NASA/TM-2009-215573
NESC-RP-05-122/05-038-E

NESC Independent Review of the Mars Reconnaissance Orbiter (MRO) Contamination Thermal/Vacuum (T/V) Anomaly Technical Consultation Report

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Prepared by

Dr. James Sutter, NASA GRC (Team Lead)
Dr. Henning Leidecker, NASA GSFC
Dr. Binayak Panda, NASA MSFC
Dr. Robert Piascik, NESC
Brian Muirhead, NESC
Dr. Debra Peeler, WPAFB

August 18, 2005

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VOLUME I: Technical Consultation Report

1.0 Authorization and Notification

The Mars Exploration Directorate requested an independent review of the Mars Reconnaissance Orbiter MRO Battery Control Module (BCM) Recovery Plan on June 3, 2005.

Mr. Ralph Roe, Director of the NASA Engineering and Safety Center (NESC), authorized a Consultation Report be prepared in an out-of-board action by the NESC Review Board (NRB) on June 24, 2005.

An independent review briefing of the MRO was created and presented on August 2, 2005 for the Safety & Mission Readiness Review (SMARR), Mission Reconfiguration Review (MRR), and the Material Review Board (MRB).

The consultation report was developed by Dr. James Sutter, NASA Glenn Research Center (GRC), and Brian Muirhead, NESC Chief Engineer (NCE).

2.0 Signature Page

Dr. James Sutter, Lead	Date	Dr. Debra Peeler	Date
Brian Muirhead	Date	Dr. Robert S. Piascik	Date
Dr. Henning Leidecker	Date	Dr. Binayak Panda	Date

3.0 List of Team Members, Ex Officio Members, and Others

NESC Review Team Members:

Dr. James Sutter, Lead, NASA GRC
Brian Muirhead, NESC Chief Engineer (NCE)
Dr. Debra Peeler, Wright Patterson Air Force Base (WPAFB)
Dr. Henning Leidecker, NASA Goddard Space Flight Center (GSFC)
Dr. Binayak Panda, NASA Marshall Space Flight Center (MSFC)
Dr. Robert Piascik, NESC Discipline Engineer for Materials

4.0 Executive Summary

The NESC was requested by the NASA Jet Propulsion Laboratory (JPL) to conduct an independent review of the Mars Reconnaissance Orbiter (MRO) Thermal/Vacuum (T/V) Anomaly Assessment. Because the anomaly resulted in the surface contamination of the MRO, selected members of the Materials Super Problem Resolution Team (SPRT) and the NASA technical community having technical expertise relative to contamination issues were chosen for the independent review (refer to Section 3.0 for team listing).

The consultation consisted of a review of the MRO Project's reported response to the assessment findings (provided in Appendix F), a detailed review of JPL technical assessment final report (provided in Appendix E), and detailed discussions with the JPL assessment team relative to their findings.

It is the judgment of the NESC Review Team that the independent JPL MRO Thermal/Vacuum Anomaly Independent Assessment Team (T/V AIAT) has addressed questions/concerns to the team's satisfaction. Moreover, the T/V AIAT assessment was complete and the conclusions of the JPL assessment identified the appropriate technical considerations so that the MRO Project can identify the approach (resolution) with minimal/acceptable risk.

5.0 Consultation Plan

The assessment of the MRO contamination issue required a review team with expertise in polymer-based materials, electronic materials, materials analytical methods, and basic knowledge in vacuum deposition and cleaning methods.

The NESC Review Team conducted an in-depth review of the following two documents, provided by JPL:

1. T/V AIAT report entitled, *MRO T/V Anomaly Independent Assessment Report – Rev H*, by Charles Whetsel, et al., April 20, 2005. Refer to Appendix E.

2. *Response by the Mars Reconnaissance Orbiter (MRO) Project to the Actions Recommended by the MRO T/V Anomaly Independent Assessment Team* (DRAFT), by Richard Zurek (MRO Project Scientist), June 13, 2005. Refer to Appendix F.

Based on the detailed review of the above documents, the NESC Review Team formulated review questions (refer to Appendices B and C). The review questions were then used as a basis for detailed technical discussions with the JPL MRO T/V AIAT. This technical exchange resolved the initial set of questions and triggered additional discussions.

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

During thermal vacuum testing of the MRO spacecraft during February 2005[1], the spacecraft was contaminated by material outgassed from a ground-support heater panel inside the chamber during the test.

Subsequent to the contamination event, the MRO project has taken steps to:

1) Identify the contaminant and its source.
2) Assess the extent of the contaminant and its impact to the contaminated surfaces.
3) Remove the contaminant from all feasible surfaces while assessing the impact to the mission from the surfaces which are impractical to clean.

During the period of April 11 through 20, 2005, an independent JPL Assessment Team from outside of the MRO Project convened to "identify, evaluate, and assess the risk to the MRO spacecraft, particularly the science payload" while making "use of existing data and information as much as practical". The JPL Assessment Team was additionally asked to "identify and discuss root cause of the anomaly, and corrective actions, in addition to the corrective actions taken for the affected hardware". Given the strong desire to complete this activity prior to the planned shipment of the spacecraft to the launch site, the team chose to prioritize activities related to the assessment of corrective actions for the affected hardware rather than the corrective actions implied for "process improvement' for the benefit of future missions. Refer to Appendix E.

[1]Performed at Lockheed Martin Astronautics (LMA) in Littleton, Colorado

7.0 Data Analysis

The independent review concentrated on the following issues:

1. Proper identification of the contaminant (analysis techniques).
2. Potential deleterious effects of the contaminant.
3. Removal of the contaminant.

Based on this review, the NESC Review Team compiled an initial set of technical questions, concerns, and suggestions relevant to the contamination issue and proposed corrective actions (refer to Appendix B). The NESC Review Team concentrated on potential harmful effects of polyurethane paint off-gases on other MRO components. Further information and suggested experiments that may determine if off-gases could affect the Solar Calibration target were required. This list was provided to Brian Muirhead (NESC Chief Engineer, JPL) and Dr. Robert Piascik (NESC Materials SPRT Lead, LaRC). The information was then relayed to the T/V AIAT.

On June 22, 2005, the NESC Review Team, the T/V AIAT Chairman (Charles Whetsel), and other T/V AIAT members conducted a teleconference to discuss the NESC Review Team's technical questions, concerns, and suggestions. At this initial meeting, the NESC Review Team requested further details of decontamination experiments, instruments used to detect contaminants and photographs that would provide an adequate description of MRO and its subsystems. Refer to Appendix C for an additional list of requested information. The NESC Materials SPRT Team completed the review of the additional MRO contamination/ decontamination data sent by Charles Whetsel on June 29, 2005.

8.0 Findings, Root Causes, Observations, and Recommendations

8.1 Findings

It is the judgment of the NESC Review Team that the independent JPL Assessment Team satisfactorily addressed all questions and concerns. Moreover, the T/V AIAT assessment was complete and the conclusions of the JPL Assessment Team, with regard to minimal/acceptable risk, are appropriate.

8.2 Recommendations

The NESC Review Team offers the following recommendations, listed in order of importance, relevant to the ongoing MRO work associated with the contamination issue.

R-1. Expose scrap SCT material to similar outgasses to reproduce the anomaly. Perform simulated UV exposure to determine effect on contaminant. Evaluate surface to observe changes in contaminant (freckling).

R-2. If MRO T/V AIAT proceeds with solvent cleaning of SCT surface, the NESC recommends evaluation of adhesive bonding SCT to its substructure to determine if the cleaning solvent has degraded bond strength.

R-3. CO_2 aerosol cleaning trials should be conducted on scrap/exposed (contaminated) SCT material. The CO_2 aerosol cleaning method may avoid issues with solvent cleaning.

The MRO Project has satisfactorily responded to the above recommendations. Refer to Appendix D for the MRO Project's response to the NESC Recommendations.

9.0 Lessons Learned

No significant lessons-learned were generated during this review.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 Minority Report

There were no dissenting opinions. Team recommendations were unanimous.

VOLUME II: APPENDICES

Appendix A. NESC Request ITA/I Form

NASA Engineering and Safety Center
Request Form

Submit this ITA/I Request, with associated artifacts attached, to: **nrbexecsec@nasa.gov**, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 6/3/2005 12:00 AM	Status: New	Reference #: 05-038-E
Initiator Name: Mars Program Office	E-mail:	Center: JPL
Phone: (818)-354-4947, Ext _____	Mail Stop:	
Short Title: Review of a Test Anomaly Resulting in Contamination of Elements of Mars Reconnaissance Orbiter (MRO) Spacecraft		
Description: This email documents a request for NESC engagement in the review of a system thermal vacuum test anomaly that resulted in contamination of various elements of the Mars Reconnaissance Orbiter spacecraft. This request for an independent review came to my office from the Mars Program Office at JPL and HQ. I proposed to have the NESC do the review and that was accepted. I discussed this request directly with Bob Piascik who felt it was something his SPRT could support. The charter is to review whether the contamination anomaly report was thorough and accurate and that the project's response has been thorough and provides reasonable mitigation of the risk to the mission. The report on the contamination event and the project's response to the recommendations are attached. The approach is to have members of the NESC review the attached documents and if, after this initial review, there are questions or issues, we will arrange a telecon with members of the original review group and/or the project. Since the project is proceeding to its launch period, which opens on 8/10, we need a timely response. I've requested that the assessment be done before the project's MRR on 6/28 if possible. If there is some indication of significant issues that need work I've asked for some insight earlier than the 28th, if at all possible. The final product requested is a concise statement of what the NESC team did and their position on the charter above. The review has already started and a telecon is tentatively scheduled for 6/22/05.		
Source (e.g. email, phone call, posted on web): email		
Type of Request: Consultation		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 6/24/2005 12:00 AM		
Potential ITA/I candidate? ☐ Yes ☒ No		
Assigned Initial Evaluator (IE):		
Date assigned (mm/dd/yyyy):		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☒ Yes ☐ No		

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 1 of 3

If yes:		
Description of action: Support MRO Reviews of Spacecraft Contamination Issues		
Actionee: Brian Muirhead		
Is follow-up required? ☒ Yes ☐ No If yes: Due Date: TBD		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		
Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐ Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐ Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐ Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐ Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

Form Approval and Document Revision History

Approved: ______________________________ __________
NESC Director Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. NESC Review Team Questions and T/V AIAT Response

NESC Question # 1.

The Aeroglaze series of coatings from Lord are typically non exotic in their resins, with additions to the resins creating the distinction between the Aeroglazes in the series. They are moisture curing polyurethanes - and a composition of expected outgasses should be available. The outgas composition would be very helpful in understanding potential re what contaminants one would expect to find, and their solubility in the cleaners being used. Please provide this information in the CD or other means of communication.

T/V AIAT Response: Results of chemical analysis subsequent to the contamination event is included on the CD-ROM being sent.

NESC follow-up: After a brief review of the CD that Charles sent, it seems that there should have been residual gas analysis done that would help put more details to the IR results that qualify the contaminants as "polyamines, etc." Low Priority.

NESC Question #2.

CO_2 aerosol might be a player in cleaning the roughened collector surface, no mention of much beyond the solvents. Were there any attempts to use these cleaning methods? Surface analysts would have cleaned with CO_2- baked and reevaluated the surface.

T/V AIAT Response: Has not been tried yet. Should be passed on to the project for evaluation.

NESC follow-up: Please follow-up with Project. Low priority.

NESC Question #3.

Re the decision to leave the Solar Calibration Target untouched. Apparently there is still some possibility that there are unwanted residues on this target, and an operational strategy has been planned to check calibrations after launch, both before serious UV exposure happens and then after some appreciable UV dose is acquired. I note that one could expose a small (a disk 2 mm in diameter) to UV now, and check the extent of darkening. Waiting until after launch for checking the potential for UV darkening is a way of ensuring that it is impossible to carry out "hands on" work with this target. Please comment on the feasibility of performing a trial as suggested above.

T/V AIAT Response: Would require comment from the project as to whether an accelerated aging test by exposure to UV is feasible.

NESC follow-up: To whom should we direct this request? This sets the stage for the recommendation made in the power point package: perform UV exposure tests on SCT scrap samples that were exposed to outgassing. If freckling of the SCT surface occurs . . . then an in-flight problem may be a larger concern. High Priority.

NESC Question #4.

What is the adhesive for the SCT?

NESC Question #5.

Could this adhesive have outgassed and contaminated the SCT?

T/V AIAT Response: These questions (#4 & #5) are beyond the scope of our investigation, but might be addressed by the project.

NESC follow-up: Issue #4, above, also leads to the concern that if there was cleaning performed on an intact SCT, that the solvent may induce some dissolution of the adhesive and contaminate the SCT surface further.

Appendix C. Additional Information Requested from T/V AIAT

(As a result of the June 22, 2005 meeting)

Deb Peeler's Comments:

1. The Aeroglaze series of coatings from Lord are typically non exotic in their resins, with additions to the resins creating the distinction between the Aeroglazes in the series. They are moisture curing polyurethanes - and a composition of expected outgases should be available. The outgas composition would be very helpful in understanding potential re what contaminants one would expect to find, and their solubility in the cleaners being used. Please provide this information in the CD or other means of communication.
2. Other well known techniques surface analysis techniques might be used in these ongoing MCS contamination identification effort. ESCA, RAMAN, FTIR spectroscopy, etc- might prove more useful based one would expect from products of this degraded coating.
3. CO_2 aerosol might be a player in cleaning the roughened collector surface, no mention of much beyond the solvents. Were there any attempts to use these cleaning methods? Surface analysts would have cleaned with CO_2- baked and reevaluated the surface.

Binayak Panda's Comments:

1. For the on-going MCS Contamination Recovery Activities, a relatively new analytical technique, UV-LINF, is being used. It was unclear to me as to the merits of this technique over the conventional FTIR, Raman or XPS. Since this analysis is on-going, is it possible for us to obtain the technical report of the findings of this technique? Please provide the details in a CD or other form of communication.

Henning Leidecker's Comments:

1. "Re HiRise: The following were reported for Location A:..., Silicone, ..." I have searched the document for "silicone" and find only this one reference to it. I would like a discussion of what this particular sort of "silicone" is, and where it came from, and why none was found anywhere else. I worry that it may be more widely present. And I note that some forms of "silicone" are effectively opaque when thicker than a few tens of monolayers. Was there any other testing not mentioned in the report that confirmed the presence of Silicone anywhere else?

2. Re the decision to leave the Solar Calibration Target untouched. Apparently there is still some possibility that there are unwanted residues on this target, and an operational

strategy has been planned to check calibrations after launch, both before serious UV exposure happens and then after some appreciable UV dose is acquired. I note that one could expose a small (say a disk 2 mm in diameter) to UV now, and check the extent of darkening. Waiting until after launch for checking the potential for UV darkening is a way of ensuring that it is impossible to carry out "hands on" work with this target. Please comment on the feasibility of performing a trial as suggested above.

Jim Sutter's Comments:

1. There are 9 or 10 Aeroglaze Z306s listed in the NASA Outgassing Database. Who has the chemical composition of the Z306 used in this HiRise ground support heater and what are the outgassing characteristics? What is the structure of the polyurethane?
2. Would any of the organic components present in the off-gasses act as a corroding agent for other MRO components or interact with its Martian orbital environment to become corrosive?
3. Are the chemical details of the PU components and their offgas byproducts revealed in the detailed information on the CD or some other form of communication?
4. Isopropyl alcohol (IPA) wipes were used on the MLI (multilayer insulation). IPA typically contains traces of water. Both IPA and H2O diffuse into Kapton . . . was the MLI (usually MLI is Ag coated PTFE or the like) in this case Kapton? What was done to ensure that these cleaning methods did not leave behind possible contaminants that could be released on orbit?
5. Since April, have the planned experiment to the MCS been performed? Results? Was a second TV rebalancing necessary? JPL could get some idea of how contamination might re-contaminate components when MRO is on orbit and undergoes heat-up (such as aerobraking).
6. Were the ethyl acetate, acetone and IPA treated to remove water and other impurities before washing MRO components? Residue from these solvents may never have been removed and they could confound the results from the NVR.
7. What were the MLI blanket surface cleanliness levels before T/V?
8. Has a TGA/FTIR (Thermogravimetric Analysis/Fourier Transform Infrared) been performed on the polyurethane in the Lord Co. product to determine if the composition of off-gasses. If not, then recommend doing the experiment in N_2 or Ar. Do not use air for this TGA experiment?
9. Where is the full reference from Bob Headsel @ Lord?

10. What type of product is formed from Aeroglaze when it is beyond its shelf-life? Is there any of this paint left? Was the paint stored according to manufacturer's suggested conditions (get temperature range for storage . . it's usually on the can)?
11. What type of Aluminum is the MCS solar calibration unit roughened metal surface?
12. Was the older Aeroglaze used in these recontamination tests?
13. The KSC UV-LINF studies on the SCT show different results than anything done at LMA. The areas tested were on the edge of the SCT. I believe that maybe an area where the underlying adhesive is located. This begs the question: What temperatures did this area of the SCT experience?
14. What is the adhesive for the SCT?
15. Could this adhesive have outgassed and contaminated the SCT?

Appendix D. MRO Project Response to NESC Recommendations

Email: Date: Mon, 11 Jul 2005 12:15:01 -0700
From: Brian K Muirhead); To: Jim Sutter, Bob Piascik

Here is the MRO project's response to your suggested recommendations from your final report. Do you have any problem with their response? It looks like they fully considered and/or acted on your recommendations (i.e. was responsive).
Thanks again for your thorough and timely support and assessment.
Brian

Here is my first reaction to the NESC report's recommendations (abbreviated here).

In short, the MCS team and MRO Project have concluded that cleaning the target is more likely to invalidate, rather than restore, the ground calibration. Emphasis is now on trying to sequence a view of the MCS solar target in early to mid-cruise. Any further testing with the MCS target cut-off (scrap) piece would be devoted to seeing if the target would darken significantly with less than 25 hours of direct exposure to sunlight in flight.

1. Expose scrap SCT material to reproduce contamination event...perform simulated UV exposure...

This was tried with MCS sample target material and by heating the cold plate painted with the same material and cured at the same time as the heater plate used in T/V. What we found was that it was difficult to get the same contamination on the samples. The material deposited had a less prominent polyurethane structure. Also, the sample pieces used were not "finished" in the same way as the final flight target. In any case the flight target did not look anything like the contaminated nor the cleaned sample pieces. The MCS Team has since located a cut-off piece which was finished in the same way as the flight target surface. Analysis of material removed from a piece of that cut-off scrap indicated that its surface had material present that was similar to the flight target. We are debating whether to expose the uncleaned portion of the target cut-off to solar radiation to see how quickly the material darkens.

2. Assess effect of solvent cleaning on target adhesive.

It was decided not to clean the target, because: 1) the acetone-brushing needed to remove contaminate appeared to be altering the target surface; 2) there was no evidence of polyurethane contaminate above the background introduced by the nylon brushing; and 3) as noted earlier, examination of a cut-off piece indicated that whatever organics are on the target may have been present during ground calibration of the target.

3. Conduct trials with CO2 aerosol cleaning...

This was considered, but previous experience indicates that this approach--effective in removing particulates--is not effective in removing deposited molecular films. Thus, this approach was not pursued.

Other:

The NESC Review Team members raised the issue of whether the adhesive used to mount the solar target plate to its substructure was itself a source of contamination. The target (in its mounting structure) was baked out at higher temperatures than were encountered during system thermal/vacuum testing and no out-gas flow was detected during calibration of the instrument in its stand-alone T/V testing.

Rich Zurek
MRO Project Scientist

Appendix E. MRO T/V Anomaly Independent Assessment Report Final, Revision H, April 20, 2005

<s> Charles Whetsel, 670,Chair/Systems Engineering	<s> George Siebes, 350, Thermal Assessment
<s> Patricia Hansen, 353, Contamination Control	<s> Fred Vescelus, 700, Payload Assessment
	<s> Robert West, 322, Science Assessment

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1. Executive Summary

During thermal vacuum testing of the Mars Reconnaissance Orbiter (MRO) spacecraft during the month of February 2005, at Lockheed Martin Astronautics (LMA) in Littleton, Colorado, the spacecraft was contaminated by material outgassed from a ground-support heater panel inside the chamber during the test.

Subsequent to the contamination event, the MRO project has taken steps to 1) identify the contaminant and its source, 2) Assess the extent of the contaminant and its impact to the contaminated surfaces, and 3) Remove the contaminant from all feasible surfaces, while assessing the impact to the mission from the surfaces which are impractical to clean.
During the period of April 11th through 20th a team of JPL employees from outside of the MRO project was convened to "identify, evaluate, and assess the risk to the MRO spacecraft, particularly the science payload" while making "use of existing data and information as much as practical." The team was additionally asked to "identify and discuss root cause of the anomaly, and corrective actions, in addition to the corrective actions taken for the affected hardware." Given the strong desire, if feasible, to complete this activity prior to the planned shipment of the spacecraft to the launch site, the independent assessment team chose to prioritize activities related to the assessment of corrective actions for the affected hardware above corrective actions implied for "process improvement' for the benefit of future missions.

In all areas except the expected performance of the contaminated Mars Climate Sounder (MCS) calibration target, the independent assessment team was provided with data that allows us to state that the residual risk remaining from this event is exceedingly unlikely to cause any degradation of the Mars Reconnaissance Orbiter mission. The MCS investigation team has stated that they believe that risk associated with cleaning their solar calibration target is greater than the expected degradation from the contamination. Additional testing is planned to determine if cleaning is feasible without damaging the target.

The project did a commendable job supporting this investigation by readily providing all requested material which was available in a timely manner. The investigation especially wishes to thank Tim Gasparrini and Neil Tice of LMA, Rich Zurek, Dan McCleese, Brian Blakkolb, Ray Garcia, and Gus Forsberg of JPL, Mike Malin and Mike Ravine of Malin Space Science Systems (MSSS), and David Paige of UCLA.

2. Description of Anomaly

Following completion of thermal vacuum (T/V) testing of the Mars Reconnaissance Orbiter during the month of February 2005, at Lockheed Martin in Littleton, Colorado, the spacecraft contamination was first noted by discoloration of germanium-coated Kapton™ radome on the UHF antenna upon completion of the test. Visual inspection, analysis of Non-Volatile Residue (NVR) wipes, and analysis of witness samples and optics from the chamber using Fourier Transform Infrared Spectrometry, and UV transmission confirmed the presence of a thin-film organic contaminant over surfaces of the spacecraft. Thermoelectric Quartz-Crystal Contamination Monitor (TQCM) and Residual Gas Analyzer (RGA) equipment was installed and used to actively monitor for potential contamination during the T/V test. The RGA was not sensitive enough to detect the presence of contamination at the levels which occurred. The TQCM's were located to optimize their ability to detect contamination along the optical axis of the sensitive payload elements, and as such, they did not register the contamination as it occurred, since the contamination flux was weak along that axis. Maps of the concentration of the contaminant were created by LMA after the test based on the material collected via NVR wipes.

The source of the contamination was isolated both by proximity as well as chemical analysis of the contamination, to be material outgassed from a ground-support heater panel inside the chamber during the test. The heater panel is referred to as the "HiRISE Test Heater Plates" (so-called because of their proximity to the HiRISE instrument when installed in their test configuration). The heater panel was specially manufactured for the MRO T/V test and painted with Aeroglaze Z306, manufactured by Lord Chemical Company. For an appropriate thermal characterization of the spacecraft, this heater panel was required to operate at a steady-state temperature of 140 °C for greater than 24 hours. This temperature has been confirmed to be in excess of the manufacturer's recommended service temperature for the paint.

3. Assessment Methodology

Given the expedited timeframe over which this investigation has had to operate, the priorities of the team were focused on assessments of the 1) efforts of the project to determine the extent of the contamination, 2) effectiveness of cleaning and recovery activities undertaken by the project, 3) residual risk to the mission after completing these activities. Given that the proximate cause, the heater panel which was the source of the contamination, was unarguably identified, a limited amount of the team's time was invested in further pursuit of the root cause, although a brief discussion of this is included

As recommended by the charter, the team attempted to conduct the investigation making "use of existing data and information as much as practical." A thorough briefing package has been maintained by LMA covering the history of the anomaly and the subsequent investigation and cleaning activities. The team also reviewed the Thermal Vacuum Test Procedure and the presentation material from the Environmental Test Readiness Review. Results of NVR and Fourier Transform Infrared (FTIR) analysis of the contaminant from the JPL Analytical Chemistry Laboratory were also reviewed.

To supplement review of this written material the independent assessment team conducted interviews at JPL with both the MRO project contamination control engineer, Brian Blakkolb, the project scientist, Richard Zurek, Ray Garcia, a member of the MRO thermal team, and Gus Forsberg, a materials properties expert from JPL's Propulsion and Materials Engineering Section, as well as teleconferences with the MRO project mechanical systems manager, Tim Gasparrini, and the lead thermal engineer, Neil Tice, from LMA.

Additionally, contemporaneous with the formation of this team, the project held a teleconference at which each investigation team provided their assessment of the extent and impact of the contamination and their plans going forward. The team also reviewed material provided by each of the instrument teams. The team requested additional material not included in these packages, as warranted. Email interactions with both the MARCI/CTX team (Mike Malin and Mike Ravine of MSSS) as well as the MCS team (Dan McCleese of JPL) were initiated by the team. Furthermore, as the investigation proceeded, additional data and results provided by the CRISM were forwarded to the team by the MRO Project Scientist. A teleconference with David Paige at UCLA, calibration lead on the MCS team was also conducted.

The team conducted the investigations using daily meetings (ranging from 1-4 hours each) and interviews together as a group with offline review of materials by individuals, and email correspondences within the team and between the team and members of the project between the dates of 4/11 and 4/19.

4. Risk Analysis

This section addresses potential risks associated with the anomaly that the independent assessment team identified and requested information from the project. For each risk area identified, a brief description of the risk is included, followed by a list of the findings presented to the team regarding this risk, our assessment of the situation, and recommendations (if any) for additional work that the project should consider completing at a later time.

4.1. Risk 1: Payload contamination

4.1.1. Risk Description

Instrument contamination compromises science objectives of mission.

4.1.2. Findings

MARCI: Measurements on witness plates revealed that the residue strongly absorbs UV radiation [cf. Reference 1]. The exterior optics of MARCI was exposed to the contaminant. After the contamination event the exterior optics were cleaned several times. Measured UV transmission at 260 nm after the first cleaning was about 10% higher than before the first cleaning. Subsequent cleanings did not improve measured transmission. The inferred contamination was significantly less than on nearby witness plates, but the witness plates were oriented more directly toward the contamination source and MARCI optics were partially shielded. These observations were reported by M. Malin, MARCI Principal Investigator, as part of References 2 and 8.

CTX: The baffle and front were visually inspected after the contamination event. There was no visible contamination on the optical surface. A spotty pattern was seen on the alignment flat but thought not be related to the TV event in question. Tests were performed on optics Modulation Transfer Function (MTF) and camera radiometric performance. These tests did not indicate any degradation. These observations were also reported by M. Malin, CTX Principal Investigator, as part of Reference 2.

HIRISE: After the contamination event, several surface samples were obtained. The two of relevance to possible optics contamination were on the interior of the struction – one on the Interior GrCE baffle, inside 1st baffle (inside past sunshade, Location A, from Reference 3), the other on the Interior - black Kapton™ Multi-layer Insulation (MLI) blanket surface (inside aperture, Location B, from Reference 3). The interior of the structure was not in a line-of-site path to the source. The exterior blanket was also sampled.

The following were reported for Location A:
NVR = 0.12 mg/ft^2, Area sampled: 96 in^2
FTIR spectra 05-0942 indicates Aliphatic Hydrocarbon, Aromatic Ester, Silicone, trace of Urethane

Note only the <u>cylindrical</u> surface of the graphite composite baffle tube was sampled, between the 1st and 2nd baffle rings, so a relatively large area was covered. No significant amount of urethane was detected. Other chemical constituents listed are commonly detected on BATC hardware.

The following were reported for Location B:
NVR = 0.43 mg/ft^2, Area sampled: 10 in^2
FTIR spectra 05-0945: Aliphatic Hydrocarbon, Ester, possible trace of Urethane.

No significant Urethane residue was detected, especially when compared to the other molecular contaminants. Since this blanket is on the secondary mirror structure, it is the best representation of the contamination that may have entered the telescope aperture and deposited on the primary mirror. Only 1/2 of the blanket area was sampled, so a second sample may be possible if deemed necessary to corroborate the first sample.

Reference 3 also states that 'No "direct line of sight" to contamination source and "cold wall" chamber precluded contamination of optics'. A triple cleaning of the external sunshade MLI surfaces by light wipe of IPA dampened Technicloth or Alphawipe cloths was recommended. As of Monday, April 18th, the project has reported that this cleaning of HiRISE external surfaces and blankets has been completed.

CRISM: The following was reported by the CRISM team in Reference 4 (underlines indicate updates to current status as of time of the report):

- Contamination was found on baffle, data processing unit (DPU), and radiator MLI
  - All had direct line-of-sight to the heater plate
  - LMA has sampled MLI and DPU Kapton™ with ethyl acetate (NVR analysis done)
  - LMA has cleaned white paint and radiator surface with IPA (no NVR)
  - LMA has cleaned baffle and radiator MLI and DPU Kapton™ with IPA

- Internal CRISM optics have not been affected
  - Analysis of data collected after event indicates no contaminant present

In Reference 5, Scott Murchie, CRISM PI, reported on work done by Dave Humm who carefully documented before/after changes in radiometric properties of the instrument determined from a calibration of a Spectralon target, placed at a 45° angle in front of the telescope, done on April 6, 2005. Changes in radiometric properties between these measurements and a prior calibration in December, if any, were within measurement uncertainty (~2.5%). Details are given in Reference 5. In summing up the evaluation, Dave Humm writes, "I conclude the contamination event in spacecraft thermal vacuum testing had no impact on VNIR performance. "

MCS: Reference 6 states: "As MCS was safed throughout this phase of the test, contamination of the instrument optics and blackbody is expected to be negligible. However, the solar target was continuously exposed and was cold (-40°C), and is strongly suspected to have suffered some contamination. "

The calibration target has a mechanically roughened aluminum surface whose purpose is to serve as a photometrically stable and well-characterized calibration target for reflected sunlight from UV to 3-microns wavelength in the infrared. The target is thermally isolated from the spacecraft and the MCS instrument, and includes temperature sensors to monitor how much radiant energy is absorbed by the target. Changes during flight of the solar-weighted average reflectivity can be monitored and understood from the temperature measurements.

The MCS team has expressed some concern over the feasibility of cleaning the solar calibration target, given the likelihood of damaging either the surface of the target or its adhesive mounting using the techniques which have been successfully employed to clean other surfaces.
As of the date of this report, the principal investigator D. McCleese has decided to not clean the calibration target unless the results of planned cleaning tests are favorable. If it is not cleaned (a worst-case scenario) the team would need to deal with the consequences of a contaminated target. The most severe impact to science in this case comes from the change in target reflectivity that occurred during the TV contamination event. Changes during flight are important as well, but temperature measurements of the target will provide a basis for knowledge of temporal change. The amount of degradation is not known. To deal with it the team might be able to make measurements of astronomical targets (the moon, Mars) which have been calibrated by other experiments.

ONC: The ONC was mounted on the far side of the spacecraft from the source of the contamination. In Reference 7, Steve Synnott, the ONC Principal Investigator, notes that the "wavelength absorption problem caused by the contamination material is almost entirely outside the bandwidth that ONC observes," and goes on with his assessment that the "combination of very low probability of ONC contamination and the non-overlapping bandwidths has made my concern about this problem negligible." ONC optics were visually inspected by Doug Beasley, JPL quality and no contamination was visible on the ONC optics.

4.1.3. Assessment

General comment: Cleaning of the external non-optical surfaces was not documented for some instruments. Re-volatilization of these surfaces during flight may pose a risk depending on the temperature these surfaces achieve. For the payload, the most critical areas would be decontamination heaters (if any) or structures which my warm during aerobraking, or any electronics parts that may have accumulated contaminant.

MARCI: Although the external optics were contaminated, they were cleaned and transmission measurements subsequent to cleaning indicate that the optics are clean. Based on this, we do not see a remaining risk.

CTX: Post-anomaly testing showed no degradation in MTF and radiometric response. We see no remaining risk.

HIRISE: The optics were protected by a 'cold window' during TV operation, so no contaminant is expected to be on the optics, and samples near the optics did not show a significant level of urethane. It is therefore unlikely that a risk remains.

CRISM: Tests indicated CRISM internal and external optics were not affected, within measurement error of ~2.5%.

MCS: There is no doubt that there will be loss to science if the worst-case scenario came to be. The team has not assessed what the magnitude of the loss might be. Nor have they assessed how well observations of the moon or Mars would compensate for the target degradation. If the instrument were to be cleaned there might still be some loss of reflectivity from interstitial contaminant in pits, cracks, or rough hollows that escaped the mechanical cleaning which is most effective.

ONC: No tests or visual inspections of ONC have been performed. Therefore there is a small risk that ONC optics were contaminated. However Synnott's assessment (that the cameras were protected by the spacecraft and that there is not a significant risk) appears to be sound. The project has asked the PI to perform a visual inspection.

4.1.4. Recommendations

R1- Proceed with planned experiments to contaminate and clean additional materials samples representative of MCS solar calibration targets, to enable an informed decision regarding the risks and benefits of MCS target cleaning.

R2- It is up to the MCS team to assess the trade-offs and to decide to clean or not. Effort should be made to recover calibration as much as possible from observations of the moon (during early cruise) and Mars (during cruise and orbital phases). This will impact cruise and orbital operations. It will require a significant and on-going effort to quantify calibration uncertainties.

R3- To address possible risk from re-volatilization of parts exposed to contamination verify that no instrument or spacecraft heaters or electronics parts were exposed to contaminant, or clean or replace if there were any.

R4- General comment for all instruments: All instruments should consider additional in-flight calibrations or test that might reveal the effects of contamination that was missed prior to launch or that may result from re-volatilization of material during aerobraking or some other phase of the mission. An example of such a test might be imaging a bright star to measure instrument PSF or transmission.

4.2. Risk 2: Engineering Sensor Contamination

4.2.1. Risk Description

Engineering sensor contamination compromises flight system abilities.

4.2.2. Findings

Two contamination-sensitive engineering sensors are located exterior to surface of the spacecraft which were affected by the contamination, the sun sensors and the star tracker. In the case of the sun sensors, which were on the side of the spacecraft where the contamination occurred, the sensors have been cleaned according to procedures recommended by the sensor providers. The star tracker was located on the side of the spacecraft opposite the contamination source (as with the ONC payload instrument) and as such is not believed to have been contaminated. Visual inspection by Jim Chapel, LMA GNC Lead and Kent Hoilman, LMA Star Tracker CPE confirmed no indication of contamination on the Star Tracker optics.

4.2.3. Assessment

Risk to the sun sensors should have been mitigated by the cleaning and risk of having contaminated the star trackers is minimal,.

4.2.4. Recommendations

None.

4.3. Risk 3: Thermal Surface Contamination

4.3.1. Risk Description

Spacecraft surface contamination compromises ability to maintain thermal control. The manifestation of this risk increases uncertainty in the analytical simulation of the thermal behavior and leads to unforeseen temperatures during the mission.

4.3.2. Findings

In response to this incidence, per Reference 1, germanium coated surfaces and painted IR radiators are being replaced with spares or new builds and other thermal control surfaces are cleaned with proven procedures:

Clean Black Kapton With Ethyl Acetate Wipe	(Complete)
Clean Silver Teflon Radiator	(Complete)
Replace Two Painted IR Radiators	(Complete)
Verify Cleanliness	(In-Process)
Clean Remaining Blankets with IPA	(Per Standard Process prior to final installation)
Germanium surfaces/UHF Radome	
Replace With Spare	(Complete)
α/ε measurements of sample cleaned blankets	(Complete)

4.3.3. Assessment

Possible consequences of this contamination, if not removed, could be that thermal optical properties change their values during the T/V test as well as long term degradation behavior (due to changes in these properties after the contamination is exposed to UV radiation during flight). These properties are integral part of the thermal design validation, the objective of this test. The questions arising from this condition are: 1) Has the validation objective been compromised, and 2) Is the ability of the thermal control system to meet flight requirements compromised?

In regards to 1), contamination tends to raise solar absorption. This is especially noticeable where initial values are low. There is typically a lesser effect on infrared emittance values. The changed solar absorption property does not enter into consideration. This is because the test did not use solar simulation to exercise this property. Changes in infrared emittance do enter in the correlation of test data. Unless the IR emittance values have been measured for contaminated surfaces, this effect can not be included into the correlation and it will carry an additional degree of uncertainty. However, the overall impact is expected to be small and can be absorbed. This is because the change in the emittance values is typically small and the thermal design is based on bounding values (Beginning-of-Life to End-of-Life) far beyond these incremental changes during the test.

In regards to 2), the optical properties for cleaned blankets are within the measured values for control specimens and pre-TVAC measured values. Concern about continued deterioration of these properties is reduced to the typical aging effect (of a clean blanket), which is included in the design.

The measured values for the black Kapton™ and perforated second-surface aluminized ("Gold") Kapton™ thermal blankets are shown in Table 1. The Control Specimen was taken from the current LMA thermal materials stock. Measurements were made prior to the thermal test (Pre-TVAC) and after the thermal test once the thermal blankets were cleaned (Post-TVAC). As you can see there is little if any variance between the three sets of measurements. This indicates that the cleaning technique used to remove the polyurethane contaminant did not degrade the BOL properties of the thermal blankets.

Table 1- Blanket Cleaning Results

Material	Control Specimen		Spacecraft Thermal Blankets			
			Pre-TVAC		Post-TVAC & Cleaning	
	α	ε	α	ε	α	ε
Black Kapton™	0.94	0.81	0.95-0.97	0.81-0.82	0.94	0.81
"Gold" Kapton™	0.39	0.73	0.40-0.43	0.72-0.75	0.41	0.73

In final assessment, the cleaning or replacement of contaminated surfaces restores the original confidence in the thermal design; with a minor residual increase of uncertainty in test data correlation due to small but currently unquantified changes in IR emittance. However, these changes are well within the margin of the thermal design.

4.3.4. Recommendations

R5 - Evaluate merits of measuring the IR properties of contaminated MLI and use in thermal model correlation (if available – otherwise consider value of re-contaminating materials specifically for this purpose).

4.4. Risk 4: Re-contamination from uncleaned surfaces

4.4.1. Risk Description

Contamination from T/V test remains on spacecraft, providing opportunity to migrate and re-contaminate other surfaces at a later time

4.4.2. Findings

The spacecraft thermal control blankets were removed from the spacecraft, cleaned and will be reintegrated onto the spacecraft at KSC prior to final closeout. The black Kapton™ blankets were cleaned with ethyl acetate. The perforated second-surface aluminized ("gold") Kapton™ blankets will be cleaned with Isopropyl Alcohol (IPA). The UHF radome germanium-coated black Kapton™ surface, as well as all other germanium coated surfaces were replaced with the flight spares or replacement units. The radiator "windows" were replaced with unexposed radiator panels (painted Kapton™) on the affected blankets (2 places). The cleaning method used was developed by the JPL Analytical Chemistry Laboratory. Both IPA and Ethyl Acetate removed the contaminant with a mechanical action similar to cleaning ordinary eyeglasses (Reference 9).

The officially documented MRO exterior surface cleanliness level requirement at launch is less than 1.0 mg/ft^2 per IEST-STD-CC-1246D (Ref.10, 11). As part of the resolution plan for the contamination anomaly, the LMA corrective action documented in their Problem/Incident Reporting System (PIRS), all affected thermal blankets would be removed and cleaned. Removed blankets were required to be cleaned to a level of 0.5 mg/ft^2 as measured by NVR analysis. Furthermore, any cleaned surface as detected by swab sampling and FTIR analysis to contain polyurethane was required to be cleaned to a level of 0.2 mg/ft^2. Based on these requirements, the residual contamination levels are well below the required levels.

The highest expected temperatures are during aerobraking. Only the outer layer of the Spacecraft Aft Deck Kapton™ blankets is expected to exceed temperatures of 100° C. The predicted temperatures range from 205° C to 345° C. The temperatures on the outer layer of the most severely contaminated blankets (HiRISE) is predicted to range from -72° C to 29° C after the aerobraking maneuver (Reference 12).

4.4.3. Assessment

The contamination remaining on the spacecraft thermal control blankets will not pose a risk to the MRO spacecraft or instruments. The contaminant will only become "mobile" when heated to the temperature at which it was deposited (approximately 160° C). The cruise and aerobraking temperatures are predicted to be well below these levels for the "contaminated and cleaned" blankets. The residual contamination will not be a risk to the MRO spacecraft or instruments. The outer layer of the thermal control blankets on the Aft Deck which will see the most severe temperatures during aerobraking. These blanket surfaces were the least contaminated during the TV test and the sample did not contain any polyurethane, the marker from the outgassing Z306 paint (Ref. 1). It is expected that these low levels of contamination, well below the exterior surface level requirement of 1.0 mg/ft^2, will not be a risk to the MRO spacecraft or instruments.

4.4.4. Recommendations

None.

5. Root Cause/Corrective Actions

Standard environmental testing practice for the MRO spacecraft would have called for solar simulation to be used to produce the required thermal input for the cruise phase of the mission. However during the chamber checkout, it was discovered that the window used for the solar simulation was cracked and needed to be replaced. The replacement window could not be delivered in time to support the MRO thermal test (Ref. 13). An alternate test set-up was devised and used during the MRO thermal test. This required a "heater panel" that would be cantilevered over the MRO spacecraft and provide the necessary thermal heating to simulate the cruise phase thermal profile.

The heater panel was designed and built by LMA. The heater panel that was used during the MRO thermal test was painted on both sides with Aeroglaze Z306. Zonal strip heaters were to provide better control of the heater panel temperatures. The upper side (away from the spacecraft) of the heater panel was covered with a Kapton™ blanket (Ref. 1). JPL provided oversight to ensure that this alternate test set-up would in fact produce the required thermal profile and thus produce valid test results, given the unavailability of solar input (Reference: personal communication with Ray Garcia, JPL, 15 April 2005).. In the amount of time available for this investigation, the independent assessment team has not had time to penetrate the LMA design process for this heater panel and thus are unable to determine what design reviews were held to approve the design of the heater panel.

The heater panel in question was required to be maintained at 140 C for an extended duration to simulate the cruise phase thermal profile. This is above the manufacturer's recommended service temperature for the paint used to coat it. The manufacturer does not recommend that the paint be used above 250° F (~ 121° C) and states that above these temperatures the paint starts to degrade. At temperatures above 300° F (~ 149° C) the paint breaks down and "ashes" (Reference: personal communication with Bob Headsel, Lord Corporation, 14 April 2005).

Due to the control loop for the heater panel, during the MRO thermal test, the heater panel temperature was initially raised to approximately 162° C for several minutes, significantly above the cruise phase temperature of 140° C, and well above the manufacturer's recommended operational temperature. This may have been due to the control loop being operated via a thermocouple in a cooler portion of the panel and thus, much of the panel may have been overdriven to reach the required temperature.

Additionally, the paint used was beyond its shelf life several times over, having been manufactured in August 2002 with a recommended shelf life of one year. Mechanical testing of adhesive properties of the paint was conducted prior to use, but no chemical testing appears to have been conducted.

Regardless of the degree to which these additional considerations did or did not contribute to the anomaly, it is clear that there was a breakdown in the development of the specification for the heater panel between the temperature that it was required to work at and the painted surface treatment chosen for the equipment. This assessment team believes that a mismatch between the intended use of the heater and the selection of the paint to cover it is the root cause of the anomaly.

6. Open Items & Work Remaining

In addition to the recommendation listed above under each specific risk the following additional recommendations are made by the team, not related to any individual risk. Except as noted, these actions have been discussed with the MRO project and the independent assessment team is under the impression that the project intends to complete these actions.

R6 – A review of the process by which support equipment design is specified to determine how usage of this Z306 paint on a heater required to operate above the recommended service temperature of the paint should be conducted. Additionally review criteria for involvement of material specialists as part of process for specifying design and fabrication of support equipment as well as flight hardware.

R7 - Additional investigations should be conducted as to whether the age of the paint in question was a significant contributing factor to incident. LMA has indicated that they intend to conduct calorimeter tests of both the paint involved in the incident (used past manufacturer recommended shelf life) and new material within its recommended shelf life. Materials practices related to use of dated materials past manufacturer recommended shelf life should be reviewed once the results of this test have been completed.

7. Index of Referenced Material

The following material was reviewed by the team (in most cases, as provided by the MRO Project) over the course of the assessment. It is included on a CD-ROM accompanying the release of this report for future reference. Charles Whetsel, team lead, may be contacted for additional copies as needed.

Reference 1: Presentation material –"TVAC_Contam_2005_04_12.ppt" dated 12 April 2005, by Tim Gasparrini

Reference 2: Presentation material - "marci_ctx_contam_vgs.ppt" dated 08 April 2005 and email from Mike Malin to Charles Whetsel dated 12 Apr 2005.

Reference 3: Presentation material – "HiRISE TV Contam Assess.ppt" (authors R. Fenolia / J. Bergstrom) dated 08 April 2005

Reference 4: Presentation material - "CRISM_telecon_04-08-05a1.ppt," by Peter Bedini, dated 08 April, 2005.

Reference 5: Email correspondence – "Assessment of CRISM contamination," Scott Murchie to Richard Zurek (based on analysis of David Humm, CRISM calibration specialist), dated 14, April 2005.

Reference 6: Presentation Material: "MCS Contamination Response.ppt" dated 08 April, 2005.

Reference 7: Email correspondence: "Contamination on ONC Optics," Steve Synnott to John Duxburry, 06 April, 2005.

Reference 8: Email correspondence: "Question re: MARCI cleaning/calibration," Mike Malin to Charles Whetsel, dated 12 April, 2005

Reference 9: JPL Interoffice Memorandum IOM Q066, M. Anderson to Brian Blakkolb, 29 March 2005

Reference 10: Contamination Control Plan for the MARS RECONNAISSANCE ORBITER, Document No. MRO-01-0013, 1 May 2002.

Reference 11: MARS RECONNAISSANCE ORBITER SYSTEM CONTAMINATION CONTROL PLAN, Document No. JPL-D-24373, MRO-21-329 Rev. 3, 25 July 2003.

Reference 12: Presentation Material: "Aerobraking Temperatures.ppt," dated 14 April, 2005

Reference 13: Mars Reconnaissance Orbiter Pre-Environmental Readiness Review Presentation Package (with supplemental presentation; R. Becker, JPL), 9 November 2004.

Appendix F. Response by the Mars Reconnaissance Orbiter (MRO) Project to the Actions Recommended by the MRO T/V Anomaly Independent Assessment Team

DRAFT

Report to the JPL Chief Engineer By Richard Zurek MRO Project Scientist
June 13, 2005

Preamble:

This report summarizes the response to date of the Mars Reconnaissance Orbiter (MRO) Project to the recommendations of the MRO T/V Anomaly Independent Assessment Report (Final, Revision H, dated April 20th, 2005).

This summary focuses on those recommendations addressing the recovery of the science payload from the contamination event that occurred in February 2005 during the MRO system thermal/vacuum (T/V) testing. That recovery is nearly complete. All instruments have sampled surfaces where the suspected contamination could lead to degraded performance of the instrument. Surrounding blankets and exterior surfaces have been cleaned. Tests showed that only the Mars Color Imager (MARCI) had optics that required cleaning and that was successfully done (as confirmed by test) in April before the spacecraft was shipped to KSC in preparation for launch in August, 2005.

The one remaining instrument issue is the potential contamination of the solar calibration target attached to the Mars Climate Sounder (MCS). This target was exposed during the T/V anomaly. However, this target has a specially prepared surface that was extensively calibrated during ground testing. A major concern has been that any cleaning agent capable of removing contamination vapor-deposited during the T/V anomaly could also alter the calibration target surface in a way that would invalidate the ground calibration. Re-calibration of the target would require its removal from the instrument; the risk to damaging the target further was sufficiently high that it was decided to investigate potential mitigations that would not require such removal. This was the situation at the time of the Independent Assessment Report, so several of their investigations naturally focused on this issue. The present report summarizes the latest findings for recovery of MCS; however, work still continues at this time.

The report is organized with statements of the action recommended in the assessment report, followed by a brief summary of the MRO Project's response. An appendix gives a more detailed overview of the MCS activities. Two actions were focused on understanding details of the T/V anomaly and possible changes in procedures to prevent future anomalies of this type. Preliminary action to prevent future anomalies has been undertaken, though formal documentation of this has received lower priority at this time.

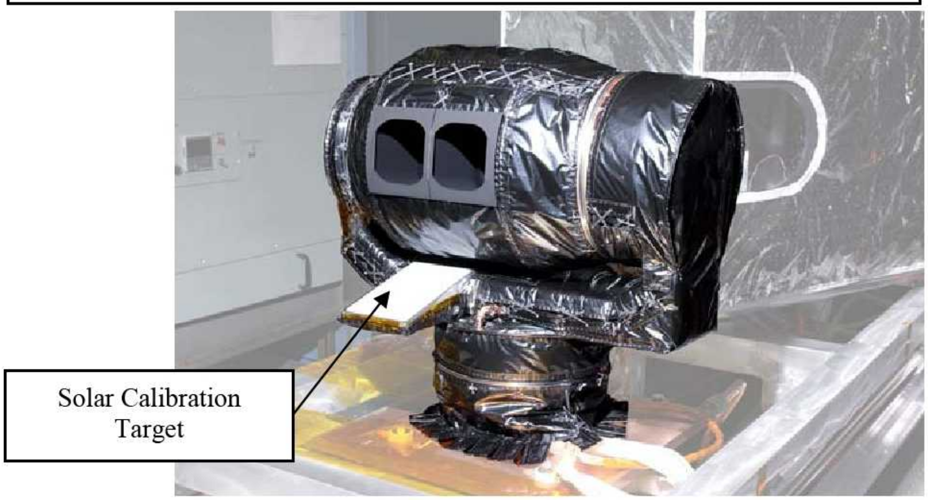
Summary Response to Actions Recommended in the Independent Assessment Report

R1- Proceed with planned experiments to contaminate and clean additional materials samples representative of MCS solar calibration target (SCT), to enable an informed decision regarding the risks and benefits of MCS target cleaning.

Response: The planned experiments were conducted but led to unexpected results. In brief, tests with the flight instrument did not establish that the cleaning approach (brushing with acetone) developed and tested using re-contaminated samples was effective and safe when used on the flight MCS Solar Calibration Target (SCT).

- From the start, a major concern has been that a cleaning method which removes the contamination may alter the target surface in such a way that invalidates the ground calibration already performed.
- A severe limitation in testing material samples representative of the MCS SCT is that only samples discarded earlier in the manufacturing process of the target were available, until just last week (June 9) when a discard of material trimmed from the flight target before calibration was located.

The Mars Climate Sounder (MCS) Instrument



R2- It is up to the MCS team to assess the trade-offs and to decide to clean or not. Effort should be made to recover calibration as much as possible from observations of the moon (during early cruise) and Mars (during cruise and orbital phases). This will impact cruise and orbital operations. It will require a significant and on-going effort to quantify calibration uncertainties.

Response: The MRO Project is now considering two possible actions:

1) Cleaning the target with the developed acetone-brushing technique. Further analysis by the MCS Team must:
   - Demonstrate that the acetone-brushing will not alter the SCT surface properties or introduce contamination.
     - This is being tested using a recently discovered off-cut of the flight SCT plate which will be cleaned and then visually inspected and characterized using an UV-Laser Induced Native Fluorescence (UV- LINF) technique
   - Validate that the visually observed brightening of the cleaned test area on the SCT is sufficient evidence that enough contamination is on the target to warrant cleaning, given the risk of altering the surface

- Validate that the inability of the UV-LINF measurements of a test area on the flight SCT to detect differences before and after cleaning do not indicate that no contamination has occurred (i.e., it is a limitation of the measurement)
-

2) Implementing an Engineering Change Request (ECR) to conduct activities in early and mid-cruise in which the MCS instrument views its SCT. Observations at L+22 days would characterize the target before it receives much direct solar UV radiation, known to darken the contamination material detected after system Thermal/Vacuum (T/V) testing.
   - Until L+30 days or so, the SCT is largely in shadow. During the rest of cruise, exposure to direct sunlight has been estimated at 50 hours.

R3- To address possible risk from re-volatilization of parts exposed to contamination, verify that no instrument or spacecraft heaters or electronics parts were exposed to contaminant, or clean or replace if there were any.

Response: The only known area of significant contamination that has not been cleaned is the MCS Solar Calibration Target. The SCT is not expected to be a significant source of contamination, given its small size and the absence of any indication of a substantial contamination of this area.

- Acetone brushing would have produced a more pronounced brightening of the SCT test area than was observed, if the SCT were to be a major source of contamination.

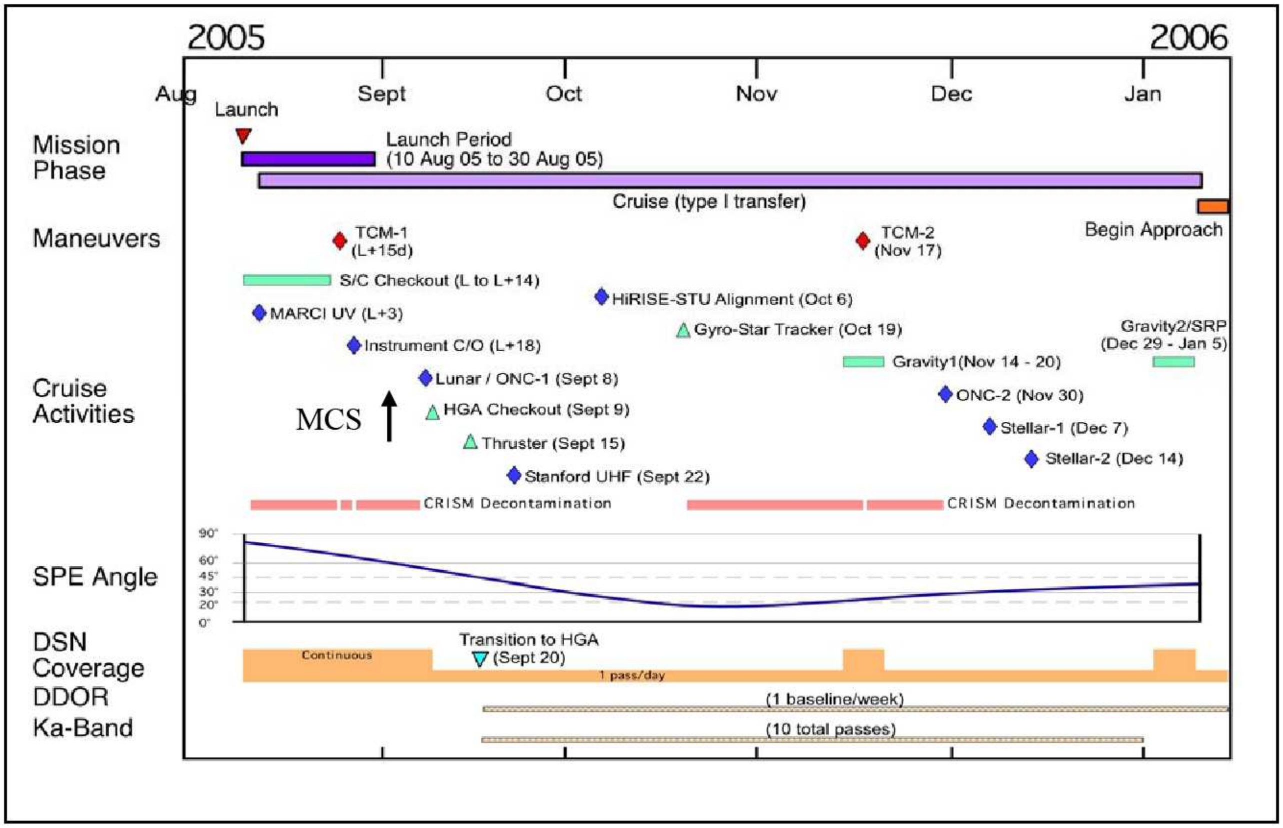
R4- General comment for all instruments: All instruments should consider additional in-flight calibrations or test that might reveal the effects of contamination that was missed prior to launch or that may result from re-volatilization of material during aerobraking or some other phase of the mission. An example of such a test might be imaging a bright star to measure instrument PSF or transmission.

Response: No new calibrations have been added or are being considered for instruments other than MCS. That is because contamination concerns and the need to check geometric alignments, to test focus mechanisms, and to provide a basic radiometric check had already led to the design of several major calibration activities in cruise and the ability to conduct stellar calibrations from Mars orbit. [See Tables 1a,b.]

- The most sensitive instrument, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), has a cover which remains closed until the transition orbit, following aerobraking and just prior to the start of the Primary Science Phase.

- All instruments have heaters that are used as decontamination heaters, and all five optical instruments use them early in Cruise (before the first course correction maneuver).

Table 1a: MRO Cruise Activity Timeline



Note: Labeled arrow indicates time proposed for observation of MCS Solar Calibration Target.

Table 1b

MRO Calibration Activities during Cruise

Calibration Activity	Time Frame	Instruments	Objectives
MARCI UV	Aug 13 (L+3)	MARCI	Radiometric in the UV bands
L+18 Instrument Checkout	L+18,19 (Aug 28-29)	HiRISE, CTX, CRISM, MARCI, SHARAD, MCS, ONC	Verify payloads survived launch and operate as expected. SHARAD EMI test
Lunar–OC and ONC-1 Calibrations	Sept 7-8 (L+28, 29)	HiRISE, CTX, ONC, IMUs and Star Trackers	HiRISE and CTX: stray light geometric, radiometric. ONC: geometric
Electra/Stanford Test	Sept 21-22 (L+41,42)	EUT (UHF Relay)	Characterize antenna pattern with stable Earth source
Gravity-1 Calibration	Nov 14-20 (L+95-101)	DSN tracking in support of TCM-2	Create baseline far from gravity fields
ONC-2 Calibration	Nov 30 (L+112)	ONC	Geometric
Stellar-1 Calibration	Dec 6-7 (L+119)	HiRISE, CTX, ONC, IMUs and Star Trackers	Geometric, Radiometric
Stellar-2 Calibration	Dec 13-14 (L+126)	HiRISE, CTX, SHARAD, MCS, CRISM, EUT, MARCI, IMUs and Star Trackers	Geometric, Jitter, EMI
Gravity-2 Calibration	Dec 29-Jan 5 (L+141-148)	Uses s/c tracking data	Create baseline far from gravity fields

HIRISE = High Resolution Imaging Science Experiment
CTX= Context Imager; MARCI= Mars Color Imager
CRISM= Compact Reconnaissance Imaging Spectrometer for Mars
MCS= Mars Climate Sounder; ONC= Optical Navigation Camera
SHARAD= Shallow Radar

Note: MCS SCT in-flight characterization not yet approved; assessment by MRO Project in progress.

R5 - Evaluate merits of measuring the IR properties of contaminated MLI and use in thermal model correlation (if available – otherwise consider value of re-contaminating materials specifically for this purpose).

Response: The spacecraft and payload surfaces (except for the MCS solar target) that were exposed to contamination during the spacecraft thermal event have been cleaned.

- The contaminated witness plate optic being used to support the MCS SCT contamination recovery activities is possibly the only remaining sample of the T/V contamination.

Re-contamination of materials in order to test effects on IR properties has not been pursued. The experience of the JPL group working with the MCS team in preparing contaminated samples is that it is difficult to get exact replication of the event. Suspected, though not demonstrated, causes of this difficulty are differences in:

- The time-history of the temperatures of the source and of surfaces where vapor-deposition; and/or
- The source of the contamination, as its composition may reflect subtle differences in the curing process of the paint.

R6 – A review of the process by which support equipment design is specified to determine how usage of this Z306 paint on a heater required to operate above the recommended service temperature of the paint should be conducted. Additionally review criteria for involvement of material specialists as part of process for specifying design and fabrication of support equipment as well as flight hardware.

R7 - Additional investigations should be conducted as to whether the age of the paint in question was a significant contributing factor to incident. LMA has indicated that they intend to conduct calorimeter tests of both the paint involved in the incident (used past manufacturer recommended shelf life) and new material within its recommended shelf life. Materials practices related to use of dated materials past manufacturer recommended shelf life should be reviewed once the results of this test have been completed.

Response to R6 and R7: Preliminary investigations of how this particular batch of Z306 paint came to be used and exposed to high temperatures have been conducted. Analyses of the paint are being conducted. Several processes are under review and lessons learned have been identified. This work is still ongoing, but has been given lower priority than expediting the recovery from the T/V contamination event.

Appendix: MCS Contamination Recovery Activities

Background

The Solar Calibration Target (SCT) on MCS is used to provide quantitative measurements of the solar radiation reflected from the Martian atmosphere and surface, particularly in the polar regions. The net radiation absorbed by carbon dioxide ice in the Martian polar regions is balanced by the latent heating/cooling of condensation/ sublimation of CO_2 ice. Thus, a quantitative measure of solar energy reflected from the seasonal frost can be translated directly into the amount of mass exchanged between the atmosphere and surface on Mars on a seasonal cycle. On Mars, as much as 30% of the atmospheric mass is exchanged in this manner. Understanding this process is key to understanding the processes operating both in the present climate and throughout Martian history.

Non-volatile-residue (NVR) wipes from the top (as positioned during the T/V contamination event) of thermal blankets on the MCS drum indicated the presence of vapor-deposited contamination, consistent with contamination deposited elsewhere on the spacecraft from the T/V heater plate. During the T/V contamination event the MCS solar calibration target (SCT) was oriented approximately vertically, somewhat orthogonal to the likely path of outgassed molecules. However, given the extended area of the contamination source (i.e., the T/V heater plate) and its detection on the nearby instrument thermal blanket, it was reasonable to assume that some contamination was present on the SCT.

As reported, the MCS team decided against removal of the solar calibration target from the instrument because such removal entailed a moderate-to-high probability that such removal would irreparably damage the target. The back-up target, the last of 6 targets originally produced for flight, beginning with Mars Observer and continuing through Mars Climate Orbiter, was judged to be significantly inferior to the flight target mounted on the instrument, even given the potential contamination of the latter. Thus, it was not an option to mitigate damage to the flight target during removal for cleaning or during in-place cleaning by use of the remaining target. Because of its inferior quality, this last target also had not undergone the full calibration procedure. Finally, it was judged not to be possible to manufacture and calibrate a new target as the original manufacturer was not available and preparation and (ground) calibration of the target entailed a lengthy process that could not be done in the time available to make a 2005 launch.

MRO project management concurred with the MCS team's recommendation to not remove the SCT from the flight instrument; that instrument, with its solar calibration target plate attached, remains in place on the spacecraft now at KSC. The MCS team then proceeded to evaluate possible *in situ* cleaning and verification processes.

Preparations for MCS SCT Cleaning

Because of the risk involved in removing the target from the instrument (discussed above), only in situ cleaning processes were considered. Cleaning of the spacecraft thermal blankets by LMA had indicated that there were cleaning agents that were effective if some pressure were applied to remove contamination. Concerns for cleaning the SCT were: 1) that the cleaning agent and/or cleaning action would alter the physical surface of the calibration target, thereby invalidating its ground calibration, and 2) that the solvent might "soak through" and weaken the bonding material holding the solar calibration target plate to its mechanical support or the temperature device used to calibrate changes in flight to the reflectivity of the SCT.

To test cleaning procedures and agents, it was decided to contaminate several samples of the material used to make the SCT plate. These samples had been parts of various larger plates used to test manufacture procedures for the flight target. They had been prepared at various times and their surfaces had been subjected to similar, though not identical, treatments to those used in the early stages of manufacturing the final set of SCT plates. Because of these differences, several target samples were chosen for testing. In adapting the target to the needs of MCS, the original target was trimmed; it was thought that the trimmed pieces had been discarded at the time of removal. They have since been located and are being used in ongoing tests of the cleaning method.

To simulate the T/V contamination event as closely as possible, the cold plate used in T/V testing was selected as a contamination source. This plate had been painted with the same material and cured along with the heater plate at the same time, but it had not been heated to high temperatures and so was not believed to have outgassed the material that contaminated the spacecraft and payload in T/V. The plate was sent by LMA to JPL where it was sectioned and then heated to the same temperatures achieved by the heater plate during T/V. NVR wipes and analysis indicated that contamination was deposited on the (4) MCS target samples, although not in the same quantity (approximately a factor of 5 less) as was measured on the MCS thermal blankets after the T/V event. Furthermore, there was an indication that the UV-visible spectrum of contamination was somewhat different from that recovered from the spacecraft, indicating that similar materials were present, but in different proportions. Later, this would prove to be a critical difference.

All samples were first cleaned by exposure to an oxygen-atom plasma known to be effective in the removal of organic material. A number of the samples were then contaminated by vapor deposition in vacuum. Parts of several samples were cleaned using acetone and a brushing procedure. Despite the small amount of contamination assayed, there were distinct visible differences between cleaned and non-cleaned areas. Examination using UV-Laser Induced Native Fluorescence (UV-LINF) indicated that most contamination had been removed in a single cleaning, but a residual film remained even after multiple cleanings. This was established by comparison with an uncontaminated sample. Examination of cleaned areas of the sample material using optical microscopy indicated no change in the structure of the surface materials. Furthermore, the high rate of evaporation of the acetone using in the cleaning technique insured that there would be no "soaking through" of the solvent.

Activities at KSC

Armed with the UV-LINF and a proven cleaning technique, the MCS team journeyed to KSC in late May. The UV-LINF equipment was used to characterize the spectral response of the MCS SCT in 6 spectral channels ranging from 0.29 to 0.55 microns. A small area on the edge of the SCT plate, outside the field of view of the instrument's detectors, was measured before and after cleaning with the acetone brushing. Two unexpected results were immediately noted:

1. The spectral signature of the SCT was different than the signatures of the contaminated samples, the original non-contaminated samples; and those samples cleaned with the oxygen atom technique.

2. The cleaning produced no measurable change in 5 of the 6 UV-LINF channels and an ambiguous result in the 6-th channel (at 0.29 microns). However, there was a subtle brightening of the test surface compared to the rest of the target, as observed visually after cleaning.

A second cleaning was attempted on the test area and there was some indication by the UV-LINF that there was more fluorescence than before, indicating that the cleaning may actually have degraded the surface or possibly contaminated it. In any case, there was no evidence of a substantial contamination of the surface. The MCS Team confirmed that the UV-LINF was working properly by re-measuring contaminated samples that had been measured at JPL and subsequently sent to KSC. Given the situation, it was decided not to clean the working area of the SCT, and the team returned to JPL.

Further Testing at JPL

The discovery of material that had been trimmed from the flight SCT plate permitted UV-LINF measurements that showed the trimmed material had a similar spectral signature to the flight SCT surface and that both were different from the samples that had been used in the contamination tests. Differences were ascribed to the final stages of manufacturing of the flight SCT, in which the surface was significantly roughed; as a result it appears darker (more precisely, it scatters light more diffusely, as desired) than either the samples or the flight spare, which was not taken through the final processing step.

Given the lack of detection of spectral change when the test area was cleaned, it was decided to measure the last remaining witness optic that still had contamination vapor-deposited on it during the T/V anomaly. These measurements were then compared to measurements of a clean (standard) witness optic. No change was detected, except possibly in the shortest wavelength channel. That is, except in one channel, the UV-LINF had been shown to be insensitive to the actual contamination, resulting in the following conclusions:

1) The flight SCT could have a thin film of contamination that was vapor-deposited during the T/V anomaly and the acetone-brushing could have removed it.
    a. Evidence for the thinness of the deposit and for its possible removal is given by the slight brightening of the target after cleaning, OR
    b. The acetone-brushing was contaminating the target in some way so that it brightened the test area where it was applied.
2) The contamination produced using what had been the cold plate from T/V testing had produced a different contamination composition than the heater plate had produced during T/V.
    a. The UV-LINF technique could easily detect the presence of contaminant produced in the JPL tests, but not of the T/V contaminant.
    b. Differences could be due to slight differences in curing, but LMA records indicate that both the cold and heater plates were painted with the same material and cured in the same chamber at the same time.

Current Activities (June 13-15)

A third of the area of the piece trimmed from the flight SCT is being cleaned to examine its visual properties and then to characterize its surface with the UV-LINF. Visual, optical microscopy and UV-LINF measurements may be able to establish that the properties of the cleaned piece remain the same as before cleaning when no contamination is present. In this case, the MCS Team may conclude that acetone-brushing of the surface will not harm the surface, and that the UV-LINF measurements at KSC of the SCT test area after cleaning were simply due to measurement noise.

If this is not the case, then no cleaning will be attempted. If the acetone brushing produces no change, then the next step is to determine whether the SCT is in fact significantly contaminated. This may have to rely on visual inspection alone, but the short-wavelength UV-LINF channel data are also being re-examined. The residue from the acetone cleaning was captured and has been returned to JPL for analysis; this may also be decisive in judging whether there is significant contamination of the SCT.

A new attempt at cleaning the SCT will be tried only if the acetone brushing can be judged to be safe and even then only if it is judged that there is sufficient residue on the SCT to warrant the risk of cleaning.

In the meantime, the proposed observation of the SCT early in cruise before solar UV may darken a contaminated surface and then later in cruise is being pursued in order to characterize any change that may occur during flight.

Appendix G. List of Acronyms

Ar	Argon
BCM	Battery Control Module
CO_2	Carbon Dioxide
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
IPA	Isopropyl Alcohol
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LaRC	Langley Research Center
LMA	Lockheed Martin Aerospace
MARCI	Mars Color Imager
MCS	Mars Climate Sounder
MLI	Multi-Layer Insulation
MRB	Material Review Board
MRO	Mars Reconnaissance Orbiter
MRR	Mission Reconfiguration Review
MSFC	Marshall Space Flight Center
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NCE	NESC Chief Engineer
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
NVR	Non-Volatile Residue
RGA	Residual Gas Analyzer
SCT	Solar Calibration Target
SMARR	Safety & Mission Assurance Readiness Review
SPRT	Super Problem Resolution Team
T/V	Thermal/Vacuum
T/V AIAT	T/V Anomaly Independent Assessment Team
TGA/FTIR	Thermogravimetric Analysis/Fourier Transform Infrared
TQCM	Thermoelectric Quartz-Crystal Contamination Monitor
UHF	Ultra High Frequency
UV	Ultraviolet
UV-LINF	UV-Laser Induced Native Fluorescence
WPAFB	Wright Patterson Air Force Base

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The NESC was requested by the NASA Jet Propulsion Laboratory (JPL) to conduct an independent review of the Mars Reconnaissance Orbiter (MRO) Thermal/Vacuum (T/V) Anomaly Assessment. Because the anomaly resulted in the surface contamination of the MRO, selected members of the Materials Super Problem Resolution Team (SPRT) and the NASA technical community having technical expertise relative to contamination issues were chosen for the independent review. The consultation consisted of a review of the MRO Project's reported response to the assessment findings, a detailed review of JPL technical assessment final report, and detailed discussions with the JPL assessment team relative to their findings.

15. SUBJECT TERMS
MRO, Thermal/Vacuum, SPRT, Aeroglaze

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