the air from condensing out on the CCD imager and damaging it. This included all instrument and rover-level integration and testing and for pre- and post- launch periods. A single maintenance cryocooler stir was conducted midway through the 9-month voyage of MSL to Mars.

Several sols after the successful landing on Mars, CheMin began a systematic checkout of its components. A checkout of the cryocooler was conducted, consisting of a partial cooldown over 15 minutes of operation. The measured CCD temperature profile was fit with an exponential decay that estimated the asymptotic temperature difference from the RAMP temperature to be ~62°C. FIGURE 7 shows the CCD temperature during one of the evening analysis periods. (This is roughly 10°C to 15°C colder than achieved during thermal vacuum tests, and can be attributed to the difference in thermal properties of Argon and the CO_2 atmosphere of Mars.) FIGURE 8 shows the coldest temperatures attained by the CCD during the analyses periods performed over the first 300 sols of the surface mission. With the nightly RAMP temperatures reaching 9°C by the end of the CheMin operations, the asymptotic temperature difference between the RAMP temperature and the CCD was consistently ~63°C. While it had been the mission plan all along to have CheMin operate at night, the added benefit and necessity of night operations is that the RAMP temperature is at its coldest, allowing the CCD to operate at its coldest to provide the best possible X-ray diffraction data quality.

The CheMin instrument is powered up and operates for approximately 5 hours per night before the early morning UHF communications pass necessitates the instrument power down. The typical CheMin surface operating scenario is as follows: At 21:30 LMST, CheMin is commanded by the rover into a cooldown phase. This phase continues for the next hour, after which control of the X-ray diffraction analysis is transferred to the FPGA controller in the CheMin instrument, and the rover's flight computer goes to sleep to save power. The controller collects a single CCD dark frame, gradually ramps the X-ray source up over a 14 minute period, and then collects a parameterized number of X-ray diffraction frames. The length of this integration is selected based on the time available for the CheMin experiment on the particular sol, and is typically limited to ~3.5 hours by a need to shut down the instrument before an early morning communications pass. After the last X-ray diffraction frame is collected, the X-ray source is gracefully ramped down over a 14 minute period, and a final CCD dark frame is collected. At this point, the cryocooler is disabled and the instrument powered off.

The two CCD dark frames and X-ray diffraction frames are stored in flash memory within the instrument. Sometime after the analysis, generally immediately after a communications pass for which the instrument was shut

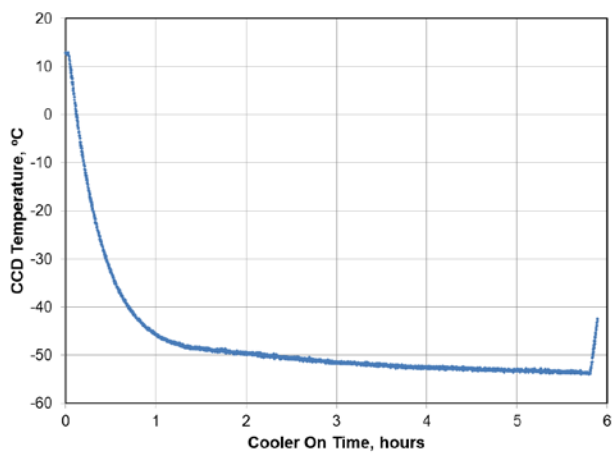

FIGURE 7. CCD temperature profile during representative analysis period.

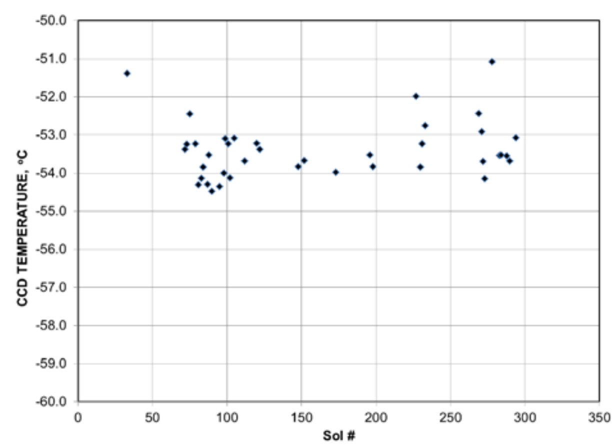

FIGURE 8. CCD temperature during each analysis period.

down, CheMin is powered on and the analysis data transferred from instrument flash to the MSL rover flight computer memory. As each frame is transferred, it is processed to eliminate background shift, emphasize the diffraction patterns, and reject noise and (for diffraction frames) fluorescence. The fluorescence energy spectra are also accumulated as histograms. The resulting processed data is roughly 40 times smaller than the stack of original raw frames, resulting in processed data volume suitable for downlink from Mars to Earth.

The complete mineralogical analysis of any one sample requires approximately 12 to 20 hours of integration, necessitating multiple evenings to measure a sample. Each analysis operates the cryocooler for 1.5 hours longer than the integration duration due to the overhead of the cooling phase and X-ray source ramp up/down. The median nightly cooler operating duration has been 5 hours (3.5 hour integration period), in which the instrument consumes approximately 250W-hr, with a peak power consumption of 54W during science operations. Empty sample cell analyses made prior to filling provide a baseline against which an analysis of a filled cell may be compared, and require less integration time. Over the first 300 sols of the surface mission, 39 cooldowns were performed, for a total cryocooler operating time of 180 hours.

CHEMIN ANALYSIS RESULTS

CheMin took its first soil samples from Curiosity for analysis on sol 71 at the Rocknest site. The fine silt and small grains of soil (< 2 mm) obtained from a drift of wind-blown particles suggest a dry, wind driven environment with low previous water activity. X-ray diffraction results from the 26.9- hour integration of the "scoop 5" sample is shown in FIGURE 9. The analysis results identified a number of different minerals, listed in TABLE 1. Simultaneous X-ray fluorescence measurements (FIGURE 10) identified the contributions from elements with atomic number 14 (silicon) and greater.

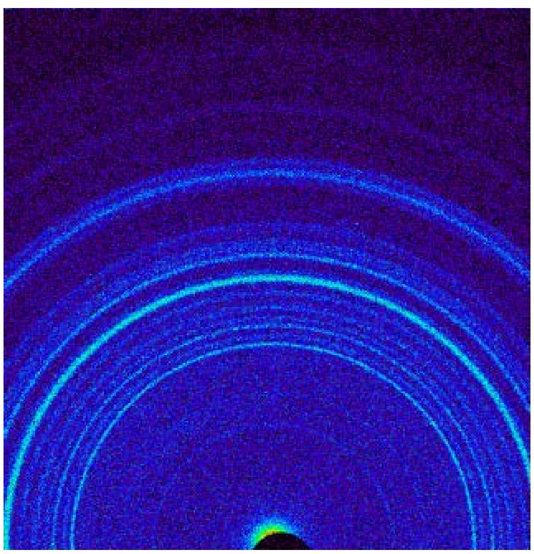

FIGURE 9. The 2-d X-ray diffraction pattern from the Rocknest soil sample. [3] The black spot at the bottom of the Rocknest picture is the beam stop. Analysis revealed a number of minerals from the crystalline components in the soil (TABLE 1).

TABLE 1. Crystalline components (amorphous-free) of the Rocknest scoop 5 soil. [3]

Mineral	Weight%	2σ
Andesine (~An50)	42.9&	3.4%
Forsterite (~Fo58)	20.5%	2.6%
Augite	16.7%	3.5%
Pigeonite	11.4%	3.9%
Sanidine	2.1%	1.9%
Magnetite	1.8%	1.1%
Quartz	1.7%	0.7%
Anhydrite	1.4%	0.9%
Hematite	0.8%	1.1%
Ilmenite	0.7%	1.2%

SUMMARY

The Ricor K508 cooler on the MSL CheMin instrument has been working fine, with a total of 39 cooldowns and 180 hours of operation logged through sol 300, representing a significant fraction of expected full mission operations. The thermal load on the cryocooler was higher than expected, preventing the CCD to be cooled to -60^{o}C as desired. However, with the CCD able to operate at -53^{o}C, and with some extended analysis time, the X-ray diffraction and X-ray fluorescence results have been able to determine mineralogy and mineral abundances as expected.

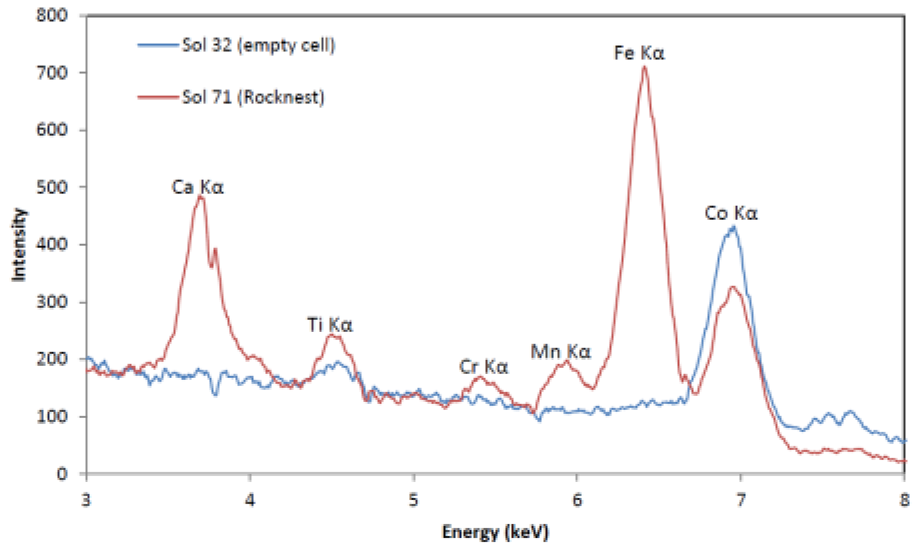

FIGURE 10. Ka X-ray fluorescence results for scoop 5 at Rocknest. [4]

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