NASA/TP—2016–218228

Advanced Exploration Systems Atmosphere Resource Recovery and Environmental Monitoring

J. Perry, M. Abney, R. Conrad, A. Garber, D. Howard, M. Kayatin, J. Knox, R. Newton,
K. Parrish, and M. Roman
Marshall Space Flight Center, Huntsville, Alabama

N. Toomarian
Jet Propulsion Laboratory, Pasadena, California

September 2016

The NASA STI Program…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>

- E-mail your question via the Internet to <help@sti.nasa.gov>

- Phone the NASA STI Help Desk at 757–864–9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681–2199, USA

NASA/TP—2016–218228

Advanced Exploration Systems Atmosphere Resource Recovery and Environmental Monitoring

J. Perry, M. Abney, R. Conrad, A. Garber, D. Howard, M. Kayatin, J. Knox, R. Newton,
K. Parrish, and M. Roman
Marshall Space Flight Center, Huntsville, Alabama

N. Toomarian
Jet Propulsion Laboratory, Pasadena, California

National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

September 2016

Acknowledgments

Special thanks to the Atmosphere Resource Recovery and Environmental Monitoring project team for advancing humanity's reach to the stars.

NASA Ames Research Center
John Hogan, Mark Kliss, Brian Koss, Gary Palmer, Tra-My Justine Richardson, and Jason Samson

NASA Glenn Research Center
Juan H. Agui, Robert Green, and Marit Meyer

NASA Jet Propulsion Laboratory
Water Module: Ara Chutjian and John MacAskill; *Microbial Monitoring*: Venkateswaran Kasthuri and Parag Vaishampayan; *RaSCal*: Margie Homer and Abhijit Shevade; *TELS*: Siamak Forouhar and Ryan Briggs; *mGM*: Murray Darrach, Richard Kidd, Stojan Madzunkov, Rembrandt Schaefer, and Juri Simci; *Management*: Benny Toomarian, Luis Arenas, Mary Romejko, and David Eisenman

NASA Johnson Space Center
Jeffrey Sweterlitsch, Glenn Waguespack, Kevin Lange, Imelda Stambaugh, Craig Broerman, Ariel Macatangay, Bruce Conger, and Molly Anderson

NASA Kennedy Space Center
Orlando Melendez, Oscar Monje, Anna Maria Ruby, Chris Bershad, Ray Wheeler, and Michele Birmele

NASA Marshall Space Flight Center
Morgan Abney, Grace Belancik, Kenny Bodkin, Shawn Breeding, Paul Carothers, Robert Coker, Charlie Cooper, Ramona Cummings, Dan Donovan, Christopher Evans, Ken Frederick, Anne Garber, Vicki Garcia, Hernando Gauto, Carlos Gomez, Rudy Gostowski, Zachary Greenwood, Melanie Holloway, Kathryn Horton-Mullins, David Howard, Enrique Jackson, Mallory Johnston, J. Scott Jones, Robert Jones, Matthew Kayatin, David Kincaid, James Knox, Curtis Leslie, Tony Mahathey, Mike McCormick, Lee Miller, Karen Mitchell, Charles Morrison, Robert Newton, Keith Parrish, David Patterson, Jay Perry, Ronald Renfroe, Monsi Roman, Richard Schunk, Joseph Scott, Alan Shapiro, Jim Sledd, Christine Stanley, Kevin Takada, John Thomas, Diep Trinh, David Watson, Phillip West, Tom Williams, Wendy Williams, and Charles Wingard

TRADEMARKS

Available from:

NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681–2199, USA
757–864–9658

This report is also available in electronic form at
<http://www.sti.nasa.gov>

EXECUTIVE SUMMARY

BACKGROUND

Future crewed long-duration space missions will need to maintain conditions for human habitability similar to the International Space Station (ISS) yet with important differences. These differences include: (1) lack of proximity to Earth for which a ground-based logistics resupply model is impractical, (2) limitations for delivering mass to the exploration destination will require a smaller habitable platform with accompanying equipment mass and volume constraints that are more challenging than the ISS, and (3) the breadth of possible exploration destinations is wide requiring a highly flexible overall approach that can accommodate a range of mission designs.

Affordability is central to enabling future deep space exploration missions. One method for addressing affordability across a range of exploration destinations that culminate in a crewed mission to Mars is to minimize destination-specific technical development. For life support systems (LSS), this means developing equipment and process architectures that enable a safe, affordable, and sustainable human presence in space regardless of the mission destination or habitable platform. Strategically, engineering an LSS consisting of a common functional core scarred for modular capability enhancement provides necessary flexibility across mission and vehicle architectures. The resulting common design minimizes mission-specific design, development, test, and evaluation (DDT&E) as well as sustaining infrastructure. Resource savings can be realized via a single technology development path. Exploration program risk related to the LSS can be reduced by acquiring operational experience as the flexible, modular LSS architecture is incrementally deployed in the deep space exploration mission progression from early efforts beyond low Earth orbit (LEO) through missions to Mars.

ATMOSPHERE RESOURCE RECOVERY AND ENVIRONMENTAL MONITORING PROJECT OBJECTIVES, GOALS, AND APPROACH

The Atmosphere Resource Recovery and Environmental Monitoring (ARREM) project was charged by the Advanced Exploration Systems program to develop the process technology and system architectural concepts needed to support future deep space exploration missions. The ARREM project was managed by NASA Marshall Space Flight Center and supported by five participating NASA field centers—Ames Research Center, Glenn Research Center, Jet Propulsion Laboratory, Johnson Space Center, and Kennedy Space Center. Each NASA field center provided leadership and subject matter expertise to assess, mature, and functionally demonstrate atmosphere revitalization subsystem (ARS) and environmental monitoring subsystem (EMS) technologies and varying levels of integration. The project's primary objective was to mature ARS and EMS technologies to reduce future exploration flight program design, development, test, and engineering (DDT&E) risks. This was to be accomplished by modifying ISS-derived components, process technologies, and subsystem architectures to achieve lower lifecycle costs and increase functional reliability and capability for future crewed space exploration missions beyond LEO. The ARREM project team focused the project on the targeted functional improvement of state-of-the-art (SOA) physico-chemical systems currently in use aboard the ISS as well as strategically targeted development and infusion of promising ARS and EMS technologies from other NASA programs such as the Small Business Innovation Research (SBIR) program, academia, and commercially available products. The ARREM team worked to develop, demonstrate, and functionally test leading process technology candidates and subsystem architectures to meet or exceeded current requirements.

The ARREM project's technology development plan was aligned with the findings documented in NASA technology development roadmaps. Capabilities enabled by the ARREM project cross-multiple deep space exploration destinations and consider platforms that include but are not limited to deep space transportation vehicles, cis-lunar space habitats, surface habitats, surface landers, multi-mission space exploration vehicle platforms, and pressurized surface rovers.

The ARREM project's main objectives were to mature ARS and EMS technologies at the component through the integrated subsystem levels that build on the ISS SOA to reduce risk, lower lifecycle cost, and validate alternative process design and subsystem architectural concepts to meet exploration mission functional figures of merit and fill exploration capability gaps. The technical goal was to significantly improve efficacy, safety, and reliability over the ISS SOA as the basis for comparison.

The specific ARREM project goals were the following:

- Demonstrate the evolution of the ISS state of the art ARS architecture and process design via targeted advancements that benefit ISS operations in LEO and exploration missions beyond LEO.

- Assess the feasibility of process architectures that offer the greatest potential to maximize process technology and equipment commonality across a variety of mission scenarios and vehicle concepts anticipated under a flexible exploration framework.

- Advance the process architecture technical maturity level as defined by NPR 7123.1 to the mid-5 range with a goal to reach the mid-6 range.

- Develop a set of resource recovery capabilities that can be added in modular fashion to a common set of core ARS and EMS equipment to allow mission planners flexibility to extend crewed mission durations without compromising core equipment functionality.

- Infuse new and/or improved ARS and EMS technologies into crewed space exploration programs.

The project accomplished these goals via functionally demonstrating components, assemblies, and integrated subsystem architectures at varying technical maturity and levels of integration. All demonstration testing was accomplished using ground-based facilities. Yet, flight operations experience gained from the ISS environmental control and life support system (ECLSS) was considered to help guide the project's technical scope. The best-suited testing, demonstration, and evaluation methods, facilities, and level of integration for each candidate process technology and/or integrated subsystem architecture was based on priorities, availability, needs, and resources. These objectives and goals were accomplished while providing maximum opportunities for the NASA workforce to engage in hands-on development projects that benefit the space exploration missions of the United States and potentially realize significant spinoff for applications on Earth.

The ARREM project conducted a series of integrated tests and architectural trade assessments encompassing expected exploration mission requirements and constraints to achieve these goals. The actual technical maturity level achieved by the project depended on available resources, funding allocations, budget modifications and shortfalls, changes in customer direction, new requirements, and/or unknown risks. The Technology Readiness Levels (TRLs) are defined by NASA Systems Engineering Processes and Requirements (NPR 7123.1, app. E). For the ARREM project, the subsystem-level TRL focused on function and, to a lesser extent, on fit, form, and software. Software development was limited to mimicking ISS flight algorithms using commercial laboratory software products and developing basic functional algorithms for new hardware components and processes. In some cases, flight software algorithms were modified to achieve functional flexibility that may benefit future exploration missions. The functional maturity demonstrated at the assembly level typically achieved TRL 5 and at the integrated subsystem level achieved TRL 4, primarily due to using ad hoc equipment in the integration. None of the test articles are considered high on the maturity scale for fit or form. Presently, the exploration vehicle specifications do not contain mass and volume allowances; therefore, to fully reach TRL 5 and higher, the fit, form, and software aspects in addition to the functional aspect must all be high on the maturity scale.

The individual technology development tasks that comprised the ARREM project were broad based and diverse. Yet, each task carried the common goals to identify and mature the most promising process technologies that build from an ISS-derived architecture and physical configuration basis to achieve greater reliability and operational economies as well as ensure that the natural environments encountered by their host spacecraft can be endured. The ARREM project's technical approach was developed over several years as a functional method to technology maturation evolved within NASA's research and technology organizations. Technical task focal areas were the following:

- Carbon dioxide (CO_2) removal and management.
- Oxygen supply and recovery.
- Trace contaminant control.
- Particulate removal and disposal.
- Environmental monitoring.

Cross-cutting technical areas included systems analysis, process simulation, and test and evaluation.

PROJECT ACCOMPLISHMENTS AND RECOMMENDED ARCHITECTURE

The ARREM project used a functional trade space approach to focus broad-based technical challenges and guide priorities. Consistent with a flexible crewed space exploration strategy, the

ARREM project demonstrated the capability to extend the functional utility of a common set of core ARS and EMS equipment by integrating them with reliable, cost-effective resource recovery capabilities that will allow long-duration human exploration missions to be sustained with minimal dependence on Earth-based logistics support. Testing at progressively complex levels of integration was the primary method used to reach the project's goals. Technical accomplishments toward the project's goals include the following:

- Developed and tested integrated subsystem architectures and compared performance versus the ISS atmosphere revitalization (AR) architecture establishing the feasibility of ISS-derived AR for deep space missions.

- Developed and refined integrated atmosphere revitalization subsystem (ARS) technology testing capabilities that are a national asset.

- Developed and implemented screening and performance characterization methods for adsorbent media used for bulk and residual drying, CO_2 removal, and trace contaminant control.

- Assessed bulk and residual drying functional trade space options that found that the ISS carbon dioxide removal assembly (CDRA) desiccant bed to be the most mass and volume efficient solution as well as indicating that the desiccant bed size can potentially be reduced for exploration class missions to save mass and volume.

- Advanced technical maturity of the methane (CH_4) plasma pyrolysis assembly (PPA) through third generation and demonstrated integrated operational performance with the Sabatier development unit (SDU).

- Tested trace contaminant control (TCC) component configurations as well as evaluated commercial adsorbent and catalyst product candidates leading to subsystem mass and volume reduction.

- Improved understanding of trace contaminant propagation through the integrated ARS architecture that provided confidence that there is minimal risk associated with volatile organic compound (VOC) poisoning of CO_2 reduction catalysts.

- Gained improved insight on CO_2 and bulk/residual drying sorbent mechanical properties and adsorption capacities as well as matured analytical predictive techniques.

- Demonstrated operational simplifications for the ISS oxygen generation assembly (OGA) that may reduce future mass and volume and address limited life hydrogen (H_2) sensor issues to reduce logistics demand.

Details on the technical accomplishments produced by the ARREM project are contained in the Technical Publication narrative.

The ARREM project took the best-performing technical results from the developmental task areas and incorporated them in three integrated functional test series summarized in the table. Each test series built upon the results from previous testing series. Testing began with the ISS ARS architecture to establish a basis for comparison and progressed through two alternative architecture test series.

Technical development efforts conducted by the ARREM project as well as future process development have benefited from multiple contributing technology maturation efforts. The primary process design concepts investigated by the AES ARREM project originated from an alternative component integration concept proposed in 2004. During the periods before 2004 and between 2004 and 2010, a number of environmental control and life support (ECLS) process technology development and maturation projects made notable progress in the CO_2 removal, TCC, CO_2 reduction, oxygen generation, and environmental monitoring functional areas. Based on this contributing development work and the work conducted by the ARREM project, AR and EM subsystem architectures were formulated for further development.

Future Work to Mature the Recommended Architecture

While significant progress has been realized toward an ARS and EMS architecture for exploration missions, the focused developmental work necessary to refine the architecture and address key gaps are the following:

1. General Operations and Integration—Refine the subsystem architecture and validate it via integrated testing.

2. Carbon Dioxide Removal Function—Select durable adsorbent media and develop adsorbent bed designs that address reliability concerns associated with the ISS SOA configuration.

3. Trace Contaminant Control Function—Continue surveying the commercial adsorbent and oxidation catalyst offerings for promising performance advances.

4. Carbon Dioxide Reduction Function—Continue developmental efforts for alternative CO_2 reduction technologies, particularly those based on the Bosch process, for incorporation into future process design concepts.

5. Oxygen Generation Function—Demonstrate and validate operational changes to the SOA OGA process technology.

6. Environmental Monitoring Function—Develop an environmental monitoring architecture, including performance requirments, and functionally integrate it with an ARS architecture.

7. Autonomous Control and Process Health Monitoring—Develop an integrated control and equipment health monitoring capability.

8. Equipment Fit and Form—Address equipment component size and integration relative to overall fit and form to fully realize the potential for performance benefits, particularly relating to mass and volume reduction as well as in-flight maintainability.

CONCLUSION

An ARS architecture that builds on the framework established by the ISS AR process design has been developed and demonstrated. Demonstration results show that the physical architecture is feasible and areas have been identified to improve reliability while reducing overall mass, volume, and complexity.

The core subsystem architecture's performance meets or exceeds the performance attained by the ISS ARS. Mass reduction of at least 35 kg with accompanying volume reduction compared to the ISS ARS were demonstrated, before attempting mission-specific sizing, by integrating the TCC components in a different manner and modifying oxygen generation assembly operational parameters. Sizing the equipment for a four crewmember metabolic load will provide additional mass and volume reduction compared to the SOA basis. Additional work is necessary relative to equipment sizing to fully quantify the potential mass and volume reduction over the SOA.

Opportunity exists to demonstrate a higher degree of resource mass closure by incorporating CH_4 post-processing techniques. Further reliability for the O_2 generation equipment architecture is possible by incorporating contemporary cell stack membrane materials and incorporating operational lessons learned from ISS flight experience. Continued work on oxygen loop closure and contemporary electrolytic cell stack designs is required.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND SYMBOLS

ACFB	adsorbent cartridge fixed bed
AES	Advanced Exploration Systems (program)
ANITA	analyzing interferometer for ambient air
AR	atmospheric revitalization
ARC	Ames Research Center
ARREM	Atmosphere Resource Recovery and Environmental Monitoring (project)
ARS	atmosphere revitalization subsystem
ASepA	acetylene separation assembly
ASRT	Allied-Signal Research and Technology
C_2H_2	acetylene
C&DH	command and data handling
CDRA	carbon dioxide removal assembly
CH_4	methane
CM	crewmember
CMA	carbon dioxide management assembly
CO	carbon monoxide
CO_2	carbon dioxide
COTS	commercial off-the-shelf
CPM	combustion product monitor
CRA	carbon dioxide reduction assembly

LIST OF ACRONYMS AND SYMBOLS (Continued)

DDT&E	design, development, test, and evaluation
dev	developmental
EChamber	environmental control chamber
ECLS	environmental control and life support
ECLSS	environmental control and life support system
EM	environmental monitoring
EMS	environmental monitoring system/subsystem
EVA	extravehicular activity
4BMS	four-bed molecular sieve
4EU	engineering unit, 4th generation
FTIR	Fourier transform infrared
FY	fiscal year
GC	gas chromatography
GRC	Glenn Research Center
H_2	hydrogen
HCl	hydrogen chloride
HCN	hydrogen cyanide
He	helium
HEOMD	Human Exploration and Operations Mission Directorate
HPHPO2	high pressure/high purity oxygen
HTCO	high temperature catalytic oxidizer

LIST OF ACRONYMS AND SYMBOLS (Continued)

H_2O	water
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEO	low Earth orbit
LfFB	low-flow fixed bed
LSS	life support system
MCA	major constituent analyzer
M-COA	Microlith-based thermal catalytic oxidizer assembly
MEMS	micro-electromechanical systems
MePA	methane purification assembly
μTAM	micro-total atmosphere monitor
MS	mass spectroscopy
MSD	mass selective detector
MSFC	Marshall Space Flight Center
N_2	dry nitrogen
NASA	National Aeronautics and Space Administration
NH_3	ammonia
O_2	oxygen
OCT	Office of the Chief Technologist

LIST OF ACRONYMS AND SYMBOLS (Continued)

OGA	oxygen generation assembly
OGS	oxygen generation system
PACRATS	Payloads and Components Real-time Automated Test System
PC	preconcentrator
PCGC	preconcentrator-gas chromatograph
PCO	photocatalytic oxidation
PEM	proton exchange membrane
PID	proportional-integral-derivative
PLOT	porous layer open tubular
PLSS	portable life support system
POIST	performance and operational issues system testbed
PPA	plasma pyrolysis assembly
PSA	pressure-swing adsorption
PSM	power supply module
QCL	quantum cascade laser
qPCR	qualitative polymerase chain reaction
RASCal	rapid analysis self-calibrating
RK-38	trade name
RSA	rotary separator assembly/accumulator
R2FD	Resource Recovery Functional Demonstration (test)
SBAR	sorbent-based atmosphere revitalization

LIST OF ACRONYMS AND SYMBOLS (Continued)

SBIR	Small Business Innovation Research (program)
SDU	Sabatier development unit
SEOS	solid electrolysis oxygen system
SMAC	spacecraft maximum allowable concentration
SMT	System Maturation Team
SOA	state of the art
TCC	trace contaminant control
TCCS	trace contaminant control subassembly
TELS	tunable laser absorption
TP	Technical Publication
TRL	Technology Readiness Level
UOP	Universal Oil Products (LLC Subsidiary of Honeywell)
VCAM	vehicle cabin atmosphere monitor
VEM	vehicle environmental monitor
VMS	volatile methyl siloxanes
VOC	volatile organic compound
WBS	Work Breakdown Structure

TECHNICAL PUBLICATION

ADVANCED EXPLORATION SYSTEMS ATMOSPHERE RESOURCE RECOVERY AND ENVIRONMENTAL MONITORING

1. INTRODUCTION

Future crewed long-duration space missions will need to maintain conditions for human habitability similar to the International Space Station (ISS) yet with important differences. These differences include: (1) lack of proximity to Earth for which a ground-based logistics resupply model is impractical, (2) limitations for delivering mass to the exploration destination will require a smaller habitable platform with accompanying equipment mass and volume constraints that are more challenging than the ISS, and (3) the breadth of possible exploration destinations is wide, requiring a highly flexible overall approach that can accommodate a range of mission designs.

Affordability is central to enabling future deep space exploration missions. One method for addressing affordability across a range of exploration destinations that culminate in a crewed mission to Mars is to minimize destination-specific technical development. For life support systems (LSSs), this means developing equipment and process architectures that enable a safe, affordable, and sustainable human presence in space regardless of the mission destination or habitable platform. Strategically, engineering an LSS consisting of a common functional core scarred for modular capability enhancement provides necessary flexibility across mission and vehicle architectures. The resulting common design minimizes mission-specific design, development, test, and evaluation (DDT&E) as well as sustaining infrastructure. Resource savings can be realized via a single technology development path. Exploration program risk related to the LSS can be reduced by acquiring operational experience as the flexible, modular LSS architecture is incrementally deployed in the deep space exploration mission progression from early efforts beyond low Earth orbit (LEO) through missions to Mars.

1.1 Advanced Exploration Systems Program Summary

In the United States Government fiscal year (FY) 2012, the National Aeronautics and Space Administration's (NASA's) Human Exploration and Operations Mission Directorate (HEOMD) established a technology maturation program dedicated to higher maturity technology development. The Advanced Exploration Systems (AES) program grew from NASA's Exploration Technology program and associated needs assessments for the Constellation program.[1] The AES program is a vital part of NASA's technology investment plan to execute projects that target high-priority capabilities necessary for successful crewed space exploration missions beyond LEO.[2] Technical capability areas pursued by the AES program include environmental control and life support (ECLS), habitation, crew mobility, logistics reduction, and extravehicular activity systems. Priorities of the AES program include integrating and functionally demonstrating prototype system architectures as early as possible. The projects pursued by the AES program are short term, hands on, and product focused. The technical maturity target was Technology Readiness Level (TRL) 6 as defined by NPR 7123.1B.[3] The NASA AES program's leadership team implemented a lean cross-Agency program guided by NPR 7120.5E that streamlined project management.[4]

1.2 Atmosphere Resource Recovery and Environmental Monitoring Project Summary

The Atmosphere Resource Recovery and Environmental Monitoring (ARREM) project was charged by the AES program to develop the process technology and system architectural concepts needed to support future deep space exploration missions. The ARREM project was managed by NASA Marshall Space Flight Center (MSFC) and supported by five participating NASA field centers—Ames Research Center (ARC), Glenn Research Center (GRC), Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), and Kennedy Space Center (KSC). Each NASA field center provided leadership and subject matter expertise to assess, mature, and functionally demonstrate atmosphere revitalization subsystem (ARS) and environmental monitoring subsystem (EMS) technologies and varying levels of integration.

The ARREM project was one of several projects within the AES program related to ECLSSs. The project's primary objective was to mature ARS and EMS technologies to reduce future exploration flight program DDT&E risks. This was to be accomplished by modifying ISS-derived components, process technologies, and subsystem architectures to achieve lower lifecycle costs and increase functional reliability and capability for future crewed space exploration missions beyond LEO. The ARREM team focused the project on the targeted improvement of state-of-the-art (SOA) physicochemical systems currently in use aboard the ISS as well as strategically targeted development and infusion of promising ARS and EMS technologies from other NASA programs such as the Small Business Innovation Research (SBIR) program, academia, and commercially available products. The ARREM team worked to develop, demonstrate, and functionally test leading process technology candidates and subsystem architectures to meet or exceeded current requirements.

The ARREM project's technology development plan was aligned with the findings documented in NASA technology development roadmaps and explorative destination studies.[5–9] Capabilities enabled by the ARREM project cross multiple deep space exploration destinations and consider platforms that include but are not limited to deep space transportation vehicles, cis-lunar space habitats, surface habitats, surface landers, multi-mission space exploration vehicle platforms, and pressurized surface rovers.

Sections 2 through 7 summarize the ARREM project plans, objectives, and results for developing and demonstrating process technologies and architectures for ARS and EMS to meet the technical demands of future crewed missions beyond LEO.

2. TECHNICAL OBJECTIVES, GOALS, AND CONTENT OVERVIEW

The ARREM project's main objectives were to mature ARS and EMS technologies at the component through the integrated subsystem levels that build on the ISS SOA to reduce risk, lower lifecycle cost, and validate alternative process design and subsystem architectural concepts to meet exploration mission functional figures of merit and fill exploration capability gaps. The technical goal was to significantly improve the efficacy, safety, and reliability over the ISS SOA as the technical platform and basis for comparison.

The specific goals of the ARREM project were the following:

- Demonstrate the evolution of the ISS state-of-the-art ARS architecture and process design via targeted advancements that benefit ISS operations in LEO and exploration missions beyond LEO.

- Assess the feasibility of process architectures that offer the greatest potential to maximize process technology and equipment commonality across a variety of mission scenarios and vehicle concepts anticipated under a flexible exploration framework.

- Advance the process architecture technical maturity level as defined by NPR 7123.1 to the mid-5 range with a goal to reach the mid-6 range.

- Develop a set of resource recovery capabilities that can be added in modular fashion to a common set of core ARS and EMS equipment to allow mission planners flexibility to extend crewed mission durations without compromising core equipment functionality.

- Infuse new and/or improved ARS and EMS process technologies into crewed space exploration missions.

The project accomplished these goals via functionally demonstrating components, assemblies, and integrated subsystem architectures at varying technical maturity and levels of integration. All demonstration testing was accomplished using ground-based facilities. Yet, flight operations experience gained from the ISS ECLSS was considered to help guide the project's technical scope. The best-suited testing, demonstration, and evaluation methods, facilities, and level of integration for each candidate process technology and/or integrated subsystem architecture was based on priorities, availability, needs, and resources. These objectives and goals were accomplished while providing maximum opportunities for the NASA workforce to engage in hands-on development projects that benefit the space exploration missions of the United States and potentially realize significant spinoff for applications on Earth.

The ARREM project conducted a series of integrated tests and architectural trade assessments encompassing expected exploration mission requirements and constraints to achieve these goals. The actual technical maturity level achieved by the project depended on available resources, funding allocations, budget modifications and shortfalls, changes in customer direction, new requirements, and/or unknown risks. The TRLs are defined by NASA Systems Engineering Processes and Requirements (NPR 7123.1, app. E). For the ARREM project, the subsystem-level TRL focused on function and, to a lesser extent, on fit, form, and software. Software development was limited to mimicking ISS flight algorithms using commercial laboratory software products and developing basic functional algorithms for new hardware components and processes. In some cases, flight software algorithms were modified to achieve functional flexibility that may benefit future exploration missions. The functional maturity demonstrated at the assembly level typically achieved TRL 5 and at the integrated subsystem level achieved TRL 4, primarily due to using ad hoc equipment in the integration. None of the test articles are considered high on the maturity scale for fit or form. Presently, the exploration vehicle specifications do not contain mass and volume allowances; therefore, to fully reach TRL 5 and higher, the fit, form, and software aspects in addition to the functional aspect must all be high on the maturity scale.

The individual technology development tasks that comprised the ARREM project were broad-based and diverse. Yet, each task carried the common goals to identify and mature the most promising process technologies that build from an ISS-derived architecture and physical configuration basis to achieve greater reliability and operational economies as well as ensure that the natural environments encountered by their host spacecraft can be endured. The ARREM project's technical approach was developed over several years as a functional method to technology maturation evolved within NASA's research and technology organizations.[10–13] Technical task focal areas were the following:

- Carbon dioxide (CO_2) removal and management.
- Oxygen (O_2) supply and recovery.
- Trace contaminant control (TCC).
- Particulate removal and disposal.
- Environmental monitoring.

Cross-cutting technical areas included systems analysis, process simulation, and test and evaluation. Figure 1 shows a simplified ARREM project structure and the project's relationship with the AES program.

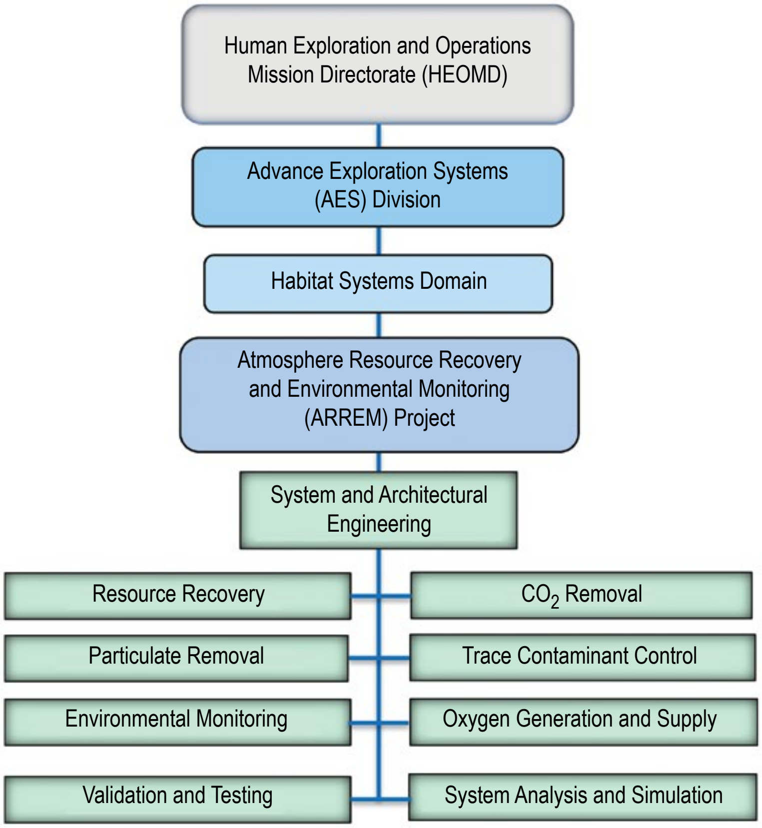


Figure 1. Simplified ARREM project structure.

3. TECHNICAL APPROACH

Examining the exploration framework as an integrated whole consisting of key functional trade spaces as shown in figure 2, opportunities were identified for demonstrating the concept of common core ARS and EMS technologies and equipment in a modular ‘building block’ fashion across a range of crewed mission designs lasting up to 1 year duration or longer.[14] The ARREM project generated technical products including, but not limited to, test results and lessons learned that are useful in guiding follow-on technology maturation and in establishing a technical foundation upon which exploration partnerships and contract strategies can be formulated.[15–17] Details on these technical products are found in the publications listed in appendix A.

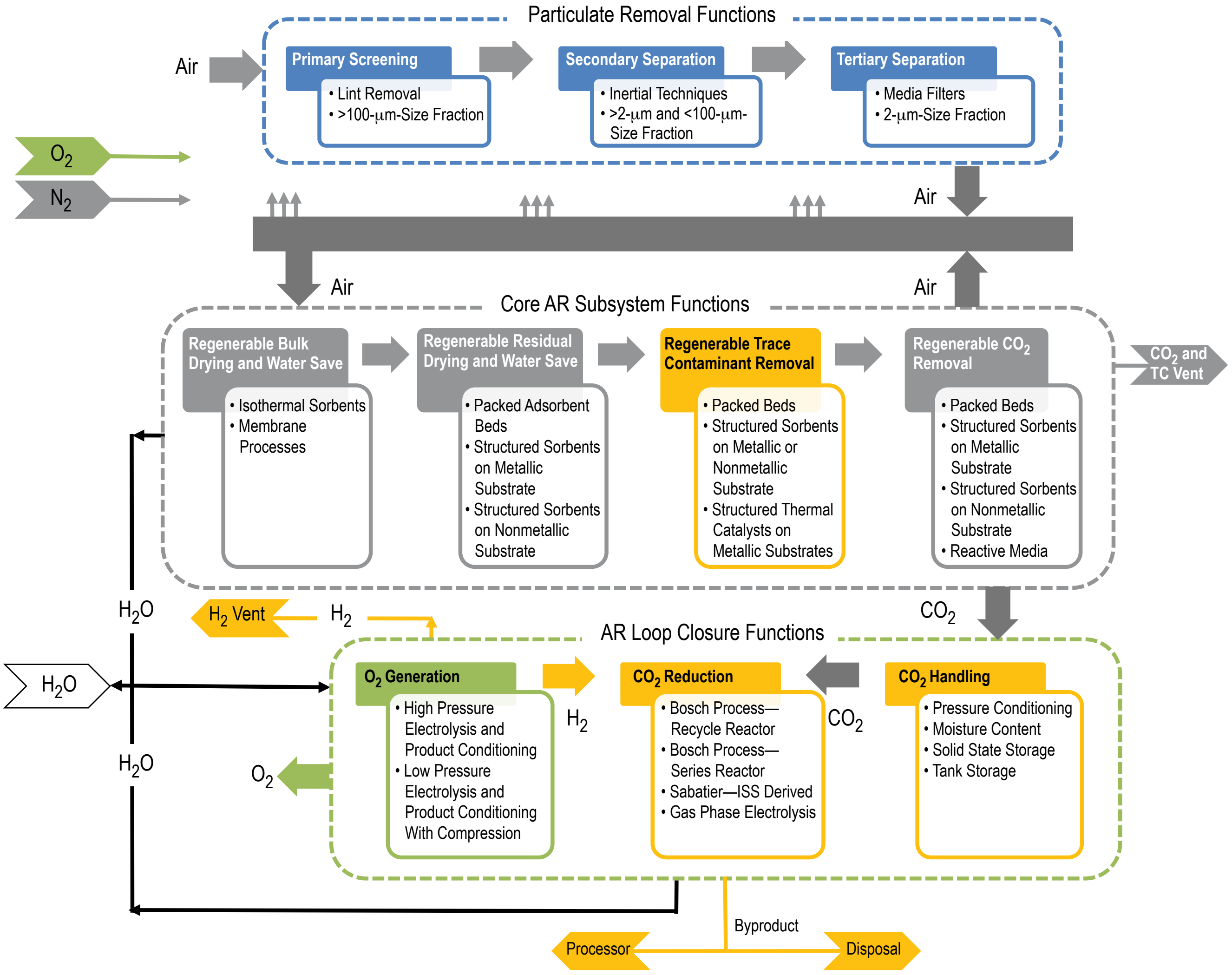


Figure 2. ARS and EMS functional trade space concept.

An initial assessment was conducted on the technical state-of-the-art ARS and EMS relative to their suitability for application to future space exploration initiatives beyond LEO. Findings from this assessment are as follows:[12]

- Most basic atmospheric revitalization (AR) process technologies such as adsorbent media and catalysts used aboard the ISS for the core AR CO_2 and TCC functions are suitable for extension to long-duration missions. However, many adsorbents and catalysts in use aboard the ISS have become commercially obsolete and new candidates must be evaluated for space flight suitability. Adsorbent and catalyst material durability as well as their long-term commercial availability must be addressed. Continued work is necessary to address obsolescence issues that will arise because of the time that will elapse between ISS technical solutions and future exploration missions.

- TCC sorbents and oxidation catalysts used aboard the ISS are suitable for long-duration missions; however, advances in ammonia sorbent capacities and power savings associated with engineered catalyst substrates can significantly reduce the size and power required for TCC equipment.

- Water electrolysis-based oxygen generation used aboard the ISS is suitable for long-duration mission applications. Components of the ISS-developed O_2 generator need modification to reduce electrolysis cell stack membrane fluorine leaching to meet reliability and maintainability demands of such missions. Operational changes can simplify equipment with resulting reliability and maintainability improvements.

- Sabatier-based CO_2 reduction under demonstration on board the ISS is suitable for missions lasting longer than 60 days. Techniques for further processing Sabatier-produced gases must be developed to further extend crewed mission duration beyond LEO to over 1 year by driving O_2 recovery closer to 100%.

- Atmosphere revitalization and environmental monitoring (EM) equipment deployed aboard the ISS require evaluation to determine whether modification is necessary to accommodate the recommended range of cabin atmospheric pressure and composition conditions encountered across exploration design reference mission concepts.

- Fit and form aspects of ISS-derived AR and EM equipment designs will change significantly to comply with detailed deep space exploration vehicle and mission requirements.

- If lower cabin pressure is selected for future vehicles, blowers and heat exchangers must be evaluated to determine whether redesign is necessary to accommodate lower cabin atmospheric pressures. As well, some wetted materials may have to be replaced to be compatible with O_2 partial pressures over 30%. In addition, some equipment on board the ISS may have to add safety containment or change process operating conditions to accommodate lower cabin atmospheric pressures.

3.1 Multi-Platform Commonality Benefits

Additional evaluation was conducted with respect to the core ARS components shown in figure 2. This evaluation found benefits for adopting an overall highly flexible, modular architectural approach for the core functional components early in LSS development to avoid duplicating

DDT&E resource expenditures as well as maintaining multiple hardware versions. These benefits can be illustrated by considering the technology development paths that were being pursued for the CO_2 control function during the Constellation program. The Constellation program consisted of several vehicle and habitat platforms that all required a core CO_2 removal function. A common multivehicle hardware concept could offer developmental and lifecycle cost economies to the program.

Orion, the first crewed element to enter into development, adopted an amine-based, vacuum-swing regenerable bed to adsorb both CO_2 and humidity from the cabin and vent it overboard. Lunar lander studies indicated that the CO_2 removal technology under development for the Orion project would likely meet its mission needs but that some degree of resizing might have been in order. A corresponding development for the extravehicular activity (EVA) portable life support system (PLSS) design also included an amine-based pressure-swing regenerable CO_2 removal component, but the small volume of the suit and packaging constraints within the PLSS drove that equipment design concept towards unique sizing and operating cycles such that EVA-derived components were not practical for use to address cabin-level functional requirements.

Lunar surface exploration using a pressurized rover would be relatively short in duration and likely would have been supportable with Orion-like or PLSS-like CO_2 removal process technology. However, the large number of excursions envisioned over an entire lunar campaign would have led to substantial consumable losses—both water (H_2O) and CO_2. The pressurized rover therefore adopted a 'water save' approach on the front end of amine-based, vacuum-swing beds to capture cabin humidity condensate for eventual return to an outpost element for reclamation. Other pressurized rover studies considered the feasibility of utilizing PLSS vacuum-swing beds in a variety of configurations. Those studies suggested that such an approach appeared feasible but would require more detailed analysis and testing to prove the efficacy.

Lunar outpost habitats, dedicated to meeting the long-duration demands of lunar surface campaigns, were envisioned to be the centers in which resource recovery capabilities would be located. To enable O_2 recovery, habitat CO_2 removal technologies were envisioned to be physical adsorption-based due to the comparatively more energy-efficient, temperature-swing adsorption process compared to the amine-based, vacuum-swing regeneration process that required a large vacuum pump. The amine cannot be heated due to substrate thermal stability and amine volatility issues, while pelletized physical adsorption media, such as zeolites, are thermally stable. Long-term concerns also existed for amine-based, vacuum-swing regenerable processes due to the amine sorbent's ammonia (NH_3) offgassing characteristics that place an added load on the TCC equipment. As well, since the amine requires a minimum amount of moisture in the process gas stream to be effective, water carry-over into downstream CO_2 reduction processes can cause thermodynamic inefficiencies. As a result, the Constellation project was headed in a direction of having a minimum of three and as many as five different design solutions for performing the CO_2 removal function, most of which were difficult and inefficient for optimizing resource recovery.

From these considerations, benefits are evident to developing a common core CO_2 removal equipment design that enables loop closure without requiring additional CO_2 conditioning yet can operate in an open-loop configuration. Equipment size, fit, and form must address the most challenging vehicle design challenge. Modular equipment for providing loop closure functions can then be added according to mission design needs.

3.2 Requirements and Figures of Merit

The SOA program requirements pertaining to ARS performance were reviewed to determine the most applicable set of project requirements for bounding analysis assumptions and testing conditions. This assessment is summarized in appendix B. Five ISS program specifications were reviewed and requirements were established for the project in six functional areas.

To assist with assessing technical progress beyond mere TRL, figures of merit were developed by the ARREM project for the project's primary functional elements. As these figures of merit became better defined during the project's second year, the responsibility for maintaining them was transferred to the NASA ECLS System Maturation Team (SMT). The figures of merit became components in the technical roadmap development headed by the ECLS SMT. ARREM project subject matter experts assisted the ECLS SMT with both maintaining the figures of merit and developing the technology maturation roadmaps. The technology maturation roadmaps provide additional detail to implement NASA's technical area roadmap 6 (TA06). Figures of merit used by the ARREM project are provided in appendix C.

3.3 Test Articles and Facilities

Existing developmental test equipment providing the core ARS functions was chosen for the initial ARREM project testing basis shown in figure 2. The assortment of test equipment includes the following:

- ISS developmental test articles.
- Developmental test articles from the former NASA Exploration Technology Development project.
- Equipment deliverables from SBIR contracts.
- Equipment developed under the NASA Office of the Chief Technologist (OCT) projects.

The test equipment was integrated and tested, in appropriate combinations, under conditions selected to encompass anticipated exploration habitable platform cabin atmospheres and loads.

Consistent with a flexible crewed space exploration strategy, the ARREM project demonstrated the capability to extend the functional utility of a common set of core ARS and EMS equipment by integrating them with reliable, cost-effective resource recovery capabilities that allow long-duration human exploration missions to be sustained with minimal dependence on Earth-based logistics support. The basis for the development was the SOA ARS equipment already operational in the ISS, as well as the products of other programs/projects within and outside of NASA. This provided the project a basis for comparison for improvements that could involve enhancements and/or replacements. Supplemental equipment for accomplishing resource recovery was sized, integrated, and operated along with core ARS equipment to demonstrate the capability to perform reliable, efficient resource recovery without compromising the reliability or performance of core functions and demonstrating seamless application of the core ARS equipment architecture as the central component of a total integrated system capable of resource recovery.

Candidate resource recovery functions included capabilities to recover latent water (humidity) collected from cabin atmospheres for eventual purification into potable water as well as capabilities to recover O_2 from metabolic CO_2. Such resource recovery capabilities can provide substantial mission lifecycle savings not just in deep space habitats but also potentially in smaller vehicles such as multi-mission space exploration vehicles and pressurized surface rovers that might find repeated use over an extended exploration campaign.

The ARREM project partnered with the ISS program to support chamber-based testing activities being performed on behalf of the ISS program which included the integration of developmental test articles representing the current ISS state-of-the-art ARS functions. Test articles included a carbon dioxide removal assembly (CDRA), oxygen generation assembly (OGA), Sabatier-based carbon dioxide reduction assembly (CRA), and trace contaminant control subassembly (TCCS). The integrated testing provided detailed ground-based performance data, including the fate of environmental contaminants as they enter and potentially pass through the CDRA and into the high-temperature CRA reactor. This testing not only supported the ISS program but also set a performance basis for comparison for alternative process technologies performing core environmental control functions. The integrated test setup also provided an integrated platform within to demonstrate alternative technologies and component configurations in an orderly fashion under a variety of conditions.

The ARREM project's environmental monitoring task, summarized in figure 3, focused on developing airborne chemical monitors for spacecraft applications as well as microbial monitoring technologies. The selection will be based on the technologies that can meet the needed assessments of the LSS and their compatibility with exploration mission demands.[18,19]

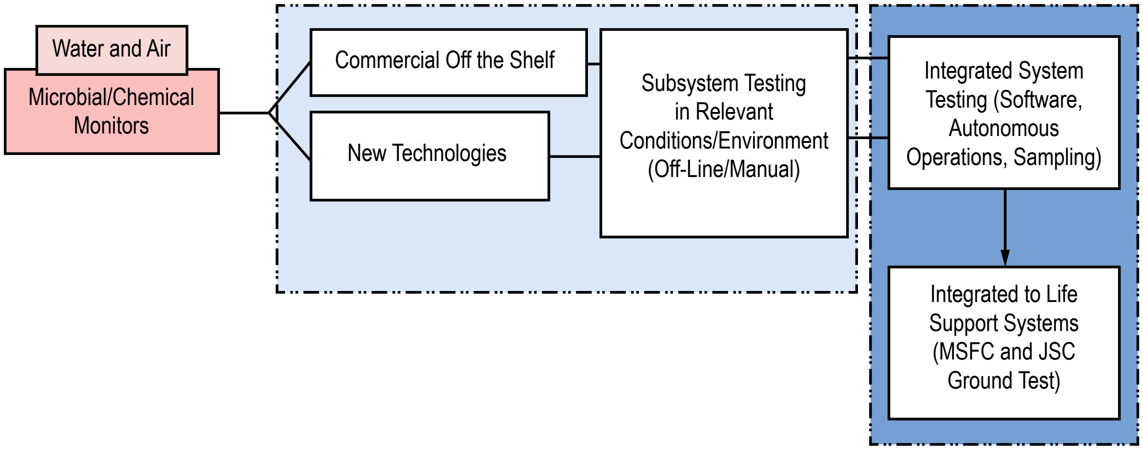


Figure 3. Environmental monitoring task structure.

Existing test articles, shown in figure 4, that build from the ISS program developmental equipment served as the starting basis. Equipment and components incorporating alternative process technologies considered as worthy candidates suited for advancing core functional capabilities beyond the current ISS SOA were incorporated into the testing architecture to the maximum extent possible.

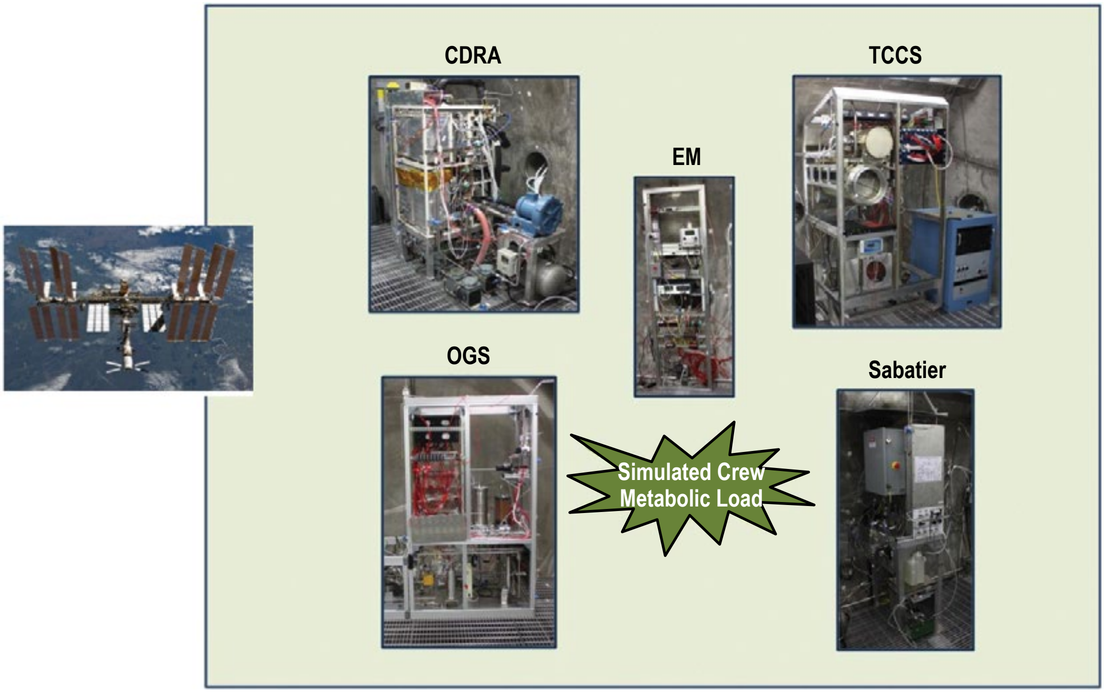


Figure 4. ISS program developmental equipment used for integrated testing.

Because these test articles came from various sources and had achieved varying degrees of maturity, they were not precisely matched with regard to size, interfaces and operating characteristics, and performance levels. Despite this reality, valid integrated test and evaluation results were achieved with only modest hardware adaptations.

Test articles included a CDRA, Sabatier CRA, OGA, and TCCS. Initial testing used the equipment arranged in the ISS ARS architecture to provide detailed ground-based performance data, including further insight on the fate of environmental contaminants as they enter and potentially pass through the CDRA and into the high-temperature CRA reactor. This testing established the basis for comparison against which alternative technologies under evaluation by the ARREM project were compared.

The ARS and EMS equipment were integrated within the environmental control chamber (EChamber) at MSFC (shown in fig. 5) and tested using combinations of pressure, O_2 partial pressure, CO_2 partial pressure, and humidity that are representative of a range of anticipated cabin atmospheric conditions and loads. The EChamber test setup provided an integrated platform within which alternative technologies and component configurations were installed in an evolutionary manner to understand how they may improve the ARS and EMS functions of the ISS. The most mature candidate process technologies were tested and evaluated against the corresponding ISS SOA functions in cycles 1 and 2 integrated tests.

Figure 5. A view of the EChamber for integrated ARS and EMS testing showing equipment complement.

4. PROJECT TECHNICAL ELEMENT OVERVIEW AND RESULTS

To properly address the challenges of each LSS functional area, a multi-disciplinary team of subject matter experts conducted focused technology development work with complementary support provided by experts located within NASA, other government agencies, federal laboratories, academia, and industry. Technology maturation was conducted for resource recovery, particulate filtration, trace chemical contaminant removal, humidity removal and recovery, and CO_2 removal. Environmental monitoring equipment concepts were developed that are responsive to needs based directly on crew health as well as LSS monitoring and process control.

Technical tasks that comprise the ARREM project addressed LSS core functional areas summarized in figure 6. Tasks were broad based and diverse, but all carried the common goal of identifying and maturing advanced life support process technologies that build from the ISS architecture and equipment characteristics to achieve greater reliability and are also capable of enduring the natural environments encountered by their host spacecraft for long-duration missions beyond LEO. The functional areas to be developed or enhanced through testing and analyses by the ARREM project are described by the following summary.

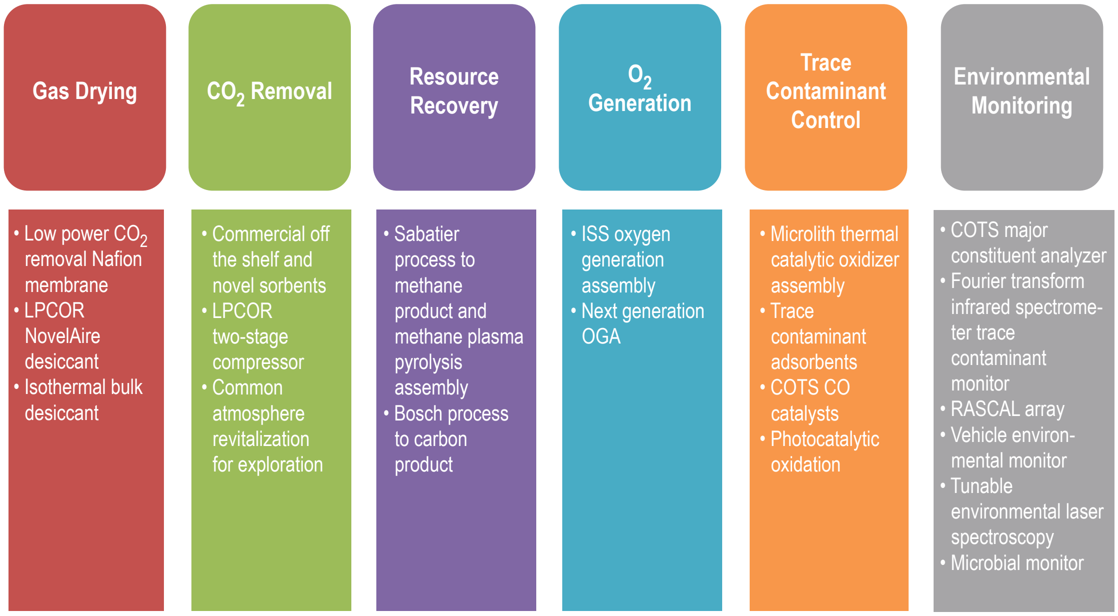


Figure 6. ARREM project functional development areas.

All developmental tasks were unified by performance testing to characterize targeted LSS process technology, validate process technology models, and simulate technical product performance on board the ISS and application to deep space exploration vehicles and habitats will be conducted.

The testing and evaluation was conducted at varying degrees of complexity starting at the component level up to the fully integrated subsystem level. The ARREM project testing objectives follow:

- To assess the feasibility of candidate improvements to the SOA LSS and their operational concepts.

- To advance, demonstrate, and integrate LSS technologies that enable future space exploration activities.

- To develop long-range, critical LSS technologies to provide the foundation for a broad set of future exploration capabilities.

- To provide an infusion path for promising game-changing LSS technologies.

The ARREM project systematically and carefully evaluated technologies at specific points of their development to determine the right approach for maturity using a stage-gate methodology.[11] Subscale and/or full-scale equipment were employed as appropriate as maturity progressed. Test articles more closely approached the specified maturity goals in function primarily and, to a lesser extent, to fit and form as the technology advanced through the maturation stages. Varying degrees of integration were employed at each maturity level. Before promoting a technology from one maturity stage to another, the effort is reviewed at each stage gate to determine if progress toward completing specific technical content is sufficient. Based on results of the stage assessment, a decision is made to promote the process technology to the next maturity level, retain it at its present level, place the development on hold, demote to a lower level, or terminate the effort. Once a technology development maturity level of TRL 5 has been demonstrated, the product is ready for infusion into a flight project development effort for further maturity (through the TRL 9 level) into flight hardware and usage as a flight-validated technology application.

4.1 Carbon Dioxide Removal and Gas Drying

Building on the ISS CDRA process architecture, this task evaluated SOA and candidate sorbents as well as opportunities to optimize the SOA CO_2 removal equipment architecture and process conditions. This task sought improved, more durable CO_2 sorbents to improve the reliability of the CO_2 removal process. Energy-efficient structured sorbents and other alternative sorbents that may prove more durable than SOA adsorbent media were identified and evaluated. Membrane and physical adsorption processes were investigated for process air drying. The best-performing options were considered for incorporating into an exploration CO_2 removal process architecture. Technical areas emphasized for the CO_2 removal function were to identify and evaluate durable physical adsorbents for CO_2 removal and evaluate process air-drying techniques and architectures.

An expanded effort to screen and characterize sorbents was undertaken as part of the ARREM project. Simple tests to screen existing and emerging sorbents for structural stability and working capacity can quickly identify sorbents with the highest potential. More detailed structural stability testing may then be conducted on selected sorbents. The equilibrium capacity and kinetics of high potential sorbents may also be characterized to further differentiate between them and to provide data for computer simulations. Where feasible, CO_2 removal and associated air-drying system development under the ARREM project took advantage of the benefits offered by recent developments in multi-physics computer modeling and simulation. Simultaneous simulation of physics such as mass transfer, heat transfer, and fluid dynamics has become possible via commercial packages. Historically, simultaneous solution of these disparate underlying equations has been elusive. Conventional and multi-physics modeling and simulation efforts have already provided key guidance to process design efforts. These simulation efforts complemented the experimental sorbent evaluation efforts in addition to benefiting from the experimental efforts.

4.1.1 Tasks and Methods Summary

The combination of comprehensive sorbent screening and characterization and computer modeling and simulation may be used to complement hardware fabrication and testing as opposed to the more traditional approach of hardware fabrication and testing alone. The process design approach used for the ARREM project integrated these three facets of design with the goals of increasing efficiency and improving the likelihood of attaining a successful design. The steps in the overall approach follow:

(1) Screen candidate sorbents and compare directly with SOA sorbents. Characterize promising sorbent candidates and select sorbent for life support process of interest.

(2) Develop new or modify existing mathematical models and computer simulations for processes of interest.

(3) Via simulation, optimize cyclic test configuration (e.g., canister design and cycle parameters).

(4) Fabricate test article and execute test series. Evaluate sorbent efficacy to make go/no go decision for continuation to next larger scale. Validate and refine simulation.

(5) For promising sorbents, repeat steps (3) and (4) while increasing the scale until a full-scale component for the process of interest is attained.

(6) Incorporate the full-scale system into the integrated AR configuration and evaluate via integrated testing.

(7) Provide technology solution to spacecraft flight system developer.

During the ARREM project in general, and in particular, the CO_2 removal and associated air-drying elements, preexisting technology approaches populate the trade spaces for the functions of bulk dryer, residual dryer, and CO_2 removal. As these subsystems are at various technology readiness levels, the general process design approach described above may not be fully applicable in some cases. However, experience thus far has indicated that, even for full-scale hardware, computer modeling and simulation can lead to significant performance gains. Similarly, alternative sorbent chemistry could be employed to improve the performance of an existing, proven sorbent format or separation process. The bulk and residual dryer functions are identified within the ARREM project as core ARS functions, along with regenerable CO_2 removal. Under bulk drying, the functional trade space included two candidate process technologies: isothermal bulk desiccant and Nafion® membrane processes. Under residual drying, the functional trade space included two candidate process technologies: the Microlith^{TM} water module and NovelAire® structured sorbent residual dryer.

4.1.2 Sorbent Screening

Screening analyses are methods used to rapidly obtain an understanding of (1) differential pressure, (2) effective sorbent capacity, and (3) structural strength for the operating conditions of interest (i.e., flow regime, sorbate partial pressures, and temperatures). The information gained from these analyses is used to determine if further, more time intensive sorbent characterization methods are warranted. Methods included sorbent particle size analysis (differential pressure influence), thermogravimetric analysis to determine working capacity, single pellet crush strength, breakthrough evaluation, equilibrium adsorption capacity isotherm determination, and bulk crush strength.

4.1.3 Bulk and Residual Drying Downselection

Trade assessments were performed in 2012 and 2013 to identify the most favorable option among mature dryer technologies for air-drying upstream of the CO_2 removal function provided by the ISS four-bed molecular sieve (4BMS) CDRA. The purpose of these trades was to determine what dryer technologies should be further developed and tested in the ARREM program. Phase 1 of the study determined the need for immediate further development in order to support ARREM cycle 2 testing, particularly the fabrication of a full-scale isothermal bulk desiccant test article. The determination is based on data from the existing test articles operated in the specific configurations considered in this study. It was noted that the existing test articles may not be optimized for these specific CO_2 removal applications. The second phase of this study provided the opportunity to optimize the technologies for each specific configuration via computer simulation and/or test article modification. At the end of phase 2, recommendations were made with respect to the configuration for cycle 2 testing.

Based on data from existing hardware, the four-bed CDRA process configuration requires the least resources. Compared to the next best alternative configuration, the CDRA requires less mass (63%), power (63%), and volume (38%). Phase 1 results did not justify the use of ARREM project resources for fabricating alternative dryer technology test articles for cycle 2 testing. It was recognized that the candidate technologies are not fully optimized for these specific applications. However, phase 2 provided the opportunity for optimization via computer simulation and additional testing. Areas for optimization of the four-bed process were identified and investigated during phase 2. The following conclusions are based on these efforts:

- Development and test of a third-scale isothermal bulk desiccant with a novel heat exchange approach has shown that high efficiencies can be obtained for bulk water removal while using standard silica gel sorbent formats without any heating required. Testing has demonstrated applicability for the ISS CDRA application as a bulk water removal device.

- Refinement of a Microlith residual water removal device, guided by computer simulations of flow channeling, has resulted in greatly improved efficiency. Testing has demonstrated applicability for the ISS CDRA application as a residual water removal device.

- The bulk and residual dryer downselection study evaluated currently available dryer technologies against the SOA approach used on the ISS CDRA. Phase 1 of this study concluded that, for the current dryer hardware configurations evaluated, the ISS CDRA dryers require the least resources. Compared to the next best alternative configuration, the CDRA requires less mass (63%), power (63%), and volume (38%).

- Improvements to the sorbent-based atmosphere revitalization (SBAR) technology underway include improvement of vacuum conductance for improved performance and incorporation of internal heaters for greater operational flexibility.

- Comparative analyses of zeolites Universal Oil Products (UOP) RK-38 and UOP Allied-Signal Research and Technology (ASRT) has shown that the RK-38 has an improved CO_2 removal capacity under ISS CDRA operational conditions over ASRT formulations. Thermogravimetric analysis (TGA), breakthrough, and equilibrium capacity testing all indicated an increased capacity. The overall average capacity increase was 8% over ASRT 1996 and 4% over ASRT 2005.

- Both pellet and bulk crush strength testing of the UOP RK-38 and UOP ASRT zeolites has shown that the RK-38 has lower crush strength. Pellet crush strength showed strength reductions compared to ASRT sorbents by an average of 24% and 26% in the dry and wet tests, respectively. Bulk crush strength testing showed a similar reduction of 31% in the dry state.

4.1.4 Future Work for Carbon Dioxide Removal

The analytical capabilities and test stands described in this Technical Publication (TP) will continue to be used to assess not only the ISS CDRA sorbent materials but also other sorbents for future manned missions. Ongoing and planned future work within the CO_2 removal technical area includes the following:

- Evaluate the sensitivity of adsorbent materials to onboard ISS contaminants including siloxanes. Recently, evaluations have shown degradation in water working capacity of silica gels returned from orbit. Continued testing is planned to evaluate the sensitivity of other sorbents used by the ISS CDRA and candidate sorbents to TCCs in the cabin atmosphere.

- Evaluate the sensitivity of adsorbent strength and attrition resistance to water vapor exposure. In-flight data suggest humidity may be escaping the desiccant beds and contributing to accelerated zeolite 5A dusting in the CO_2 sorbent bed.

- Evaluate the hydrothermal stability of sorbent media to determine if repeated temperature cycling under humid conditions is contributing to the observed accelerated dusting.

- Test CDRA-4EU equipment to map performance for both low CO_2 levels and high crew loadings. The former testing is of considerable interest for exploration missions as current CO_2 levels have been implicated in crew health problems in microgravity environments.

The efforts and results represented here and in publications listed in appendix A will be continued to support the design of CO_2 removal systems under AES. These efforts are expected to provide optimized CO_2 removal systems for ARSs used in future exploration vehicles.

4.2 Oxygen Generation and Resource Recovery

Building on the ISS OGA equipment platform, this task conducted work toward realizing a more robust, reliable water electrolysis cell stack that addresses observed ISS reliability issues. Oxygen drying and compression options—both temperature swing adsorption-based and mechanical compressor-based—were considered. Plasma methane (CH_4) pyrolysis, the leading method for recovering additional H_2 from the ISS Sabatier process waste methane, was evaluated. Methods for handling H_2 and acetylene (C_2H_2) within the OGA-Sabatier-methane post-processing string were investigated. Specific technical areas of emphasis for O_2 generation and resource recovery are the following:

- Improvements in SOA proton exchange membrane (PEM) water electrolysis systems.

- Developing CH_4 pyrolysis technologies and methods to recover more O_2 with CO_2 reduction processes.

- Gas handling and management to compress, separate, and/or condition process gases such as CO_2, H_2, C_2H_2, and O_2 gas streams within the ARS architecture.

4.2.1 Oxygen Generation and Resource Recovery Background

Under ARREM, the Resource Recovery and Oxygen Generation Work Breakdown Structure (WBS) element was tasked with developing technology for long-duration missions that either provided breathable oxygen to the crew or recovered and recycled oxygen from metabolically-produced carbon dioxide. Existing ISS technology for these purposes either have reliability issues or do not achieve the 90% recovery goal laid out by NASA's technology roadmaps. The element was separated into three subelements including oxygen generation, high pressure/high purity oxygen (HPHPO2), and oxygen recovery. The Oxygen Generation subelement involved evaluating ISS heritage hardware, identifying the potential for increasing reliability and robustness for future long-duration missions, and conducting testing to evaluate options for improvements beyond the SOA. The HPHPO2 subelement involved the design, development, and/or testing of technology to provide high purity oxygen to the crew at a pressure of 24.8 MPa (3,600 psi). Finally, the Oxygen Recovery subelement sought to identify and develop technology capable of increasing oxygen recovery to >50%.

4.2.2 Oxygen Generation and Resource Recovery Technical Approach and Task Summary

The Oxygen Generation subelement was tasked with evaluating the on-orbit OGA, identifying areas for improved robustness and reliability, and testing options to address those areas with the intention that modifications could be made for next-generation missions, with the potential for ISS on-orbit modifications, if practical.

4.2.2.1 Oxygen Generation. The SOA OGA has been reliably producing breathing oxygen for the crew aboard the ISS for over 7 years. Lessons learned from operating the ISS OGA have led to proposing incremental improvements to advance the baseline design for use in a future long-duration mission. These improvements promise to reduce system weight, crew maintenance time, and resupply mass from Earth while increasing reliability. The baseline ISS OGA is a unique cathode feed electrolysis ambient pressure design, adapted from a Navy submarine oxygen generator design. For future long-duration missions, high-pressure oxygen generation is also required to support EVA operations. The specific tasks to advance SOA ambient pressure oxygen generation and extend its application to high-pressure oxygen generation technology were the following:

- Replace hydrogen sensor—Hydrogen sensors require frequent maintenance and calibration. Recombiner technology is being investigated as a replacement.

- Delete wastewater interface—Simplify future system design. Requires bench testing of the rotary separator assembly (RSA) to verify no adverse effects from feedwater with entrained oxygen bubbles.

- Delete nitrogen purging equipment—Simplify future system design. Using the OGA testbed, verify safe operation with nitrogen purging disabled.

- Replace cell membranes—Current membrane material is obsolete. Build and test single cells with modern membrane materials. Then build a cell stack with new membranes and test in the OGA testbed.

- Replace vacuum dome—The dome encases the cell stack, RSA, and other components. This prevents access by the crew for maintenance. Demonstrate safe operation of the OGA testbed without a dome.

- Redesign cell stack power supply—The 45.4 kg (100 lbm) power supply is designed to support oxygen production for a crew of 11. It is likely that future missions will have a crew size of four. The power supply can be redesigned to save approximately 30% mass/volume.

- Design, build, and test a high-pressure cell stack—There is currently no capability to generate high-pressure oxygen in space. A development high-pressure cell stack has been designed, built, and tested on the ground.

The oxygen generation tasks were jointly funded with resources from the ARREM project and the ISS program.

4.2.2.2 High Pressure/High Purity Oxygen Generation. The AR team was tasked with demonstrating and measuring the purity, flow, and pressure of the integrated solid electrolysis oxygen system (SEOS) payload through a series of ground tests. The SEOS is a ceramic stack that heats the air stream, thereby dissociating the diatomic oxygen, allowing the single atoms to pass through the membrane. Once cooled, the oxygen recombines and does not pass back through the membrane. Specifically, the testing focuses on proving that nothing but oxygen passes through the membrane as well as demonstrating continuous operations with no degradation in the output flow. These test data will be incorporated into hazard analysis and the SEOS design will be subjected to the rigors of the safety review process. Upon risk and design acceptance, it is hoped that the ISS will approve the SEOS as a payload and the technology development proceeds to launch.

4.2.2.3 Oxygen Recovery. The oxygen recovery subelement was tasked with increasing oxygen recovery beyond the SOA ISS capability. Under the ARREM project, SOA Sabatier technology was assumed as the baseline and as such, methane post-processing technology was developed. The plasma pyrolysis assembly (PPA) was explored to maximize hydrogen recycle while maintaining gaseous byproducts through a step-wise scaling from one-half to a full-scale four crewmember methane processing rate. Additionally, various Sabatier-based oxygen recovery architectures were explored to maximize performance while minimizing complexity. Finally, methane and hydrogen purification technologies were explored and advanced. Specific high-level tasks during the 3 years are summarized in table 1.

Table 1. Oxygen recovery tasks.

Task	Description
1	Develop PPA to one-crew member methane processing rate
2	Develop PPA to four-crew member methane processing rate
3	Explore methane purification technology
4	Explore hydrogen purification technology
5	Explore oxygen recovery architectures

4.2.3 Oxygen Generation and Resource Recovery Accomplishments and Findings

4.2.3.1 Oxygen Generation. In 2012, the developmental OGA (OGA testbed) was removed from storage, reassembled, and refurbished to support the investigation of proposed improvements. The OGA testbed is functionally equivalent to the ISS OGA. It contains a flight-like cell stack, rotary separator accumulator (RSA), recirculation pump, and cell stack power supply.

Replacement of the hydrogen sensors was investigated in 2013–2014. A catalytic oxidizer (i.e., recombiner) is proposed as a replacement. The design is simple with a potential life of several years. Bench testing in 2013 confirmed the thermal response of the recombiner when exposed to low levels of hydrogen in oxygen (1%). In other words, the recombiner can act as a sensor and indicate a hydrogen leak via increase in internal temperature. In 2013, the hydrogen sensors in the OGA testbed were replaced with a recombiner and over 100 hours of safe operation was demonstrated.

Another improvement investigated was the deletion of the wastewater interface from the baseline design, allowing for system design simplification. The purpose of this interface is to reject feed water with an excessive amount of oxygen gas bubbles. There is a safety concern that this oxygen could mix with hydrogen in the downstream RSA if water with oxygen is not rejected. In 2013 and 2014, a developmental RSA was designed and manufactured. Unfortunately, testing was not able to be conducted prior to the end of the program.

The next area of improvement that was investigated was the deletion of the nitrogen purging equipment from the baseline OGA design, allowing a savings of 22.7 kg (50 lbm) of mass and simplification of the system design. In the baseline design, oxygen is purged from the anode cavity upon shutdowns to create an inert unpowered condition. In 2013 and 2014, the OGA testbed was modified to delete nitrogen purging. Safe conditions were verified even without nitrogen purging. Without nitrogen purging, it is known that hydrogen and oxygen can mix in the anode cavity upon shutdown. The presence of catalyst on the membranes promotes the formation of water from hydrogen and oxygen and this humid environment is a safe unpowered configuration.

Replacement of the cell membranes was investigated from 2012 to 2014. The baseline ISS cell stack design contains obsolete membrane material (nonchemically stabilized Nafion 117). Giner, Inc. was contracted to investigate the performance of single cells that are of the same design as the ISS OGA, but with new, modern membrane material and catalyst. Giner built three single cells and tested them over a 10-month period. Excellent performance was demonstrated, with minimal voltage degradation over the entire test period.

The deletion of the vacuum dome was investigated in 2014. The purpose of the dome is to detect leakage of hydrogen out of the cell stack or RSA via a pressure rise in the dome. The dome is not removable by the crew on-orbit, preventing the crew from performing maintenance on the internal components (cell stack, RSA, valves, sensors, etc.). In 2014, work began to replace the vacuum dome with an ambient pressure shroud in the OGA testbed. This included adding a blower, recombiner, a flow meter, and other equipment, to force air over the cell stack and RSA and detect hydrogen leakage via the recombiner.

Redesign of the cell stack power supply module (PSM) was proposed but not extensively pursued during the project period. It was decided that since the requirements for a next-generation OGA are not yet fully defined, a PSM redesign should not be performed at this time. High-level discussions with the PSM designers indicate that an ~30% reduction in weight/volume is possible.

Contracts with two vendors were initiated to study the design of a high-pressure cell stack. Giner, Inc. built a development high-pressure cell stack in 2013. In 2014, endurance testing of the stack was performed. Unfortunately, a leakage failure occurred, requiring a redesign. The new design was tested successfully. A second company, Proton OnSite, started the design of a high-pressure cell stack in 2014.

4.2.3.2 High Pressure/High Purity Oxygen Supply. The development of an SEOS for HPHPO2 supply accomplished the following:

- The SEOS configuration tested in December 2013 has the demonstrated capability of producing HPHPO2 that meets ISS high pressure oxygen needs for EVA and/or medical purposes.

- After testing, the glass within the SEOS unit at the high operating temperatures was allowing water vapor into the flow stream. Now that the source of moisture has been found, and low pressure and high pressure desiccant beds have been added, the SEOS device should be capable of delivering aviator's breathing oxygen (ABO) grade O_2, even if the process air contains >5% CO_2, or >100 ppm methane, helium, hydrogen, Freon 218, acetaldehyde, methanol, ethanol, or any other contaminant that has ever been found in the ISS atmosphere at levels >10 ppm. This capability must be further demonstrated.

- The SEOS configuration tested in December 2013 has a nominal delivery rate of 2 L/min. With modifications that increase the weight of the system by <10%, the modified device can be built that can deliver emergency medical oxygen at 5–15 L/min and up to 100 psig delivery pressure, if the system is not operated for more than 250 hours.

Three tests were planned for future work:

(1) Helium will be introduced into the flow stream to confirm that not even the smallest molecular density can pass through the ceramic oxide membrane.

(2) The SEOS unit will undergo exposure to Freon 218 to confirm that the unit does not convert the Freon to harmful hydrogen fluoride (HF).

(3) The SEOS unit will be operated at higher temperatures to characterize the output under fast flow conditions for medical operations (5–15 L/min).

It should be mentioned that a dual unit configuration to increase the flow was considered but it was determined that the available volume could not support a dual configuration.

4.2.3.3 Oxygen Recovery. Via the key tasks described above, the PPA was advanced from one-half-crewmember scale. Because of the complexity of scaling the microwave-based technology, a one-crewmember reactor was developed and delivered by UMPQUA Research Company. The one-crewmember reactor was integrated into the one-half-crewmember PPA assembly and the one-half-crewmemember reactor was returned to UMPQUA for modification. The results of testing of the one-crewmember system is reported in documentation listed in appendix A, but a considerable improvement was observed and the final results are shown below. Based on this performance, a four-crewmember PPA system development effort was undertaken by UMPQUA and the system delivered in FY 2015. A new reactor design was used in the four-crewmember system to accommodate the larger gas flows. Initial testing at UMPQUA and MSFC demonstrated another dramatic improvement in overall performance. A summary of the observed performance at each scale is summarized in table 2.

Table 2. Plasma pyrolysis observed performance.

Parameter	One-Half Crewmember PPA Performance	One-Crewmember PPA Performance	Four-Crewmember PPA Performance
CH_4 flow	160 sccm	400 sccm	1,400 sccm
Microwave power	700 W	463 W	832 W
Energy efficiency	6.2%	11.4%	25.4%
$\%CH_4$ conversion	80%	90%	$\geq$90%
C_2H_2 selectivity	62%	$\geq$86%	~90%

In addition to PPA development, various Sabatier-based oxygen recovery architectures were explored. These architectures are described in documents listed in appendix A. The down-selected architecture involves a modification to the Sabatier operation (operating hydrogen-rich to eliminate carbon dioxide in the methane product stream), the PPA, and a single purification step shown in figure 7 as the acetylene separation assembly (ASepA). Originally, a methane purification step was considered, but later eliminated to reduce complexity.

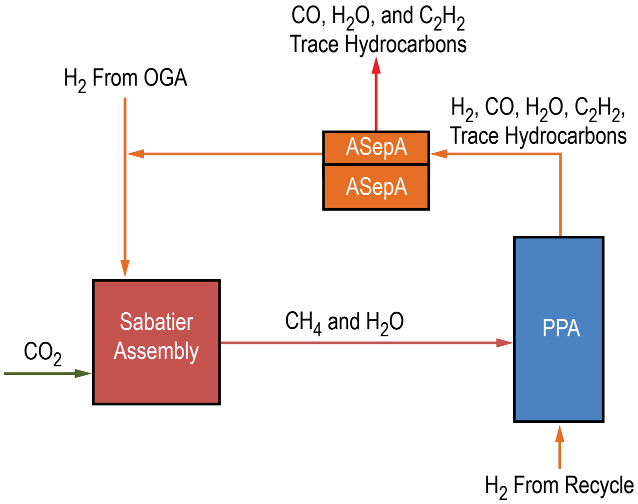


Figure 7. Simplified Sabatier post-processing schematic.

Finally, several methane and hydrogen purification technologies were explored. Ultimately, none of the approaches explored were successful. The SBIR program was used to solicit ideas from industry, resulting in two approaches—one sorbent-based approach and one polymer electrolyte membrane-based approach. These SBIR efforts were ongoing at the end of the ARREM program.

4.2.4 Oxygen Generation and Resource Recovery Future Work

Continued operation of the recombiner in the OGA testbed must continue to gain technical confidence and understand the long-term operational characteristics of the technical approach. After system testing is completed, bench testing must be repeated periodically to determine if the recombiner is still performing nominally after long-term operation in the OGA testbed. The rotary separator assembly (RSA) must be tested to determine the effect of allowing oxygen (in the feedwater) into the RSA where water and hydrogen are present. After completing single-cell testing, the next logical technical step is to build a cell stack of an appropriate size for an exploration mission. This cell stack must integrate easily with existing OGA testbed infrastructure. Once the exploration-sized cell stack is built and delivered, it operated long term to demonstrate its useful life meets exploration mission needs. Additional development and endurance testing high-pressure cell stacks should also be accomplished to complement HPHPO2 developmental products.

During the ARREM project, the PPA was advanced to a level such that a flight experiment is warranted to explore the effects of microgravity on the plasma and corresponding chemical reactions. Future work should involve this flight experiment. Ongoing SBIR projects are expected to result in two viable options for hydrogen purification in a Sabatier post-processing architecture. Recent advancements in metal hydrides (specifically, advances in carbon monoxide-resistance) make them a potential option for hydrogen purification. It is recommended that at least one of these options be fast-tracked such that an ISS demonstration is possible before its retirement. Finally, Bosch technology and electrolytic approaches to carbon dioxide reduction were options not funded under ARREM. It is recommended that these approaches be considered for future development.

4.3 Trace Contaminant Control

The best-performing adsorbent media and catalysts were characterized and applied to a TCC process design for exploration missions. Commercially available and developmental particulate filtration media and indexing media filter concepts were evaluated to improve the performance of the ISS particulate filtration architecture. Based on system architecture trade assessment, options for integrating TCC and particulate matter control equipment with CO_2 removal equipment to achieve a common core atmosphere revitalization architecture for deep space exploration missions was investigated and demonstrated. Options for applying advanced TCC adsorbents and catalysts to the ISS TCC equipment to further improve operational robustness were considered and communicated to the ISS program. Catalytic ammonia removal was investigated as an alternative to expendable adsorbent-based ammonia control. Further development of photocatalytic oxidation processes to apply to niche TCC applications was conducted. The technical area evaluated various commercial and developmental filters in the Particulate Filtration Testing Facility located at GRC. Also, the indexing media filter system was further developed toward future integrated testing. Specific areas of emphasis for the TCC technical area and responsible NASA field centers were the following:

- TCC design, requirements, and integration concepts (MSFC).
- Microlith thermal catalytic oxidation (MSFC).
- Commercial adsorbents and catalyst characterization (KSC).
- Photocatalytic oxidation (KSC).
- Catalytic ammonia removal (KSC).
- Commercial and developmental filtration media characterization (GRC).
- Indexing media filter system (GRC).
- Particulate load model updates for filtration equipment design specification (GRC).

The TCC technical area used analysis and testing methods to accomplish the technical tasks. The overall TCC requirements were developed and minimum flow rate and power targets were established based on the project's technical requirements and the figures of merit. The integration concepts evaluated TCC components integrated with the CO_2 removal and cabin ventilation equipment. These concepts were demonstrated to comply with the project's technical requirements, goals, and figures of merit. The minimum mass and volume reduction relative to the ISS SOA is approximately 12 kg and 15 L.

A Microlith-based thermal catalytic oxidizer assembly (M-COA) was demonstrated in two configurations closely integrated with the CO_2 equipment. One configuration supplies the inlet flow to the M-COA from a mid-point location downstream of the CO_2 removal assembly blower while the second location supplies inlet flow directly from the cabin with the exhaust connecting to the CO_2 removal assembly's inlet. The first concept was able to easily achieve flow rates up to 3.4 m^3/hr (2 ft^3/min) which provides a 27% margin relative to the most challenging exploration mission design for a four-crewmember Mars transit and 138% margin over the absolute minimum required flow of 1.4 m^3/hr (0.84 ft^3/min) for this mission class. Integrating the M-COA at the CO_2 removal system inlet could achieve only 1.5 m^3/hr (0.9 ft^3/min) flow which provides only a 5% margin relative to the absolute minimum flow. While integrating the M-COA at the CO_2 removal assembly inlet has functional advantages in that the unit is not isolated from the full trace contaminant load by incidental removal by an upstream desiccant bed, additional work is necessary to address meeting the more challenging exploration mission flow requirement. Key to this objective is reducing the unit's pressure drop. An advanced M-COA was designed and built for the ARREM project by Precision Combustion, Inc., under SBIR phase III contracts. This unit possesses a more simple recuperative heat exchanger design that may yield a lower overall assembly pressure drop to allow for achieving higher flow rates.

Two primary TCC adsorbent bed configurations were evaluated. The first employed a low flow, high aspect ratio bed similar to that used aboard the ISS. Flow through the bed was set at 10 m^3/hr (6 ft^3/min) which is the minimum for a four-crewmember exploration mission. This bed was integrated directly with the cabin ventilation duct downstream of the main cabin fan. The objective was to use the motive force from the cabin fan to provide flow through the bed. Testing found that a small booster fan was necessary to achieve the necessary flow. As a result, a second concept that placed a high flow, low aspect ratio activated carbon cartridge concept (Barnabey Sutcliffe Division of Calgon Carbons) in the cabin ventilation duct immediately upstream of the cabin fan was tested. This concept performed much better than expected with respect to contaminant breakthrough, particularly for high molecular weight compounds such as volatile methyl siloxanes (VMS) that are suspected of being associated with both CO_2 removal assembly, humidity control, and water processing equipment performance degradation aboard the ISS. Further evaluation of this high flow, low aspect ratio adsorbent cartridge concept will be pursued in the future.

Market research was conducted to select candidate commercially-available adsorbents for removing ammonia and volatile organic compounds (VOCs). Similar market research was conducted on ambient temperature carbon monoxide catalysts. The adsorbents and catalysts were characterized for their performance by researchers at KSC. A best-performing ammonia removal adsorbent (Ammonasorb II, Calgon Carbons) and carbon monoxide catalyst (Sofnocat 423, Molecular Products) were determined. Further work to characterize the ammonia adsorbent at low ammonia concentrations as well as evaluate co-removal of VOCs must be completed to optimize the TCC equipment architecture. Additional market research to identify candidate activated carbons targeting dilute VOC concentration loads must be completed and selected candidates characterized.

Particulate matter removal tasks focused on evaluating advanced filtration media, developing a scroll-type filter design to minimize crew time and involvement with filter element maintenance, developing methods for assessing filter service life and integrity, and updating the particulate generation source model used for design specifications. Advanced filtration media produced under SBIR contacts by Giner, Inc. and Seldon Technologies were evaluated to add to the performance database of commercial filtration media. Design modifications and improvements for the scroll-type media filter concept were identified and designs were generated to implement the improvements—a breadboard prefilter concept for the scroll type. The filtration literature was surveyed and filter leak testing standards were procured. Based on these standards, filter testing protocols and apparatus were developed and used to demonstrate filter integrity testing methods. These methods may be amenable to checking filter element integrity in flight. A literature survey effort was conducted to update the particulate generation source model listed in NASA/TP—1998–207978 used for cabin filtration system and component design.[20] This updated model was documented in reference 21.

Additional work was conducted on developing an ammonia catalytic reduction reactor and further evaluating the efficacy of photocatalytic oxidation (PCO) processes for spacecraft TCC applications. Efforts on the ammonia catalytic reduction reactor completed a subscale concept demonstration and evaluated catalyst candidates, both commercially available and custom formulations. Reactor performance at full scale is the focus of future work. The PCO developmental work developed a hybrid design that employed an ultraviolet light-emitting diode illumination source. The hybrid design consisted of PCO and adsorbent stages to address production of partial oxidation products such as aldehydes that are commonly produced by PCO processes. Such a hybrid design may be possible as part of an overall TCC architecture based on the high flow, low aspect ratio adsorbent cartridges evaluated in the ARREM project's integrated testing efforts. Producing partial oxidation products and the potential for catalyst poisoning by VMS compounds were considered significant challenges to adoption PCO as part of the overall TCC process architecture. These challenges were evaluated versus other architecture options and PCO was not incorporated into the recommended spacecraft TCC process architecture.

Based on the results obtained in the TCC technical area during the ARREM project, recommended future development work follows:

- Test and characterize high flow, low aspect ratio adsorbent cartridges for their service life characteristics.

- Test, characterize, and evaluate the advanced M-COA unit.

- Characterize the performance of candidate commercially available ammonia and VOC adsorbent media as well as ambient temperature carbon monoxide oxidation catalysts across wider ranges of concentration and cabin temperature and relative humidity conditions.

- Design, fabricate, and test a high-fidelity prototype scroll filter concept in a cabin ventilation system functional mockup.

- Demonstrate ammonia catalytic reduction process efficacy at the scale necessary for exploration missions.

4.4 Environmental Monitoring

The available performing atmospheric monitoring candidates demonstrated onboard the ISS to date were operated in a cabin-like environment to help determine the optimal suite of instruments necessary to provide vehicle operational autonomy necessary for deep exploration missions. Early warning instruments targeting specific analytical targets were demonstrated. Extending air quality instrument function to include front-end processors to allow for volatile organic monitoring in potable water was demonstrated. Areas of technical emphasis for environmental monitoring follows:

- Vehicle environmental monitor (VEM) to expand gas chromatography (GC)/mass spectrometry (MS) technology used for cabin atmosphere analysis to address water analysis.

- Micro-gas monitor (mGM) to achieve major size reduction to GC/MS without loss of capability.

- Micro-electromechanical GC to achieve major size reduction to GC/MS.

- Tunable laser absorption (TELS) to apply solid state laser developments to targeted gas analytes.

- Rapid analysis self-calibrating (RASCal) array to apply advanced array analysis and hardware to dramatically improve response time and calibration time.

- Commercial major constituent gas and VOC analyzer market research.

- Commercial Fourier transform infrared (FTIR) demonstration.

4.4.1 Environmental Monitoring Background

The EMSs task objectives were to develop and demonstrate onboard monitoring, detection, and analysis capabilities that will replace the SOA need to frequently return air, water, and microbial samples to Earth for ground-based laboratory analysis. This effort will addressed these challenges by adopting new analytical technologies and techniques that will allow for a modular EMS architecture that integrates multiple sensing modalities to address the monitoring needs of future deep space exploration missions. The EMS architecture has incorporated micro-electromechanical systems (MEMS) technologies to enable significant miniaturization over current systems, and selected monitoring techniques that offer both low (and potentially none) resource consumption and highly reliable operation for lifecycle affordability. The EMS architecture leveraged previous NASA developmental results in the field and emerging commercial and academic accomplishments to achieve these goals.

The EMS task has worked with the ECLSS SMT to ensure the developed technologies and systems meet or exceed current requirements and fill the identified capability gaps. In doing so, the EMS significantly improved the efficiency, safety, and reliability over the current SOA.

The EMS has matured at least two techniques, the combustion product monitor (CPM) and micro-total atmosphere monitor (µTAM), through a series of ground tests simulating expected exploration mission requirements and constraints. As a result, the CPM and µTAM achieved an appropriate technical maturity for EMS to transition these monitoring technologies into flight demonstration efforts.

4.4.2 Environmental Monitoring Technical Approach and Task Summary

The EMS led the development of a common needs and performance specification for environmental monitoring with consultation and participation from environmental monitoring experts at MSFC and JSC. The EMS team at JPL conducted the following technical tasks in chemical and microbial composition monitoring to address aspects of the common needs assessment:

- Water module—Expands GC/MS technology to address water analysis.
- mGM—Major size reduction to GC/MS without loss of capability.
- TELS—Solid state laser development for targeted gas components.
- RASCal array—Advanced array analysis and hardware to dramatically improve response time and calibration time.
- Microbiological monitors (water/air)—Assess the current state of the community.

4.4.3 Environmental Monitoring Accomplishments and Findings

4.4.3.1 Micro-Gas Monitor. This major constituent instrument based on JPL wireless MS has been developed and tested. This concept was presented to the ISS program. Incorporating the JPL MEMS gas chromograph and gas manifold, a µ-TAM mode that is currently being pursued as a tech demo has been developed as follows:

- Demonstrated major constituent analysis (MCA) operated with ion and getter pump.
- Demonstrated hydrogen as a carrier gas.
- Demonstrated MCA with high stability.
- Demonstrated MCA with high resolution.
- Demonstrated operation of JPL's quadruple ion trap interfaced with Cbana's MEMS GC technology, radically reducing the size and power consumption in respect to vehicle cagin atmosphere monitor (VCAM) technology.
- Fabricated preconcentrator (PC)s and GCs at JPL based on Cbana Labs Tech.
- Improved GC yield by 10× using JPL MEMS foundry.

- Tested MEMS GC with two different column types: 5% phenyl polydimethylsiloxane stationary phase (OV-5) and porous layer open tubular (PLOT).

- With current progress, it is much easier to customize MEMS preconcentrator-gas chromatograph (PCGC) based upon project needs, e.g.,
  – Developing PLOT columns for separating light gases (e.g., carbon monoxide, nitrogen, methane).
  – Testing in vacuum chamber to retire risk of operation on lunar surface.

4.4.3.2 Tunable Laser Absorption-Combustion Product Monitor. Tasks for the TELS combustion product monitor included the following:

- Developed low power consumption quantum cascade laser (QCL) at 4.7 mm for detection of CO that consumes only 2 W of power compared to a commercially available laser that consumes 40 W.

- Developed a single-channel instrument for CO detection using the QCL. This instrument was successfully tested in the EChamber at MSFC.

- Developed and delivered a five-channel combustion product monitor (CPM) that can detect CO, CO_2, HCl, HCN, hydrogen fluoride, and water. This instrument uses JPL-developed low power lasers. This CPM is able to continuously monitor spacecraft air quality.

4.4.3.3 Water Module. Water module tasks included the following:

- Developed a water module for analyzing water with a GC that does not interfere with any existing air sampling capabilities. This instrument is capable of microgravity operation with detection levels for light volatile organics of >1 ppm.

- Developed and characterized a preconcentrator based, as well as a split-splitless injection water module.

- Tested both water modules with an MS and a thermal conductivity detector.

- Demonstrated detection levels ≤ 0.1 ppm.

- Tested the split-splitless injection water module with humidity condensate from the Environmental Chamber at MSFC.

4.4.3.4 Microbial Monitoring. Tasks for microbial monitoring included the following:

- Conducted a NASA Microbial Monitoring workshop on April 19, 2011. The workshop outcome was that quantitative polymerase chain reaction (qPCR) is a valuable technology, suitable for further study by NASA.

- Supported commercial qPCR evaluation, being carried out by MSFC, JSC, KSC, and JPL (iCubate and Razor).

- Evaluated sample concentration modules from several sources:
  - Mars Program Office funded, Innova Prep—successful.
  - The Computational Fluid Dynamics Research Corp. (CFDRC) technology—did not capture all micro-organisms.
  - JPL in-house funded with University of Southern California MEMS-based technology—successful.

4.4.3.5 RasCal Array. The RasCal array tasks included the following:

- Developed sensor array algorithms that uses sensor response time to identify and quantify organics, ammonia, and CO in the air.

- Demonstrated array self-calibration using sensor drift corrections.

- Demonstrated RASCal in MSFC EChamber.

4.4.4 Environmental Monitoring Future Work

Some of the future work for environmental monitoring includes the following:

- µTAM be developed and demonstrated onboard ISS as a technology demonstration.

- Combustion products monitor.
  - Complete the ammonia/hydrazine detection capability demonstration.
  - Calibrate, validate, and characterize current CPM at GRC.
  - Incorporate lessons learned and develop flight demonstration hardware for integration with the Spacecraft Fire Safety Demonstration project.

- Water Module
  - Extend water analysis to include inorganics and metals.

- Microbial Monitoring
  - Collaborate with WetLab-2 project at ARC to develop sample concentration/transfer module.
  - Develop a prototype for the ‘Sample Smart-concentrator’ that is microgravity insensitive.
  - Demonstrate intracellular adenosine triphosphate (iATP) system onboard the ISS for quantitatively measuring microbial burden.

- RASCal
  - Extend our array-based sensing capability to color detection of siloxanes and dimethylsilanediol in water.
  - Demonstrate further decreased array response time (under 1 minute).

4.4.5 Environmental Monitoring Commercial Analyzer Market Research

A proven approach to lowering risk and lifecycle costs is to use commercial off-the-shelf (COTS) hardware as opposed to producing ‘few-of-a-kind’ end items, as long as critical performance parameter(s) are not compromised by doing so. Commercial market research was conducted in the first 2 years of the ARREM project to assess the availability of instruments suited for major constituent gas analysis and VOC analysis. These assessments followed earlier assessments conducted in 2004.[22,23] The intent was to identify promising instruments and target them for demonstration during the ARREM project's integrated testing series. The assessments were conducted in two parts: (1) Considered instruments for monitoring oxygen, carbon dioxide, and moisture and (2) considered instruments for monitoring VOCs.

The assessments found that analyzers for oxygen, carbon dioxide, and water vapor are readily available. For the most part, this investigation focused on industrial or laboratory grade units due to their perceived superiority to consumer units with respect to robustness, performance, and estimated lifetime. Product literature for many of the analyzers indicated the use of the same basic sensing technology as that used in the baseline instruments procured in 2004; laser diode detection for oxygen, solid state infrared for carbon dixoide, and thin-film capacitance for water vapor. Electrochemical sensors are also widely employed in oxygen analyzers but are not well suited for space-based applications. Summary information highlighting some of the more important discriminators for each instrument follows:

- Oxygen analyzers—Some of the analyzers reviewed only detect and measure oxygen concentrations, while others combine oxygen and carbon dioxide analyzers into one integrated unit. Handheld units are capable of measuring zero to 100 vol% oxygen, weigh less than 0.45 kg (1 lb), and cost less than $200. However, these units are not optimized for continuous, long-term operation. A portable oxygen analyzer is available for <$2,000, and according to the product literature, appears robust enough for continuous, longer term operation. Yet, it has a relatively narrow dynamic range. At the other end of the spectrum is a $12,000 unit weighing approximately 2.7 kg (6 lb), but is designed for very low volume analysis (i.e., headspace analysis). No unit reviewed appears to offer superior performance when compared to the oxygen analyzer currently in operation (Oxigraf Model O2) in the ECLSS test facility.

- Carbon dioxide analyzers—Most CO_2 analyzers reviewed utilize infrared sensor technology. Similar to the above case for oxygen analyzers, the existing baseline carbon dioxide analyzer (Sable Systems CA-2A) offers equal or superior performance when compared to the current class of COTS CO_2 analyzers. Efficiencies in size/volume may be realized by utilizing a COTS analyzer that measures oxygen and carbon dioxide within the same instrument rather than employing separate analyzers, which exists in the current test configuration.

- Humidity analyzers—The selection of humidity analyzers considered robust enough for possible use in long-term manned spaceflight usage appears to be more limited than for either oxygen or carbon dioxide monitoring. Water vapor analyzers often combine the detection of temperature, carbon dioxide, and humidity into one integrated instrument. No COTS device was located that appears to offer superior performance as compared to the unit currently in service in the ECLSS test facility (Sable Systems RH-100).

COTS analyzers are available for detecting oxygen, carbon dioxide, and relative humidity within the concentrations deemed important for monitoring the cabin atmosphere of manned space flight vehicles. Some vendors offer integrated units that simultaneously measure two out of the three constituents of interest. One manufacturer offers a unit that measures all three constituents using an integrated instrument package about the size of a briefcase. A compact, integrated unit that measures all three constituents is appealing, but the unit's overall performance is not superior to the current in-house baseline unit(s) and the oxygen analyzer employs fuel cell technology, a less desirable technology given our unique operational requirements. As such, the expense does not appear to justify the volume savings.

In summary, there appears to have been no significant technology breakthroughs since the 2004 market study that would warrant investing resources into upgrading or replacing the existing COTS baseline major constituent instrument package residing in the EChamber.

The need to monitor and mitigate certain air pollutants (i.e., trace contaminants) onboard manned spacecraft is well documented. The majority of these are known as VOCs. Even though NASA has extensive experience in this area, the Agency is continually exploring new approaches and/or advancements in air monitoring technology, especially for long-duration manned spaceflight where the ability to return samples to Earth for analysis will not be available.

Complicating this effort is the need to monitor specific compounds rather than merely quantifying the total amount of VOCs. For example, the PhoCheck, offered by Ion Sciences, is a 0.68 kg (1.5 lb), handheld COTS VOC analyzer capable of detecting over 250 VOC gases from the parts per billion to the percent range (i.e., 10,000 ppm). This unit is even upgradable to include the detection of oxygen, carbon monoxide, and hydrogen sulfide. Yet, because the required minimum detection limit varies greatly from compound to compound, the use of a noncompound-specific VOC monitor is unacceptable from a crew health perspective. However, the onboard availability of a unit such as the above could possibly well serve a crew as a backup unit or to serve as an independent validation of overall cabin air quality as it pertains to VOC gases.

Characteristics of an ideal compound-specific monitor in this category would include very small size, requiring few consumables, high reliability, and the capability to detect a wide range of known and unknown compounds with high sensitivity. Such instruments must also be affordable. The commercial market assessment found that two of the most promising candidates, both of which employ well-established technologies, are GS/MS and infrared spectroscopy, specifically, FTIR.

The commercial market assessment found that there appears to be no COTS instrument(s) available that meet all of the size, performance, and reliability requirements for monitoring trace contaminants aboard crewed spacecraft. However, a field portable FTIR unit manufactured by Gasmet (model DX4040), was identified as a possible candidate for evaluation during the ARREM project integrated testing series.

5. COMPLEMENTARY PROJECT AND PROGRAM RELATIONSHIPS

Collaboration and synergy within NASA and the LSS technical community is necessary and imperative to maintaining a long-term human presence in space beyond LEO. The ARREM project consisted of the following participating NASA field centers that brought subject matter expertise to the project:

- Marshall Space Flight Center—project management, CO_2 removal, TCC, resource recovery, and integrated subsystem testing.
- Jet Propulsion Laboratory—environmental monitoring instrument development.
- Johnson Space Center—O_2 and CO_2 compression and conditioning.
- Ames Research Center—gas drying and solid state CO_2 compression.
- Kennedy Space Center—TCC adsorbent and catalyst characterization; photocatalytic oxidation efficacy evaluations.
- Glenn Research Center—particulate filtration and disposal technology.

The ARREM project developed and maintained technical and programmatic relationships outlined in figure 8 with multiple NASA field centers as well as other research and technology programs and projects which were complementary and integral to developing operational capabilities for exploration missions of the future. These complementary projects investigated technologies for water processing and logistics reduction. Some logistics reduction equipment may produce concentrated chemical waste streams that the ARS or ARS derived technologies must process making technical interchange between the projects highly advantageous. Water processing equipment could potentially be purifying water produced by the CO_2 reduction system, and the OGA will use product water for the electrolysis process. In addition, the ARREM project worked with the habitat design projects to ensure the latest mission requirements were considered and to coordinate the incorporation of ARREM products into habitat design architectures.

While conducting the core technical tasks, the ARREM project monitored the ISS program relative to lessons learned from flight operations. Past flight operations experience was incorporated during the ARREM project's initial technical content formulation; however, during the ARREM project's period of performance, flight operations were monitored for emerging technical challenges. Two challenges were identified:

(1) The first challenge involves the suspected role of VMS compounds and observed water processing system, CO_2 removal assembly, and humidity control equipment performance degradation.

(2) The second challenge involves the durability and hydrothermal stability of adsorbent media used in the CO_2 removal assembly. The ARREM project periodically assessed its technical content and made adjustments to be responsive to these and other technical challenges noted from

ISS flight operations that may be of importance to future exploration missions. For these two challenges, the TCC architecture considered high flow, low aspect ratio adsorbent cartridges as a potential solution to the VMS load challenge. Likewise, the CO_2 and moisture removal adsorbent media characterization work was reformulated to address various aspects of mechanical durability and process environment stability.

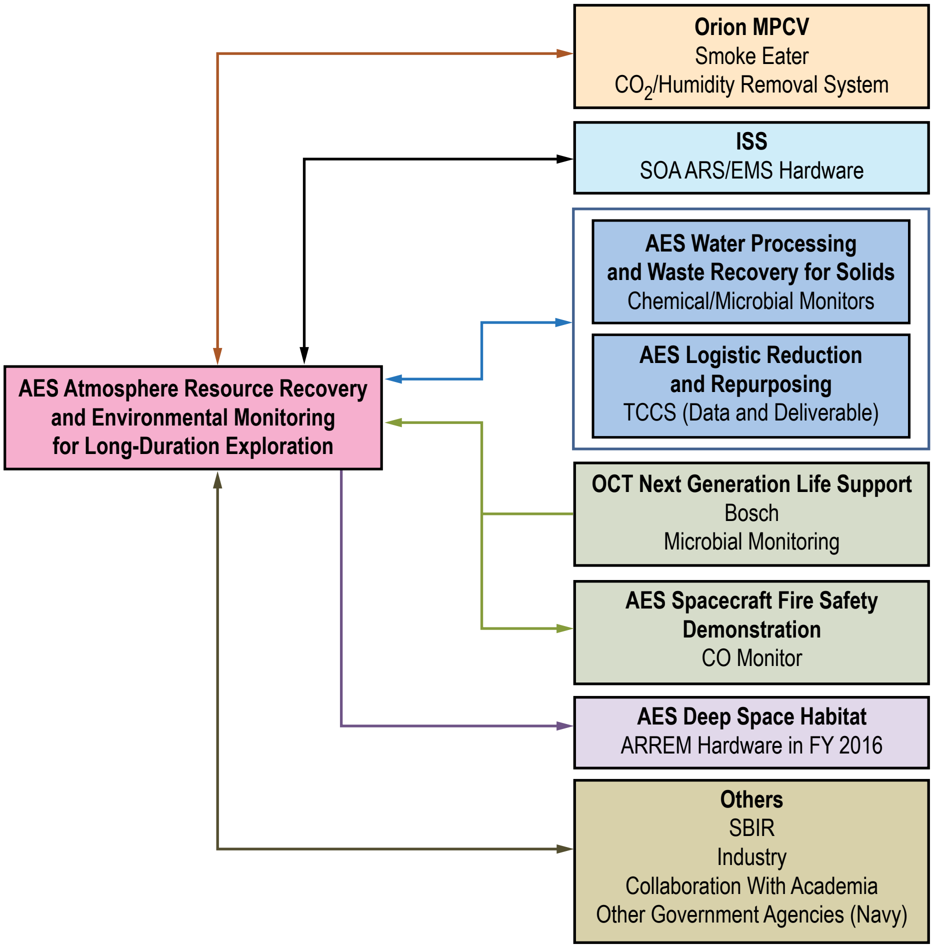


Figure 8. Relationships with complementary research and technology efforts.

6. PROJECT ACCOMPLISHMENTS

The ARREM project used a functional trade space approach to focus broad-based technical challenges and guide priorities.[14,15] Consistent with a flexible crewed space exploration strategy, the ARREM project demonstrated the capability to extend the functional utility of a common set of core ARS and EMS equipment by integrating them with reliable, cost-effective resource recovery capabilities that will allow long-duration human exploration missions to be sustained with minimal dependence on Earth-based logistics support. Testing at progressively complex levels of integration was the primary method used to reach the project's goals.[15,16] Technical accomplishments toward the project's goals include the following:

- Developed and tested integrated subsystem architectures and compared performance versus the ISS AR architecture establishing the feasibility of ISS-derived AR for deep space missions.

- Developed and refined integrated ARS technology testing capabilities that are a national asset.

- Developed and implemented screening and performance characterization methods for adsorbent media used for bulk and residual drying, carbon dioxide removal, and TCC.

- Assessed bulk and residual drying functional trade space options that found that the ISS CDRA desiccant bed to be the most mass and volume efficient solution as well as indicating that the desiccant bed size can potentially be reduced for exploration class missions to save mass and volume.

- Advanced technical maturity of the methane PPA through third generation and demonstrated integrated operational performance with the Sabatier development unit (SDU).

- Tested TCC component configurations as well as evaluated commercial adsorbent and catalyst product candidates leading to subsystem mass and volume reduction.

- Improved understanding of trace contaminant propagation through the integrated ARS architecture that provided confidence that there is minimal risk associated with VOC poisoning of carbon dioxide reduction catalysts.

- Gained improved insight on carbon dioxide and bulk/residual drying sorbent mechanical properties and adsorption capacities as well as matured analytical predictive techniques.

- Demonstrated operational simplifications for the ISS OGA that may reduce future mass and volume and address limited life hydrogen sensor issues to reduce logistics demand.

- Details on numerous technical accomplishments produced by the ARREM project are contained in the publications listed in appendix A.

7. INTEGRATED TESTING PROGRESSION AND RESULTS

The ARREM project took the best-performing technical results from the developmental task areas and incorporated them in an integrated functional test series. Each test series built upon the results from previous testing series. Testing began with the ISS ARS architecture to establish a basis for comparison and progressed through two alternative architecture test series. Sections 7.1 through 7.5 describe each test and the primary results.

7.1 Basis for Comparison Versus ARREM Project Integrated Architectures

Evolving the ISS ARS equipment architecture has been proposed as a leading strategy for enabling future crewed deep space exploration missions.[24,25] The ISS ARS architecture was assessed according to functional trade spaces to establish a basis for comparison.[14] These trade spaces, shown in figure 2, served to define the project WBS and integrated testing architecture. Integrated functional architectures representing the ISS ARS and changes indicated by the architectural assessment to the ISS architecture were tested in a sealed environmental chamber using a phased approach summarized in table 3.[12] The testing series began with the Resource Recovery Functional Demonstration (R2FD) test to establish the basis for comparison. The R2FD test used ISS ARS flight-like developmental hardware configured according to the ISS ARS architecture. The ARREM cycles 1 and 2 tests used many of the same test articles as the R2FD test but configured differently to realize targeted functional improvements and subsystem complexity reductions. The following discussion briefly describes the R2FD and integrated testing configurations for cycles 1 and 2.

7.2 Testing Facility and Methods

The testing facility is a 9,290-m^2 high-bay area containing bench-scale and sealed chamber testing platforms that allow a full range of testing capabilities ranging from bench-scale demonstration of individual components and assemblies through fully integrated subsystems and systems. Since 1985, the facility has been instrumental in the development, performance evaluation, and sustaining engineering support for the ISS ECLSS equipment as well as evaluating new technical developments in ECLSS process technologies and integrated architectures.

Table 3. ARREM project test progression summary.

Chamber Outfitting	Trade Space	Cycle 1	Cycle 2	Candidate AES Phase II
	Carbon dioxide removal	Bulk/residual dryer: ISS CDRA desiccant media CO_2 removal: ISS CDRA bed ORU redesign No. 3 sorbents	Bulk dryer: CDRA-4 desiccant Residual dryer: CDRA-4 desiccant CO_2 removal: ISS CDRA-4 RK-38 zeolite 5A or alternative sorbents	Bulk dryer: Silica gel-NovelAire hybrid dryer Residual dryer: Silica gel-NovelAire hybrid dryer CO_2 removal: Temperature swing two-stage compressor; SBAR-derived; or CDRA-derived with alternative sorbent
	Resource recovery	Sabatier with methane purification assembly, ISS piston compressor with CO_2 accumulator; ISS OGA	Sabatier with full-scale third generation plasma pyroysis assembly, ISS piston compressor with CO_2 accumulator; ISS OGA	Sabatier, full-scale PPA, full-scale HyPA, full-scale ASepA; Microlith Sabatier; O_2 compression
	Trace contaminant control	Microlith HTCO unit; mixed media sorbent bed; ambient temperature CO oxidation catalyst	Adsorbent cartridge concept containing alternative media; Microlith HTCO unit	Alternative TCC technologies, e.g., PCO and ammonia catalytic removal; advanced adsorbent bed architecture; Microlith HTCO unit
	Particulate removal	Commercial high-efficiency media filter	Commercial high-efficiency media filter	Indexing media filter with inertial separator
	Environmental monitoring	First-round commercial major constituent analyzer	Second-round commercial MCA; commercial volatile organic analyzer; VCAM, mGM, TELS	Third-round commercial MCA; VEM; mGM; TELS; RASCaL array
Development	Carbon dioxide removal	Bulk dryer: membrane and isothermal bulk desiccant Residual dryer: NovelAire and H_2O Microlith CO_2 removal: Temperature swing two-stage compressor and alternative CO_2 sorbent characterization	Bulk dryer: Silica gel alone; hybrid silica gel/NovelAire Residual dryer: Silica gel alone; hybrid silica gel/ NovelAire CO_2 removal: Temperature swing two-stage compressor and SBAR	CO_2 removal: Temperature swing two-stage compressor, SBAR, or alternative sorbent packed bed
	Resource recovery	One and four-person PPA; ASepA; O_2 compression	Full-scale PPA and subscale HyPA; O_2 compression	Bosch process development
	Trace contaminant control	Photocatalyst development; ammonia catalytic removal; commercial adsorbent and catalyst characterization; ISS TCCS lessons learned	Photocatalyst development; ammonia catalytic removal; commercial adsorbent and catalyst characterization; ISS TCCS lessons learned	ISS TCCS lessons learned
	Particulate removal	Indexing media filter; intertial separations	Indexing media filter; intertial separations	Filter media life extension
	Environmental monitoring	VEM; mGM; TELS; RASCaL array	VEM; mGM; TELS; RASCaL array	ISS VCAM, AQM, and ANITA operations lessons learned

7.2.1 Test Chamber Overview

The 90.6-m^3 EChamber, shown in figure 5, provided the integrated testing infrastructure during the R2FD and ARREM cycles 1 and 2 integrated testing series. The EChamber is outfitted with test support equipment to:

- Inject trace chemical contaminants.
- Provide chamber ventilation, temperature, and humidity control.
- Provide chamber atmospheric pressure control.
- Simulate human metabolic loads and demands.
- Monitor the chamber's internal conditions.
- Provide a space vacuum simulation resource.
- Accommodate thermal and power loads in support of assembly- and system-level integrated tests.

Automated test operations control and data acquisition are provided via LabVIEW (National Instruments) software, and data archiving is provided by the MSFC Payloads and Components Real-time Automated Test System (PACRATS) software. The EChamber atmospheric pressure is selectable from slightly above local barometric pressure to <55.2 kPa. An enclosure surrounds the EChamber to minimize the effects of external temperature changes in the facility high bay on the EChamber's internal pressure.

7.2.2 Analytical Method Overview

The EChamber's inline analytical methods provide data necessary for determining that the test objectives are being met. The analytical instrumentation used during the R2FD and ARREM cycles 1 and 2 testing series can be divided into two groups: instruments used for trace contaminant propagation studies and instruments used to monitor major constituents of the chamber atmosphere. The instruments used to monitor major constituents of the chamber atmosphere also serve as a test article for the MCA function. The trace contaminant monitoring instruments were located in the large high bay facility outside the EChamber enclosure. The temperature inside the high bay was maintained at approximately 23 °C throughout the duration of the tests. Sample delivery from the EChamber to the trace contaminant instrumentation was accomplished via a 6.4-mm- (0.25-in-) diameter × 12.2-m (40-ft) stainless steel, unheated transfer tubing. This tubing was solvent cleaned and extensively purged with dry nitrogen prior to being placed into service. The sample flow was provided by a small pump located near the analytical instrumentation. A multi-port valve provided flexibility with respect to sampling location inside the EChamber. The MCA instrumentation was rack mounted inside the EChamber. These instruments sampled the EChamber atmosphere directly, requiring no transfer lines.

7.2.2.1 Trace Contaminant Monitoring Methods. All quantitative analyses with respect to trace contaminants were carried out with an Agilent 6890 GC utilizing a single analytical column and a flame ionization detector. The column was a 30-m- (98.4-ft-) long intermediate polarity capillary column with a 0.53-mm inner diameter. The film thickness was 3 µm. Ultrahigh-purity helium was used as the carrier gas. Facility grade nitrogen was used to perform instrument blanks between sample runs.

Sample concentration and delivery to the GC was accomplished with a Markes TT24-7 thermal desorption system. This is an electrically-cooled, two-trap system with the traps operating sequentially. The measurements were accomplished by sampling from each sample port for 10 minutes during an approximate 25-minute cycle. The traps were packed with Tenax TA™ and Unicarb™ in order to retain both low and high volatility compounds.

The airborne concentration inside the EChamber for the VOCs generated from the liquid injection mixture was expected to be in the low parts per million range, the exception being during the initial EChamber conditioning at the start of the test once the door had been closed and sealed. This step was necessary in order to passivate the inner surfaces of the EChamber itself as well as the various items of hardware contained inside. The initial spiking was achieved by using multiple 1-mL injections in rapid succession.

All analytical target compounds were calibrated using standard multi-point methods summarized in table 4. During the R2FD test, both liquid and commercially purchased gas standards were used for calibrating the GC. The liquid phase standards were first injected onto a sorbent tube. Next, the sorbent tube was desorbed at high temperature onto the cold traps of the Markes 24-7 unit. Finally, the cold traps were rapidly heated, causing the VOCs to desorb and flow onto the GC column via a heated transfer line. The gas phase standards, contained in pressurized cylinders, were introduced directly onto the cold traps in the same fashion as a typical air sample. During the ARREM cycle 1 and cycle 2 tests, GC calibration was achieved using gas phase standards generated on demand via a National Institute for Standards and Technology traceable permeation tube gas generator manufactured by Kin-Tek. While the GC method error was compound specific, overall, the order of magnitude was in the 25% to 30% range.

Table 4. Gas chromatograph calibration method summary.

Compound	Calibration Method		
	R2FD	Cycle 1	Cycle 2
2-propanol	Liquid	*	Permeation tube
Ethanal	Liquid	Permeation tube	Permeation tube
2-propanone	Liquid	Permeation tube	Permeation tube
Benzyl alcohol	Liquid	*	*
Dichloromethane	Liquid	Permeation tube	Permeation tube
Ethanol	Certified Gas	Permeation tube	Permeation tube
Methanol	Liquid	*	Permeation tube
1,2-propanediol	Liquid	*	*
1,3-dimethylbenzene	Liquid	Permeation tube	Permeation tube
Trimethylsilanol	*	*	Permeation tube
Hexamethylcycletrisiloxane	*	*	Permeation tube

*Compound not included in injection mixture.

A second GC, an Agilent 7890 utilizing a single analytical column with both a flame ionization and a mass selective detector, was employed for screening and unknown compound identification during portions of ARREM cycle 1 and cycle 2 tests. This GC was coupled with a Gerstel

Thermal Desorption System and in the future will be used in conjunction with the Agilent 6890/ Markes 24-7 system to provide more robust testing capabilities than were previously possible.

An FTIR spectrometer Gasmet DX4040 was used for analyzing target compounds near real-time. The Gasmet DX4040, which was identified by commercial market analysis for portable VOC analyzers, is capable of simultaneously monitoring up to 25 infrared-active compounds. Specific VOC compounds monitored included acetaldehyde, acetone, dichloromethane, ethanol, isopropanol, methanol, and xylene. Water vapor (%) as well as carbon dioxide and carbon monoxide were also monitored. Sampling was accomplished via 9.1 m (30 ft) of 6.35 mm (0.25 in) stainless followed by 3.05 m (10 ft) of 6.35 mm (0.25 in) polytetrafluoroethylene tubing. A sample pump internal to the Gasmet DX4040 FTIR supplied a flow rate in excess of 1 L/min. A typical sample cycle consisted of pumping atmospheric air from the EChamber to the FTIR and through the FTIR sample cell for 5 minutes and after disengaging the sample pump, performing spectrum acquisition for 5 minutes. The pump would then reengage and the cycle would repeat. Sample effluent was returned to the EChamber via a line so that a closed loop could be maintained. Other than for daily rebaselining the instrument with nitrogen, sampling was usually performed nonstop. The Gasmet DX4040 provided a more rapid sampling rate than the GC units. Analytical results indicate that when compared to the GC-MS, the Gasmet DX4040 tended to overstate the actual concentration present by an average of 10% to 40%, especially for water-soluble compounds such as alcohols. In the case of CO_2 and CO, the unit produced results within the range of other CO_2 and CO monitors used in the testing facility.

7.2.2.2 Major Constituent Analysis Instrumentation. The major constituents monitored during the R2FD and ARREM cycle 1 investigations included oxygen, carbon dioxide, and water vapor. An instrument array demonstrated in 2002 through 2003 and described by reference 21 provided the function. In this array, shown in figure 9, oxygen was monitored using an Oxigraf model oxygen analyzer. This device utilizes a solid-state laser diode absorption system and measures oxygen concentrations ranging from 0.01% to 100% by volume. Carbon dioxide was monitored using a Sable Systems CA-2A analyzer, which utilizes solid-state infrared absorption technology and can measure between 1 ppm and 10% carbon dioxide. Relative humidity was measured using a Sable Systems RH-100 meter, employing a solid-state, thin-film capacitance detection system. This instrument is capable of measuring relative humidity between 0.01% and 99%. The instrument array performance was stable throughout both the R2FD and ARREM cycle 1 and cycle 2 testing series.

7.2.3 Test Data Error Analysis Overview

The importance of having an accurate mass balance determination for oxygen and the other major constituents, carbon dioxide and water, cannot be overemphasized. The ARREM project's goal of researching a regenerable closed-loop ECLSS required that there be minimal error in the test instrumentation. One of the most important aspects of a regenerable system is creating 'enough' oxygen and water to survive in space when resupply is no longer possible or feasible. Having sufficient constituents, or tolerances for the major constituents, is a potential subject for spirited debate. Suffice to say, while the technique used by the ARREM project may lend itself to overestimating the error, a good rule of thumb is to always have more oxygen in the system than what is minimally required.

Figure 9. Major constituent analysis instrument array.

A generalized uncertainty analysis was conducted by the ARREM project to understand test instrumentation error propagation. The simplified analysis technique used by the ARREM project is summarized in appendix D and has been reviewed versus NASA-HDBK-8739.19-3 to determine an approach for expanding the uncertainty analysis to a more rigorous level.[26] The difference between AAREM's methodology and NASA's handbook, as well as recommendations for expanding the scope of the ARREM uncertainty analysis is also included in appendix C.

The ARREM project based its error analysis for the integrated system on *Experimentation and Uncertainty Analysis for Engineers*.[27] Section 4 of Coleman and Steele's text discusses the propagation of errors within an experiment and covers biases, precision errors, varying sample sizes, varying orders (0th–*n*th), and transient versus steady-state experiments. All of the instrumentation manufacturers utilized in the ARREM project integrated testing configuration for R2FD, cycle 1, and cycle 2 provided data sheets disclosing sources of error for the instrumentation.

The instrumentation manufacturers also provided instructions on how to calculate respective instrumentation error on each data sheet. Instrumentation error is a percentage of the instrument readings added to a percentage of the full scale of the instrument. The ARREM project recorded its instrument readings using the PACRATS data acquisition software. The applicable test data were then selected, downloaded, and analyzed. Each parameter was assigned an instrument and had a unique identifier.

Initially, the ARREM project's integrated testing instrumentation error analysis considered the steady-state parameters. Analysts studied the standard deviations of the test parameters checking for large deviations that could indicate malfunctions or leaks. The study later evolved to include the transient parameters such as flow meters and totalizers which lead to considering error propagation.

Results from the generalized error analysis applied to the integrated test mass balance found that the mass flow control and measurement sensors used for simulating the metabolic carbon dioxide load and oxygen demand contribute the greatest to the overall error in the mass balance. Propagated error associated with the CO_2 mass balance found that the error associated with the simulated metabolic CO_2 load ranged between ±0.054 and ±0.89 kg (±0.12 and ±1.97 lbm). The discrete mass balance differential on CO_2 was within 0.5 kg (1.1 lbm) on average during integrated testing phases. The higher error was associated with an error component applied to the discrete measurement itself. Because the flow instrumentation consisted of a mass flow totalizer, a mass totalizer value starting at a high discrete value resulted in a larger error component than when the totalizer was reset to a lower starting discrete value. The propagated error associated with the simulated O_2 production was in a range between ±0.68 and ±1.95 kg (±1.5 and ±4.3 lbm), which represented over 90% of the total mass balance error. The discrete O_2 mass balance differential was within 0.43 kg (0.96 lbm) on average during testing. Similarly, for the water mass balance error, the water production load error ranged between ±0.11 and ±0.33 kg (±0.25 and ±0.72 lbm) which accounted for over 90% of the total mass balance error. The discrete mass balance on water was within 1.5 lbm during integrated testing phases. These findings indicated that the instrumentation error can be greater in magnitude than the discrete mass balance differential. Therefore, more precise instrumentation for the simulated metabolic loads and demands as well as for simulating loop closure functions will benefit the testing results.

7.3 The Basis for Comparison—the International Space Station Architecture

The R2FD test configuration, shown schematically in figure 10,[12] duplicates the ISS ARS architecture. Over time, that architecture has evolved to enable a higher degree of loop closure by adding O_2 generation and CO_2 reduction functions. The core ISS ARS equipment used for the R2FD test included a developmental CO_2 removal assembly (dev-CDRA), a Sabatier-based CO_2 reduction assembly development unit (SDU), the ISS trace contaminant control system development unit 1.1 (TCCS dev-1.1), and the ISS developmental O_2 generation assembly (dev-OGA). The dev-OGA equipment was not operational in time for the test so the function was simulated using facility-provided O_2 and H_2 feeds to the chamber atmosphere and the SDU, respectively. Carbon dioxide flow pulses to the SDU were dampened using a carbon dioxide management assembly (CMA), which consisted of a two-stage commercial compressor and flight-like accumulator tanks. Because the commercial compressor discharge pressure was 414 kPa compared to the flight CRA compressor's 827 kPa, the flight-like accumulator tank volume was increased from 19.8 to 48.1 L using a supplementary tank. An array of commercially available analyzers described in reference 12 provided the MCA function. Testing conditions and events are summarized in appendix E.

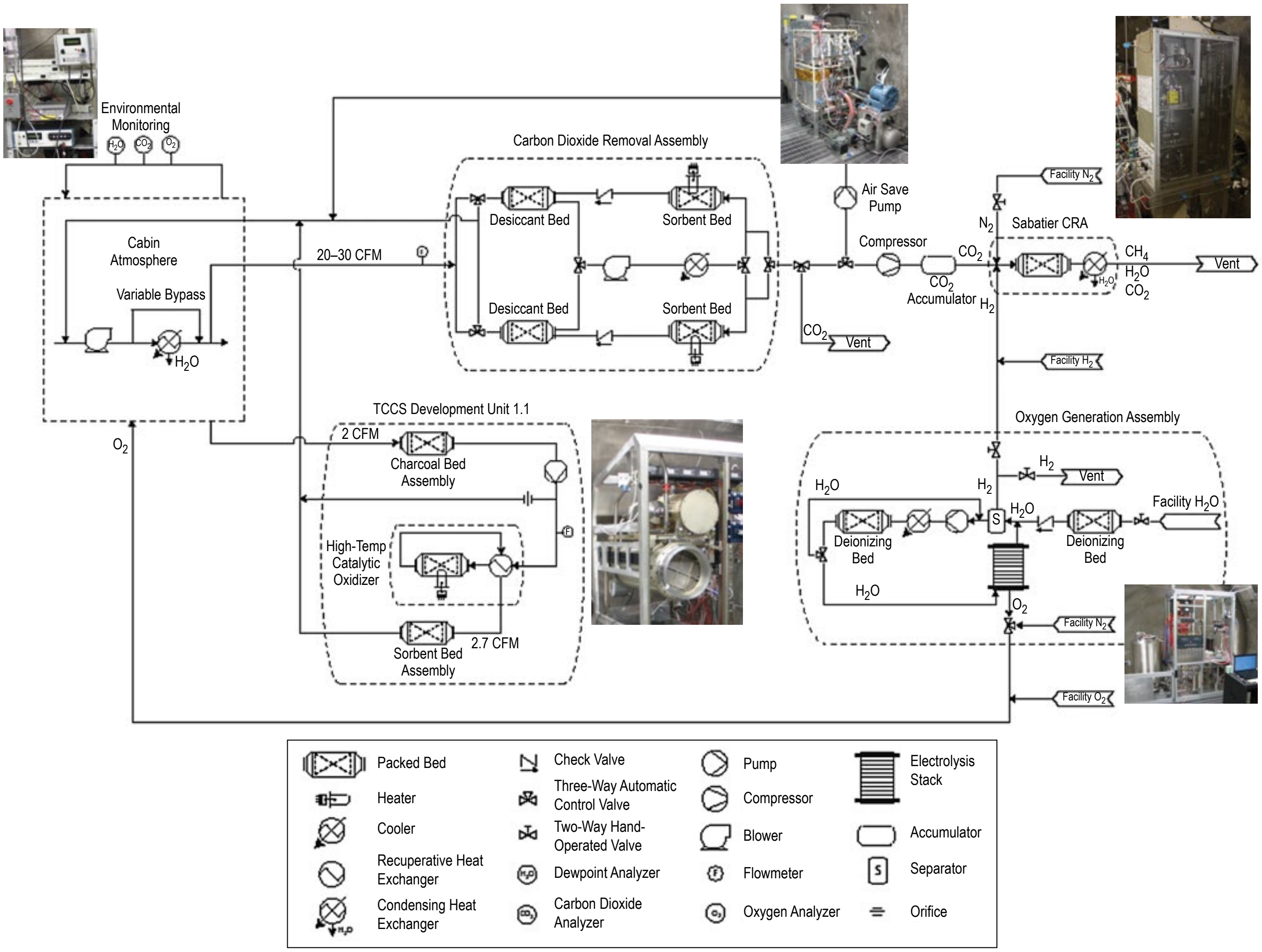


Figure 10. Resource recovery functional demonstration test schematic.[12]

7.3.1 Phase 1 International Space Station Atmosphere Revitalization Subsystem Resource Recovery Architecture Functional Demonstration

The core ARS equipment consisting of the CDRA and CO_2 management assembly was operated for a minimum of 4 days. The system was challenged with a CO_2 and moisture load equivalent to three people under nominal activity levels. The progression for this testing phase included CDRA standalone operations for a minimum of 2 days and integrated CDRA and CO_2 management assembly operation for a minimum of 2 days.

7.3.2 Phase 2 Investigation of Trace Contaminant Propagation Through the International Space Station Atmosphere Revitalization Subsystem

Trace contaminant propagation through the core ARS equipment and concentration by a medical oxygen concentrator were evaluated during phase 2.

7.3.2.1 Phase 2A Evaluation of Trace Contaminant Propagation Into the Carbon Dioxide Removal Assembly Carbon Dioxide Product. The ARS equipment consisting of the CDRA, TCCS, and CO_2 management assembly was operated for a minimum of 7 days. The metabolic load for three people was simulated during the test phase. Trace contaminants that were injected into the test chamber and monitored include ethanol, o-/m-dimethylbenzene, dichloromethane, acetone, and acetaldehyde. The carbon dioxide product was sampled from the CO_2 management assembly accumulator and analyzed for trace contaminant content four times per test day.

7.3.2.2 Phase 2B Evaluation of SeQual Eclipse Medical Oxygen Concentrator. The SeQual Eclipse medical oxygen concentrator is a commercial unit that is also under development for use in providing medical oxygen supply to an injured or sick astronaut. As a co-investigator on a National Space Biological Research Institute grant, MSFC evaluated this unit for spaceflight applicability. The R2FD testing provided an opportunity to evaluate the Eclipse while it also provided the function of simulating metabolic oxygen consumption. Aspects of interest were the effects of increased CO_2 partial pressure on Eclipse performance, and investigation of the potential for concentration of trace contaminants present in spacecraft atmospheres by the Eclipse unit. If in use as a medical oxygen supply device, concentration of trace contaminants could result in higher than allowable levels being present in the oxygen stream supplied to an astronaut. Also of interest was the potential for Eclipse sorbent poisoning and performance degradation due to trace contaminants present in spacecraft. These effects can only be detected by exposure to a simulated spacecraft atmosphere. To determine the impact of the spacecraft atmosphere on the Eclipse, the unit oxygen effluent stream was analyzed for impurities.

7.3.3 Phase 3 Extended Duration Resource Recovery Functional Demonstration

The core AR equipment consisting of the CDRA, TCCS, carbon dioxide management assembly, and CRA were operated continuously for a minimum of 7 days. The metabolic simulation was equivalent to three people. Trace contaminant injection consisted of methanol, ethanol, 2-propanol, ethanol, acetaldehyde, o-/m-dimethylbenzene, dichloromethane, acetone, methane, and carbon monoxide.

7.3.4 Resource Recovery Functional Demonstration Results Summary

Specific testing objectives were focused on understanding the propagation of trace contaminants through the core ARS equipment and the resulting effect on the purity of product CO_2 being fed to the SDU. As-run test events and results are provided in appendix E. The TCCS showed the ability to keep the EChamber atmosphere trace contaminant concentrations within the expected range while processing the simulated contaminant loading of a three-person crew. The TCCS used the phosphoric acid-treated activated carbon (Barnabey Sutcliffe Type 3032) and palladium catalyst (Engelhard Corp.) used aboard the ISS. The total trace contaminant load was maintained below

1.5 ppm. Trace contaminant propagation through the CDRA equipment resulted in approximately 0.025 ppm total VOC loading in the CO_2 being fed to the CRA. The average humidity condensate removed from the EChamber was 7.86 kg/day. The CMA performed properly according to the control logic but some inefficiencies were observed that can affect CRA operations due to CO_2 accumulator pressure maintenance challenges when the pressure dropped below 137.9 kPa. Low accumulator pressure caused the CRA to periodically transition to standby mode. The CDRA performance analysis confirmed that the operation during R2FD testing compared with previous operations as far as CO_2 removal efficiency with a three-person metabolic load. The CO_2 concentration was maintained at approximately 0.3 vol%. This performance was provided using a flow at 34.6 m^3/ hr over ASRT zeolite 5A adsorbent media.

7.4 ARREM Project Cycle 1 Architecture

The functional architecture for the ARREM project cycle 1 test was an effort to reduce the total ARS complexity and part count with minimal change to ISS ARS components.[11] The test included all of the same equipment used during the R2FD test with two exceptions. First, the TCCS equipment was rearranged with a thermal catalytic oxidizer assembly, shown in figure 11(a), integrated directly with the dev-CDRA and a fixed activated carbon bed integrated in parallel with the cabin condensing heat exchanger as shown in figure 12. The objective was to eliminate an avionics box, blower with acoustic treatment, and a post-sorbent bed assembly while maintaining full TCC functionality. The catalytic oxidizer assembly also incorporated an engineered ultrashort channel metal monolith catalytic reactor design that has been demonstrated to be more energy efficient and more easily maintained in flight than the ISS TCCS catalytic reactor design.[28] These changes may realize mass and volume savings up to 12.4 kg and 14.7 L, respectively, compared to the ISS ARS architecture while maintaining trace contaminant removal performance. Adsorbents and catalysts that have been evaluated and determined to be suitable replacements for those used in the ISS ARS equipment were used during the testing.[29,30]

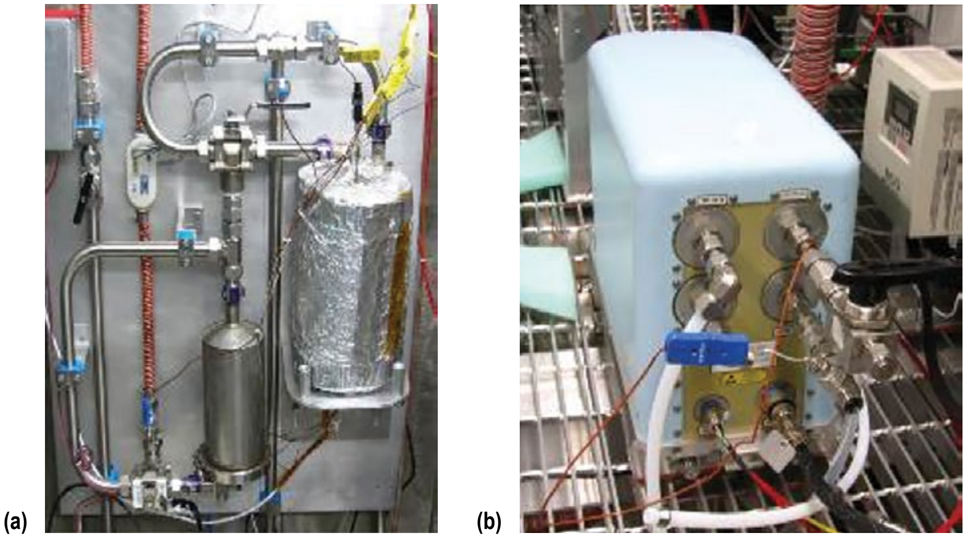


Figure 11. TCC and CO_2 management components: (a) Thermal catalytic oxidizer assembly and (b) piston compressor.

The fixed activated carbon bed was packed with Chemsorb 1425 (Molecular Products) activated carbon to replace type 3032 activated carbon (Barnebey Sutcliffe) that is commercially obsolete. The dev-CDRA carbon dioxide adsorbent beds were packed with RK-38 zeolite 5A as a replacement for ASRT zeolite 5A. The CMA compressor was replaced with a flight-like piston compressor manufactured by Southwest Research Institute shown in figure 11(b). This change allowed the carbon dioxide accumulator tank volume to be reduced to the ISS flight-like 19.8 L. The SDU was configured to test a methane purification post-processing stage. The MCA function was again provided by the array of commercially available instruments. Demonstrating flow rate balancing and evaluating the cycle 1 ARS architecture's performance relative to performance observed during the R2FD testing series were the primary testing objectives. The SDU was operated during the late testing phases. The dev-OGA was not included in the testing due to the equipment's readiness status. For this reason, as with the R2FD test, the oxygen generation function was simulated. Operational details and as-run testing conditions are provided in appendix F.

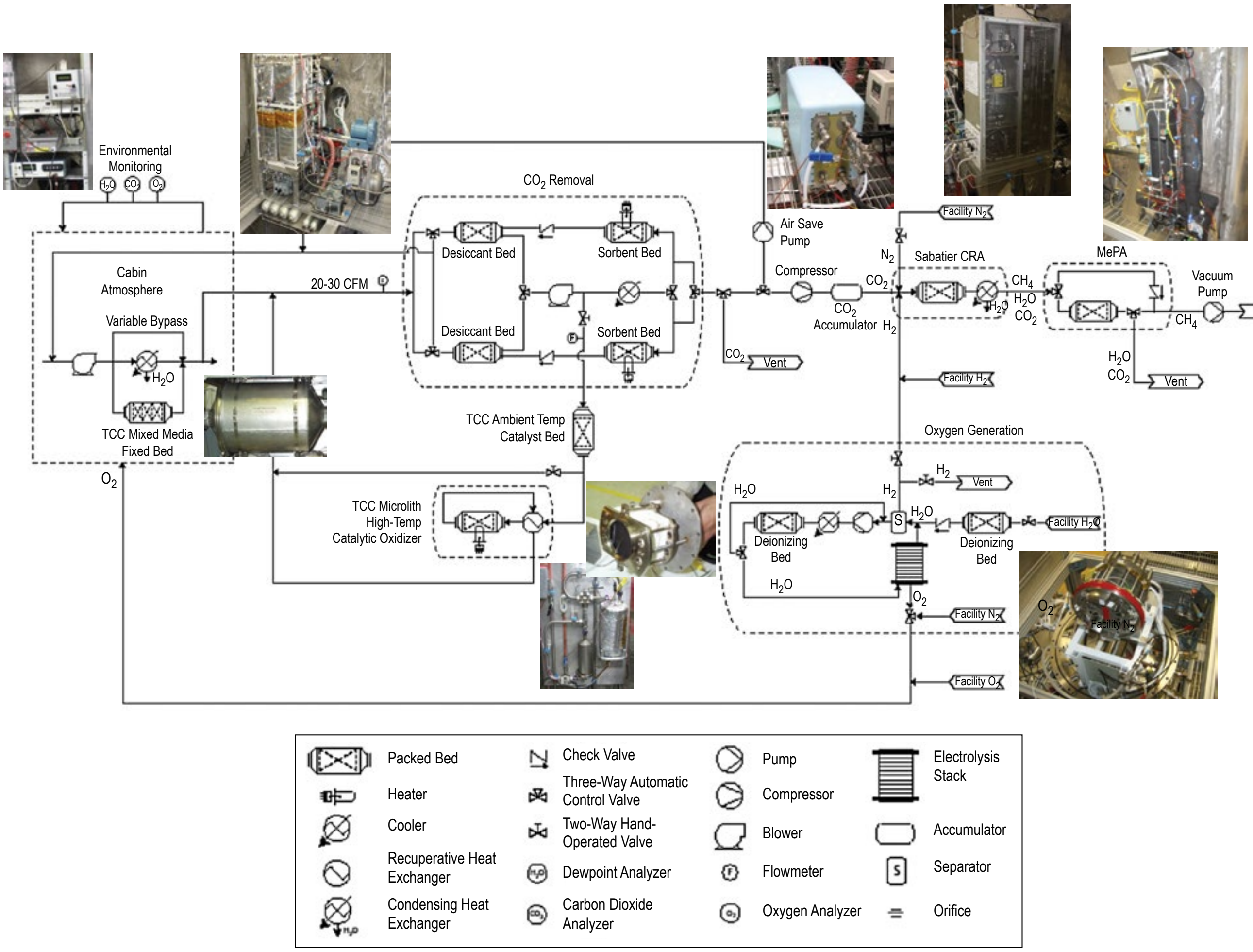


Figure 12. ARREM project cycle 1 integrated testing architecture.[15]

The cycle 1 functional demonstration of a closed-loop ECLS ARS consisted of four primary phases summarized as follows:

(1) Phase 0A—Assembly level performance.
0B—Core ARS flow balancing.

(2) Phase 1A—Demonstrate functional performance of the core ARS using the performance and operational issues system testbed (POIST) CDRA in CO_2 vent mode integrated with the Microlith HTCO and the adsorbent fixed bed (AFB) assembly operating in parallel.

Phase 1B—Demonstrate partial functional performance of the core ARS equipment when operating in a resource recovery mode that includes integration with CMA equipment.

(3) Phase 2—Investigate propagation of trace contaminants through the core ARS equipment with emphasis on CO_2 removal, CMA equipment, and CRA equipment.

(4) Phase 3—Demonstrate the full resource recovery functional performance of the ISS ARS including the TCC, carbon dioxide removal, CMA, CRA, MePA, and dev-OGA (as available) functions.

All testing phases were conducted at 1 ± 0.01 atm (14.71 ± 10.2 psia) chamber pressure. Selected testing phases were repeated using chamber pressures set at 0.68 ± 0.01 atm (10 ± 0.2 psia) and 0.54 ± 0.01 atm (8 ± 0.2 psia). Temperature, humidity, and metabolic simulation requirements varied according to specific test phase objectives. The SeQual Eclipse oxygen concentrator was operated similarly as during R2FD testing.

7.4.1 Phase 0—Assembly-Level Performance and Flow Balancing

Phase 0A consisted of POIST CDRA performance testing and TCC component flow versus pressure drop mapping. The POIST CDRA containing new bed materials was subjected to a three-point performance mapping for comparison to earlier bed packing configurations.

Phase 0B established core AR equipment flow balancing and demonstrate the capability to provide the required flow rates to the CO_2 removal and TCC equipment at 1 ± 0.01 atm (14.7 ± 0.2 psia) chamber pressure. The capability to deliver required flow rates to the CO_2 removal and TCC equipment was repeated using chamber pressures set at 0.68 ± 0.01 atm (10 ± 0.2 psia) and 0.54 ± 0.01 atm (8 ± 0.2 psia). The core ARS equipment consisted of the POIST CDRA and TCC components. Flow rates through all TCC components were demonstrated to comply with flow conditions necessary for exploration missions.

7.4.2 Phase 1—Core Atmosphere Revitalization Performance With Partial Loop Closure

The core ARS equipment consisting of the POIST CDRA and CMA was operated for a minimum of 4 days. The system was challenged with an incremental two- to six-person carbon dioxide and moisture load consistent with normal daily activity levels. The progression for this testing phase included POIST CDRA standalone operations for a minimum of 2 days and integrated POIST CDRA and CMA operation for a minimum of 2 days.

7.4.3 Phase 2—Trace Contaminant Propagation Through the Core Process Architecture

The ARS equipment consisting of the POIST CDRA, TCC equipment, and CMA was operated for a minimum of 7 days. The two- to six-person metabolic load was simulated during the test phase. Trace contaminants that were injected into the test chamber and monitored included ethanol, o-/m-xylene, dichloromethane, acetone, and acetaldehyde. The CO_2 product was sampled from the CMA accumulator and analyzed for TCC four times per test day.

7.4.4 Phase 3—Functional Demonstration of the Partially Closed Process Architecture

The core AR equipment consisting of the POIST CDRA, TCC equipment, CMA, CRA, and MePA was operated continuously for a minimum of 7 days. The metabolic simulation was equivalent to two to six people. Trace contaminant injection consisted of methanol, ethanol, 2-propanol, ethanol, acetaldehyde, o-/m-xylene, dichloromethane, acetone, methane, and carbon monoxide.

7.4.5 ARREM Project Cycle 1 Results Summary

Details regarding testing events and test conditions are provided in appendix F. Relative to the primary objectives to evaluate the comparative performance of using RK-38 versus ASRT zeolite 5A for CO_2 removal, phase 1 testing indicated comparable performance. However, when integrated with the TCC M-COA catalytic oxidation assembly at the midpoint, ~5.9 m^3/hr of flow was diverted away from the CO_2 removal beds. As a result, the integrated process performance controlled the CO_2 concentration to 0.45 vol% for the three-crewmember metabolic loading condition. While this level is acceptable for long-duration missions, this particulate flow condition is not adequate for a crew of four or more. Additional flow up to 37 m^3/hr at the CDRA inlet is necessary to accommodate up six crewmembers and incorporate the TCC catalytic oxidizer assembly integrated at the point just upstream of the CO_2 removal beds. This flow condition is possible using existing CDRA blower technology.

The TCC function was comparable to that observed during the R2FD test with total VOC concentration maintained below 2 ppm. The flow through the carbon bed at 8.5 m^3/hr was tailored for an exploration mission and is 44% lower than the 15.3 m^3/hr flow through the TCCS carbon bed used for the R2FD test. Effective removal flow, the product of measured flow and the VOC single-pass removal efficiency, was 13.5 m^3/hr for the R2FD test that used Barnabey Sutcliffe Type 3032 carbon and 7.8 m^3/hr for the cycle 2 activated carbon bed configuration that used Chemsorb 1425 (Molecular Products) carbon. The trace contaminant propagation through the core AR equipment was statistically comparable to that observed during the R2FD testing. The discrete total VOC concentration in the CO_2 fed to the CRA was ~0.04 ppm which is within the experimental error band (±0.02 ppm) of the 0.025 ppm VOC concentration observed during the R2FD test.

The cycle 1 testing series demonstrated that an ISS-derived architecture is feasible for exploration mission applications. Such an architecture can provide equivalent or improved performance relative to the ISS SOA. The simple TCC component reconfiguration is projected to reduce ARS mass by at least 12 kg and volume by 15 L. Potential exists for using smaller CO_2 removal beds since the beds designed for ISS possess substantial operational margin for a four-crewmember exploration metabolic load. The degree of loop closure provided by the CRA was adequate, yet a higher degree of loop closure must be demonstrated to reach exploration figure of merit goals.

7.5 ARREM Project Cycle 2 Architecture

The ARREM cycle 2 test configuration is depicted in figure 13. In this testing series, TCC system components trade a low flow fixed bed for high flow cartridges mounted in the ventilation duct. The CO_2 removal test article is upgraded to a CDRA-4 fidelity and CO_2 reduction post-processing demonstrated CH_4 plasma pyrolysis. The primary ARS developmental equipment used for ARREM cycle 2 testing consisted of a TCC adsorbent cartridge fixed bed (ACFB) assembly packed with alternative adsorbent media (Ammonasorb II, Calgon Carbons), a TCC Microlith-based, HTCO assembly, the CDRA version 4 ground test unit with beds packed with ISS CDRA-4 materials, an SDU CO_2 reduction assembly, and a dev-OGA. A CMA consisting of a compressor and accumulator tanks were located downstream of the CO_2 removal equipment to condition the product CO_2 and to serve as a collection buffer that dampens flow rate pulses to the SDU. The compressor and accumulator tanks simulate the functional ‘scar’ in the ISS oxygen generator system (OGS) rack.

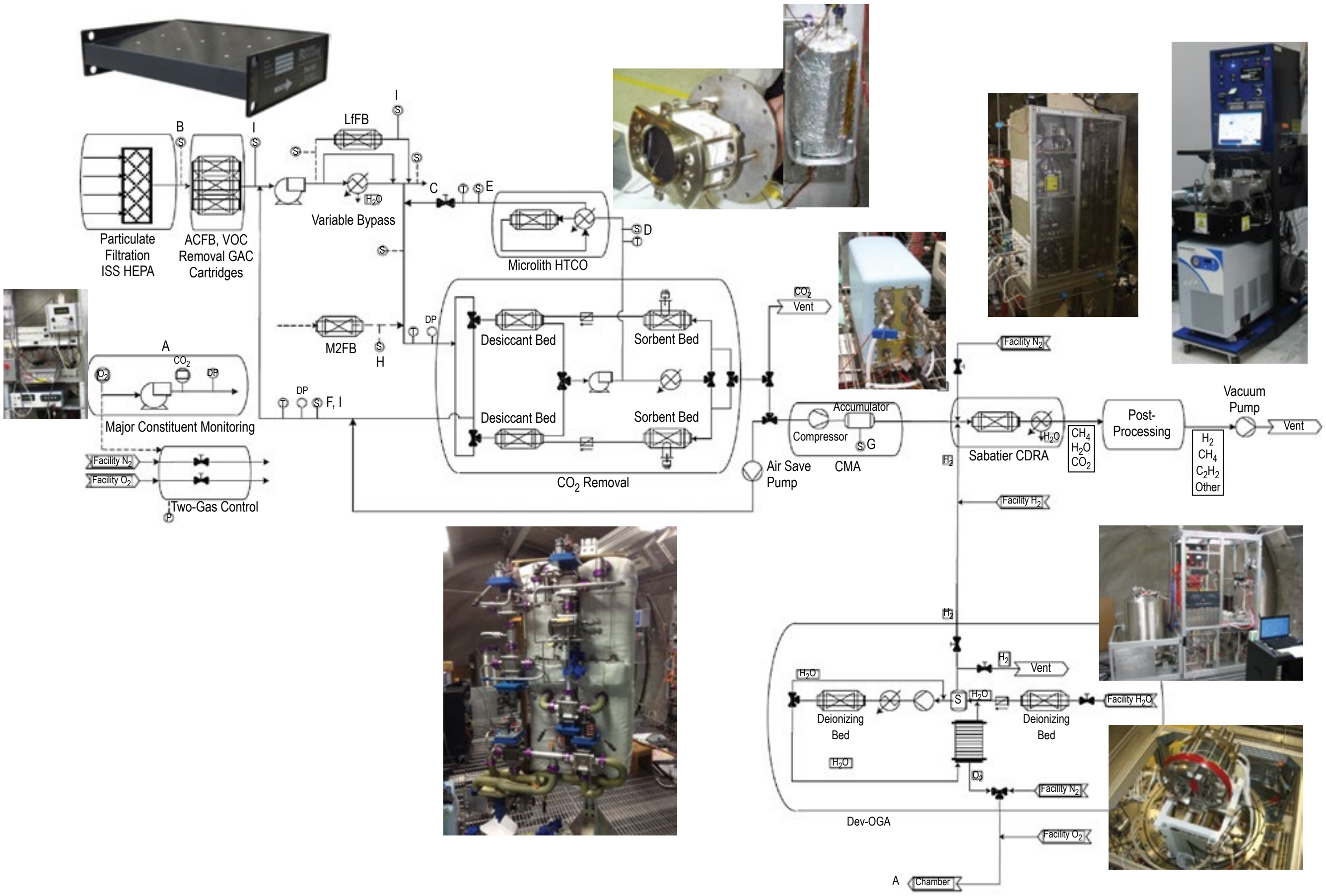


Figure 13. ARREM project cycle 2 integrated testing architecture.

Environmental monitoring equipment was provided to monitor major atmospheric constituents and VOCs. Major constituent analysis was provided by a commercial instrumentation array consisting of an Oxigraf model oxygen analyzer, a Sable Systems Inc. model CA-2A CO_2 analyzer, and a Sable Systems, Inc. model RH-100 dewpoint meter described in reference 21. A commercially available portable FTIR unit (Gasmet model DX4040) was demonstrated as an analogue to the European Space Agency's ANITA instrument which was demonstrated aboard the ISS in 2008. Selected environmental monitoring instruments were demonstrated according to JPL-developed testing requirements.

Cycle 2 integrated testing series phases are as follows:

- Phase 1—Demonstrate CDRA-4EU four-point test series with and without M-COA integration, demonstrate low CO_2 partial pressure control capability, and demonstrate nine crewmember support capability.

- Phase 2—Demonstrate major constituent monitoring and two-gas chamber pressure control performance.

- Phase 3—Demonstrate selected dev-OGA control modifications and integrated 'recombiner' performance.

- Phase 4—Evaluate TCC concept architectures.

- Phase 5—Demonstrate full subsystem architecture with step-wise metabolic challenge at three-, four-, and six-crewmember loads.

- Phase 6—Demonstrate full subsystem architecture with four-crewmember dynamic metabolic load.

- Phase 7—Demonstrate selected environmental monitoring instruments.

All testing phases were conducted at 1 ± 0.01 atm (14.7 ± 0.2 psia) chamber pressure. Selected testing phases may be repeated using chamber pressures set at 0.68 ± 0.01 atm (10 ± 0.2 psia) and 0.54 ± 0.01 atm (8 ± 0.2 psia). Temperature, humidity, and metabolic simulation requirements varied according to specific test phase objectives.

7.5.1 Phase 1—Carbon Dioxide Removal Assembly Engineering Unit Performance Mapping

Phase 1 consisted of CDRA-4EU performance testing and establishing flow balance with TCC components. The CDRA-4EU equipment was subjected to a three-point performance mapping for comparison to earlier bed packing configurations. The basic three-point test was expanded to include a fourth point at 5 torr CO_2 partial pressure.

As part of phase 1, the flow balance between the M-COA and CDRA-4EU equipment was established. Additional testing during phase 1 investigated the CDRA-4EU equipment's capabilities to control the CO_2 partial pressure below the 1,000-day spacecraft maximum allowable concentration (SMAC) at three static crew metabolic loading conditions as well as the capability to support nine crewmembers.

7.5.2 Phase 2—Major Constituent Monitoring and Chamber Pressure Control Demonstration

The EChamber was outfitted to include a total pressure and oxygen/nitrogen partial pressure control capability. The equipment configuration to provide the major constituent composition control and chamber total pressure control were exercised through several cycles. The equipment employed a flight-like control algorithm used aboard the ISS.

7.5.3 Phase 3—Alternative Oxygen Generation Assembly Configuration Demonstration

Phase 1 focused on specific oxygen generation equipment operational and physical configuration changes to partially or fully address technical aspects pertaining to the following:

- Demonstrate an operational approach with an alternative (or no) hydrogen sensor.
- Demonstrate an operational approach leading to eliminating the cell stack containment dome.
- Demonstrate an approach to eliminate the nitrogen purge.
- Demonstrate a recirculation loop flush/sampling capability.
- Demonstrate the effects of different current levels.
- Demonstrate a cell discharge procedure.
- Demonstrate an approach to eliminate the wastewater interface.

7.5.4 Phase 4—Full Ventilation Flow Adsorbent Cartridge Trace Contaminant Challenge

Phase 4 demonstrated the function of the ACFB assembly versus a low-flow fixed bed (LfFB) assembly. The EChamber ventilation system, condensing heat exchanger, and contaminant injection equipment was included in the testing phase. Contaminant injection and humidity injection established an initial condition and the ventilation system was operated to provide chamber atmospheric mixing. The trace contaminant concentrations were monitored during the testing phase to determine the performance of the ACFB and LfFB concept architectures. The performance for each concept architecture was compared and the ACFB architecture was selected for implementation in phases 5 and 6.

7.5.5 Phase 5—Core Architecture Performance Mapping

The core AR equipment consisting of the CDRA-4EU, TCC equipment, CMA, CRA, and dev-OGA was operated continuously for a minimum of 8 days. The metabolic simulation was static and progressed through levels equivalent to three, four, and six crewmembers. Trace contaminant injection and monitoring was conducted during the testing phase to understand the fate of specific chemical contaminants in the core architecture.

7.5.6 Phase 6—Dynamic Metabolic Control Demonstration

Phase 6 repeated the testing conducted during phase 5 with the exception that the metabolic simulation was dynamic, accounting for sleep, normal activity, and exercise periods for a four-crewmember load.

7.5.7 Phase 7—Environmental Monitoring Demonstration

Phase 7 demonstrated selected environmental monitoring instruments. The selected instruments monitored both static and dynamic chamber air quality environments according to NASA JPL-developed testing requirements.

7.5.8 ARREM Project Cycle 2 Results Summary

A brief summary of results for phases 1 and 3 through 7 is provided by the following discussion. Details on phase 2 testing events are provided in appendix A. Phase 2 successfully demonstrated a facility-provided test support function that enabled later testing phases. Because phase 2 was test support centric instead of ARS technology centric, the details are not discussed here.

Phase 1 investigated whether the OGA can be safely operated without startup or shutdown nitrogen purges by making use of hydrogen and oxygen recombination that occurs naturally at the anode catalyst sites. The test consisted of three, 1-week runs consisting of a baseline run with both purges, a run with the startup purge disabled, and a run with both the startup and shutdown purges disabled. Each of the nitrogen purge deletion tests were conducted twice for repeatability which was observed. The overall conclusion is that disabling nitrogen purging does not appear to introduce new safety risks to operating the OGA. Eliminating the nitrogen purging for an exploration OGA eliminates ~22.7 kg (~50 lb_m) equipment mass and volume associated with the purge. Additional exploration mission mass reduction associated with spare parts may also be realized. According to analysis conducted by the White Sands Test Facility, if no hydrogen/oxygen recombination occurs and a combustible mixture forms, the 'backfire' produced would release energy equivalent to a single firecracker.[31] It was noted that water in the oxygen outlet that results from the hydrogen/oxygen recombination process needs to be removed to prevent damage to downstream H_2 sensors or recombiners.

At the beginning of phase 3, a four-point CO_2 concentration challenge test on the CDRA-4EU was conducted to establish the performance baseline for both forwards comparison on future bed materials, test conditions, etc., and backwards comparison to the previous CDRA configuration used during R2FD and cycle 1 testing. For phase 3 runs, the target air flow was 34.66 m^3/hr (20.4 scfm) with the CDRA operated on 155-minute half cycles. The CDRA sorbent bed material was from the flight lot of RK38 zeolite 5A while the desiccant bed was predominantly a layered arrangement of zeolite 13X (44.4% of bed volume) and Sylobead SG 125 B silica gel (46.5% of bed volume). After completing the four-point challenge runs, the potential for increasing the CO_2 removal performance resulting from increases in process flow rate was investigated. The nominal flow of 34.66 m^3/hr was increased to 42.48 m^3/hr, while the cycle time was reduced to 90 minutes, the minimum that would allow time for the CO_2 sorbent beds to heat to the nominal setpoint of 204 °C (400 °F). Performance results from this test were favorable; the test results demonstrated that one key exploration objective was met, e.g., reducing cabin CO_2 levels to 2 mmHg with four crewmembers. Removal capacity for a high crew load (nine crewmembers) was also demonstrated. The combination of higher flow rates and reduced cycle times resulted in considerably higher power requirements. Heater power alone increased by 200 W (average) compared to a nominal operational configuration; blower power (not measured) would also increase significantly. The 42.48 m^3/hr flow combined with a 90-minute half cycle was selected for the CDRA-4EU operating condition for phases 5 and 6.

Phase 4 testing compared the performance of two activated charcoal bed architectures—the ACFB and the LfFB. In this test phase, each architecture was operated independently. Although, similar in magnitude of charcoal mass contained (~23.5 kg for the ACFB and 21 kg for the LfFB), each bed varies in process air flowpath. The ACFB, consisting of three vertically-stacked cassettes 15.24 cm high × 60.96 cm wide × 35.56 cm deep (6 inches high × 24 inches wide × 14 inches deep) with a volume of 13.5 L (825 in^3) of Ammonasorb II (4 × 8 mesh) each, resided on the inlet of the main ventilation ductwork and saw the full 849.5 m^3/hr (500 scfm) ventilation flow while the LfFB, a cylindrical bed 33.02 cm diameter × 38.1 cm long (13 inches in diameter × 15 inches long) with a volume of 32.6 L (1,991 in^3) packed with Ammonasorb II (6 × 12 mesh), received only 20.4 m^3/hr (12 scfm) of the ventilation flow via a side branch. The high flow rate of the ACFB is exposed to a shorter bed length of charcoal compared to the cylindrical LfFB. Bed architecture performance was characterized by its ability to maintain a high single-pass adsorption efficiency for each compound. Both computer simulation and intuitive experience suggested a breakthrough of light compounds such as acetaldehyde and methanol for these beds. This was observed experimentally in both cases, although faster than predicted for the LfFB. This was likely due to differences in the charcoal capacity used in simulations and experiments. Computer simulations also suggested the ACFB would maintain some single-pass efficiency for siloxane compounds. Experimental data showed that as late as test day 6 into phase 4 testing that the ACFB still maintained a capacity for siloxane and organosilicone compounds which maintained the chamber atmospheric concentration near or below facility analytical instrument detection limits. Performance was also maintained for xylene.

In addition, acetone and isopropanol were held at low levels as compared to the LfFB, in part due to the much higher flow rate through the ACFB, increasing chamber scrubbing rates. It was thought that this high flow would also promote early breakthrough; however, this was not exactly as predicted. Due to the atmospheric profile maintained during the ACFB phase and, in particular, its ability to still control hexamethylcyclotrisiloxane (the lowest molecular weight cyclic siloxane), the ACFB was selected for further testing in phases 5 and 6 to characterize its breakthrough profile. Note that the LfFB also maintained high efficiency for siloxane removal but the novelty and potential applicability of the ACFB design, either alone or in tandem with a polishing LfFB architecture, to mitigate trace contaminant problems aboard ISS attributed to siloxanes and other high molecular weight compounds made the ACFB an attractive option to further test. As the test progressed and more compounds exhibited breakthrough behavior, the relative atmospheric profile changed. Breakthrough at the high ACFB velocity appeared to be molecular weight dependent with the heavy hexamethylcyclotrisiloxane and xylene remaining under control. Conversely, the LfFB maintained high single-pass efficiency throughout the test but due to its low flow rate, only a small amount of the cabin atmosphere could be effectively scrubbed of chemical at one time. Testing results indicate that exploration ARS architectural considerations may benefit from using combined ACFB and an LfFB combined with a catalytic oxidation stage.

Phase 5 conducted static metabolic loading challenges on the integrated ARS (CDRA-4EU, Sabatier, TCCS M-COA, TCCS ACFB, and OGA) and run at three-, four-, and six-crewmember metabolic rates for a minimum of 48 hours apiece. The two-crewmember rate was dropped because the OGA could not operate below a 2.7 crewmember rate and exploration mission architectures are focusing on crew sizes greater than three. During phase 5, the EChamber atmosphere ethanol concentration slowly rose from an initial concentration of 2 ppm to just over 6 ppm by the end of test day six, which is still well below the 180-day SMAC of 1,000 ppm. The same can be said for methane (topping out at 55 ppm with a 180-day SMAC of 5,300 ppm). Carbon monoxide (CO) exhibited the same slow rise, topping out at 17 ppm which is still below the 55-ppm, 7-day SMAC but above the 15-ppm, 30-day/180-day/1,000-day SMAC. The latter SMAC of 15 ppm is the target for exploration missions. The ACFB, TCCS M-COA, and the condensing heat exchanger were the primary contaminant removal components during phase 5. The TCCS M-COA's performance was compromised somewhat by a lower than expected throughput 1.4 m^3/hr versus 3.4 m^3/hr (0.85 scfm versus 2 scfm) and possible siloxane contamination of the catalyst.

Posttest evaluation found that thermal control of the M-COA is more difficult below 1 scfm when using deadband control logic for regulating catalytic reactor temperature. As a result, the M-COA unit operated at an average lower temperature. Post-test evaluation also found 94% single-pass oxidation efficiency for CO. The thermal dynamics observed may be corrected by implementing proportional-integral-derivative (PID) control rather than the typical deadband control logic. Based on the post-test evaluation, the increasing CO concentration was attributed to an injection rate into the EChamber higher than targeted. The CO_2 management assembly worked according to the updated control logic. The larger working amount (along with attention paid as to when to sample the CO_2 accumulator) allowed for no CRA standbys (except for anomalies) during phase 5. There were also very few, if any, instances of the CDRA-4EU dumping CO_2 to space vacuum because the CO_2 accumulator was full. The EChamber O_2 level was maintained much better than in cycle 1 with only a 0.6% variance during phase 5. The EChamber dewpoint was maintained between 15 °C and 18 °C which is comparable to cycle 1 data. The EChamber CO_2 concentration also compared favorably to cycle 1 data ranging between 0.3% and 0.5% indicating that CDRA-4EU was performing nominally at the selected 25 scfm flow and 90-minute half-cycle condition.

Phase 6 was a direct follow-on test from phase 5 and subjected the integrated ARS to a dynamimetabolic load based on four crewmembers. During this phase, the EChamber atmosphere ethanol concentration settled into a range of 4–8 ppm which is well below the 180-day SMAC of 1,000 ppm. Methane concentration rose to ~33 ppm over the 3 days of phase 6 (well below the 180 SMAC of 5,300 ppm). Carbon monoxide rose slowly, topping out at just under 12 ppm. This level is below the 55-ppm, 7-day SMAC as well as below the 15-ppm, 30-day/180-day/1,000-day SMAC. The ACFB, TCCS M-COA, and the condensing heat exchanger were the primary trace contaminant removal components for phase 6 as they were in phase 5. The testing data indicated that the integrated ARS test articles handled the dynamic metabolic load without anomaly or excursion outside habitable limits.

Phase 7 supported functional demonstration of several environmental monitoring instruments. The test articles included the TELS, RaSCal array, VEM water module, and a micro-gas chromatograph 'LunchBox.' All of the articles were provide by JPL. EChamber facility-generated environmental monitoring data were delivered to the various phase 7 instrument principal investigators for analysis and comparison to data generated by the test articles. Details on instrument performance during phase 7 are contained in reports outside the scope of this TP.

8. RECOMMENDED ARCHITECTURE AND FUTURE IMPROVEMENTS

Technical development efforts conducted by the ARREM project as well as future process development have benefited from multiple contributing technology maturation efforts. The primary process design concepts investigated by the AES ARREM project originated from an alternative component integration concept proposed in 2004.[32] During the periods before 2004 and between 2004 and 2010, a number of ECLS process technology development and maturation projects made notable progress in the CO_2 removal, TCC, CO_2 reduction, O_2 generation, and environmental monitoring functional areas. Based on this contributing development work and the work conducted by the ARREM project, ARS and EMS architecture shown in figures 14 and 15 are recommended for further development. The architecture depicted in figure 14 is more closely ISS derived while the architecture depicted in figure 15 incorporates alternative CO_2 removal and CO_2 reduction process technologies. The following discussion summarizes features of both architectures.

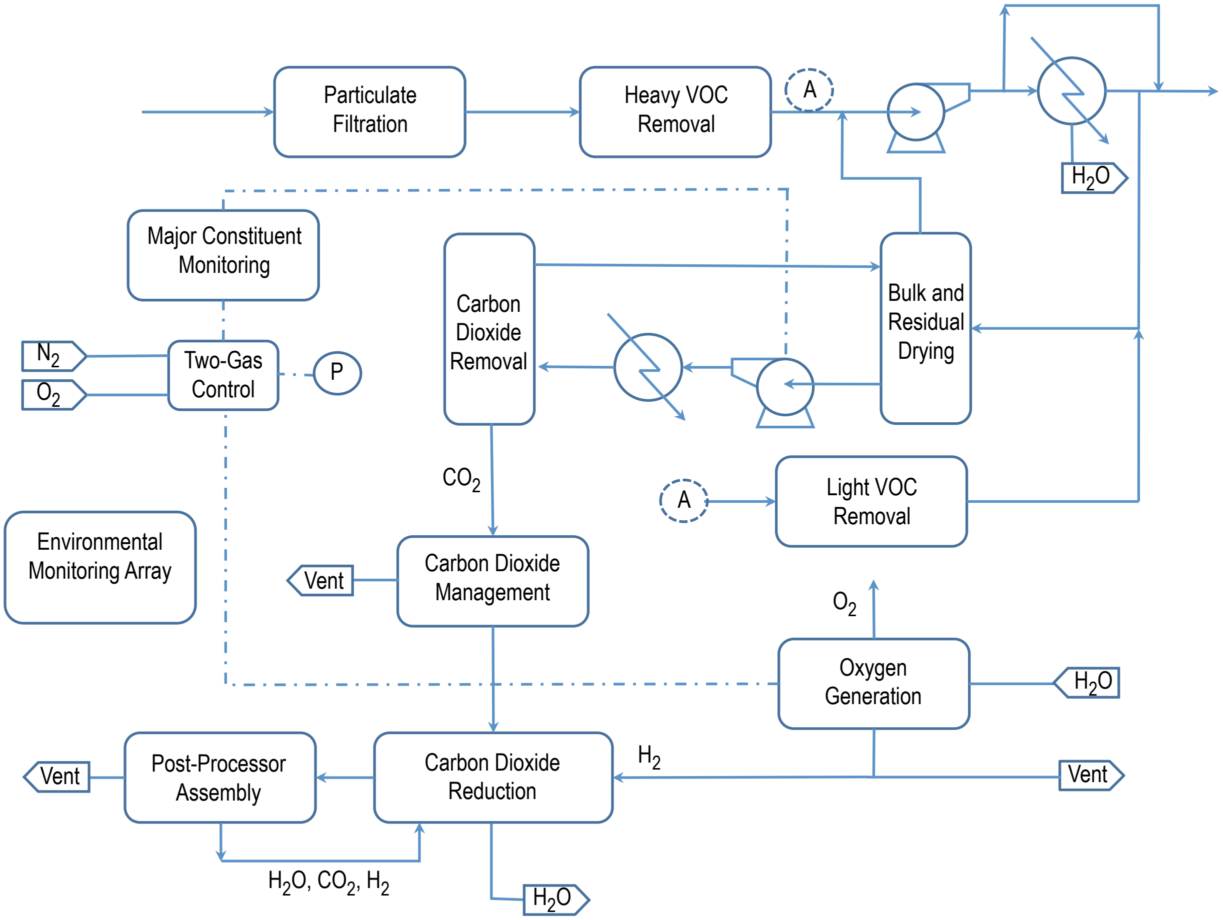


Figure 14. Recommended ARS and EMS architecture.

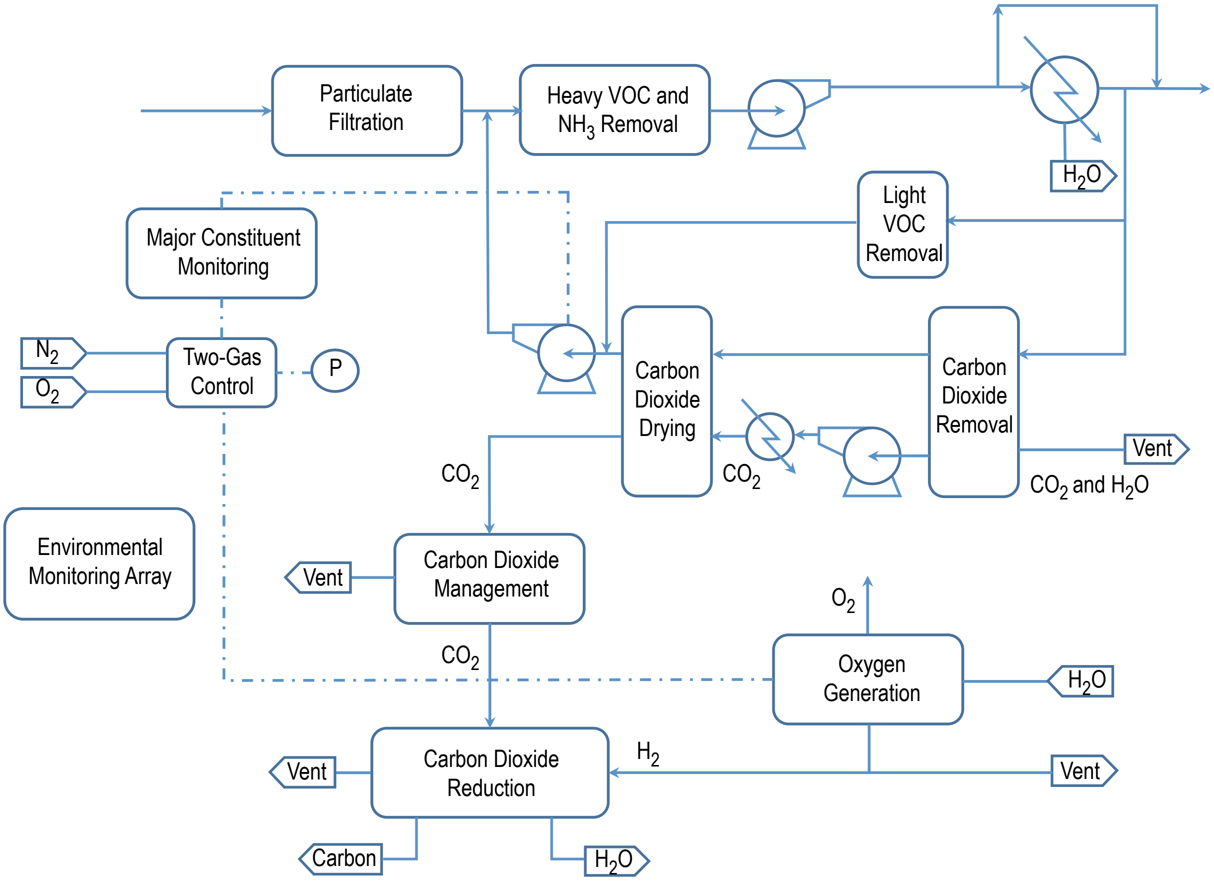


Figure 15. Variant of a recommended ARS and EMS architecture.

8.1 Features of the Recommended Atmosphere Revitalization Subsystem and Environmental Monitoring Subsystem Architectures

Features common to the recommended ARS and EMS architectures include core particulate filtration, temperature and humidity control, TCC, and major constituent monitoring hardware. The core CO_2 removal portion of the architecture is either based on physical adsorption as is used aboard the ISS or thermally regenerable amines. The latter is an extension of the vacuum-swing regenerable amine process included in the Orion vehicle's ARS design.

The particulate removal concept is a three-stage process consisting of course debris screening, mid-sized particulate filtration, and a high-efficiency polishing stage. Debris screening and mid-sized particulate filtration stages are amenable to a distributed architecture and function to keep the main ventilation supply ducts clean. The high-efficiency polishing stage concept is envisioned to consist of an indexing media filter assembly close coupled with the heavy VOC removal stage just upstream of the cabin fan and condensing heat exchanger package.

The TCC components consist of heavy and light VOC removal stages. The light VOC removal stage also targets methane, hydrogen, and carbon monoxide. These stages are distributed in the architecture. The heavy VOC removal stage concept is a high volumetric flow, low aspect ratio adsorbent cartridge concept derived from a commercially available design (Barnabey Sutcliffe Division, Calgon Carbons). This cartridge design is packed with a combination of activated carbons formulated to remove ammonia and low concentration VOCs. Leading activated carbon candidates include Ammonasorb II (Calgon Carbons) and odor and VOC carbon (Calgon Carbons). The light VOC removal stage is integrated closely with the core CO_2 removal equipment. This stage consists of a thermal catalytic oxidation reactor coupled with a recuperative heat exchanger. The catalytic oxidation reactor is based on Microlith technology (Precision Combustion, Inc.). An advanced recuperative heat exchanger design has also been developed and a fully integrated unit designed and fabricated by Precision Combustion, Inc. A small adsorbent bed targeting ammonia, sulfur compounds, and volatile methyl siloxane compounds is positioned upstream of the M-COA.

For the architecture depicted in figure 14, the process gas drying and CO_2 removal stages consist of modified versions of the ISS CDRA-4 beds. Alternative adsorbent media and bed sizes tailored to exploration mission metabolic loads are key features. The process must be capable of operating in both open- and closed-loop modes as well be amenable to deployment across multiple exploration vehicle and habitat platforms. The CO_2 removal stage may contain features of the SBAR concept that is capable of simultaneous moisture and CO_2 removal for open-loop applications. Combined with an upstream drying stage that enables water recovery, the system can accommodate closed-loop applications.

The architecture depicted in figure 15 uses a thermally-regenerated amine process that is being explored to extend vacuum-regenerated amine technology used for open-loop architectures such as that for the Orion vehicle to closed-loop architectures that are necessary for deep space exploration missions. The process includes a thermally regenerable amine stage to remove CO_2 from the cabin atmosphere. The CO_2 and water that is removed from the process air stream concurrently are sent to a drying stage that operates under a pressure-swing adsorption (PSA) regime. This unit could be similar to the isothermal bulk desiccant concept considered under the bulk and residual drying downselect study. By drying only the CO_2, there is the potential that the drying stage can be smaller than if the full process air stream is dried upstream of the CO_2 removal stage. A first stage blower-compressor provides pressurization of the water-saving PSA and when regenerated, the primary CO_2 removal blower provides a regeneration pressure at just below the cabin ambient condition. The CO_2 removal stage is configurable to operate in either open- or closed-loop fashion.

Carbon dioxide management equipment in both architectures consists of a mechanical piston compressor (Southwest Research Institute) and accumulator tanks—ISS SOA. An alternative approach uses a temperature-swing adsorption process to combine the CO_2 removal, storage, and compression functions; however, the technical maturity achieved during the ARREM project has not allowed for a rigorous trade assessment. Further work is necessary to mature the combined CO_2 removal, storage, and compression concept to conduct the necessary functional trade assessment to determine whether replacing the ISS SOA is appropriate.

The oxygen generation functional architecture is predominately the ISS SOA with some operational and equipment updates. Operational changes include operating without a nitrogen purge that reduces equipment complexity and reduces mass. Equipment changes include an electrolytic cell stack that incorporates contemporary chemically-stabilized Nafion membrane material and replacing a hydrogen sensor with an advanced sensor technology or using an external catalytic unit that reacts to hydrogen carryover through a temperature increase. The architectures in figures 14 and 15 are supplemented by high-pressure oxygen generation to support extravehicular activity provided via external compression, either provided by a solid oxide process combined with a mechanical compression stage or a pressure-swing adsorption process combined with a mechanical compression stage. Future development on high-pressure water electrolysis is also a candidate for this function. The architectural aspects with these options for supplying high-pressure oxygen are likely significant and warrant detailed trade assessment.

For the architecture depicted in figure 14, oxygen recovery is provided via Sabatier-based CO_2 reduction to provide mid-range O_2 resource recovery. A downstream methane plasma pyrolysis process provides further loop closure by converting the methane to a mixture of hydrogen and acetylene. This combination is limited in its degree of loop closure and alternative Bosch-based processes and other carbon formation stages that may be suited for integration with a Sabatier-based process must be developed to achieve the absolute maximum degree of loop closure. The architecture depicted in figure 15 incorporates a series Bosch reactor configuration that has been under development.

The environmental monitoring architecture consists of an array of instruments to monitor major and trace cabin atmospheric constituents as well as combustion products and toxic chemical hazards. Major constituents are monitored primary using an advanced miniaturized mass spectrometer (JPL). This mass spectrometer is a second generation design based on the successful vehicle cabin atmosphere monitor flight demonstration equipment. The functional backup for the mass spectrometer consists of a diode laser-based oxygen analyzer (Oxigraf Model O2) and an infrared-based carbon dioxide analyzer (Sable Systems Model CA-2A) operating in series. Trace constituents are monitored using a second miniature mass spectrometer integrated with a MEMS GC (JPL). Near real-time targeted toxic chemical hazard monitoring is provided using a commercial FTIR unit (Gasmet Model DX4040). An advanced optical array based on the TELS (JPL) is used to monitor carbon monoxide and specific combustion products.

8.2 Future Work to Mature the Recommended Architecture

While significant progress has been realized toward ARS and EMS architecture for exploration missions, focused developmental work is necessary to refine the architecture and address key gaps. The following discussion summarizes technical areas requiring developmental focus and investment.

8.2.1 General Operations and Integration

Throughout the ARREM project, integrated testing series—the alternative ARS configurations evaluated—demonstrated that ISS-derived architecture is feasible and practical for exploration mission applications. The alternative configurations evaluated for the TCCS components did not impact the core architecture's ability to achieve targeted flow rates to all areas with the exception of the instance for the M-COA inlet obtained from the chamber ventilation duct. Additional engineering will be necessary for that integration concept to be fully viable. The need to enhance the overall integration fidelity is evident in that tubing lengths and wetted materials used need to move toward addressing integrated subsystem fit and form as well as materials offgassing challenges. Carbon dioxide removal performance necessary to maintain the concentration below 2 mm Hg was successfully demonstrated. To achieve this performance for exploration missions, a new blower design is necessary unless a future bed design can reduce pressure drop sufficiently to use heritage blower designs.

8.2.2 Carbon Dioxide Removal Function

The desiccant beds and adsorbent beds contained in the dev-CDRA ground test unit used during both the R2FD and ARREM cycle 1 testing series have slightly different aspect ratios and, therefore, slight size differences compared to the ISS protoflight CDRA beds used during cycle 2 testing. Even so, the developmental CDRA equipment used during all testing series has been proven to provide valuable, comparative performance data consistent with the ISS flight CDRA equipment that has proven valuable for supporting both flight operations and technology development initiatives. The developmental CDRA equipment adsorbent beds containing either ASRT or RK-38 zeolite 5A met the required CO_2 removal capacity for exploration missions. Overall, further investigating both the moisture removal and CO_2 removal performance is necessary to determine whether the bed sizes can be further optimized for exploration metabolic loads. As well, evaluating various candidate adsorbent media, including the media used in the ISS CDRA-4 equipment, is necessary to fully characterize durability and hydrothermal stability aspects leading to a final adsorbent media selection.

Beyond a CDRA-derived process design, developmental work on an alternative architecture derived from a combined temperature-swing adsorption-based CO_2 removal and compression process design concept must be evaluated and considered for incorporation into future process architectures.[33,34] Components and features of the combined CO_2 removal and compression process and ISS CDRA-4 with a downstream CO_2 compressor and accumulator must be studied to determine where functional benefits may be realized. The potential for combining the CO_2 removal and management functions into a single, physical adsorption-based component that may eliminate the mechanical CO_2 compressor and associated accumulator tanks is attractive. Efforts to evaluate the efficacy of a thermally regenerable amine process also must be conducted.

Emerging evidence that CO_2 concentrations aboard ISS contribute to headache sensitivities in some crewmembers as well as potentially reduce decision-making capacity may result in significantly lower maximum allowable concentration limits, conceivably below 2 mm Hg. Therefore, the ultimate CO_2 removal assembly design must provide functional robustness capable of providing cabin CO_2 concentrations below 2 mm Hg to enhance crew health and performance during future crewed exploration missions.[35]

8.2.3 Trace Contaminant Control Function

The TCC architecture for future ARREM testing cycles investigated alternative integration approaches to eliminate blower and avionics components as well as provide broader operational flexibility and functional performance. The TCC component architectures incorporated commercially available, high flow capacity activated carbon bed containment components and best-performing commercial activated carbon products as well as an advanced catalytic oxidation assembly reactor design. Advances in ammonia removal and photocatalytic oxidation of VOCs were evaluated for their potential within an overall process design. While photocatalytic oxidation was found to have significant limitations for its use in crewed spacecraft due to partial oxidation product generation, ammonia removal using a thermal catalytic reduction process must be further evaluated to determine its efficacy in future exploration mission ARS architectures. The commercial adsorbent and oxidation catalyst product offerings should be surveyed periodically to determine whether new advances can offer additional improvement.

8.2.4 Carbon Dioxide Reduction Function

Carbon dioxide reduction developed higher fidelity methane post-processing options. Plasma methane pyrolysis, hydrogen purification, and other post-processing stages were evaluated independently and in integrated architectures with the SDU, dev-OGA, and developmental CDRA equipment.[36] Continued developmental results from alternative CO_2 reduction technology evaluation projects, particularly those based on the Bosch process, must be evaluated and considered for incorporation into future process design concepts.[37]

8.2.5 Oxygen Generation Function

The ARREM project pursued operational changes that had the greatest likelihood for reducing equipment complexity and increasing reliability. These operational changes were identified from lessons learned through ISS flight OGA operational experience. The opportunity exists to use the dev-OGA equipment to evaluate additional control software changes and procedural changes that may lead to more simple operations. Developing and demonstrating procedures to conduct cell stack polarization scans as a means to monitor cell stack health were conducted. Hardware configuration changes to further improve equipment service life to enable deep space exploration missions, including the ability to operate in low cabin pressure environments, operate with a high cell stack pressure, evaluate new cell stack membrane technologies, and address reliability challenges associated with the ISS OGA hydrogen sensor must be evaluated.

8.2.6 Environmental Monitoring Function

Developing an environmental monitoring architecture and functionally integrating it with an ARS architecture is a future technical goal. The role of environmental monitoring and its relationship with the ARS has been well established.[18,19,38] Developmental instruments consisting of commercially available FTIR spectrometry and custom-developed GC, mass spectrometry, electrochemical, and optical instruments were functionally demonstrated. Developing specific performance requirements and developing and demonstrating a complete environmental monitoring subsystem architecture that addresses major atmospheric constituent, combustion product, general VOC loading, and noncombustion chemical contamination event monitoring must be a focus for future work.

8.2.7 Autonomous Control and Process Health Monitoring

The ECLSS must become more tightly integrated with respect to core functionality, control, and equipment health monitoring to enable future exploration missions. The role of the Earth-based mission control team will change to focus on slow changes and long-term trending of baseline performance. However, under circumstances that produce changes in performance that are more rapid than the communication turnaround time with the mission control team, ECLS control will require the crew to interact with the ECLSS equipment and advanced autonomous control software. The control system must either be self-adaptable or enable the crewmembers to adapt the ECLSS to rapidly changing situations, to solve system problems, and to efficiently anticipate and schedule maintenance.[39]

The ideal function of an autonomous control system must manage the ECLSS in response to failures, functional trends, configuration changes, and environmental conditions that occur over periods in the range of tens of minutes. The control system must enable the ECLSS to operate seamlessly with no ground-based intervention under such circumstances while providing an appropriate level of automation that minimizes crew interaction as well as maintains safety-critical operations and procedures. When crew interaction is necessary, the control system must be intuitive and 'crew centered.' Beyond providing functional autonomy and an appropriate automation level, additional aspects of autonomous control and process health monitoring include command and data handling (C&DH), software development and testing to achieve maturity comparable to core ECLSS process technologies, hardware-software complexity, and crew interfaces.[40] Achieving these objectives and achieving maturity comparable to core ECLSS process technologies requires the following:

- Defining autonomous control of ECLS.
- Dividing autonomous ECLS roles between software and crew.
- Evaluating hardware-software complexity.
- Implementing ECLS process health monitoring.
- Defining C&DH for software.
- Ensuring crew control over the level of automation.
- Ensuring resulting software runs on flight hardware.
- Developing and testing software.
- Defining crew interfaces.

Review of existing ECLSS control architectures will also seek to define areas where functional gaps relative to achieving a level of autonomy make the greatest impacts on operational robustness and mission success. The following narrative develops the framework for an approach to advancing autonomous control and process health monitoring software technical maturity and demonstrating hardware-software functional integration for targeted developmental areas.

8.2.8 Equipment Fit and Form

The components and test articles used during the ARREM project spanned a range of maturity from developmental through ISS flight-like functional mockup based on flight hardware drawings. Integration between components and assemblies was functional only. Results obtained during the ARREM project have indicated the potential for reducing the equipment size in nearly all functional areas. Addressing equipment component size and integration relative to overall fit and form must be accomplished to fully realize the potential for performance benefits, particularly relating to mass and volume reduction. To accomplish this, detailed process and instrumentation diagrams for the entire equipment architecture must be developed and component size characteristics determined. From this information, detailed computer-aided design solid models must be prepared to facilitate fit and form studies for the core AR system architecture and its extension to missions requiring a high degree of mass closure.

9. CONCLUSION

An ARS architecture that builds on the framework established by the ISS AR process design has been developed and demonstrated. Demonstration results show that the physical architecture is feasible and areas have been identified to improve reliability while reducing overall mass, volume, and complexity.

The core subsystem architecture's performance meets or exceeds the performance attained by the ISS ARS. Mass reduction of at least 35 kg with accompanying volume reduction compared to the ISS ARS were demonstrated by integrating the TCC components in a different manner and modifying OGA operational parameters. Additional savings beyond the ARS may be possible through reducing the trace contaminant load presented to humidity condensate which can reduce logistics demands for the water processing subsystem. Incorporating results of detailed engineering analysis of the four-bed CO_2 removal process architecture to size the equipment for a four crewmember metabolic load as well as incorporating contemporary adsorbent media and adjusting process conditions will provide additional mass and volume reduction compared to the SOA basis. Additional work is necessary in this area to quantify the potential mass and volume reduction.

The optically-based environmental monitoring equipment providing the MCA function performed steadily and reliably throughout all testing phases. Methods were demonstrated for monitoring volatile compounds in water, transient carbon monoxide concentrations, transient concentrations for targeted VOCs, and general cabin VOC monitoring. These instruments have the potential for providing a more capable instrumentation architecture compared to methods used aboard the ISS. Continued work to mature the candidate instruments is required to fully understand their benefits over the SOA basis.

Opportunity exists to demonstrate a higher degree of resource mass closure by incorporating methane post-processing techniques. Further reliability for the oxygen generation equipment architecture is possible by incorporating contemporary cell stack membrane materials and incorporating operational lessons learned from ISS flight experience. Continued work on oxygen loop closure and contemporary electrolytic cell stack designs is required.

APPENDIX A—ARREM PROJECT PUBLICATIONS

The following publications document details and technical results from the AES ARREM.

Carbon Dioxide Removal and Management

C. Junaedi, S. Roychoudhury, D. Howard, J. Perry, and J. Knox, "Microlith-based Structured Sorbent for Carbon Dioxide, Humidity, and Trace Contaminant Control in Manned Space Habitats," AIAA 2011-5215, *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

L. Miller and J. Knox, "Development and Testing of a Sorbent-based Atmosphere Revitalization System 2010/2011," AIAA 2011-5217. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Perry, J. Knox, D. Howard, S. Roychoudhury, and C. Junaedi, "Performance Evaluation of Engineered Structured Sorbents for Atmosphere Revitalization Systems on board Crewed Space Vehicles and Habitats," AIAA 2011-5218. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Knox, R. Gostowski, D. Watson, and J. Hogan, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems," AIAA 2012-3642, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, K. Kittredge, R. Coker, R. Cummings, and C. Gomez, "Developments in Atmosphere Revitalization Modeling and Simulation," AIAA 2012-3584, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Hogan, B. Luna, L. Mulloth, M. Varghese, B. Koss, G. Palmer, P. Linggi, J. Melton, and Z. Lu, "The Low-Power CO_2 Removal and Compression System: Design Advances and Development Status," AIAA 2012-3587 *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, R. Gostowski, D. Watson, J. Hogan, E. King, and J. Thomas, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems," AIAA 2012-3642 *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, H. Gauto, R. Gostowski, D. Trinh, D. Watson, J. Hogan, J. Thomas, and E. King, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2012-2013," AIAA 2013-3422. *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Coker, J. Knox, R. Cummings, C. Gomez, and C. Evans, "Additional Developments in Atmosphere Revitalization Modeling and Simulation," AIAA-2013-3455. *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

"Simulation Helps Improve Atmosphere Revitalization Systems for Manned Spacecraft," COMSOL User Story, 2014.

R. Coker, J. Knox, H. Gauto, and C. Gomez, "Full System Modeling and Validation of the Carbon Dioxide Removal Assembly," ICES-2014-168, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

D. Jan, J. Hogan, B. Koss, G. Palmer, T.J. Richardson, P. Linggi, and J. Knox, "Performance of Silica Gel in the Role of Risidual Air Drying," ICES-2014-243, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Hogan, D. Jan, G. Palmer, T.J. Richardson, P. Linggi, and Z. Lu, "Development and Testing of a Two-Stage Air Drying System for Spacecraft Cabin CO_2 Removal Systems," ICES-2014-220, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Knox, H. Gauto, R. Gastowski, D. Watson, J. Thomas, L. Miller, R. Coker, and C. Stanley, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2013-2014," ICES-2014-160, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

D. Jan, T. Richardson, and J. Hogan, "Progress on the CO_2 Removal and Compression System," ICES-2015-64, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

T. Richardson, D. Jan, and J. Hogan, "Carbon Dioxide Compression and Storage Trade Assessment," ICES-2015-65, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Knox, R. Gatens, R. Coker, T. Huff, L. Miller, and C. Stanley, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2014-2015," ICES-2015-177, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Knox and C. Stanley, "Optimization of the Carbon Dioxide Removal Assembly (CDRA-4EU) in Support of the International Space Station and Advanced Exploration Systems," ICES-2015-165, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Knox, L. Miller, and H. Gauto, "Development of a Test for Evaluation of the Hydrothermal Stability of Sorbents used in Closed-Loop CO_2 Removal Systems," ICES-2015-200, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

D. Watson, J. Knox, P. West, C. Stanley, and R. Bush, "Sorbent Structural Impacts due to Humidity of Carbon Dioxide Removal Sorbents for Advanced Exploration Systems," ICES-2015-166, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

R. Coker, J. Knox, C. Gomez, and G. Schunk, "Computer Simulation and Modeling of CO_2 Removal Systems for Exploration," ICES-2015-160, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

Oxygen Supply and Recovery

C. Junaedi, K. Hawley, S. Roychoudhury, M. Abney, and J. Perry, "Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction," AIAA-2011-5033. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Mansell and M. Abney, "Influence of Oxygenated Compounds on Reaction Products in a Microwave Plasma Methane Pyrolysis Assembly for Post-Processing of Sabatier Methane," AIAA 2011-5035. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

M. Abney and L. Miller, "Evaluation of Sorbents for Acetylene Separation in Atmosphere Revitalization Loop Closure," AIAA 2011-5057. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

E. Schmitt, T. Norman, R. Roy, B. Murach, and K. Ogle, "Development of High-Pressure Cathode Feed Water Electrolysis Cell Stacks for Microgravity Environments," AIAA 2011-5058. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

C. Junaedi, K. Hawley, D. Walsh, S. Roychoudhury, S. Busby, M. Abney, J. Perry, and J. Knox, "Compact, Lightweight Adsorber and Sabatier Reactor for CO_2 Capture and Reduction for Consumable and Propellant Production," AIAA 2012-3482. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

R. Wheeler, N. Hadley, R Dahl, M. Abney, Z. Greenwood, L. Miller, and A. Medlen, "Advanced PPA Reactor and Process Development," AIAA 2012-3553. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Swickrath and M. Anderson, "The Development of Models for Carbon Dioxide Reduction Technologies for Spacecraft Air Revitalization," AIAA 2012-3586. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Abney, L. Miller, Z. Greenwood, M. Iannantuono, and K. Jones, "Methane Post-Processor Development to Increase Oxygen Recovery beyond State-of-the-Art Carbon Dioxide Reduction Technology," AIAA 2013-3513, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

T. Nalette, P. Yu, J. Perry, and M. Abney, “Investigation of the Potential Impact of Trace Contaminants on the Performance of the Sabatier Catalyst,” AIAA 2013-3528, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Wheeler, N. Hadley, S. Wambolt, and M. Abney, “Third Generation Advanced PPA Development,” ICES-2014-34, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Z. Greenwood, M. Abney, J. Perry, L. Miller, J. Agui, R. Green, M. Meyer, R. Dahl, N. Hadley, S. Wambolt, and R. Wheeler, “Increased Oxygen Recovery from Sabatier Systems Using Plasma Pyrolysis Technology and Metal Hydride Separation,” ICES-2015-120, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Holtsnider, R. Wheeler, r. Dewberry, M. Abney, and Z. Greenwood, “Hydrogen Purification in Support of Plasma Pyrolysis of Sabatier Derived Methane,” ICES-2015-195, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Preston, T. Molter, K. Murdoch, M. Abney, and Z. Greenwood, “Electrolyte Membrane Hydrogen Recovery for Advanced Oxygen Recovery Architecture,” ICES-2015-262, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

M. Abney, M. Mansell, M. Nur, R. Beassie, C. Junaedi, S. Vilekar, and B. Atkins, “Advanced Oxygen Recovery via Series-Bosch Technology,” ICES-2015-82, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

K. Takada, A. Ghariani, and S. Van Keuren, “Advancing the Oxygen Generation Assembly Design to Increase Reliability and Reduce Costs for a Future Long Duration Mission,” ICES-2015-115, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

R. Green, J. Agui, M. Meyer, R. Vijayakumar, M. Abney, Z. Greenwood, and G. Berger, “Characterization of Carbon Particulates in the Exit Flow of a Plasma Pyrolysis Assembly Reactor,” ICES-2015-304, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

Trace Contaminant Control

J.L. Perry, M.W. Pruitt, R.M. Wheeler, and O. Monje, “Atmosphere Resource Recovery and Environmental Monitoring Trace Contaminant Control through FY 2012,” NASA/TM-2013-217496, NASA, 2013.

O. Monje and S. Nolek, “Solar Simulator Testbed: Demonstration of a Solar Photocatalytic Oxidation System,” AIAA 2012-3426, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

L. Levine, J. Coutts, P. Hintze, and C. Clausen, “Review of Transforming TiO_2 into a Visible-Light-Responsive Catalyst for Water and Air Purification,” AIAA 2012-3629, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

O. Monje and O. Melendez, “Low Temperature Catalyst for NH_3 Removal,” AIAA 2013-3423, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

O. Monje, J. Surma, M. Johnsey, and O. Melendez, “Evaluating the Adsorptive Capacities of Chemosorb 1000 and Chemsorb 1425, ICES-2014-282, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Perry and M. Kayatin, “Trace Contaminant Control Design Considerations for Enabling Exploration Missions,” ICES-2015-108, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

S. Vilekar, K. Hawley, C. Junaedi, B. Crowder, J. Prada, R. Mastanduno, J. Perry, and M. Kayatin, “Microlith®-based Catalytic Reactor for Air Quality and Trace Contaminant Control Applications,” ICES-2015-278, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

O. Monje, “Evaluation of Low Temperature CO Removal Catalysts,” ICES-2015-294, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

Particulate Removal and Disposal

J. Agui and R. Vijayakumar, "Development of an Indexing Media Filtration System for Long Duration Space Missions," AIAA 2013-3486, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

M. Meyer, "ISS Ambient Air Quality: Updated Inventory of Known Aerosol Sources," ICES-2014-199, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

R. Green, R. Vijaykumar, and J. Agui, "Development of Test Protocols for International Space Station Particulate Filters," ICES-2014-216, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Agui and R. Vijayajumar, "Characterization of a Regenerable Impactor Filter for Spacecraft Cabin Applications," ICES-2015-206, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. Coe, A. Luthra, and A. Ravi, "The Dust Library: Enhanced Infrared Spectra of Individual Respirable Dust Particles," ICES-2015-248, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

Environmental Monitoring

M. Darrach, A. Chutjian, B. Bornstein, V. Carkanian, V. Hoemmerle, J. Hofman, D. Karmon, J. Kenny, R. Kidd, J. MacAskill, S. Madzunkov, N. Toomarian, and R. Shaefer, "Trace Chemical and Major Constituent Measurements of the International Space Station Atmosphere by the Vehicle Cabin Atmosphere Monitor," AIAA 2012-3432, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

D. Jan and R. Newton, "Environmental Monitoring as Part of Life Support: Preparing for Deep Space Missions," AIAA 2012-3433, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

B. Bae, J. Kim, J. Yeom, Q. Chen, and M. Shannon, "Development of a Portable Gas Analyzer Using a Micro-Gas Chromatograph/Flame Ionization Detector for NASA's Environmental Missions," AIAA 2012-3435, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Homer, A. Shevade, and R. Huerta, "Rapid Analysis, Self-Calibrating Array for Air Monitoring," AIAA 2012-3457, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

O. Monje, S. Volling, J. Cornish, and K. Rojdev, "Dynamic Sampling of Cabin VOCs during the Mission Operations test of the Deep Space Habitat," AIAA 2013-3312, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

M. Homer, A. Shevade, J. Fonollosa, and R. Huerta, "Faster Array Training and Rapid Analysis for A Sensor Array Intended for an Event Monitor in Air," AIAA 2013-3451

J. Li, A. Hannon, Y. Lu, B. Kim, and E. Contes-de Jesus, "A Phone Sensor for Trace Chemical Detection," AIAA 2013-3452, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

S. Madzunkov, J. Simcic, R. Kidd, M. Darrach, and B. Bae, "Recent Developments in Gas Chromatograms and Mass Spectrometers for Crewed and Robotic Space Missions," AIAA 2013-3453, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Briggs, C. Frez, S. Forouhar, R. May, and G. Ruff, "Portable 4.6 μm Laser Absorption Spectrometer for Carbon Monoxide Monitoring and Fire Detection," AIAA 2013-3474, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

J. MacAskill and E. Tsikata, "Recent Advances in Water Analysis with Gas Chromatograph Mass Spectrometers," ICES-2014-316, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. MacAskill, R. Newton, M. Kayatin, K. Frederick, and J. Scott, “GCMS Water Testing and Results from the MSFC Environmental Chamber,” ICES-2015-199, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

J. MacAskill and A. Chutjian, “Improved Water Analysis for Long-Duration Manned Space Exploration,” ICES-2015-169, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

S. Madzunkov, B. Bae, R. Schaefer, E. Neidholdt, D. Nikoic, J. Gill, W. Relergert, R. Kidd, and M. Darrach, “Report on Developmental Status of the Micro Total Atmosphere Monitor for ISS and Orion,” ICES-2015-142, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

R. Briggs, C. Frez, S. Forouhar, R. May, M. Meyer, M. Kulis, and G. Berger, “Qualification of a Multi-Channel Infrared Laser Absorption Spectrometer for Monitoring CO, HCl, HCN, HF, and CO_2 Aboard Manned Spacecraft,” ICES-2015-300, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

APPENDIX B—PROGRAM OF RECORD REQUIREMENTS REVIEW

In an effort to help formulate a set of success criteria for ARREM, five ISS specifications were reviewed for ISS ARS performance and functionality requirements. Requirements that were determined to have some potential bearing on the ARREM project were identified and collected. A subset of this group was used to write requirements for the Cycle 1 test in the EChamber at MSFC. Requirements for Cycle 1 have been grouped by the functions they apply to, including the facility/chamber, environmental monitoring, trace contamination control, carbon dioxide removal, and resource recovery. The original ISS requirements that the test requirements flow from are listed beneath each test requirement. The reader can find the original requirements that were collected from the five ISS specifications in sections I through IV of this appendix. These specifications include:

- System Specification for the International Space Station (SSP 41000)
- Segment Specification for the United States On-Orbit Segment (SSP 41162)
- Prime Item Development Specification for Node 3 (SSP 50318)
- Prime Item Development Specification for United States Laboratory (S683-29523)
- Sabatier for ISS Sabatier Assembly (SA) Requirements Specification (SSP 50873)

The requirements in sections I through IV should be reviewed before each testing cycle (Cycle 1, Cycle 2, etc.). Not every requirement that was identified as having a potential impact on the ARREM project was included in the test requirements for Cycle 1. Some of those that were left out may be applicable to future testing cycles.

Facility/Chamber

1. The chamber pressure shall be maintained at 14.7 psia +0.2/-0.5 psia.
   References: SSP 41000 3.2.1.1.1.1.a, 3.7.1.3.1.1.b

2. The low-pressure alarm for the chamber shall be set at 13.9 psia.
   References: SSP 41000 3.2.1.1.1.1.a, 3.7.1.3.1.1.b

3. The ppO_2 of the chamber atmosphere shall be maintained within the range of 2.83 to 3.35 psia.
   References: SSP 41000 3.2.1.1.1.1.c, 3.7.1.3.1.2.b

4. The chamber atmosphere shall have a maximum O_2 concentration of 24.1% by volume.
   References: SSP 41000 3.7.1.3.1.2.b

5. The ppN_2 of the chamber atmosphere shall be maintained below 11.6 psia.
   References: SSP 41000 3.7.1.3.1.1.c

6. The chamber atmosphere temperature shall be maintained within the range of 65 to 85°F.
   References: SSP 41000 3.2.1.1.1.2.a, 3.7.8.3.2.1.2.a

7. The chamber atmosphere temperature shall be monitored over the range of 60 to 90°F with an accuracy of +/- 2°F.
   References: SSP 41000 3.7.8.3.2.1.1

8. The chamber atmosphere relative humidity shall be maintained within the range of 25 to 75%.
   References: SSP 41000 3.2.1.1.1.2.b

9. The chamber atmosphere dewpoint shall be maintained within the range of 40 to 60°F. *References: SSP 41000 3.2.1.1.1.2.c*

10. Humidity condensate within the chamber shall be collected. *References: SSP 41000 3.7.8.3.2.2.2*

11. The facility shall provide up to 2.2 lbm of water per person per day for oxygen generation. *References: SSP 41000 3.2.1.1.1.16.h*

12. The chamber shall limit atmosphere leakage to 0.1 lbm/day. *References: SSP 41000 3.3.12.7, SSP 50318 3.3.12.4.2, S683-29523 3.3.12.4.2*

13. Facility consideration: The chamber atmosphere temperature shall be within +/-2°F of the selected temperature. *References: SSP 41000 3.7.8.3.2.1.2.b*

Environmental Monitoring (EM)

1. The EM system shall monitor the atmosphere total pressure over the range of 0 to 15.2 psia with an accuracy of +/- 0.01 psia. *References: SSP 41000 3.7.1.3.1.1.a; SSP 50318 3.2.1.1*

2. The EM system shall monitor the ppO_2 of the chamber atmosphere over the range of 0 to 5.8 psia with an accuracy of +/- 2.0% of full scale. *References: SSP 41000 3.7.1.3.1.2.b, 3.7.8.3.1.2.1.a*

3. The EM system shall monitor the $ppCO_2$ of the chamber atmosphere over the range of 0 to 15 mm Hg with an accuracy of +/- 3.0% of full scale. *References: SSP 41000 3.7.1.3.14.1.b, 3.7.8.3.14.1.3.c, SSP 41162 3.7.1.3.96.a*

4. Trace contaminant detection levels shall be as defined in NASA/TM-2004-213144. *References: SSP 41000 3.7.1.3.14.2.c*

5. The TELS and RASCAL arrays shall detect combustion products over the ranges specified in Table X4. *References: SSP 41000 3.7.1.3.8.3.a*

TABLE X4. Combustion product detection.

Compound	Range
Carbon Monoxide (CO)	3 to 400 parts per million (PPM)
Hydrogen Cyanide (HCN)	0.4 to 30 ppm

6. The TELS and RASCAL arrays shall detect and quantitate compounds as indicated in Table X4 above. *References: SSP 41162 3.7.30.3.9.1.1*

7. The VEM shall draw air from the chamber atmosphere and accept manually introduced air samples for analysis of the trace contaminants identified in Table X5. *References: SSP 41162 3.7.30.3.11.1.1*

TABLE X5. VEM trace gas detection range.

Compound	**Monitoring detection range Milligrams per cubic meter (mg/m^3)**
methanol	0.2 to 0.5
n-butanol	1.0 to 5.0
ethanol	qualitative
o, m, p-xylenes	0.5 to 10
toluene	0.3 to 3.0
dichloromethane	0.25 to 0.5
propanone	0.3 to 1.0
2-butanone	0.4 to 5.0
ethyl acetate	0.4 to 5.0
2-propanol	0.8 to 1.0

Trace Contaminant Control

1. Trace gases shall be controlled below 180-day Spacecraft Maximum Allowable Concentrations (SMAC) levels as specified in JSC 20584 (2008). If no SMAC is listed in JSC 20584 (2008), then earlier versions of the document released in 1995 and 1999 shall be consulted. If there is still no available SMAC, then a default SMAC of 0.1 mg/m^3 will be used.
   References: SSP 41000 3.2.1.1.1.15.d-e

2. Trace gases which have been removed from the cabin atmosphere shall be disposed of via sorbent bed maintenance and/or regeneration.
   References: SSP 41000 3.7.8.3.14.2.2

3. The generation rates (from equipment and metabolism) for the trace gases to be controlled shall be as specified in SAE 2009-01-2592.
   References: SSP 41000 3.7.1.3.14.2.a

TABLE XX. Trace contaminant generation rates and SMACs.

Contaminant	SMAC (mg/m3)	Rate	
		Equipment (mg/kg-d)	**Metabolic (mg/person-d)**
Methanol	90	1.3×10^{-3}	0.9
Ethanol	2000	7.8×10^{-3}	4.3
n-butanol	40	4.7×10^{-3}	0.5
Methanal	0.12	4.4×10^{-6}	0.4
Ethanal	4	1.1×10^{-4}	0.6
Benzene	0.2	2.5×10^{-5}	2.2
Methylbenzene	15	2×10^{-3}	0.6
Dimethylbenzenes	37	3.7×10^{-3}	0.2
Furan	0.07	1.8×10^{-6}	0.3
Dichloromethane	10	2.2×10^{-3}	0.09
2-propanone	52	3.6×10^{-3}	19
Trimethylsilanol	4	1.7×10^{-4}	0
Hexamethylcyclosiloxane	9	1.7×10^{-4}	0
Ammonia	2	8.5×10^{-5}	50
Carbon monoxide	17	2×10^{-3}	18
Hydrogen	340	5.9×10^{-6}	42
Methane	3800	6.4×10^{-4}	329

CO_2 Removal

1. The CO_2 removal system shall control the $ppCO_2$ to a maximum daily average of 5.3 mm Hg under static or variable metabolic loads obtained from Table X1.
   References: SSP 41000 3.2.1.1.1.15.a

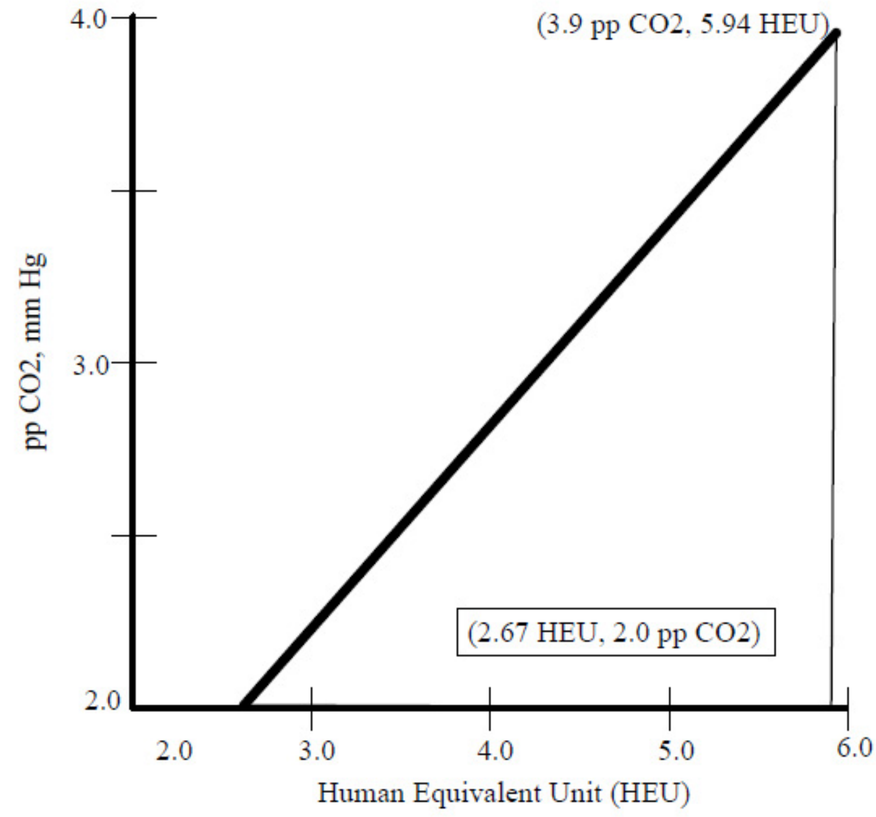
TABLE X1. Carbon dioxide metabolic load.

Crew member metabolic rates	
Sleep − 8 hrs per person−day (lbm/person−hr)	0.0525
Normal activity − 14 hrs per person−day (lbm/person−hr)	0.0764
Exercise − 2 hrs per person−day (lbm/person−hr)	0.335
Metabolic rate (lbm/person−day)	2.2

2. The $ppCO_2$ peak levels shall be no greater than 7.6 mm Hg.
   References: SSP 41000 3.2.1.1.1.15.b

3. The $ppCO_2$ in the cabin atmosphere shall be controlled in accordance with Figure Z1.
   References: SSP 41000 3.7.1.3.14.1.a

FIGURE Z1. Carbon dioxide removal performance requirement.



Notes:
(1) Shaded area defines carbon dioxide removal performance region.
(2) 1.0 HEU = 2.2 pounds per person per day CO2 removed.
(3) Equation of line defined by:
HEU >/= 1.723 pp CO2 (mm Hg) − 0.7805 for 2.0 </= pp CO2 </= 3.9
(4) The ppCO2 pressures apply to the pressurized volumes allocated to the carbon dioxide removal function.

Resource Recovery

1. Oxygen shall be introduced into the chamber atmosphere to support human metabolic needs of 1.84 lbm per person per day.
   References: SSP 41000 3.7.1.3.1.2.c

2. The OGA shall generate a minimum of 12 lbm/day of oxygen at a selectable rate between 5.1 and 20.4 lbm/day.
   References: SSP 50318 3.7.6.3.a-b

3. The OGA shall supply oxygen directly to the chamber atmosphere at a rate of 0.05 to 0.15 lbm/min.
   References: SSP 50318 3.7.6.3.c

4. The oxygen produced by the OGA shall meet the quality specified in Table X3.
   References: SSP 50318 3.7.6.3.d

TABLE X3. Oxygen quality.

Parameter	**Maximum Value**
Hydrogen	1%
Dewpoint	90°F
Temperature	113°F
Liquid Moisture	<5 cc/day

5. The Sabatier shall produce liquid water at an efficiency of 90% or higher based on the stoichiometry of the Sabatier reaction when run with excess CO_2: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. The conversion efficiency shall be verified at the following operating point representing 3-crew cyclic operation.
   H2 feed flow rate: 0.05 lb/hr
   Equivalent OGA Current: 21.7 A
   CO_2 feed flow rate: 0.31 lb/hr
   Equivalent Crew Loading: 3
   Molar Ratio: 3.5
   Operating Mode: 53 minute Process/37 minute Standby
   References: SSP 50873 3.1.4

6. The total liquid content of the flow delivered by the Sabatier to the product vent interface shall not exceed 1% by volume of the total liquid flow production.
   References: SSP 50873 3.1.4.4.1

7. The total free gas delivered by the Sabatier to the wastewater bus interface shall not exceed 1% by volume of the total fluid volume (both gas and liquid interface) delivered at 70°F and 14.7 psia.
   References: SSP 50873 3.1.4.4.2

8. The maximum particle size permitted in the water at the wastewater bus interface shall not exceed 100 microns.
   References: SSP 50873 3.1.4.4.3

Other

1. Airborne particulate and microbial contaminants in the chamber shall be collected with HEPA-rated filters. When choosing filters, selected performance criteria in DOE STD-3020-2005 ("Specification for HEPA Filters Used by DOE Contractors") should be considered.
   References: SSP 50318 3.2.1.51, S683-29523 3.7.43.3

2. The filter element shall be capable of operating in the test environment for a minimum of 2160 hours without requiring replacement. *References: S683-29523 3.7.43.3*

ISS Requirements for ARREM

The following summary contains all the requirements that were collected from five ISS specifications as being potentially applicable to the ARREM project. These specifications include:

- System Specification for the International Space Station (SSP 41000)
- Segment Specification for the United States On-Orbit Segment (SSP 41162)
- Prime Item Development Specification for Node 3 (SSP 50318)
- Prime Item Development Specification for United States Laboratory (S683-29523)
- Sabatier for ISS Sabatier Assembly (SA) Requirements Specification (SSP 50873)

The requirements have been grouped by subject matter. Most of the requirements listed in this appendix are comprised of several parts, and only some of those parts are relevant to ARREM. Only the relevant portions have been included here. Any unlisted parts of requirements fall into one of two categories. They either (1) do not apply to ARREM, or (2) are covered by another requirement listed in the document.

It should be noted that if the five specifications listed above are searched thoroughly, similar requirements for other segments or nodes (such as the Russian Segment, the Japanese Experiment Module, Node 1, Node 2, and the Airlock, to name a few) may be found. These requirements are generally similar enough to the requirements for the ISS, USOS, Node 3 or the U.S. Laboratory to be left out as redundant information. Requirements pertaining to some of these other segments or nodes have been included on the rare occasion that information in those requirements was not found elsewhere in the specs and could possibly have some bearing on the ARREM project.

I. PRESSURE

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.2.1.1.1.1	**Capability: Control atmospheric pressure**	
The purpose of this capability is to maintain proper total and oxygen partial pressures (ppO_2) in order to provide a habitable cabin atmosphere for the on−orbit Space Station crew. a. The on−orbit Space Station shall maintain the total atmosphere pressure nominally between 14.2 and 14.9 psia with a minimum pressure of 13.9 psia. c. The on−orbit Space Station shall maintain the ppO_2 of the atmosphere in the range of 2.83 to 3.35 psia.		
ES62 Notes:		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.1.3.1.1	**Control total pressure**	
a. The USOS shall monitor the atmosphere total pressure over the range of 0 to 15.2 psia. b. The USOS shall maintain the atmosphere total pressure of the on−orbit Space Station nominally between 14.2 and 14.9 psia with a minimum pressure of 13.9 psia. c. The USOS shall maintain the atmosphere nitrogen partial pressure below 11.6 psia.		
ES62 Notes: *These requirements are repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.1.*		

SSP 50318 (Node 3)	**Rev H**	**9 May 2011**
3.2.1.1	**Monitor total pressure**	
The Node 3 shall monitor total pressure in the range of 0 to 15.2 psia with an accuracy of +/− 0.01 psi and report the cabin atmospheric pressure at least once per minute to the United States On−orbit Segment (USOS) in accordance with SSP 41178−13.		
ES62 Notes: *This requirement is repeated in the USOS spec (SSP 41162) at 3.7.1.3.1 and in the USL spec (S683-29523) at 3.2.1.1.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.1.3.1.2	**Control oxygen partial pressure**	
a. The USOS shall monitor the on−orbit Space Station atmosphere ppO_2 over a range of 0.0 to 5.8 psia with an accuracy of +/−2.0% of full scale. b. The USOS shall control the atmosphere ppO_2 in the on−orbit Space Station between 2.83 and 3.35 psia with a maximum concentration of 24.1% by volume. c. The USOS shall introduce oxygen into the atmosphere to support human metabolic needs of 1.84 lbm per person per day for four crewmembers and animal metabolic needs of 2.38 lbm per day. f. The USOS shall fill a 15 cubic foot oxygen tank from 1950 +/− 50 psia to 2650 +/− 50 psia within 16 hours, when supplied with recharge oxygen from the Orbiter in accordance with NSTS 21000−IDD−ISS, paragraph S.6.3.2.2.		
ES62 Notes: *These requirements are repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.2.* *Part f may apply if tank recharge is a function dictated by future mission ops concepts.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.1.2.1	**Monitor oxygen partial pressure**	
a. The Node 3 shall monitor ppO_2 in the range of 0 to 5.8 psia with an accuracy of +/− 2% of full scale, from atmosphere samples, when supplied with total pressure and associated location. b. The Node 3 shall monitor ppO_2 in the USOS during a 10.2 psia camp−out in the range of 0 to 5.8 psia with an accuracy of +/− 2% of full scale from USOS atmosphere samples.		

ES62 Notes:
These requirements are repeated in the USOS spec (SSP 41162) at 3.7.1.3.3, the Node 3 spec (SSP 50318) in 3.2.1.3, and in the USL spec (S683-29523) at 3.2.1.3.
This requirement applies to AES ARREM major constituent analyzer (MCA) development.

II. TEMPERATURE, HUMIDITY, AND CONDENSATION

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.2.1.1.1.2	**Capability: Condition atmosphere**	
The purpose of this capability is to maintain temperature and humidity levels within the on−orbit Space Station cabin atmosphere and to provide proper atmosphere circulation within the habitable volumes. a. The on−orbit Space Station shall maintain the interior atmosphere temperature within the range of 65 to 85°F. b. The on−orbit Space Station shall maintain the interior atmosphere relative humidity within the range of 25 to 75%. c. The on−orbit Space Station shall maintain the interior atmosphere dewpoint within the range of 40 to 60°F.		
ES62 Notes: *Part a of this requirement is repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.5.* *Part b of this requirement is repeated in the ISS spec (SSP 41000) at 3.7.1.3.2.2 and 3.7.8.3.2.2.1, in the USOS spec (SSP 41162) at 3.2.1.1.1.6 and 3.7.1.3.9, and in the USL spec (S683-29523) at 3.2.1.9. A similar requirement (with a slightly altered range of 25-70%) is covered in the Node 3 spec (SSP 50318) at 3.2.1.10. The requirement is also repeated in the USOS spec for other nodes in the USOS. These "others" are comparable to the requirements already mentioned and do not need to be listed.* *Part c of this requirement is repeated in the ISS spec (SSP 41000) at 3.7.1.3.2.2 and 3.7.8.3.2.2.1, in the USOS spec (SSP 41162) at 3.2.1.1.1.6 and 3.7.1.3.9, and in the USL spec (S683-29523) at 3.2.1.9. The requirement is repeated in the USOS spec for other nodes in the USOS. These "others" are comparable to the requirements already mentioned and do not need to be listed.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.2.1.1	**Monitor atmosphere temperature**	
The Node 3 shall monitor the Node 3 atmosphere temperature over the range of 60 to 90°F with an accuracy of +/− 2°F and provide status data to the USOS in accordance with SSP 41175−32.		
ES62 Notes: *The requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.8. Similar temperature monitoring requirements are included in the USL spec (S683-29523) at 3.2.1.7 and in USOS spec (SSP 41162) at 3.7.1.3.7. The requirement is repeated in the USOS spec for other nodes in the USOS. These "others" are comparable to the requirements already mentioned and do not need to be listed.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.2.1.2	**Remove atmospheric heat**	
a. The Node 3 shall maintain a crew selectable cabin temperature of between 65 and 80°F under nominal heat loads defined in 6.1. b. The stabilized Node 3 cabin temperature, within the aisleway, shall be within +/− 2°F of the selected temperature.		
ES62 Notes: *The requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.9. Similar cabin temperature requirements are included in the USL spec (S683-29523) at 3.2.1.8 and in the USOS spec (SSP 41162) at 3.7.1.3.8. The requirement is repeated in the USOS spec for other nodes in the USOS. These "others" are comparable to the requirements already mentioned and do not need to be listed. Note that in these other requirements, the required accuracy varies between +/2 and +/3°F.*		

SSP 41162 (USOS)	**Rev BA**	**30 Dec 2008**
3.7.8.3.2.1.2 **Remove atmospheric heat**		
a. During campout (see 6.1), the Airlock shall maintain a crew selectable cabin temperature between 65 and 80°F, with an accuracy of +/− 3°F.		
ES62 Notes:		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.3.12.9 **Preclude condensation**		
Surfaces exposed to the cabin atmosphere shall preclude condensation of atmosphere moisture. See appendix B for exceptions to this requirement.		
ES62 Notes: *This requirement is repeated in the USOS spec (SSP 41162) at 3.3.16 and in the USL spec (S683-29523) at 3.3.14.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.2.2.2 **Dispose of removed moisture**		
The Node 3 shall be capable of returning humidity condensate to USOS in accordance with SSP 41140, paragraph 3.2.2.2.14.		
ES62 Notes: *This requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.11. A similar requirement is included in the USL spec (S683-29523) at 3.2.1.10.* *AES ARREM test support equipment shall provide a controlled humidity condition in the test chamber.*		

III. CARBON DIOXIDE AND CONTAMINANTS

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.2.1.1.1.15	**Capability: Control internal carbon dioxide and contaminants**	

The purpose of this capability is to remove metabolic carbon dioxide and internally generated contaminants from the on−orbit Space Station habitable atmosphere.

a. The on−orbit Space Station shall control the carbon dioxide partial pressure ($ppCO_2$) to a maximum daily average to which a crewmember is exposed of 5.3 mm Hg based on the metabolic loads of six crewmembers and biological specimens as defined in Table VII.

b. The $ppCO_2$ peak levels shall be no greater than 7.6 mm Hg.

c. During crew changeout, the on−orbit Space Station shall control $ppCO_2$ to a maximum daily average to which a crewmember is exposed of 7.6 mm Hg with peak levels of 10 mm Hg based on the metabolic loads defined in Table VII*.

d. Trace gases generated during normal operations shall be controlled below Spacecraft Maximum Allowable Concentrations (SMAC) levels as specified in Table VIII** for the habitable atmosphere. See appendix B for the exception to this requirement.

e. If no SMAC value is listed in Table VIII*** for a particular compound of interest, the 7 day SMAC values as specified in NHB 8060.1, appendix D, shall apply. See appendix B for the exception to this requirement.

f. The on−orbit Space Station shall limit the average atmosphere particulate level to 100,000 particles per cubic foot with peak concentrations less than 2 million particles per cubic foot for particles greater than 0.5 microns in size.****

g. The on−orbit Space Station shall limit the daily average airborne microbes to 1000 Colony Forming Units (CFU) per cubic meter.****

ES62 Notes:

A portion of part c of this requirement is repeated in the USOS spec (SSP 41162) at 3.7.15.3.48.

Part f is repeated in the ISS spec (SSP 41000) at 3.7.1.3.14.3 and 3.7.8.3.14.3.1, in the USOS spec (SSP 41162) at 3.2.1.1.1.60 and 3.7.1.3.100, in the Node 3 spec (SSP 50318) at 3.2.1.50, and in the USL spec (S683-29523) at 3.2.1.106. Other instances of part f may be found at several other locations in the ISS and USOS specs, where it is levied on non-US segments of the ISS and various nodes in the USOS.

Part g is repeated in the ISS spec (SSP 41000) at 3.7.1.3.14.4 and 3.7.8.3.14.4.1, in the USOS spec (SSP 41162) at 3.2.1.1.1.61, 3.7.1.3.102, and 3.7.15.3.53, in the Node 3 spec (SSP 50318) at 3.2.1.52, and in the USL spec (S683-29523) at 3.2.1.108. Other instances of part g may be found at several other locations in the ISS and USOS specs, where it is levied on non-US segments of the ISS and various nodes in the USOS.

**Part c: Research animal metabolic rates do not need to be considered for ARREM. Therefore the "Biological specimen metabolic rate" in Table VII can be ignored.*

*** Part d: ARREM will use JSC 20584 (2008) as the primary SMAC reference. Consideration between 180-day and 1000-day SMACs will be traded to determine design impacts on TCC concept equipment design.*

**** Part e: If no SMAC is listed in JSC 20584 (2008), then earlier versions of the document released in 1999 and 1995 will be consulted. If there is still no available SMAC, then a default SMAC of 0.1 mg/m^3 will be used.*

***** Parts f, g: The particulate and airborne microbial standards will be that recommended on page 14 of NASA/TP-1998-207978.*

SSP 41000 TABLE VII. Carbon dioxide metabolic load.

Crew member metabolic rates:	
Sleep − 8 hrs per person−day (lbm/person−hr)	0.0525
Normal activity − 14 hrs per person−day (lbm/person−hr)	0.0764
Exercise − 2 hrs per person−day (lbm/person−hr)	0.335
Metabolic rate (lbm/person−day)	2.2
Biological specimen metabolic rate − maximum (lbm/day)	2.70 (1)
Space Station crew complement (humans)	6 (2)
Duration	90 days
Space Station crew complement (humans) − Crew change−outs	11 (3)
Duration	4 days
Location	(4)
Biological specimen location	USOS

Notes:
(1) Supported by USOS.
(2) Four crewmembers maximum supported by the USOS and three crewmembers maximum supported by the RS.
(3) Five additional crewmembers from the Orbiter supported by the Space Station.
(4) Crewmember locations during crew change−outs are considered to be equally distributed among habitable pressurized volumes.

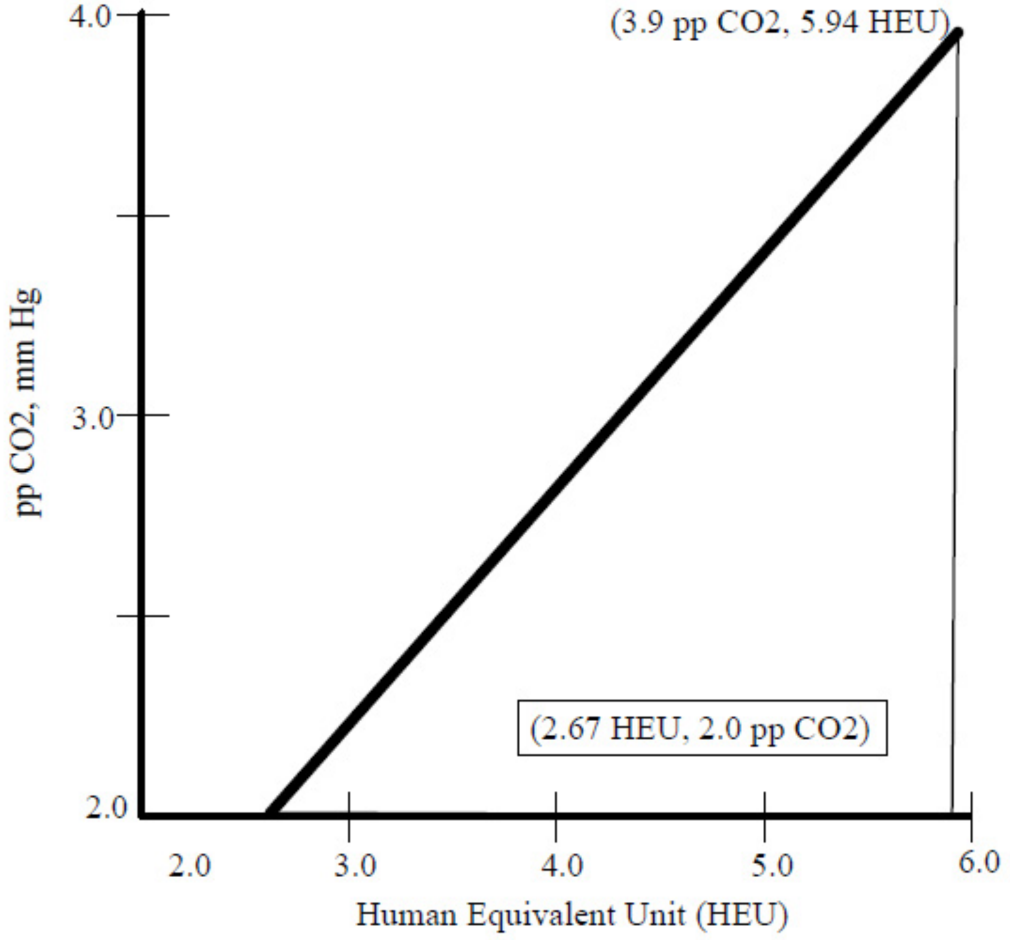
SSP 41000 TABLE VIII. Spacecraft maximum allowable concentrations.

[TABLE DELETED - NOT USED FOR ARREM]

JSC 20584 (2008) will be the primary SMAC reference for ARREM. Consideration between 180-day and 1000-day SMACs will be traded to determine design impacts on TCC concept equipment design. If no SMAC is listed in JSC 20584 (2008), then earlier versions of the document released in 1999 and 1995 will be consulted. If there is still no available SMAC, then a default SMAC of 0.1 mg/m^3 will be used.

SSP 41000 (ISS)		**Rev BV**	**30 Sept 2011**
3.7.1.3.14.1	**Control carbon dioxide**		
a. The USOS shall control the ppCO$_2$ in the atmosphere of the USOS in accordance with Figure 15. b. The USOS shall monitor atmospheric carbon dioxide levels over a range of 0 to 15 mm Hg with an accuracy of +/−3.0% of full scale.			
ES62 Notes: *This requirement is repeated in the ISS spec (SSP 41000) at 3.7.8.3.14.1.1, which is levied on Node 3. This requirement references Figure 29, which is the same as Figure 15 except for an additional note on the plot. The requirement is also repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.58 and 3.7.1.3.94, in the USL spec (S683-29523) at 3.2.1.100, and in the Node 3 spec (SSP 50318) at 3.2.1.45.* *This requirement applies to AES ARREM major constituent analyzer (MCA) development.*			

SSP 41000 FIGURE 15. USOS carbon dioxide removal performance requirement.



Notes:
(1) Shaded area defines carbon dioxide removal performance region.
(2) 1.0 HEU = 2.2 pounds per person per day CO2 removed.
(3) Equation of line defined by:
HEU >/= 1.723 pp CO2 (mm Hg) − 0.7805 for 2.0 </= pp CO2 </= 3.9
(4) The ppCO2 pressures apply to the pressurized volumes allocated to the carbon dioxide removal function.

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.14.1.3	**Monitor carbon dioxide**	

c. The Node 3 shall provide detected $ppCO_2$ levels over a range of 0 to 15 mm Hg with an accuracy of +/− 3% of full scale from provided samples, including the Node 3 atmosphere, to the USOS in accordance with SSP 41178−12.
d. In support of $ppCO_2$ level detection by Node 3, Node 3 shall receive the total atmospheric ambient pressure, with an accuracy of +/− 0.01 psia, and associated location, from the USOS in accordance with SSP 41178−12.
e. The Node 3 shall provide detected $ppCO_2$ levels in the USOS during a 10.2 psia campout, over a range of 0 to 15 mm Hg, with an accuracy of +/− 3% of full scale.
f. In support of Node 3 USOS $ppCO_2$ level detection, Node 3 shall receive the USOS total atmospheric ambient pressure with an accuracy of +/− 0.01 psia, from the USOS in accordance with SSP 41178−12.

ES62 Notes:
This requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.47.

S683-29523 (US Lab)	**Rev R**	**31 Aug 2009**
3.2.1.102	**Monitor carbon dioxide**	

a. The USL, using USL atmospheric constituency data, shall monitor the ppCO2 from any valid ISS location in a range of 0 to 15.0 mm Hg with an accuracy of +/− 3% of full scale from provided samples, including the USL atmosphere when supplied with total pressure in accordance with SSP 41178-13, and Node 3 partial pressure measurements in accordance with SSP 41178-12.
e. The USL, using USL atmospheric constituency data, in accordance with SSP 41178-12, shall monitor ppCO2 in the Airlock during a 10.2 psia campout in the range of 0 to 15.0 mm Hg with an accuracy of +/− 3% of full scale. When the Airlock ppCO2 is required, the Airlock total atmospheric pressure must be obtained, with an accuracy of +/- 0.01 psia, in accordance with SSP 41178-13.
g. The USL, using Node 3 atmospheric constituency data, in accordance with SSP 41178-12, shall monitor ppCO2 in the Airlock during a 10.2 psia campout in the range of 15 mm Hg, with an accuracy of +/− 3% full scale, when the Airlock ambient pressure is provided to the USL with an accuracy of +/− 0.01 psia.
h. The USL, using Node 3 atmospheric constituency data, in accordance with SSP 41178-12, shall monitor ppCO2 from any valid ISS location, in a range of 0 to 15 mm Hg with an accuracy of +/− 3% of full scale from provided samples, including the USL atmosphere, when supplied with total pressure in accordance with SSP 41178-13 and Node 3 total pressure measurements from the SMC in accordance with SSP 41178-13.

ES62 Notes:
This requirement is repeated in the USOS spec (SSP 41162) at 3.7.1.3.96, where an accuracy of +/-1% of full scale is called for. However, the version of the USOS spec that we have (Rev BA) is out of date. The more recent USL spec calls for an accuracy of +/-3%. Therefore, the USL spec is being called out here.
This requirement applies to AES ARREM major constituent analyzer (MCA) performance.

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**

3.7.1.3.14.2 **Control gaseous contaminants**

a. The USOS shall control the trace gases generated during normal operations in the atmosphere of the on−orbit Space Station below the SMAC levels as specified in Table VIII.*
b. If no SMAC value is listed in Table VIII** for a particular compound of interest, the seven day SMAC values as specified in NHB 8060.1, appendix D, shall apply.
c. The USOS shall monitor trace gases in the station atmosphere at the detection limit as defined in Table LVII.***

ES62 Notes: These requirements are repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.59 (parts a-c and h).
**Part a: Per Jay Perry, contaminant generation rates (both metabolic and from equipment) should be taken from SAE 2009-01-2592, "A Design Basis for Spacecraft Cabin Trace Contaminant Control". The SMACs for these contaminants are also listed in this document; however, the project should verify that they are in agreement with JSC 20584 (2008) before using them.*
***Part b: ARREM will use JSC 20584 (2008) as the primary SMAC reference. Consideration between 180-day and 1000-day SMACs will be traded to determine design impacts on TCC concept equipment design.*
****Part c: Target compounds to monitor shall be from the ISS Medical Operations Requirement Document, Rev. C, and the more extensive list in NASA/TM-2004-213144. A subset of these compounds shall be used during testing as is determined by pre-test assessment to adequately demonstrate testing goals and success criteria. ther relevant performance parameters should be used (precision, accuracy, etc).*

SSP 41000 TABLE LVII. Trace gas detection limits.

Compound	Monitoring detection range (mg/m^3)	Sample for ground-based analysis
methanol	0.2 to 0.5	
ethanol		X
2-propanol	0.8 to 1.0	
2-methyl-2-propanol		X
n-butanol	1.5 to 5.0	
ethanol	qualitative	
benzene		X
o-, m-, p-xylenes	0.5 to 1.0	
toluene	0.3 to 3.0	
dichloromethane	0.25 to 0.5	
dichlorodifluoromethance (Freon 12)		X
chlorodifluoromethane (Freon 22)		X
trichlorofluoromethance (Freon 11)		X
1,1,1-trichloroethane		X
1,1,2-trichloro-1,1,2-trifluoroethane (Freon 113)		X
n-hexane		X
n-pentane		X
methane		X
2-methyl-1,3-butadiene		X
propanone	0.3 to 1.0	
2-butanone	0.4 to 5.0	
hydrogen		X
hexamethylcyclotrisiloxane		X
trimethylsilanol		X
2-butoxyethanol		X
trifluorobromomethance (Halon 1301)		X
carbonyl sulfide		X
acetic acid		X
4-hydroxy-4-methyl-2-pentanone		X
ethyl acetate	0.4 to 5.0	

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**

3.7.8.3.14.2.1 Remove gaseous contaminants

a. The Node 3 shall control contaminant concentrations in the atmosphere to levels less than or equal to the SMAC levels specified in Table VIII and Table LXIX.*

b. For those compounds listed in Table LXIX, the control shall be based on the generation rates listed in Table VIII, a total internal mass of 75,000 kg, and a metabolic equivalent of 5.25 men (four crew plus 1.25 metabolic equivalent for animals).**

ES62 Notes: This requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.48. Similar requirements are included in the USOS spec (SSP 41162) at 3.7.1.3.97 and in the USL spec (S683-29523) at 3.2.1.103 and 3.7.20.3.

**Part a: SAE 2009-01-2592 ("A Design Basis for Spacecraft Trace Contaminant Control") will be the primary ARREM reference for trace contaminant generation rates. JSC 20584 (2008) will be the primary reference for SMACs.*

***Part b: For AES ARREM the total internal mass contributing to equipment offgassing shall be based on 150 kg/m^3 of cabin free volume. The reference cabin free volume shall be that of the ISS JEM module as specified in SSP 50623 Table 4.2-1. (124.79 m^3). Total crew size shall be assumed to be 4 with no metabolic equivalent for research animals.*

SSP 41000 TABLE LXIX. Spacecraft trace contaminant generation rates and SMACs

[TABLE DELETED - NOT USED FOR ARREM]

SAE 2009-01-2592 ("A Design Basis for Spacecraft Trace Contaminant Control") will be the primary ARREM reference for trace contaminant generation rates. JSC 20584 (2008) will be the primary reference for SMACs. Table 1 in SAE 2009-01-2592 is considerably shorter than SSP 41000 Table LXIX; Table 1 contains the only contaminants ARREM will concern itself with. It should also be noted that Table 1 lists SMACs for each of the 17 contaminants it contains, but these SMACs should be compared against JSC 20584 for accuracy.

Contaminant	**SMAC (mg/m3)**	**Rate**	
		Equipment (mg/kg-d)	**Metabolic (mg/person-d)**
Methanol	90	1.3×10^{-3}	0.9
Ethanol	2000	7.8×10^{-3}	4.3
n-butanol	40	4.7×10^{-3}	0.5
Methanal	0.12	4.4×10^{-6}	0.4
Ethanal	4	1.1×10^{-4}	0.6
Benzene	0.2	2.5×10^{-5}	2.2
Methylbenzene	15	2×10^{-3}	0.6
Dimethylbenzenes	37	3.7×10^{-3}	0.2
Furan	0.07	1.8×10^{-6}	0.3
Dichloromethane	10	2.2×10^{-3}	0.09
2-propanone	52	3.6×10^{-3}	19
Trimethylsilanol	4	1.7×10^{-4}	0
Hexamethylcyclosiloxane	9	1.7×10^{-4}	0
Ammonia	2	8.5×10^{-5}	50
Carbon monoxide	17	2×10^{-3}	18
Hydrogen	340	5.9×10^{-6}	42
Methane	3800	6.4×10^{-4}	329

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.8.3.14.2.2	**Dispose of gaseous contaminants**	
The Node 3 shall dispose of trace gases which have been removed from the Node 3 atmosphere.		
ES62 Notes: *This requirement is repeated in the Node 3 spec (SSP 50318) at 3.2.1.49. A similar requirement for the USL is included in the USOS spec (SSP 41162) at 3.7.1.3.98 and in the USL spec (S683-29523) at 3.2.1.104.* *Disposal of trace gases shall be via sorbent bed maintenance and/or regeneration. The actual method is a trade space.*		

SSP 50318 (Node 3)	**Rev H**	**9 May 2011**
3.2.1.51	**Dispose of airborne particulate contaminants**	
Node 3 shall accommodate removal of particulate contaminant filter(s).		
ES62 Notes: *A similar requirement may be found in the USL spec (S683-29523) at 3.2.1.107. Similar requirements for various nodes of the USOS may be found in the USOS spec (SSP 41162).* *Disposal of contaminants is accomplished by either by periodically replacing filter elements or developing filtration/particulate separations processes that are regenerable. The typical service life of the ISS filter elements is 2.5 years (NASA TM-2005-213846 ISS Bacteria Filter Element Service Life Evaluation).*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.1.3.14.4	**Control airborne microbial growth**	
a. The USOS shall limit the daily average airborne microbes in the USOS atmosphere to 1000 CFU per cubic meter. b. The USOS shall support sample collection to monitor the station atmosphere for bacteria and fungi.		
ES62 Notes: *Part a of this requirement is repeated in the ISS spec (SSP 41000) at 3.2.1.1.1.15.* *The entire requirement is repeated in the USOS spec at 3.2.1.1.1.61. Other instances of this requirement may be found at several other locations in the ISS and USOS specs, where it is levied on non-US segments of the ISS and various nodes in the USOS.* *This is not a focus area for ARREM, but the filtration function should be HEPA rated at a minimum to address airborne microbial growth.*		

S683-29523 (US Lab)	**Rev R**	**31 Aug 2009**
3.7.43.3	**Performance characteristics (Cabin Air Filter Assembly)**	
The cabin air filter assembly removes a minimum of 98% of all particulates and bacteria from spent cabin air, which exceeds 0.5 microns, major dimension. The filter element shall be capable of operating in the specified environment for a minimum of 2,160 hours without requiring replacement.		
ES62 Notes: *For ARREM, this requirement should be changed to specify that the particulate filtration/separations function shall comply with a minimum HEPA rating and consider selected performance criteria documented in DOE STD-3020-2005, "Specification for HEPA Filters Used by DOE Contractors".*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.7.1.3.8.3	**Respond to hazardous atmosphere**	
a. The USOS shall detect combustion products over the ranges specified in Table LIV.		
ES62 Notes: *This requirement is repeated in the USOS spec (SSP 41162) at 3.2.1.1.1.28.* *This requirement applies to AES ARREM TELS and RASCAL array sensor development.*		

SSP 41000 TABLE LIV. Combustion product and total hydrocarbon detection

Compound	Range
Carbon Monoxide (CO)	3 to 400 parts per million (PPM)
Hydrogen Cyanide (HCN)	0.4 to 30 ppm

SSP 41162 (USOS)		**Rev BA**	**30 Dec 2008**
3.7.30.3.9.1.1	**Support detection**		
The CSA−CP shall detect and quantitate specific compounds as indicated in Table VIII.			
ES62 Notes: *SSP 41162 Table VIII is the same as Table LIV in SSP 41000 (see above).* *This requirement applies to the targeted monitors - TELS and RASCAL array.*			

SSP 41162 (USOS)		**Rev BA**	**30 Dec 2008**
3.7.30.3.11.1.1	**Accept samples**		
The VOA shall draw air from the cabin atmosphere and accept manually introduced air samples for analysis of the trace gas contaminants identified in Table LXXI.			
ES62 Notes: *This requirement applies to the VEM monitor development; replace “VOA” with “VEM”.*			

SSP 41162 TABLE LXXI. VOA trace gas detection range

Compound	Monitoring detection range Milligrams per cubic meter (mg/m^3)
methanol	0.2 to 0.5
n-butanol	1.0 to 5.0
ethanol	qualitative
o, m, p-xylenes	0.5 to 10
toluene	0.3 to 3.0
dichloromethane	0.25 to 0.5
propanone	0.3 to 1.0
2-butanone	0.4 to 5.0
ethyl acetate	0.4 to 5.0
2-propanol	0.8 to 1.0

IV. OXYGEN GENERATION, INTRODUCTION & PROVISION

SSP 50318 (Node 3)	**Rev H**	**9 May 2011**
3.7.6.3	**Performance characteristics (OGS)**	

a. The OGS shall be capable of cyclic operation which generates a minimum of 12 lbm/day of oxygen when generating oxygen at 20.4 lbm/day over a 53 minute period during each orbital duration of 90 minutes. The above represents lightside/darkside operation.
b. The OGS shall be capable of generating oxygen at a selectable rate of between 5.1 and 20.4 lbm/day when operated continuously.
c. The OGS shall supply oxygen directly to the Node 3 atmosphere as specified in SSP 50316, paragraph 3.2.1.4.9.
d. The oxygen produced by the OGS shall meet the quality specified in Table LVI.

ES62 Notes:
Need to scale the oxygen production to cover 4 crewmembers. Day-night cycling noted in part a is not required for AES ARREM.

SSP 50318 TABLE LVI. Oxygen quality

PARAMETER	MAXIMUM VALUE
Hydrogen	1%
Dewpoint	90°F
Temperature	113°F
Liquid Moisture	<5 cc/day

SSP 50318 (Node 3)	**Rev H**	**9 May 2011**
3.2.1.5	**Introduce oxygen**	

b. Node 3 shall generate oxygen at a rate of at least 12 lb/day nominal and 20.4 lb/day maximum.
l. Node 3 shall introduce oxygen into its atmosphere at a rate of 0.05 to 0.15 lbm/min when supplied with oxygen at the temperatures and pressures specified in SSP 41140, paragraph 3.2.2.2.3, when the only oxygen use point is introduction into the Node 3 atmosphere.

ES62 Notes:
Part b of this requirement is repeated in the ISS spec (SSP 41000) at 3.7.8.3.1.2.2.
Part l of this requirement is repeated in the USOS spec (SSP 41662) at 3.7.1.3.4 and in the USL spec (S683-29523) at 3.2.1.4.

SSP 41162 (USOS)	**Rev BA**	**30 Dec 2008**
3.7.15.3.5	**Introduce oxygen**	

j. The Airlock shall measure the oxygen temperature prior to entry into the tank with an accuracy of +/− 5°F over the range of 30 to 130°F, not to exceed an accuracy of +/− 10°F for temperatures outside this range but within −120 to 160 °F.

ES62 Notes:

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.2.1.1.1.16	**Capability: Provide water**	

h. The on−orbit Space Station shall provide up to 2.2 lbm (1.0 kg) of water per person per day for oxygen generation.

ES62 Notes:
This requirement should be scaled to 4 crewmembers for AES ARREM.

V. SABATIER

SSP 50873 (Sabatier)		Rev Baseline	August 2009
3.1.4	**Capability requirements**		
The SA shall produce liquid water at an efficiency of 90% or higher based on the stoichiometry of the Sabatier reaction when run with excess CO_2: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. The conversion efficiency shall be verified at the following operating point representing 3-crew cyclic operation. H2 feed flow rate: 0.05 lb/hr Equivalent OGA Current: 21.7 A CO_2 feed flow rate: 0.31 lb/hr Equivalent Crew Loading: 3 Molar Ratio: 3.5 Operating Mode: 53 minute Process/37 minute Standby			
ES62 Notes:			

SSP 50873 (Sabatier)		Rev Baseline	August 2009
3.1.4.4.1	**Liquid carryover in the vent gas**		
The total liquid content of the flow delivered by the SA to the product vent interface shall not exceed 1% by volume of the total liquid flow production over the range of conditions specified in SSP 50875.			
ES62 Notes:			

SSP 50873 (Sabatier)		Rev Baseline	August 2009
3.1.4.4.2	**Wastewater gas content**		
The total free gas delivered by the SA to the wastewater bus interface shall not exceed 1% by volume of the total fluid volume (both gas and liquid at this interface) delivered at 70°F and 14.7 psia over the range of conditions specified in SSP 50875.			
ES62 Notes:			

SSP 50873 (Sabatier)		Rev Baseline	August 2009
3.1.4.4.3	**Wastewater particle content**		
The maximum particle size permitted in the water at the wastewater bus interface shall not exceed 100 microns.			
ES62 Notes:			

VI. OTHER

SSP 50318 (Node 3)		**Rev H**	**9 May 2011**
3.7.12.3	**Performance characteristics (ARS)**		

a. The ARS performance characteristics shall be in accordance with SSP 50310 and S683−34649.

b. The ARS CDRA shall remove CO2 from the ISS atmosphere in order to maintain the CO2 partial pressure in accordance with Figure 4.

c. The ARS TCCS shall remove gaseous contaminants from the ISS atmosphere in accordance with 3.2.1.48.

d. The ARS MCA shall monitor the partial pressure of oxygen over the range and with the accuracy specified in 3.2.1.3.

e. The ARS MCA shall monitor the partial pressure of CO2 over the range and with the accuracy specified in 3.2.1.47.

ES62 Notes:
Similar requirements may be found in the USL spec (S683-29523) at 3.7.18.3 and 3.7.21.3.
SSP 50318 Figure 4 is the same as SSP 41000 Figure 15 (reproduced earlier in this document).

SSP 41000 (ISS)		**Rev BV**	**30 Sept 2011**
3.3.12.7	**Atmosphere leakage**		

a. The Space Station shall limit atmosphere leakage to equal to or less than the allocations identified in Table XLV.

b. The Space Station shall not preclude additional resources to accommodate leakage up to 4.5 lb per day.

ES62 Notes:
This requirement is repeated in the USOS spec (SSP 41162) at 3.3.12.6.
AES ARREM shall determine a test chamber leakage specification/rate based on pretest leakage testing.

SSP 41000 TABLE XLV. Atmosphere leakage.

Segment	Atmosphere leakage (lbs/day)
USOS	1.4
APM	0.2
JEM	0.5
RS	0.044
HTV	0.5 (1)
ATV	0.22 (1)
MSS	N/A
Node 3	0.1
Cupola	0.008 (2)
ISS Allocated Total	3.226

Notes:
(1) Leakage through the interface from ISS to HTV/ATV, not including CBM interface leakage.
(2) This allocation is for a single Cupola only.

SSP 50318 (Node 3)	**Rev BV**	**9 May 2011**
3.3.12.4.2	**Atmosphere leakage**	
a. At beginning of life, Node 3 shall leak no greater than 0.117 pounds per day of atmosphere at 14.7 psia with hatches closed. b. At beginning of life, Node 3 shall leak no greater than 0.100 pounds per day of atmosphere at 14.7 psia in the final ISS configuration (hatches open).		
ES62 Notes: *We will derive a test chamber leakage specification for all testing phases based on pre-test chamber leakage testing.*		

S683-29523 (US Lab)	**Rev R**	**31 Aug 2009**
3.3.12.4.2	**Atmosphere leakage**	
At beginning of life, the USL shall leak no greater than 0.109 lb/day of atmosphere at 14.7 psia with hatches closed. At beginning of life, the USL shall leak no greater than 0.09 lb/day of atmosphere at 14.7 psia in the final ISS configuration (hatches open).		
ES62 Notes: *We will derive a test chamber leakage specification for all testing phases based on pre-test chamber leakage testing.*		

SSP 41000 (ISS)	**Rev BV**	**30 Sept 2011**
3.2.1.1.8.1	**Capability: Support EVA operations**	
c. The Space Station shall provide for the measurement of ammonia (NH_3), nitrogen tetroxide (N_2O_4), monomethyl hydrazine (MMH), and dimethyl hydrazine (UDMH) during ingress from EVA in accordance with JSC 65129.		
ES62 Notes: *Ammonia monitoring is desired for basic air quality purposes. Ammonia monitoring should be captured in the general cabin air quality monitoring aspects of AES ARREM. Propellant monitoring is not a focus of AES ARREM (out of scope).*		

APPENDIX C—FIGURES OF MERIT

ARREM Project Fiscal Year 2013 Figures of Merit

WBS	Functional Trade Space	Figure of Merit	Basis for Comparison	Target Value	Achieved Value	Notes	References
Carbon Dioxide Removal	Assembly level	Equipment mass/volume	≤ ISS CDRA	<173.3 kg/380 liters		NASA TM-1998-206956, p. 132 (1998)/NASA TM-108441, p. 36 (1994).	
		Complexity	Part count	<19		Major ORU assemblies/sub-components	ISS ECLS ADD
			Control sensor/effector count	<29		Temperature (13), pressure (2), motor speed (2), valve position (12)	ISS ECLS ADD
	Remove carbon dioxide	Functional stage mass	≤ ISS CDRA CO_2 Sorbent Beds	<35.5 kg		NASA TM-1998-206956, p. 132 (1998)	
		Adsorbent working capacity	≥ ISS CDRA	TBD		Determined from AES ARREM testing program	
		Adsorbent media durability	≥ ISS CDRA	TBD		Bulk crush strength of CO_2 adsorbents determined from AES ARREM testing program and/or other TBD measures for structured media	
		CO_2 product purity	≥ ISS CDRA	>97%			
	Remove bulk and residual moisture	Functional stage mass	≤ ISS CDRA Desiccant Beds	<47.2 kg		NASA TM-1998-206956, p. 132 (1998)	
		Dryer media working capacity	≥ ISS CDRA	TBD		Determined from AES ARREM testing program	
		Dryer media durability	≥ ISS CDRA	TBD		Bulk crush strength of desiccant media determined from AES ARREM testing program and/or other TBD measures for membranes and structured media	
		Energy for regeneration	≤ ISS CDRA	TBD		Determined from AES ARREM testing program	
Trace Contaminant Control and Particulate Removal	Remove and dispose of particulate matter	Equipment mass	≤ ISS BFE	<30.6 kg		Lab module basis with 6 filter locations; 3 kg housing and 2.1 kg filter element; 364 cfm total flow	Specification SVHS12855 (1991); measured filter element weight
		Complexity	Part count ≤ ISS Lab BFE assembly total	≤18		Housing, HEPA media/box, prefilter screen at 6 locations	Specification SVHS12855 (1991)
		Loading capacity	≥ ISS BFE	>305 grams		50.89 grams/BFE; 6 BFEs in the ISS Lab module	ISS VCN No. USL-3.2.1.107-10 (1999)
		Maintainability	Service interval	≥2.5 years		ISS BFE service interval for ISS Lab module	
	Remove and dispose of chemical contaminants	Equipment mass/volume	≤ ISS TCCS	<63.1 kg/92.1 liters	50.8 kg/77.4 liters	63.1 kg/92.1 liters ISS TCCS; eliminate blower, flow meter, EIA, and SBA components	TCCS Mission Support Handbook, LMSS/P548946
		Peak power	≤ ISS TCCS	<200.3 W	<170 W	Eliminate flow meter (3.7 W) and blower (33.6 W); use Microlith catalytic reactor technology	TCCS Mission Support Handbook, LMSS/P548946; NASA/TM-2005-214061
		Adsorbent VOC capacity	≥ ISS TCCS	≥5.4 mg/g		Dichloromethane capacity from AES ARREM testing program	Specification No. 5844655A (1996)
		Adsorbent capacity (NH_3)	≥ ISS TCCS	≥32.2 mg/g	37 mg/g	Ammonia as key driver at 25 ppm and 40% relative humidity; Chemsorb 1425 replaces Barnebey-Sutcliffe Type 3032	AIAA-2010-6062
		Complexity	Part count	<6	2	Eliminate blower, EIA, flow meter, and SBA.	TCCS Mission Support Handbook, LMSS/P548946
			Control sensor/effector count	<4	2	Eliminate blower (speed sensors) and flow meter; catalytic oxidizer temperature control only	TCCS Mission Support Handbook, LMSS/P548946
Loop Closure	Supply oxygen	Equipment mass/volume	≤ ISS OGA	<410.8 kg/475 liters		OGA and PSM mass basis/ORU volume basis	SLS-JA21-012 Rev. D (2005)
		Complexity	Part count	TBR			
			Control sensor/effector count	TBR			
		Maintainability	Service interval for major components	TBR		Primary components: cell stack, RSA, etc.	
	Recover gaseous resources	Percentage O_2 recovery	> ISS CRA	>42%		Recovery from CO_2	
		Annual O_2 recovered	≥ ISS CRA	>112.5 kg/CM-year		CM = crewmember	
		Complexity	Part count	TBR			
			Control sensor/effector count	TBR			

ARREM Project Fiscal Year 2013 Figures of Merit

WBS	Functional Trade Space	Figure of Merit	Basis for Comparison	Target Value	Achieved Value	Notes	References
Environmental Monitoring	Monitor major consituents - micro Gas monitor (mGm)	Equipment mass/volume	≤ ISS MCA	<53 kg/84.4 liters **mGM Target = 3.4kg / 8 liters**	6.8 kg/15.8 liters	COTS sensor array minus verification gas: O2-2.3 kg/4 liters; CO2-3 kg/9.4 liters; H2O-1.5 kg/2.4 liters	SAE 941503; http://www.sablesys.com/products-subj_5.html; http://www.oxigraf.com/
		Peak power	≤ ISS MCA	<103.5 W **mGM Target = 25W (peak)** **20 W (nominal)**	<50 W	MCA 87.6 W average; COTS sensor array	ISS ECLS ADD; http://www.sablesys.com/products-subj_5.html; http://www.oxigraf.com/
		Complexity	Sensor/effector count	<90 **mGM Target < 10 effectors**		Sensor/effector list in the ISS ECLS ADD	ISS ECLS ADD
			Space vacuum interface	Yes **mGM Target = NO Space Vacuum Interface**	None	Optical methods require no vacuum interface providing reduced complexity	ISS ECLS ADD
		Accuracy	≥ ISS MCA	<2%/<1% full scale **mGM Target = <1% of Full Scale**	1%/0.003%	Oxygen/carbon dioxide	SAE 951468; NASA/TM-2004-213392
	Monitor trace chemical contaminants - micro Gas monitor (mGm)	Equipment mass/volume	≤ ISS ANITA/VCAM demos	**mGM Target = 3.4 kg / 8 liters**		ANITA, VCAM, and grab sample basis	
		Complexity	Part count	**mGM Target < 90 part count**			
		Target analyte count	≥ ISS ANITA/VCAM demos	**30** **mGM Target = at least same # analytes as VCAM + methanol**			
		Accuracy	≥ ISS ANITA/VCAM demos	**mGM Target = ± 40%**			
		Precision	≥ ISS ANITA/VCAM demos	**mGM Target = ± 20%**			
		Capability to identify unknowns	none	**YES**			
		Multi-functional capability	none	**Possible water monitoring**			
	Water Module for Detection of Trace Chemical Species in Water	Equipment mass/volume	CSPE instrument			The WM is deliverable in FY14. Conceptually, its functionality can be expanded to include future detection of trace species in air, and major constituents in air.	
		Complexity	CSPE instrument				
		Accuracy	undergoing laboratory testing				VOC Species and concentrations as given in Spacecraft Water Exposure Guidelines (JSC-63414, 11/08)
		Precision	undergoing laboratory testing				
		Target analyte count	≥ 10 VOCs in water at ppm to ppb levels			VOCs species and concentrations selected from SWEG reference	
		capability to identify unknowns		yes			
		Multi-functional capability		yes		adds detection of water species to trace gas or event monitoring instrument	
	Continuous monitoring for events, spills, and target gases - Tunable Laser Absorption (TELS)	Equipment mass/volume	≤ ISS ANITA/VCAM demos	<3 kg			
		Complexity	Part count ≤ ISS AQM/CSA-CP/E-Nose demo				
		Calibration		not needed during op			
		Consumables					
		Reliability		>2 years			
		Detection range		CO [0..500ppm]±5ppm	CO [0..500ppm]±5ppm		Ryan Briggs, ICES paper 2013
		Target analyte count		5 - CO, HCl, HF, HCN, Formaldehyde			
		Capability to identify unknowns		no			
		Time to identify event	< Enose Tech Demo	< 1 sec			
		Multi-functional capability		yes			
	Continuous monitoring for events, spills, and target gases - Rapid Analysis Self-Calibrating (RASCal) Array	Equipment mass/volume	≤ ISS ANITA/VCAM demos				
		Complexity	Part count ≤ ISS AQM/CSA-CP/E-Nose demo				
		Calibration		minimal or no recalibration			
		Consumables					
		Reliability		>2 years			
		Detection range		SMAC ranges			
		Target analyte count		5-10 analytes		may identify some chemical families, eg. Alcohols	
		Capability to identify unknowns		yes		it is possible to back-determine unknowns	see Enose Gen 3 Final Report,
		Time to identify event	< Enose Tech Demo	< 10 minutes			
		Multi-functional capability					
	Monitor selected microbial contaminants	Kit Consumables	Consumables from current ISS hardware -Microbial Air Sampler Kit (MASK), Environmental Health System (EHS) Water Kit, Surface Sampler Kit (SSK), and hardware enabling sample transfer to Earth	TBD			SSP50260, Medical Operations Requirements Document (MORD)
		Consumables shelf life	Consumables from current hardware - Microbial Air Sampler Kit (MASK), Environmental Health System (EHS) Water Kit, Surface Sampler Kit (SSK), and hardware enabling sample transfer to Earth	TBD			SSP50260, Medical Operations Requirements Document (MORD)
		Crew Time	Total crew time using current monitoring approach on ISS (MASK, EHS Water Kit, SSK, and sample transfer)	Less than TBD hours annually			SSP50260, Medical Operations Requirements Document (MORD)
		Accuracy	Quantification and identification of selected contaminants compared to current ISS hardware and ground analysis	Quantification of total viable microbial concentration analogous to current heterotrophic plate counts Identification of any single selected contaminant to 1 or more viable cells per 100 ml			SSP50260, Medical Operations Requirements Document (MORD)
		Precision	Quantification and identification of selected contaminants compared to current ISS hardware and ground analysis	TBD			SSP50260, Medical Operations Requirements Document (MORD)

NASA System Maturation Team Figures of Merit Derived from ARREM Project

Capability Area	Function	Need/Gap	Enabling/ Enhancing	Performance Parameter	SoA	Into Solar System (1-6 mos ug)	Exploring Other Worlds (>6 mos ug + short lunar surface)	Planetary Exploration (>6 mos ug + long Mars surface)
Atmosphere Conditioning	CO2 removal			Maintenance crew-hrs/yr	3.7 (spec) vs ~16 actual	–	–	–
		Improved reliability/no unplanned maintenance	Enabling	**OR**: time between failure or unplanned maintenance?	~0.5	1 year	3 years	3 years
		Able to lower crew ppCO2	Enhancing	CO2 removal rate, kg/day/torr ppCO2 or crew equivalent/torr ppCO2	1.77	1.77	2	2
	Trace Contaminant Control	Replace obsolete bulk sorbents	Enabling	Bulk sorbents commercially available (yes/no)	no	yes	yes	yes
			Enhancing	Adsorbent capacity (NH3), mg/g @<1 ppm	11.9	17.4	32.2	32.2
			Enhancing	Adsorbent capacity (VOCs), mg/g (for dichloromethane)	5.4	≥5.4	≥5.4	≥5.4
	Particulate Filtration	Surface dust pre-filter	Enabling	Safe exposure estimate (SEE), mg/m3, for lunar dust	NA	NA	0.5	0.5
	O2 Recovery from CO2	Recovery of O2 from CO2	Enabling	% recovery of O2 from CO2	42	NA	75	90
			Enabling	Break even point, yrs	0.3	NA	0.3	0.3
				OR: lbs equipment/lb O2 recovered?	0.482954545	NA	–	–
			Enhancing	Max by-product venting, %	50	NA	50	10
Atmosphere Pressure Management	O2 Generation	Reliable O2 generation	Enabling	Time between maintenance, yrs	0.173913043	NA	3	3
			Enhancing	Hardware mass per O2 produced (lb/lb)	0.38	NA	<0.2	<0.2
	High Pressure O2	High pressure O2 for EVA	Enabling	Supply pressure, psia	2700	3600	3600	3600
				Mass savings over stored HP gas for given mission, %	0	50	50	50
				O2 purity, %	99.5	99.989	99.989	99.989
Environmental Monitoring	Major Constituents	Continuous monitoring of O2, N2, CO2, H2, CH4, H2O	Enabling	see MC tab				
		Reliable - no routine maintenance	Enabling	Continuous operation without maintenance, months	12	12	36	36
		allowance	Enabling	Mass, lbs	120	19.8	19.8	19.8
	Trace VOCs	In-flight detection of required list of compounds	Enabling	List of compounds & detection limits (see tab)	17	NA	33	33
		Ability to handle unknowns in a reasonable manner	Enabling	TBD	limited capability	NA	TBD	TBD
	Targeted gases	hydrazine, combustion products	Enabling	Response time, seconds		5	5	5
		duration	Enabling	Calibration interval, months	9-24	24	36	36
		Minimal crew time	Enabling	Crew time				
		Ability to survive vacuum	Enabling	Survive vacuum	no	yes	yes	yes
	Particulates	On-board measurement of particles	Enhancing	Particle size range, um				
		Tolerate dormancy	Enhancing	Dormancy period, months	0	NA	12	18
		Work in low pressures	Enhancing	Operating pressure, psia	14.7	NA	10.2	8
	Microbial monitor	Non-culture based in flight monitor	Enabling	Culture/non-culture	culture	NA	non-culture	non-culture
		Detection limit (by species)	Enabling	See separate tab				
		In-flight species identification	Enabling	# target compounds identified in flight	0	NA	12	12
		Minimal crew time	Enhancing	Crew time, hrs/sample	1.7	NA	<1	<1
		Minimal consumables	Enhancing	Consumables, lbs/year	29	NA		
		Fast response time	Enabling	Response time, hrs	48	NA	6	6
		viable	Enabling	viable/non-viable distinction (yes/no)	yes	NA	yes	yes
	Biocide Monitor	Lower consumables	Enhancing	Consumables, lbs/year		NA		
	Water monitor	quantification of species in water	Enabling	# target compounds identified in flight	0	NA		
		Minimal crew time	Enhancing	Crew time, hrs/month		NA		
		Minimal consumables	Enhancing	Consumables, lbs/year		NA		
	Acoustic monitor	Minimal crew time	Enhancing	Crew time, hrs/month		NA		
		Alerting feature	Enhancing	yes/no	no	NA	yes	yes

APPENDIX D—GENERAL ERROR ANALYSIS NOTES

Instrumentation Review and Propagation of Error Assessment of ARREM Project Cycle 1

The general methodology for error propagation is as follows (Coleman and Steele, 1989):

Measure $x1, x2, \ldots, xn$ with uncertainties $\pm x1, \pm x2, \ldots, \pm xn$. The purpose of these measurements is to determine q, the result of a given equation, which is a function of $x1, \ldots, xn$.

$$q = f(x1, \ldots, xn)$$

The uncertainty in q is then

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x_1}\delta x_1\right)^2 + \ldots + \left(\frac{\partial q}{\partial x_n}\delta x_n\right)^2}$$

In the ARREM SAS WBS FY14 presentation, *Performance Modeling Tool Development and Correlation*, the following example was discussed explaining the error analysis process (Appendix. XII.d):

Assume values **x** and **y** are parameters OGACFR061 and PCAFTo100. To obtain data for the error analysis, an analyst would login to PACRATS and pull these parameters for a given interval.

Intervals were chosen based on the following criteria:

- For crew sizes of 2.4, 3, 4 and 6, each PACRATS data interval should begin at 12 hours after the EChamber door is closed.
- Each time stamp for each data interval should be compared to the corresponding Gas Chromatograph time stamp. (logbook to logbook)

Good data pulls were defined as follows:

1) The data pull for the interval should have a low standard deviation in relation to the value.
2) If possible, avoid time periods that include known issues as recorded in log books for the GC and PACRATS data.: (sometimes it was unavoidable)

- Pressure control or other systems being shut down
- Leaks in the system
- Hardware incorrectly installed, e.g., a valve was installed backwards
- Software or sensors malfunctioning
- The EChamber door being opened, e.g., tour groups visiting the E Chamber.

OGACFR061 measures O2 from the O2 Generation Assembly tank. PCAFTo100 is the Missile Grade Air mass totalizer. (multiplied by mass fraction) Below, consumable mass (M) entering the system is defined for O2.

$$\sum M_{in\_O2} = \int \dot{M}_{O2\ Generation} dt + \Delta M_{MGA\_O2}$$

Or, Min_O2 = OGACFR061 + PCAFTo100.

From the manufacturer's data sheets for these sensors, the instrumentation error is ±x = 0.8% of the reading plus 0.2% of FS and ± y = 1% FS, respectively for OGACFR061 and PCAFTo100.

From the text (Coleman and Steele, 1989):

$$U_{r_{RSS}} = \sqrt{((B_r)^2 + (P_r)^2)}$$

Here, $U_{r_{RSS}}$ is the uncertainty in the experimental result and RSS represents the Root-Sum-Square. The bias in the instrumentation is Br and the precision is Pr.

FS is reported in standard liters per minute (SLPM) or standard cubic feet per minute (SCFM) and converted to pounds per minute (lbs/min.). For each parameter, it should be noted that standard conditions applied impacting the SLPM and SCFM conversions. For O_2, the standard conditions were 1 atm, 0 deg C or 32 deg F, and 14.696 psia.

By the rules related to propagation of errors for a system, if x and y have independent/random manufacturer errors ±x and ±y then,

$$\text{Min\_O2} = z = x + y \text{ and } \delta z = \sqrt{\delta x^2 + \delta y^2}.$$

This technique is commonly known as the root-sum-square (RSS) (Coleman and Steele, 1989).

Note, where applicable, the propagation of the errors for multiplication or division in x and y are defined respectively as $z = xy \ or \ x/y$ and z is set to the calculated value for the mass balance.

$$\text{The result: Min\_O2} = \sqrt{(.0047)^2 + (4.27)^2} = 4.27 \text{ lbs.}$$

This result would then be used as a variable in the following equation:

$$\sum M_{Mass\_Balance\_O2} = \sum M_{in\_O2} - \sum M_{out\_O2} - \Delta M_{accumulation\_O2}$$

Stated another way, the total mass balance system error is equal to the square root of the squared sum of the errors for the mass in, mass out and mass accumulation (or leakage) for each constituent.

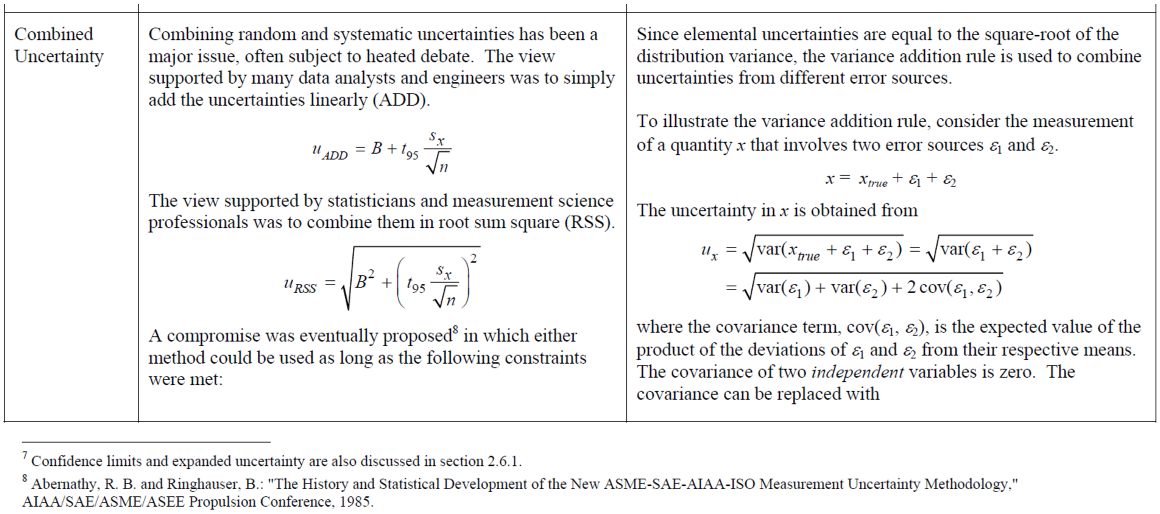
$$\text{Sum\_M\_mass\_balance\_O2} = z = w + x + y \text{ and } \delta z = \sqrt{\delta w^2 + \delta x^2 + \delta y^2}.$$

$$\text{Or, Sum\_M\_mass\_balance\_O2\_error} = \sqrt{((\text{Min}_{\text{O2}_{\text{error}}})^2 + (\text{Mout}_{\text{O2}_{\text{error}}})^2 + (\text{Maccumulation}_{\text{O2}_{\text{error}}})^2)}$$

For a top-level integrated system error determination, the RSS would be repeated or propagated throughout the system-level equations. An analyst would use the parameters and the provided manufacturer data sheets for each instrument used in an equation to find the error for MoutO2 and Delta_M_Accumulation_O2. Using the RSS technique, a total uncertainty would be calculated for O_2 (the Sum of Mass_Balance_O2 as depicted above). Then, the technique would be used to find the error for the remaining major constituents, e.g., CO_2 and H_2O. If desired, these error results could be used to capture the consumable mass balance for the entire integrated system. At this point in time, discovering a discrete value for error associated with the mass balances of major constituents is sufficient; ARREM is a non-flight experimental project.

From *Measurement Uncertainty Analysis Principles and Methods (NASA Measurement Quality Assurance Handbook – ANNEX 3* NASA-HDBK-8739.19-3):

Pre Handbook **NASA Guidance**

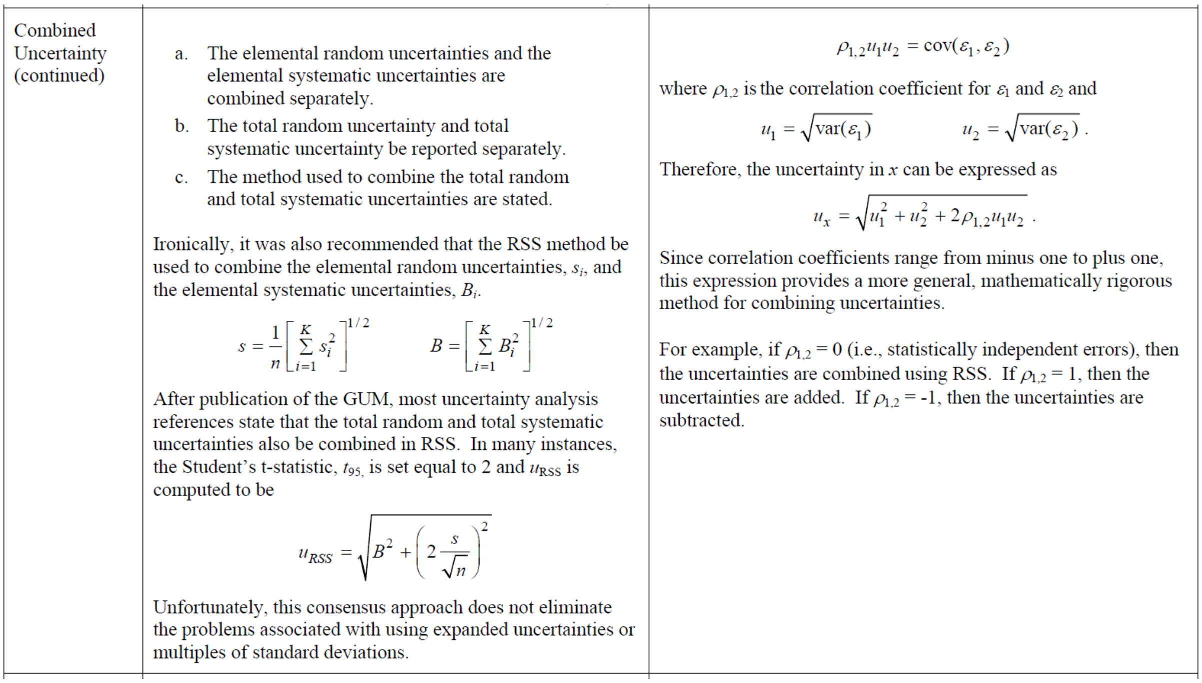


Combined Uncertainty	Combining random and systematic uncertainties has been a major issue, often subject to heated debate. The view supported by many data analysts and engineers was to simply add the uncertainties linearly (ADD). $u_{ADD} = B + t_{95}\frac{s_x}{\sqrt{n}}$ The view supported by statisticians and measurement science professionals was to combine them in root sum square (RSS). $u_{RSS} = \sqrt{B^2 + \left(t_{95}\frac{s_x}{\sqrt{n}}\right)^2}$ A compromise was eventually proposed[8] in which either method could be used as long as the following constraints were met:	Since elemental uncertainties are equal to the square-root of the distribution variance, the variance addition rule is used to combine uncertainties from different error sources. To illustrate the variance addition rule, consider the measurement of a quantity x that involves two error sources ε_1 and ε_2. $x = x_{true} + \varepsilon_1 + \varepsilon_2$ The uncertainty in x is obtained from $u_x = \sqrt{\mathrm{var}(x_{true} + \varepsilon_1 + \varepsilon_2)} = \sqrt{\mathrm{var}(\varepsilon_1 + \varepsilon_2)}$ $= \sqrt{\mathrm{var}(\varepsilon_1) + \mathrm{var}(\varepsilon_2) + 2\,\mathrm{cov}(\varepsilon_1, \varepsilon_2)}$ where the covariance term, $\mathrm{cov}(\varepsilon_1, \varepsilon_2)$, is the expected value of the product of the deviations of ε_1 and ε_2 from their respective means. The covariance of two *independent* variables is zero. The covariance can be replaced with

---

[7] Confidence limits and expanded uncertainty are also discussed in section 2.6.1.

[8] Abernathy, R. B. and Ringhauser, B.: "The History and Statistical Development of the New ASME-SAE-AIAA-ISO Measurement Uncertainty Methodology," AIAA/SAE/ASME/ASEE Propulsion Conference, 1985.



Combined Uncertainty (continued)	a. The elemental random uncertainties and the elemental systematic uncertainties are combined separately. b. The total random uncertainty and total systematic uncertainty be reported separately. c. The method used to combine the total random and total systematic uncertainties are stated. Ironically, it was also recommended that the RSS method be used to combine the elemental random uncertainties, s_i, and the elemental systematic uncertainties, B_i. $s = \frac{1}{n}\left[\sum_{i=1}^{K} s_i^2\right]^{1/2}$ $B = \left[\sum_{i=1}^{K} B_i^2\right]^{1/2}$ After publication of the GUM, most uncertainty analysis references state that the total random and total systematic uncertainties also be combined in RSS. In many instances, the Student's t-statistic, t_{95}, is set equal to 2 and u_{RSS} is computed to be $u_{RSS} = \sqrt{B^2 + \left(2\frac{s}{\sqrt{n}}\right)^2}$ Unfortunately, this consensus approach does not eliminate the problems associated with using expanded uncertainties or multiples of standard deviations.	$\rho_{1,2}u_1u_2 = \mathrm{cov}(\varepsilon_1, \varepsilon_2)$ where $\rho_{1,2}$ is the correlation coefficient for ε_1 and ε_2 and $u_1 = \sqrt{\mathrm{var}(\varepsilon_1)}$ $u_2 = \sqrt{\mathrm{var}(\varepsilon_2)}$. Therefore, the uncertainty in x can be expressed as $u_x = \sqrt{u_1^2 + u_2^2 + 2\rho_{1,2}u_1u_2}$. Since correlation coefficients range from minus one to plus one, this expression provides a more general, mathematically rigorous method for combining uncertainties. For example, if $\rho_{1,2} = 0$ (i.e., statistically independent errors), then the uncertainties are combined using RSS. If $\rho_{1,2} = 1$, then the uncertainties are added. If $\rho_{1,2} = -1$, then the uncertainties are subtracted.

APPENDIX E—RESOURCE RECOVERY FUNCTIONAL DEMONSTRATION DETAILED TEST REPORT

ES62-ARREM-RPT-13-001

Advanced Exploration Systems (AES)

Atmosphere Resource Recovery and Environmental Monitoring (ARREM)

Resource Recovery Functional Demonstration (R2FD)
Test Data and Summary Report

Prepared By: 3/26/13

Keith J. Parrish
Test Director/ES62

Ken Frederick Test Conductor/ES62	Chris Stanley CDRA Test Conductor/ Qualis-ES62	Dr. Robert Newton Environmental Monitoring/ES62
Joseph Scott GC/Micro GC Operator/ Jacobs-ES62	Gena Dalton Chemistry Lab Analyst/ Qualis-ES62	Dr. Matthew Kayatin GC Data Analyst/ES62

Reviewed By: 3/27/13

Jay Perry
Principal Investigator/ES62

Approved By: 3/27/13

Bob Bagdigian
ECLSS Development Branch Chief/ES62

1.0 OVERVIEW

The Resource Recovery Functional Demonstration (R2FD) test was run to establish a baseline set of operational data for the ISS state-of-the-art atmosphere revitalization system. The requirements for the test were established by the Atmosphere Revitalization Subsystem Loop Closure Functional Demonstration Test Requirements Document (3/8/10) and Atmosphere Revitalization Subsystem Resource Recovery Functional Demonstration Test Requirements (5/16/11). A summation of that work is as follows:

1) Facility Functional Check out including chamber leakage rate, metabolic simulation, trace contaminant monitoring, space vacuum simulation, and ventilation, temperature, and humidity control.
2) Carbon Dioxide Removal Assembly (CDRA) Functional Checkout (Phase 1A)
3) Carbon Dioxide Management Assembly Functional Check out (Phase 1B)
4) Investigation of Traced Contaminant Propagation – CDRA Carbon Dioxide Product (Phase 2A)
5) Evaluation of SeQual Eclipse Medical Oxygen Concentrator (Phase 2B)
6) Extended Duration Resource Recovery Functional Demonstration (Phase 3)

The Resource Recovery Functional Demonstration test was performed in the Exploration Test Chamber (E–Chamber) in MSFC Building 4755. This facility provided the following capabilities:

1) DC and AC power
2) Software Automated Control and Data Acquisition
3) Metabolic Simulation (CO_2 injection, H_2O $_{(v)}$ injection, and O_2 removal)
4) Chamber atmosphere and Subsystem temperature control via Chilled Water distribution
5) Condensate Collection
6) Contaminant Injection
7) Pressure Control via High Purity Air injection and Chamber atmosphere venting
8) Space Vacuum simulation
9) Chamber atmosphere constituency control via O_2 injection
10) Chamber atmosphere and subsystem constituency monitoring via GC and FTIR
11) Hazardous Gas removal via pump with N_2 purge

The subsystems participating in the R2FD test were the CDRA, TCCS, and the Sabatier Carbon Dioxide Reduction Assembly. The Oxygen Generator Assembly was not ready in time to participate in the test and its functions were simulated.

2.0 ECHAMBER AND FACILITY CHECKOUTS

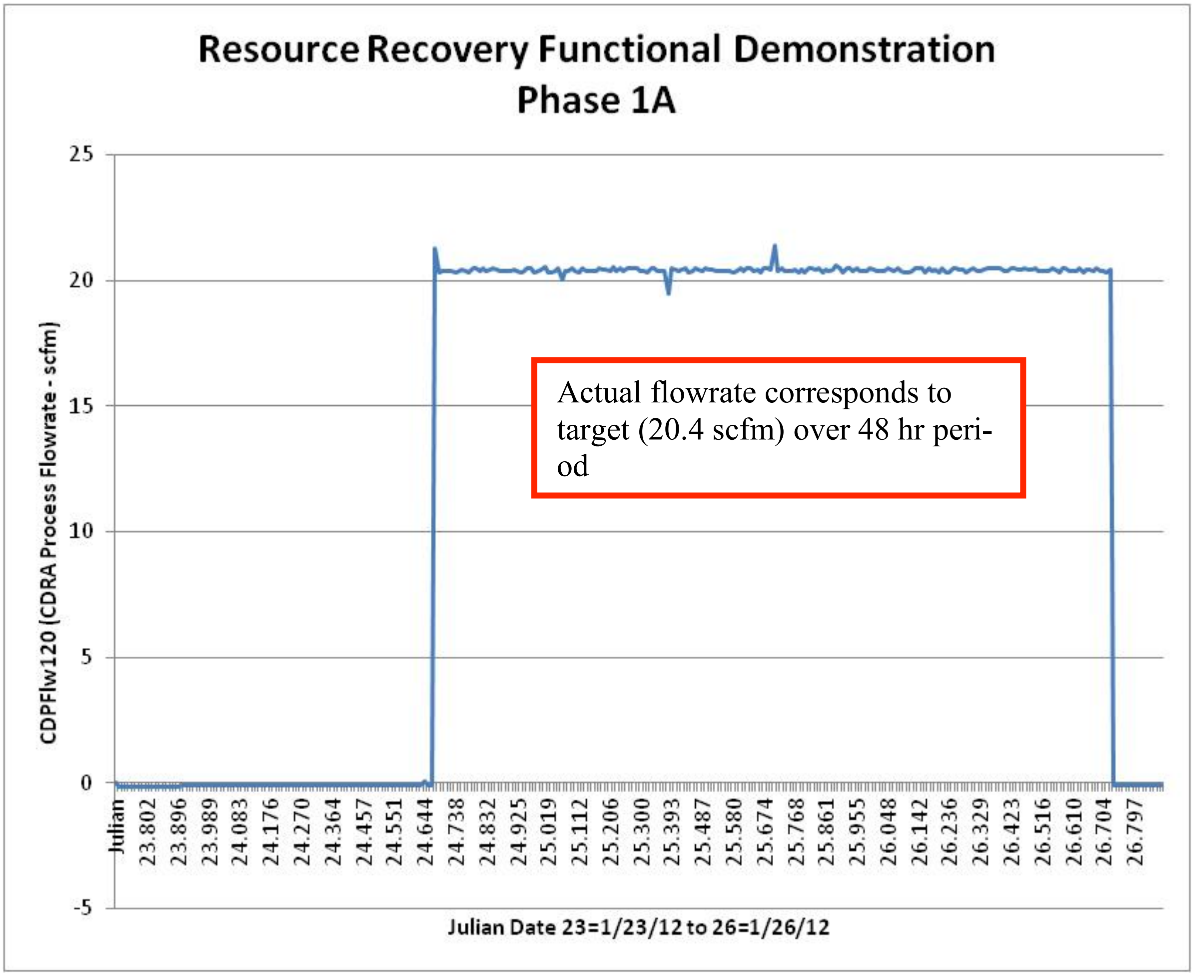
Baseline Leak Rate (5/10/11 – ES62-TPS-RRR-11-001): The EChamber baseline leak rate was determined to be approximately 1.43 lb/day when held at a minimum of 3 mmHg above atmospheric pressure.
Metabolic Simulator (fall 2011 – ES62-TPS-RRR-11-003): The metabolic simulator functions (CO2 injection, H2O (v) injection, and O2 removal were checked over several runs in the latter half of 2011. The ability to inject CO2 at the low and high ends of the requirement (0.21 – 0.59 lb/hr) and the ability to remove O2 at the low and high ends of the requirement (0.19 – 0.47 lb/hr) were proven in September, 2011. The humidity injection system proved to be more difficult. Steps were taken to prime the system between the low and high flow rates but the system proved unable to meet even the low flow rate requirement (0.68 lb/hr) in September, 2011. The system was re-designed from a pump system to a DI water source/controlling flow regulator system between September, 2011 and November, 2011. The high flow rate (1.66 lb/hr) test was passed on 11/4/11, but the low flow rate test failed high (0.92 lb/hr instead of the expected 0.68 lb/hr). A pressure regulator on the DI water source was installed the system was able to control below the low flow rate requirement by 1/09/12 – test data showed capability down to 0.3 lb/hr.
Contaminant Injection (3/23/12 – ES62-TPS-RRR-12-012): The first attempt to run a Contaminant Injection system test (3/21/12) ended when there was a communication error with the liquid contaminant

injection control software. Run #2 (3/23/12 – 3/30/12) was a successful test showing capability to quickly inject liquid contaminant and read via Fourier Transform Infrared (FTIR) and also to settle into a maintenance mode of slowly injecting contaminant to mimic the ISS atmosphere. There was another communication error on 3/24 which prevented injection over that weekend but beginning on 3/26 there was a 4 day period of injection leading to the conclusion that the interior surfaces had been passivated and the atmosphere was stable at about 5 ppm Ethanol.

System Software Safety Shutdowns Validation (4/16/12 – ES62-TPS-RRR-12-013): the following Safety Shutdowns were successfully verified – CDRA Sorbent bed temperatures out of range, CDRA blower delta pressure = 0, CDRA control driver error, CDRA CO2 outlet pressure (CDPPrs020) high (all CDRA modes of the half cycle), CDRA loss of communication with Chamber Control Console, Space Vacuum Simulator valve closed (resulting in high CDRA bed pressure), AFcCO2100 (EChamber CO2 sensor) high, AFcO2_100 (EChamber O2 sensor) low, Loss of humidity injection source, Loss of Oxygen Concentrator, Loss of CO2 injection source, AFcHG_100 (EChamber hazardous gas sensor), EChamber smoke detector, Loss of O2 injection (OGA simulator), Liquid Contaminant Injection temperature low, Liquid Contaminant Injection temperature high, TCCS high current, TCCS catalytic oxidizer temperature high offset limit, TCCS catalytic oxidizer temperature low offset limit, TCCS OT1 and OT2 Drift limits (catalytic oxidizer temperature measurements agreement), TCCS catalytic oxidizer flow high, and TCCS catalytic oxidizer flow low.

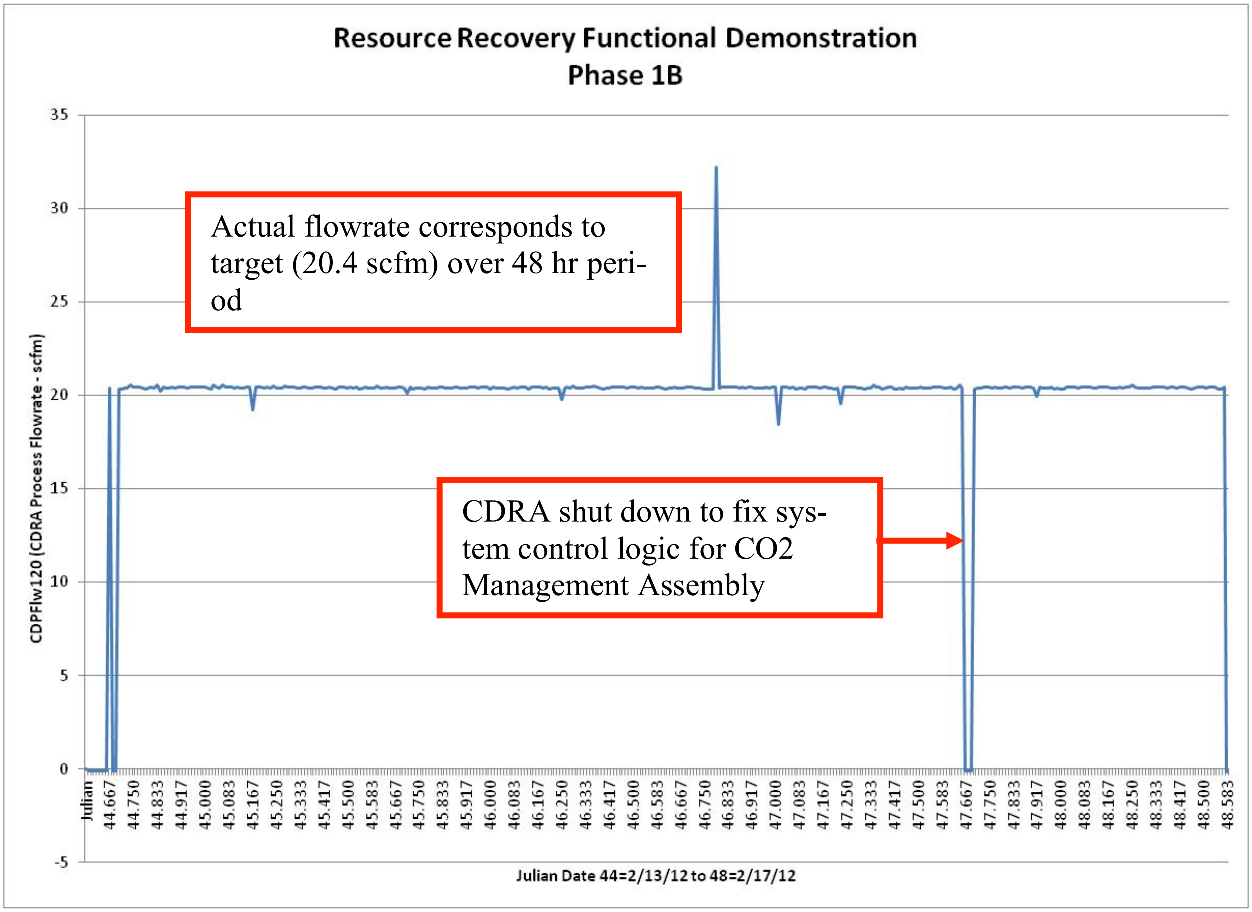
3.0 RESOURCE RECOVERY FUNCTIONAL DEMONSTRATION TEST RESULTS

Phase 1A (1/23/12 to 1/26/12 – ES62-TPS-RRR-11-006): The objective of Phase 1A was to show that the CDRA was functional and could process an air stream with a 3-person rate of CO2 injected into the EChamber. After getting the facility support up and running on 1/23, the EChamber door was shut and the CDRA was put into Auto mode in the afternoon of 1/24. It ran nominally for 48 hours in open loop mode (CO2 vented to the Space Vacuum Simulator).



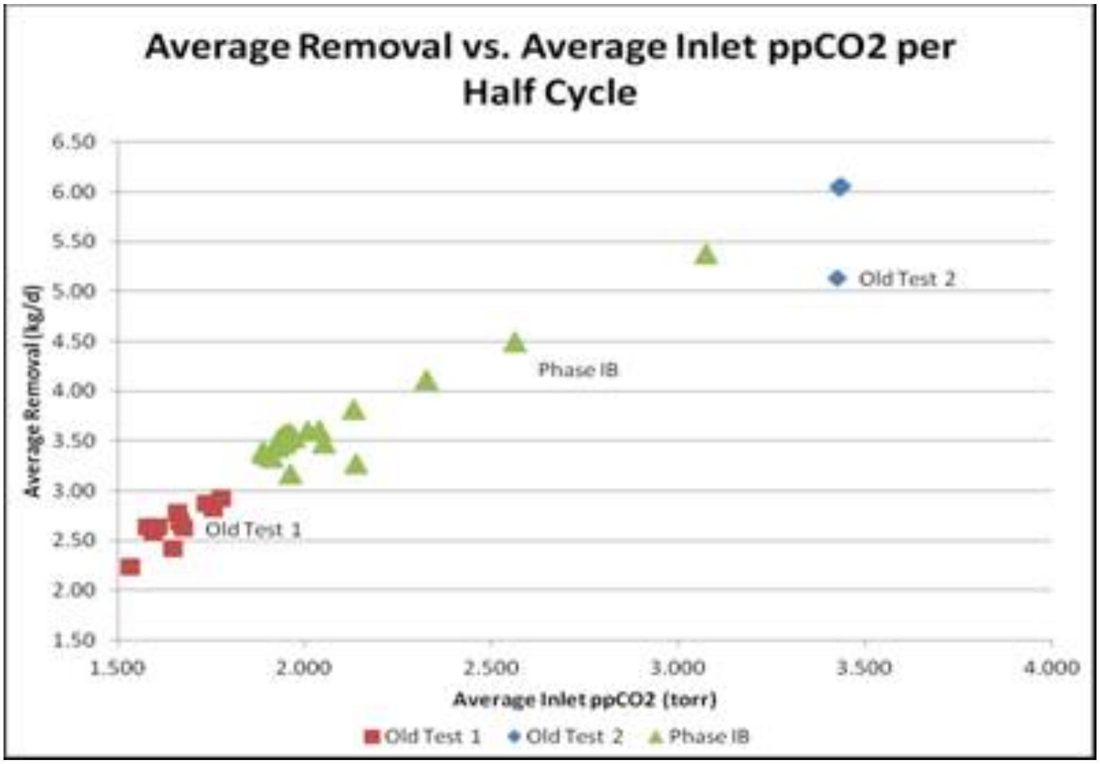
Actual flowrate corresponds to target (20.4 scfm) over 48 hr period

Phase 1B (2/13/12 to 2/17/12 – ES62-TPS-RRR-12-010): The objective of Phase 1B was to add the CO2 Management Assembly (a commercial compressor and accumulator) and its control logic to CDRA operations. The control logic caused several aborted attempts to run Phase 1B as fixes were required to the control program to properly implement those rules. One of the fixes came about when the control logic ignored the top end rule to dump to space vacuum when the accumulator pressure reached 55 psia. Another came after an overnight run where the compressor dumped to the Space Vacuum Simulator all night when conditions did not warrant it. The logic also was “stuck” once one of the transition points of the standby to operate logic. Once these fixes were in place Phase 1B was successfully performed from 2/13/12 to 2/17/12 showing the proper CO2 Management Assembly control including CO2 consumption via a Sabatier simulator.

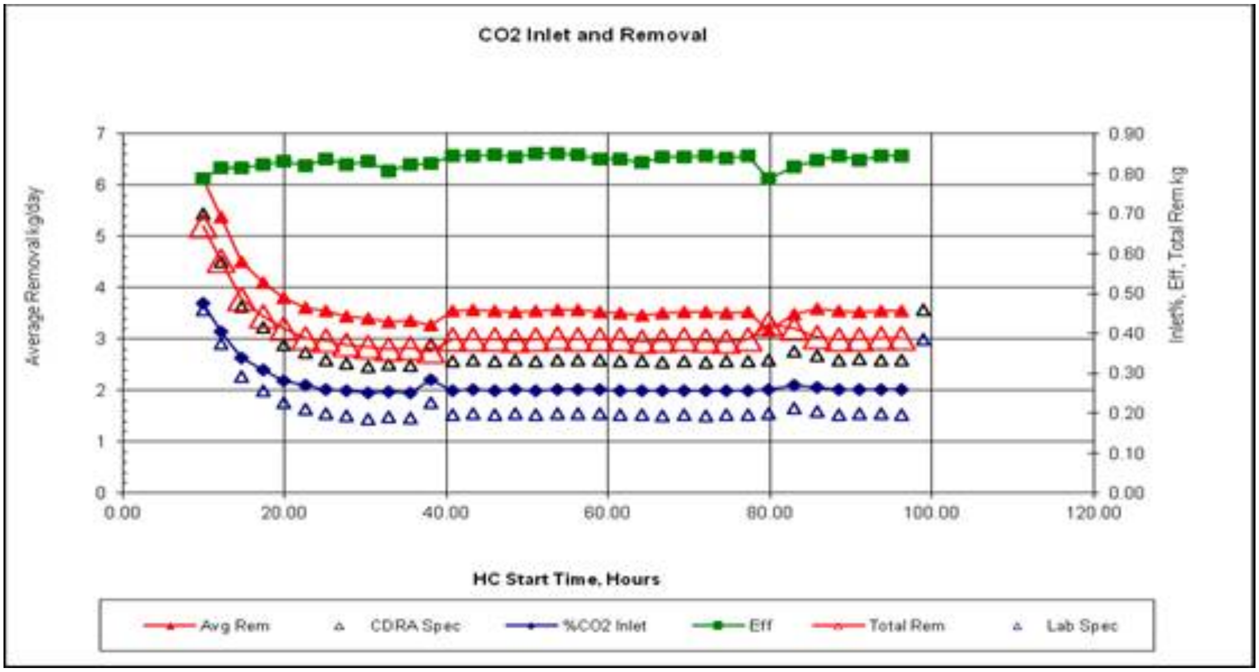


Two comparisons for CDRA were made: 1) compare performance to previous tests to determine that hardware is performing within an acceptable range, and 2) to compare test data with the CDRA specification based on inlet concentration.

The CDRA performed within acceptable ranges for both comparisons. The plot below shows the comparison between the Phase IB data and data taken from two tests that were performed in 2005. The Phase IB data falls nicely between the old data, indicating that the hardware is functioning as expected and performance has not change since the hardware was last operational.



The plot below shows the Phase IB performance compared to the CDRA specification and Module specification. The starting CO_2concentration in the module was quite high at the beginning of the test as indicated on the graph. As the test progressed, the inlet CO_2 concentration dropped to approximately the percentage that was being injected. The CDRA performed well throughout the test, meeting or exceeding the required removal rate for both the module and CDRA. The data located to the right of the 80 hour mark shows where the CDRA was stopped for a short while to adjust the valve logic for the CO_2 Management System.



The data located to the right of the 80 hour mark shows where the CDRA was stopped for a short while to adjust the valve logic for the CO2 Management System. Once the adjustment was made, the CDRA and CO2 Management System operated as expected.

Phase 2 Overview (4/30/12 to 5/13/12 – ES62-TCP-ARS-12-001): The objective of Phase 2 was to add contaminant injection and the Trace Contaminant Control System to the previously proved out parts of the Atmosphere Revitalization System. The propagation of contaminants into the CO2 product of the CDRA was of particular concern. There was also a side objective to prove that the SeQual O2 concentrator also did not concentrate any of the contaminants into its O2 product stream.

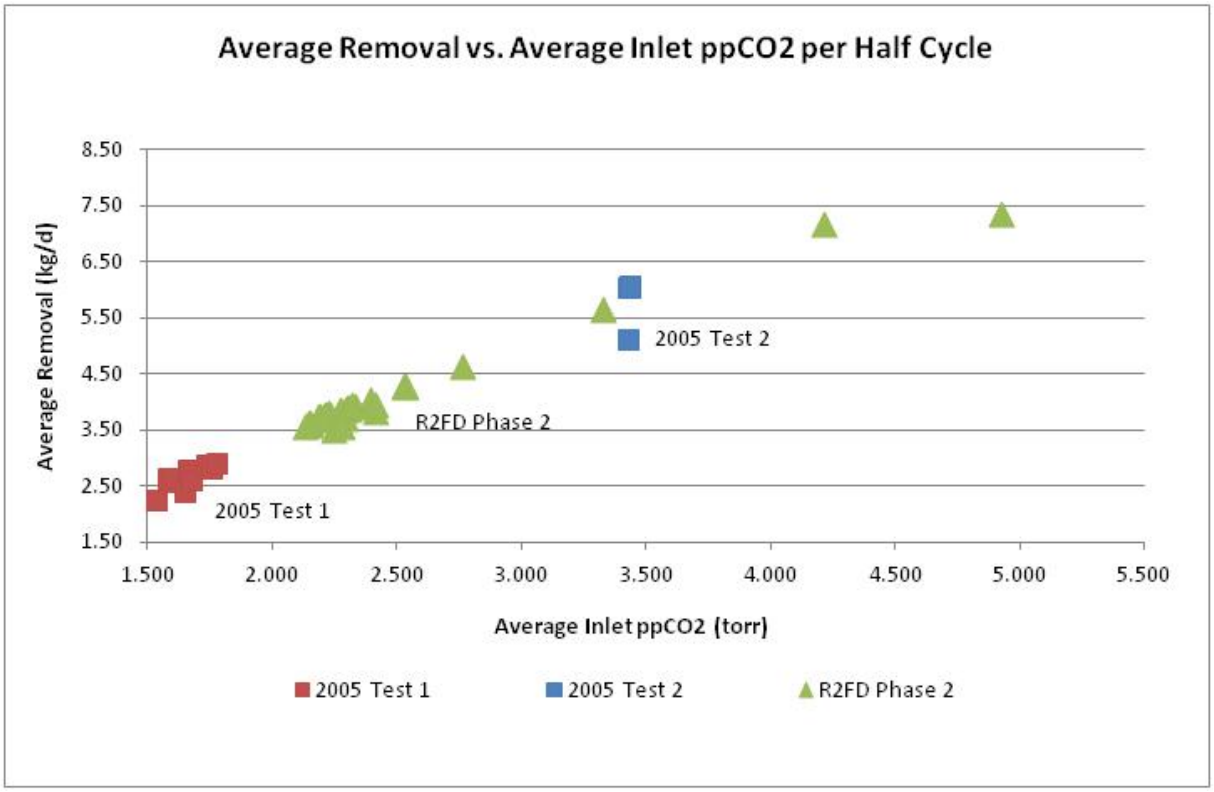
Phase 2 Event Summary 4/30/12 – Day 0A – Oxygen Concentrator and facility support items (Micro GC/GC/FTIR, Pressure control via high purity air, oxygen and nitrogen for two-gas balance, metabolic simulator (setting the rate for the Oxygen Concentrator) activated. The following samples were taken: 2 EChamber atmosphere, 4 Oxygen Concentrator, 2 EChamber atmosphere, 6 Oxygen Concentrator, and 2 EChamber atmosphere. These actions were performed to get a baseline on the Oxygen Concentrator prior to any contaminant injection into the EChamber. The final activity of the day was to initialize, by way of manual contaminant injection, the EChamber atmosphere in preparation for TCCS activation the next day. When that was done the Contaminant Injection system was put in automatic control.
5/1/12 – Day 0B – CDRA and TCCS started to allow them to warm up (for TCCS this is expected to take 17 hours). However, the program had to be shut down due to a CDRA logic error which ended up taking 3 days to fix.
5/4/12 – Re-start Day 0A – all facility support activations were completed but the sampling was not repeated.
5/5/12 – Re-start Day 0B – CDRA and TCCS started for warm up time. One program shutdown required because of a data acquisition delay. TCCS shutdown late in the day due to a Catalytic Oxidizer temperature cycling problem. The temperatures exceeded the negative offset condition causing the shutdown. A parameter update for the negative offset should allow the TCCS to operate nominally. Sample schedule was changed slightly to obtain more data from the TCCS effluent prior to resuming normal schedule (EChamber atmosphere overnight).

5/6/12 – Test Day 1 – Nominal day with all sampling operations completed for the day by 1800. Had to troubleshoot the Micro GC/GC plumbing for the O2 effluent (GC did not get flow). Found a 3-way valve with the common port in the wrong position. Able to make a change in the way the sample was pulled without making a plumbing change.
5/7/12 – Test Day 2 – Nominal day with no anomalies noted.
5/8/12 – Test Day 3 – Nominal day (CDRA analyst noticed that the CDRA air inlet dew point was running a little high (52.8 °F – reset the EChamber temperature to 49 °F to compensate).
5/9/12 – Test Day 4 – Nominal day with no anomalies noted.
5/10/12 – Test Day 5 – Nominal day with no anomalies noted.
5/11/12 – Test Day 6 – Nominal day with no anomalies noted.
5/12/12 – Test Day 7 – Nominal day with no anomalies noted.

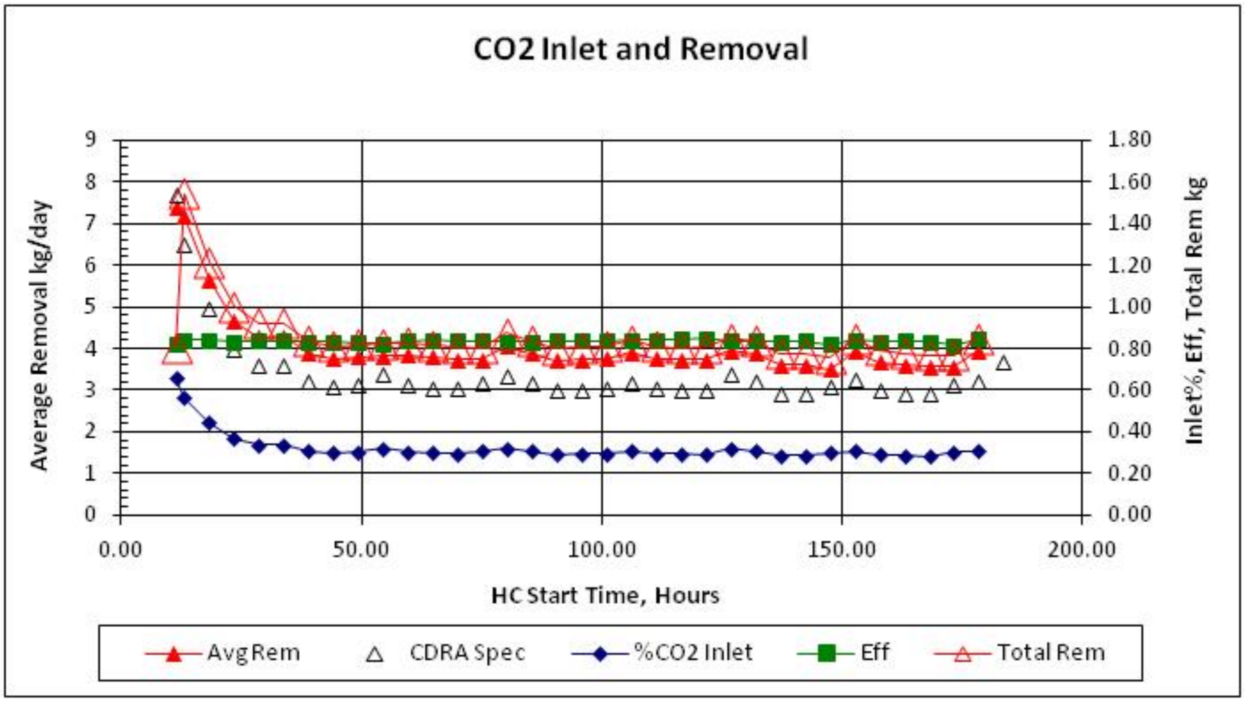
Phase 2 Test Results The TCCS showed the ability to keep the EChamber atmosphere ethanol concentration below 1% while processing the simulated contaminant loading of a 3-person crew. Condensate sampling results showed an average of 5.95 ppm Methanol, 15.49 ppm of Ethanol, and a Total Organic Carbon average of 16.06 ppm. The average humidity condensate removed from the EChamber was 17.32 lb/day. The CO2 Management Assembly worked according to the control logic but some inefficiencies were noted which would affect Phase 3 Sabatier operations. There were several CRA simulator "dropouts" during Phase 2 due to the CO2 accumulator level dropping below 20 psia. During Phase 3 these would be shutdowns of the Sabatier CRA for lack of CO2 to process. The Metabolic Simulator CO2 injection and O2 removal functions performed nominally while the H2O injection was lower than expected (17.99 lb/day actual .vs. 21.06 lb/day expected). Facility dewpoint sensors read in the low to mid 50's ºF compared to the main sensor (AFcDwp100) which read in the high 50's to low 60's ºF. A redundant CO2 sensor read about 0.3% which is in agreement with the main sensor (AFcCO2100). See plots of AFcDwp100 and AFcCO2100 in the results section below.

CDRA analysis confirmed that the operation during Phase 2 was in family with previous operations as far as CO2 removal efficiency with a 3-person metabolic load. Two comparisons were made; 1) compare the CDRA POIST performance to previous ground tests to determine that hardware is performing within an acceptable range and 2) compare test data with the CDRA specification based on inlet concentration.

The CDRA performed within acceptable ranges for both comparisons. The plot below shows the comparison between the Phase 2 data and data taken from two tests that were performed in 2005. The Phase 2 data falls nicely between the previous test data, indicating that the hardware is functioning as expected and performance has been maintained from Phase IB performance.



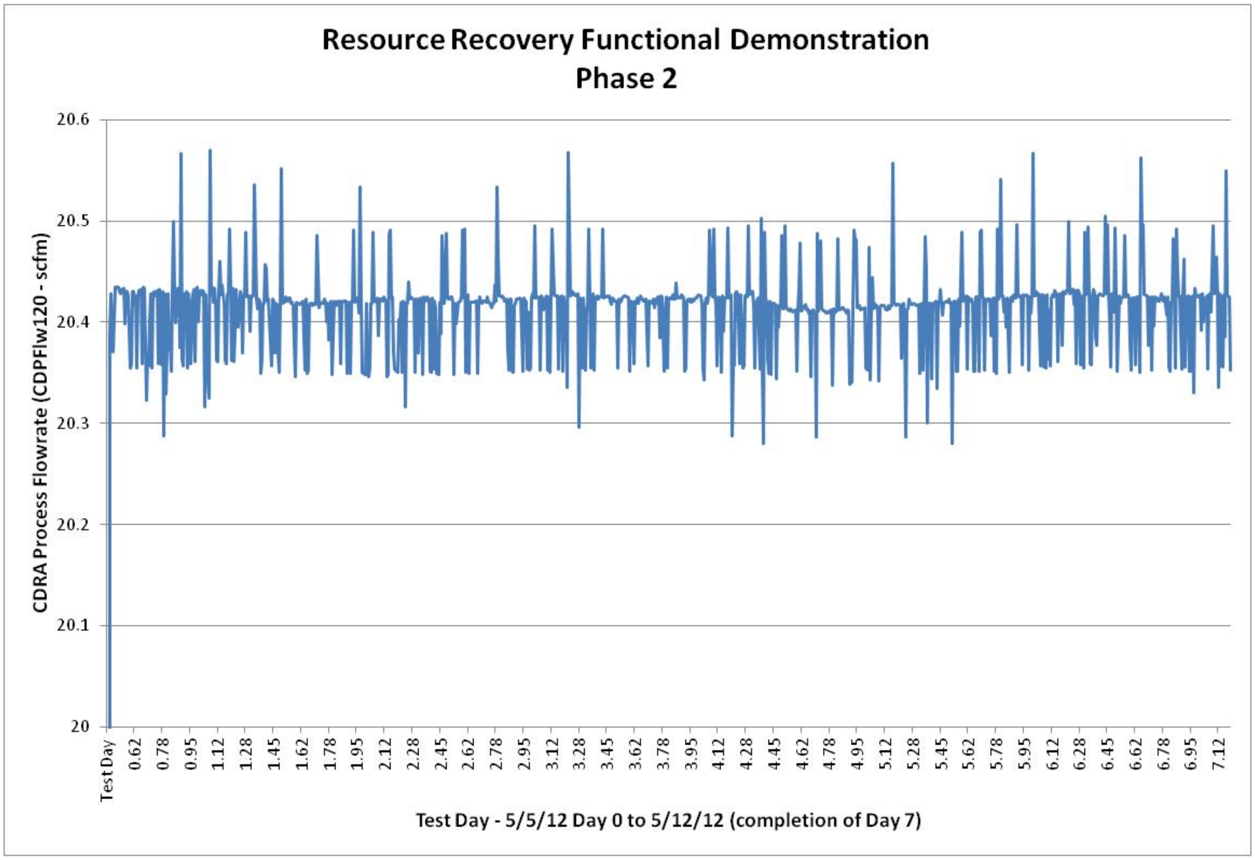
The plot below shows the Phase 2 performance compared to the CDRA specification for average removal (kg/day). The graph signifies that the CDRA performed well throughout the test; the average mass of CO2 removed per day meets or exceeds the required removal rates.

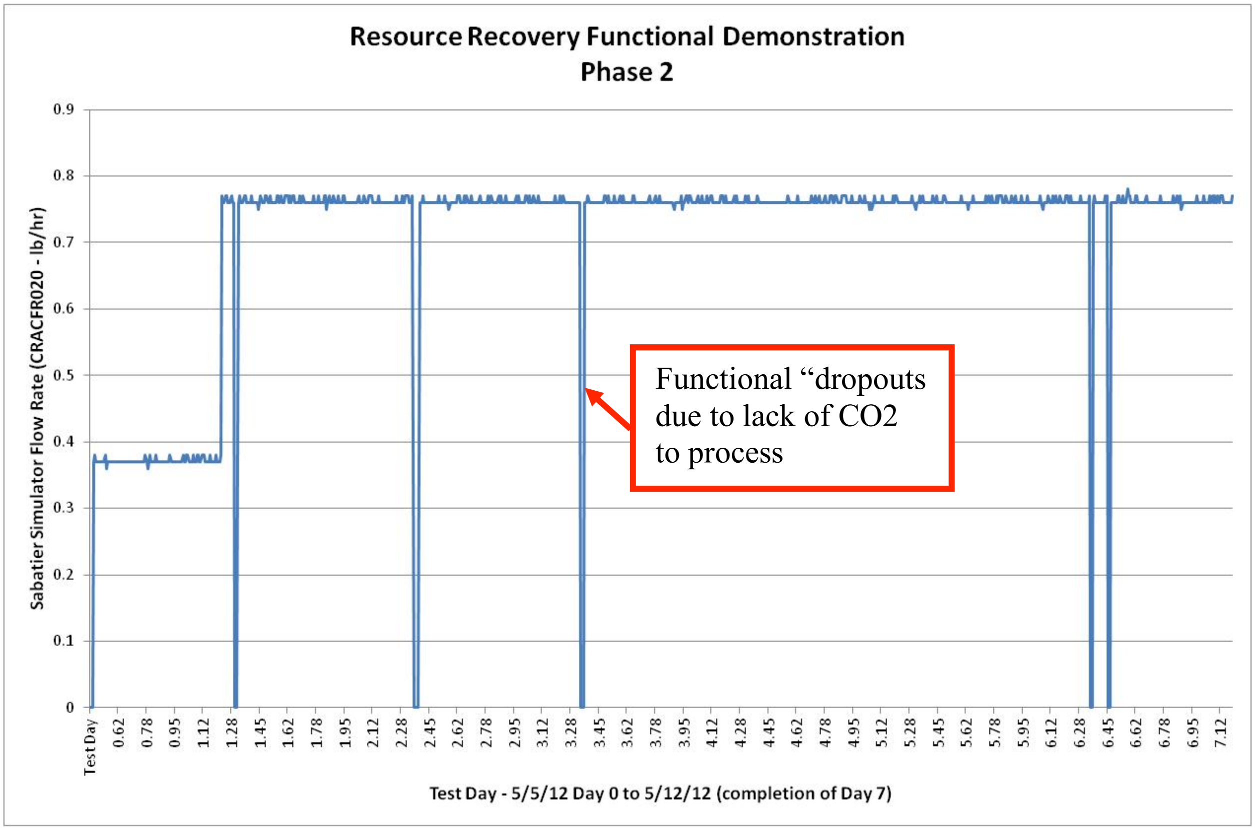


R2FD Phase 2 Carbon Dioxide Removal Performance Compared to CDRA specification.

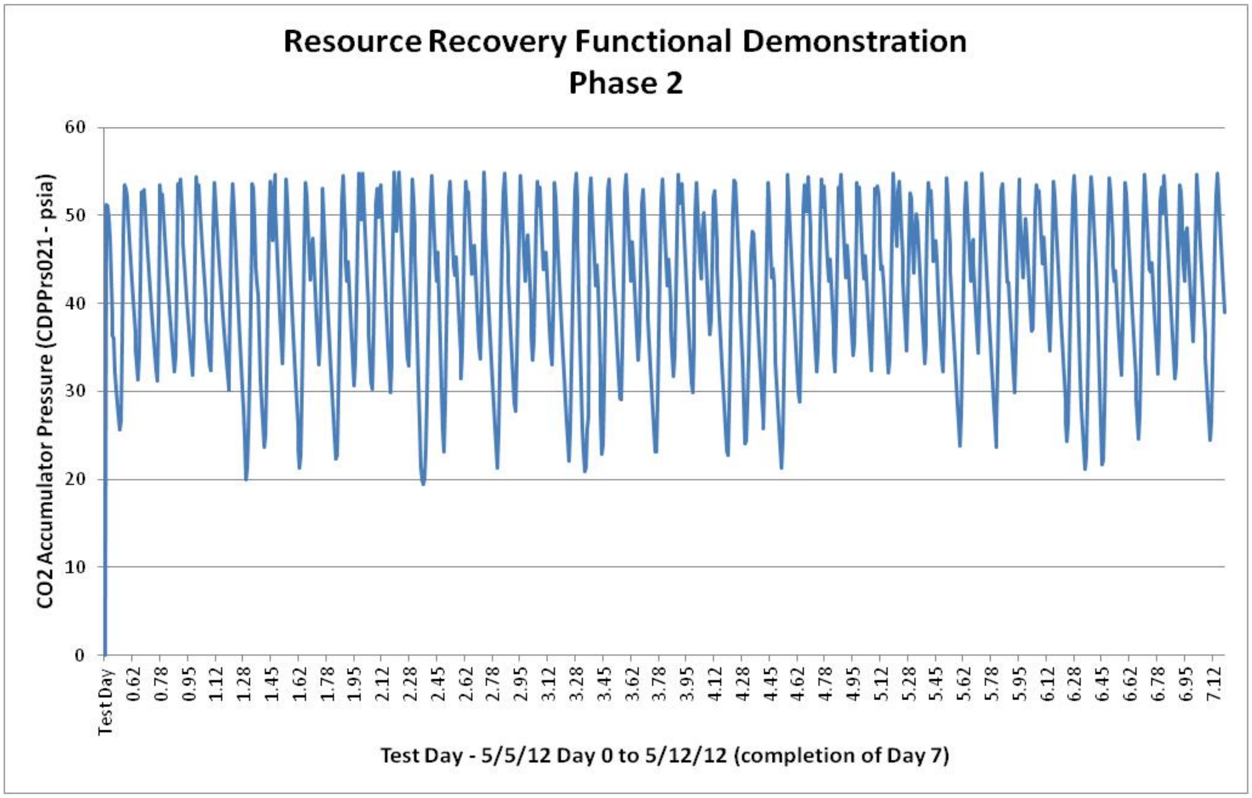
Table 1: Resource Recovery Functional Demonstration Phase 2
Humidity Condensate

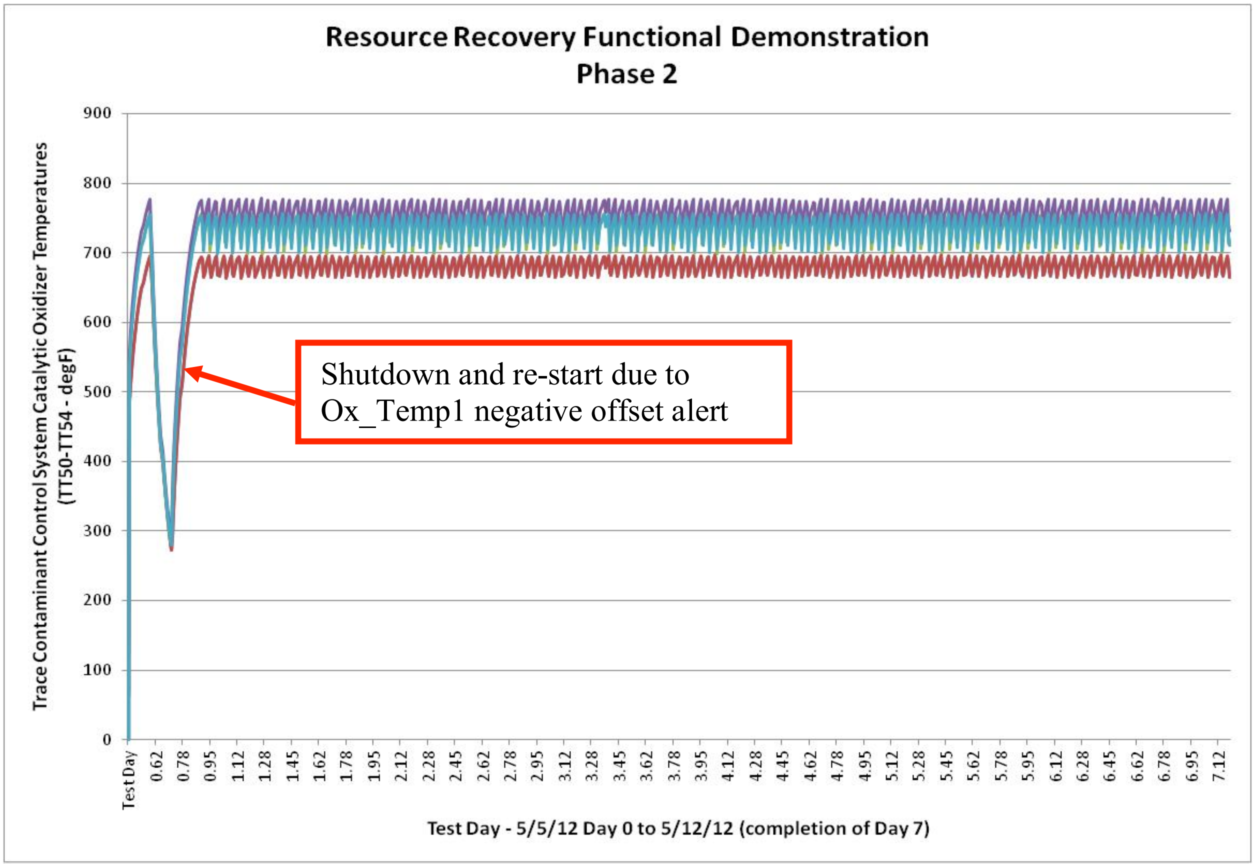
Analyte	Test Day						
	1	2	3	4	5	6	7
Condensate (lb)	19.36	15.95	19.4	17.3	16.95	14	18.3
Methanol (ppm)	6.6	6.5	5.8	7.3	6.2	5.5	5.1
Ethanol (ppm)	27.9	14.9	13.5	14.3	13.6	13	13.1
Acetone (ppm)	<1	<1	<1	<1	<1	<1	<1
1-propanol (ppm)	1.6	<1	<1	<1	<1	<1	<1
2-propanol (ppm)	<1	<1	<1	<1	<1	<1	<1
2-methyl 2-propanol (ppm)	<1	<1	<1	<1	<1	<1	<1
2-butanol (ppm)	<1	<1	<1	<1	<1	<1	<1
Total Organic Carbon (ppm)	29.4	14.6	18.4	19.1	10.9	10.4	10.9



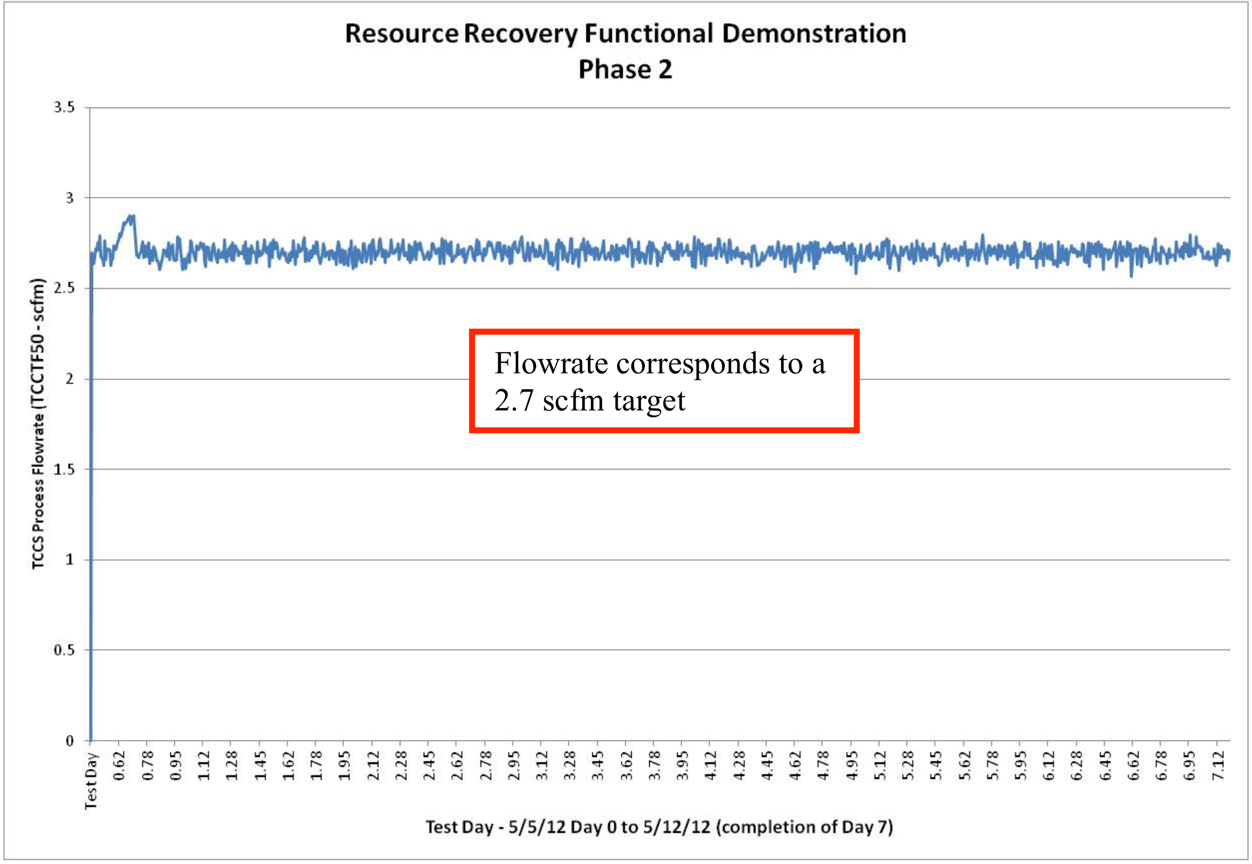


Functional “dropouts due to lack of CO2 to process

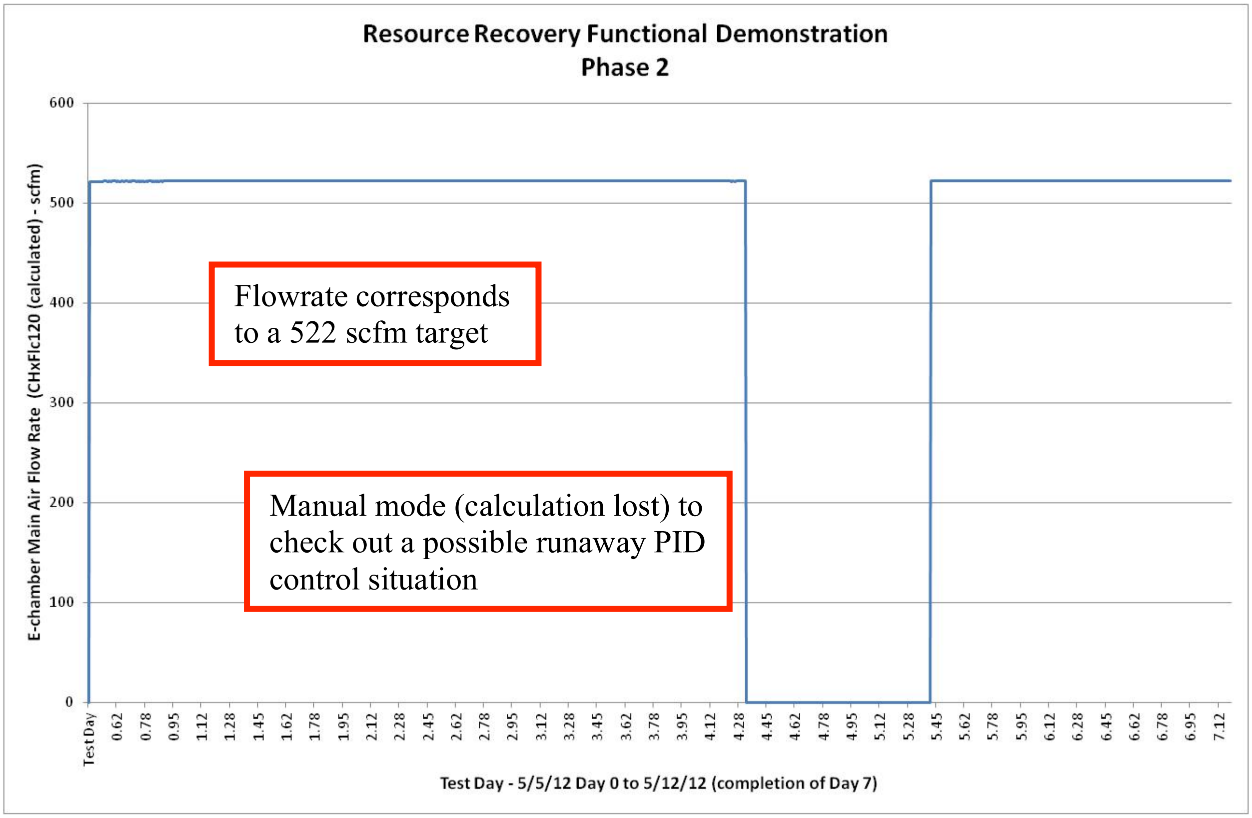




Shutdown and re-start due to Ox_Temp1 negative offset alert

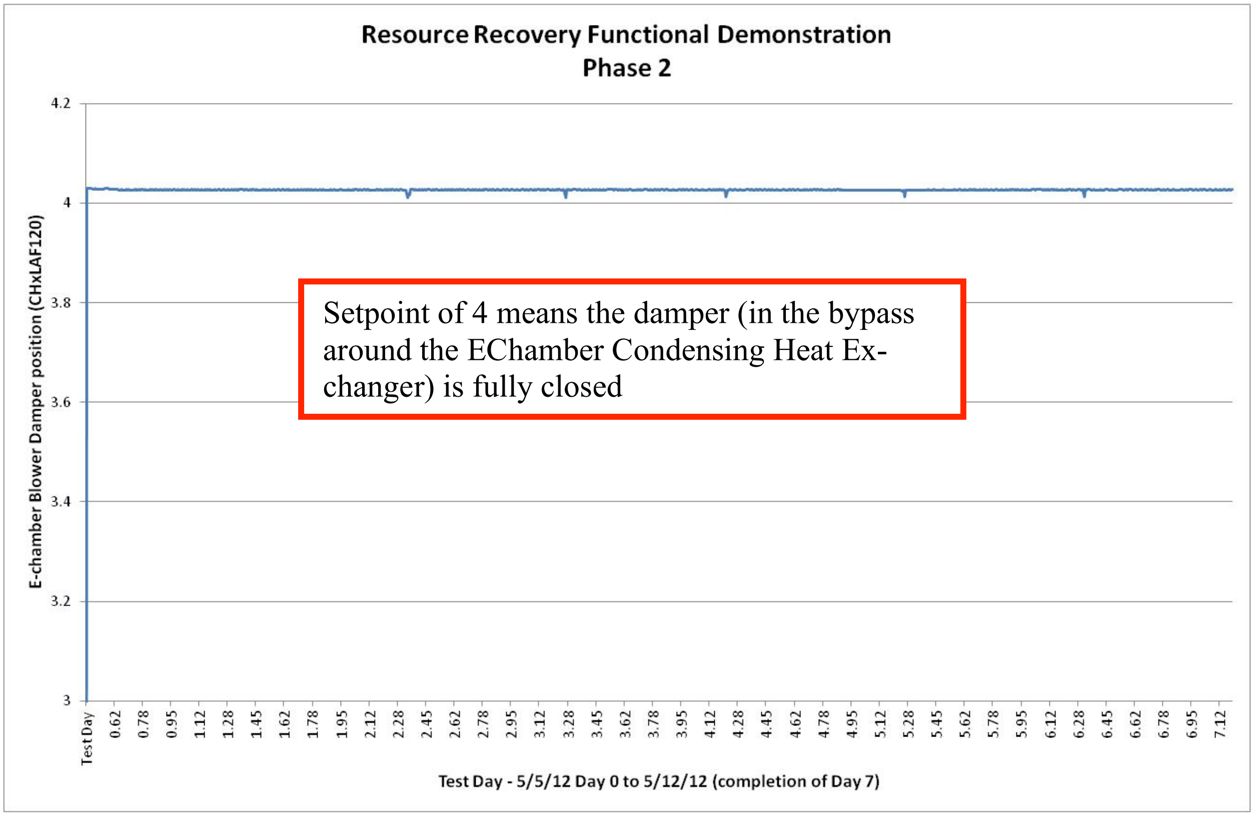


Flowrate corresponds to a 2.7 scfm target

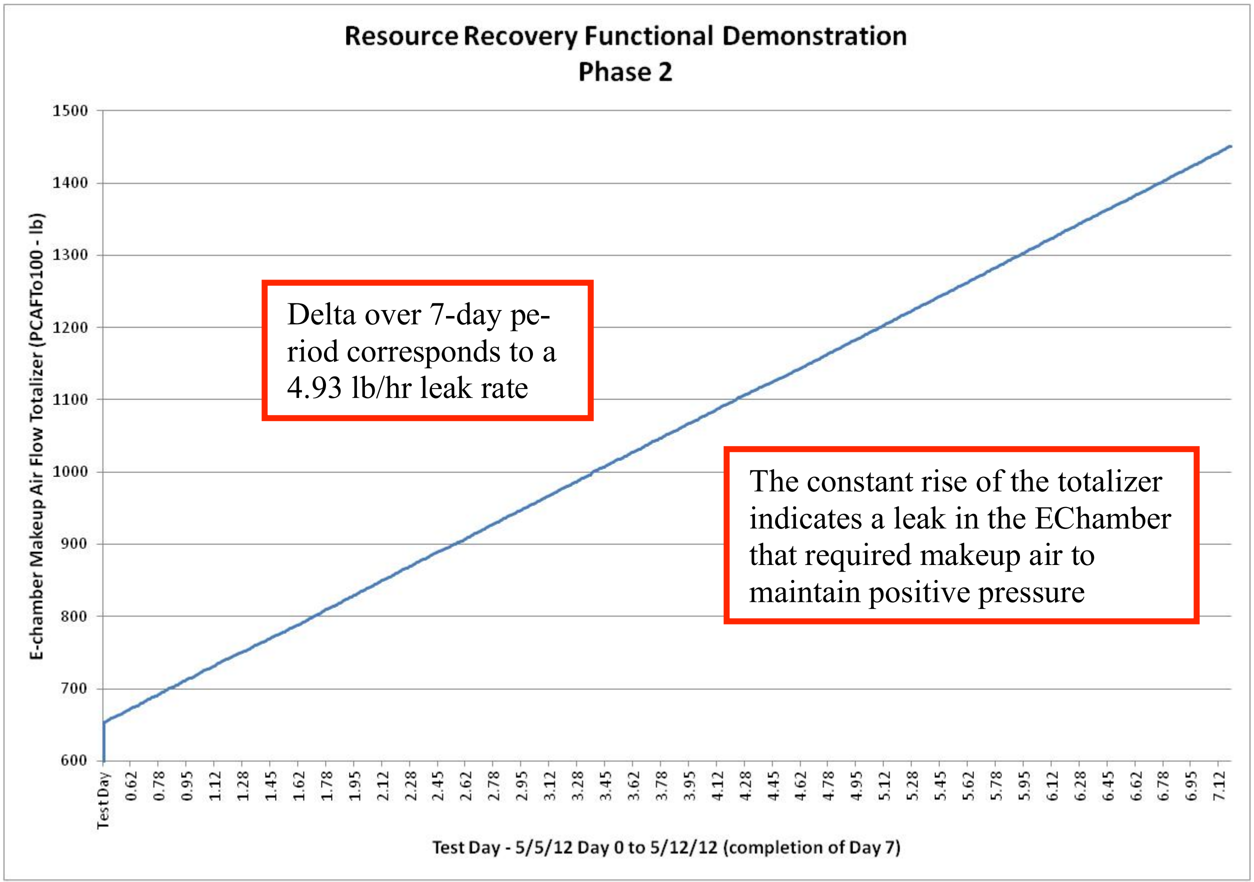


Flowrate corresponds to a 522 scfm target

Manual mode (calculation lost) to check out a possible runaway PID control situation

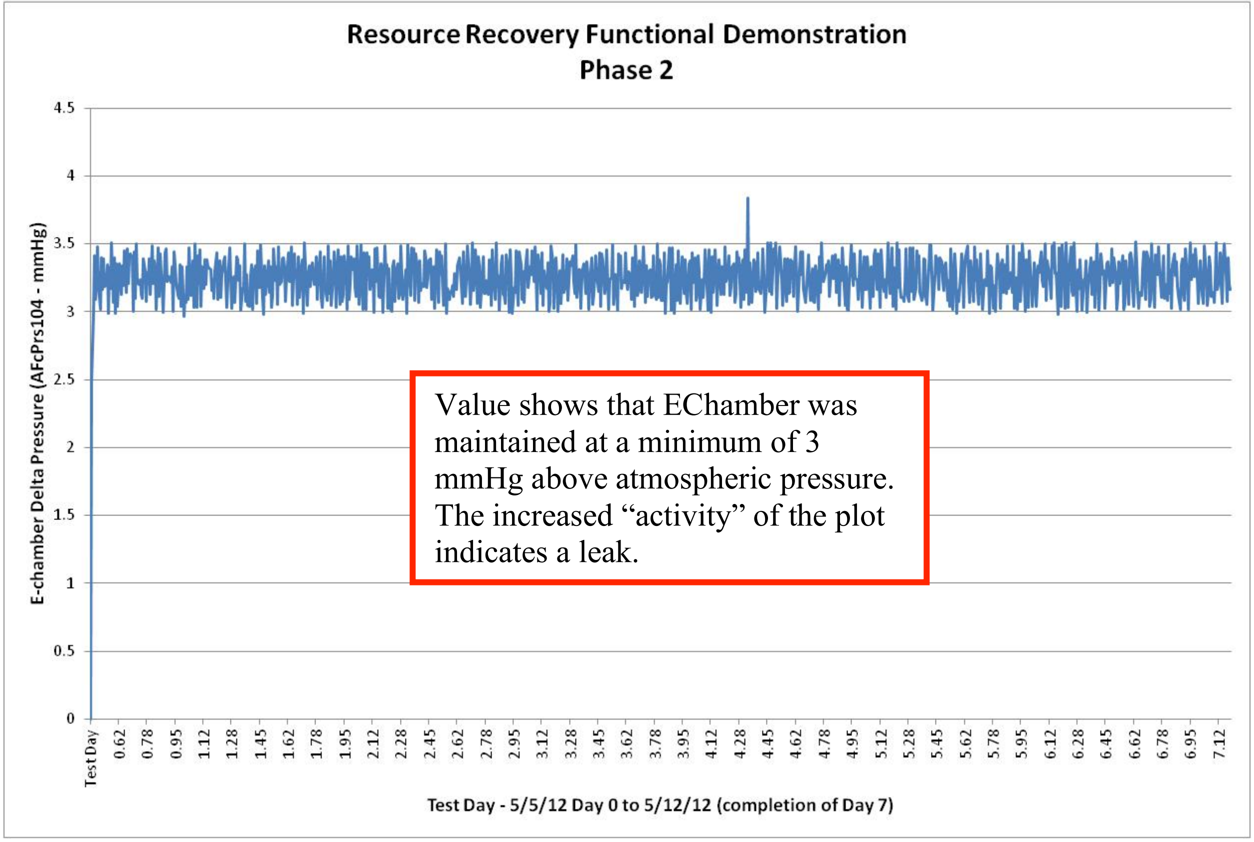


Setpoint of 4 means the damper (in the bypass around the EChamber Condensing Heat Exchanger) is fully closed

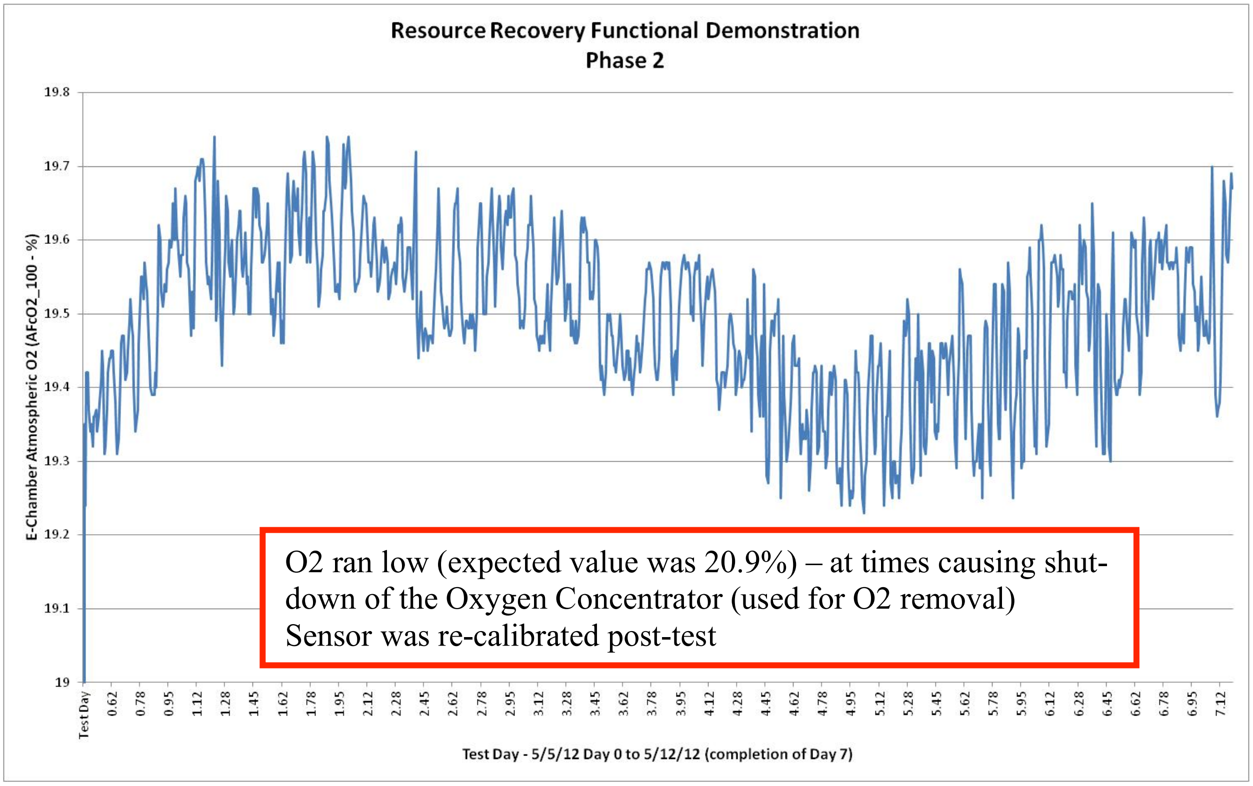


Delta over 7-day period corresponds to a 4.93 lb/hr leak rate

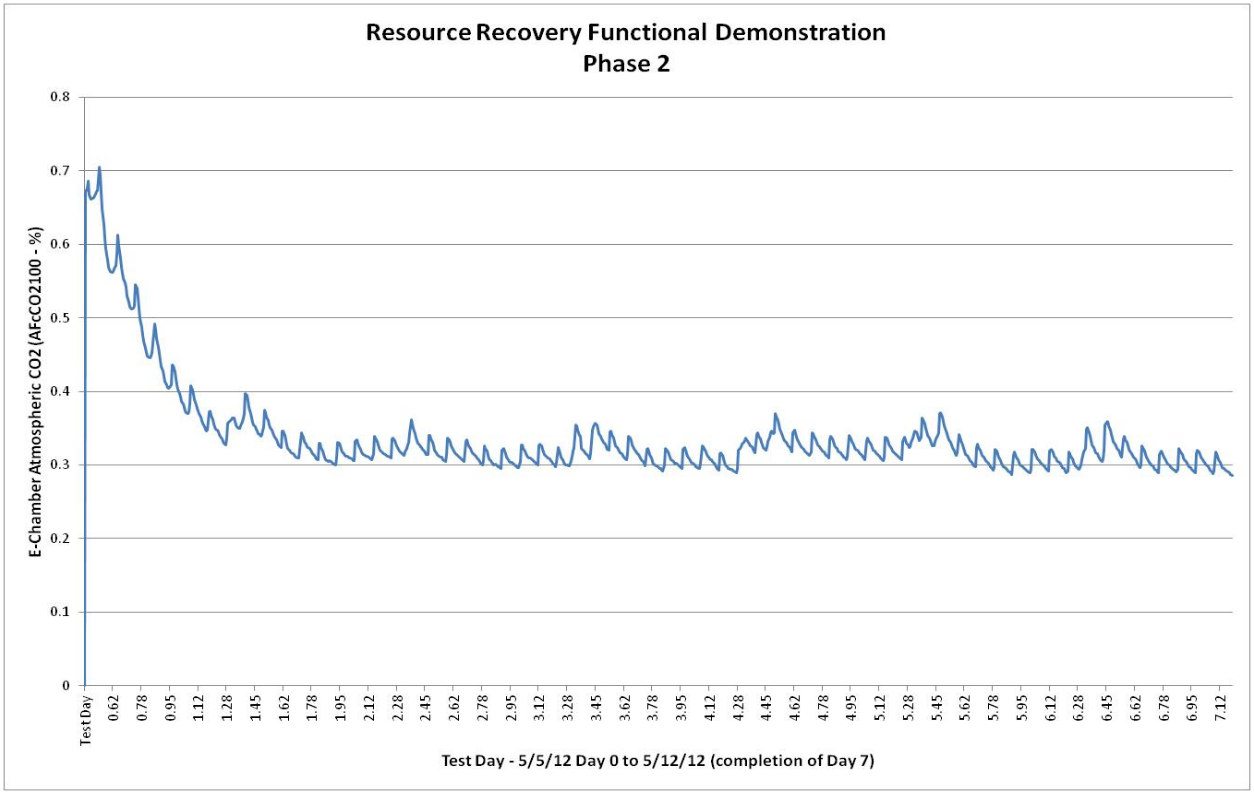
The constant rise of the totalizer indicates a leak in the EChamber that required makeup air to maintain positive pressure

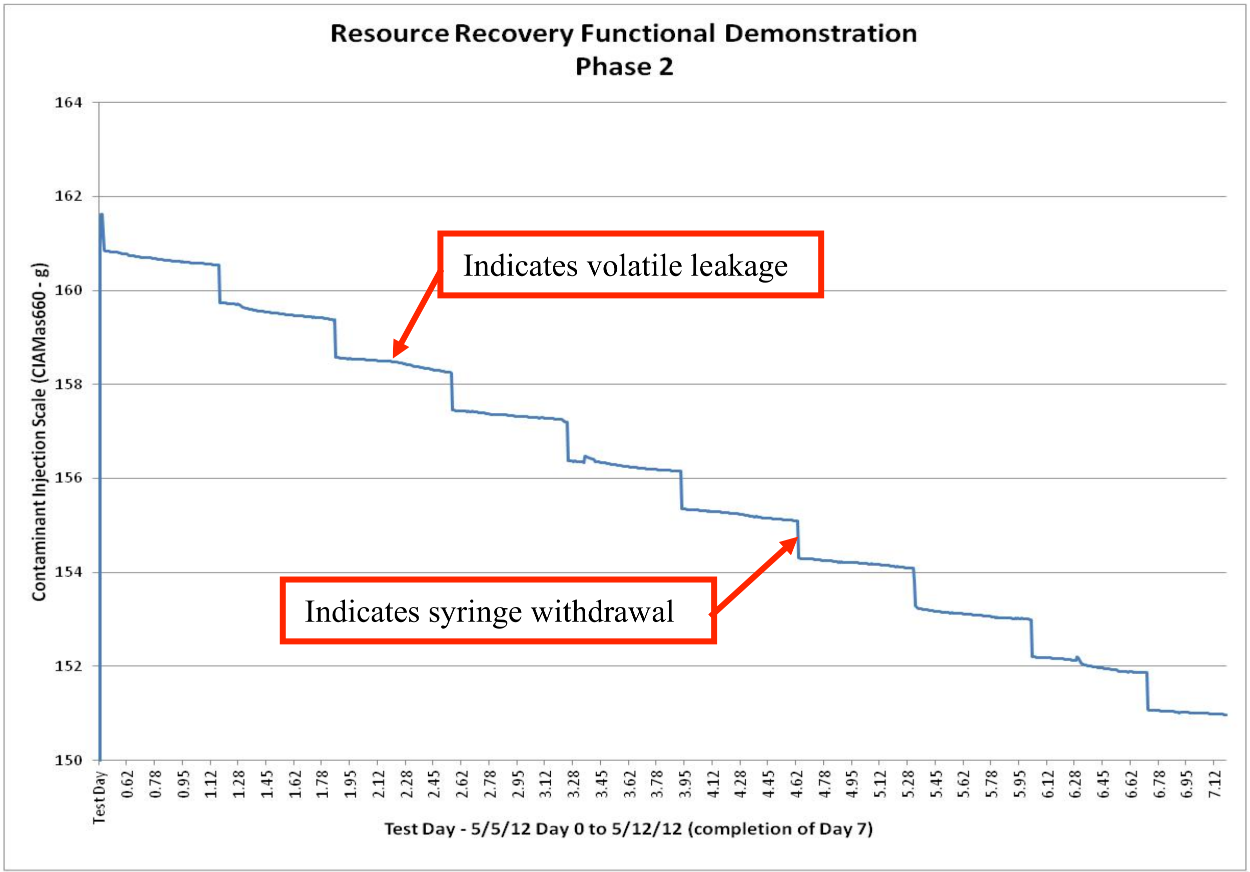


Value shows that EChamber was maintained at a minimum of 3 mmHg above atmospheric pressure. The increased "activity" of the plot indicates a leak.



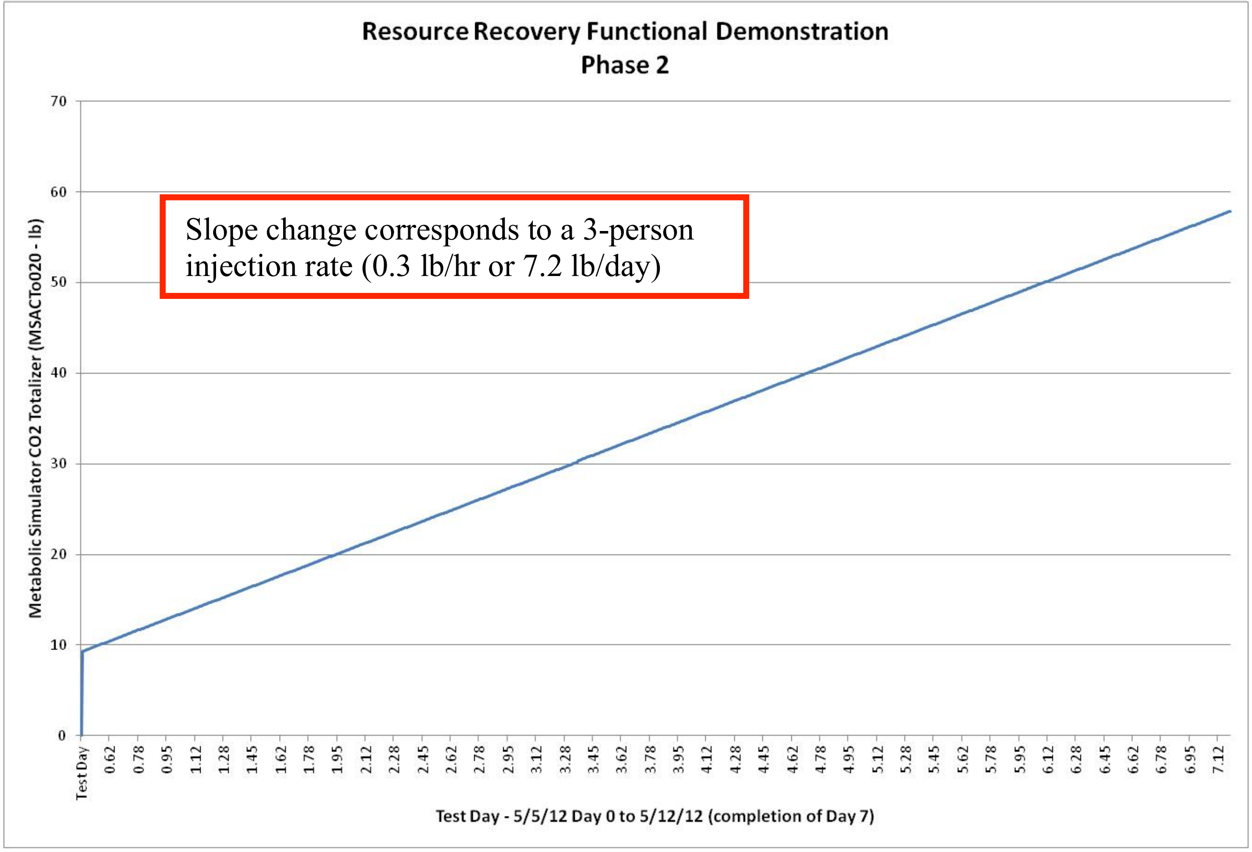
O2 ran low (expected value was 20.9%) – at times causing shut-down of the Oxygen Concentrator (used for O2 removal)
Sensor was re-calibrated post-test



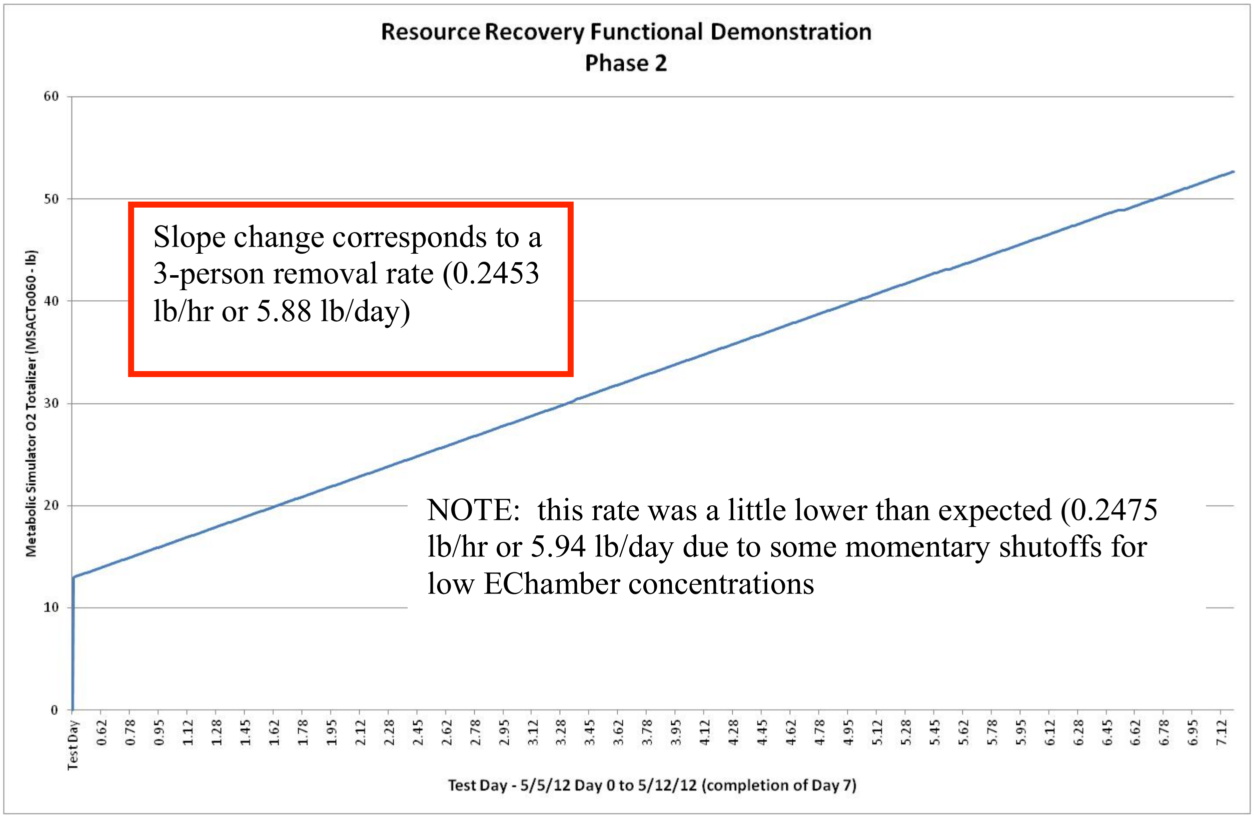


Indicates volatile leakage

Indicates syringe withdrawal

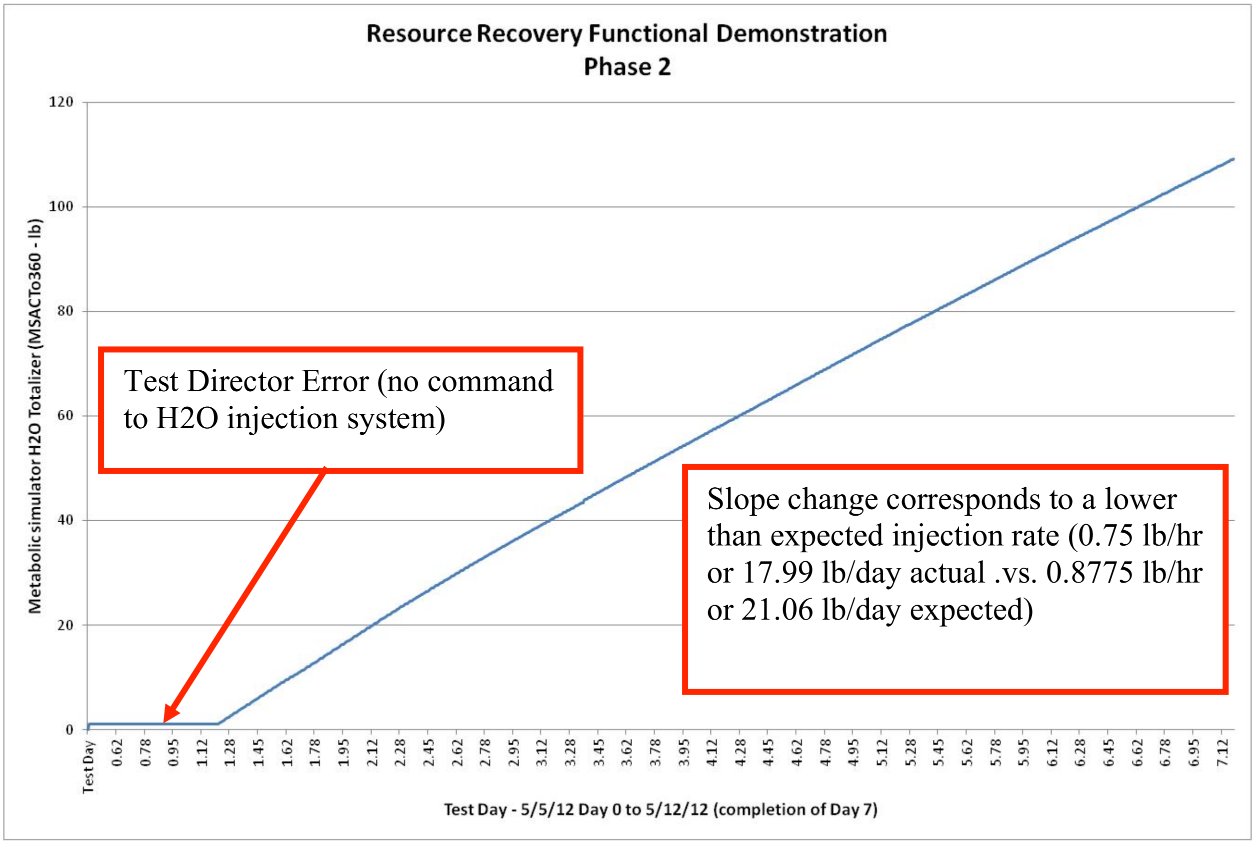


Slope change corresponds to a 3-person injection rate (0.3 lb/hr or 7.2 lb/day)



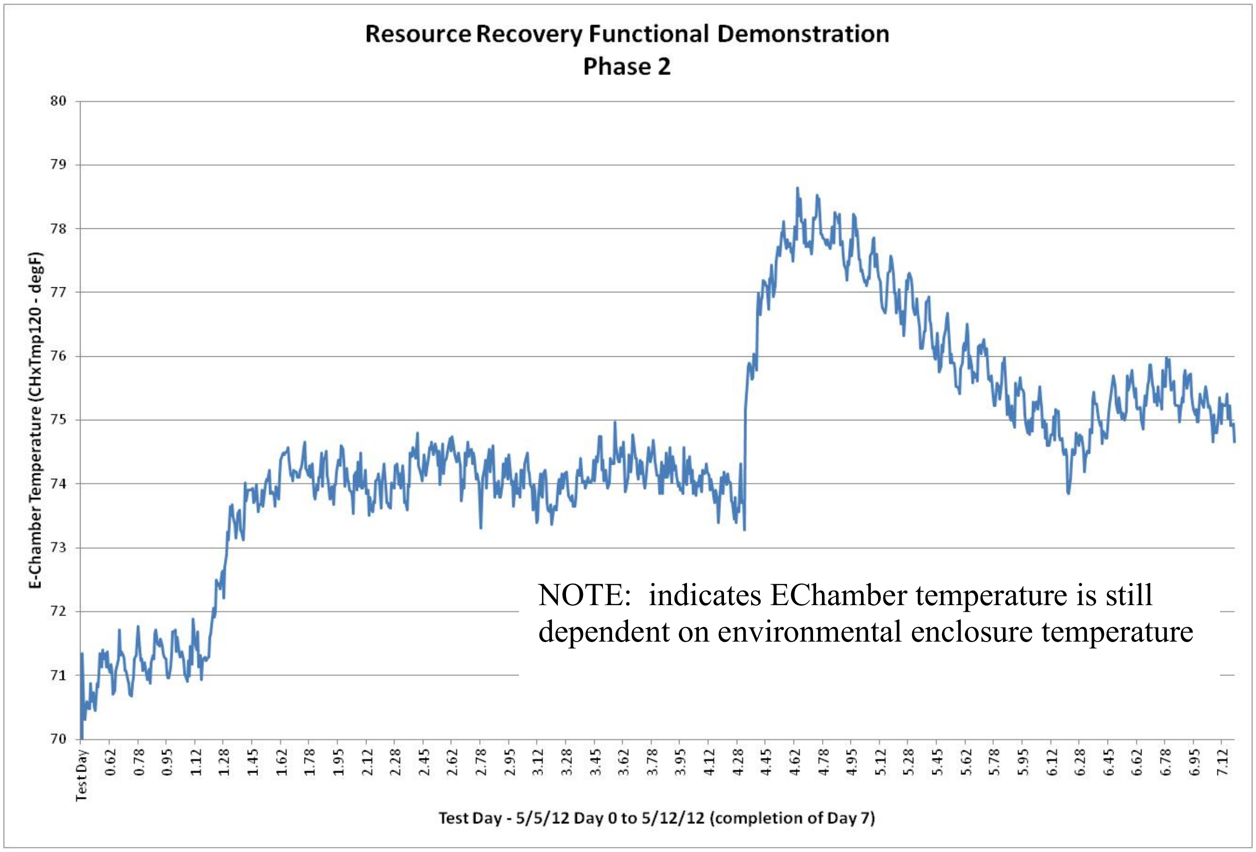
Slope change corresponds to a 3-person removal rate (0.2453 lb/hr or 5.88 lb/day)

NOTE: this rate was a little lower than expected (0.2475 lb/hr or 5.94 lb/day due to some momentary shutoffs for low EChamber concentrations

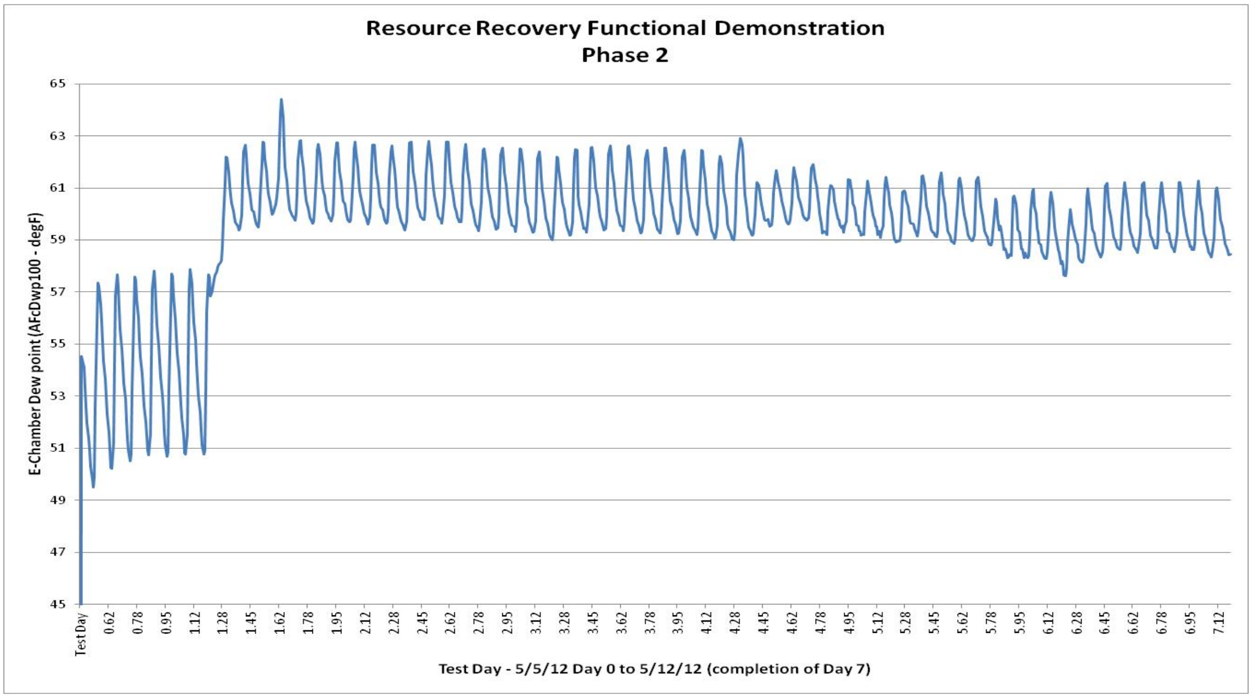


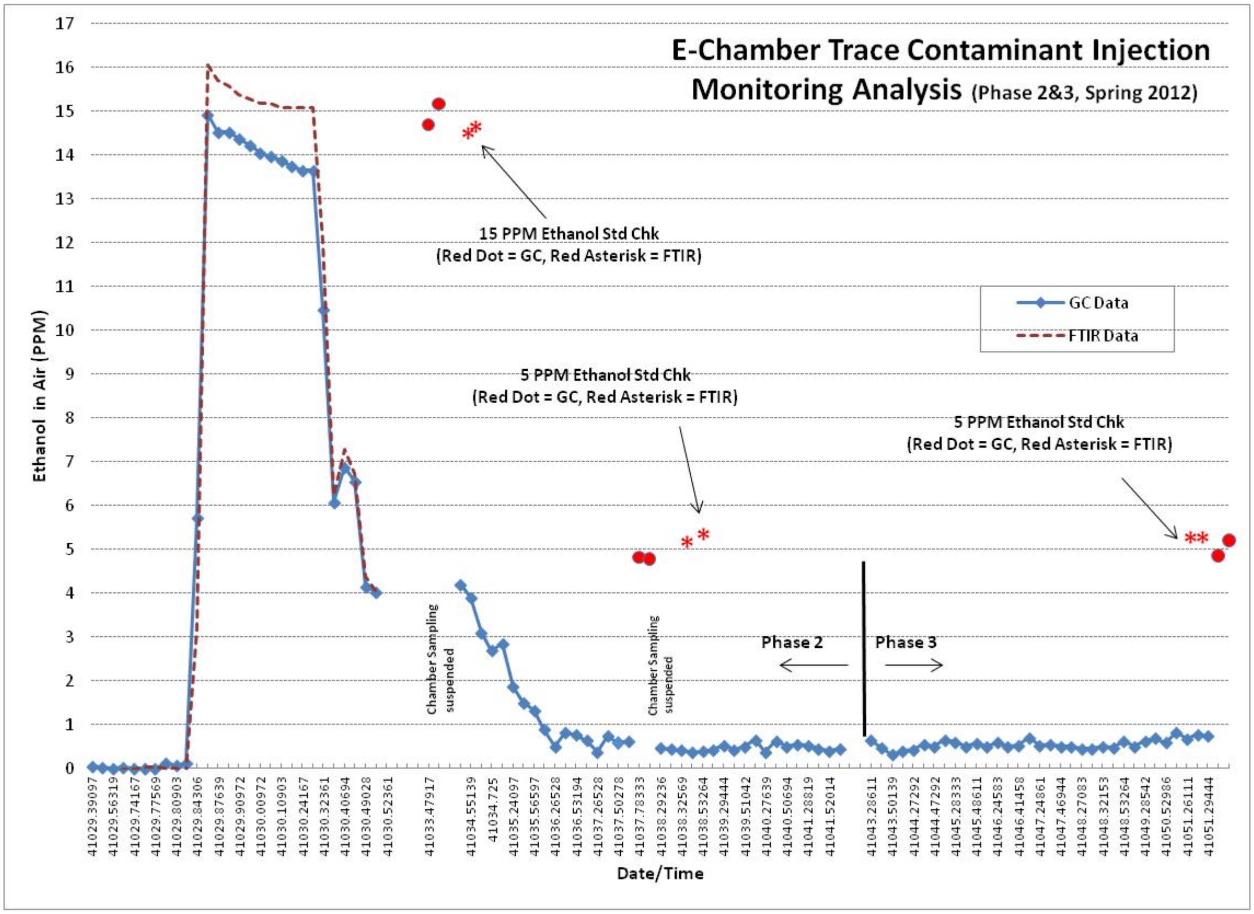
Test Director Error (no command to H2O injection system)

Slope change corresponds to a lower than expected injection rate (0.75 lb/hr or 17.99 lb/day actual .vs. 0.8775 lb/hr or 21.06 lb/day expected)



NOTE: indicates EChamber temperature is still dependent on environmental enclosure temperature





Phase 3 Overview (5/14/12 to 5/22/12 – ES62-TCP-ARS-12-002): When it appeared that everything was in working order (especially the GC which had been repaired numerous times leading up to R2FD Phase 2), the Principal Investigator decided to proceed directly from Phase 2 to Phase 3 with no pre-test activities. There was a 1-day hold to closeout data gathering and evaluation before Phase 3 started on 5/14/12. Previous data evaluation of contaminant propagation into the CO2 product had already led to the conclusion that the Sabatier would be getting the quality of CO2 required for safe operations. The objective of Phase 3 was to replace the CRA simulator with the Sabatier CRA to reduce CO2 leaving only the OGA as a simulated subsystem in the Atmosphere Revitalization System.

Phase 3 Event Summary 5/14/12 – Test Day 1 – EChamber door stayed open most of the day as integration issues with Sabatier had to be fixed. Ran Sabatier on facility CO2 for about 6 hours before achieving full integration and closing the EChamber door. Even though positive pressure (and therefore EChamber atmosphere) was lost, the Principal Investigator did not change contaminant injection. The system was allowed to slowly re-establish the atmosphere. Principal Investigator decided to re-start Test Day 1 on 5/15/12.

5/15/12 – re-start Test Day 1 – Nominal day with no anomalies noted.

5/16/12 – Test Day 2 – Lost 3 hours of Sabatier operation because the facility H2 cylinder ran out in the middle of the night. Sabatier continued to run but no reaction was performed in the absence of H2. No other anomalies noted.

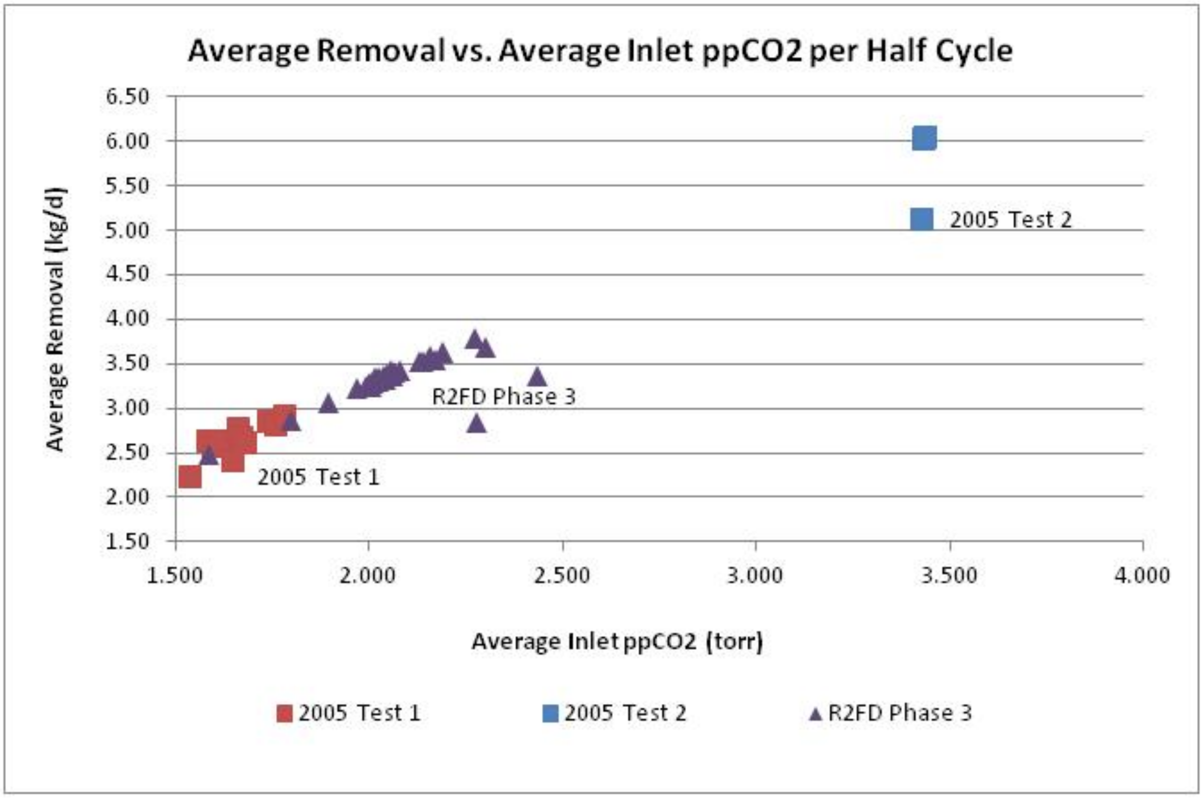
5/17/12 – Test Day 3 – In the overnight hours between Test Days 2 and 3, the problem with CO2 accumulation first seen in Phase 2 re-occurred. CDRA recorded a high bed pressure warning which caused it to switch over to dump to the Space Vacuum Simulator. Less than an hour later the Sabatier entered Standby mode due to lack of CO2. The Sabatier test engineer suggested that the CO2 Management Assembly logic be changed to allow the Sabatier to start up at 25 psia (instead of 35 psia) in order to process

CO2 and possibly avoid the CDRA high bed pressure problem. This would remain an issue for the rest of Phase 3. Post-test evaluation led to the conclusion that the commercial compressor needed to be re-built. It became increasingly unable to deliver against the back pressure of the CO2 accumulator which caused the CDRA high bed pressure. Also, CDPSV_021 (a solenoid valve in a line between the CO2 accumulator and the Space Vacuum Simulator) was found to be plumbed backwards. It was still able to function but it was not leak tight with the delta pressures between the CO2 accumulator and the Space Vacuum Simulator. Both of these anomalies led to the loss of CO2 from the system which reduced the duty cycle of the Sabatier. Also on day 3, the EChamber door was momentarily opened in order to install a drain line for the Sabatier product water to convey the product outside the EChamber. The product water scale was an important data point for Sabatier operations and keeping it from going offline was necessary.
5/18/12 – Test Day 4 – The host control program was stopped once to implement a chance in the CO2 Management control logic. This final fix was the implementation of logic that sent CO2 to the Space Vacuum Simulator if the product CO2 line pressure (CDPPrs020) reached 8 psia at any point beyond midway in the CO2 production mode (A2 or B2) of the CDRA half-cycle. This logic was an oversight in the earlier program which might have alleviated the CDRA high bed pressure warning seen on Day 3. It would not, however, fix the problem of lost CO2 to the Sabatier.
5/19/12 – Test Day 5 – Nominal day with no anomalies noted.
5/20/12 – Test Day 6 - Nominal day with no anomalies noted.
5/21/12 – Test Day 7 – Routine day with one notation that the Oxygen Concentrator shutdown due to low oxygen concentration in the EChamber. This sensor had been reading low throughout the test. Post-test it was re-calibrated.
5/22/12 – completion of Phase 3 was achieved when the last condensate sample was collected.

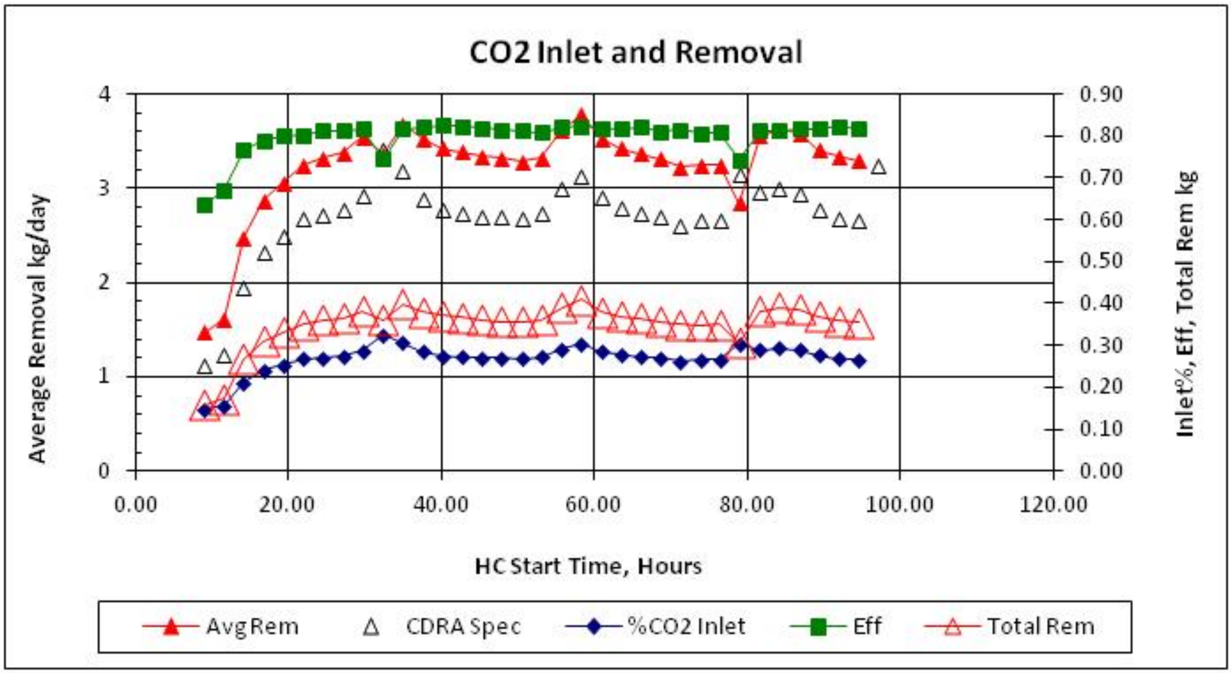
Phase 3 Test Results Once again, the TCCS showed the ability to keep the EChamber atmosphere ethanol concentration below 1% while processing the simulated contaminant loading of a 3-person crew. Condensate sampling results showed an average of 5.03 ppm Methanol, 14.98 ppm of Ethanol, and a Total Organic Carbon average of 18.38 ppm. The average humidity condensate removed from the EChamber was 15.08 lb/day. The CO2 Management Assembly worked according to the control logic but the leaking valve between the Assembly and the Space Vacuum Simulator grew progressively worse during Phase 3. There were several Sabatier CRA "dropouts" during Phase 3 due to the CO2 accumulator level dropping below 20 psia (see plot for CRA_MFC005 – the Sabatier CO2 process flowmeter on page tbd). The Metabolic Simulator CO2 injection and O2 removal functions performed nominally while the H2O injection was lower than expected (11.2 lb/day actual .vs. 21.06 lb/day expected). The suspected cause of the lower result was humidity injection atomizer dryout. The facility O2 bottle ran out late on Test Day 6 and in order to keep the O2 level balanced in the EChamber the Oxygen Concentrator was shut down for the duration of the test. Facility dewpoint sensors read in the low to mid 50's ºF compared to the main sensor (AFcDwp100) which read in the high 50's to low 60's ºF. A redundant CO2 sensor read about 0.3% which is in agreement with the main sensor (AFcCO2100). See plots of AFcDwp100 and AFcCO2100 in the results section below.

For CDRA, as with Phase 1B and Phase 2, two comparisons were made; 1) compare the CDRA POIST performance to previous ground tests to determine that hardware is performing within an acceptable range and 2) compare test data with the CDRA specification based on inlet concentration.

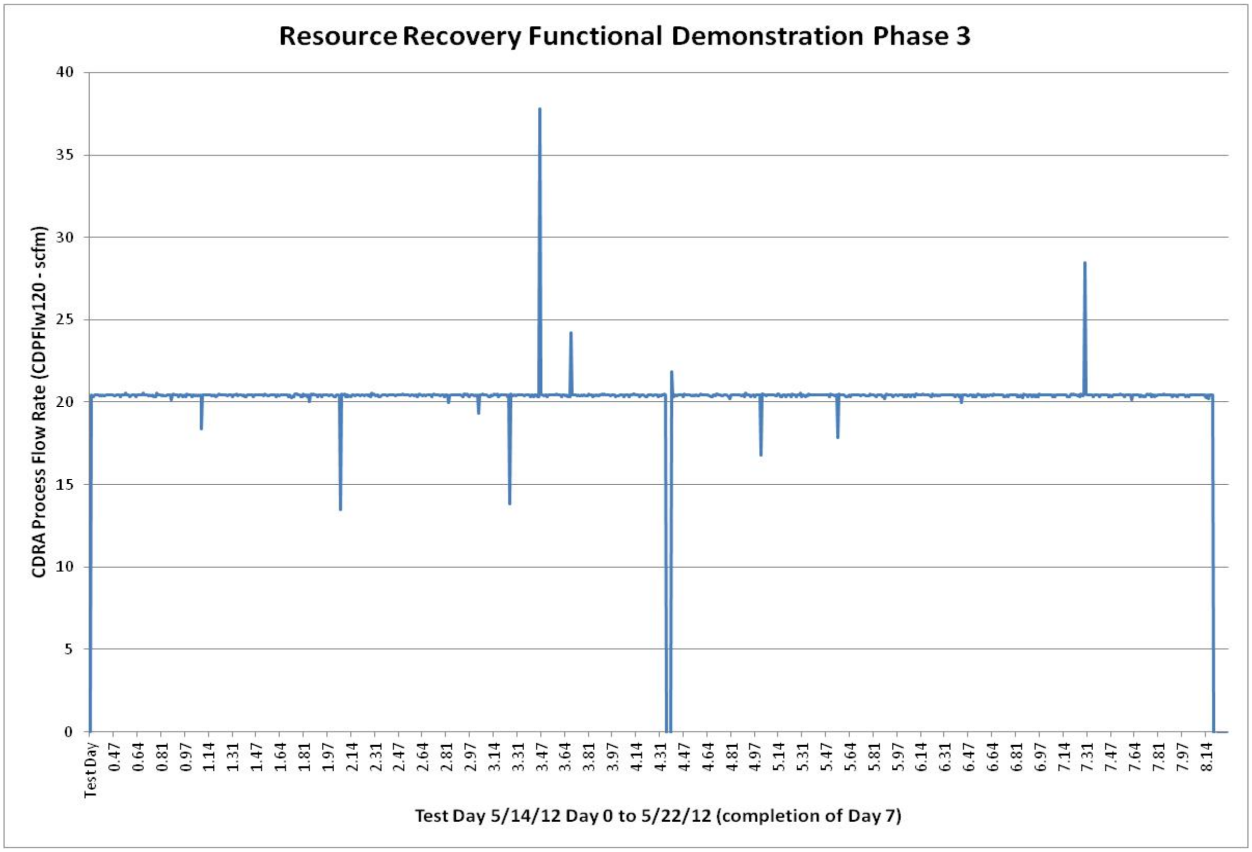
The CDRA performed within acceptable ranges for both comparisons. The plot below shows the comparison between the Phase 3 data and data taken from two tests that were performed in 2005. The Phase 3 data falls nicely in line the previous test data, indicating that the hardware is functioning as expected and performance is acceptable.

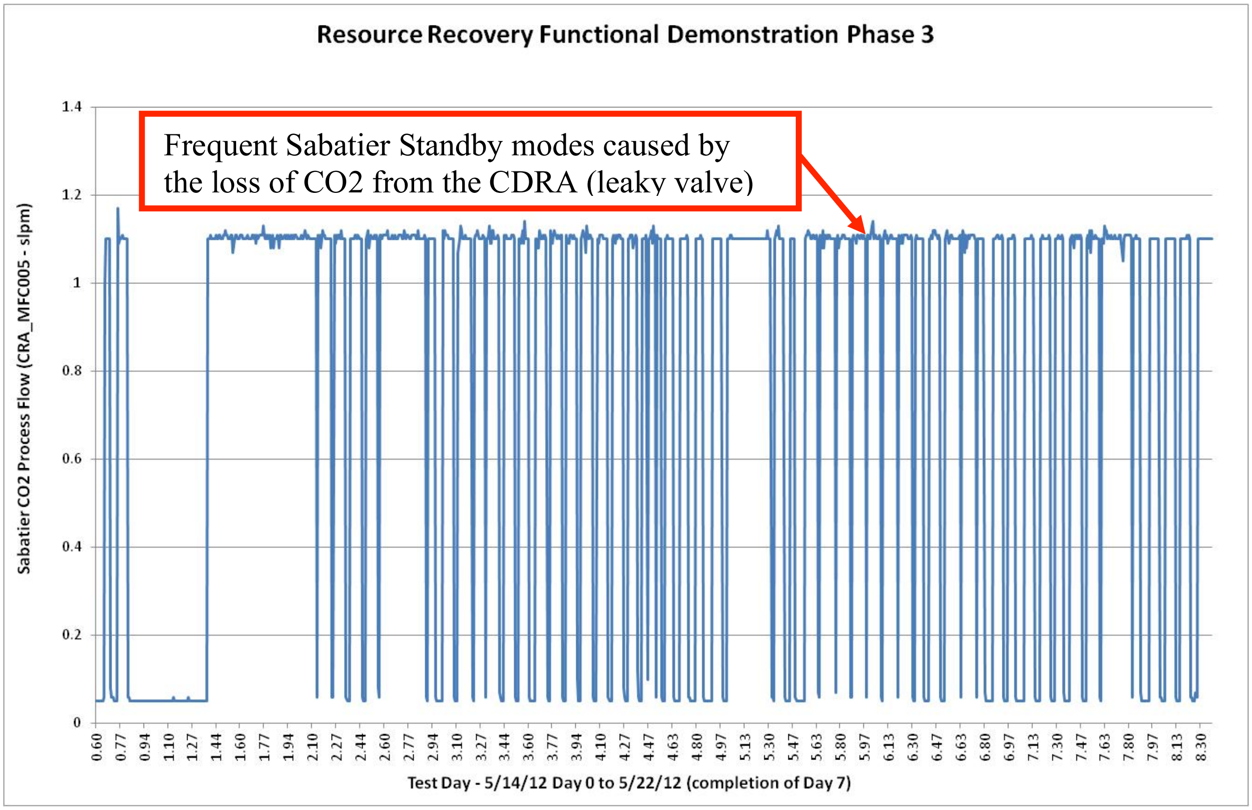


The plot below shows the Phase 3 performance compared to the CDRA specification. The CDRA performed well throughout the test, meeting or exceeding the required removal rate for the CDRA. The areas about the 35 hour mark and right before the 80 hour mark denote at what times the system was shut down and restarted. As the graph indicates, the short shut down periods did not affect performance.

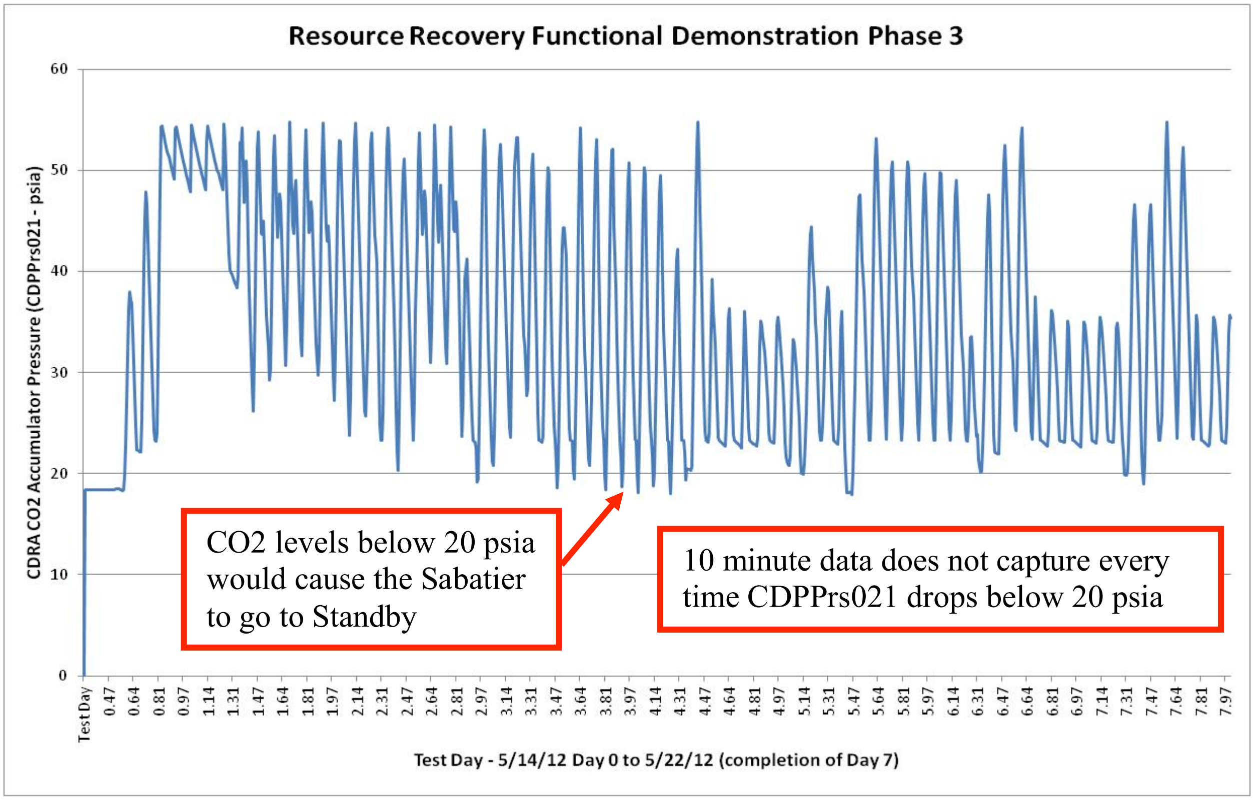


Resource Recovery Functional Demonstration Phase 3 Humidity Condensate							
Analyte	Test Day						
	1	2	3	4	5	6	7
Condensate (lb)	12.45	15.85	14.9	No data	18.3	13.9	No data
Methanol (ppm)	5.2	4.8	4.6	5.1	5.1	5.4	No data
Ethanol (ppm)	13.7	13.8	15.4	15	15	17	No data
Acetone (ppm)	<1	<1	<1	<1	<1	<1	No data
1-propanol (ppm)	<1	<1	<1	<1	<1	<1	No data
2-propanol (ppm)	<1	<1	<1	<1	<1	<1	No data
2-methyl-2-propanol (ppm)	<1	<1	<1	<1	<1	<1	No data
2-butanol (ppm)	<1	<1	<1	<1	<1	<1	No data
Total Organic Carbon (ppm)	19	19.1	16.3	16.7	17.4	21.8	No data



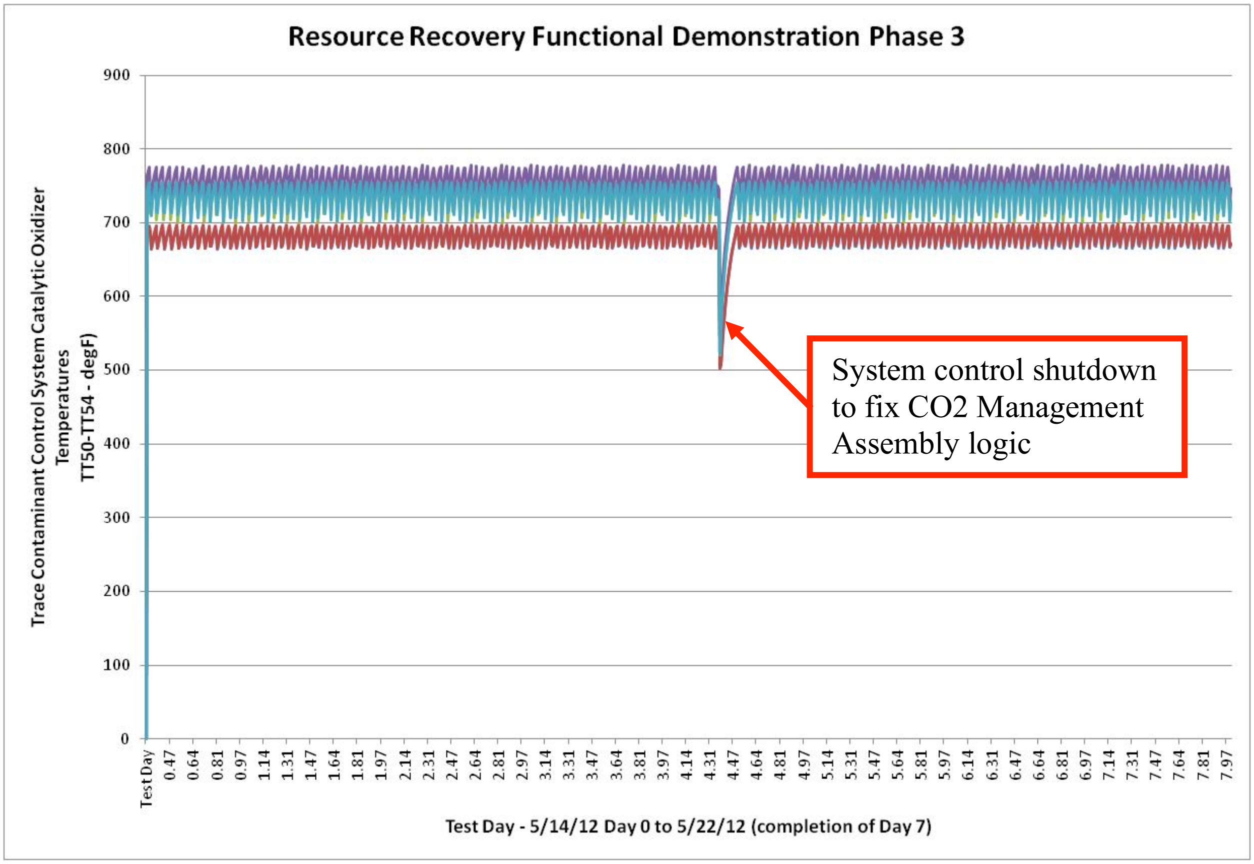


Frequent Sabatier Standby modes caused by the loss of CO2 from the CDRA (leaky valve)

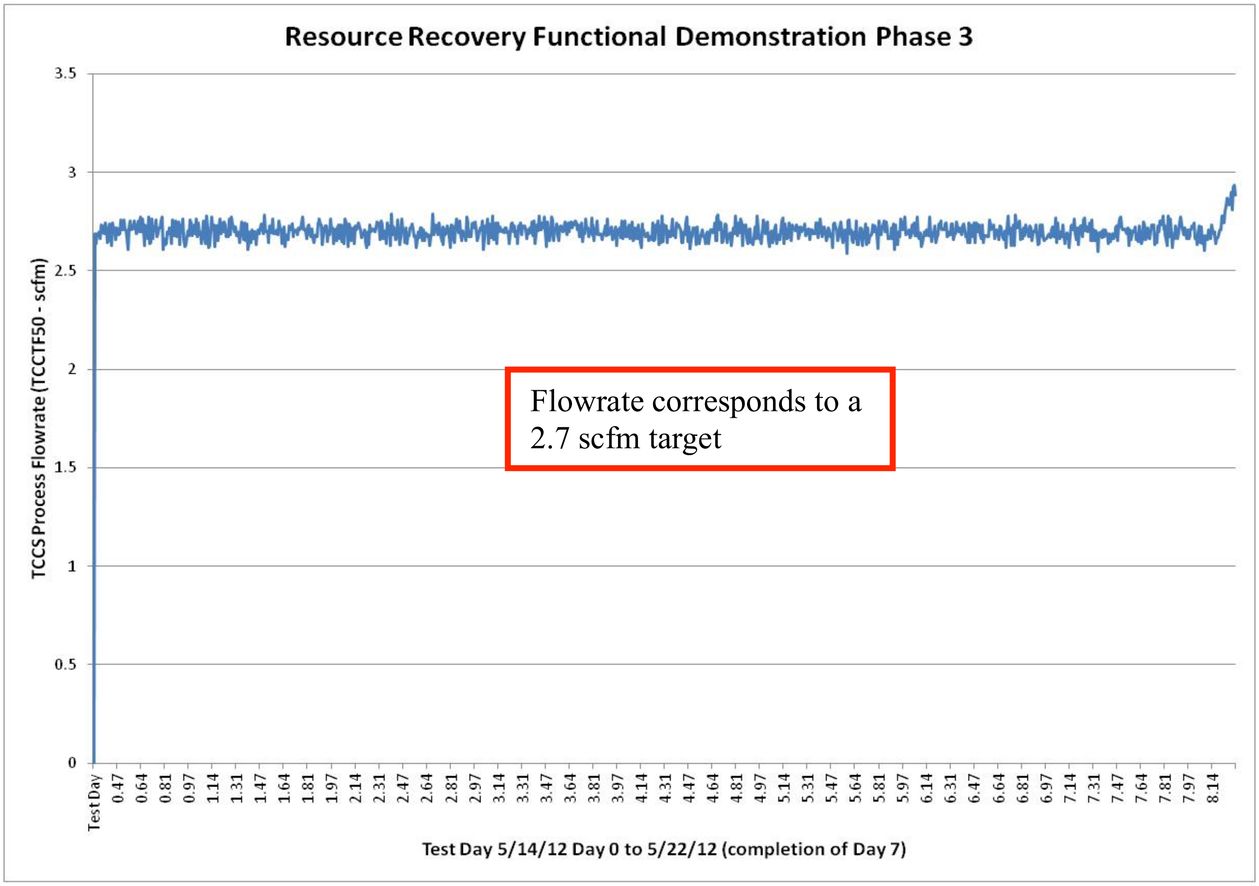


CO2 levels below 20 psia would cause the Sabatier to go to Standby

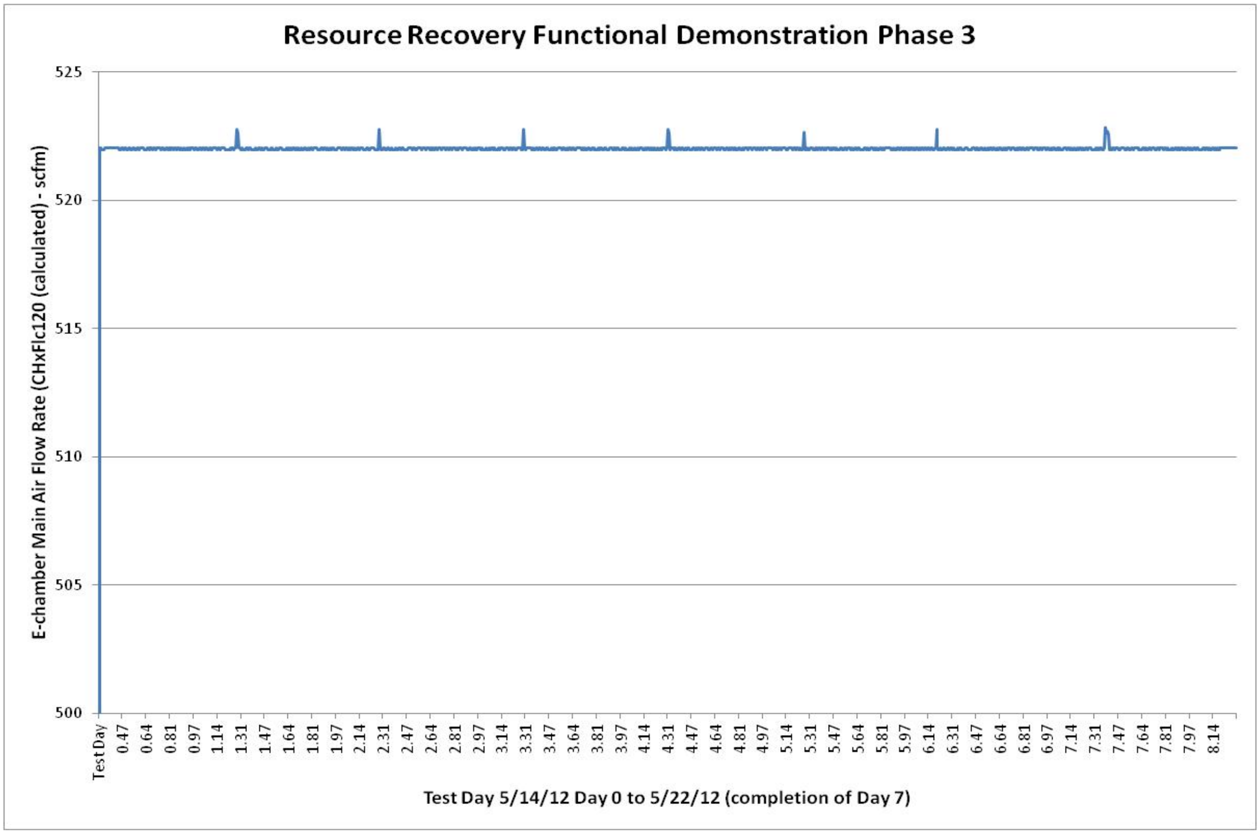
10 minute data does not capture every time CDPPrs021 drops below 20 psia

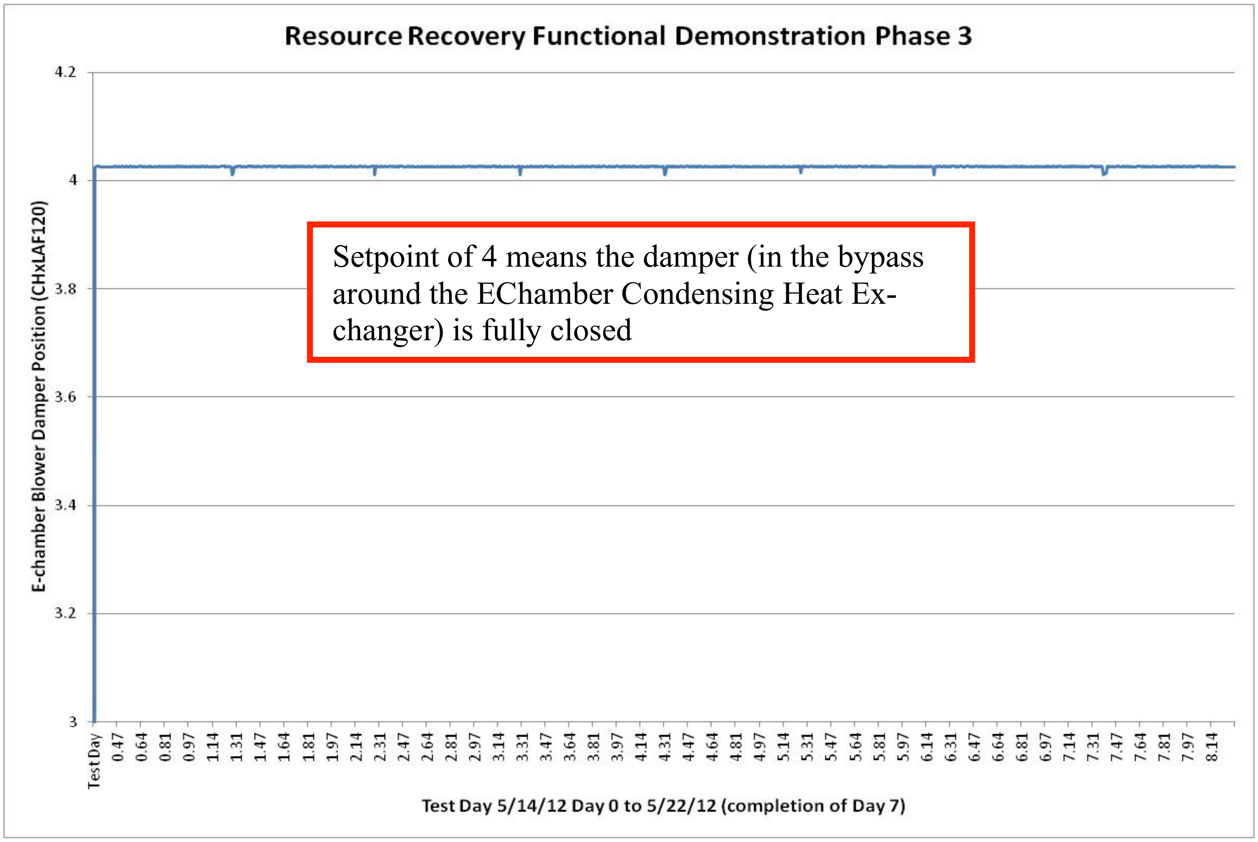


System control shutdown to fix CO2 Management Assembly logic

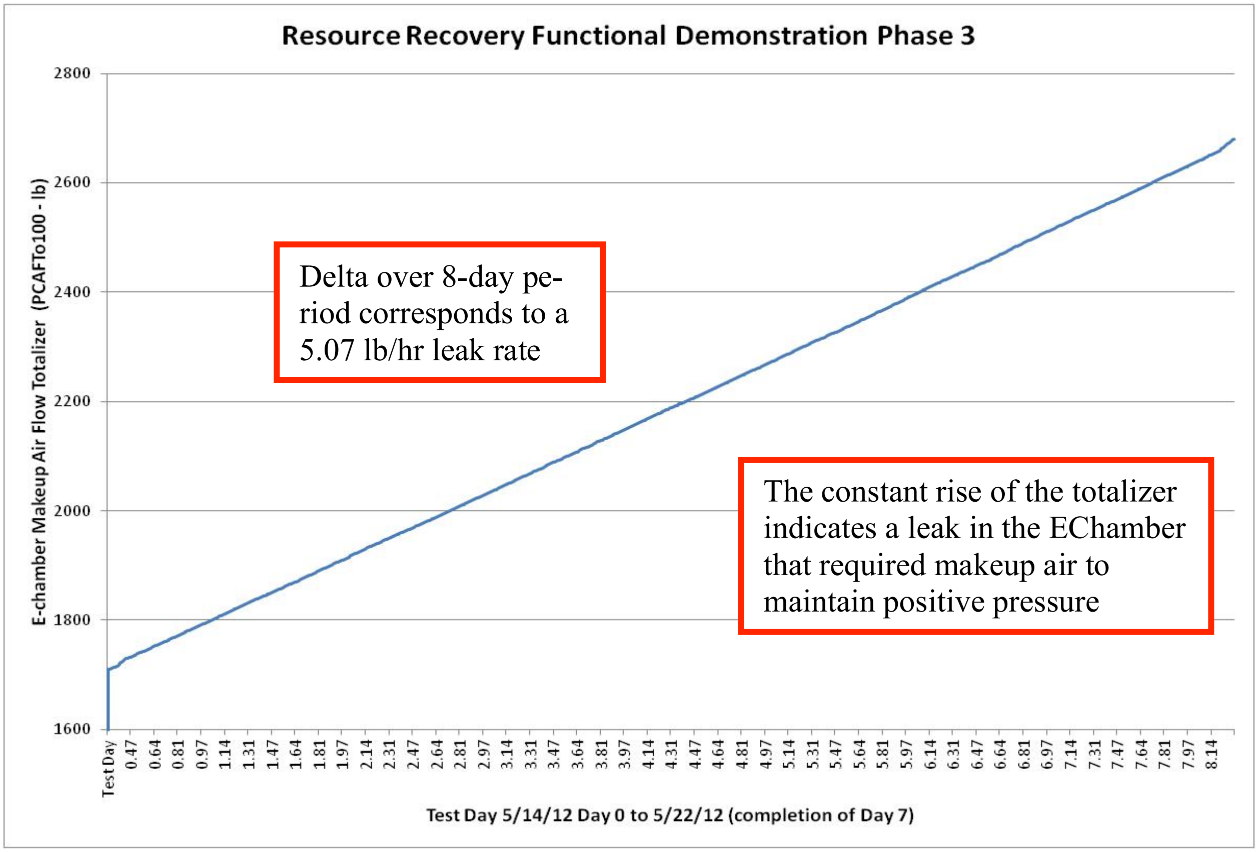


Flowrate corresponds to a 2.7 scfm target



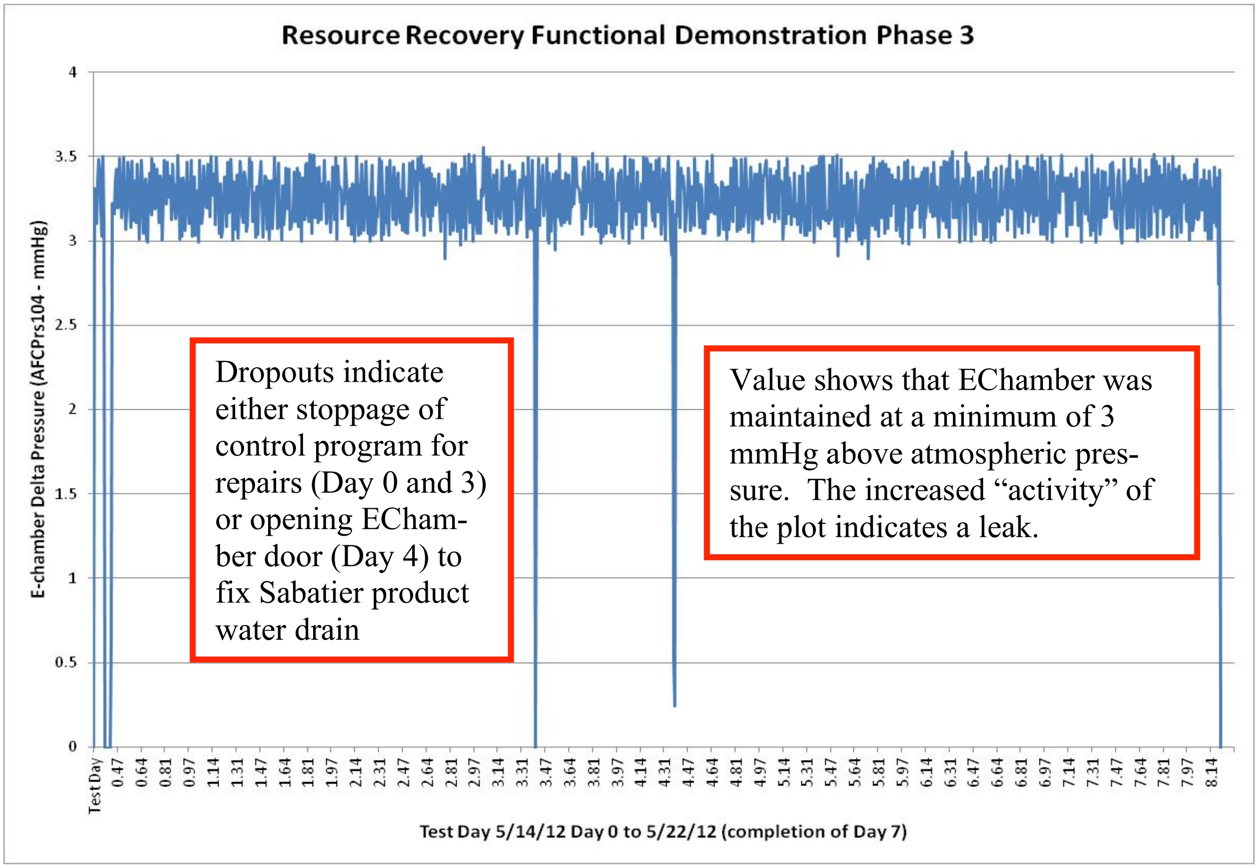


Setpoint of 4 means the damper (in the bypass around the EChamber Condensing Heat Exchanger) is fully closed



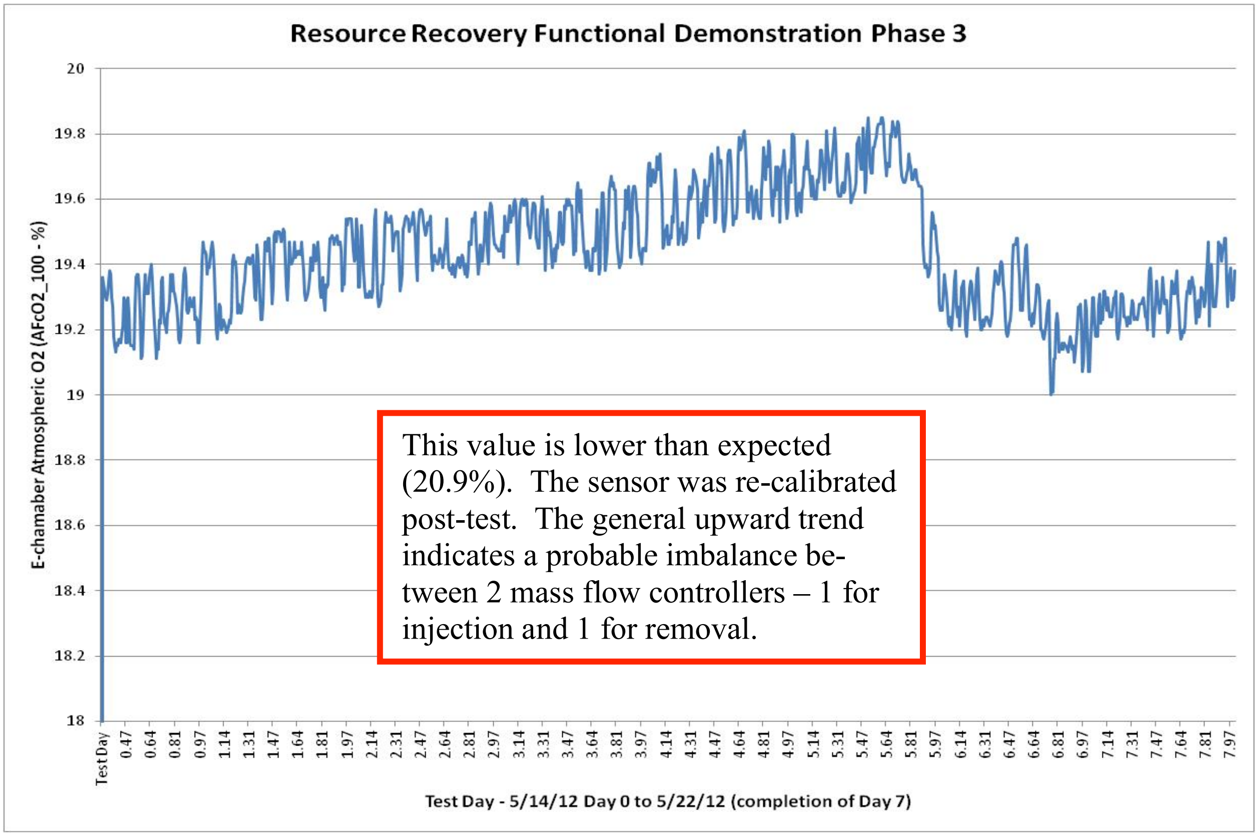
Delta over 8-day period corresponds to a 5.07 lb/hr leak rate

The constant rise of the totalizer indicates a leak in the EChamber that required makeup air to maintain positive pressure

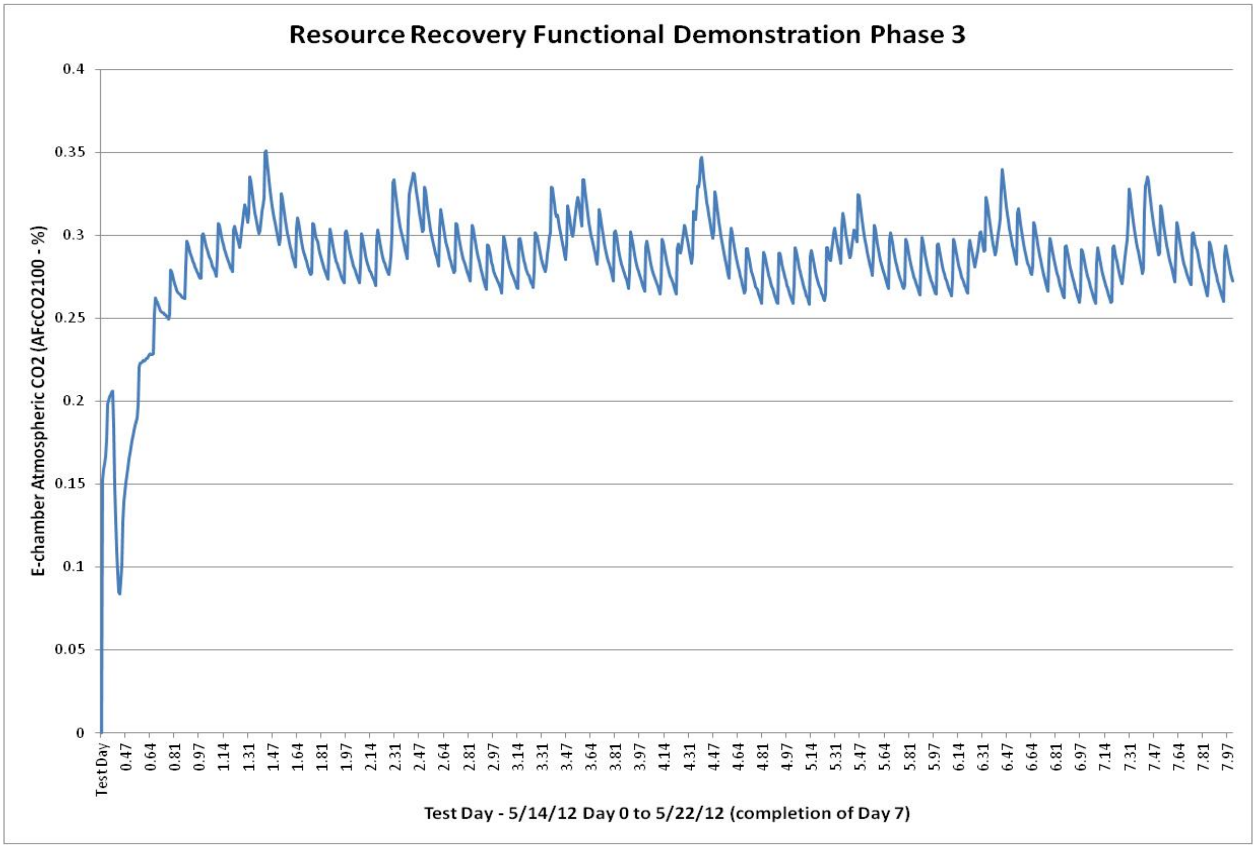


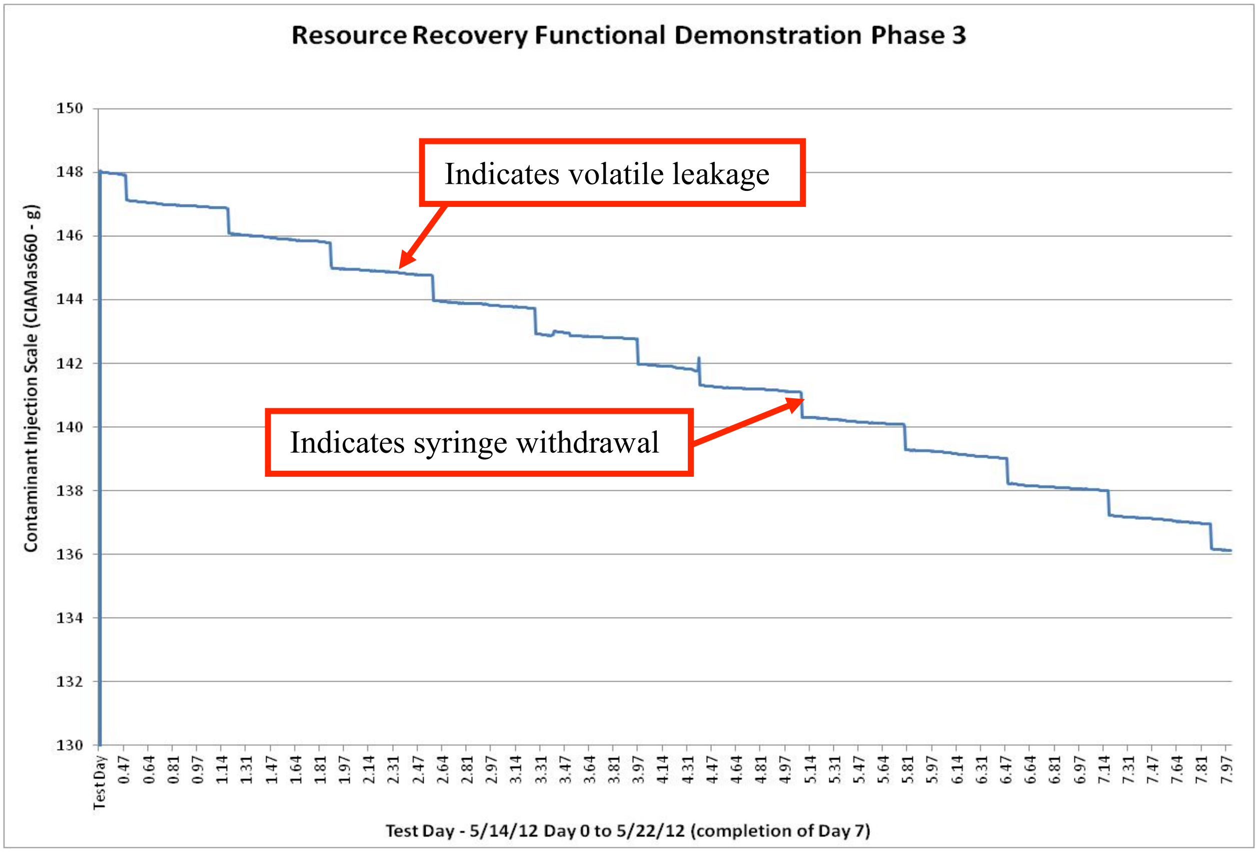
Dropouts indicate either stoppage of control program for repairs (Day 0 and 3) or opening EChamber door (Day 4) to fix Sabatier product water drain

Value shows that EChamber was maintained at a minimum of 3 mmHg above atmospheric pressure. The increased "activity" of the plot indicates a leak.



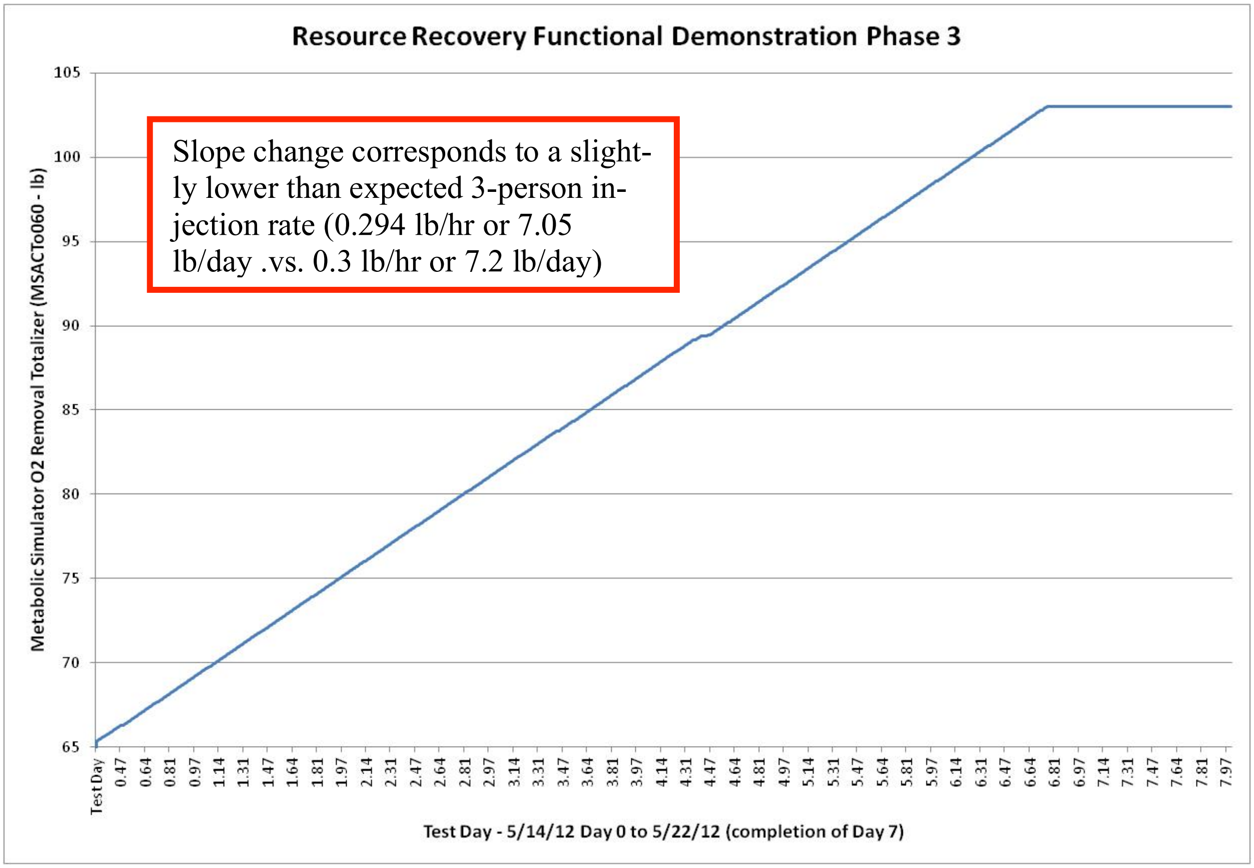
This value is lower than expected (20.9%). The sensor was re-calibrated post-test. The general upward trend indicates a probable imbalance between 2 mass flow controllers – 1 for injection and 1 for removal.



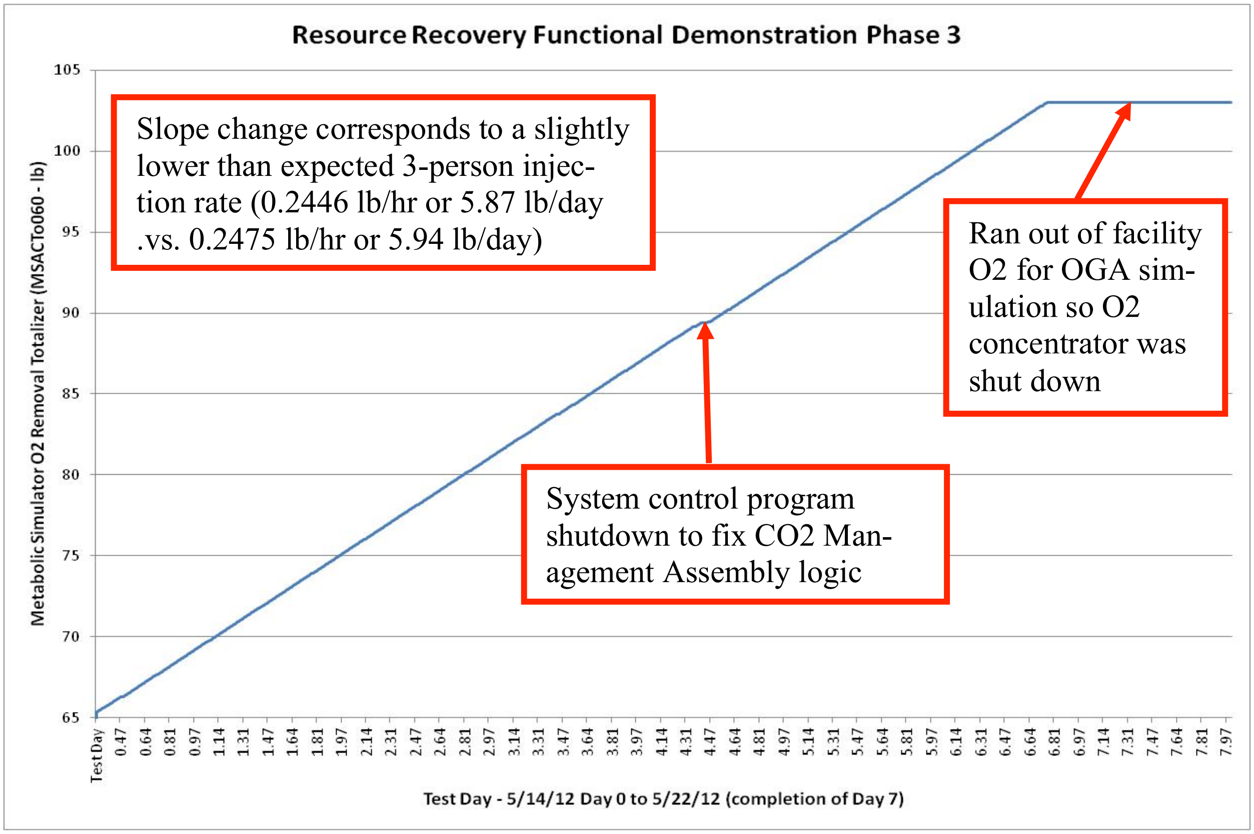


Indicates volatile leakage

Indicates syringe withdrawal



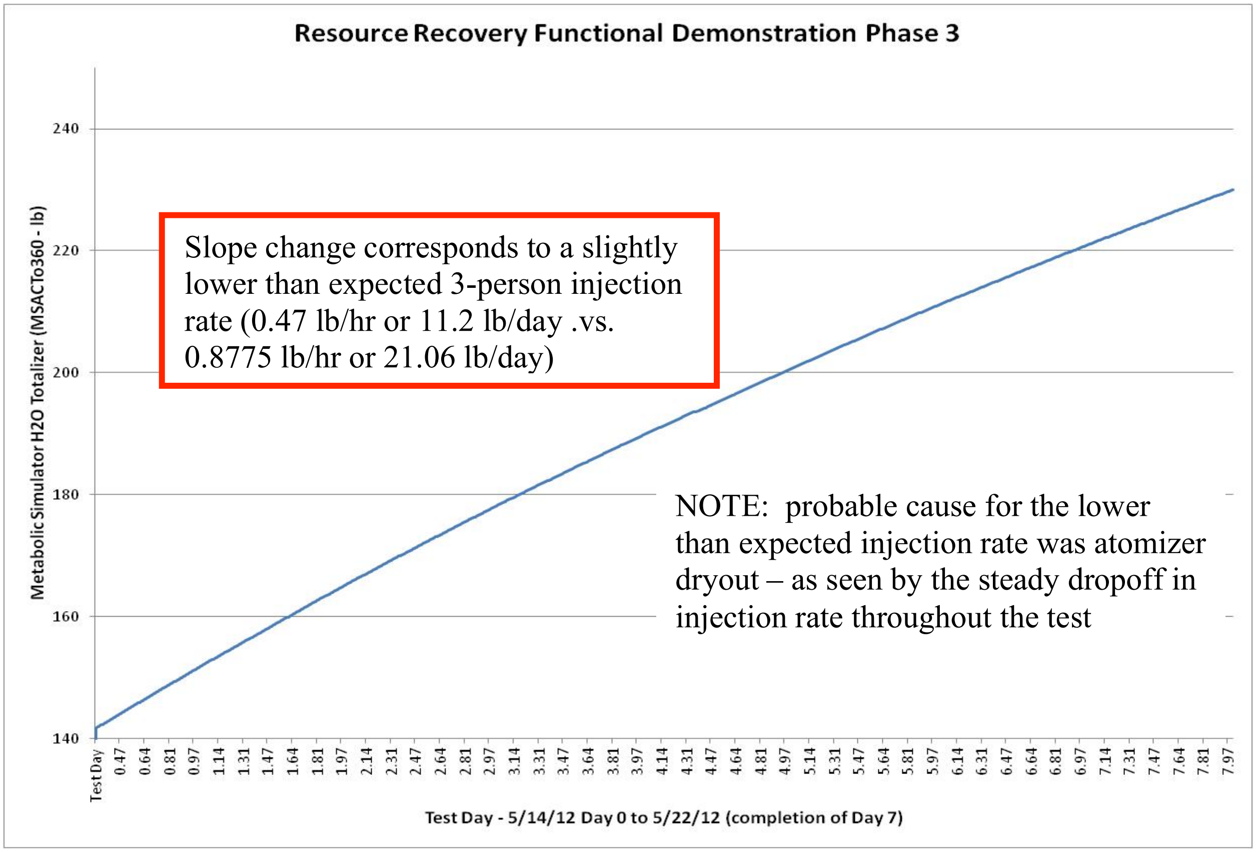
Slope change corresponds to a slightly lower than expected 3-person injection rate (0.294 lb/hr or 7.05 lb/day .vs. 0.3 lb/hr or 7.2 lb/day)



Slope change corresponds to a slightly lower than expected 3-person injection rate (0.2446 lb/hr or 5.87 lb/day .vs. 0.2475 lb/hr or 5.94 lb/day)

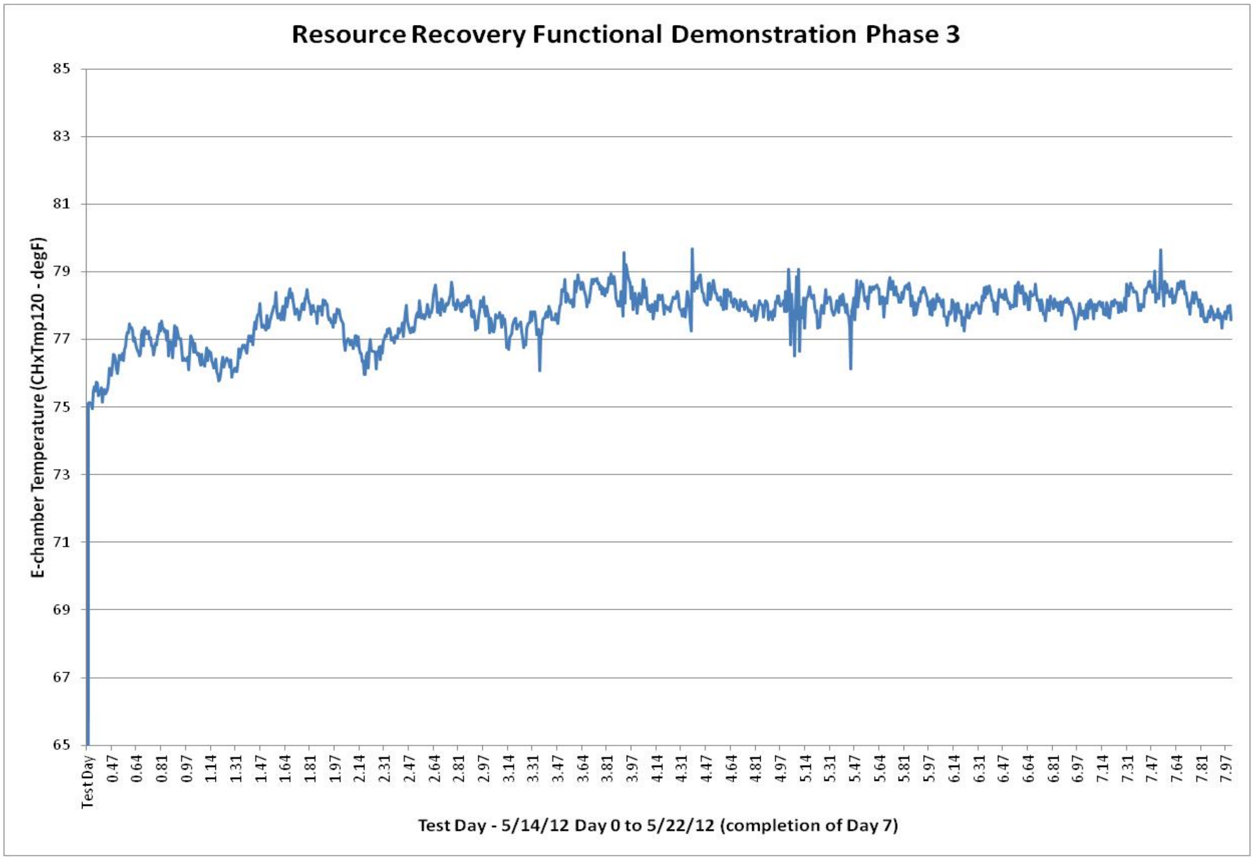
Ran out of facility O2 for OGA simulation so O2 concentrator was shut down

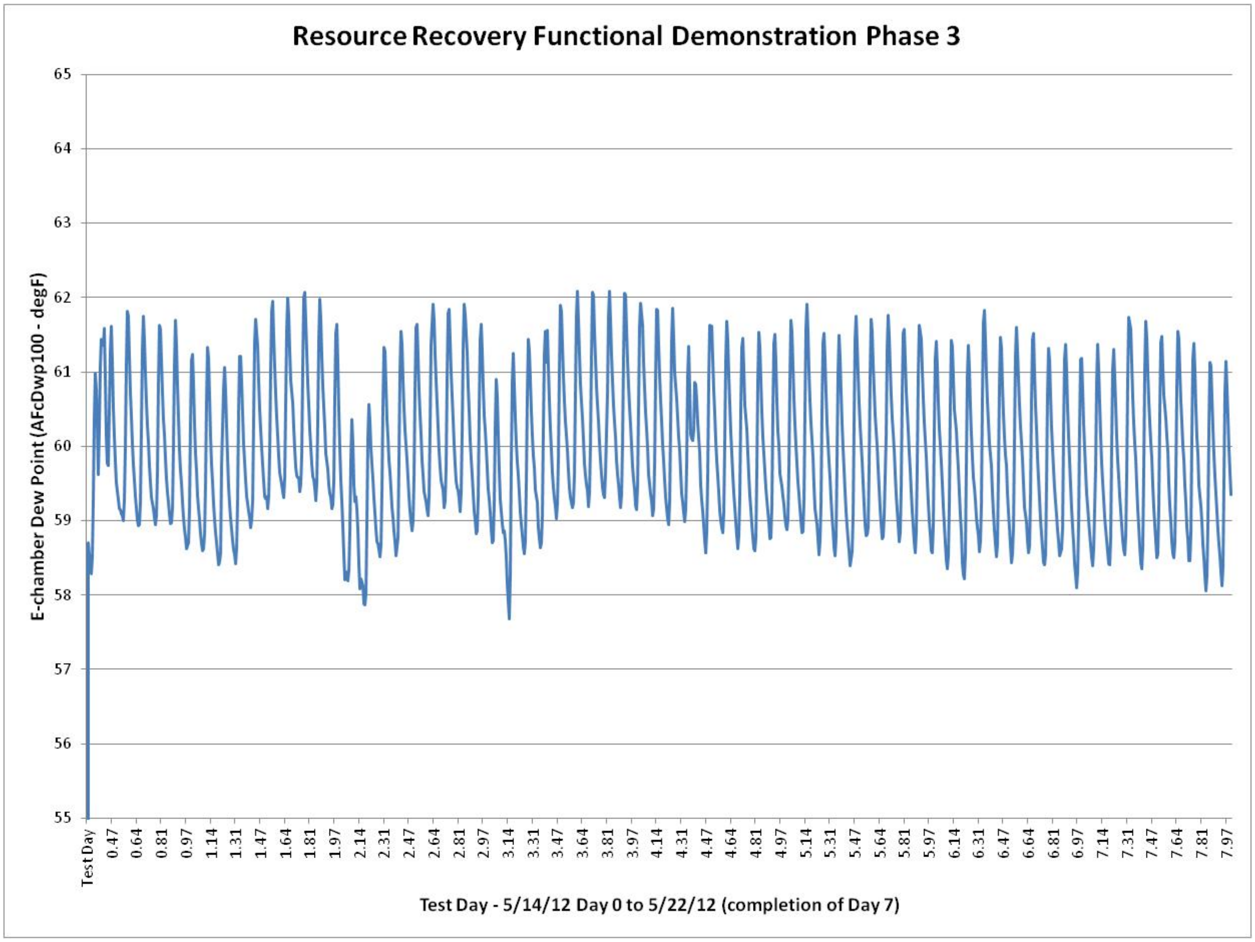
System control program shutdown to fix CO2 Management Assembly logic



Slope change corresponds to a slightly lower than expected 3-person injection rate (0.47 lb/hr or 11.2 lb/day .vs. 0.8775 lb/hr or 21.06 lb/day)

NOTE: probable cause for the lower than expected injection rate was atomizer dryout – as seen by the steady dropoff in injection rate throughout the test





Additional data, such as raw PACRATS data for other sensors and tabulated Gas Chromatograph data not included in this report, is available on the ES62 server at the following location: \\msnaf01\es62\1Echamber\Engineering Documents\R2FD\R2FDTestData.

APPENDIX F—ARREM PROJECT CYCLE 1 DETAILED TEST REPORT

ES62-ARREM-RPT-13-002

Advanced Exploration Systems (AES)
Atmosphere Resource Recovery and Environmental Monitoring (ARREM)

Cycle 1
Test Data and Summary Report

Prepared By: Keith J Parrish 4/30/13

Keith J. Parrish
Test Director/ES62

Ken Frederick
Test Conductor/ES62

Chris Stanley
CDRA Test Conductor/
Qualis-ES62

Dr. Robert Newton
Environmental Monitoring/ES62

Lee Miller
Sabatier CRA Test
Conductor/ECLSS
Technologies-ES62

Kevin Takada
OGA Test Conductor/

Joseph Scott
GC/Micro GC Operator/ Jacobs-
ES62

Gena Dalton
Chemistry Lab Analyst/
Qualis-ES62

Dr. Matthew Kayatin
GC Data Analyst/ES62

Reviewed By: Jay L. Perry

Jay Perry
Principal Investigator/ES62

Approved By:

Bob Bagdigian
ECLSS Development Branch Chief/ES62

1.0 OVERVIEW

ARREM Cycle 1 was run as the first step to advance and evolve the ISS state-of-the-art atmosphere revitalization system. The requirements for the test were established by the Advanced Exploration System Atmosphere Resource Recovery and Environmental Monitoring Cycle 1 Integrated Test Plan and Requirements (Revision B: June 29, 2012). A summation of that work is as follows:

1) Carbon Dioxide Removal Assembly (CDRA) Functional Checkout after Sorbent Bed re-packing (Phase 0A)
2) Functional Checkout of Exploration Test Chamber – internal leak check at sub-ambient pressure
3) Integrated CDRA and Trace Contaminant Control System (TCCS) Components Flow Balancing (Phase 0B)
4) CDRA with integrated TCCS components Functional Checkout (Phase 1A)
5) Carbon Dioxide Management Assembly Functional Check out (Phase 1B)
6) Investigation of Trace Contaminant Propagation – CDRA Carbon Dioxide Product (Phase 2)
7) CDRA Functional Checkout after Desiccant Bed re-packing and Extended Duration Resource Recovery Functional Performance (Phase 3)

Cycle 1 was performed in the Exploration Test Chamber (E–Chamber) in MSFC Building 4755. This facility provided the following capabilities:

1) DC and AC power
2) Software Automated Control and Data Acquisition
3) Metabolic Simulation (CO_2 injection, $H_2O_{(v)}$ injection, and O_2 removal)
4) Chamber atmosphere and Subsystem temperature control via Chilled Water distribution
5) Condensate Collection
6) Contaminant Injection
7) Pressure Control via High Purity Air injection and Chamber atmosphere venting
8) Space Vacuum simulation
9) Chamber atmosphere constituency control via O_2 injection
10) Chamber atmosphere and subsystem constituency monitoring via GC and FTIR
11) Hazardous Gas removal via pump with N_2 purge

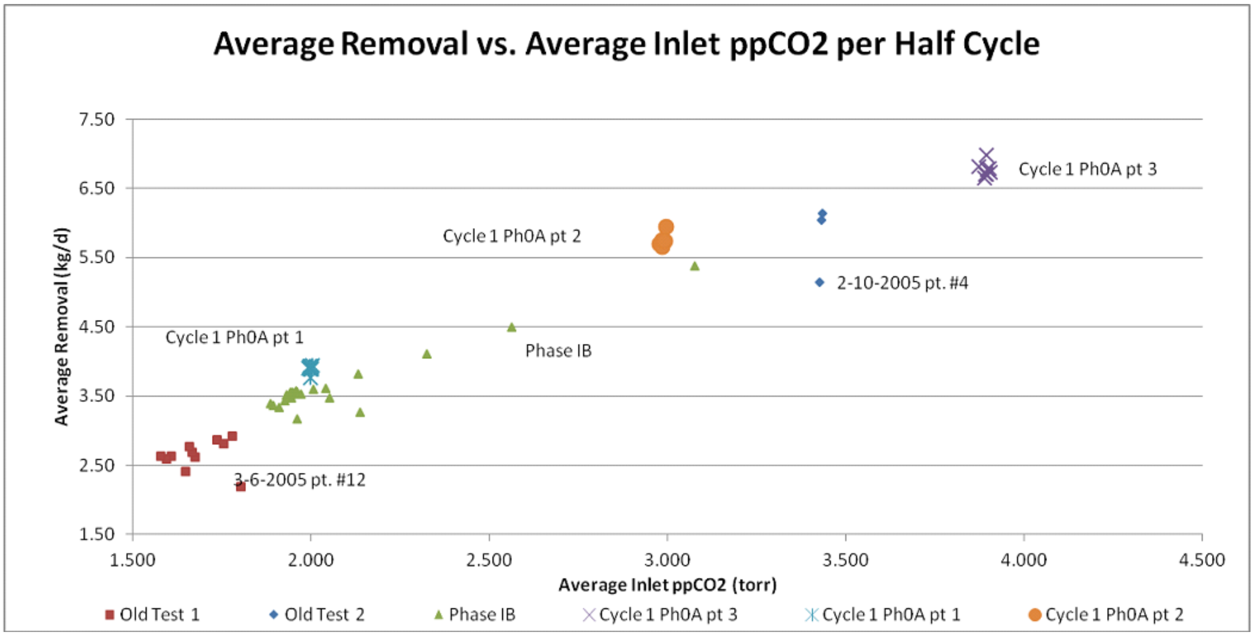
The subsystems participating in Cycle 1 were the CDRA, TCCS, Sabatier Carbon Dioxide Reduction Assembly, and Oxygen Generator Assembly.

2.0 ECHAMBER AND FACILITY CHECKOUTS

Internal Leak Rate (8/14/12 – ES62-TPS-RRR-11-015): The EChamber baseline leak rate was determined to be below 1.5 lb/day at 10 psia and 6.3 psia. Actual leak rate undetermined because temperature rise more than accounted for any pressure rise seen on sensors.

3.0 CYCLE 1 TEST RESULTS

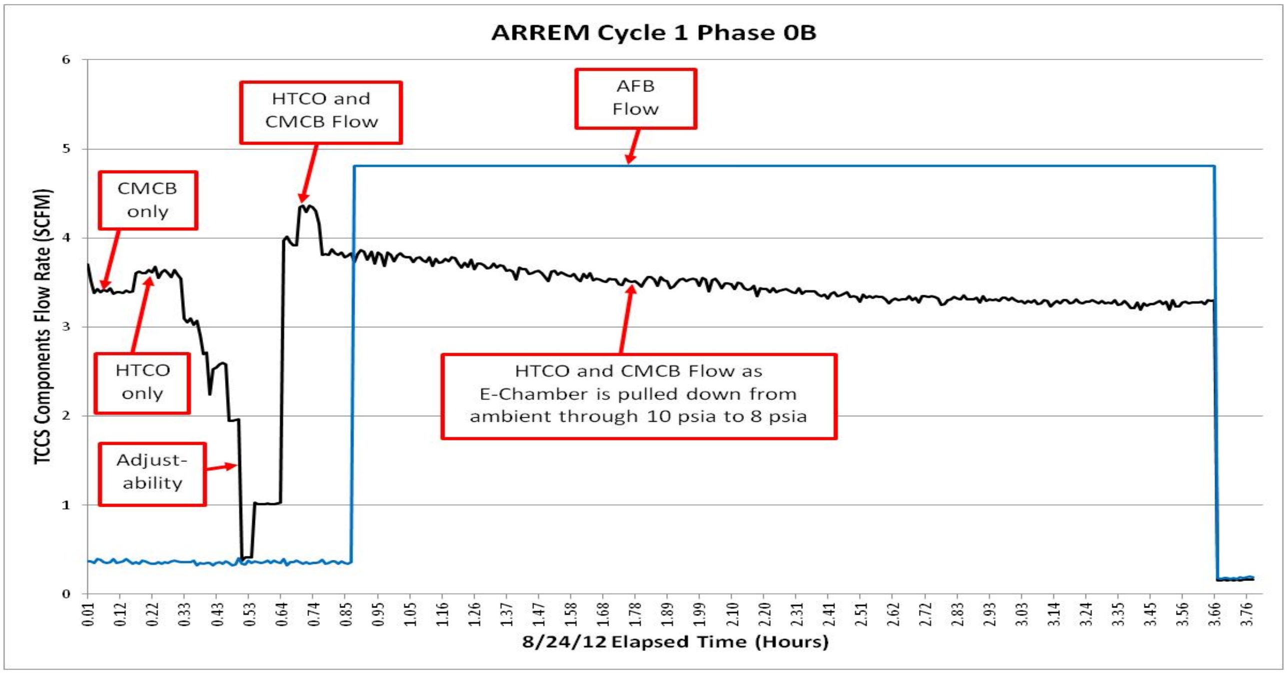
Phase 0A (7/25/12 to 7/30/12 – ES62-TPS-RRR-12-014): The objective of Phase 0A was to show that the CDRA performance was comparable to historical data after re-packing the sorbent beds with RK-38. After getting the facility support up and running on 7/25, the EChamber door was clamped (but not bolted) shut and the CDRA was put into Auto mode. Each data point (0.267% CO2, 0.402 % CO2, and 0.518% CO2) was run for 24 hours. The CDRA was allowed to continue running until 7/30 while data analysis occurred. Analysis indicated that there was not a significant performance difference between RK-38 and the previous bed material (5A).



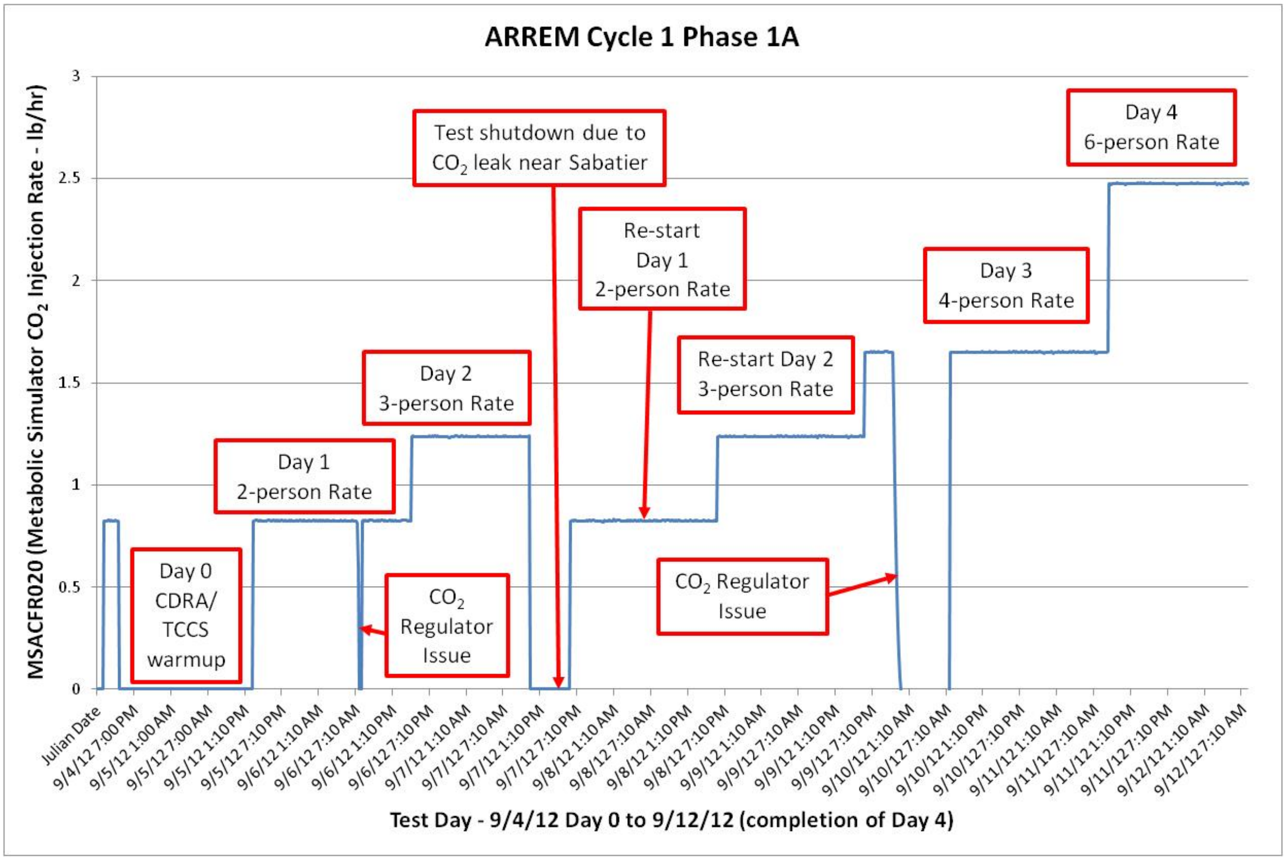
NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

Phase 0B (8/21/12 to 8/24/12 – ES62-TPS-RRR-12-016): The objective of Phase 0B was to verify that the TCCS components integrated with the CDRA (the High Temperature Catalytic Oxidizer (HTCO) and the Combined Media Catalyst Bed (CMCB)) could receive required flow using only the CDRA blower. It should be noted that the CMCB is an Orion vehicle-class TCC bed. There were some facility problems with electromagnetic interference on the TCCS Adsorbent Fixed Bed (AFB) flow meter that delayed the test for a couple of days. However, when the test was run on 8/24/12 data indicated that, while a little lower than the expected 3.7 SCFM, the CDRA blower was able to maintain performance with diverted flow to the TCCS components. This test was performed at ambient pressure and also with the EChamber pulled down through 10 psia to 8 psia as shown in the plot below. The AFB was located in a branch of the main air trunk of the EChamber with a facility booster fan. This fan was shown to deliver about 4.8 SCFM with maximum voltage delivered to the fan no matter what the pressure was in the EChamber.

NOTE: between Phases 2 and 3 a discrepancy was discovered in the flow through the TCCS components. The valve positions were determined to be reversed of what is reported below. Therefore, CMCB only is really HTCO only and vice versa. The HTCO and CMCB flow is really with both beds bypassed.



Phase 1A (9/4/12 to 9/12/12 – ES62-TPS-RRR-12-017 and ES62-TPS-RRR-12-017A): The objective of Phase 1A was to show that the CDRA was functional at different metabolic rates for CO_2 injection into the EChamber. Run #1 was quickly aborted after noticing that the reading for the Adsorbent Fixed Bed flow meter again was not responding as it should. The test was re-started on 9/5/12 after changing the sensors input/output from serial to analog. After a Day 0 operation to get the subsystems warmed up, Day 1 began on 9/6/12. There was a CO_2 empty cylinder alert early that day which was caught quickly and fixed. However, this same phenomenon would cause more problems later in the test. Test Day 2 began in the afternoon of 9/6/12 when the metabolic CO_2 injection rate was changed to 3-person. On the morning of 9/7/12, it became apparent that there was a buildup of CO_2 into the EChamber that could not be accounted for by the 3-person injection rate. The test was delayed and the EChamber door was opened to find the source of the CO_2. It was found in the Sabatier CO_2 facility plumbing (the Sabatier was running independently at the time). The troubleshooting and repair lasted for approximately 6 hours and the system was re-started at the 2-person metabolic CO_2 injection rate at approximately 1800 on 9/7/12. Test Days 1 and 2 were then successfully completed and Test Day 3 (the 4-person metabolic rate) was running when the CO_2 injection problem occurred again. Unfortunately, this time it occurred at about 2239 (when personnel were absent) and approximately 7 hours of CO_2 injection was lost. The culprit was determined to be a compound regulator in the 2 bottle CO_2 injection system. The regulator does not allow automatic switching to the other bottle unless it is fully against the stops. CO_2 injection at the 4-person rate was re-established on the morning of 9/10/12 and the test was completed without further incident.


ARREM Cycle 1 Phase 1A
MSACFR020 (Metabolic Simulator CO_2 Injection Rate - lb/hr)
0
0.5
1
1.5
2
2.5
3
Test Day - 9/4/12 Day 0 to 9/12/12 (completion of Day 4)
Julian Date
9/4/12 7:00PM
9/5/12 1:00AM
9/5/12 7:00AM
9/5/12 1:10PM
9/5/12 7:10PM
9/6/12 1:10AM
9/6/12 7:10AM
9/6/12 1:10PM
9/6/12 7:10PM
9/7/12 1:10AM
9/7/12 7:10AM
9/7/12 1:10PM
9/7/12 7:10PM
9/8/12 1:10AM
9/8/12 7:10AM
9/8/12 1:10PM
9/8/12 7:10PM
9/9/12 1:10AM
9/9/12 7:10AM
9/9/12 1:10PM
9/9/12 7:10PM
9/10/12 1:10 AM
9/10/12 7:10 AM
9/10/12 1:10 PM
9/10/12 7:10 PM
9/11/12 1:10 AM
9/11/12 7:10 AM
9/11/12 1:10 PM
9/11/12 7:10 PM
9/12/12 1:10 AM
9/12/12 7:10 AM
Day 0 CDRA/ TCCS warmup
Day 1 2-person Rate
Day 2 3-person Rate
CO_2 Regulator Issue
Test shutdown due to CO_2 leak near Sabatier
Re-start Day 1 2-person Rate
Re-start Day 2 3-person Rate
CO_2 Regulator Issue
Day 3 4-person Rate
Day 4 6-person Rate

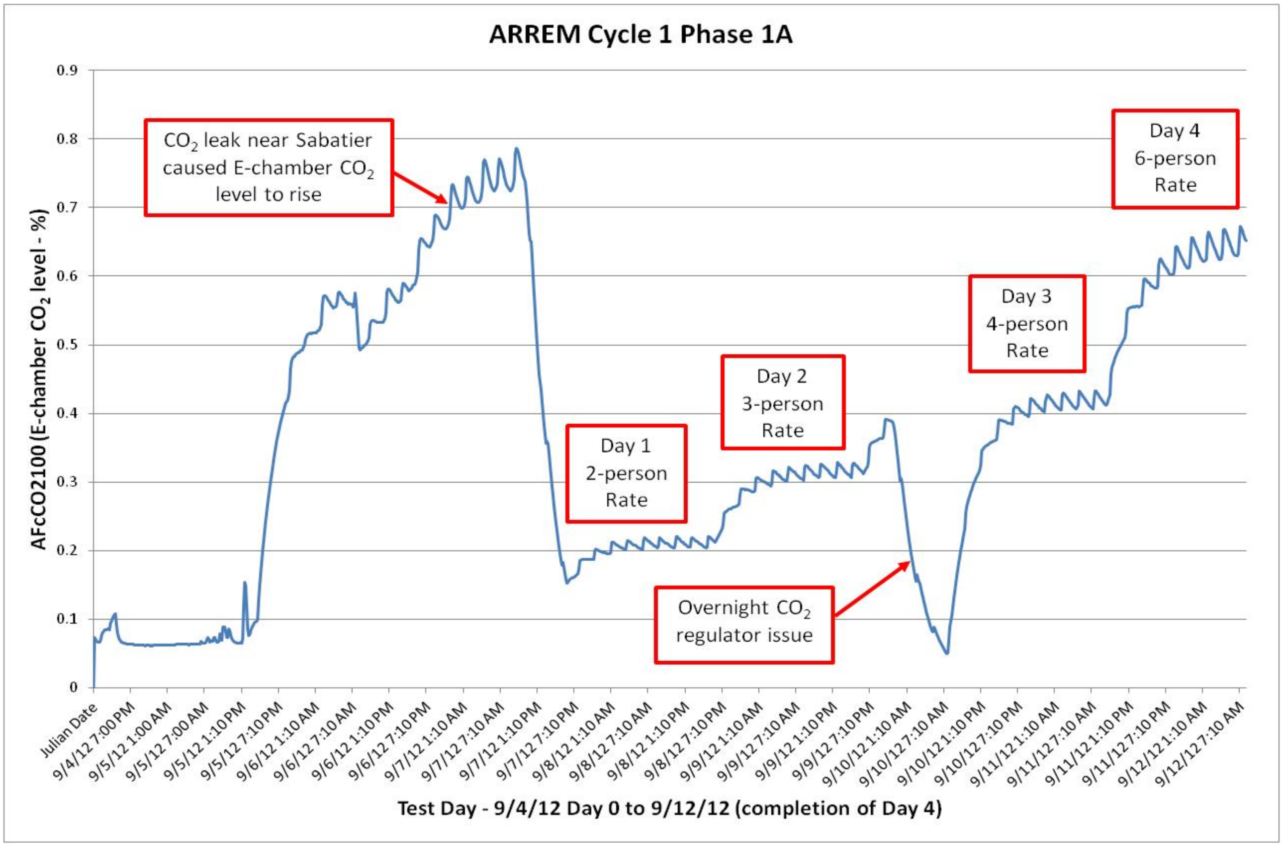
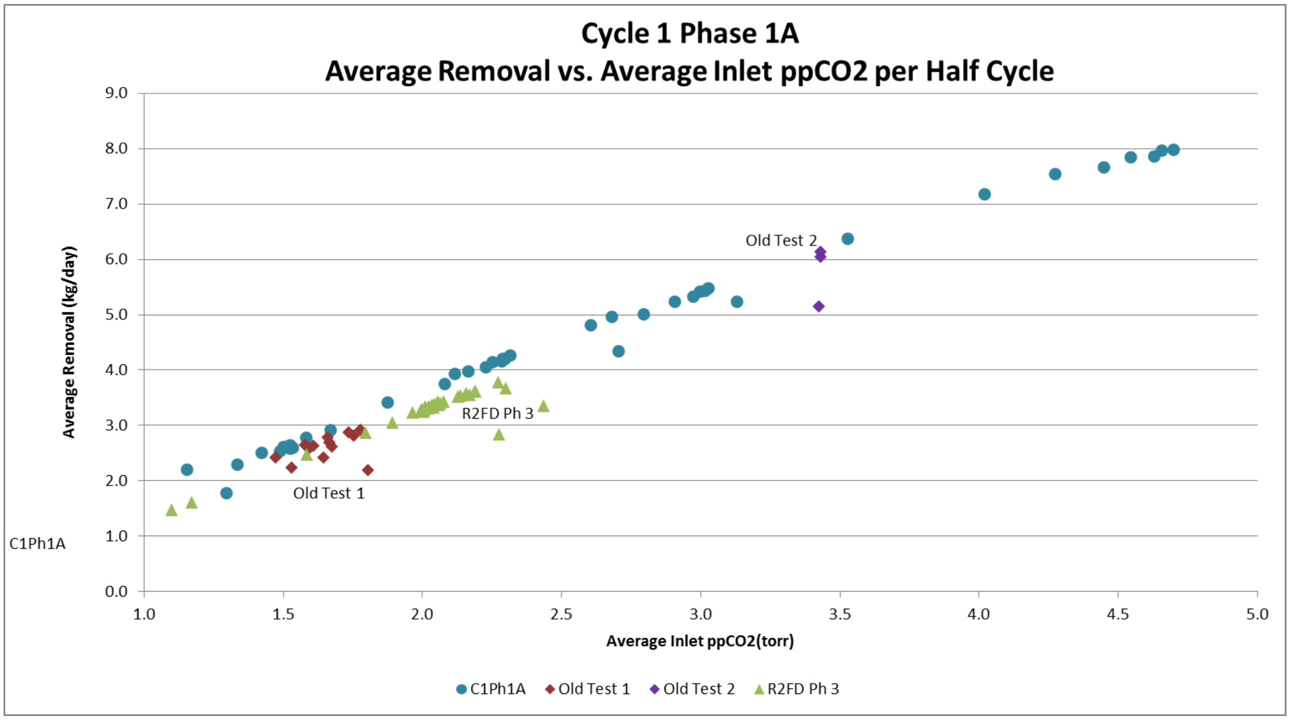

ARREM Cycle 1 Phase 1A
AFcCO2100 (E-chamber CO_2 level - %)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Test Day - 9/4/12 Day 0 to 9/12/12 (completion of Day 4)
Julian Date
9/4/12 7:00PM
9/5/12 1:00AM
9/5/12 7:00AM
9/5/12 1:10PM
9/5/12 7:10PM
9/6/12 1:10AM
9/6/12 7:10AM
9/6/12 1:10PM
9/6/12 7:10PM
9/7/12 1:10AM
9/7/12 7:10AM
9/7/12 1:10PM
9/7/12 7:10PM
9/8/12 1:10AM
9/8/12 7:10AM
9/8/12 1:10PM
9/8/12 7:10PM
9/9/12 1:10AM
9/9/12 7:10AM
9/9/12 1:10PM
9/9/12 7:10PM
9/10/12 1:10 AM
9/10/12 7:10 AM
9/10/12 1:10 PM
9/10/12 7:10 PM
9/11/12 1:10 AM
9/11/12 7:10 AM
9/11/12 1:10 PM
9/11/12 7:10 PM
9/12/12 1:10 AM
9/12/12 7:10 AM
CO_2 leak near Sabatier caused E-chamber CO_2 level to rise
Day 1 2-person Rate
Day 2 3-person Rate
Overnight CO_2 regulator issue
Day 3 4-person Rate
Day 4 6-person Rate

Table 1: Cycle 1 Phase 1A Humidity Condensate	
Test Day	Condensate (lb)
1	14.25
2	19.8
3	26.3
4	17.05

NOTE: Day 4 condensate drain occurred approximately 15 hours into the Test Day. There is no data for a 2nd drain after the test was completed although more condensate would have been expected.
NOTE: since there was no contaminant injection, there were no samples taken for analysis.

As stated previously, prior to the start of Cycle 1 testing, the sorbent material in the adsorbent beds was upgraded from the ASRT 5A zeolite to the new material, RK-38 5A zeolite. Three comparisons for CDRA were made: 1) compare performance to previous tests to determine that hardware is performing within an acceptable range, 2) compare test data with the CDRA specification based on inlet concentration, and 3) compare CDRA performance with the old ASRT 5A zeolite adsorbent bed material to the CDRA performance with the new RK-38. The R2FD Phase 3 data was used to make the comparison between the two materials.

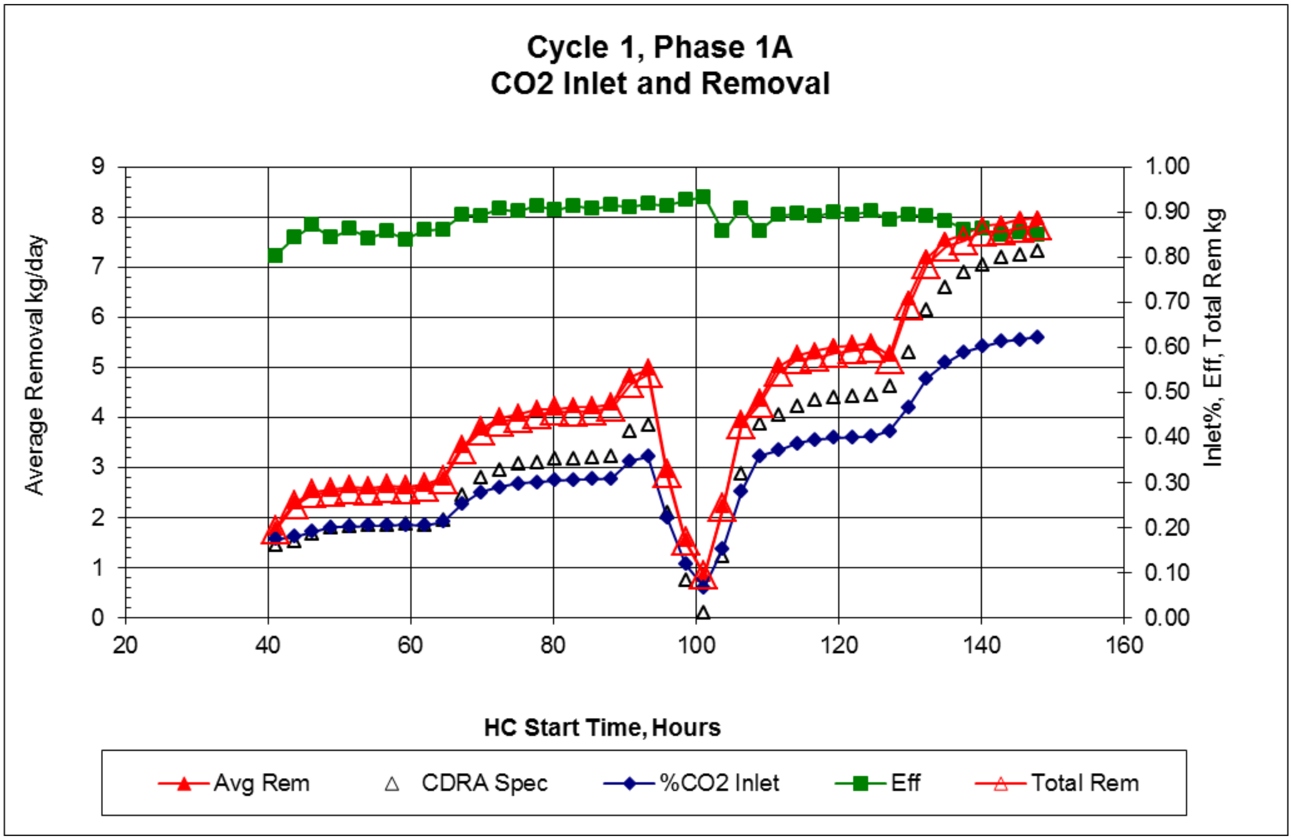
NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).
shows the comparison between the Cycle 1 Phase 1A data, data taken from two tests that were performed in 2005, and data from the R2FD Phase 3 Test. The Cycle 1-Phase 1A data shows a slight increase in performance compared to the previous tests. The increased performance indicates that the RK-38 5A zeolite is a good replacement for the ASRT 5A zeolite.



NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

Figure 2. Cycle 1 Phase 1A CDRA POIST Comparison

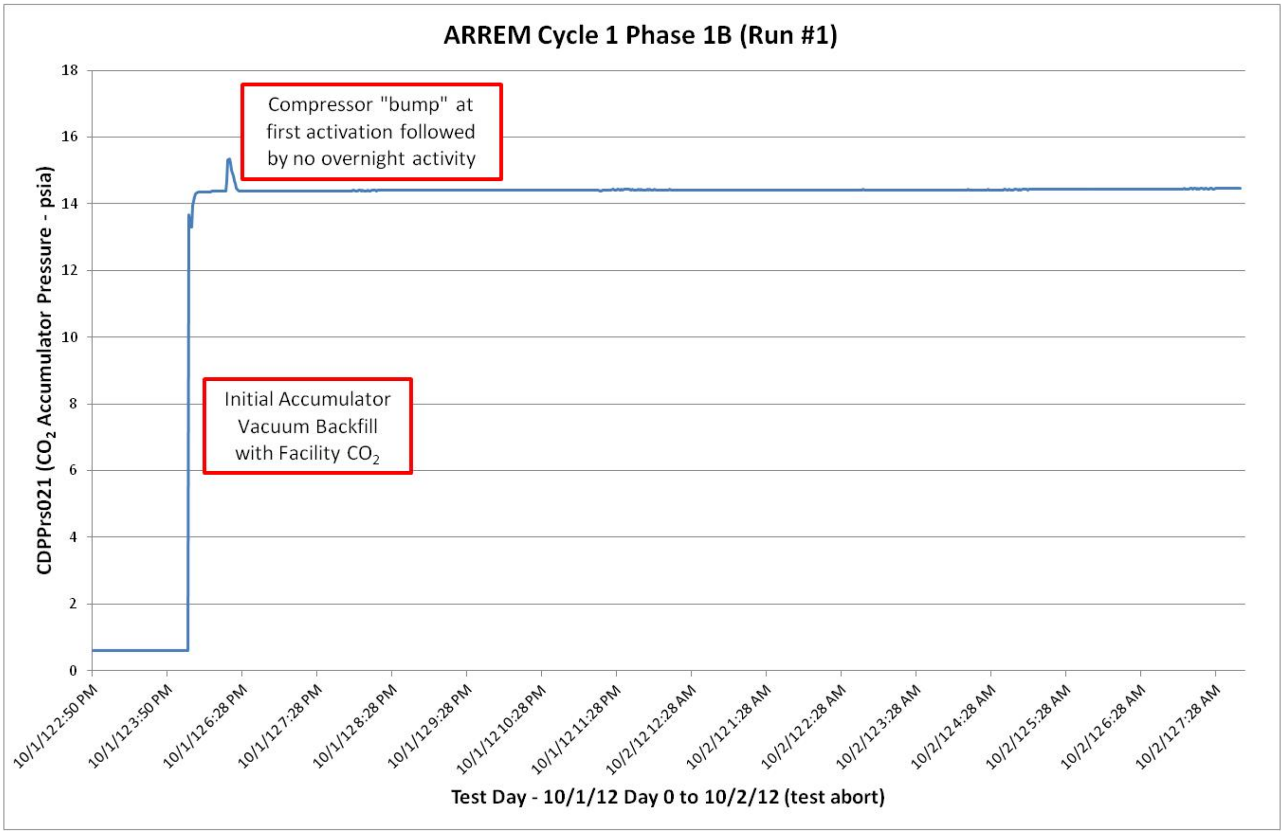
The chart in **Error! Reference source not found.** shows the Cycle 1 Phase 1A performance compared to the CDRA specification for average removal (kg/day). The graph signifies that the CDRA performed well throughout the test; the average mass of CO2 removed per day meets or exceeds the required removal rates for each of the inlet CO2 concentrations. The dip in the graph at about hour 100 shows where the CO2 supply had been exhausted. The CO2 was replenished and testing continued.



Cycle 1 Phase 1A Carbon Dioxide Removal Performance Compared to CDRA specification.

Phase 1B Overview (10/1/12 to 1/13/13 – ES62-TPS-RRR-12-018, A, B, C, and D): The objective of Phase 1B was to add the CO_2 Management Assembly, which consisted of a UTC Aerospace Systems flight spare compressor re-furbished by Southwest Research Institute and a facility accumulator volume equivalent to the ISS CO_2 accumulator, and its control logic to CDRA operations. As in the Resource Recovery Functional Demonstration test, Phase 1B proved to be the most difficult to run requiring several attempts before it was successfully completed from 1/7/13 to 1/13/13. A summary of the aborted attempts is as follows:

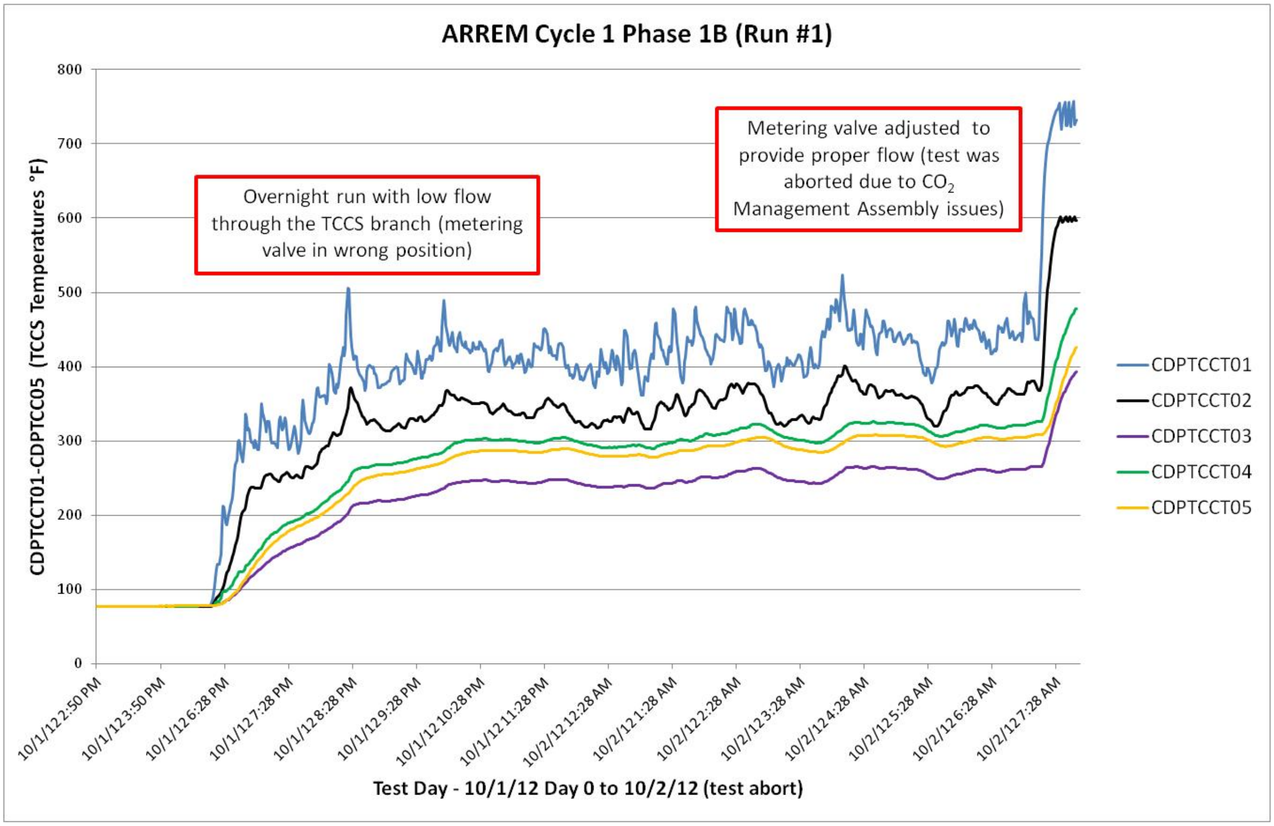
Run #1 (10/1/12 to 10/2/12 – ES62-TPS-RRR-12-018): All of the Day 0 activities were successfully completed and the CDRA was left running overnight. A manual “bump” of the compressor showed some activity as witnessed by a short, slight increase in the accumulator pressure. However, on 10/2/12, evidence indicated that the CO_2 compressor never activated. Another problem also occurred with the CDRA/TCCS. Data indicated that the metering valve controlling flow in the TCCS branch of the CDRA was closed off too much and flow was low in the area causing the TCCS Catalytic Oxidizer to be unable to reach its optimum operating temperature of 750 °F. That problem was quickly rectified and the TCCS showed signs that it would respond prior to the test being aborted for the CO_2 Management Assembly issues. Troubleshooting for the CO_2 compressor problem focused on pinpointing the issue to either the compressor itself or the motor controller. After finding blown fuses in the original motor controller and an identical replacement unit, a commercial motor controller was placed with the CO_2 compressor and the unit operated nominally from that point.



ARREM Cycle 1 Phase 1B (Run #1)

Compressor "bump" at first activation followed by no overnight activity

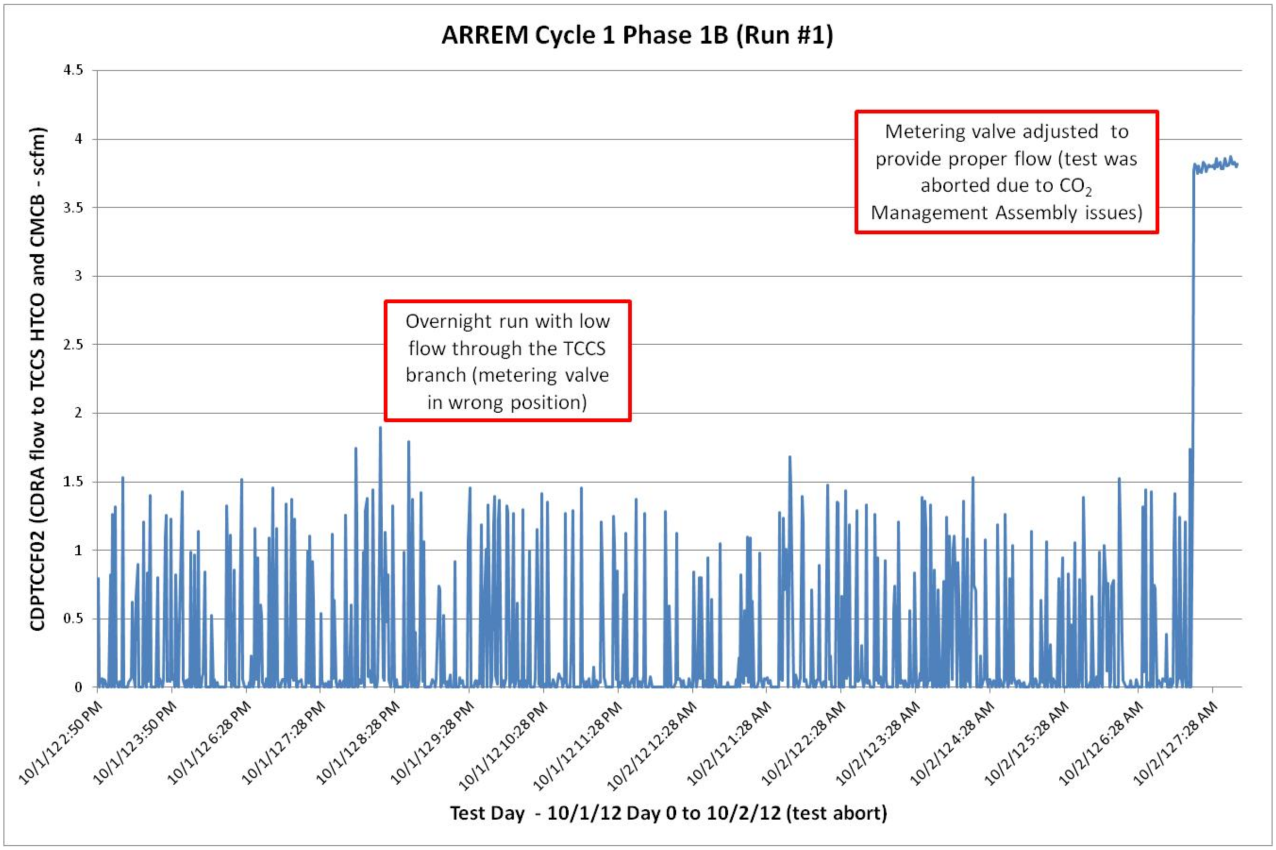
Initial Accumulator Vacuum Backfill with Facility CO_2



ARREM Cycle 1 Phase 1B (Run #1)

Overnight run with low flow through the TCCS branch (metering valve in wrong position)

Metering valve adjusted to provide proper flow (test was aborted due to CO_2 Management Assembly issues)



Metering valve adjusted to provide proper flow (test was aborted due to CO_2 Management Assembly issues)

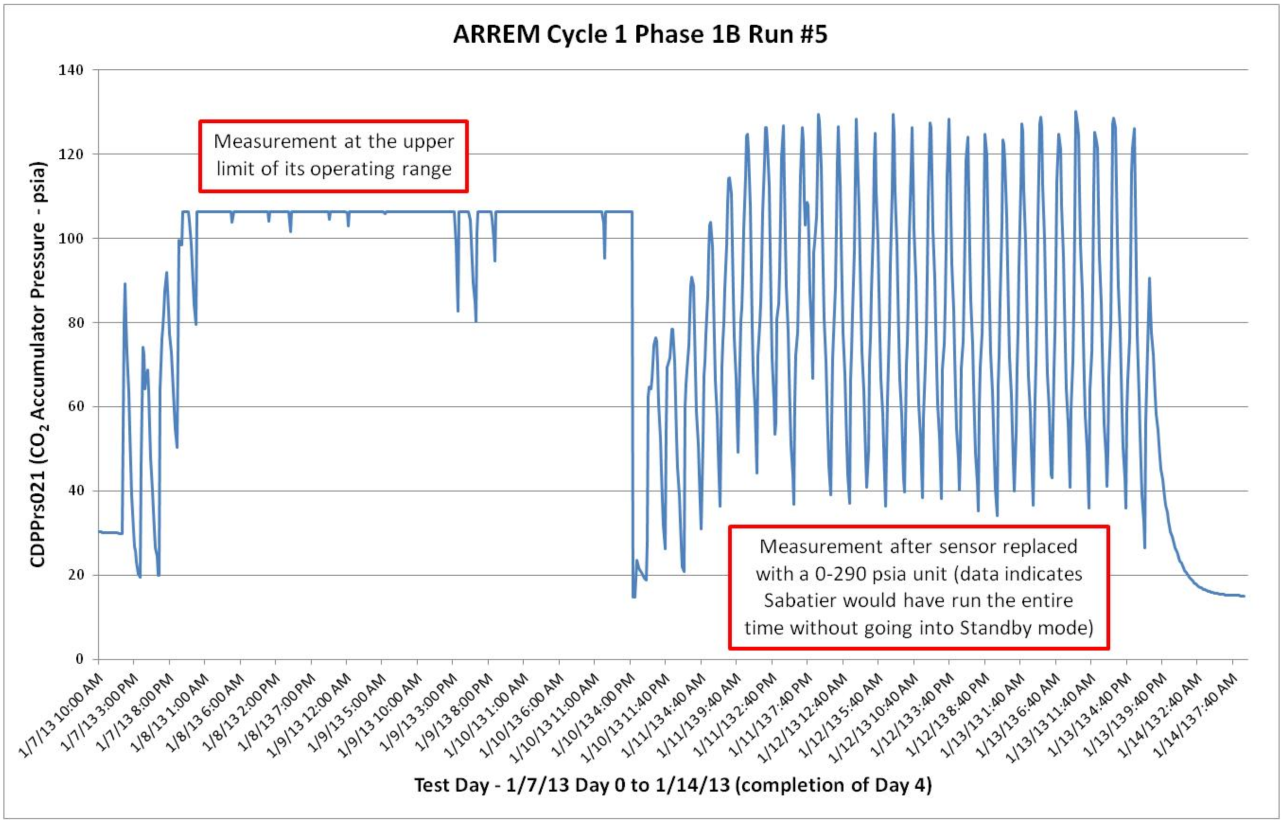
Overnight run with low flow through the TCCS branch (metering valve in wrong position)

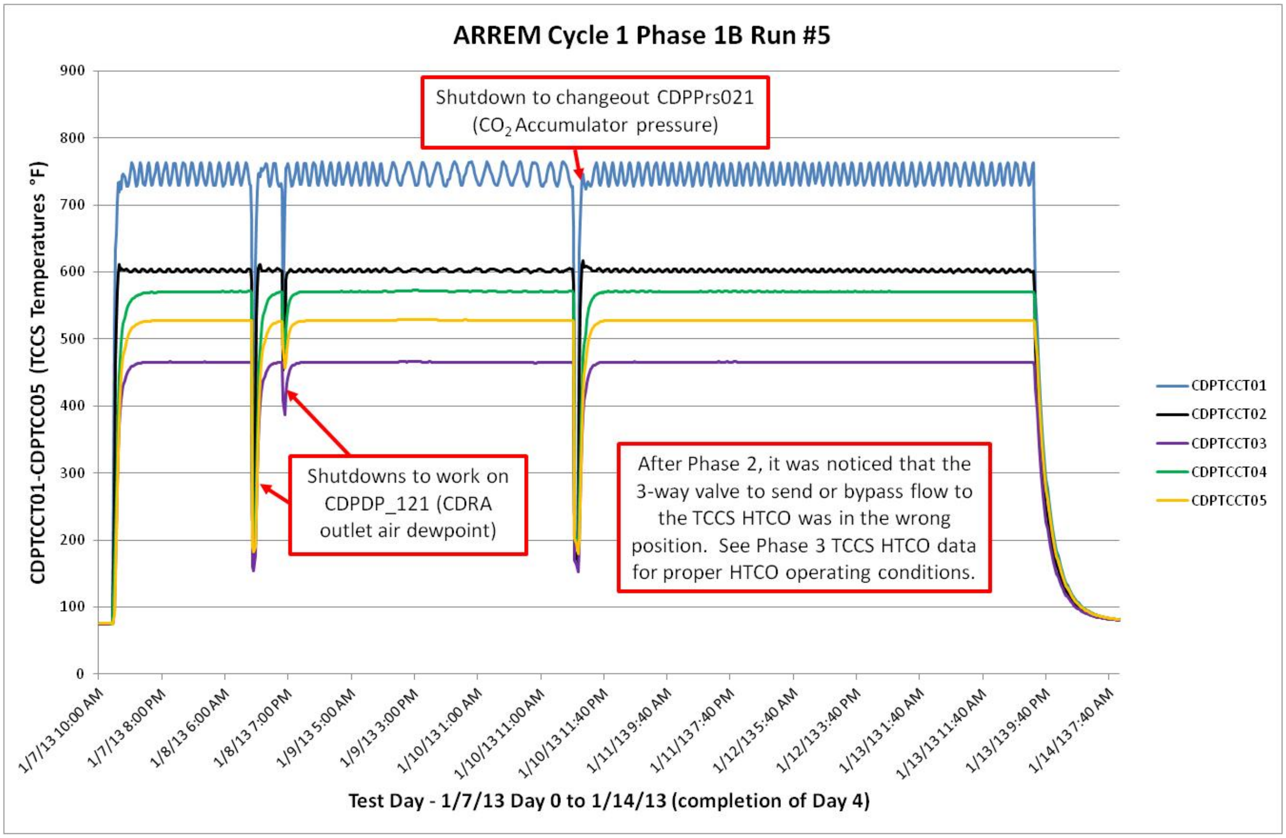
Run #2 (11/5/12 to 11/6/12 – ES62-TPS-RRR-12-018A): two attempts were made and quickly aborted due to issues with chillers. These problems would continue for two months. Eventually, the facility chillers for both the Low Temperature Loop and Moderate Temperature Loop were replaced with units taken from the Regenerative ECLSS Module Simulator.

Run #3 (11/13/12 to 11/14/12 – ES62-TPS-RRR-12-018B): Day 0 facility setup was completed but on the afternoon of 11/13/12 the CDRA seemed to be stuck in open loop mode (dumping CO_2 to the Space Vacuum Simulator). Several other errors with the physical setup and the control logic for the CO_2 Management Assembly were encountered. CDP3WV021, the 3-way valve that selected to deliver CO_2 either to the Sabatier simulator or to CDPSV_021 (which, when opened, delivered to the Space Vacuum Simulator), was found to be plumbed with those outputs backwards. CDPFlt020, a filter in that delivery line, was also cleaned and re-installed during troubleshooting. A logic error was holding the CDRA CO_2 outlet valve closed. An older version of that sub-program was re-installed to fix that. The final problem that caused this test to be aborted was a logic error in the Sabatier simulator which did not stop the consumption of CO_2 at 20 psia as it should. For all of the facility problems the CDRA showed consistent performance with earlier runs.

Run #4 (12/5/12 to 12/6/12 – ES62-TPS-RRR-12-018C): Day 0 facility setup and CDRA/TCCS overnight operations were completed but on 12/6/12, an electrical fire was discovered in one of the chiller pump motors and the test was aborted. At this point, with another chiller replacement coming and the end of the year approaching, the decision was made to complete a CDRA 3-point test and try Phase 1B again in January, 2013.

Run #5 (1/7/13 to 1/13/13 – ES62-TPS-RRR-12-018D): Day 0 facility setup and CDRA/TCCS overnight operations were completed on 1/7/13 but the CDRA outlet dew point sensor (CDPDP_121) had a "service" light which would not go away. It was replaced with a different unit but the reading continued to be so high as to be unbelievable (at one point it read 214 °F). After several attempts to get a working CDPDP_121 measurement, the CDRA Principal Investigator and the Overall Principal Investigator decided that Phase 1B could be run without this measurement. At 1300 on 1/9/13, the EChamber door was closed and Phase 1B Day 1 was started. After 2 days it was apparent that CDPPrs021 was not reaching the upper control point of 120 psia (it topped out at 106.25 psia). Further investigation revealed that the sensor had an operating range of 0-100 psia and should have been replaced when the new CO_2 Management Assembly compressor was installed into the system with the higher control point. The CO_2 accumulator had to be de-pressurized to ambient in order to replace CDPPrs021. At 1430 on 1/13/13 (Test Day 4) the O_2 injection rate was found at 0 because the cylinder was empty. This was quickly rectified by a changeout to the alternate cylinder. Phase 1B was successfully completed at 1750 on 1/13/13.



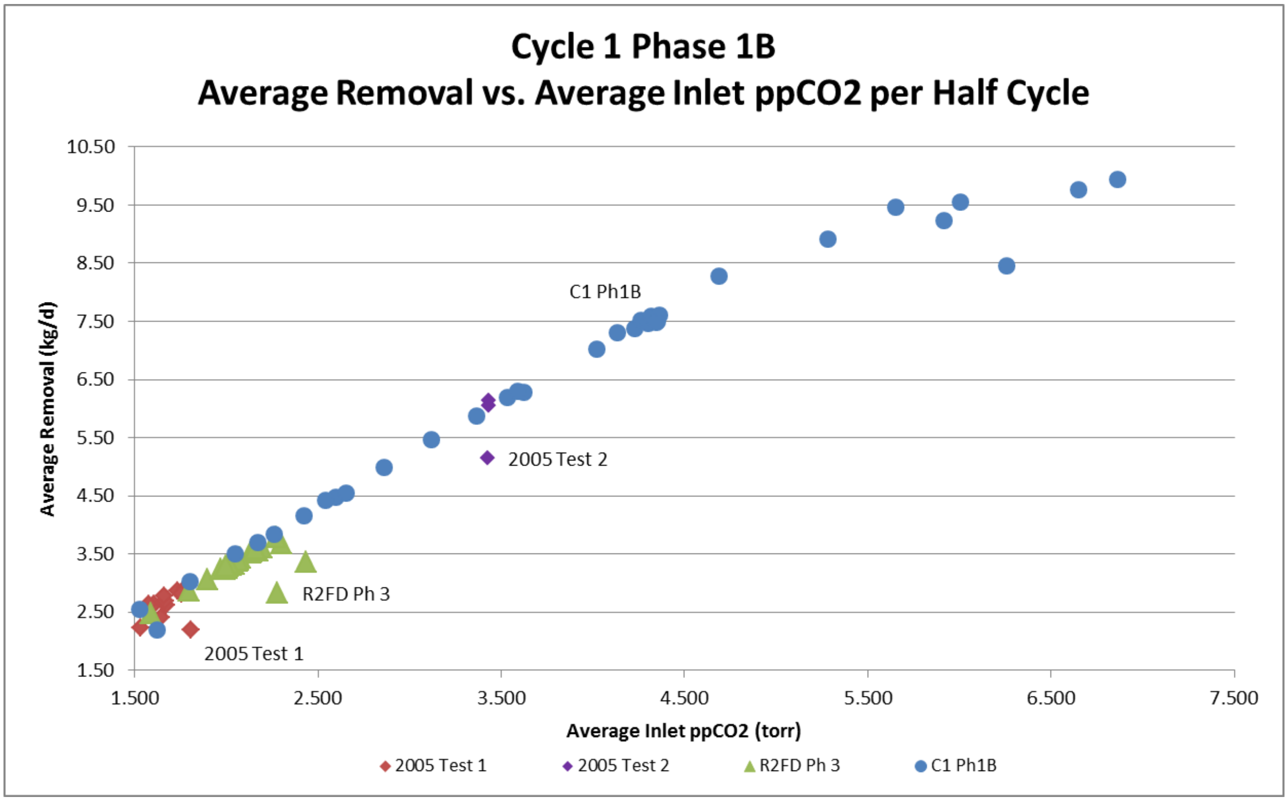


As with CDRA in Phase 1A, three comparisons were made; 1) compare the CDRA POIST performance to previous ground tests to determine that hardware is performing within an acceptable range, 2) compare test data with the CDRA specification based on inlet concentration and 3) to compare CDRA performance with the old ASRT 5A zeolite adsorbent bed material to the CDRA performance with the new RK-38.

The CDRA performed within acceptable ranges for all three comparisons. NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in “Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)” (September, 2010).

NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in “Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)” (September, 2010).

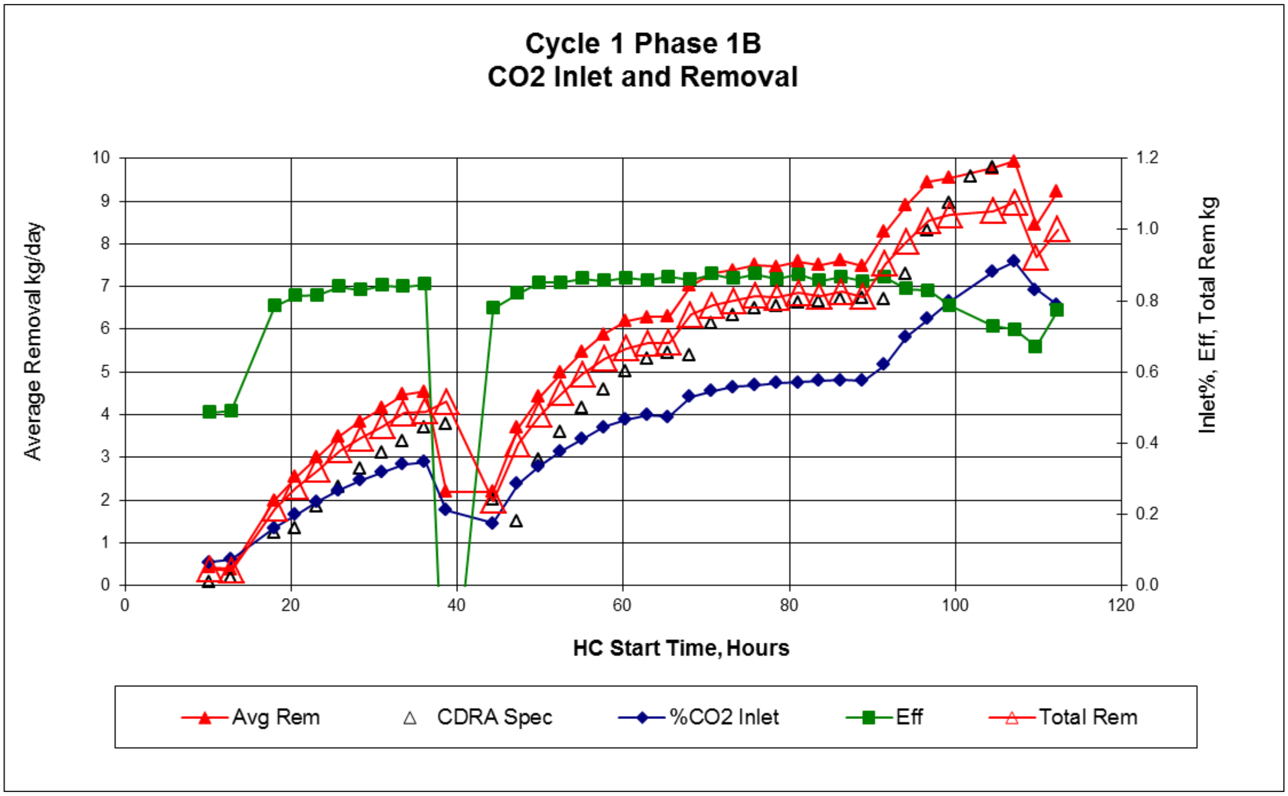
shows the comparison between the Cycle 1 Phase 1A data, data taken from two tests that were performed in 2005, and data from the R2FD Phase 3 Test. The Cycle 1 Phase 1B data shows a slight increase in performance as was observed in Cycle 1 Phase 1A, indicating that the hardware is functioning as expected and that the increased performance has been maintained.



NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

Cycle 1-Phase 1B CDRA POIST Comparison

The chart in **Error! Reference source not found.** shows the Cycle 1 Phase 1B performance compared to the CDRA specification. The CDRA performed well throughout the test, meeting or exceeding the required removal rate for the CDRA. The area approximately between the 37 hour mark and the 42 hour the mark denotes when the system was partially shut down and restarted to replace a pressure sensor. There is an appreciable rise in inlet CO_2 percentage at approximately the 90 hour mark when the injection rate increased to the 6-person level. Because there was only 24 hours of testing at this level the CO_2 percentage did not have time to settle out. See Phase 2 and Phase 3 results for longer runs at this injection rate.



Cycle 1 Phase 1B Carbon Dioxide Removal Performance Compared to CDRA specification.

Phase 2 Overview (1/23/13 to 2/7/13 – ES62-TCP-ARS-13-003): The objective of Phase 2 was to add contaminant injection (challenging the Trace Contaminant Control System) to the previously proved out parts of the Atmosphere Revitalization System. As in R2FD testing, the propagation of contaminants into the CO_2 product of the CDRA and the SeQual O_2 concentrator was of particular concern. In order to get 4 data points at each metabolic rate and keep a 2-shift GC sampling schedule, the test was extended to 3 days per metabolic rate.

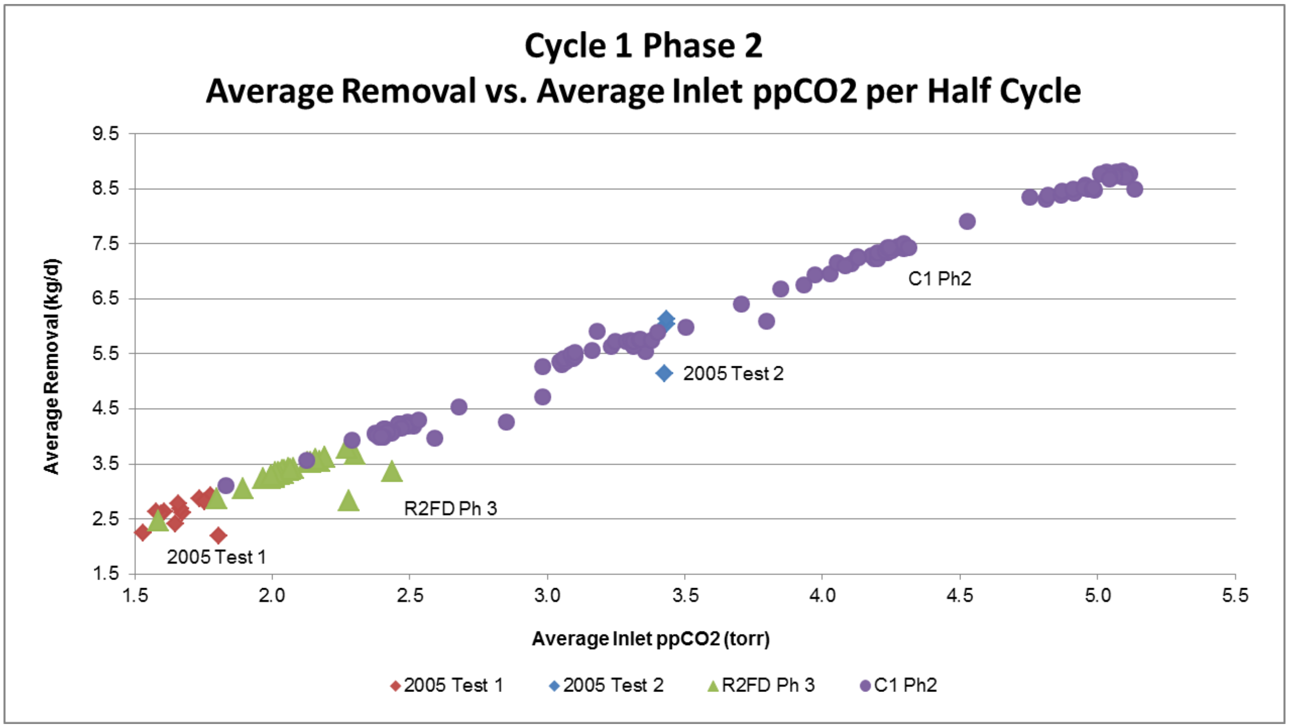
Phase 2 Event Summary 1/23/13 – Day 0A – Facility support items (chilled water, Nitrogen, Micro GC/GC/FTIR, Pressure control via high purity air, condensate collection, and metabolic simulator (setting the rate for the Oxygen Concentrator)) were activated. The final activity of the day was to initialize, by way of manual contaminant injection, the EChamber atmosphere in preparation for TCCS activation the next day. When that was done the Contaminant Injection system was put in automatic control.
1/24/13 – Day 0B – CDRA and TCCS started to allow them to warm up (for TCCS this is expected to take 17 hours). There was a momentary delay when CDRA valve 103 did not respond to command. The EChamber door was opened and troubleshooting found a severed wire for that valve. Once that was repaired (about a 90 minute delay), Day 0B continued without anomaly.
1/25/13 – Test Day 1 (which ended up being Day 0C) – The CDPDP_121 (CDRA outlet air dewpoint) measurement continued to be an issue as the new sensor placed there had an alarm that could not be cleared. The sensor swap had to be undone. In the end, a change was implemented to automatically re-initiate data transfer if there was an interruption. The troubleshooting and resolution took long enough that Day 1 activities could not begin on 1/25/13 so another pre-test day was agreed upon by the Test Director and the Principal Investigator.
1/26/13 – Test Day 1 – The first day of the 2-person metabolic rate was a nominal day with only a couple of minor glitches. 1) had to open the EChamber door to remove a second, "confirming" dew point sensor for CDPDP_121 because it was needed elsewhere and, 2) after some work on a calibration curve for the

liquid contaminant injection syringe pumps, the Test Conductor reverted back to a direct injection rate per Principal Investigator requirements.
1/27/13 – Test Day 2 – Nominal day with no anomalies noted.
1/28/13 – Test Day 3 – Nominal day with no anomalies noted.
1/29/13 – Test Day 4 – An issue with the CRA Simulator appeared when it failed to respond to a CDP-Prs021 (CO2 Accumulator pressure) reading below 20 psia. Similar behavior was witnessed during Run #3 of Phase 1B and it was thought fixed by the time Phase 1B was completed. CRACFR020 (the CRA Simulator CO_2 flowrate) should have dropped to 0 slpm when CDPPrs021 dropped below 20 psia. It appears that the program was fixed for when the CRA Simulator was in Auto mode but not in Manual mode. That change was made here and the CRA Simulator functioned nominally for the rest of Cycle 1 testing.
1/30/13 – Test Day 5 – Nominal day. About 30 minutes of PACRATS data was lost when the application locked up while looking at historical data.
1/31/13 – Test Day 6 – Nominal day with no anomalies noted.
2/1/13 – Test Day 7 – The first day of the 4-person metabolic rate was a nominal day with no anomalies noted.
2/2/13 – Test Day 8 – Nominal day with no anomalies noted.
2/3/13 – Test Day 9 – Nominal day with no anomalies noted.
2/4/13 – Test Day 10 – The first day of the 6-person metabolic rate was a nominal day with no anomalies noted. NOTE: because of an imbalance between O_2 injection (OGA Simulator) and O_2 removal rates, the EChamber O_2 concentration rose to 22.5% and an automatic shutdown of the OGA Simulator occurred. O_2 injection did not begin again until the afternoon of Test Day 11.
2/5/13 – Test Day 11 – Nominal day with no anomalies noted.
2/6/13 – Test Day 12 – Nominal day with no anomalies noted.

Phase 2 Test Results The EChamber atmosphere ethanol concentration stayed below 2 ppm. Post-Cycle 1 investigation showed that the contaminant injection system put in only about 25% of the target rate during Phase 2. The low ethanol data, along with TCCS temperature data caused the Principal Investigator to question the configuration. Post-test troubleshooting revealed that CDP3WV101 was in the wrong position and the TCCS HTCO was bypassed and the CMCB was in the process stream (this was the intended Phase 3 configuration). In essence the HTCO provided a heat load to the EChamber but provided no function. The CMCB, AFB, and the Condensing Heat Exchanger were the removal components for Phase 2. The CO_2 Management Assembly worked according to the control logic. There were a few CRA simulator "dropouts" during Phase 2 at the 6-person metabolic rate but this seemed to be a normal characteristic of the way the CO_2 Management Assembly logic worked. At the higher metabolic rate, the CO_2 produced by the CDRA was quickly pumped into the accumulator by the compressor. At the halfway point of the CDRA CO_2 production mode if CDPPrs020 (CDRA CO_2 outlet pressure) reached 8 psia it triggered a configuration change and the remaining CO_2 was "lost" to the Space Vacuum Simulator. Sometimes this phenomenon allowed enough time for the CRA simulator to drain the accumulator down to 20 psia causing the CRA simulator to go to "Standby" for lack of CO_2. This effect would also be seen on the Sabatier during Phase 3. The Metabolic Simulator CO_2 injection, H_2O injection, and O_2 removal functions performed nominally at the 2-, 3-, 4-, and 6-person rates. NOTE: during Cycle 1 Phase 3, the O_2 removal totalizer was discovered not to be set properly to account for the O_2 stream's low 90's % purity. This was a major factor in the rise of EChamber O_2 levels. Facility dewpoint sensors read in the low to mid 50's ºF compared to the main sensor (AFcDwp100) which read in the low to mid 60's ºF. A redundant CO_2 (AFcCO2101) sensor ranged from about 0.3% to 0.7% (corresponding to the changing metabolic rates) which is in agreement with the main sensor (AFcCO2100). See plots of AFcDwp100 and AFcCO2100 in the results section below. The average humidity condensate removed from the EChamber was as follows: 8.8 lb/day at the 2-person metabolic rate, 15.7 lb/day at the 3-person rate, 22.85 lb/day at the 4-person rate, and 33.98 lb/day at the 6-person rate. Condensate sampling results showed <1 ppm of Methanol no matter the metabolic rate. The metabolic rate averages for Ethanol and Total Organic Car-

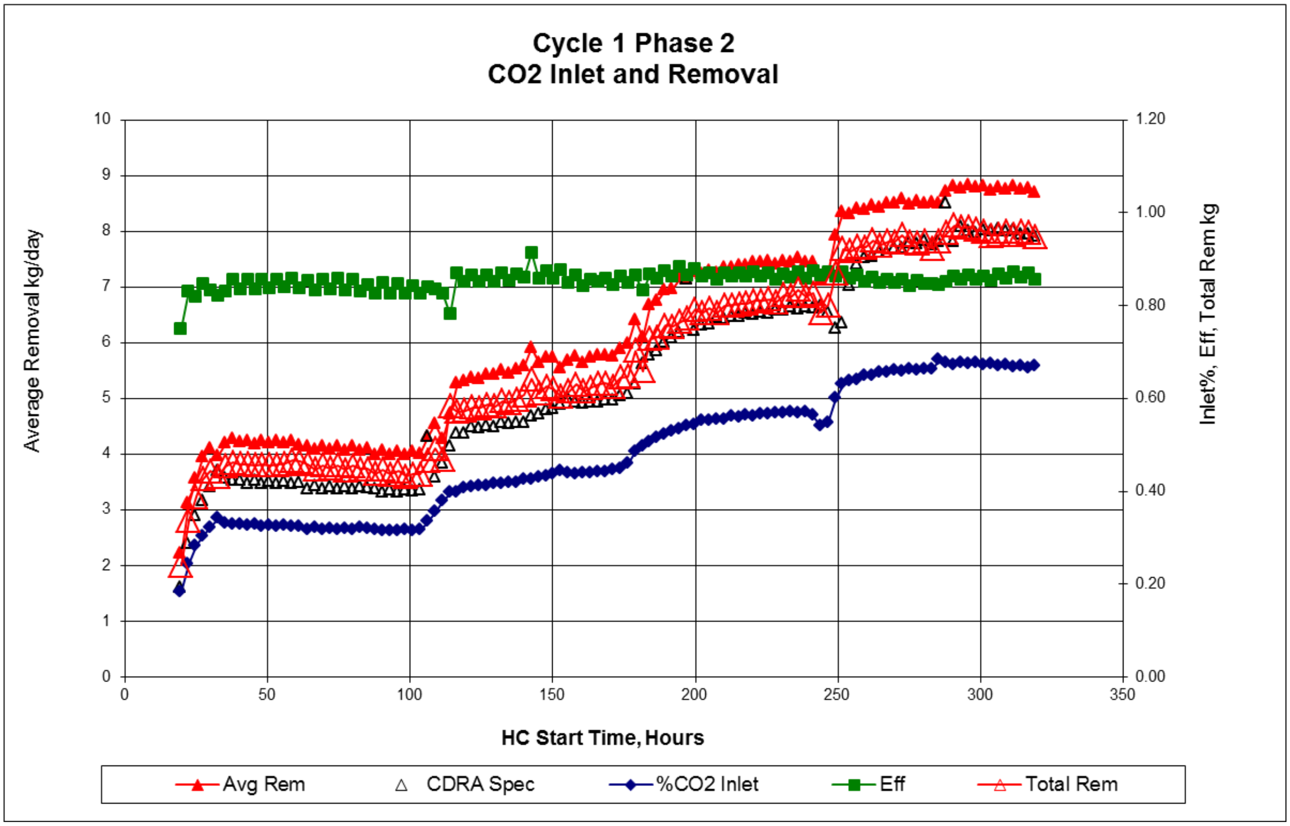
bon (TOC) were as follows: 2-person Ethanol and TOC – 44.4 ppm; 3-person Ethanol – 33.9 ppm and TOC – 29 ppm; 4-person Ethanol – 27.4 ppm and TOC – 22.5 ppm; and 6-person Ethanol – 25.9 ppm. Due to a lab instrument failure only the 6-person rate reading for TOC was 18.8 ppm on Test Day 10.
The same three CDRA comparisons were made as with the other phases; 1) compare the CDRA POIST performance to previous ground tests to determine that hardware is performing within an acceptable range, 2) compare test data with the CDRA specification based on inlet concentration and 3) compare CDRA performance with the old ASRT 5A zeolite adsorbent bed material to the CDRA performance with the new RK-38.

The CDRA performed within acceptable ranges for all three comparisons. During Cycle 1 Phase 2, the data fell more closely in line with previous tests. The inlet temperature was slightly elevated during this test and may have had a marginal effect on overall performance.



Cycle 1-Phase 2 CDRA POIST Comparison
NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

The chart in **Error! Reference source not found.** shows the Cycle 1 Phase 2 performance compared to the CDRA specification. The CDRA performed well throughout the test, meeting or exceeding the required removal rate for the CDRA.

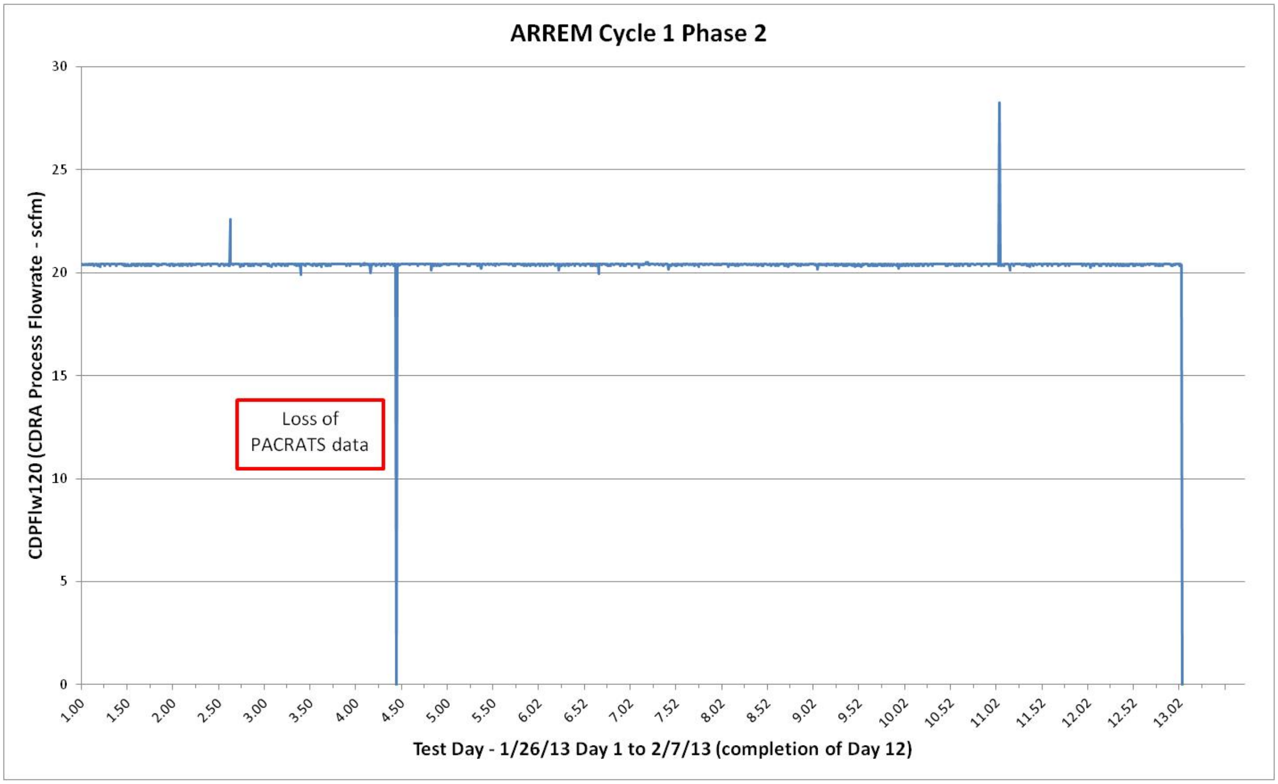


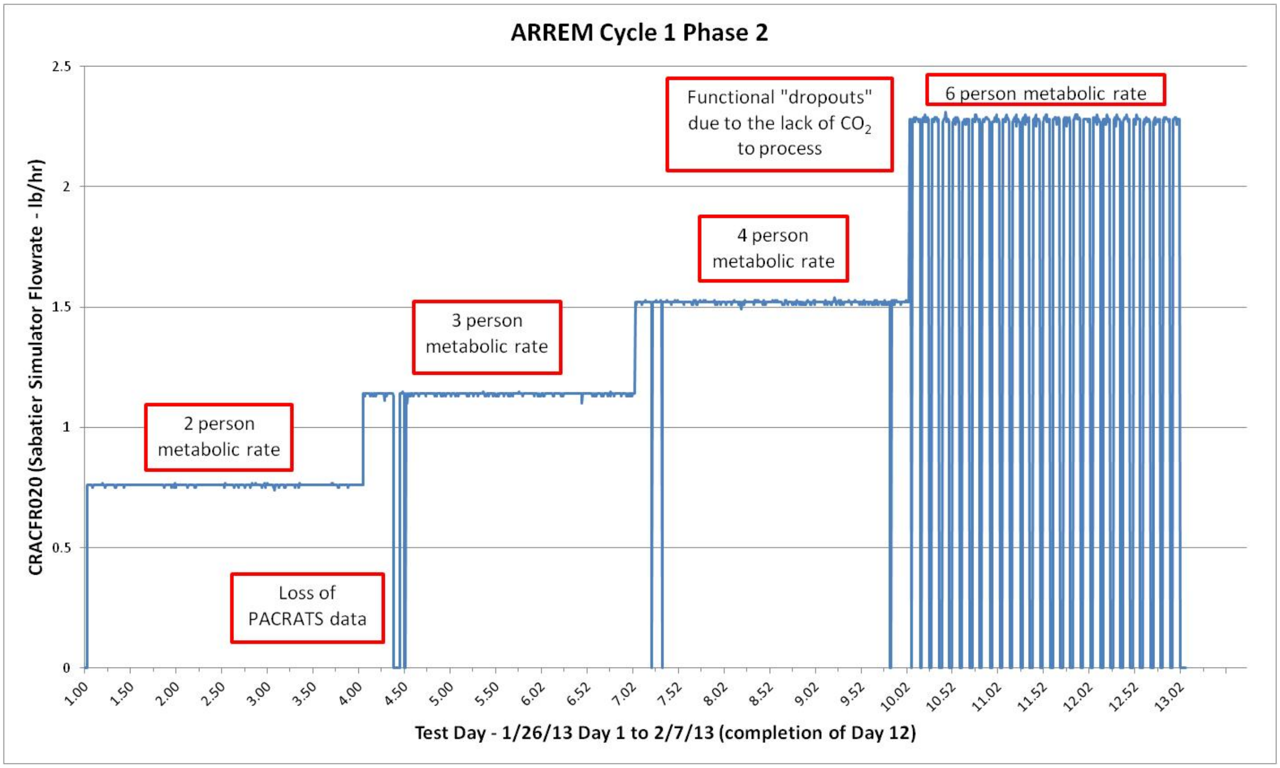
Cycle 1 Phase 2 Carbon Dioxide Removal Performance Compared to CDRA specification.

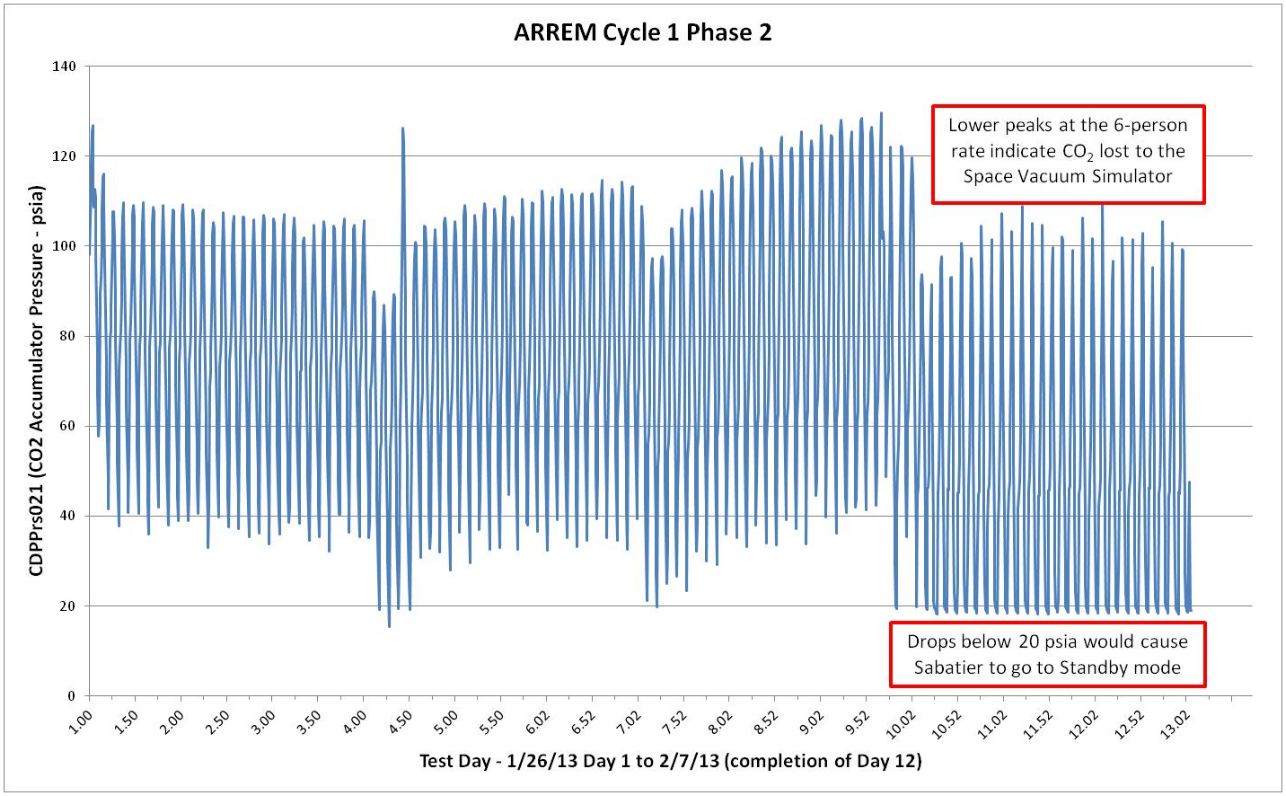
Table 1: Cycle 1 Phase 2 Humidity Condensate (NOTE: ND is Not Detected)						
Analyte	Test Day					
	1	2	3	4	5	6
Condensate (lb)	7.25	9.3	9.8	14.5	N/A (no data recorded)	16.9
Methanol (ppm)	<1	<1	<1	ND	<1	<1
Ethanol (ppm)	45.2	44.96	43	36.8	33	32
Acetone (ppm)	<1	<1	<1	<1	<1	<1
1-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-propanol (ppb)	365	377	365	334	305	304
2-methyl 2-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-butanol (ppm)	ND	ND	ND	ND	ND	ND
Total Organic Carbon (ppm)	48.6	44.96	39.6	30.6	29.2	27.22

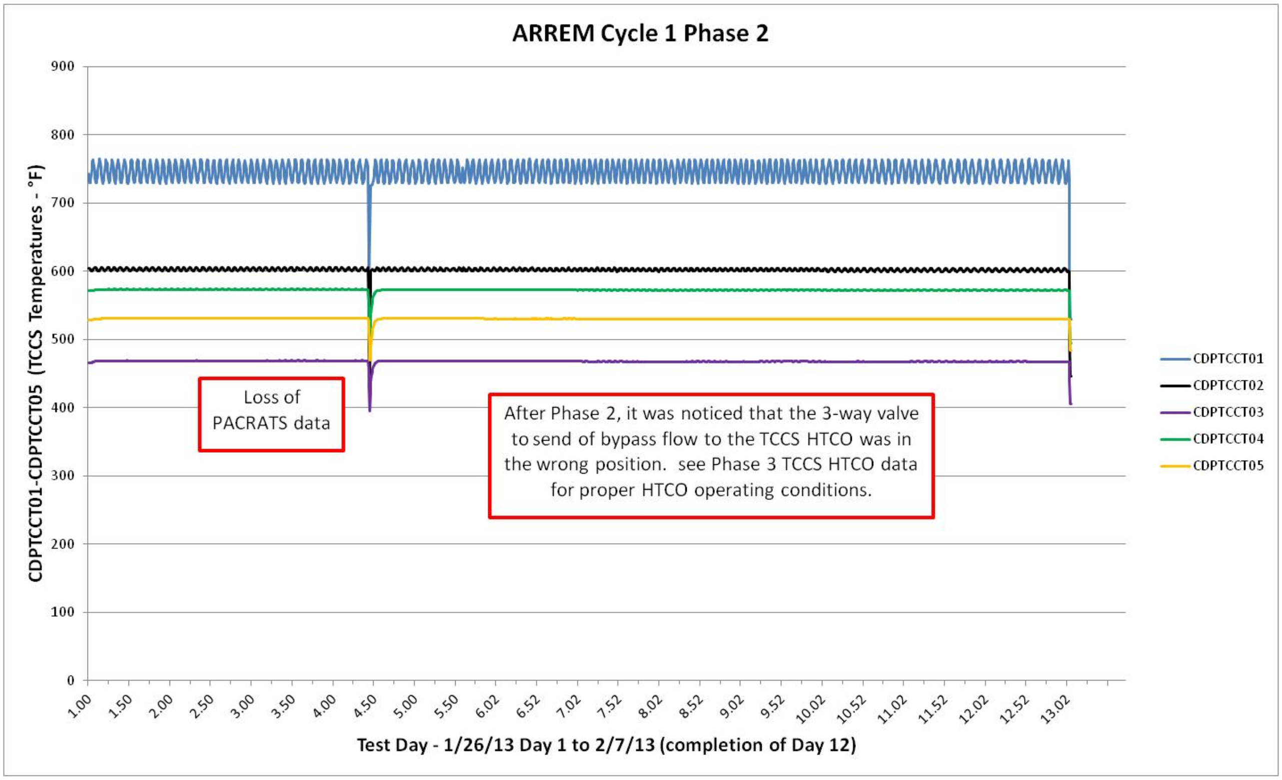
Table 1: Cycle 1 Phase 2 (continued)
Humidity Condensate

Analyte	Test Day					
	7	8	9	10	11	12
Condensate (lb)	22.5	22.8	23.25	32.25	33.05	36.65
Methanol (ppm)	<1	<1	<1	<1	<1	<1
Ethanol (ppm)	28	26.96	27.2	24.4	24	29.2
Acetone (ppm)	<1	<1	<1	<1	<1	<1
1-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-propanol (ppb)	286	284	278	292	272	273
2-methyl 2-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-butanol (ppm)	ND	ND	ND	ND	ND	ND
Total Organic Carbon (ppm)	24.2	22	21.4	18.8	N/A (instrument failure)	N/A (instrument failure)



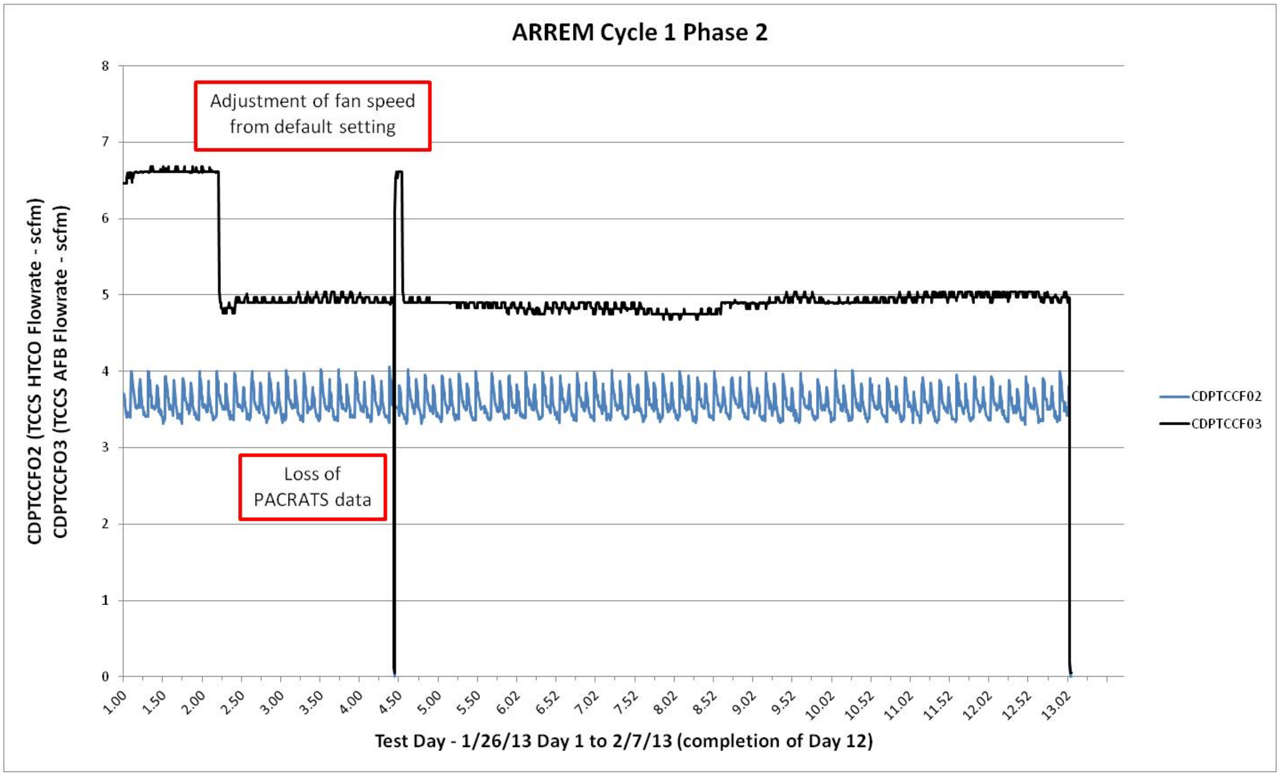

ARREM Cycle 1 Phase 2
CRACFR020 (Sabatier Simulator Flowrate - lb/hr)
2.5
2
1.5
1
0.5
0
Functional "dropouts" due to the lack of CO$_2$ to process
6 person metabolic rate
4 person metabolic rate
3 person metabolic rate
2 person metabolic rate
Loss of PACRATS data
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.02
6.52
7.02
7.52
8.02
8.52
9.02
9.52
10.02
10.52
11.02
11.52
12.02
12.52
13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)


ARREM Cycle 1 Phase 2
CDPPrs021 (CO2 Accumulator Pressure - psia)
140
120
100
80
60
40
20
0
Lower peaks at the 6-person rate indicate CO$_2$ lost to the Space Vacuum Simulator
Drops below 20 psia would cause Sabatier to go to Standby mode
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.02
6.52
7.02
7.52
8.02
8.52
9.02
9.52
10.02
10.52
11.02
11.52
12.02
12.52
13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)



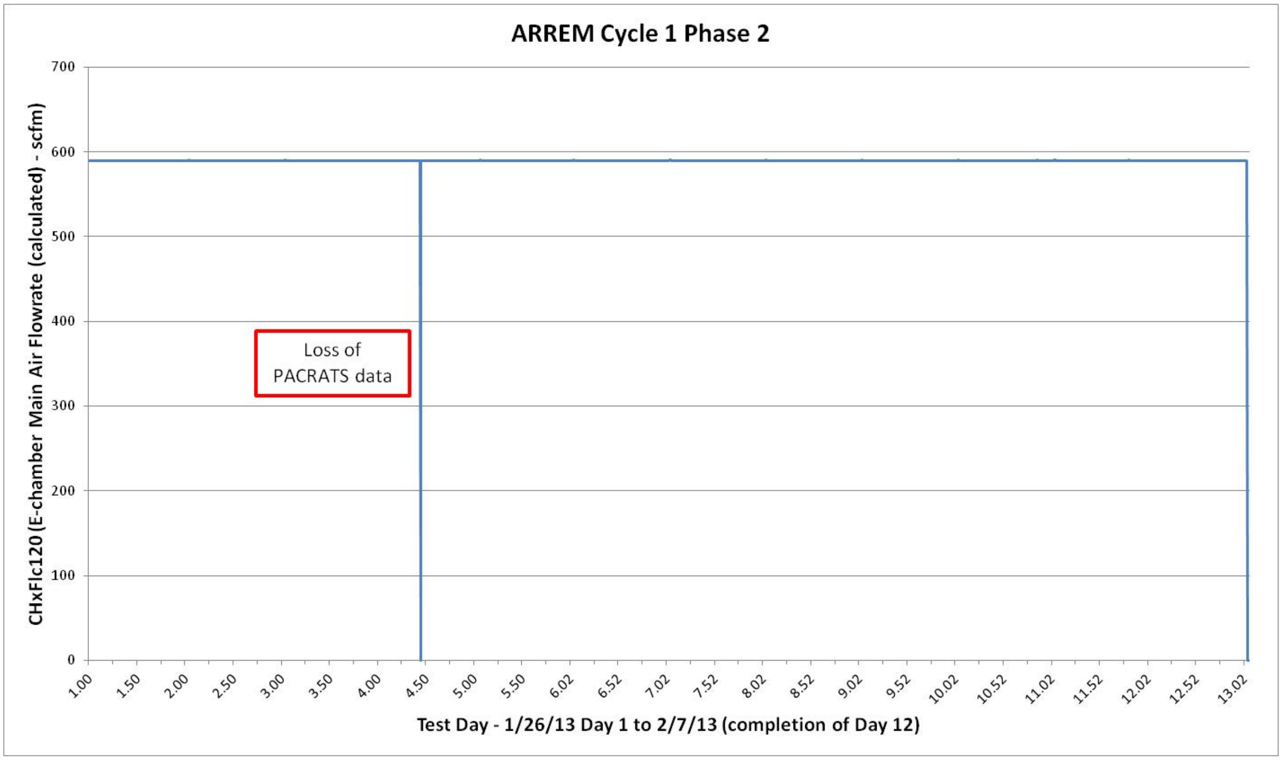
Loss of PACRATS data

After Phase 2, it was noticed that the 3-way valve to send of bypass flow to the TCCS HTCO was in the wrong position. see Phase 3 TCCS HTCO data for proper HTCO operating conditions.



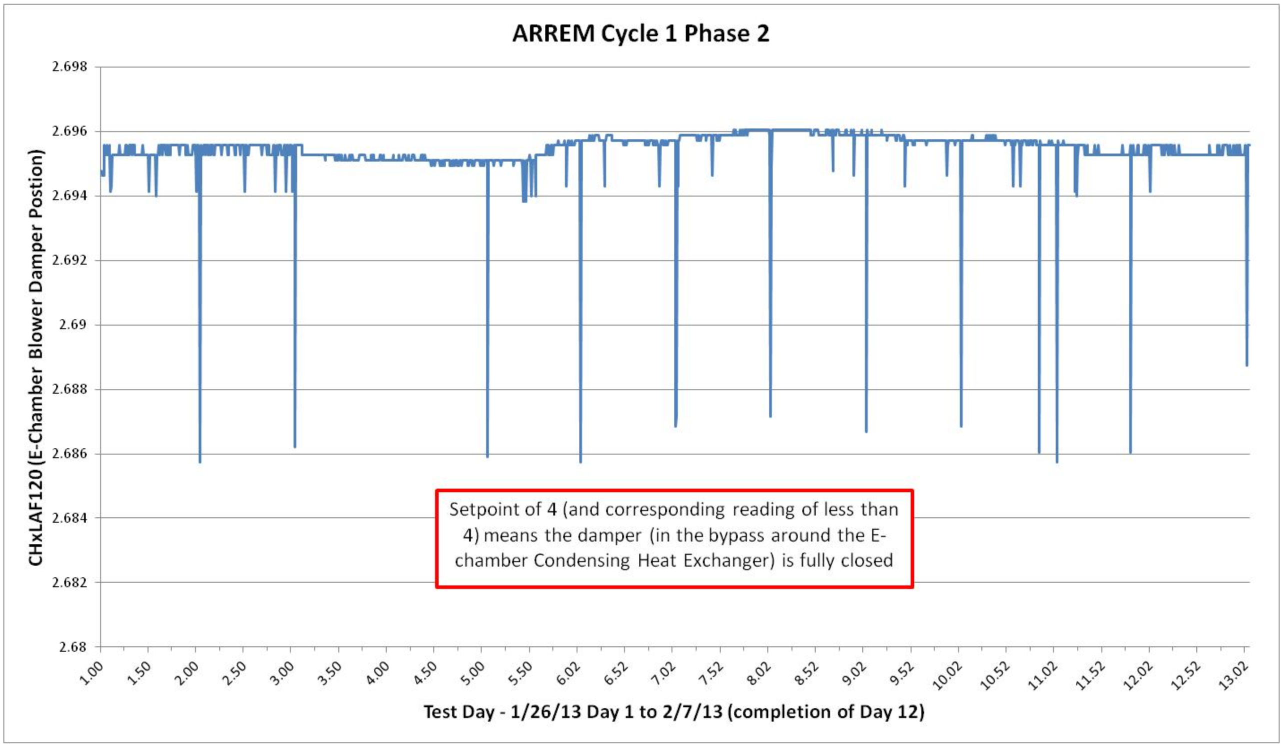
Adjustment of fan speed from default setting

Loss of PACRATS data



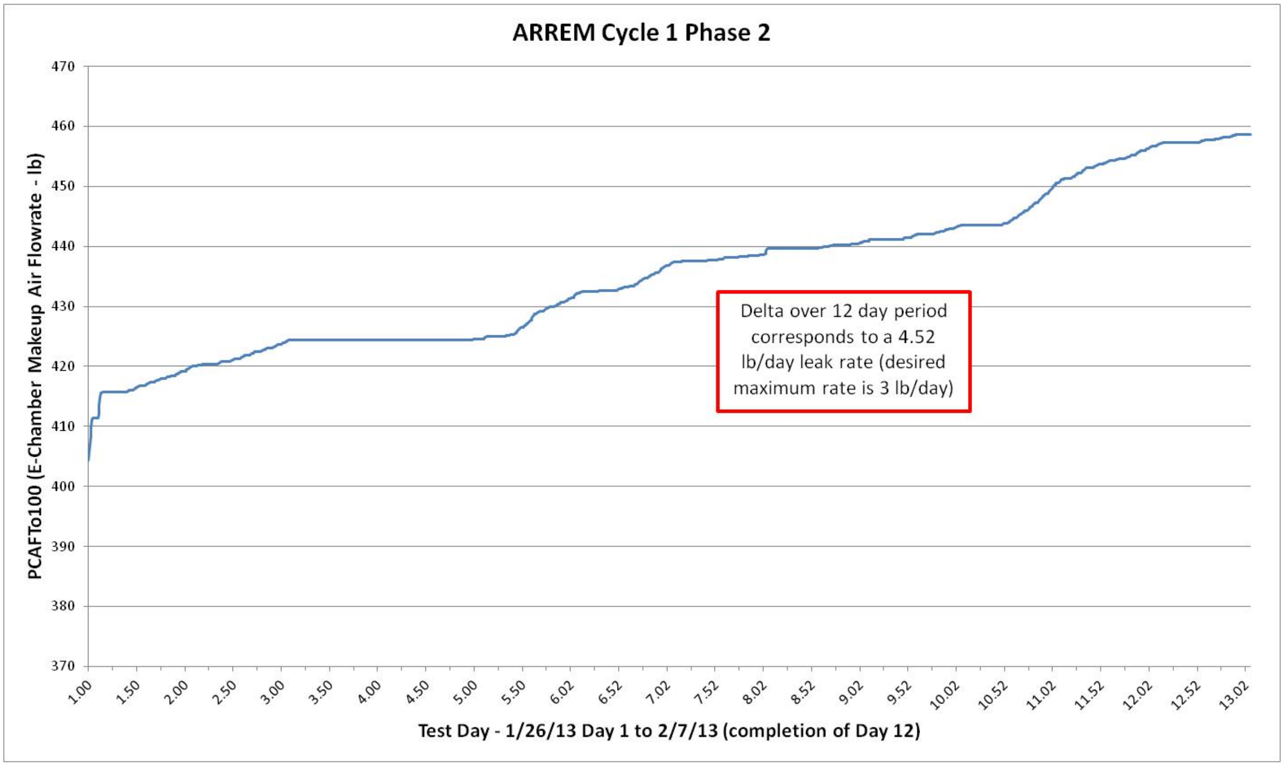
ARREM Cycle 1 Phase 2

Loss of PACRATS data

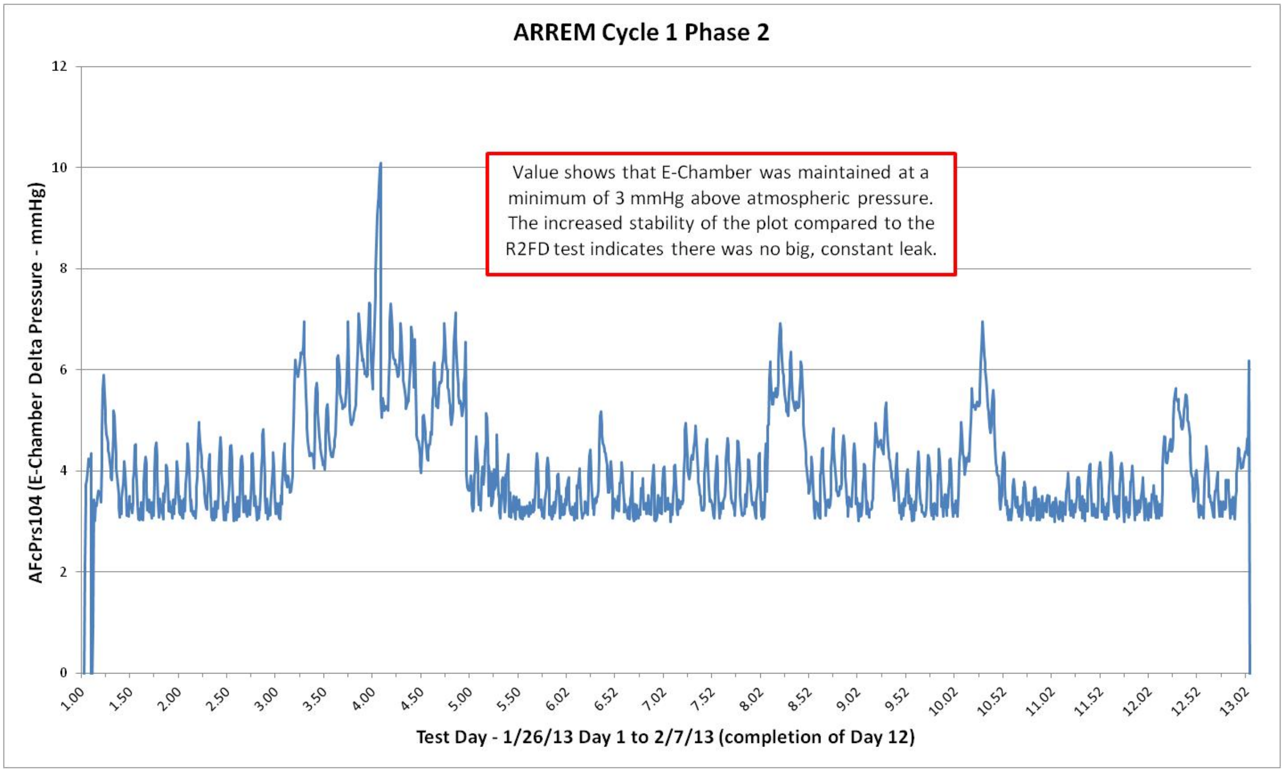


ARREM Cycle 1 Phase 2

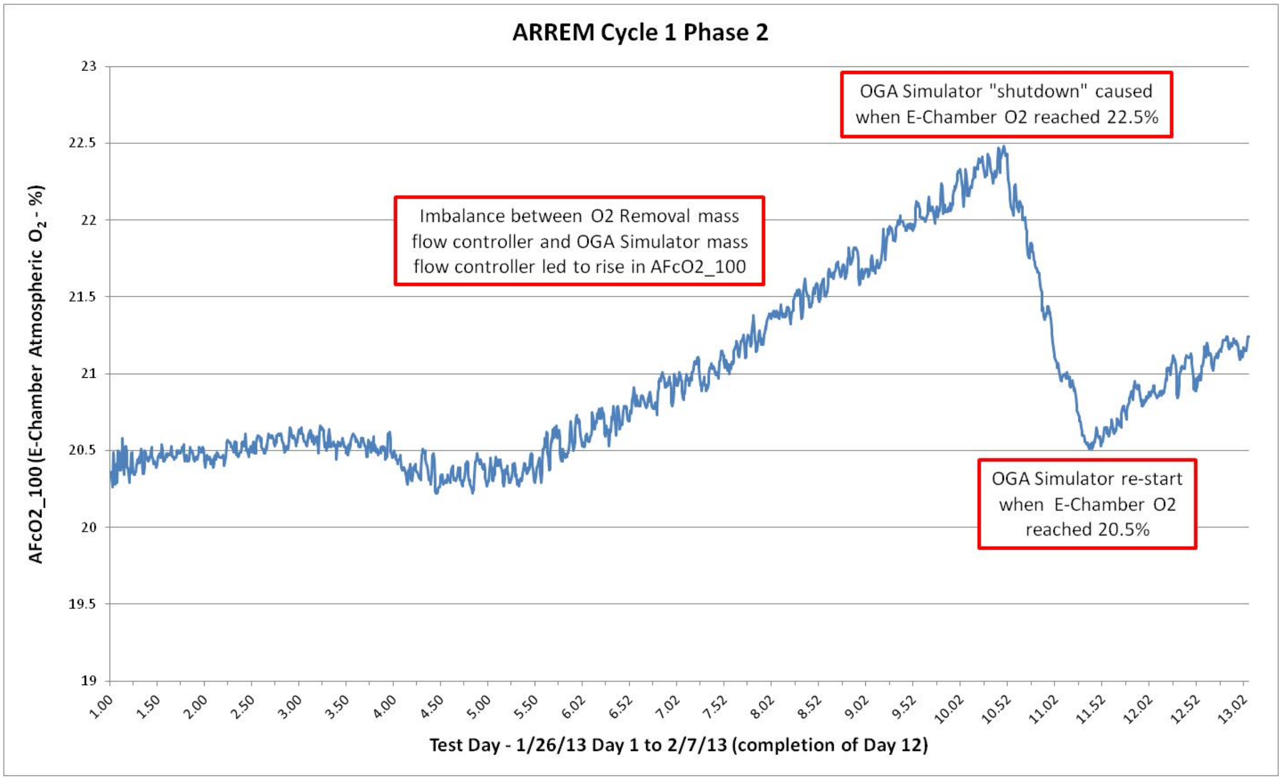
Setpoint of 4 (and corresponding reading of less than 4) means the damper (in the bypass around the E-chamber Condensing Heat Exchanger) is fully closed



Delta over 12 day period corresponds to a 4.52 lb/day leak rate (desired maximum rate is 3 lb/day)



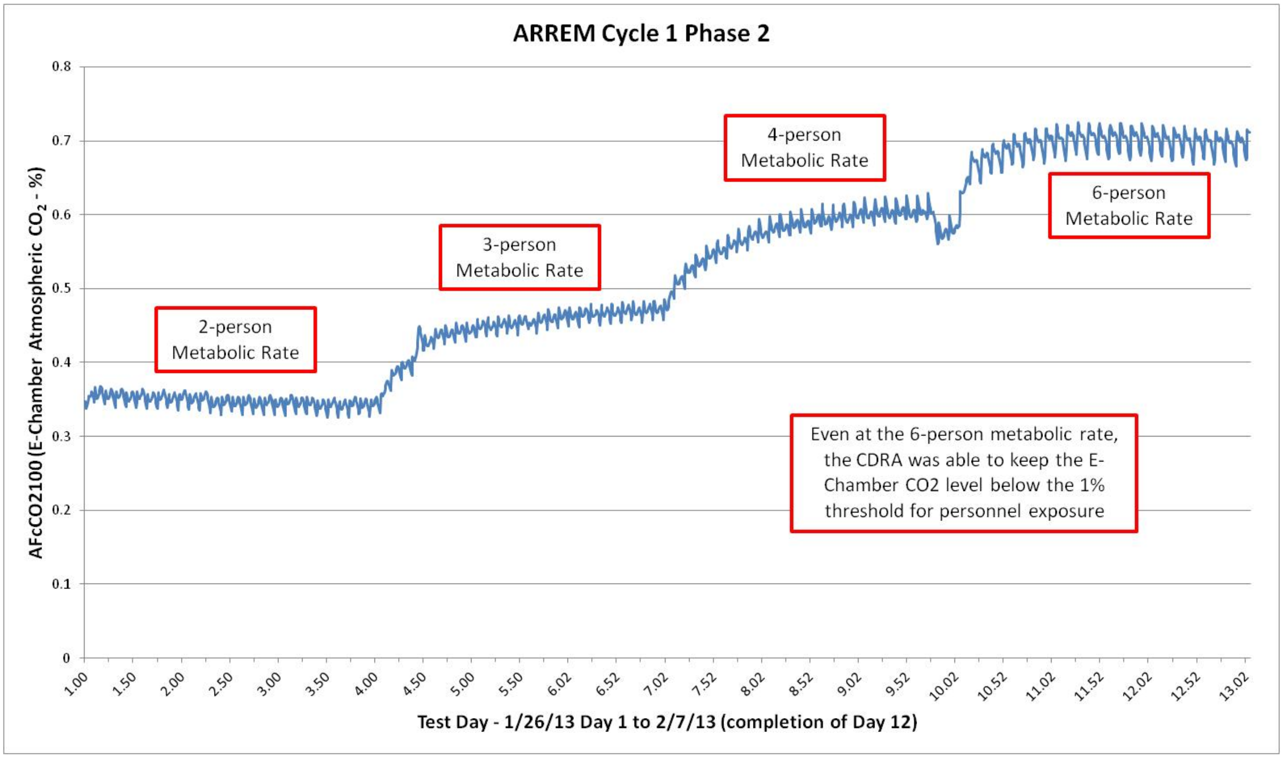
Value shows that E-Chamber was maintained at a minimum of 3 mmHg above atmospheric pressure. The increased stability of the plot compared to the R2FD test indicates there was no big, constant leak.



OGA Simulator "shutdown" caused when E-Chamber O2 reached 22.5%

Imbalance between O2 Removal mass flow controller and OGA Simulator mass flow controller led to rise in AFcO2_100

OGA Simulator re-start when E-Chamber O2 reached 20.5%



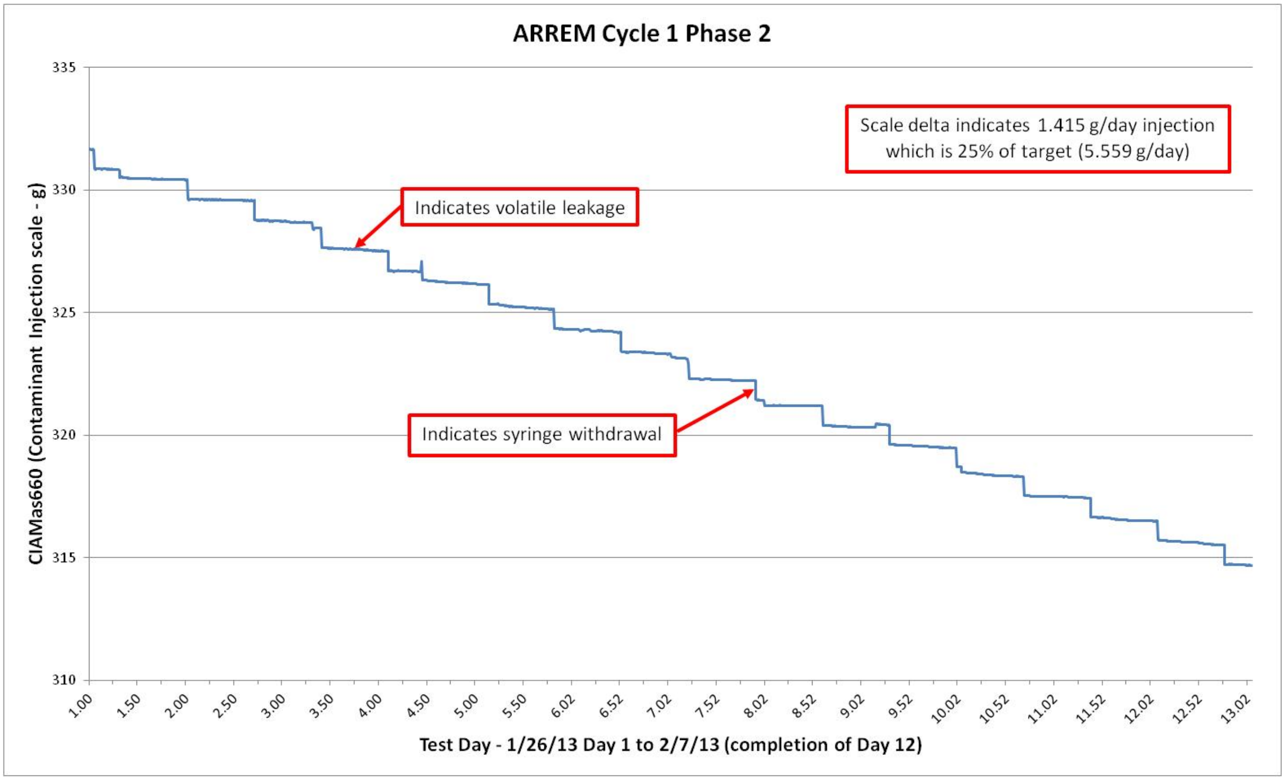
4-person Metabolic Rate

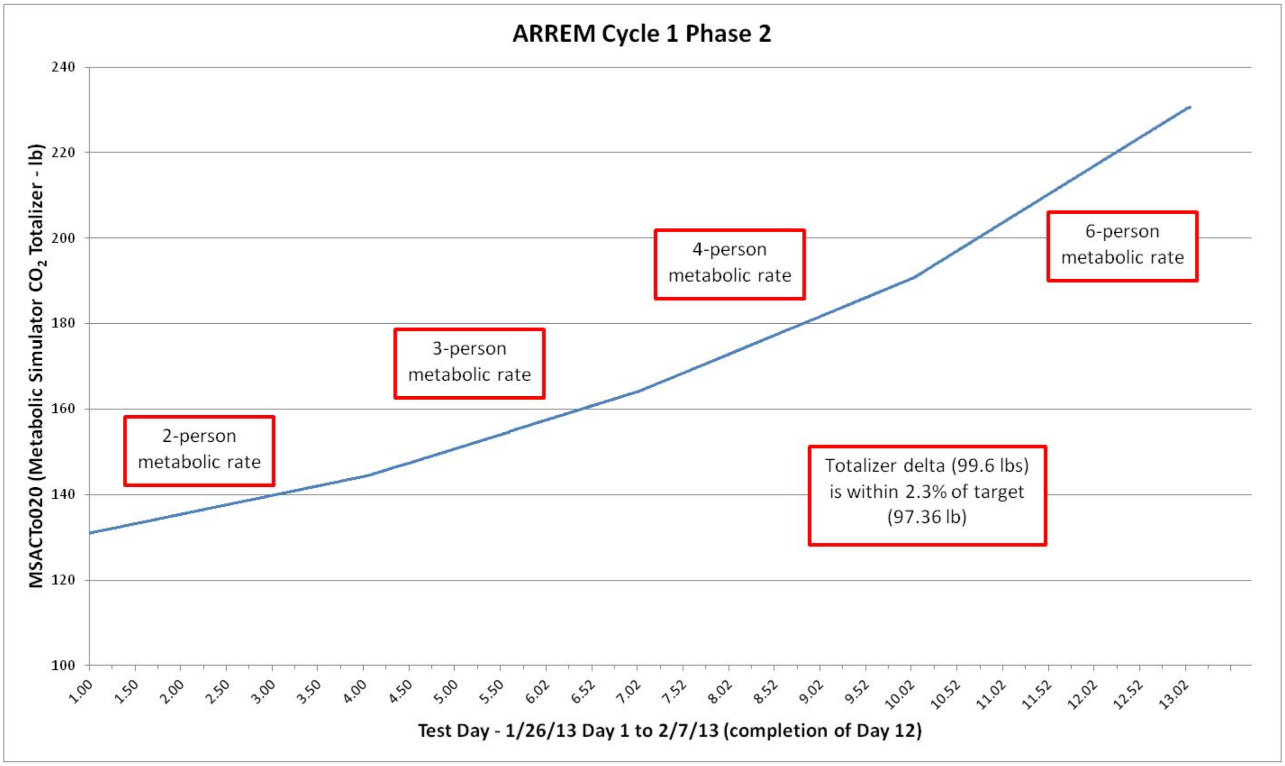
3-person Metabolic Rate

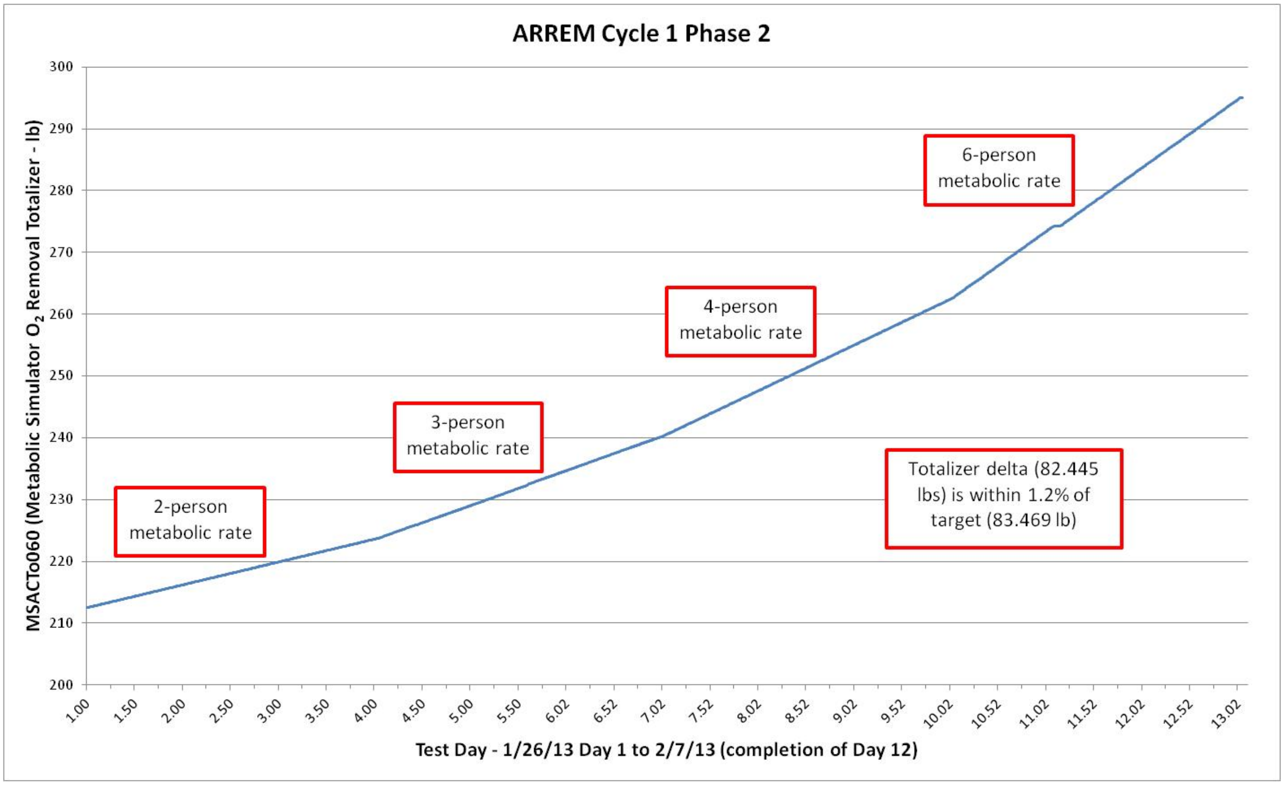
6-person Metabolic Rate

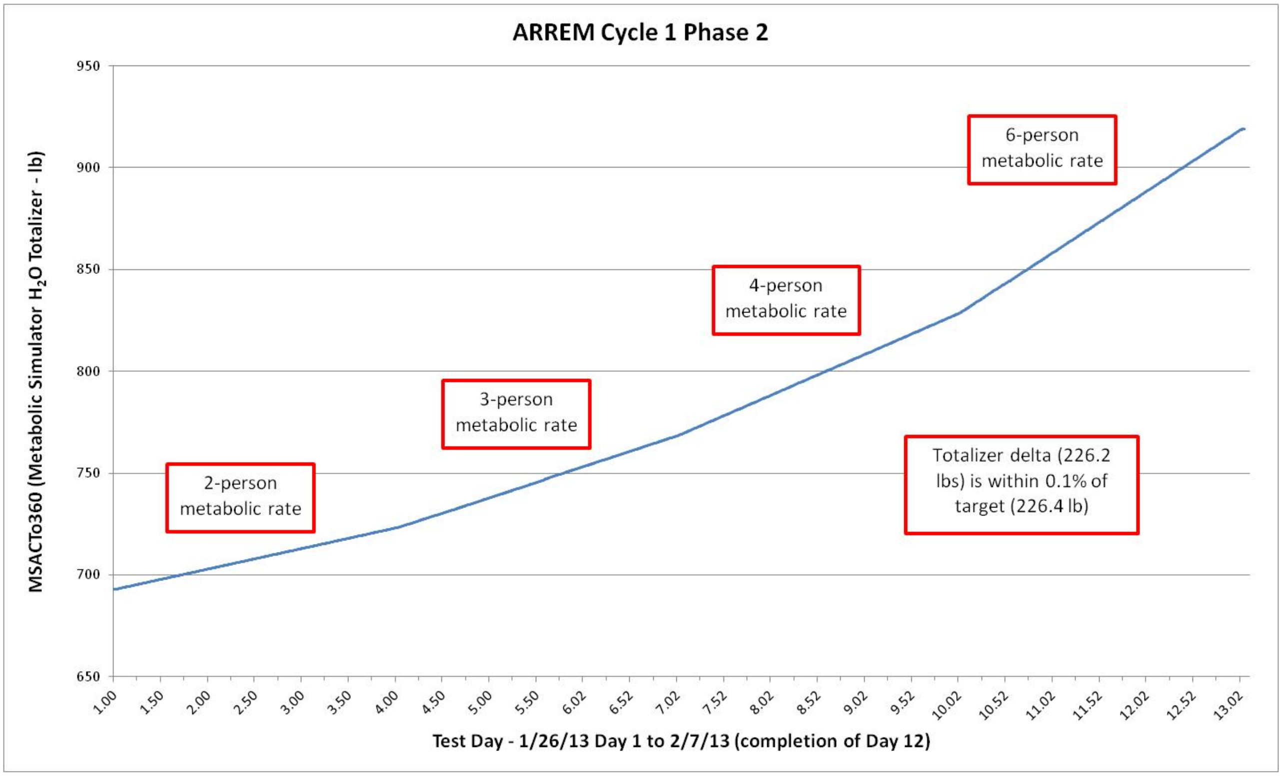
2-person Metabolic Rate

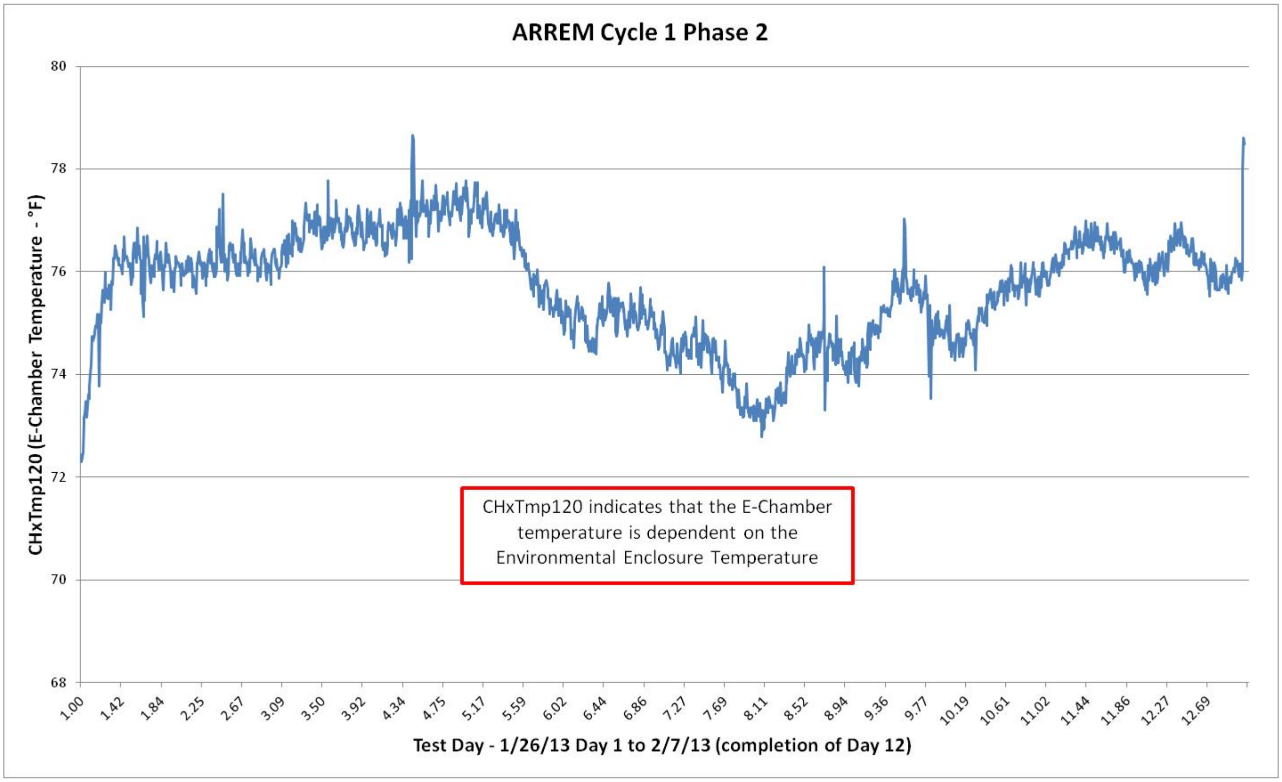
Even at the 6-person metabolic rate, the CDRA was able to keep the E-Chamber CO2 level below the 1% threshold for personnel exposure


ARREM Cycle 1 Phase 2
CIAMas660 (Contaminant Injection scale - g)
335
330
325
320
315
310
Scale delta indicates 1.415 g/day injection which is 25% of target (5.559 g/day)
Indicates volatile leakage
Indicates syringe withdrawal
1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.02 6.52 7.02 7.52 8.02 8.52 9.02 9.52 10.02 10.52 11.02 11.52 12.02 12.52 13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)


ARREM Cycle 1 Phase 2
MSACTo020 (Metabolic Simulator CO₂ Totalizer - lb)
240
220
200
180
160
140
120
100
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
Totalizer delta (99.6 lbs) is within 2.3% of target (97.36 lb)
1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50 5.00 5.50 6.02 6.52 7.02 7.52 8.02 8.52 9.02 9.52 10.02 10.52 11.02 11.52 12.02 12.52 13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)

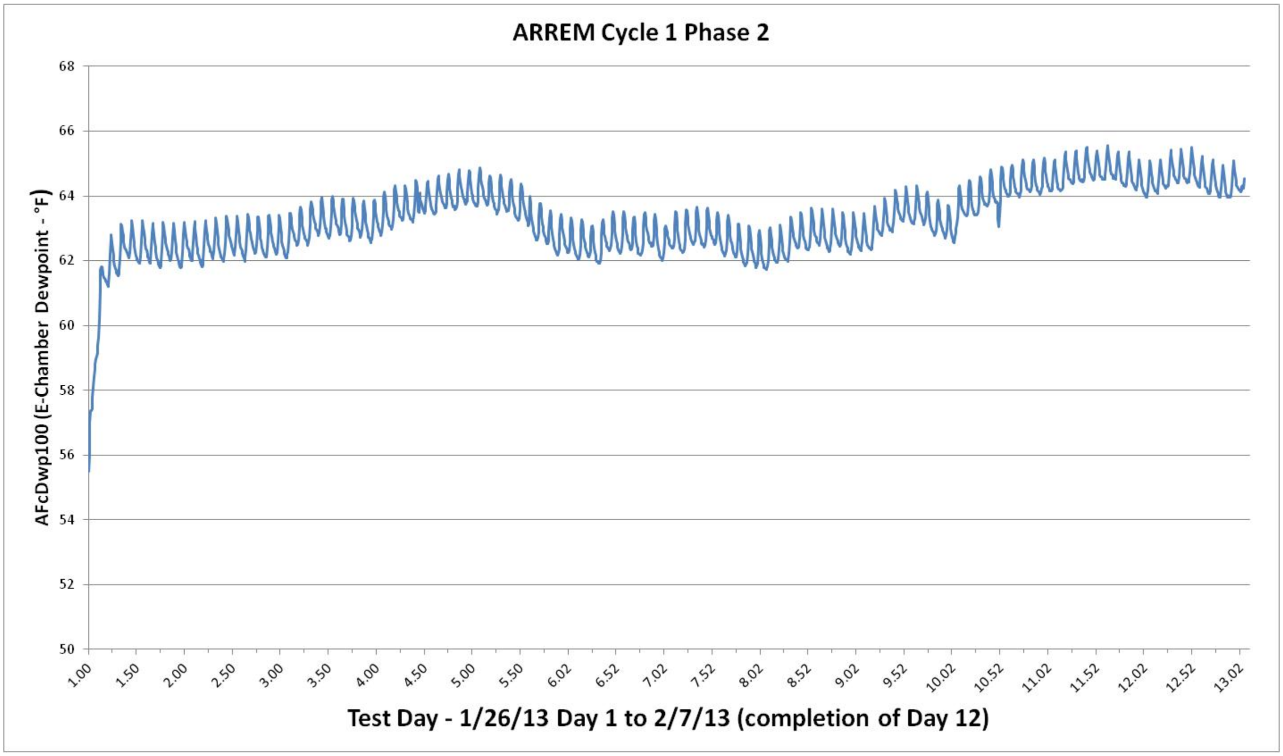

ARREM Cycle 1 Phase 2
MSACT0060 (Metabolic Simulator O2 Removal Totalizer - lb)
300
290
280
270
260
250
240
230
220
210
200
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.02
6.52
7.02
7.52
8.02
8.52
9.02
9.52
10.02
10.52
11.02
11.52
12.02
12.52
13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
Totalizer delta (82.445 lbs) is within 1.2% of target (83.469 lb)


ARREM Cycle 1 Phase 2
MSACT0360 (Metabolic Simulator H2O Totalizer - lb)
950
900
850
800
750
700
650
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
5.50
6.02
6.52
7.02
7.52
8.02
8.52
9.02
9.52
10.02
10.52
11.02
11.52
12.02
12.52
13.02
Test Day - 1/26/13 Day 1 to 2/7/13 (completion of Day 12)
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
Totalizer delta (226.2 lbs) is within 0.1% of target (226.4 lb)

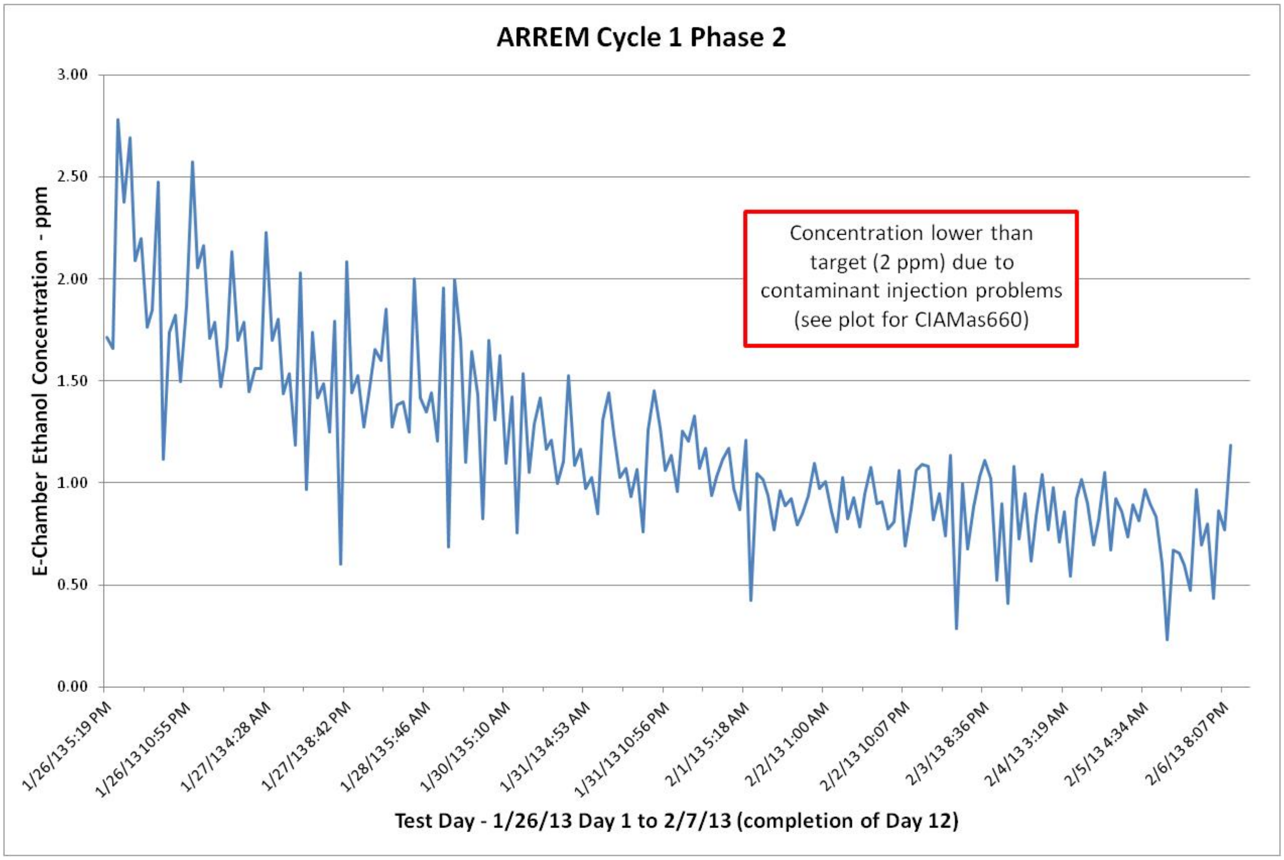


ARREM Cycle 1 Phase 2

CHxTmp120 indicates that the E-Chamber temperature is dependent on the Environmental Enclosure Temperature

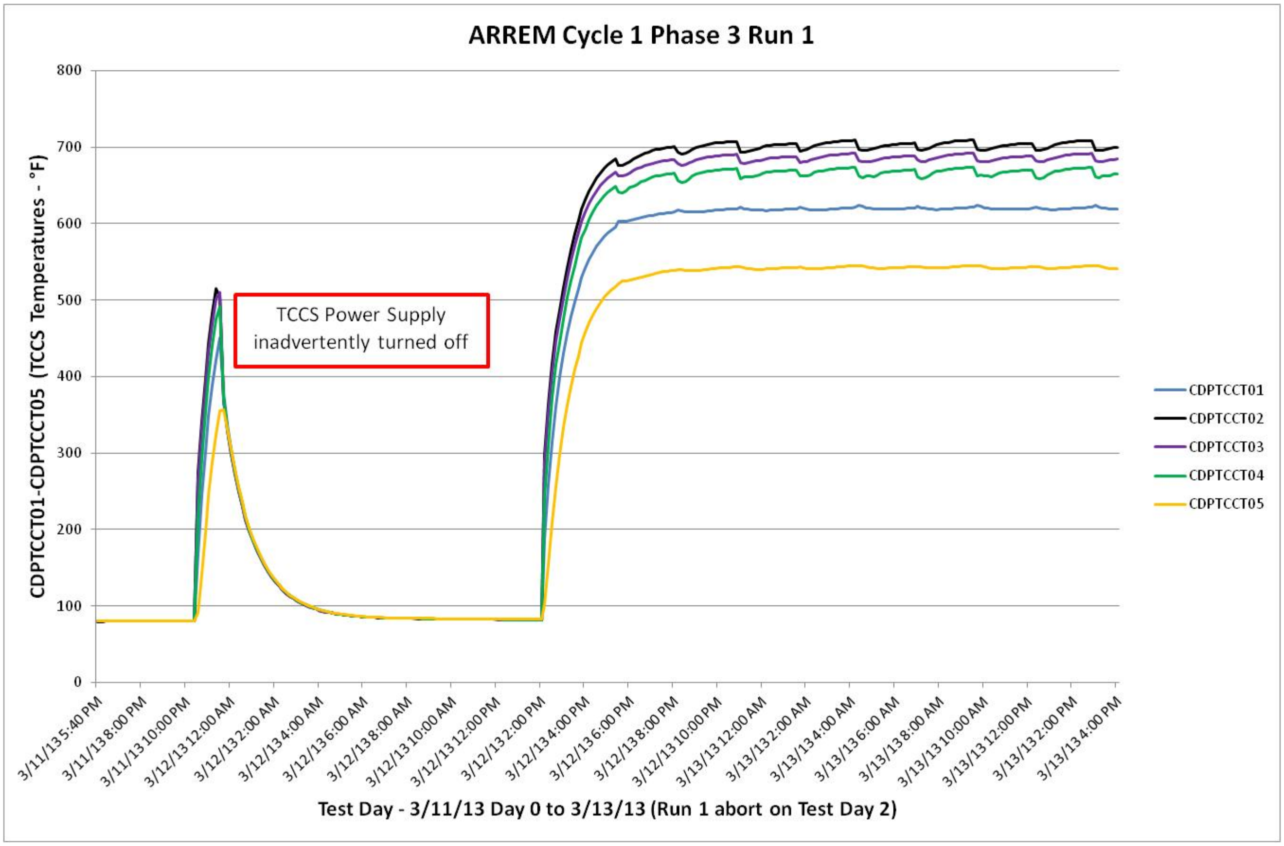


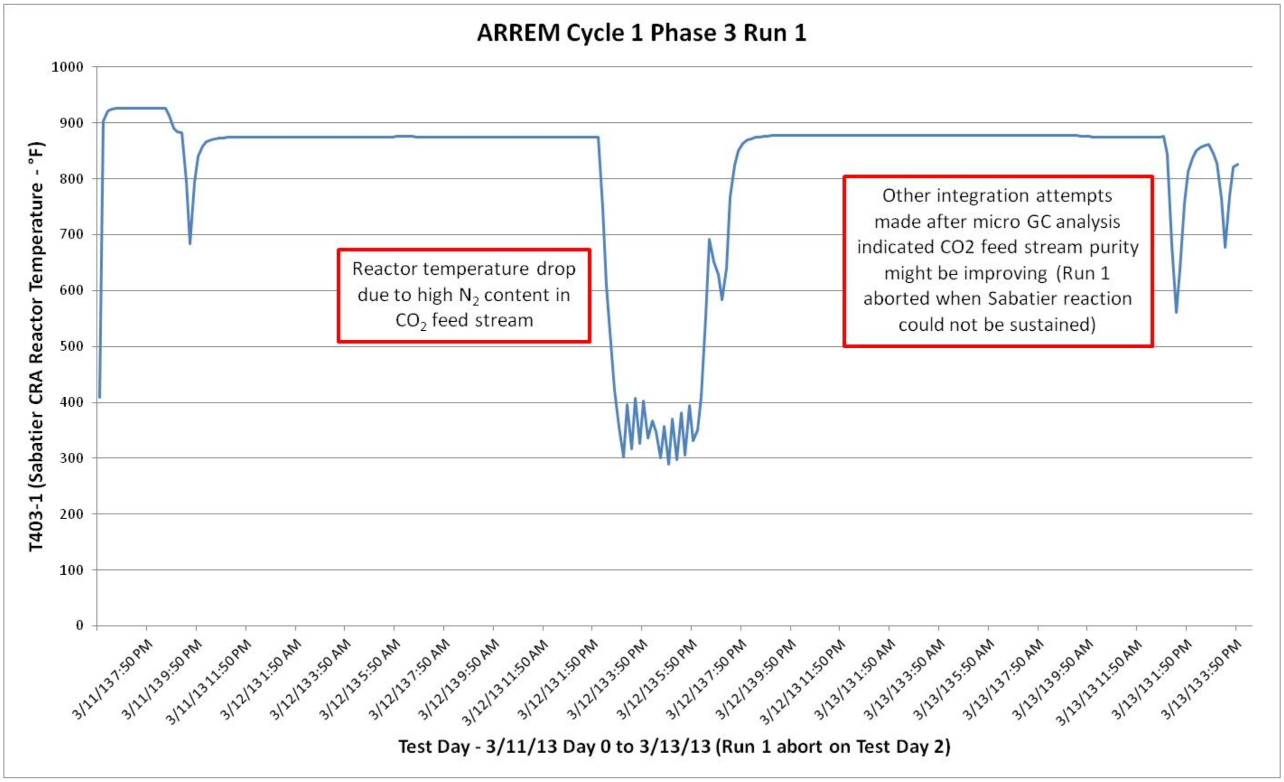
ARREM Cycle 1 Phase 2



Phase 3 Overview (3/12/13 to 3/28/13 – ES62-TCP-ARS-13-004): After Phase 2, the CDRA desiccant beds were re-packed. Two 3-point tests were performed before and after the re-packing operation. Previous data evaluation of contaminant propagation into the CO_2 product had already led to the conclusion that the Sabatier would be getting the quality of CO_2 required for safe operations (that conclusion would turn out to be in error – see the event summary for Run #1 below). The objective of Phase 3 was to replace the CRA simulator with the Sabatier CRA to reduce CO_2 and the OGA simulator with the OGA to produce O_2 for simulated crew consumption. An additional step in the loop closure process was also run during this test – the Methane Purification Assembly (MePA) – which took CH_4 product from the Sabatier CRA and removed H_2O vapor and unreacted gases from the stream. The outputs from the Sabatier CRA, MePA and OGA were diverted to a Hazardous Gas Pump which added N_2 in enough quantity to make the gas mixture safe to vent outside of Building 4755.

Run #1 (3/12/13 to 3/14/13 – ES62-TCP-ARS-13-004 Run #1): Day 0 operations progressed nominally until the very end of the day when the TCCS components power supply was inadvertently turned off. The HTCO was found to be cool the following morning. Tracing the problem (not knowing the power supply had been turned off) meant opening the EChamber door. Once engineers were satisfied everything was in order inside, they traced backwards until finding the power supply off. The TCCS HTCO was reactivated and the Principal Investigator approved with proceeding into Day 1 of the test while it was heating up. Manual contaminant injection was also performed to make up for what was lost when the EChamber door was opened. One of the highlights of Day 1 was supposed to be the integration of the CDRA/Sabatier CRA/OGA. However, when the valves were configured to send CO_2 from the accumulator and H_2 from the OGA to the Sabatier, the Sabatier reactor temperature immediately began to drop. The accumulator was flushed with facility CO_2 and the Sabatier was able to run on it but not for long. Eventually, micro GC analysis was done on the CO_2 from the accumulator and N_2 and O_2 contamination was found. Late on Test Day 1 more micro GC analysis was done and the data looked a little better. The Test Director decided to continue running through the night and try integrating the subsystems again the next day under the assumption that the CDRA was now putting higher purity CO_2 into the accumulator. A couple of attempts on Test Day 2 to integrate were unsuccessful and Run #1 was aborted on Test Day 2 to do some intensive and invasive leak checks on the plumbing between the CDRA and Sabatier CRA. Some leaks were found on the pressure side of the accumulator but none were found on the suction side. However, after the leak repairs to the pressure side were made, micro GC analysis of the accumulator revealed that the CDRA outlet was >98% CO_2.





Phase 3 Event Summary 3/19/13 – Test Day 0 – The facility supplies were brought up as normal with the intent of trying the Sabatier CRA/CDRA integration again before proceeding into Phase 3. The activation of the OGA and Oxygen Concentrator were moved to Test Day 1 to avoid unnecessary run time should the CO_2 interface fail again. The Sabatier CRA successfully ran integrated with the CDRA overnight on 3/19 leading to the decision to begin Phase 3 on 3/20/13.

3/20/13 – Test Day 1 – The first day of the 2-person metabolic rate had only a couple of minor anomalies during the day. Manual intervention (cracked fitting upstream of drain) was required to get Sabatier product H_2O to drain (probable vapor lock in the gravity drain system). While this repair was being made, a hose in the contaminant injection system was pulled loose (lost about 20 minutes of contaminant injection). Overnight operations of the Sabatier CRA were lost due to a procedural error. Appendix E was added to procedure to clarify Sabatier CRA and OGA "handshaking" operations. The sample schedule was re-worked per direction from the Principal Investigator to collect 3 data points (instead of 4) for each sample port during a 2-day run (instead of 3) at each metabolic rate. This shortened the test by 4 days.

3/21/13 – Test Day 2 – 28 minutes of Sabatier CRA/OGA integrated operations were lost because a secondary computer with OGA operations residing on it was re-booted about the same time as the primary computer requested data from the secondary computer. This caused the execution rate of the primary computer to slow down which was interpreted by the Sabatier CRA as "OGA not ready". The only other off nominal event was the Principal Investigator noticing that the contaminant injection lines had bubbles in them. The lines were flushed and monitored to verify that they were clear all the way to the manifold.

3/22/13 – Test Day 3 – The first day of operations at the 3-person metabolic rate was nominal with no anomalies noted.

3/23/13 – Test Day 4 – Nominal day with no anomalies noted.

3/24/13 – Test Day 5 – The first day of operations at the 4-person metabolic rate was nominal with a couple of minor anomalies noted. 1) AFcO2_100 (EChamber O_2 level) rose from 21.1% to 21.5% on Test Day 5. The O_2 removal rate was increased in order to compensate. When troubleshooting this occurrence, the test conductor noted that the calculation for O_2 removal was based on 100% purity (data

showed it was about 93%) which led to the imbalance between O_2 removal and O_2 generation rates and the rise in EChamber O_2. In the evening on Test Day 5, the contaminant injection syringe got stuck during withdrawal. A 1 ml manual injection was performed to compensate for lost time during the repair.
3/25/13 – Test Day 6 – Nominal day with only minor anomalies noted. Adjusted O_2 removal rate again to try and bring EChamber O_2 level down. The OGA had a shutdown during activation which was quickly overcome with a second try. The EChamber main air duct fan speed was lowered to try and help lower the CDRA inlet dew point as it approached the high limit of 50 °F.
3/26/13 – Test Day 7 – First day of supposed 6-person metabolic rate was not completely achieved. The OGA and the Sabatier CRA were left at 4-person rate to bring down EChamber O_2 level. The CDRA processed at the 6-person rate. The Sabatier was moved up to the 6-person rate for overnight operations while the OGA simulator was set to 0. This achieved a significant lowering of the EChamber O_2 to less than 21%. There was a spontaneous host control computer re-boot at 2148 by MSFC to push a software update. NOTE: the host control computer was supposed to be on a list to avoid these actions. The CDRA shut down but the Sabatier CRA and OGA did not (their control software resides on different computers). It took about 1 hour to get everything back up and running prior to setting up the overnight operations (OGA to shutdown and Sabatier CRA to H_2 from facility).
3/27/13 – Test Day 8 – Full integrated operations at the 6-person metabolic rate were achieved on Test Day 8. In the evening, there was a Serial input/output error for AFcPrs320 (Hazardous Gas Pump Pressure) that could not be cleared without shutting down the host control computer. This in turn caused about a 2 hour delay in getting CDRA re-started because of data issues and a high pump inlet pressure. The CO2 Management Assembly was mistakenly left in Manual mode after the host control computer re-boot which allowed the Space Vacuum Simulator to vent up. The last 2 GC samples of the day were moved to the morning of 3/28/13 because the upset in TCCS operations would have artificially affected the data.
3/28/13 – completion of Test Day 8 – the condensate drain and sample and the leftover GC samples were completed by 1000 and test shutdown was accomplished at 1026 on 3/28/13.

Phase 3 Test Results The EChamber atmosphere ethanol concentration stayed below 2 ppm. Post-Cycle 1 investigation showed that the contaminant injection system put in only about 25% of the target rate during Phase 3. The plot for CIAMas660 (see below) showed erratic behavior when compared to Phase 2. The most obvious sign that there was a problem was the bubbles that were found in the line. The TCCS showed the ability to keep the EChamber atmosphere ethanol concentration low but it was not challenged to anywhere near its removal capacity. The CO_2 Management Assembly worked according to the control logic which this time allowed the Sabatier CRA to run continuously on CDRA produced CO_2 until the 6-person metabolic rate. At the 6-person metabolic rate there were both anomalous and “naturally” occurring – per compressor logic – empty accumulator conditions. Despite a few handshaking problems with the OGA, the Sabatier CRA processed nominally with an average H_2O production rate of 3.06 lb/day. This was approximately 81% of the target production based on the different metabolic rate settings. There were several process interruptions (especially at the 6-person rate) which account for much of the delta between theoretical and actual. The OGA processed nominally with an average O_2 production rate of 3.75 lb/day. This was approximately 97% of the target production based on the different metabolic rate settings. The Metabolic Simulator CO_2 injection and H_2O injection performed nominally at the 2-, 3-, 4-, and 6-person rates. O_2 Removal via the SeQual oxygen concentrator was approximately 20% higher than the target as adjustments were made during the test to overcome the high O_2 level in the EChamber. A partial reason for this imbalance was discovered on Test Day 5: the O_2 removal rate was based on 100% purity when in actuality it was around 93%. In future tests, this occurrence should be avoided with this accounted for. Facility dewpoint sensors read in the high 40’s to mid 50’s ºF compared to the main sensor (AFcDwp100) which read in the low to mid 60’s ºF. A redundant CO_2 (AFcCO2101) sensor ranged from about 0.3% to 1.0% (corresponding to the changing metabolic rates) which is in agreement with the main sensor (AFcCO2100). The CDRA shutdowns (see Phase 3 Event Summary for Days 7 and 8) made the EChamber CO2 level data more erratic than expected late in the test. See plots of

AFcDwp100 and AFcCO2100 in the results section below. The average humidity condensate removed from the EChamber was as follows: 9.3 lb/day at the 2-person metabolic rate, 14.08 lb/day at the 3-person rate, 18.93 lb/day at the 4-person rate, and 27.75 lb day at the 6-person rate. Condensate sampling results for the metabolic rates were as follows: 2-person Methanol – 8 ppm, Ethanol – 47.8 ppm, and TOC – 43.8 ppm; 3-person Methanol – 8.55 ppm, Ethanol – 29.75 ppm, and TOC – 33.7 ppm; 4-person Methanol – 9.05 ppm, Ethanol – 33 ppm, and TOC – 29.65 ppm; and 6-person Methanol – 7.35 ppm, Ethanol – 28.6 ppm, and TOC – 25 ppm.

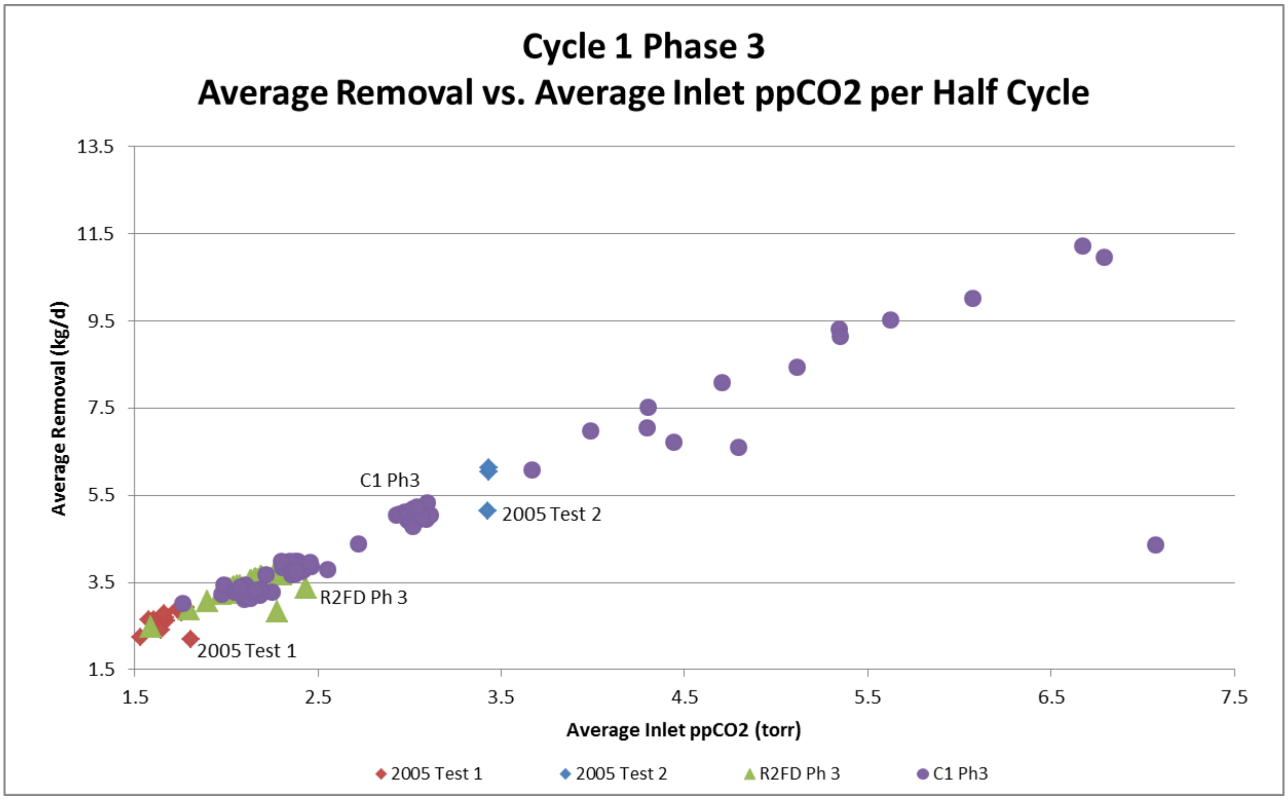
Prior to the start of Cycle 1 Phase 3 testing, the sorbent material in the desiccant beds was upgraded from Grace Davison Grade 40 silica gel to the new material, Grace Davison Sylobead SG B125. The POIST CDRA is now fully packed with the new materials. In keeping with the previous testing, three comparisons for CDRA were made: 1) compare performance to previous tests to determine that hardware is performing within an acceptable range, 2) compare test data with the CDRA specification based on inlet concentration, and 3) compare CDRA performance with the old materials to performance with the new materials.

The TCCS, which is tied into the CDRA, was operating during this phase. The plot shown in NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

Cycle **1 Phase 3 CDRA POIST Comparison**

NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

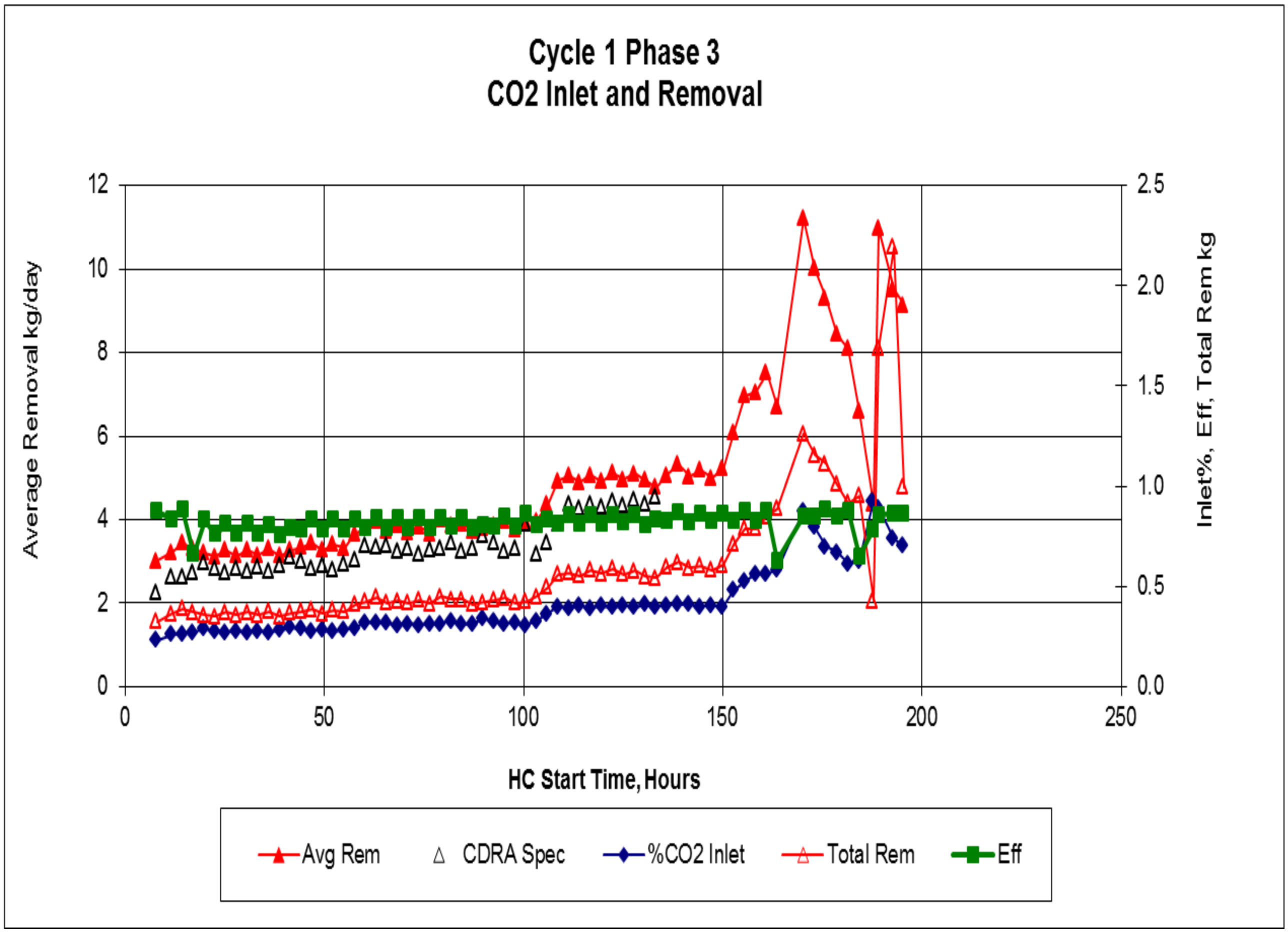
Figure 8: Cycle 1 Phase 3 CDRA POIST Comparison shows that a small drop in performance was observed during this phase. The TCCS flows into the inlet of the CDRA at a higher temperature than the 40-50°F required temperature for the CDRA which created a slight increase in inlet temperature and dew point. In addition, the TCCS pulls a 3 cfm flow from the CDRA process flow prior to the flow entering the adsorbent beds. It was later discovered that the TCCS flow is taken downstream of the flow meter. While the data showed the CDRA adsorbent beds received the full 20.4 cfm process flow, in actuality it was only receiving 17.4 cfm. The higher inlet dew point and inlet temperature along with the decreased flow rate entering the adsorbent beds could explain the decreased performance observed during this phase.



Cycle 1 Phase 3 CDRA POIST Comparison

NOTE: Old Test 1 and Old Test 2 (2005) data points were acquired during the Integrated Evaluation of Air Revitalization System Components testing and documented in "Integrated Evaluation of Air Revitalization System (ARS) Components: 4-Bed Molecular Sieve (4BMS), Mechanical Compressor Engineering Development Unit (CEDU), Temperature Swing Adsorption Compressor (TSAC), Sabatier Engineering Development Unit (SEDU)" (September, 2010).

Although a decrease in overall performance of the CDRA during Cycle 1 Phase 3 was observed, the graph in **Error! Reference source not found.** shows that CDRA met the CO2 removal requirements. It should be noted that the data on the graph after about the 160th hour is not representative of the CDRA performance during the last hours of the test. The data acquisition and control computer malfunctioned at this point and the data is not wholly reliable from that point on.

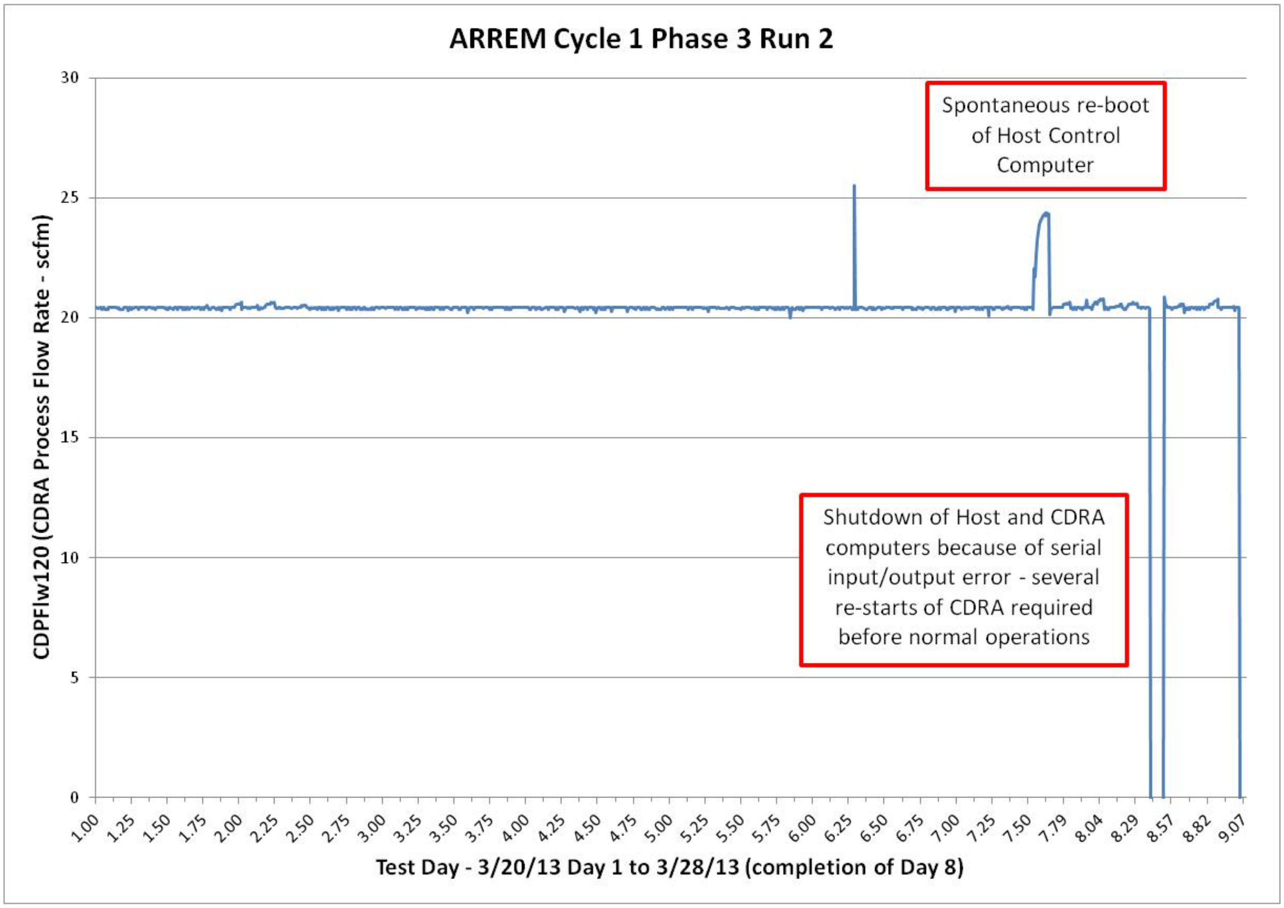


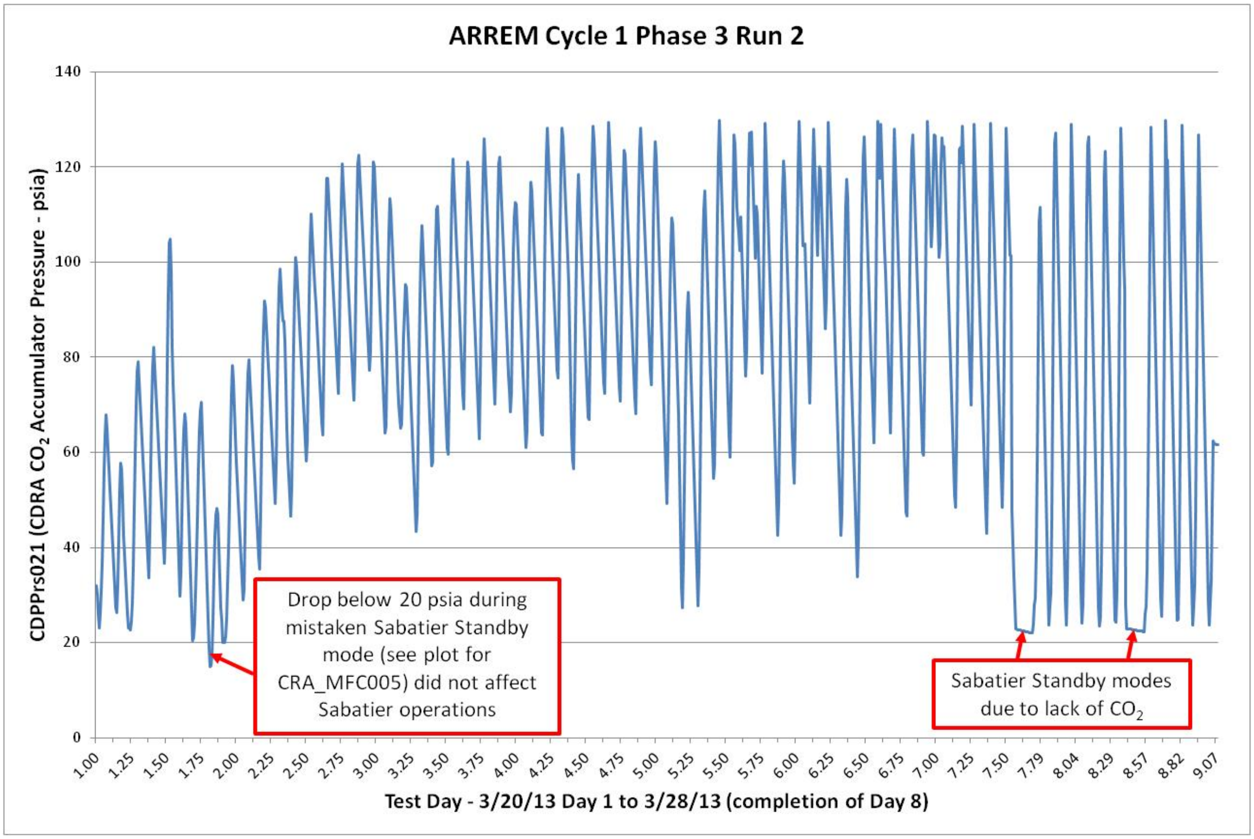
Cycle 1 Phase 3 Carbon Dioxide Removal Performance Compared to CDRA specification.

Table 2: Cycle 1 Phase 3
Humidity Condensate
(NOTE: ND is Not Detected)

Analyte	Test Day							
	1	2	3	4	5	6	7	8
Condensate (lb)	9.15	9.45	14.15	14	18.55	19.3	26.3	29.2
Methanol (ppm)	9.3	6.7	10.6	6.5	9.1	9	7.5	7.2
Ethanol (ppm)	55.6	40	36.3	23.2	32.8	33.2	29.2	28
Acetone (ppm)	<1	<1	<1	<1	<1	<1	<1	<1
1-propanol (ppm)	ND	ND	ND	<1	ND	ND	ND	ND
2-propanol (ppm)	2.6	1.8	1.4	<1	1.18	1.2	1	<1

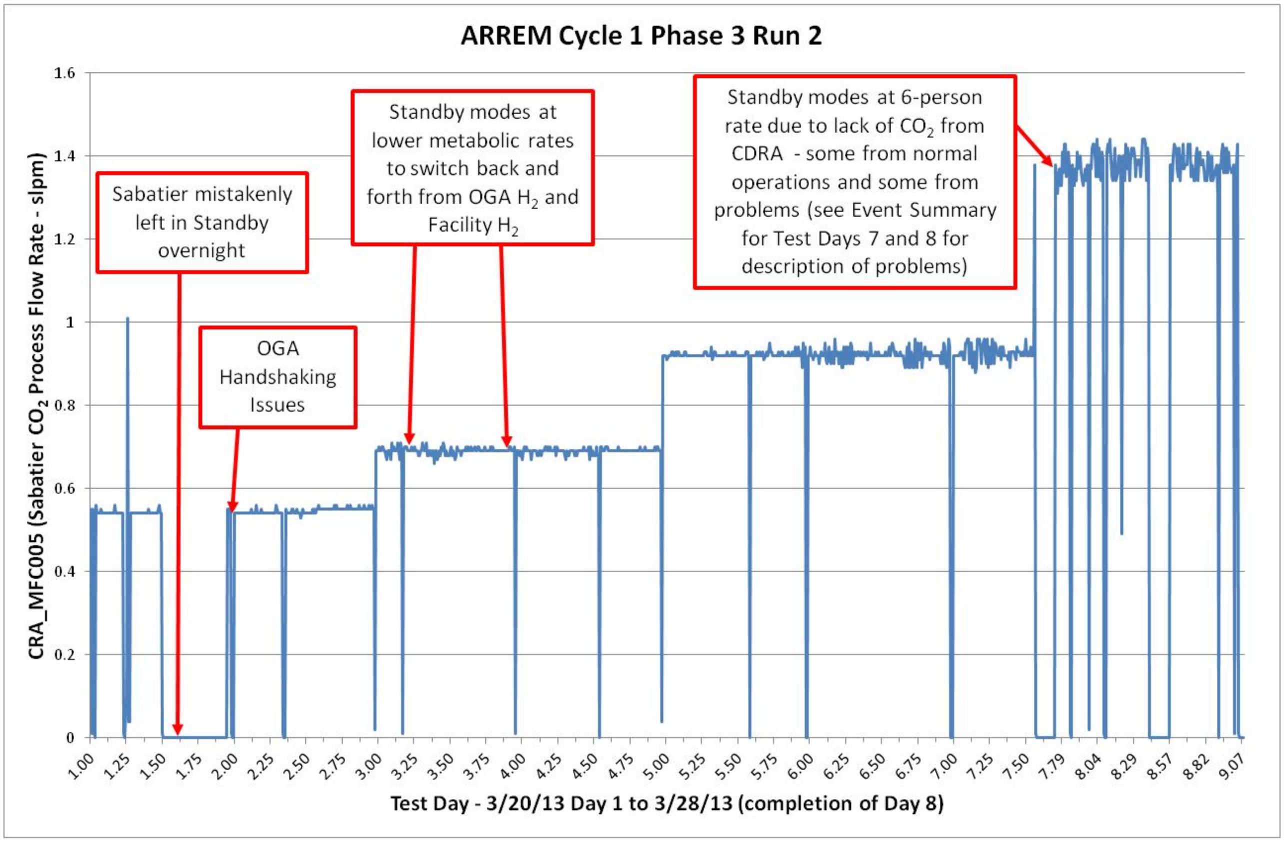
	Test Day							
Analyte	1	2	3	4	5	6	7	8
2-methyl-2-propanol (ppm)	ND	ND	ND	ND	<1	<1	<1	ND
2-butanol (ppm)	ND	ND	ND	ND	ND	ND	ND	ND
Total Organic Carbon (ppm)	50	37.6	35.3	32.1	29.8	29.5	25.9	24.1





Drop below 20 psia during mistaken Sabatier Standby mode (see plot for CRA_MFC005) did not affect Sabatier operations

Sabatier Standby modes due to lack of CO_2

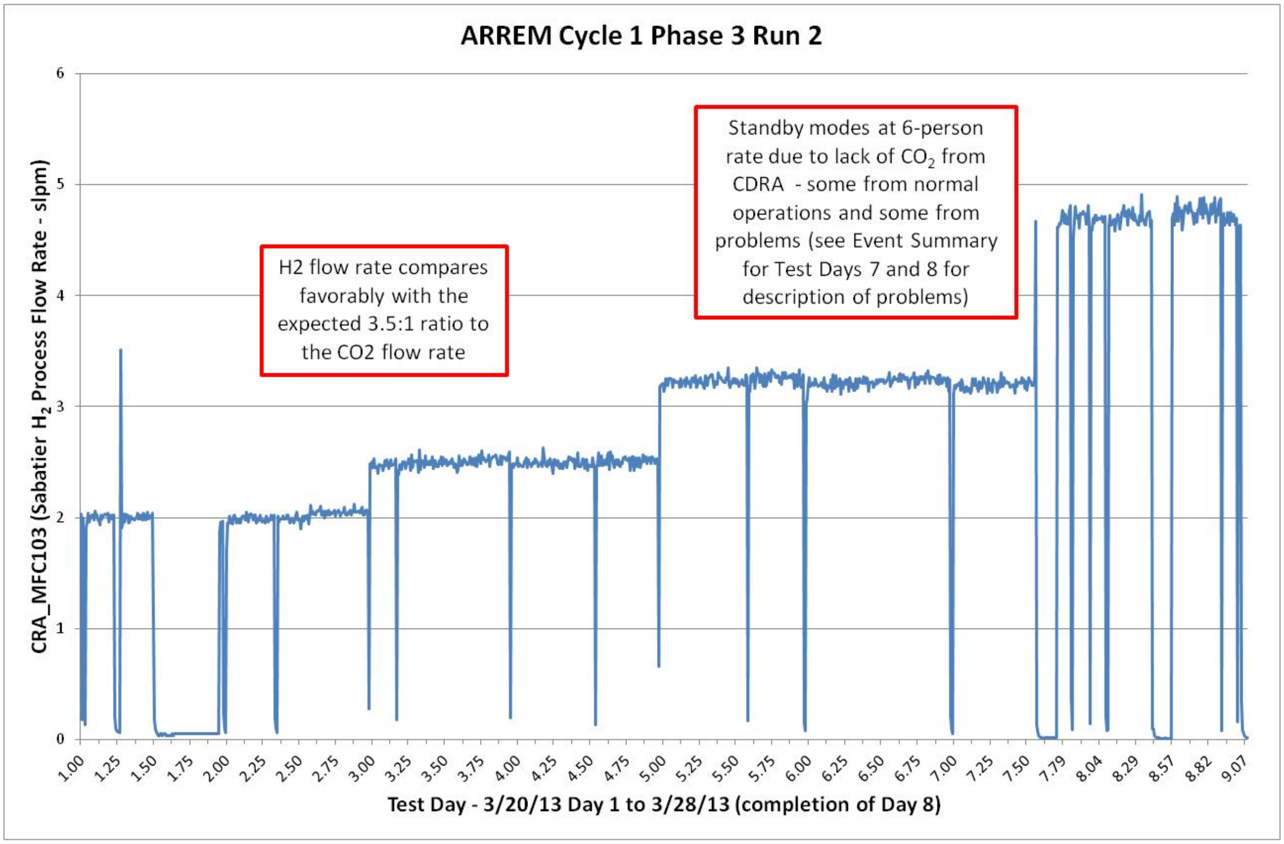


Sabatier mistakenly left in Standby overnight

OGA Handshaking Issues

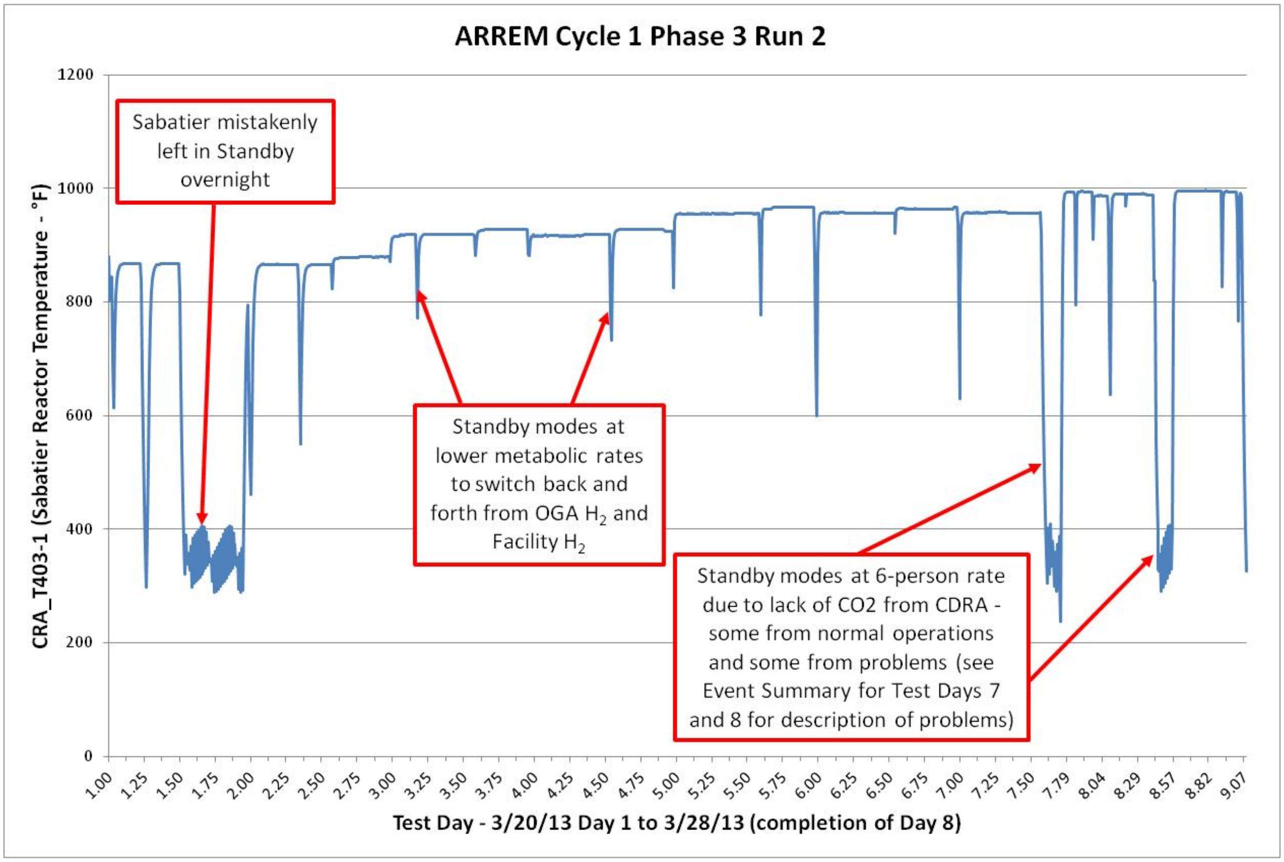
Standby modes at lower metabolic rates to switch back and forth from OGA H_2 and Facility H_2

Standby modes at 6-person rate due to lack of CO_2 from CDRA - some from normal operations and some from problems (see Event Summary for Test Days 7 and 8 for description of problems)



H2 flow rate compares favorably with the expected 3.5:1 ratio to the CO2 flow rate

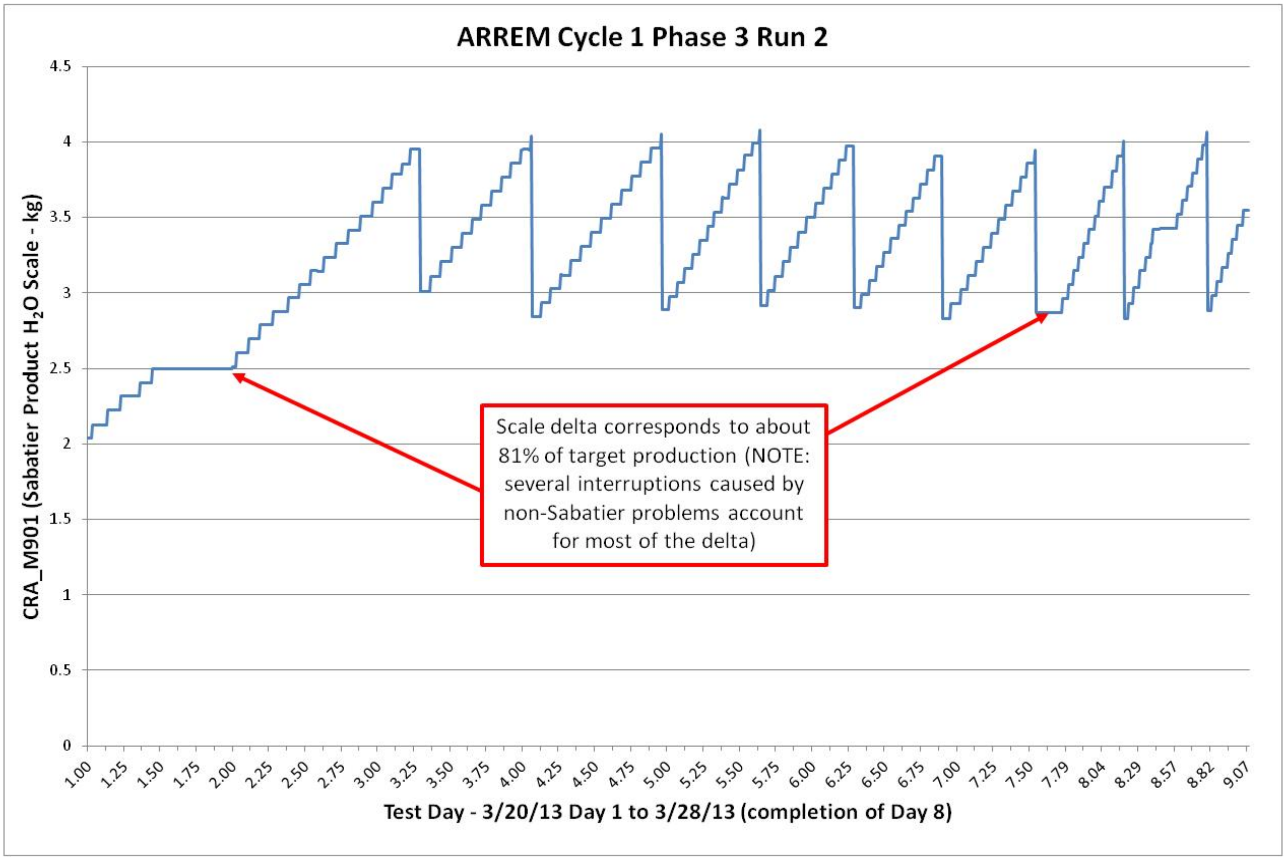
Standby modes at 6-person rate due to lack of CO_2 from CDRA - some from normal operations and some from problems (see Event Summary for Test Days 7 and 8 for description of problems)



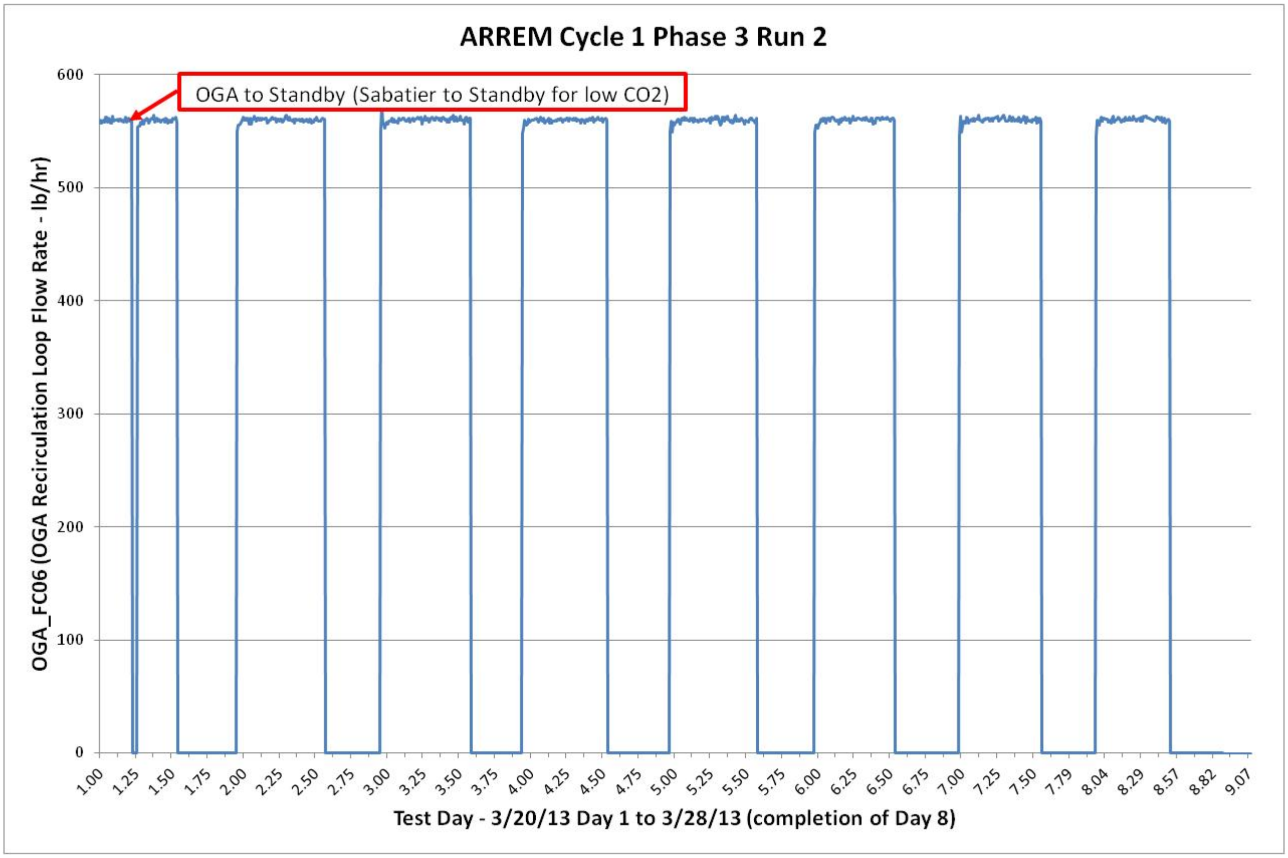
Sabatier mistakenly left in Standby overnight

Standby modes at lower metabolic rates to switch back and forth from OGA H_2 and Facility H_2

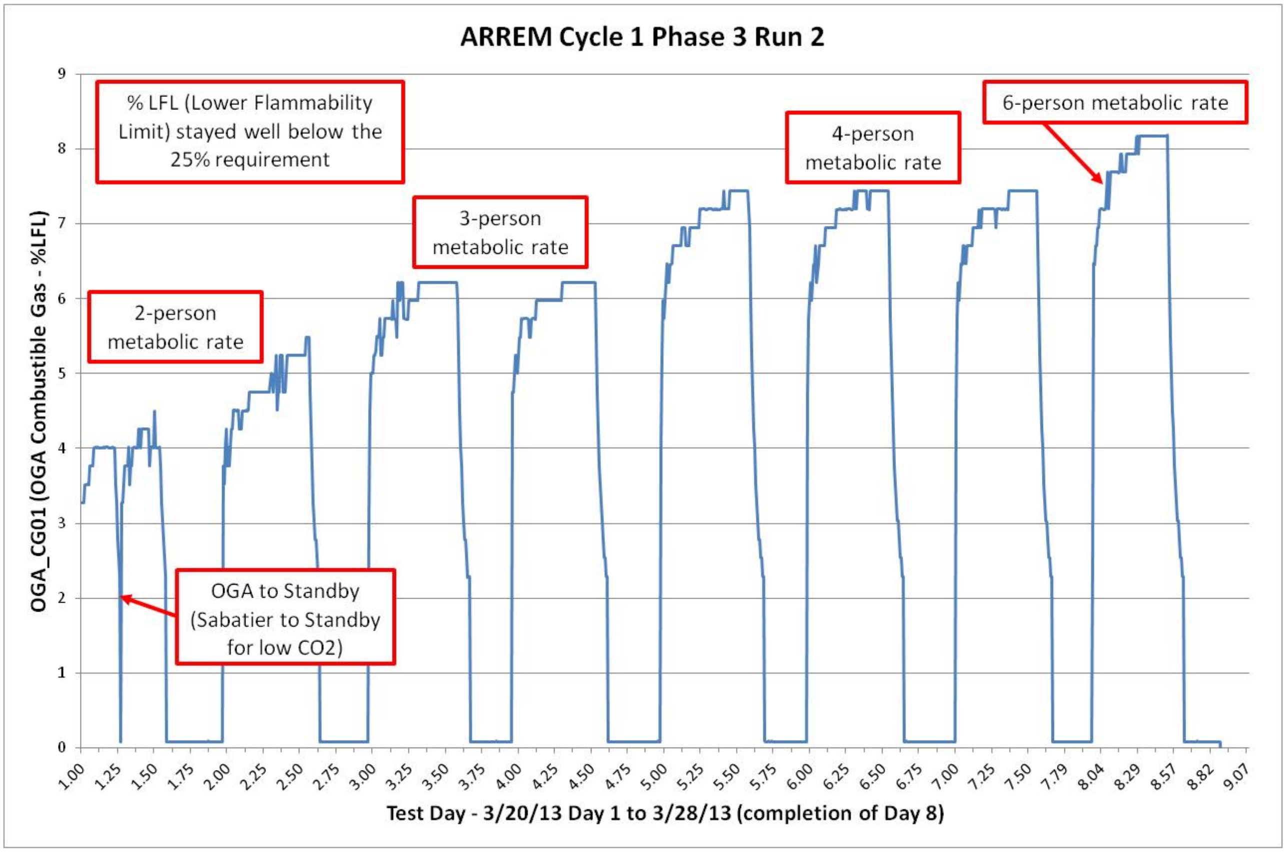
Standby modes at 6-person rate due to lack of CO2 from CDRA - some from normal operations and some from problems (see Event Summary for Test Days 7 and 8 for description of problems)

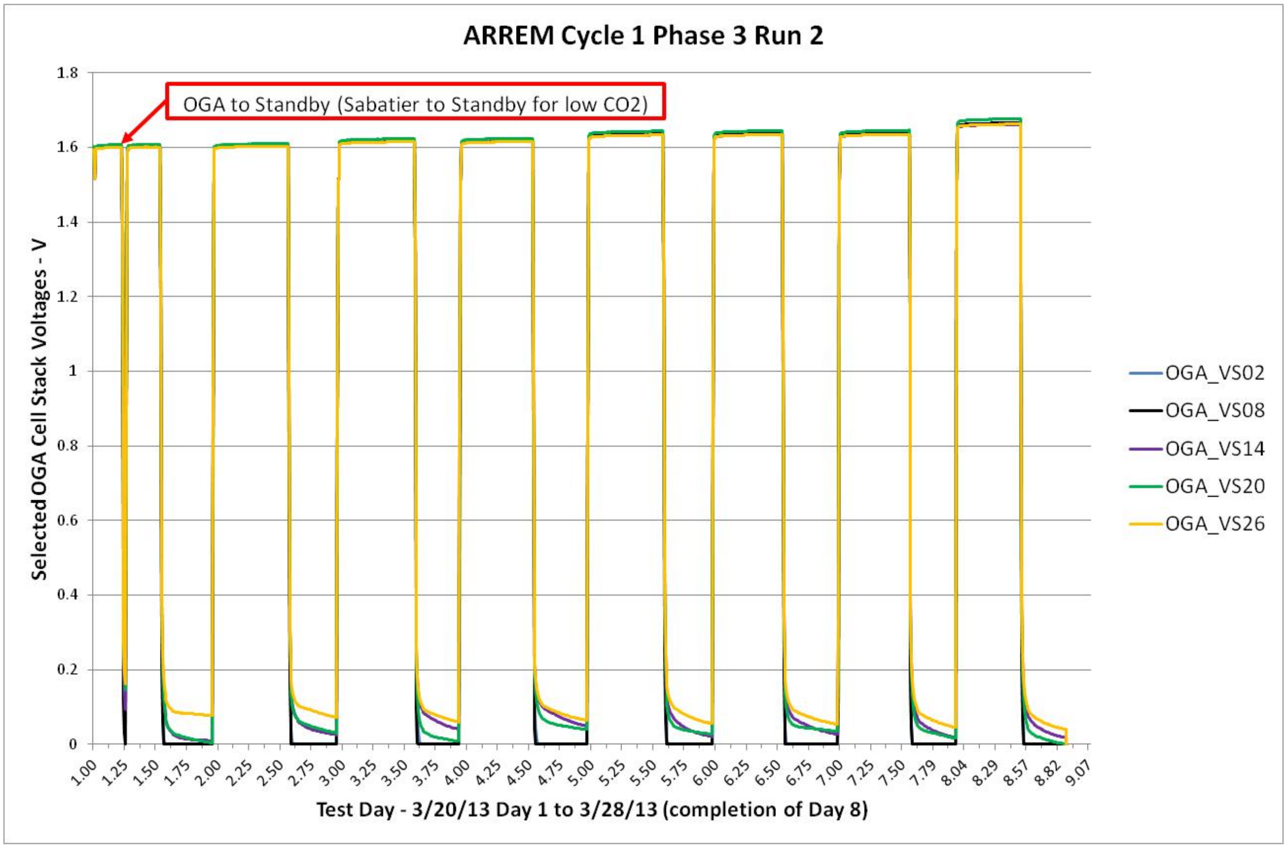


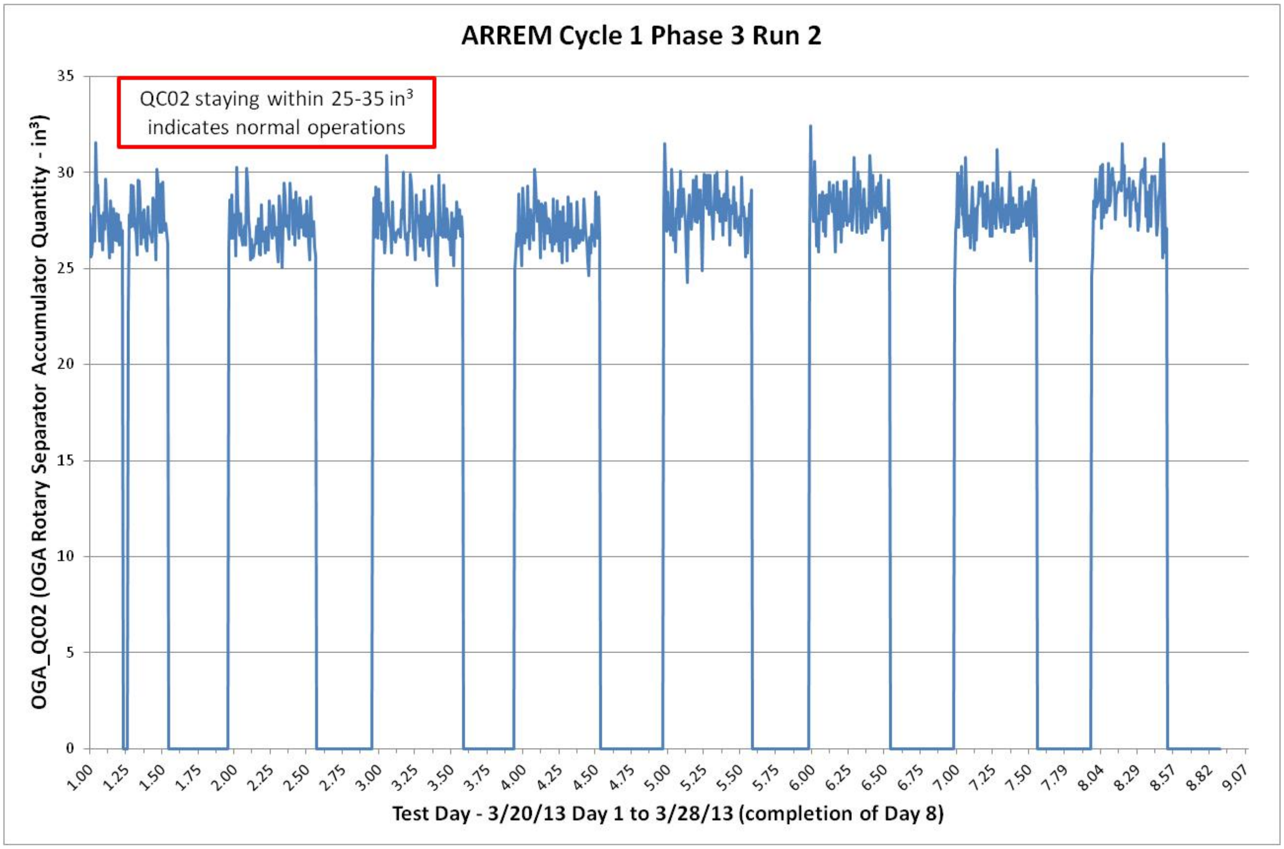
Scale delta corresponds to about 81% of target production (NOTE: several interruptions caused by non-Sabatier problems account for most of the delta)

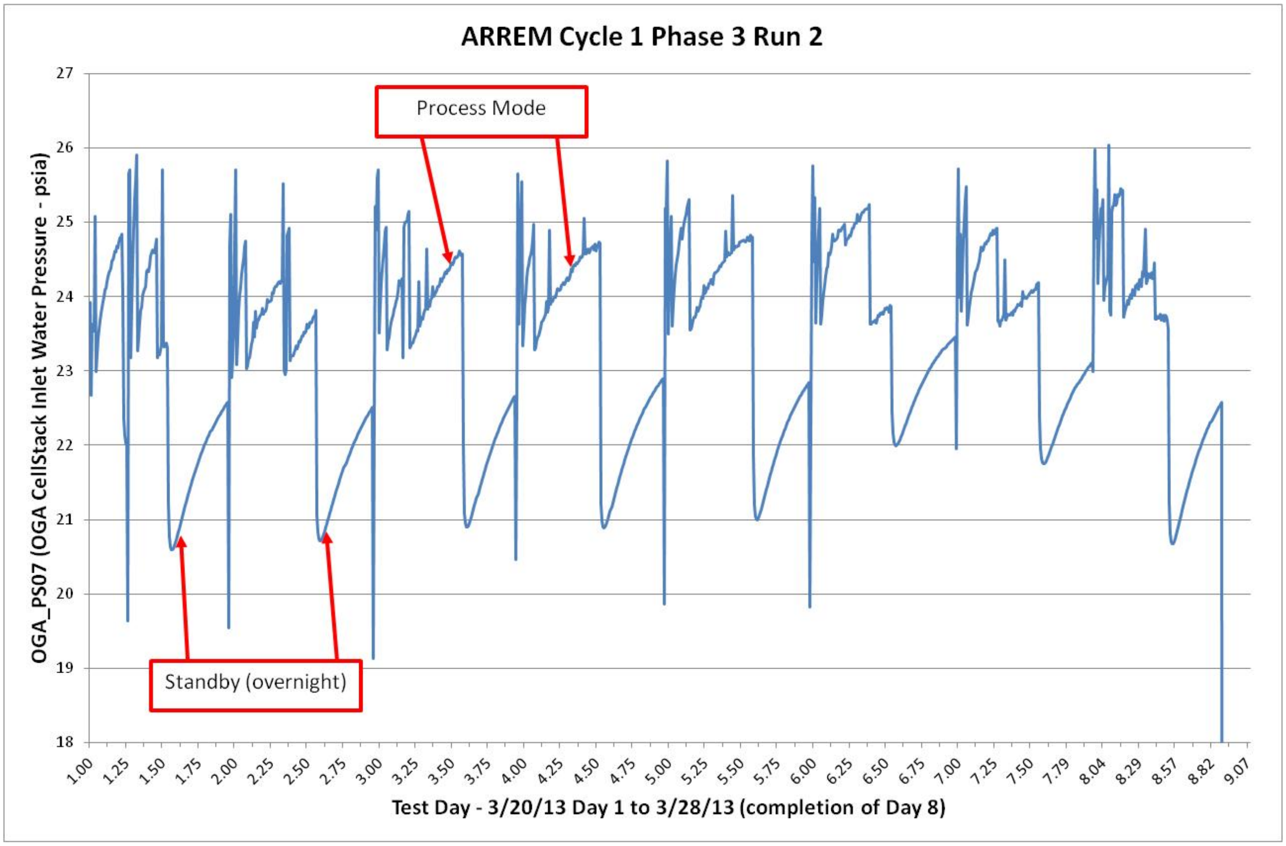


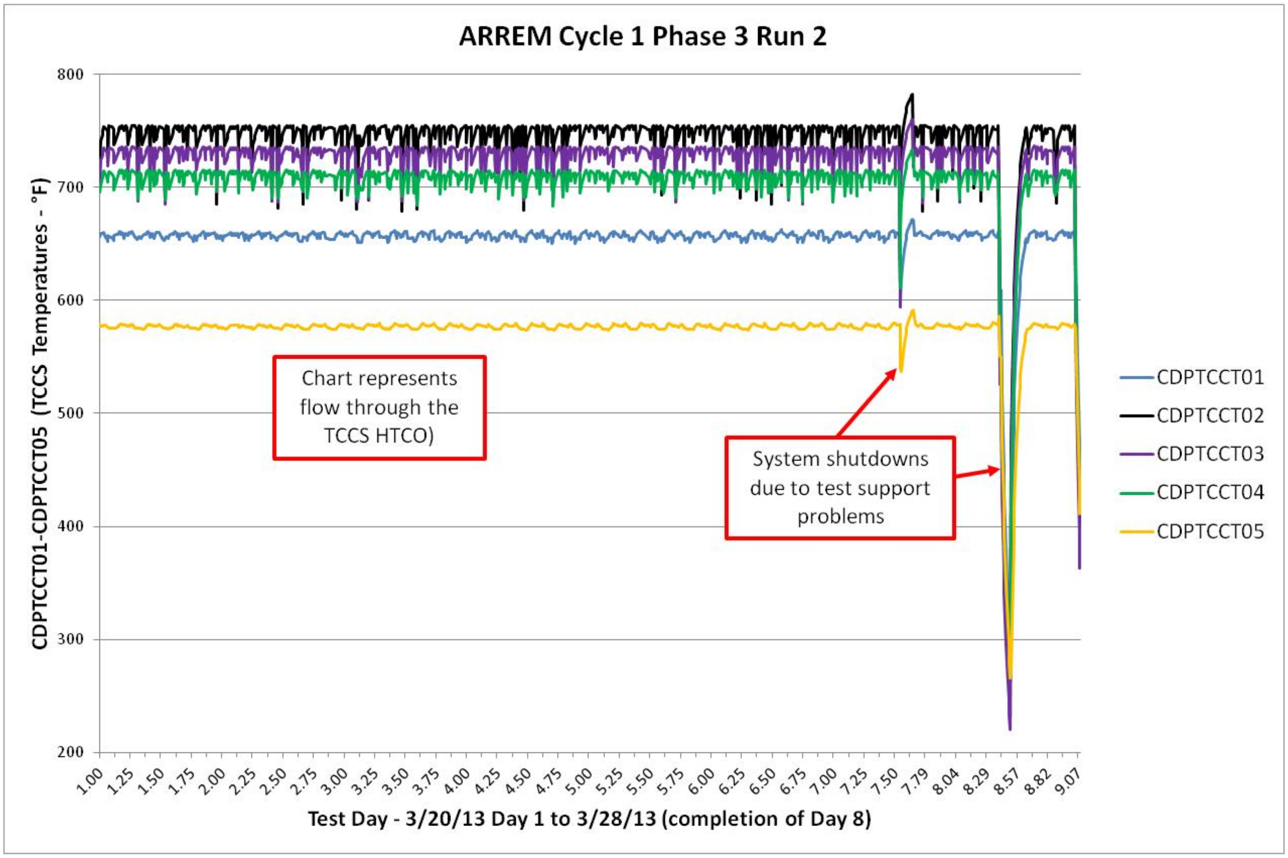
OGA to Standby (Sabatier to Standby for low CO2)


ARREM Cycle 1 Phase 3 Run 2
OGA_CG01 (OGA Combustible Gas - %LFL)
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
% LFL (Lower Flammability Limit) stayed well below the 25% requirement
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
OGA to Standby (Sabatier to Standby for low CO2)
0
1
2
3
4
5
6
7
8
9
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07


ARREM Cycle 1 Phase 3 Run 2
Selected OGA Cell Stack Voltages - V
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
OGA to Standby (Sabatier to Standby for low CO2)
OGA_VS02
OGA_VS08
OGA_VS14
OGA_VS20
OGA_VS26
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07


ARREM Cycle 1 Phase 3 Run 2
QC02 staying within 25-35 in³ indicates normal operations
OGA_QC02 (OGA Rotary Separator Accumulator Quantity - in³)
35
30
25
20
15
10
5
0
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)

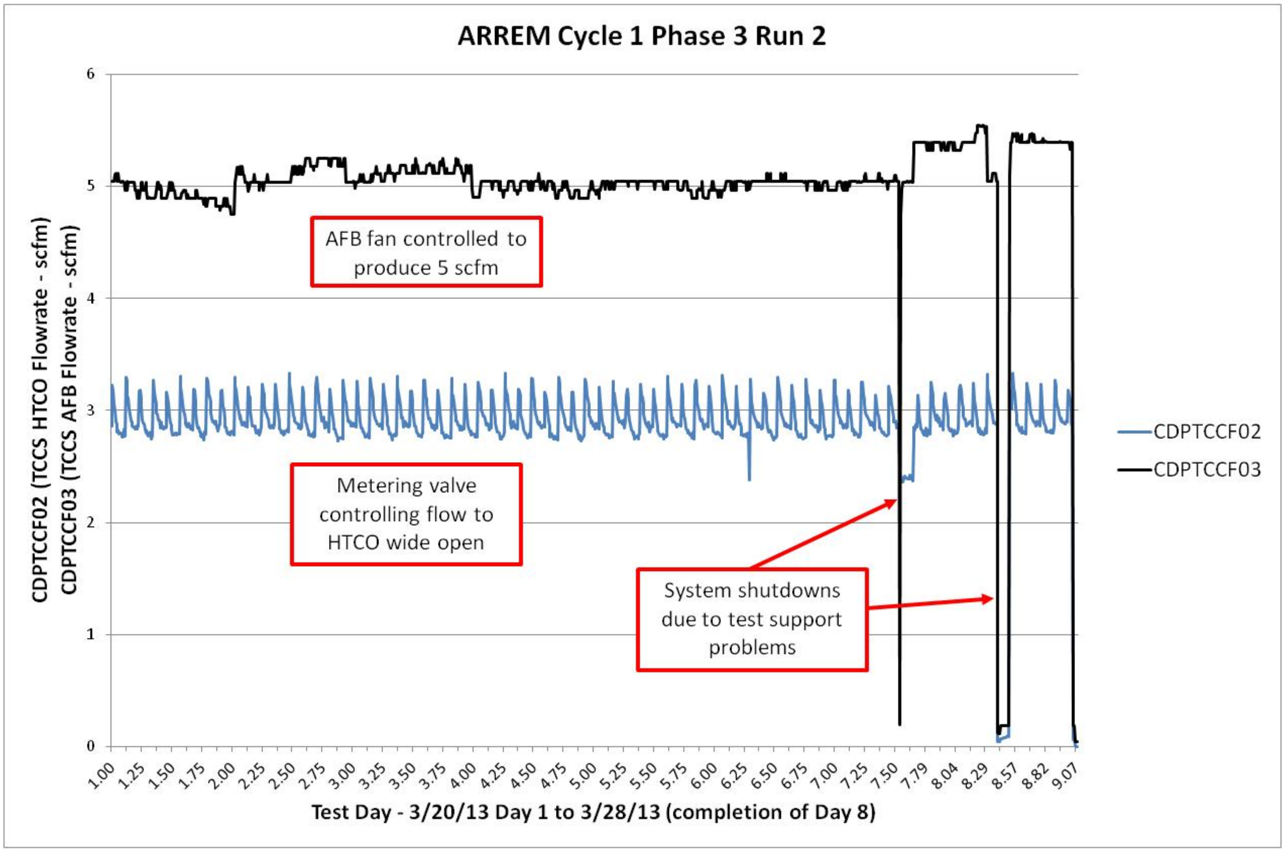

ARREM Cycle 1 Phase 3 Run 2
Process Mode
Standby (overnight)
OGA_PS07 (OGA CellStack Inlet Water Pressure - psia)
27
26
25
24
23
22
21
20
19
18
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)



ARREM Cycle 1 Phase 3 Run 2

Chart represents flow through the TCCS HTCO)

System shutdowns due to test support problems

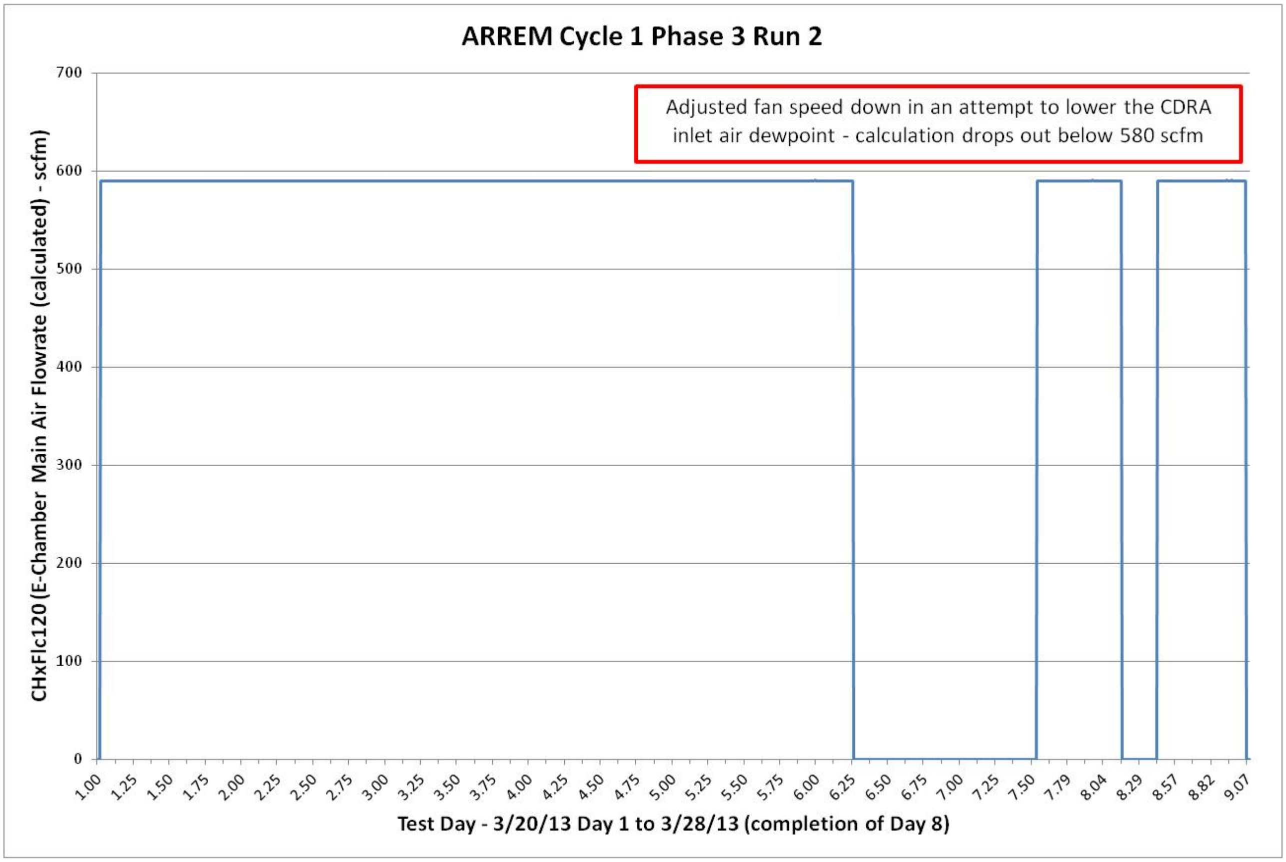


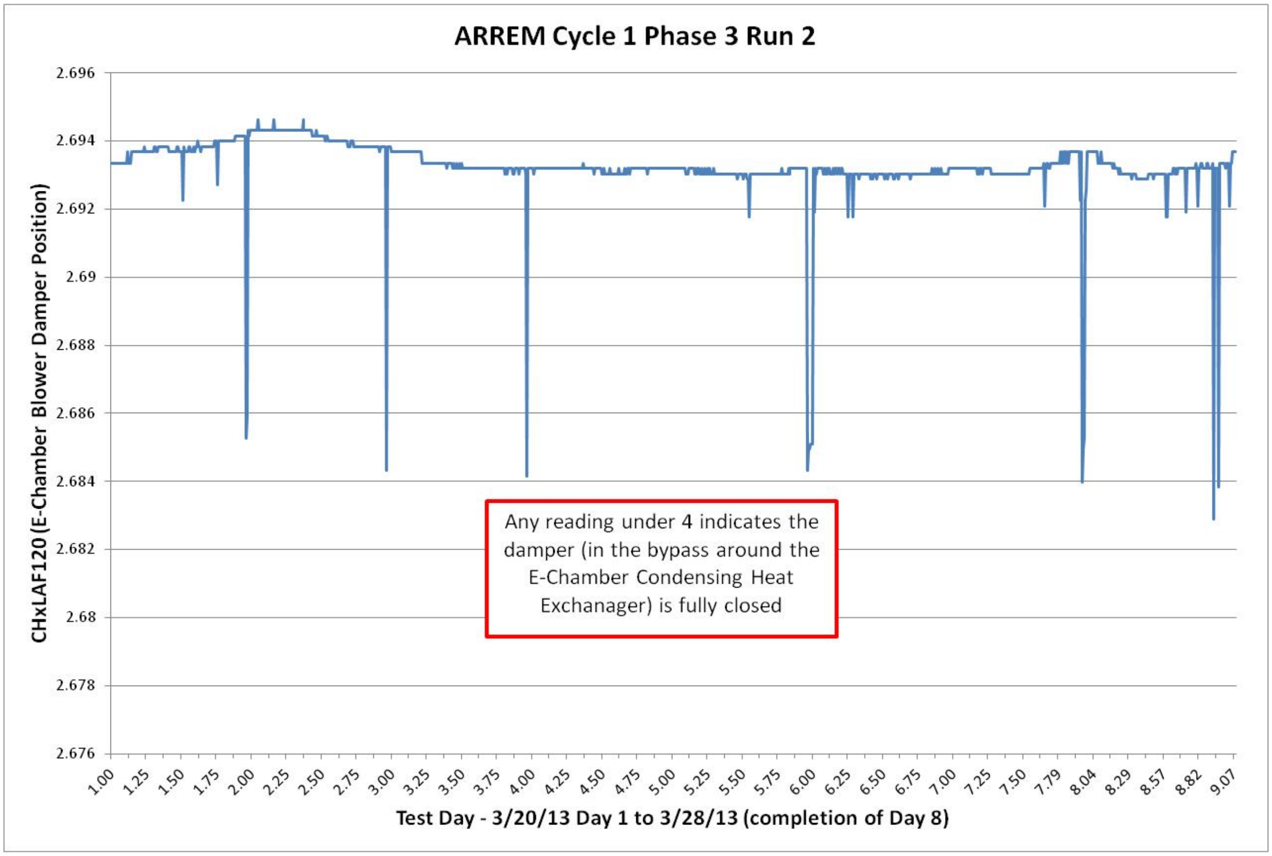
ARREM Cycle 1 Phase 3 Run 2

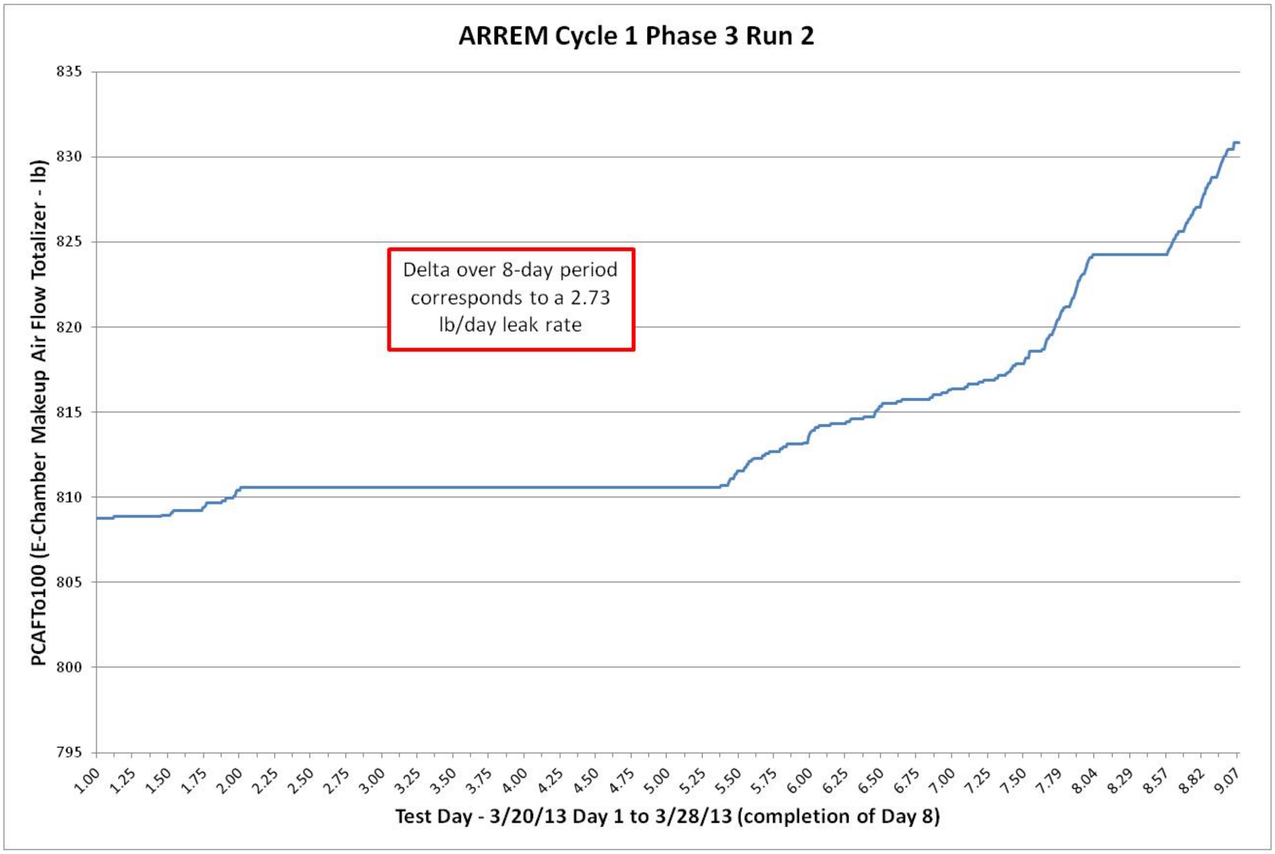
AFB fan controlled to produce 5 scfm

Metering valve controlling flow to HTCO wide open

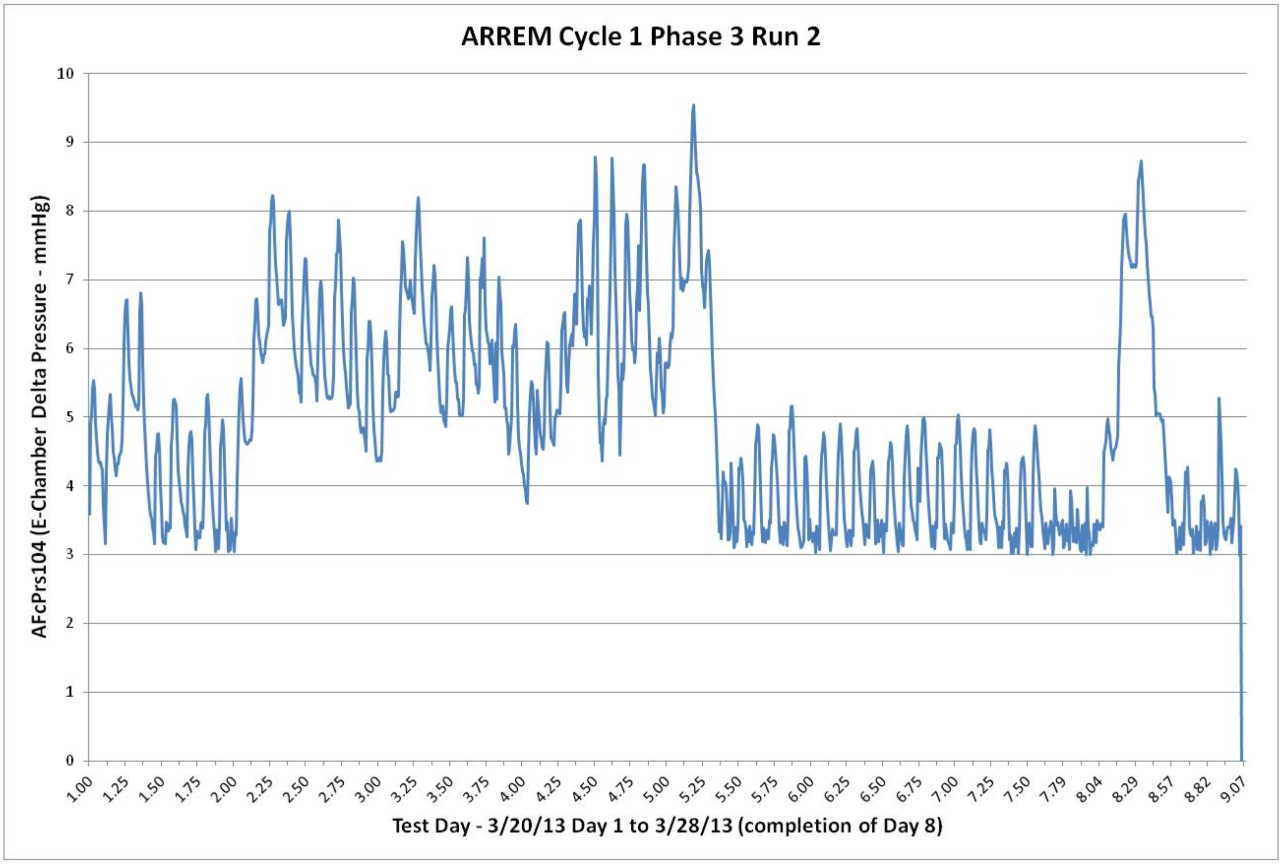
System shutdowns due to test support problems

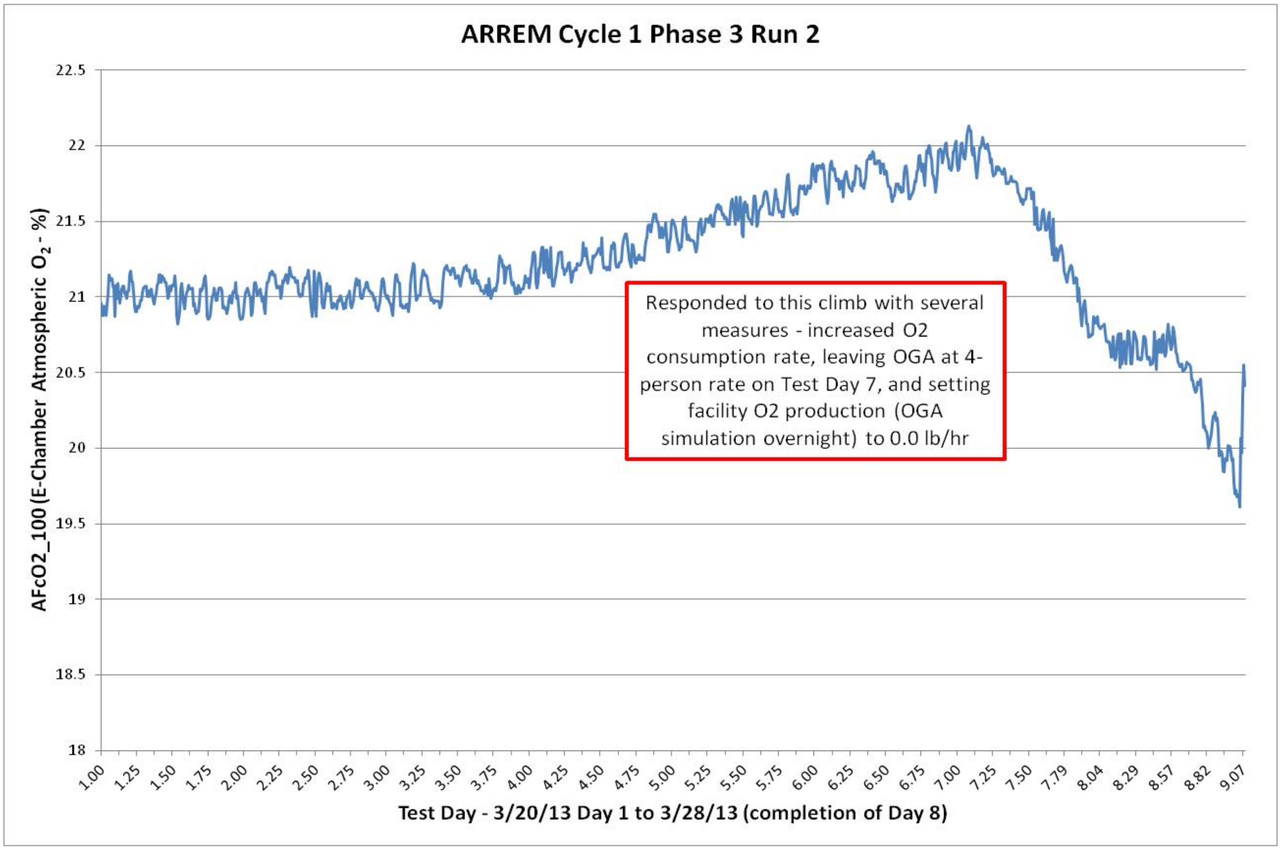

ARREM Cycle 1 Phase 3 Run 2
Adjusted fan speed down in an attempt to lower the CDRA inlet air dewpoint - calculation drops out below 580 scfm
CHxFlc120 (E-Chamber Main Air Flowrate (calculated) - scfm)
700
600
500
400
300
200
100
0
1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50 4.75 5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75 7.00 7.25 7.50 7.79 8.04 8.29 8.57 8.82 9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)


ARREM Cycle 1 Phase 3 Run 2
Any reading under 4 indicates the damper (in the bypass around the E-Chamber Condensing Heat Exchanager) is fully closed
CHxLAF120 (E-Chamber Blower Damper Position)
2.696
2.694
2.692
2.69
2.688
2.686
2.684
2.682
2.68
2.678
2.676
1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50 4.75 5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75 7.00 7.25 7.50 7.79 8.04 8.29 8.57 8.82 9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)

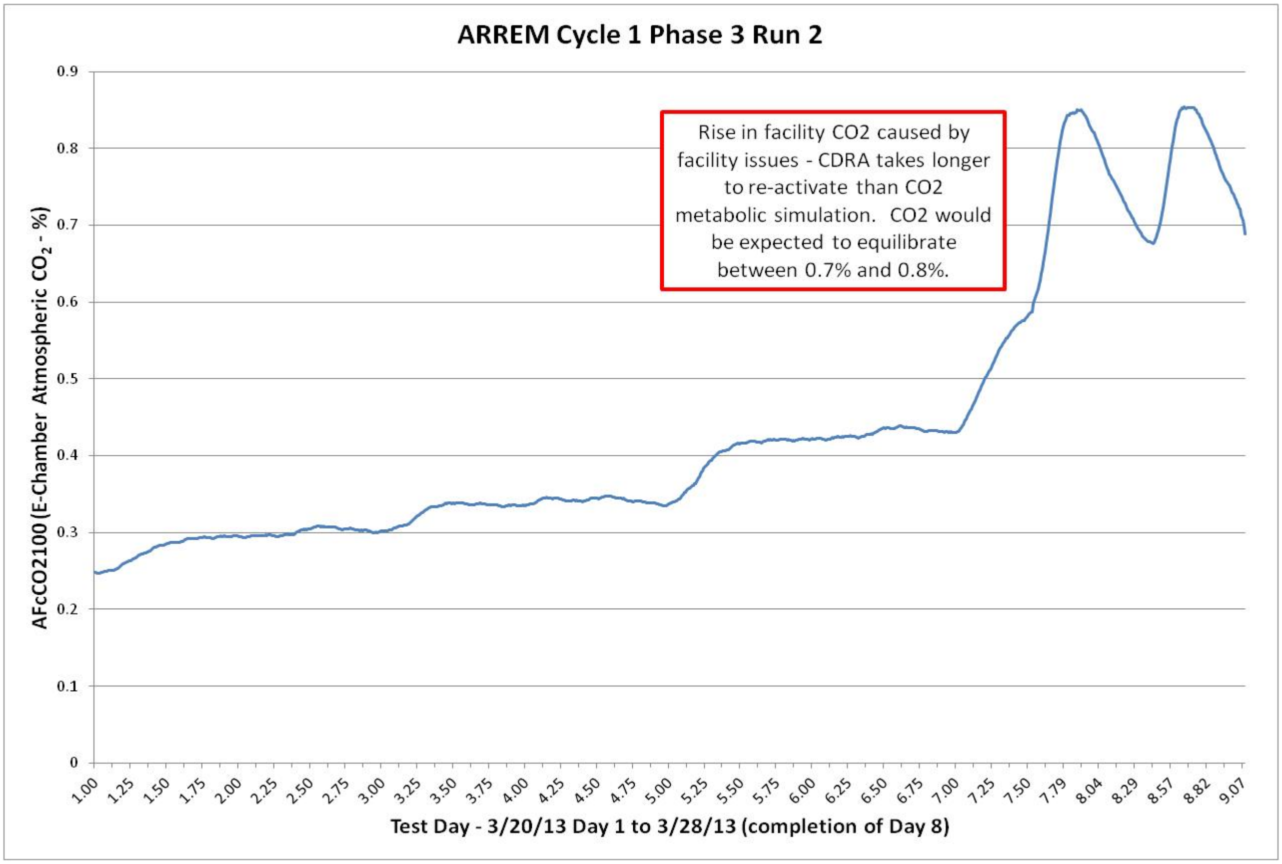


Delta over 8-day period corresponds to a 2.73 lb/day leak rate

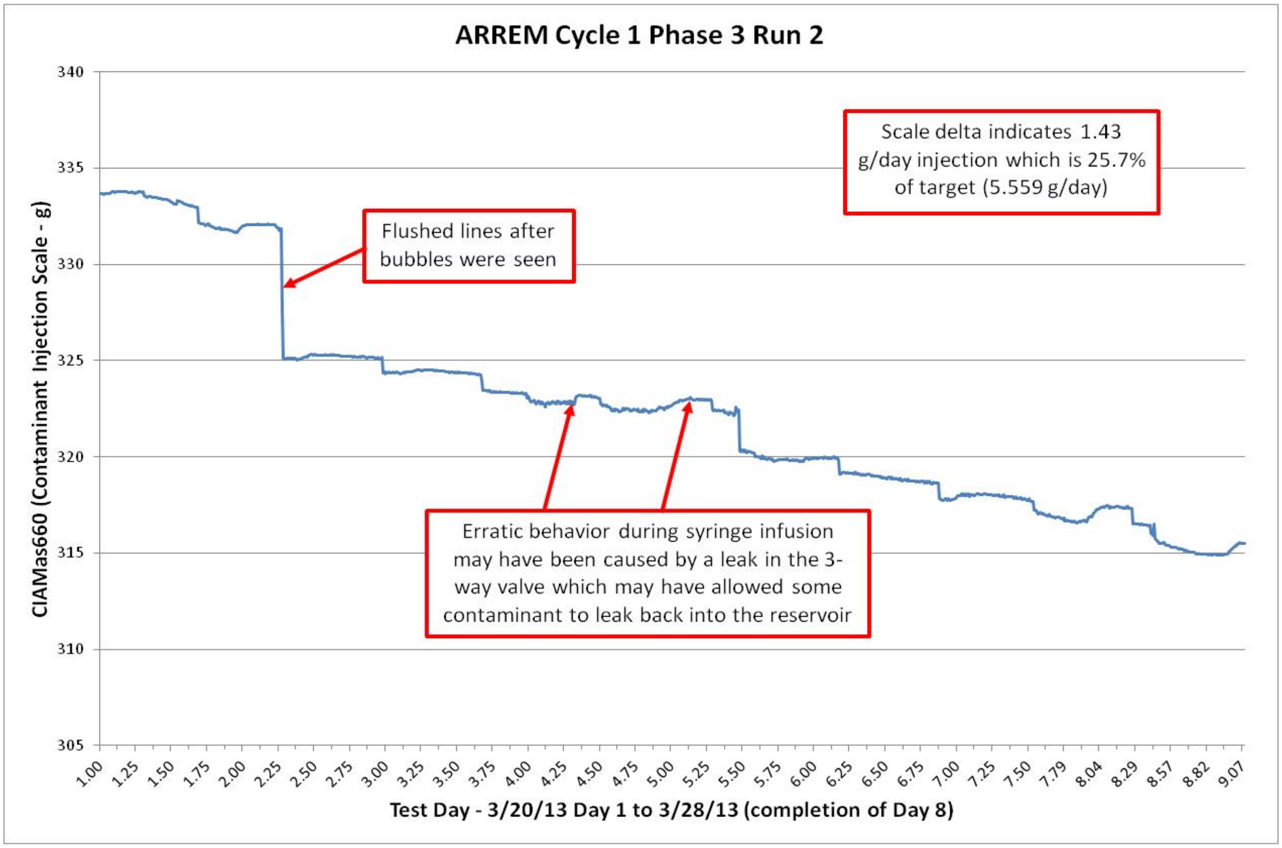


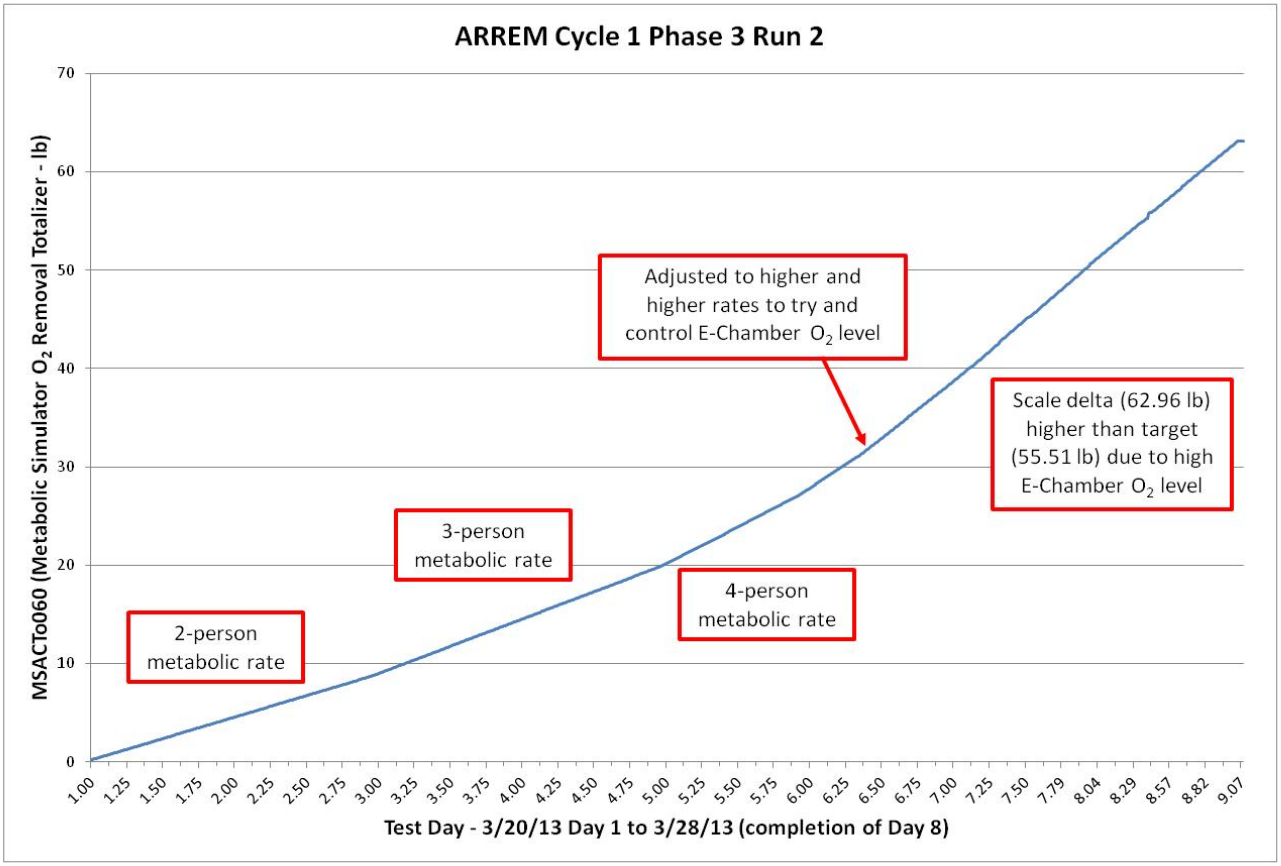


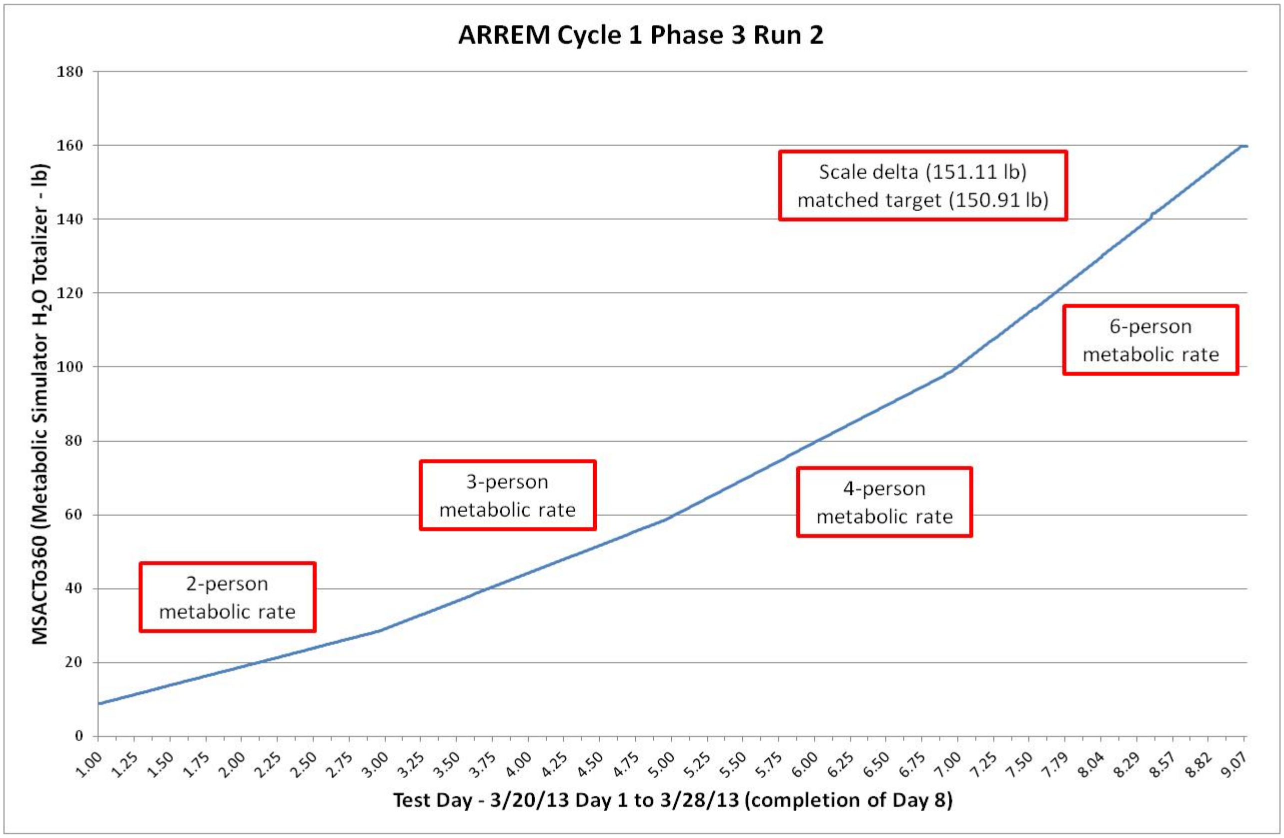
Responded to this climb with several measures - increased O2 consumption rate, leaving OGA at 4-person rate on Test Day 7, and setting facility O2 production (OGA simulation overnight) to 0.0 lb/hr

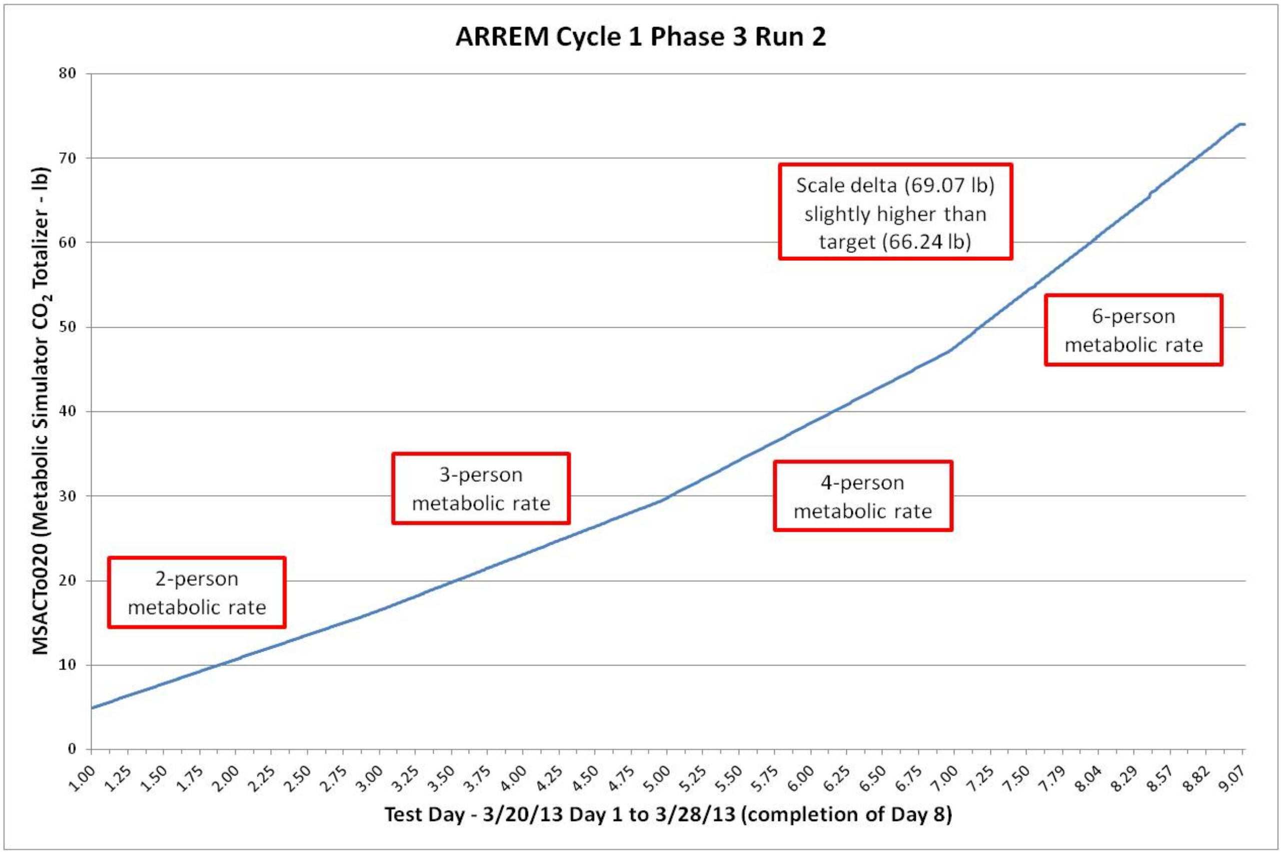


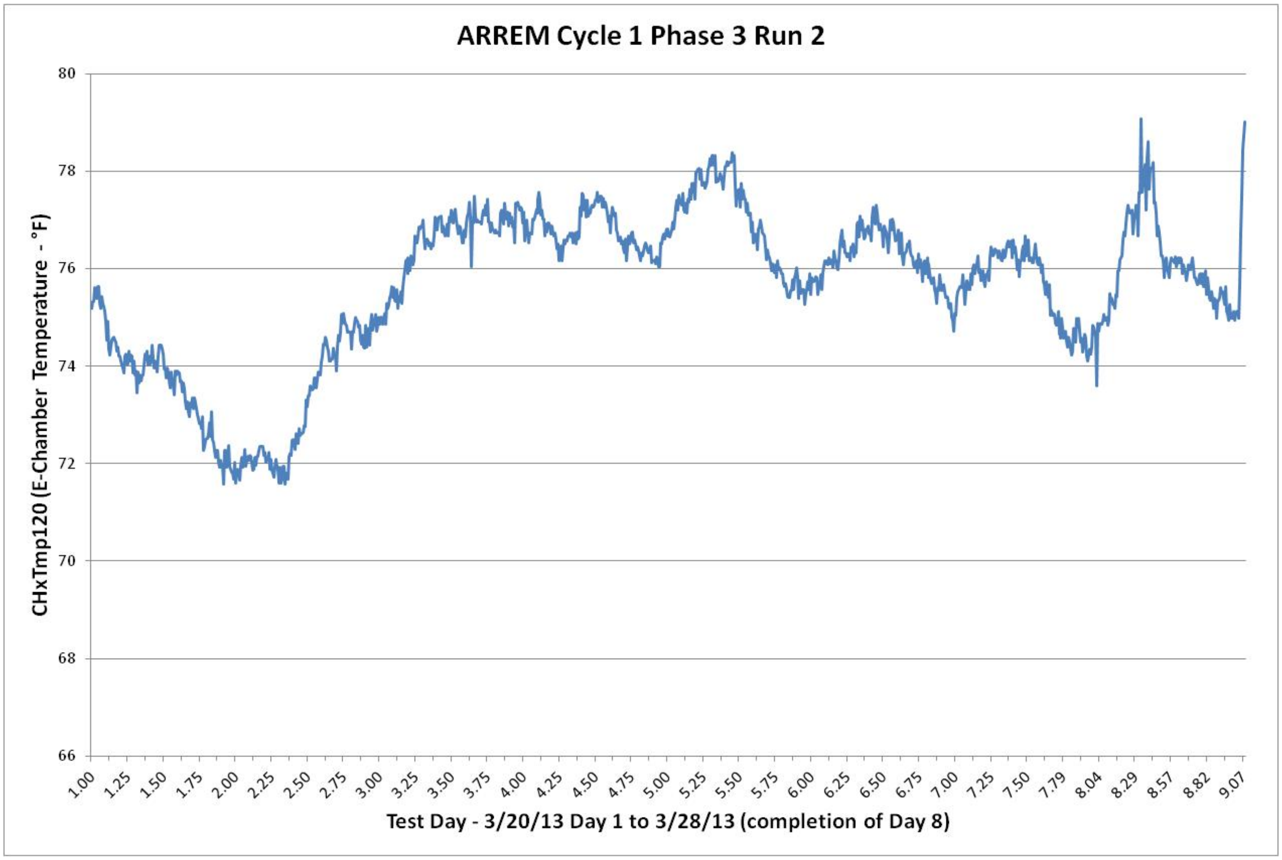
Rise in facility CO2 caused by facility issues - CDRA takes longer to re-activate than CO2 metabolic simulation. CO2 would be expected to equilibrate between 0.7% and 0.8%.

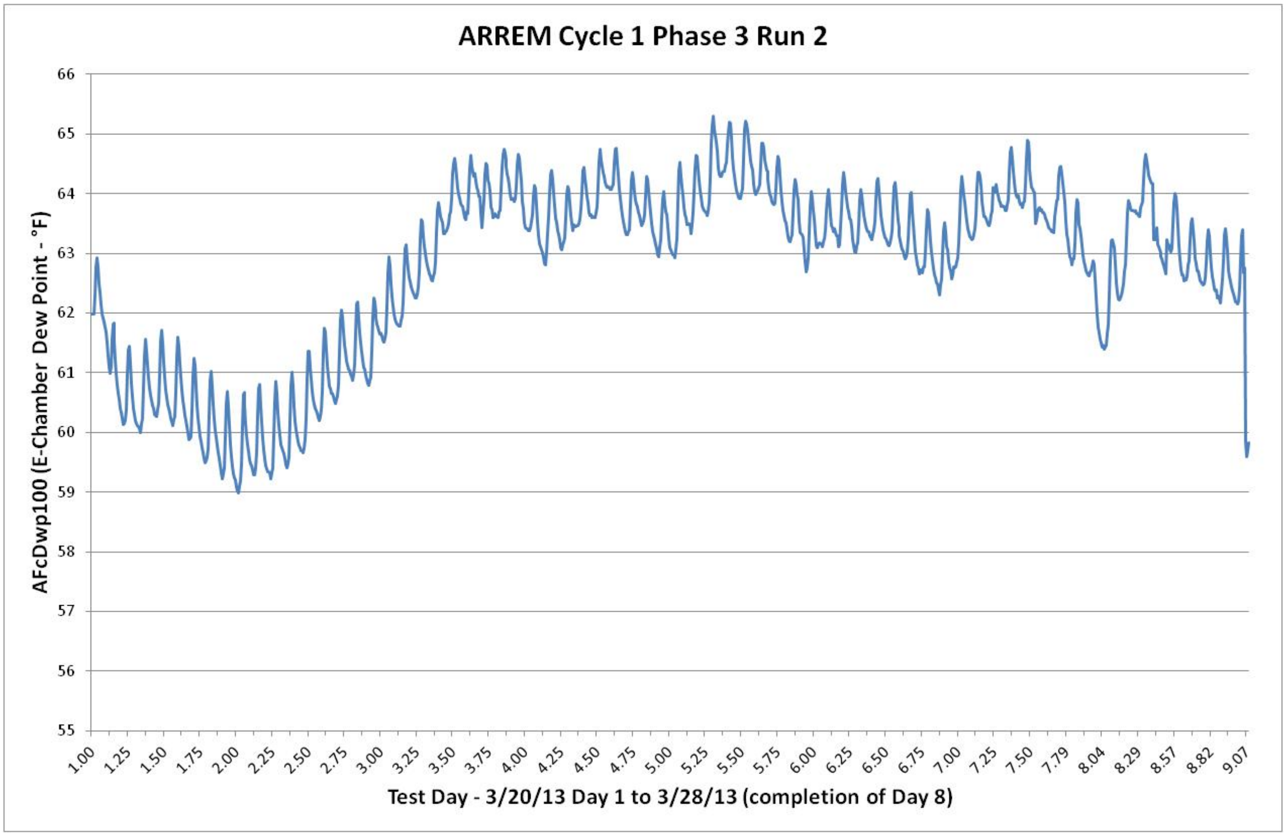

ARREM Cycle 1 Phase 3 Run 2
CIAMas660 (Contaminant Injection Scale - g)
340
335
330
325
320
315
310
305
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Flushed lines after bubbles were seen
Scale delta indicates 1.43 g/day injection which is 25.7% of target (5.559 g/day)
Erratic behavior during syringe infusion may have been caused by a leak in the 3-way valve which may have allowed some contaminant to leak back into the reservoir

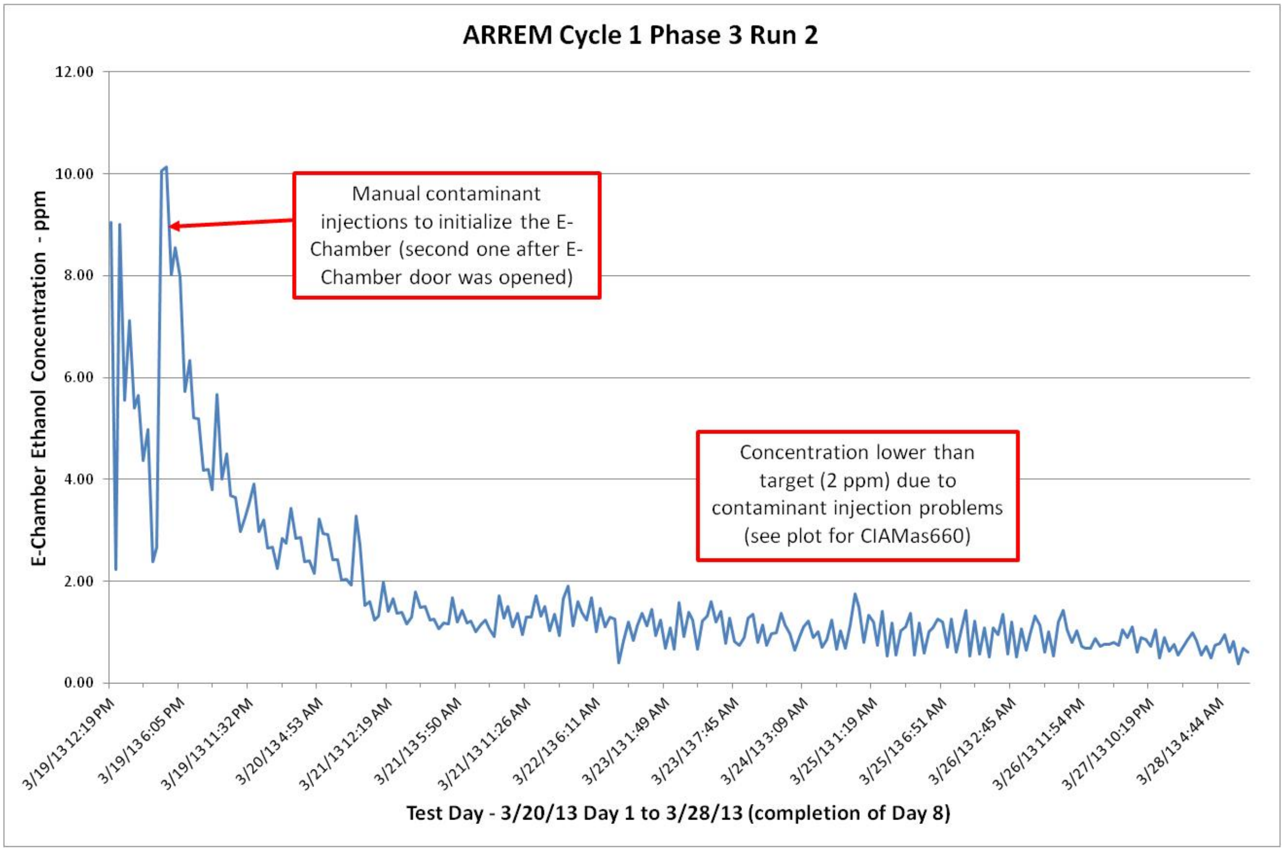

ARREM Cycle 1 Phase 3 Run 2
MSACTo060 (Metabolic Simulator O2 Removal Totalizer - lb)
70
60
50
40
30
20
10
0
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Adjusted to higher and higher rates to try and control E-Chamber O2 level
Scale delta (62.96 lb) higher than target (55.51 lb) due to high E-Chamber O2 level
3-person metabolic rate
4-person metabolic rate
2-person metabolic rate


ARREM Cycle 1 Phase 3 Run 2
MSACTo360 (Metabolic Simulator H_2O Totalizer - lb)
0
20
40
60
80
100
120
140
160
180
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50 4.75 5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75 7.00 7.25 7.50 7.79 8.04 8.29 8.57 8.82 9.07
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
Scale delta (151.11 lb) matched target (150.91 lb)


ARREM Cycle 1 Phase 3 Run 2
MSACTo020 (Metabolic Simulator CO_2 Totalizer - lb)
0
10
20
30
40
50
60
70
80
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)
1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00 4.25 4.50 4.75 5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75 7.00 7.25 7.50 7.79 8.04 8.29 8.57 8.82 9.07
2-person metabolic rate
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
Scale delta (69.07 lb) slightly higher than target (66.24 lb)


ARREM Cycle 1 Phase 3 Run 2
CHxTmp120 (E-Chamber Temperature - °F)
80
78
76
74
72
70
68
66
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)


ARREM Cycle 1 Phase 3 Run 2
AFcDwp100 (E-Chamber Dew Point - °F)
66
65
64
63
62
61
60
59
58
57
56
55
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50
7.79
8.04
8.29
8.57
8.82
9.07
Test Day - 3/20/13 Day 1 to 3/28/13 (completion of Day 8)



Additional data, such as raw PACRATS data for other sensors and tabulated Gas Chromatograph data not included in this report, is available on the ES62 server at the following location: \\msnaf01\es62\1Echamber\Engineering Documents\Cycle1\Cycle1TestData.

APPENDIX G—ARREM PROJECT CYCLE 2 DETAILED TEST REPORT

ES62-ARREM-RPT-14-001

Advanced Exploration Systems (AES)
Atmosphere Resource Recovery and Environmental Monitoring
(ARREM)

Cycle 2
Test Data and Summary Report

Prepared By: Keith J Parrish 11/3/14
Keith J. Parrish
Test Director/ES62

Ken Frederick
Test Conductor/ES62

Chris Stanley
CDRA-4EU Test Conductor/
Qualis-ES62

Dr. Robert Newton
Environmental Monitoring/ES62

Lee Miller
Sabatier CRA Test
Conductor/ECLSS
Technologies-ES62

Kevin Takada
OGA Test Conductor/

Joseph Scott
GC/Micro GC Operator/ Jacobs-
ES62

Gena Dalton
Chemistry Lab Analyst/
Qualis-ES62

Dr. Matthew Kayatin
GC/FTIR Operator/Data
Analyst/ES62

Reviewed By: Jay L. Perry
Jay Perry
Principal Investigator/ES62

Approved By: Bob Bagdigian 11/20/14
Bob Bagdigian
ECLSS Development Branch Chief/ES62

1.0 OVERVIEW

ARREM Cycle 2 was run as the next step to advance and evolve the ISS state-of-the-art atmosphere revitalization system following the successful Cycle 1 test in 2013. The requirements for the test were established by the Advanced Exploration Systems Atmosphere Resource Recovery and Environmental Monitoring Cycle 2 Integrated Test Plan and Requirements (Revision C: October 31, 2013). A summation of that work is as follows:

1) Demonstrate selected development Oxygen Generator Assembly (OGA) control modification and integrated "recombiner" performance (Phase 1)
2) Demonstrate major constituent monitoring and 2-gas chamber pressure control performance (Phase 2)
3) Demonstrate Carbon Dioxide Removal Assembly -4 Engineering Unit (CDRA-4EU) four point test series with and without Trace Contaminant Control System (TCCS) Microlith-Catalytic Oxidizer Assembly (M-COA) integration, demonstrate low CO_2 partial pressure control capability, and demonstrate 9 crewmember support capability (Phase 3)
4) Evaluate TCCS concept architectures (Phase 4)
5) Demonstrate full subsystem architecture with step-wise metabolic challenge at 2-, 3-, 4-, and 6-crewmember loads (Phase 5). NOTE: The 2-crewmember test was dropped since the OGA cannot run below a 2.7 crewmember metabolic rate.
6) Demonstrate full subsystem architecture with 4-crewmember dynamic metabolic load (Phase 6)
7) Demonstrate selected environmental monitoring instruments. (Phase 7)
   NOTE: for photos of the hardware tested see Appendix A.

Cycle 2 was performed in the Exploration Test Chamber (E–Chamber) in MSFC Building 4755. This facility provided the following capabilities:

1) DC and AC power
2) Software Automated Control and Data Acquisition
3) Metabolic Simulation (CO_2 injection, $H_2O_{(v)}$ injection, and O_2 removal)
4) Chamber atmosphere and Subsystem temperature control via Chilled Water distribution
5) Condensate Collection
6) Contaminant Injection
7) Pressure/2-gas control Control via Nitrogen (N_2)/Oxygen (O_2) injection and Chamber atmosphere venting
8) Space Vacuum simulation
9) Subsystem simulations via O_2 injection (OGA), CO_2 transfer from accumulator (Sabatier)
10) Chamber atmosphere and subsystem constituency monitoring via Gas Chromatograph (GC) and Fourier Transform Infrared (FTIR)
11) Hazardous Gas removal via pump with N_2 purge

The subsystems participating in Cycle 2 were the CDRA-4EU, TCCS, Sabatier Carbon Dioxide Reduction Assembly (CRA), and OGA.

2.0 ECHAMBER AND FACILITY CHECKOUTS

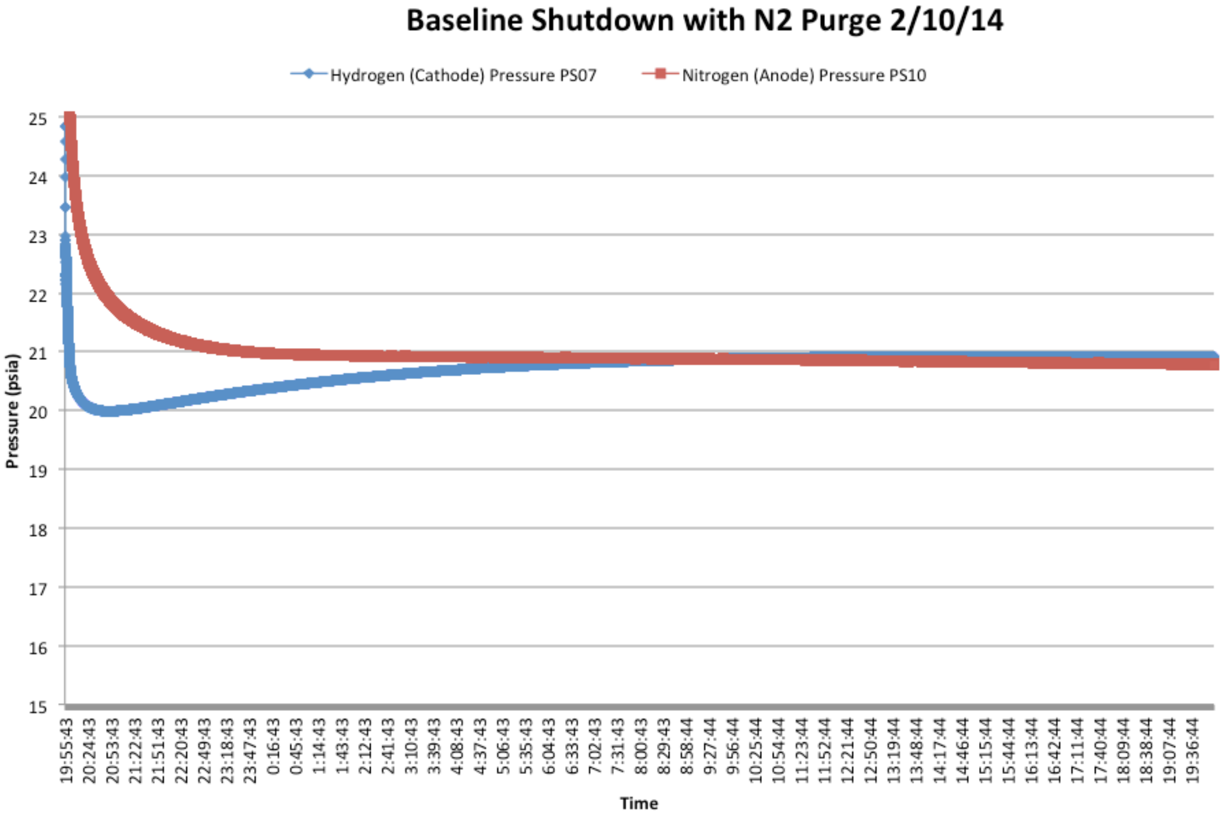
External Leak Rate (2/6/14): The EChamber baseline leak rate was determined to be below 1.5 lb/day at 3 mmHg above ambient pressure. After the initial input of High Purity Air to establish 3 mmHg above ambient pressure, there was no further re-supply to the EChamber until the door was opened. Therefore, the actual leak rate was undetermined because environmental factors more than accounted for any pressure rise seen on AFcPrs104 (delta pressure between ambient and the EChamber).

3.0 CYCLE 2 TEST RESULTS

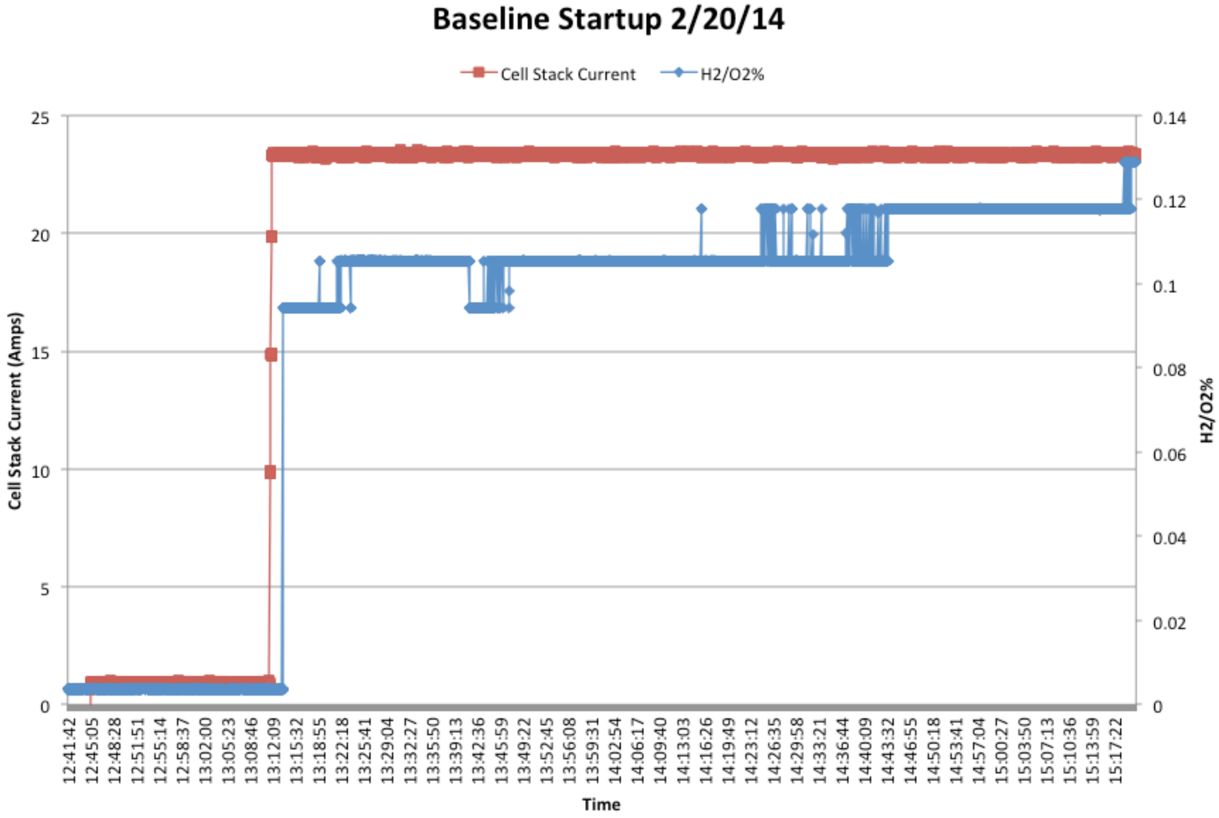
NOTE: the phases of Cycle 2 were accomplished at opportune times when hardware was ready. The following section is laid out in chronological order not phase order. It also accounts for repeated attempts to accomplish phases.

Phase 1.3 (Demonstrate an approach to eliminate the OGA N_2 purge) (2/10/14 to 3/4/14 – ES62-TPS-RRR-14-001 & ES62-TPS-RRR-14-002): The objective of Phase 1.3 was to investigate whether the OGA could be safely operated without startup or shutdown N_2 purges by making use of H_2 and O_2 recombination that occurs naturally at the anode catalyst sites. The test consisted of 3 one week runs: a baseline run with both purges, a run with the startup purge disabled, and a run with both the startup and shutdown purges disabled.

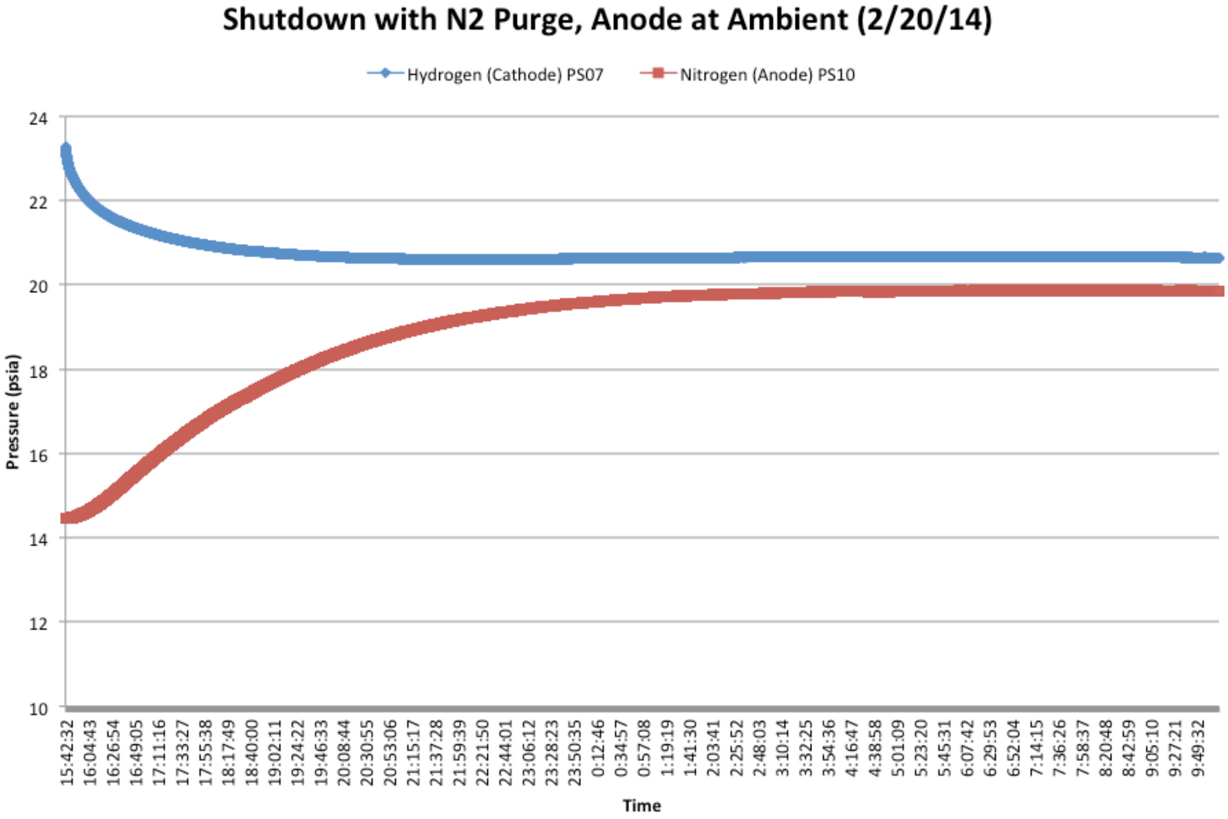
The Baseline shutdown was performed on 2/10/14 with an N_2 purge. As shown on the plot below the initial condition was the anode (N_2) pressure higher than the cathode (H_2). The anode and cathode pressures equalized within about 10 hours (indicating that N_2 was permeating from anode to cathode).



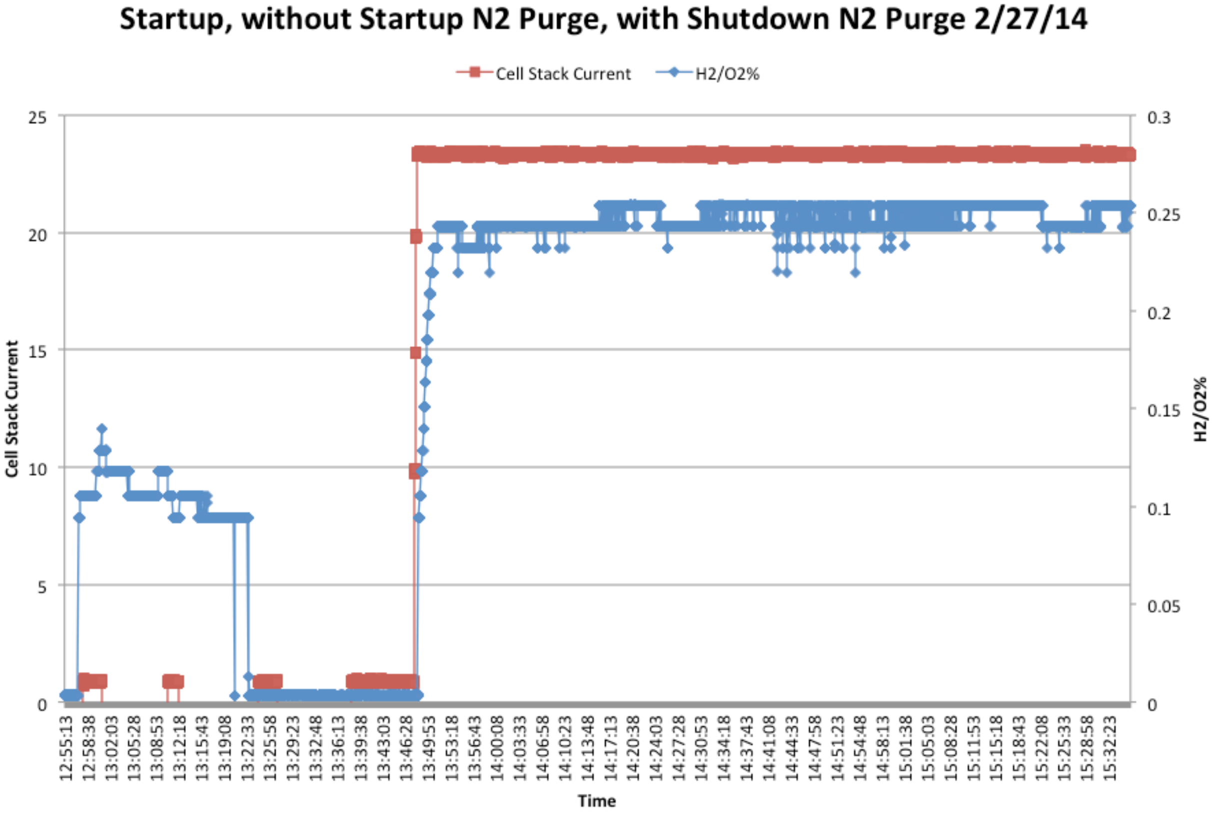
The Baseline startup was performed on 2/20/14. After approximately 2 hours of runtime, the H_2/O_2% was 0.13% which is well below the 4% explosive limit and there was no H_2O in the oxygen outlet.



The Disable Startup N_2 Purge test was performed from 2/20/14 to 2/27/14. The changes from the Baseline test were to perform the N_2 purge at shutdown but with anode side pressure decreased to ambient pressure and then to perform a startup without N_2 purge. As shown on the plot below, the initial condition was the cathode (H_2) pressure higher than the anode (N_2). As in the Baseline test, the anode and cathode pressures equalized to within 0.5 psi in about 9 hours (indicating that H_2 was permeating from cathode to anode – reverse flow from the Baseline test).

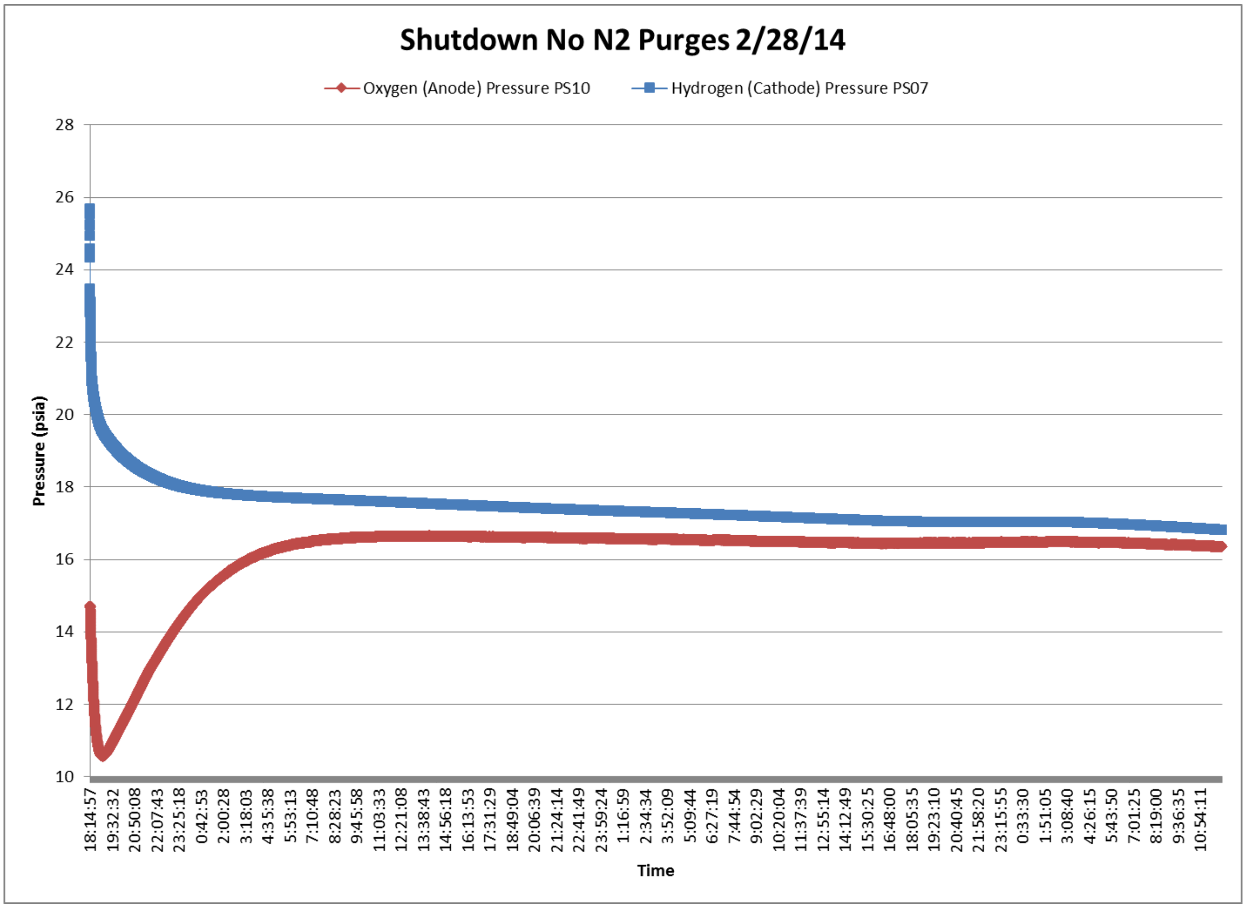


The Disable Startup N_2 Purge startup was performed on 2/27/14. After approximately 100 minutes of runtime, the H_2/O_2% was 0.25% still well below the 4% explosive limit and there was 50 ml H_2O in the oxygen outlet (this is a concern to be addressed in the future).

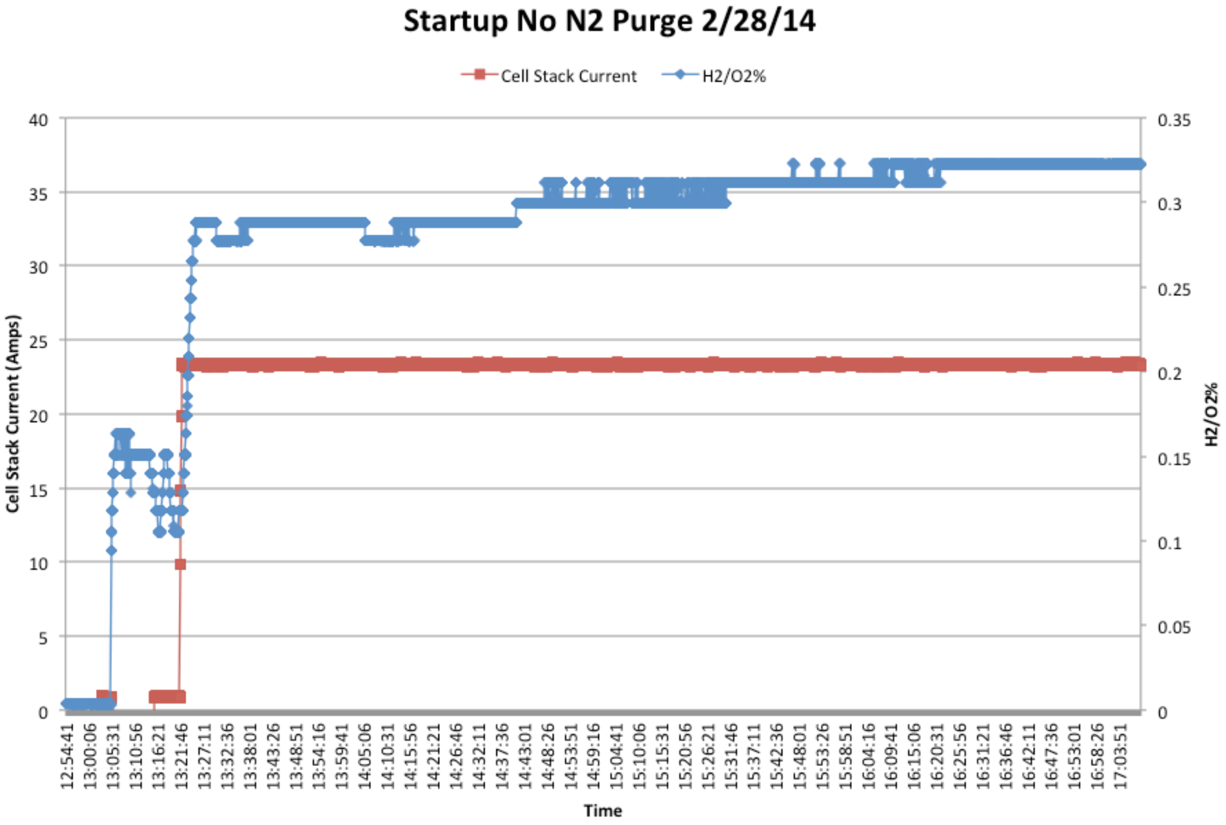

Startup, without Startup N2 Purge, with Shutdown N2 Purge 2/27/14

NOTE: the eccentricities in the Standby current readings (early in the run time) were due to some early shutdowns caused by some conservative voltage shutdown limits. These shutdowns are not related to any N2 purge issue and subsequent OGA runs in later Cycle 2 Phases without these shutdowns do not have these erratic Standby current readings.

The Disable Shutdown and Startup N_2 Purge test was performed on 2/28/14. As shown on the plot below, the initial condition was the cathode (H_2) pressure higher than the anode (O_2). There is an initial drop in anode pressure but the anode and cathode pressures equalized to within 0.5 psi in about 19 hours (the initial drop indicating that H_2 was permeating from cathode to anode and safely recombining with O_2).



The Disable Shutdown and Startup N_2 Purge startup was performed on 2/28/14. After approximately 4.5 hours of runtime, the $H_2/O_2\%$ was 0.32% still well below the 4% explosive limit and there was 125 ml H_2O in the oxygen outlet (again, a concern to be addressed in the future).



NOTE: the eccentricities in the Standby current readings (early in the run time) were due to some early shutdowns caused by some conservative voltage shutdown limits. These shutdowns are not related to any N2 purge issue and subsequent OGA runs in later Cycle 2 Phases without these shutdowns do not have these erratic Standby current readings.

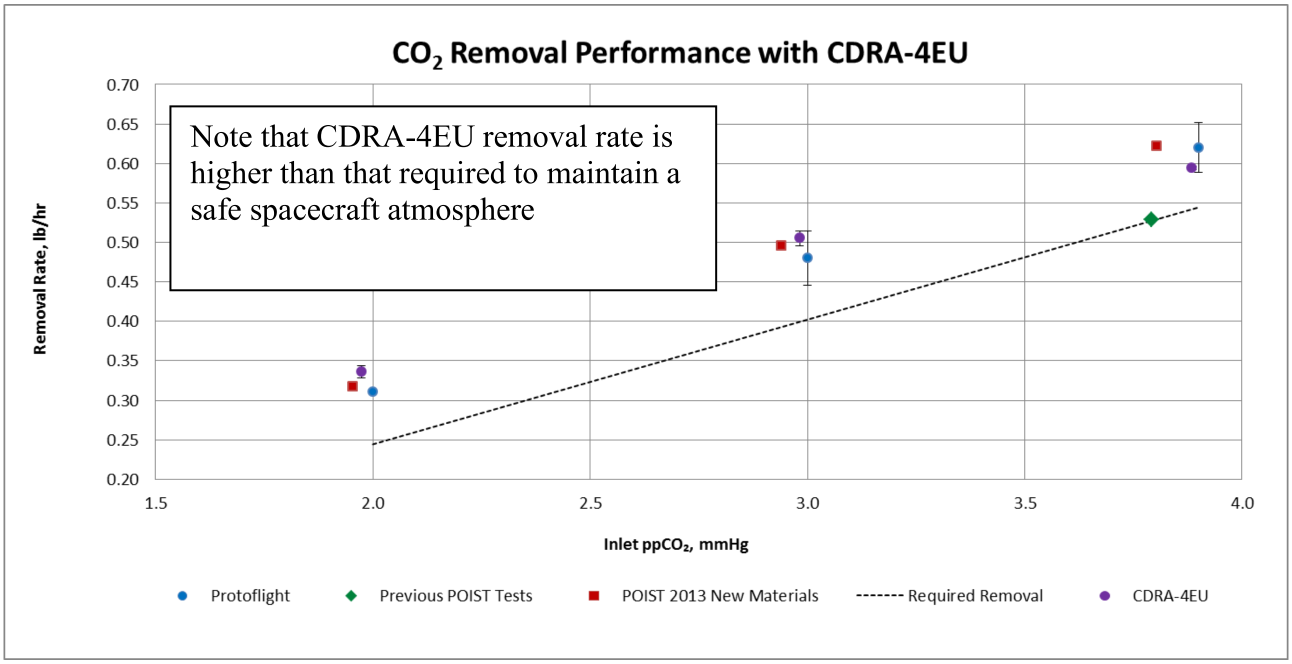
Each of the N_2 purge deletion tests were conducted twice more for repeatability which was observed. Overall conclusions: disabling N_2 purging does not appear to introduce new safety risks to operating the OGA. If no re-combination occurred and a combustible mixture formed it would be equivalent to a "backfire" with the energy of 1 firecracker (this analysis is documented in a White Sands Test Facility memo HMEM.013). The water in the oxygen outlet needs to be removed to prevent damage to downstream H_2 sensors or recombiners. NOTE: other Phase 1 testing delayed beyond Cycle 2 because of testing delays at White Sands Test Facility.

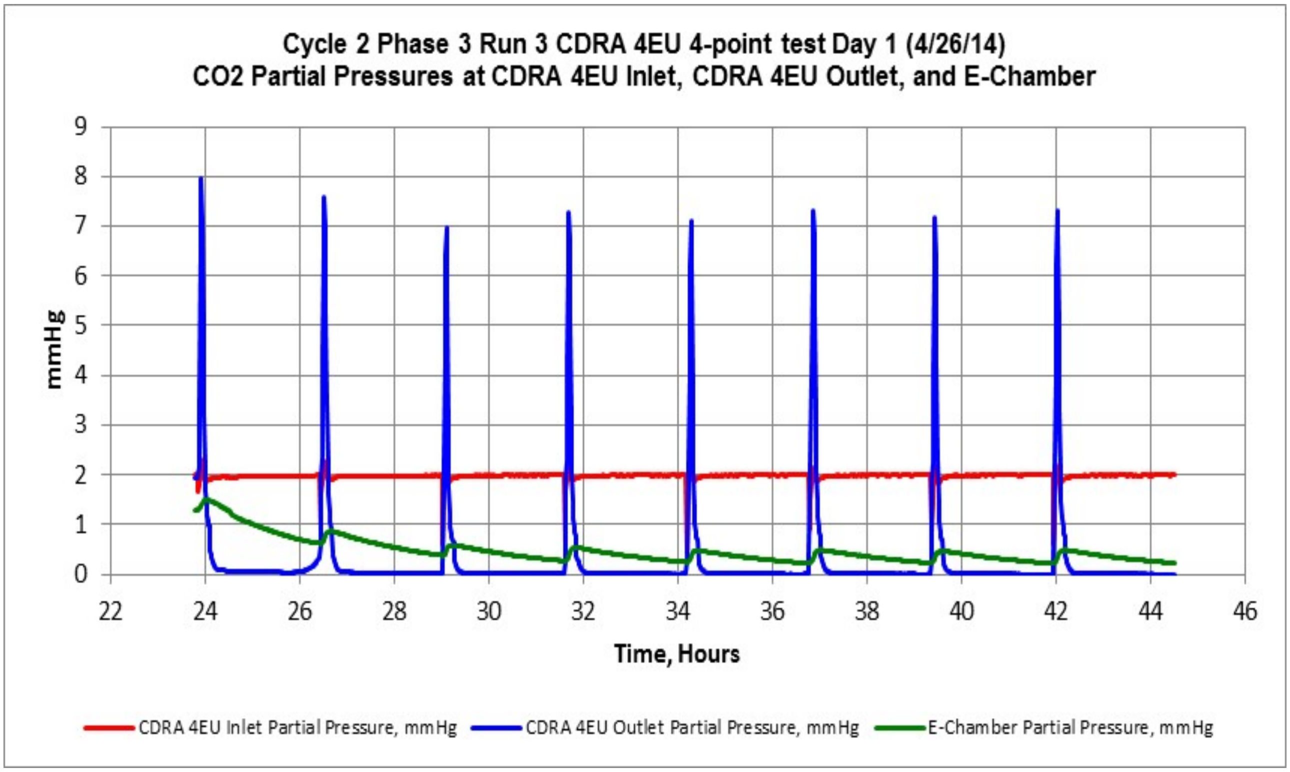
Phase 3 Run 1 (4-point CDRA-4EU Baseline) (3/6/14 – ES62-TPS-RRR-14-004): The objective of Phase 3 was to perform a 4-point CO_2 injection test on the CDRA-4EU as a subsystem baseline for both forwards comparison on future bed materials, test conditions, etc., and backwards comparison to the previous CDRA subsystem from Cycle 1. For the Phase 3 runs, the target air flow was 20.4 SCFM with the CDRA operating on 155 minute half cycles. The CDRA sorbent bed material was from the flight lot of RK38 while the desiccant bed was predominantly a layered arrangement of zeolite 13X (44.4% of bed volume) and Sylobead SG 125 B Silica Gel (46.5% of bed volume). This run was quickly aborted when no CO_2 removal was observed. This launched a series of troubleshooting activities and checkout runs related to the following issues: heater temperatures (3/7/14, 3/12/14, and 3/17/14), vacuum pressure (3/7/14 and 3/12/14), blower delta pressure (3/7/14), dew point measurements (3/13/14 through 4/2/14), and flow rates (3/7/14 through 4/2/14).

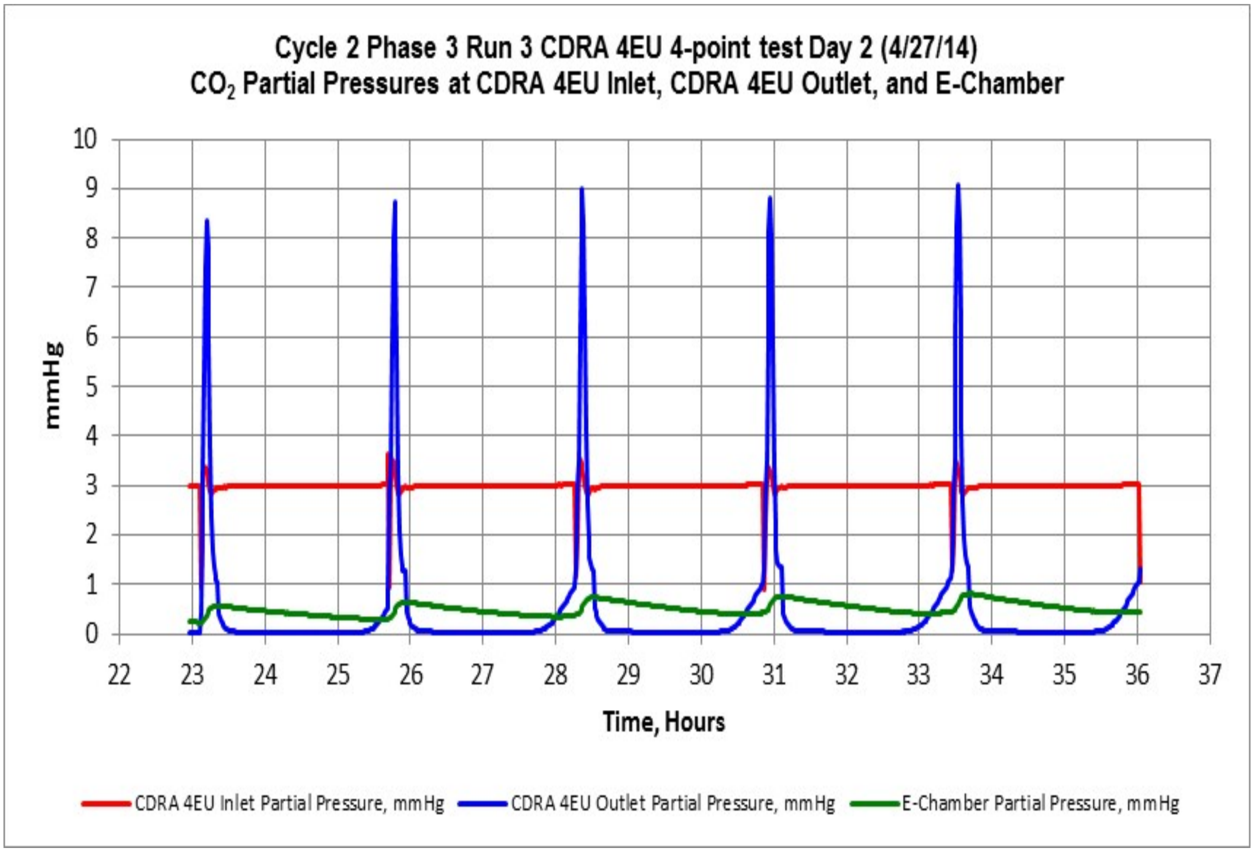
Phase 3 Run 2 (4/3/14 to 4/7/14 – ES62-TPS-RRR-14-004A): with many of the facility issues put to rest, the CDRA-4EU 4-point CO2 injection baseline test was attempted again starting on 4/3/14. All four points were completed but flow meter issues persisted such that the CDRA-4EU Principal Investigator could not get a reliable mass balance from the data. CO2 breakthrough was observed prior to half-cycle completion at the higher injection rates. At this point, the flow meters were sent to the calibration laboratory. The available time was used to investigate and understand a data discrepancy in the CO2 injection system and to perform a leak check CDRA-4EU in the area where TCCS components were going to be installed.

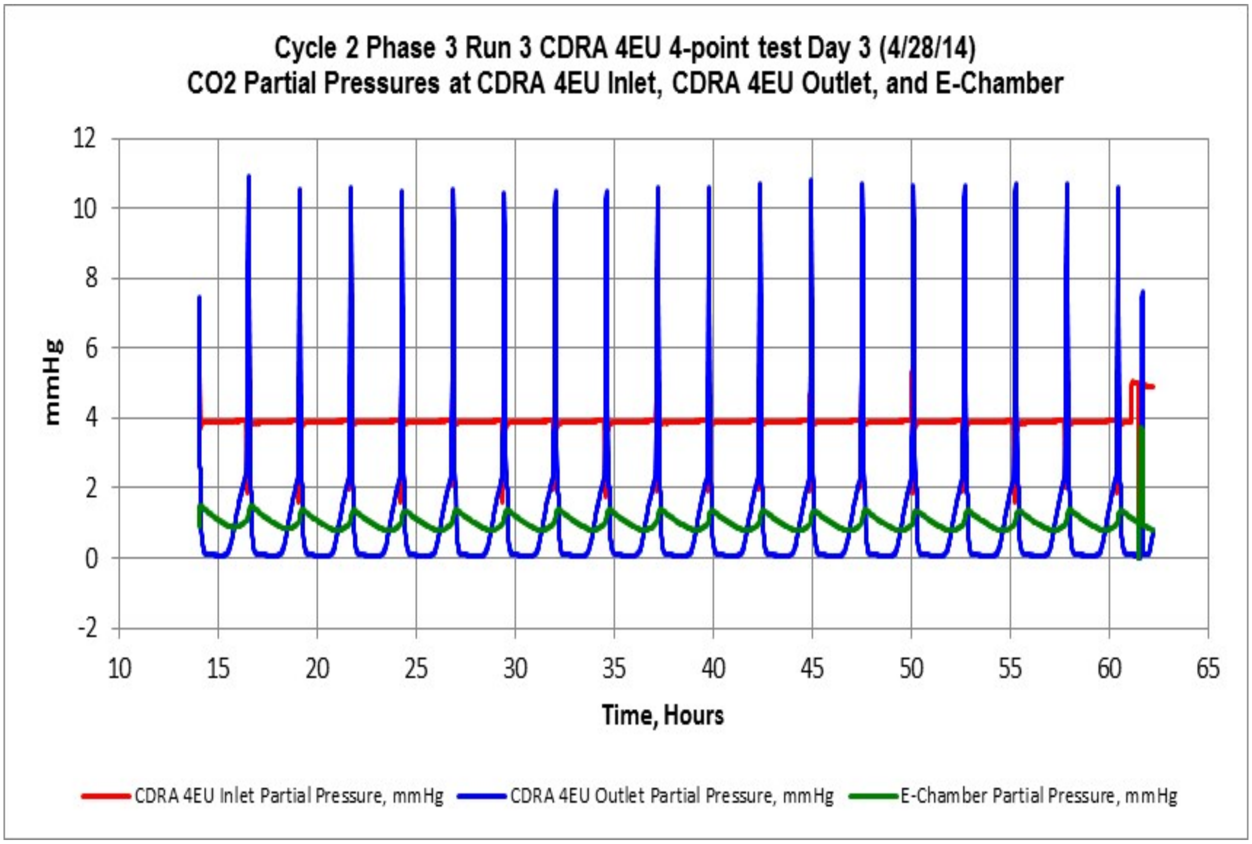
Phase 2 (Pressure Control Assembly 2-gas Control Checkout) (4/14/14 – ES62-TPS-RRR-14-005): The objective of Phase 2 was to test the Pressure Control Assembly for 2-gas (N2 and O2) control. In all, 15 different responses related to starting and stopping N2 injection, starting and stopping O2 injection, and opening and closing the relief valve were successfully tested for the PCA's control of the EChamber atmosphere. See Appendix B for the 2-gas control logic diagram.

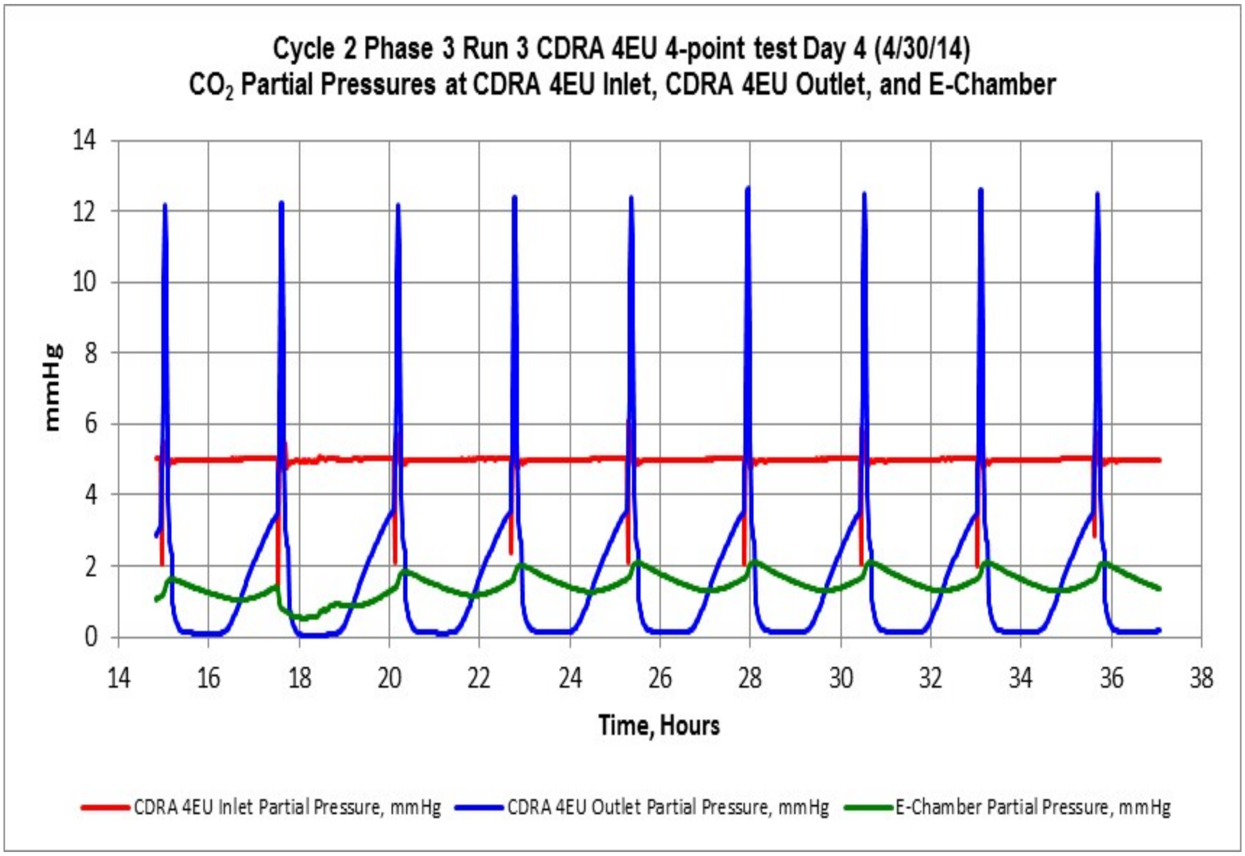
Phase 3 Run 3 (4/25/14 to 4/30/14 – ES62-TPS-RRR-14-004B): run 3 was a complete 4-point test for CDRA-4EU. Early breakthrough was still observed at the higher CO2 injection rates, however the EChamber CO_2 concentration was controlled below 2 mmHg which is well below the requirement. The data from this test was used to compare with the previous CDRA hardware configuration/bed material. At lower injection rates, there was an increase (approximately 4%) in CO_2 removal rate while at higher CO_2 injection rates there was a decrease (approximately 4%). The first plot below shows the removal rates comparison between CDRA-4EU and previous CDRA hardware. The next 4 plots show CO_2 concentration data for the 4 test days showing the early breakthrough at higher CO_2 injection rates. NOTE: Test Day 3 actually lasted for an extra 48 hours because MSFC had a weather related closure on 4/29/14.



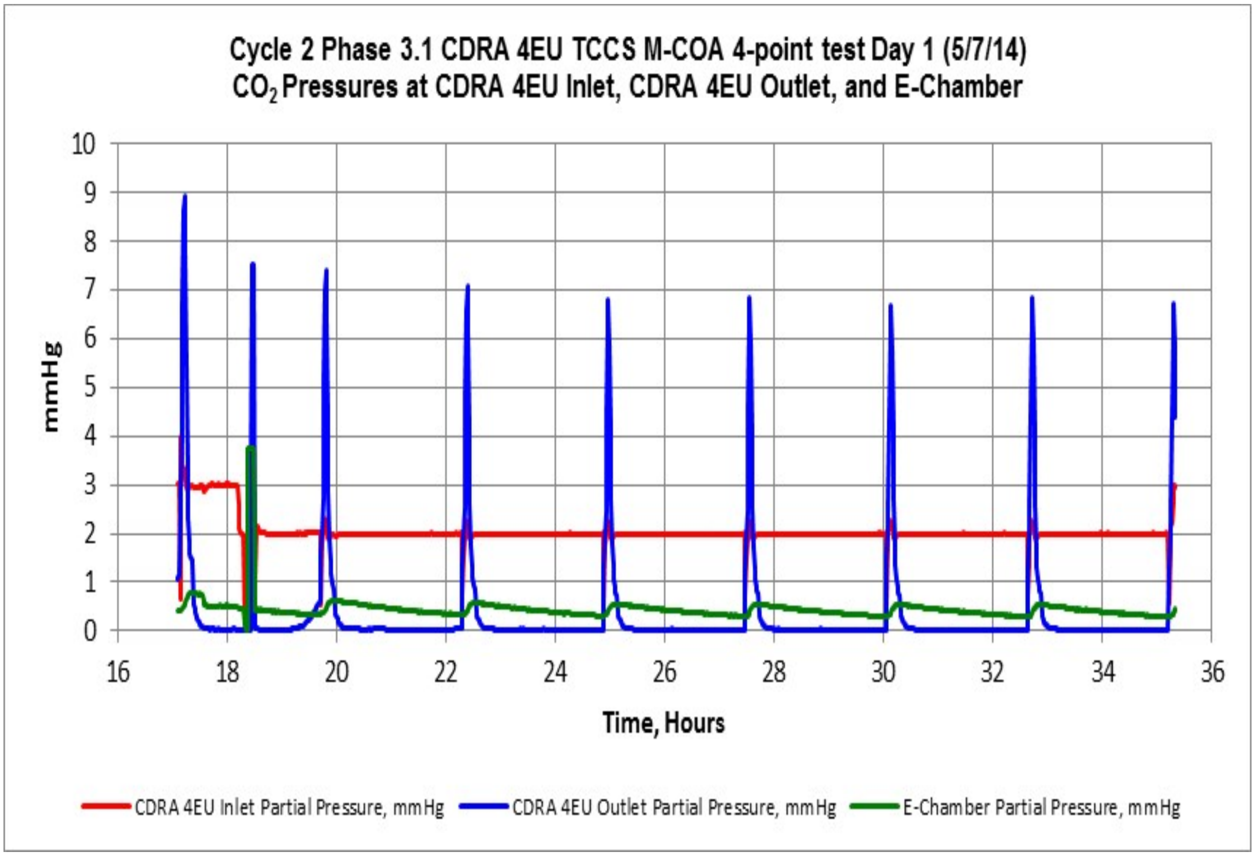

Cycle 2 Phase 3 Run 3 CDRA 4EU 4-point test Day 1 (4/26/14)
CO2 Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
0
1
2
3
4
5
6
7
8
9
22
24
26
28
30
32
34
36
38
40
42
44
46
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg

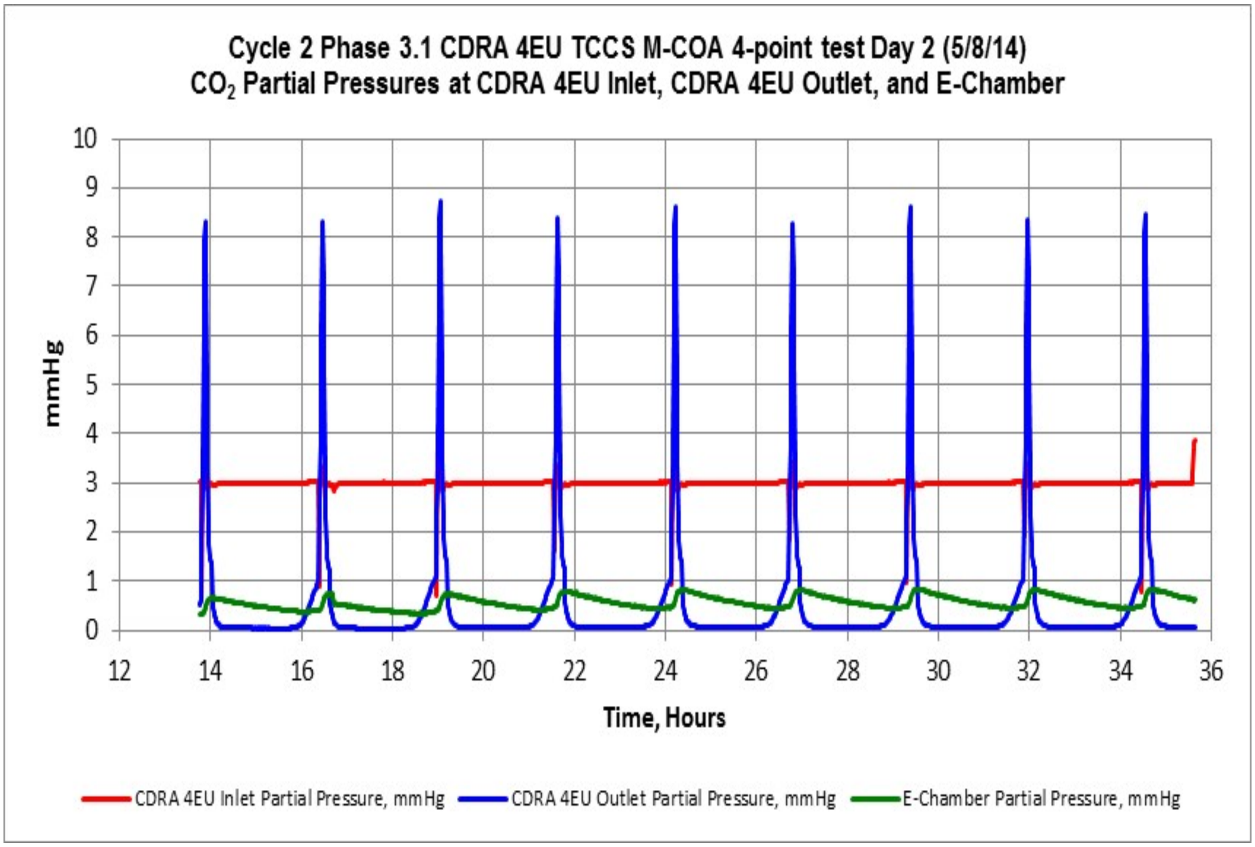

Cycle 2 Phase 3 Run 3 CDRA 4EU 4-point test Day 2 (4/27/14)
CO$_2$ Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
0
1
2
3
4
5
6
7
8
9
10
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg


Cycle 2 Phase 3 Run 3 CDRA 4EU 4-point test Day 3 (4/28/14)
CO2 Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
12
10
8
6
4
2
0
-2
10
15
20
25
30
35
40
45
50
55
60
65
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg

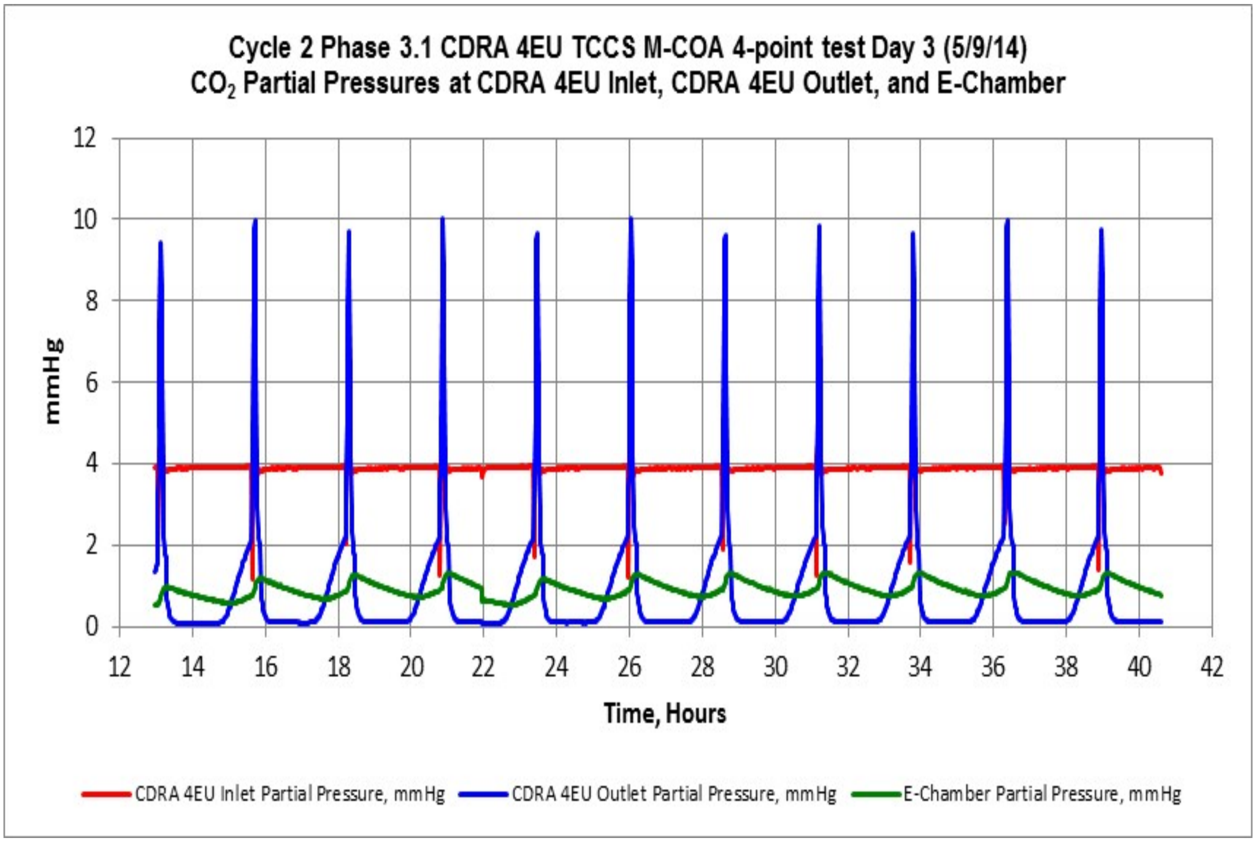

Cycle 2 Phase 3 Run 3 CDRA 4EU 4-point test Day 4 (4/30/14)
CO₂ Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
14
12
10
8
6
4
2
0
14
16
18
20
22
24
26
28
30
32
34
36
38
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg

Phase 3.1 (4-point CDRA-4EU Baseline with TCCS M-COA) (5/6/14 – 5/12/14 – ES62-TPS-RRR-14-006): Phase 3.1 was similar to earlier 4-point tests for the CDRA-4EU except this time the TCCS M-COA was added to the flow path. The CDRA-4EU half cycle remained unchanged at 155 minutes. The TCCS M-COA was plumbed as a recycle loop with supply flow taken from between the CDRA-4EU desiccant and sorbent beds and return flow plumbed at the CDRA-4EU air inlet. On the first day (5/6/14), 22.4 scfm was set as the total flow rate with a 2 scfm slipstream flow sent to the TCCS M-COA. This setup was in error and along with an anomaly caused Test Day 1 to be repeated. The outlet thermocouple of the TCCS did not read properly and the EChamber door had to be opened to get a fix (a sensor wire had been cut during other installation activities). Once that was fixed the test was re-started with a 20.4 scfm flow rate at the CDRA-4EU inlet with a 2 scfm slipstream flow sent to the TCCS M-COA. Early breakthrough was still observed at the higher CO_2 injection rates. The overall conclusion was that the CDRA-4EU with a 20.4 scfm flow rate could keep the EChamber CO_2 partial pressure under control (even at higher crew member metabolic loading) allowing for trace contaminant control via an integrated TCCS M-COA with a 2 scfm slip stream flow.

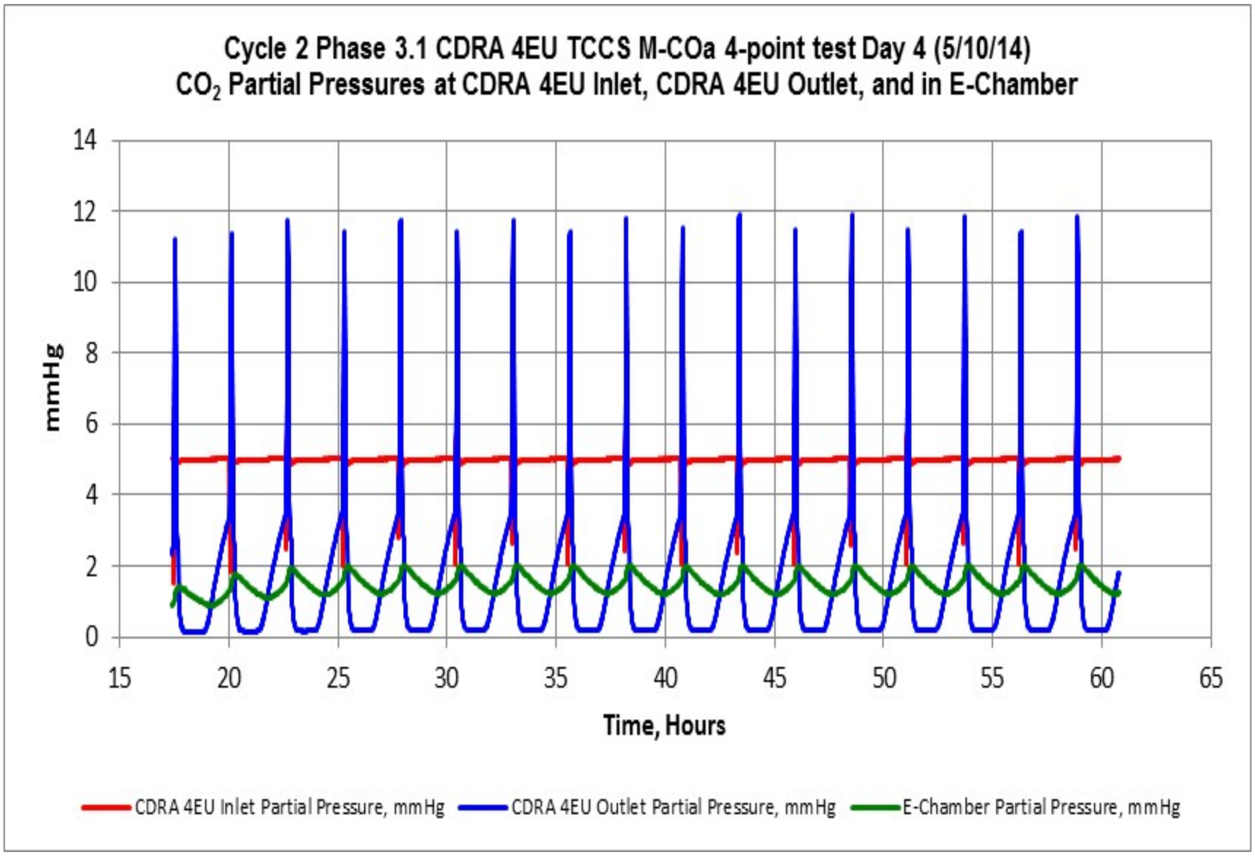


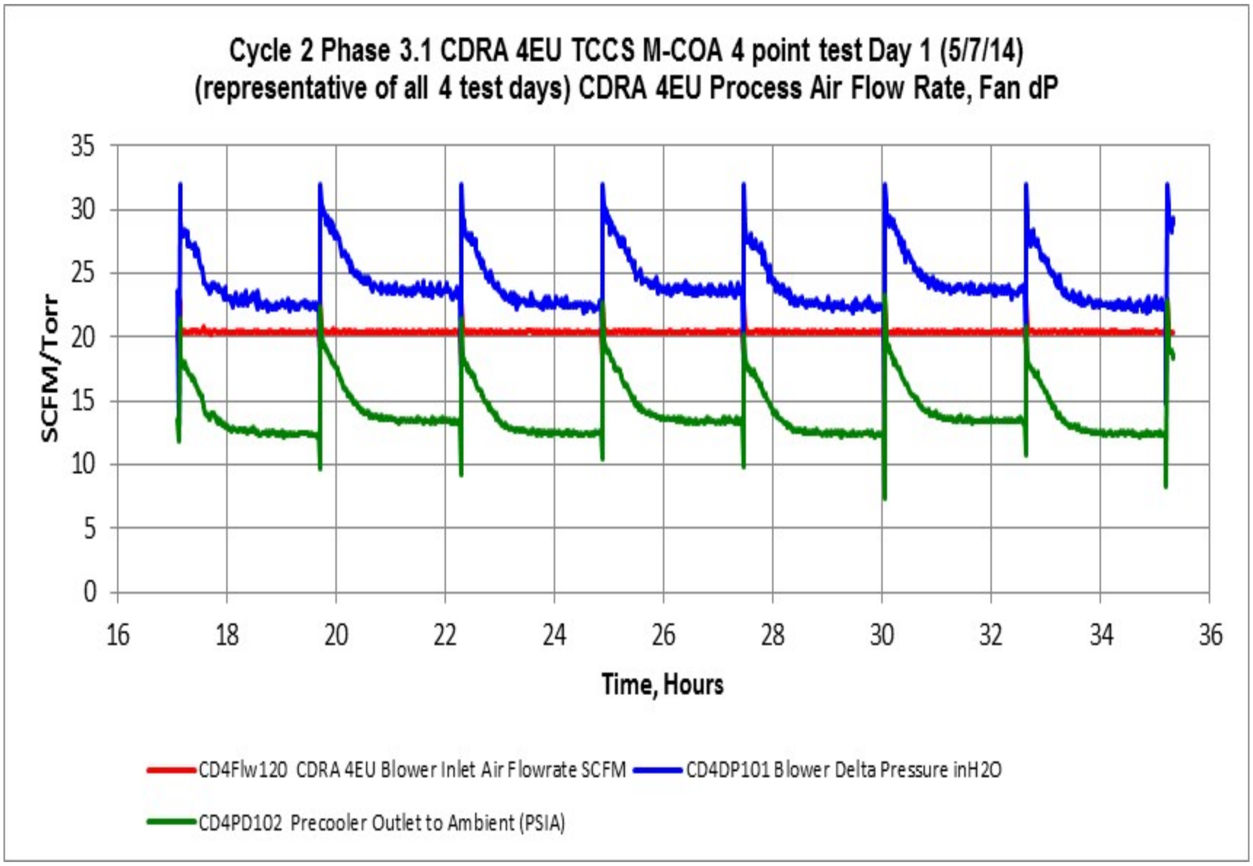


Cycle 2 Phase 3.1 CDRA 4EU TCCS M-COA 4-point test Day 2 (5/8/14)
CO2 Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
10
9
8
7
6
5
4
3
2
1
0
12
14
16
18
20
22
24
26
28
30
32
34
36
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg

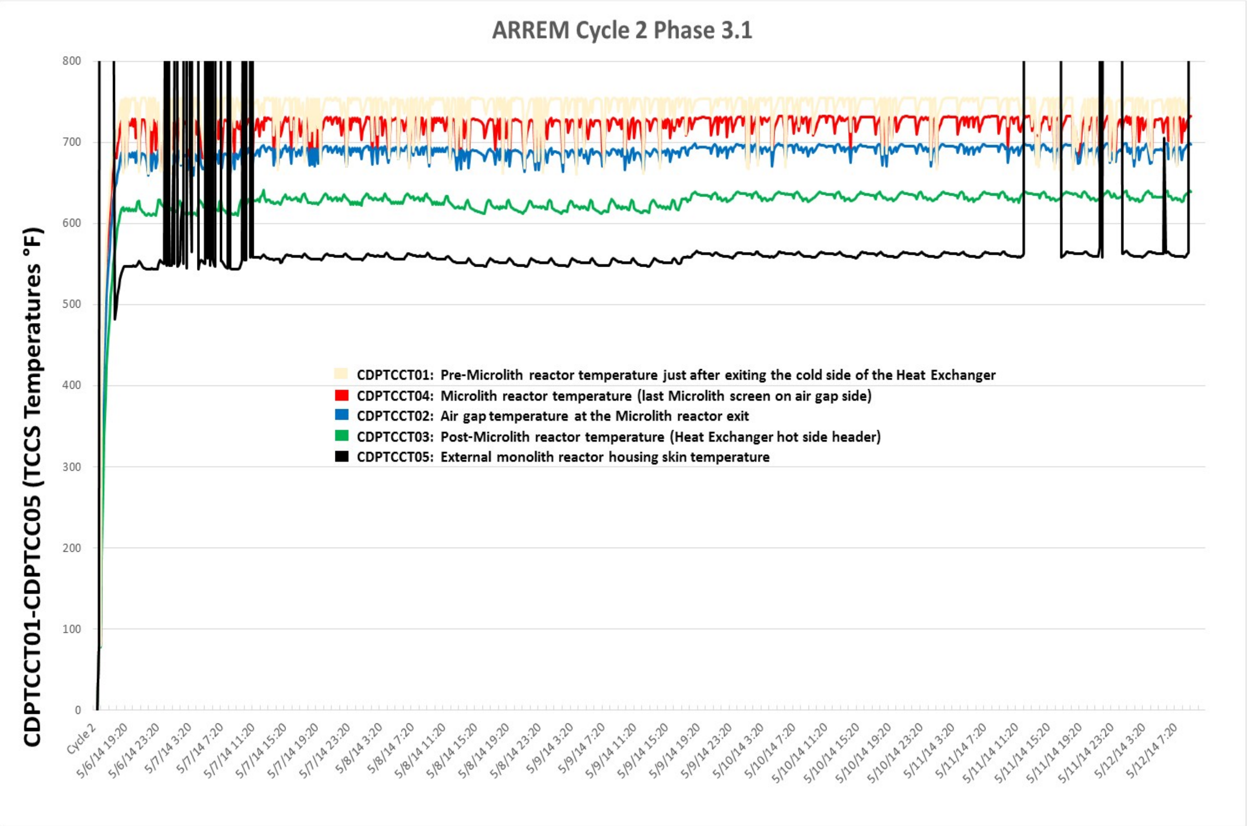


Cycle 2 Phase 3.1 CDRA 4EU TCCS M-COA 4-point test Day 3 (5/9/14)
CO2 Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and E-Chamber
mmHg
12
10
8
6
4
2
0
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg

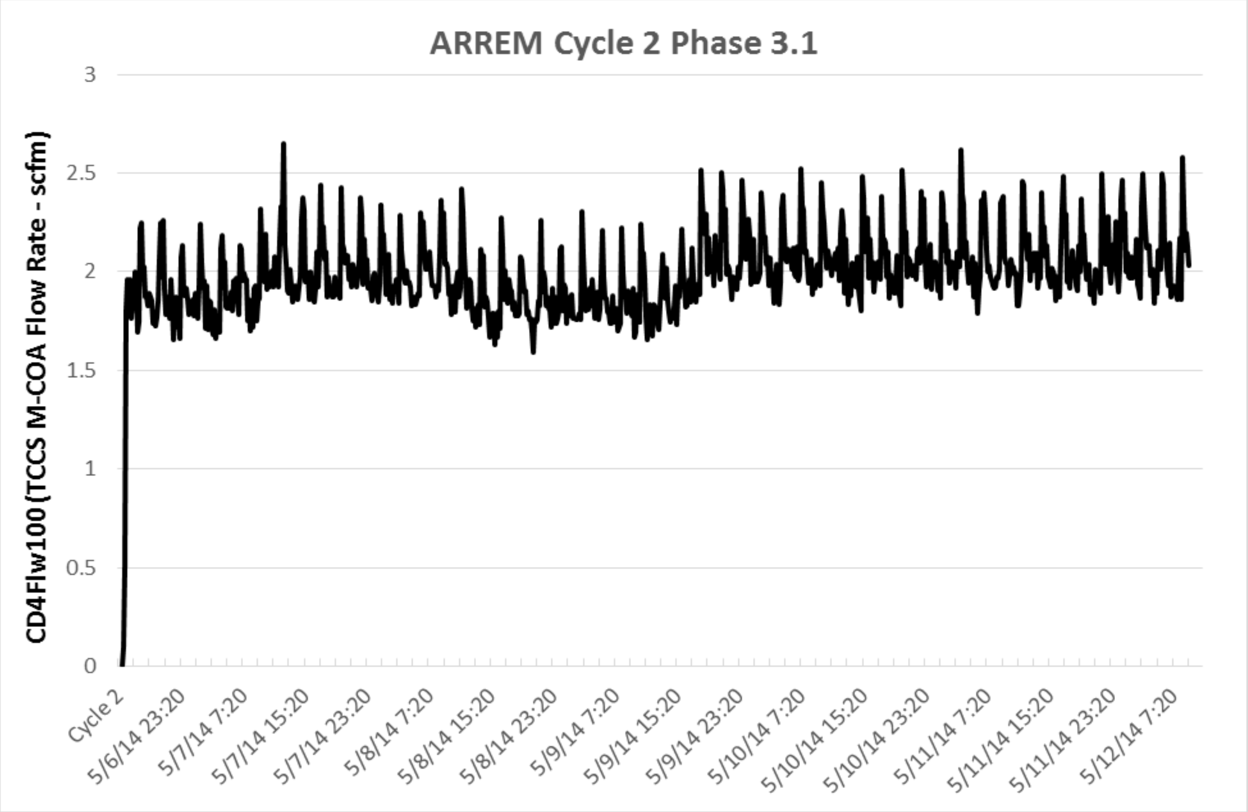

Cycle 2 Phase 3.1 CDRA 4EU TCCS M-COa 4-point test Day 4 (5/10/14)
CO_2 Partial Pressures at CDRA 4EU Inlet, CDRA 4EU Outlet, and in E-Chamber
mmHg
14
12
10
8
6
4
2
0
15
20
25
30
35
40
45
50
55
60
65
Time, Hours
CDRA 4EU Inlet Partial Pressure, mmHg
CDRA 4EU Outlet Partial Pressure, mmHg
E-Chamber Partial Pressure, mmHg



Cycle 2 Phase 3.1 CDRA 4EU TCCS M-COA 4 point test Day 1 (5/7/14) (representative of all 4 test days) CDRA 4EU Process Air Flow Rate, Fan dP



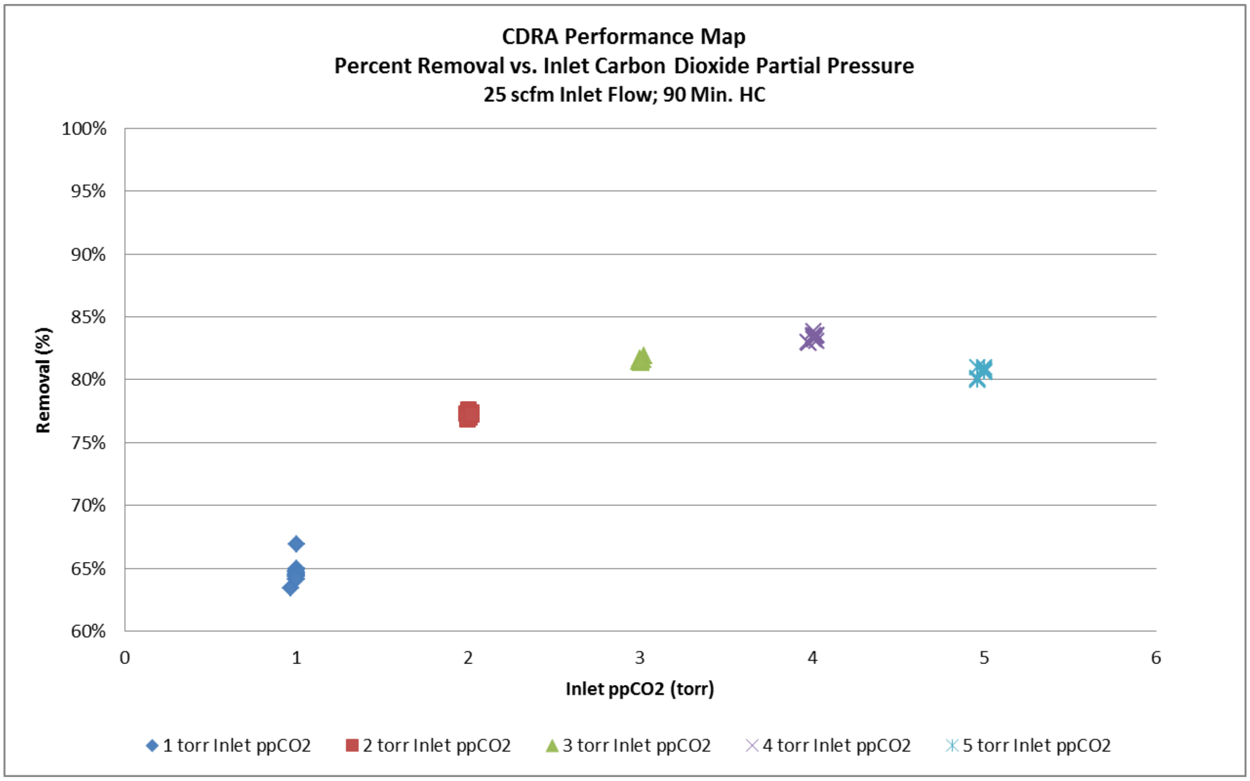
ARREM Cycle 2 Phase 3.1



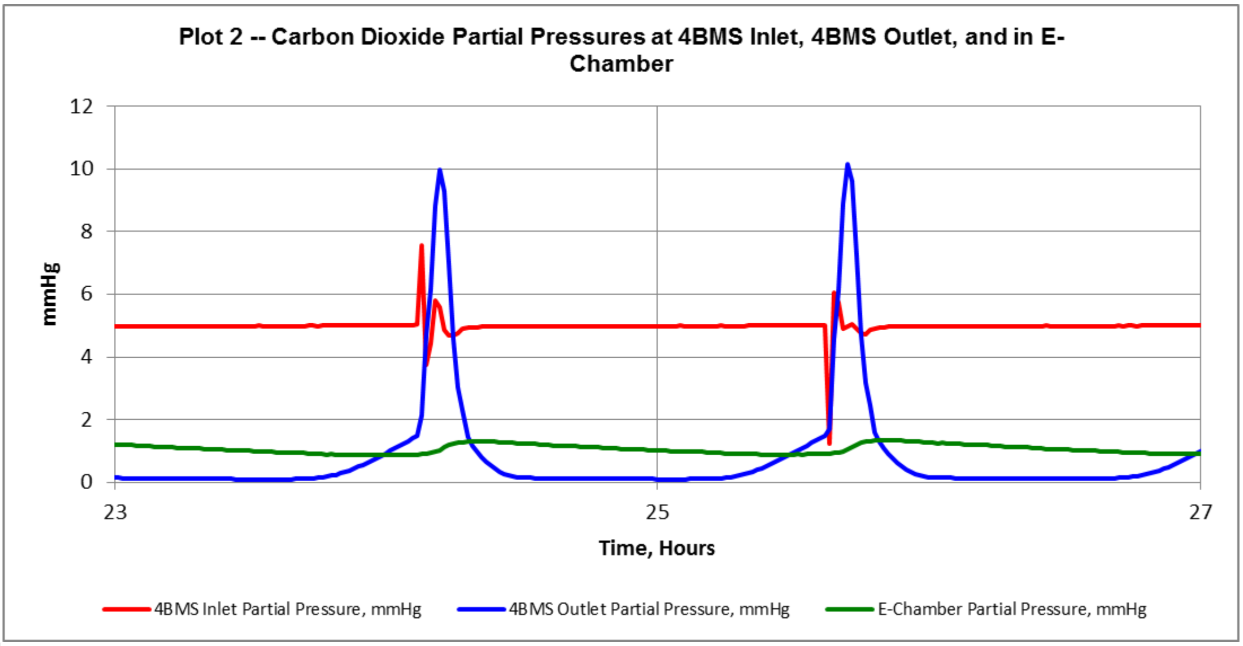
Phase 3.2 (CDRA-4EU performance mapping) (5/16/14 – 5/27/14 – ES62-TPS-RRR-14-007): Phase 3.2 was to test the increase in CO_2 removal performance resulting from increases in process flow rate. The nominal flow of 20.4 standard cubic feet per minute (SCFM) was increased to approximately 25 SCFM, while the cycle time was reduced to 90 minutes, the minimum that would allow time for the CO_2 sorbent beds to heat to the nominal set point of 400 °F. NOTE: tests at even higher flow rates (30 scfm and maximum achievable up to 35 scfm) had to be postponed until after the rest of Cycle 2 was completed due to facility blower issues. Performance results from this test were favorable; the test results demonstrated that one key exploration objective was met, that is, reducing cabin CO_2 levels to 2 torr with 4 crew members. Removal capacity for a high crew load was also demonstrated.

However the combination of higher flow rates and reduced cycle times resulted in considerably higher power requirements. Heater power alone increased by 200 Watts (average) compared to a nominal operational configuration; blower power (not measured) would also increase significantly.

The results of the test are shown in the plot below. Cabin CO_2 partial pressures levels were maintained below 2 torr for all test points.



The CO_2 adsorbent beds did not experience CO_2 breakthrough during the first 4 runs. Breakthrough was observed during the run with the highest inlet CO_2 partial pressure, 5 torr, as shown in the plot below.

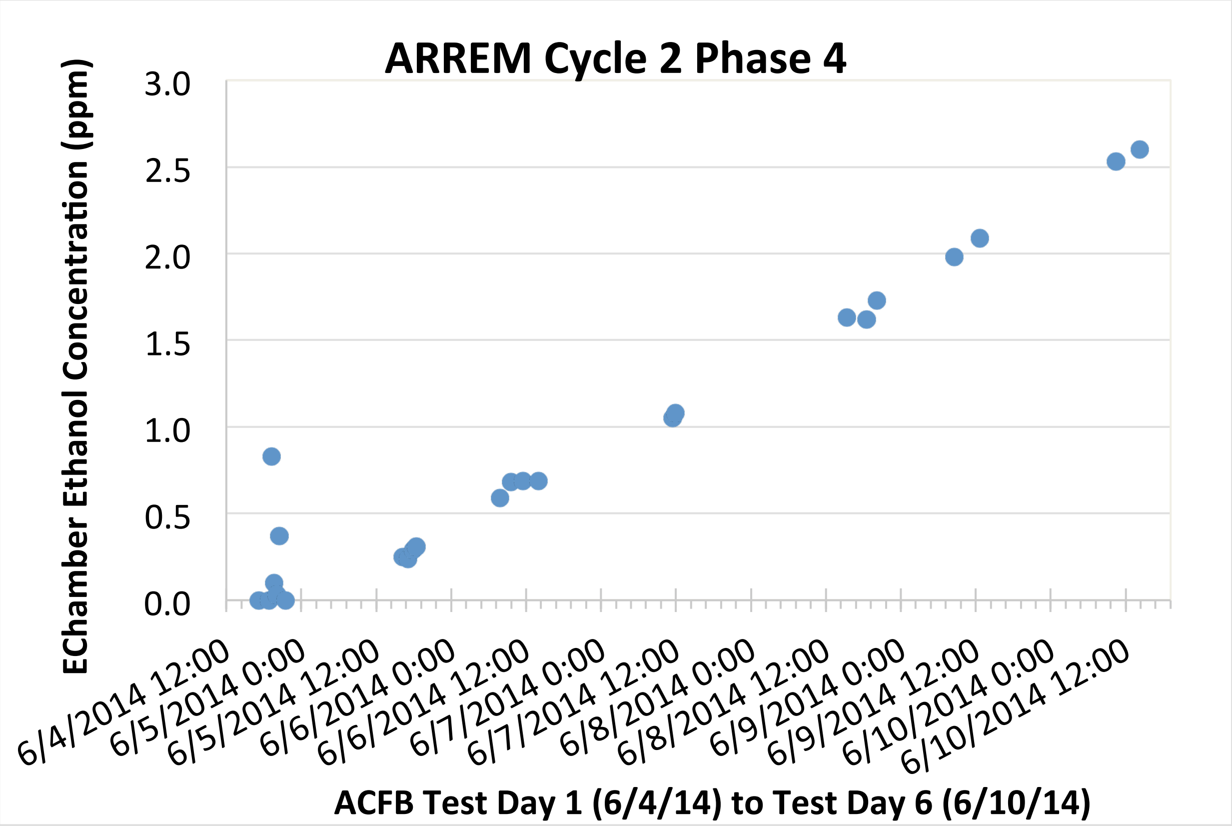


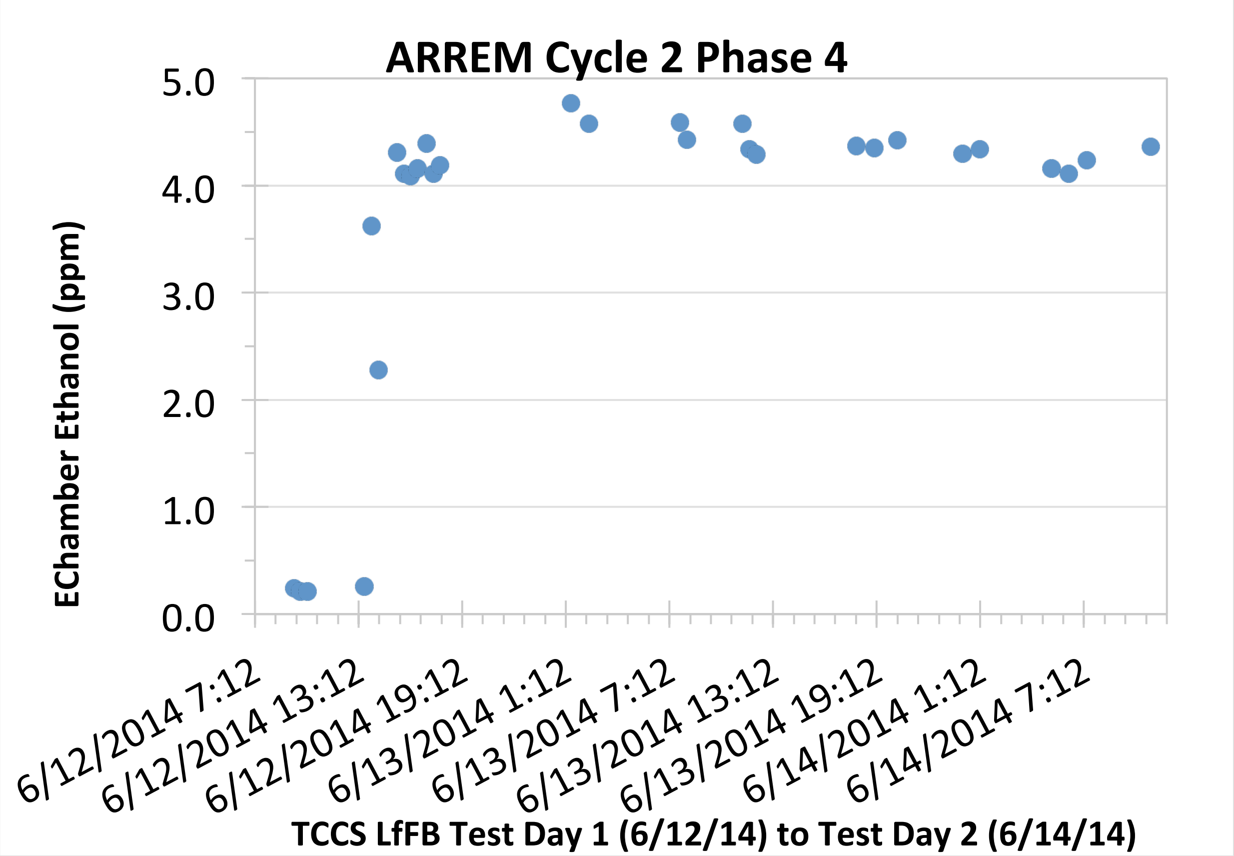
[1] "Advanced Exploration Systems Life Support Systems Project Work Plan FY15-17"

Phase 4 (Evaluation of TCCS Concept Architectures) (6/4/14 – 6/14/14 – ES62-TPS-RRR-14-003): Phase 4 testing aimed to compare the performance of two activated charcoal bed architectures; the Adsorbent Cartridge Fixed Bed (ACFB) and the Low-flow Fixed Bed (LfFB). In this test phase, each architecture was operated independently. Although, similar in magnitude of charcoal mass contained (approx 23.5 kg for the ACFB and 21 kg for the LfFB) each bed varies in process air flowpath. The ACFB, 3 vertically stacked cassettes 6” H x 24” W x 14” D with a volume of 825 in^3 of Ammonasorb II (4 x 8 mesh) each, resides on the inlet of the main ventilation ductwork and sees all ventilation flow pulled in at a rate of 500 SCFM while the LfFB, a cylindrical bed (13” diameter and 15” long) with a volume of 1991 in^3 packed with Ammonasorb II (6 x 12 mesh), receives only 12 SCFM of the ventilation flow via a side branch. Furthermore, the high flowrate of the ACFB is exposed to a shorter bed length of charcoal compared to the cylindrical LfFB. Bed architecture performance was characterized by its ability to maintain a high single-pass adsorption efficiency for each compound. Both computer simulation and intuitive experience suggested breakthrough of light compounds such as acetaldehyde and methanol for these beds. This was observed experimentally in both cases, although faster than predicted for the LfFB. . This was likely due to differences in the charcoal capacity used in simulation and experiment. Computer simulations also suggested the ACFB would maintain some single pass efficiency for siloxane compounds. Experimental data showed that as late as Day 6 into Phase 4 testing that the ACFB still maintained a capacity for siloxane and organosilicon compounds which maintained the chamber atmospheric concentration near or below GC/MS detection limits. Performance was also maintained for xylene. In addition, acetone and isopropanol were held at low levels as compared to the LfFB. This was in part due to the much higher flowrate through the ACFB increasing chamber scrubbing rates. It was thought that this high flow would also promote early breakthrough, however, but this was not exactly as predicted. Due to the atmospheric profile maintained during the ACFB phase and in particular its ability to still control hexamethylcyclotrisiloxane (the lowest molecular weight cyclic siloxane), the ACFB was selected for further testing in Phases 5 and 6 to characterize its breakthrough profile. Note that the LfFB also maintained high efficiency for siloxane but the novelty and potential applicability of the ACFB design to mitigate current trace contaminant problems on ISS made the ACFB an attractive option to further test.

In addition to single-pass efficiency, the characteristic behavior of compound breakthrough in each architecture was evaluated and can be described by examining the chamber atmospheric loading behavior. The following plots show the chamber profile of ethanol, which was the predominant chemical compound injected. For the ACFB architecture an initial chamber spike (~1.0 ppm) was seen early in the test duration due to chemical injection followed by a steady rise in concentration towards 2.5 ppm. This behavior indicated that initially in the test, ethanol was well controlled by the ACFB but due to degradation of the ACFB single-pass efficiency the chamber accumulation steadily grew over time. Due to the high flowrate of the ACFB, the chamber loading was maintained very low initially (e.g. the chemical cocktail dose was knocked back down to low levels). As the test progressed and more compounds exhibited breakthrough behavior, the relative atmospheric profile changed. Breakthrough at the high ACFB velocity appeared to be molecular weight dependent with the heavy hexamethylcyclotrisiloxane and xylene remaining under control. Conversely, the LfFB maintained high single pass efficiency throughout the test (as indicated by the concentration plateau) but due to its low flowrate only a small amount of the cabin atmosphere could be effectively scrubbed of chemical at one time. Therefore, chemicals accumulated very rapidly in the LfFB but were eventually maintained at a plateau concentration (~4.5 ppm). The concentration profile of the LfFB was as anticipated based on Cycle 1 test architecture.

Table 1: Cycle 2 Contaminant Mix			
Compound	Target Concentration (mg/m^3)	Injection Rate (mg/hr)	Amount (grams)
Methanol	0.7	26.2	36.8
Ethanol	4.8	159.9	224.5
2-Propanol	0.4	11.2	15.7
Ethanal (Acetaldehyde)	0.6	17.4	24.4
Xylene	0.2	5.4	7.6
DCM (Methylene Chloride)	0.1	3.1	4.4
2-Porpanone (Acetone)	0.5	14.4	20.2
TMS (Trimethylsilanol)	0.2	5.4	7.6
Hexamethylcyclotrisiloxane (solid)	1.5	40.6	57.0





Phase 5 (Integrated Atmosphere Revitalization System) Overview (7/24/14 – 7/31/14 – ES62-TCP-ARS-14-005): The objective of Phase 5 was to integrate the atmosphere revitalization system (CDRA-4EU, Sabatier, TCCS M-COA, TCCS ACFB, and OGA) and run at 3, 4, and 6 crew member metabolic rates for a minimum of 48 hours apiece. The 2 crew member rate was dropped because the OGA cannot run below a 2.7 crew member rate.

Phase 5 Event Summary 7/24/14 – Day 0 – Facility support items (chilled water, N_2, Micro GC/GC/FTIR, contaminant injection, 2-gas pressure control via N_2/O_2, condensate collection, and metabolic simulator (CO_2 injection, $H_2O_{(v)}$ injection, and O_2 removal)) were activated. The final activity of the day was to activate the CDRA-4EU (along with the CO_2 Management Assembly) and TCCS M-COA to allow them to warm up for Day 1. The CRA Simulator exposed a problem with the CO_2 injection system. There was an imbalance between the injected amount and the amount removed. An adjustment had to be made to the CO_2 injection amount in order to properly balance CO_2 in advance of Sabatier operations on Day 1.

7/25/14 – Test Day 1 – The math error found on Day 0 was again accounted for in the MSA setting for CO_2 injection. GC results indicated a siloxane compound in the sample taken from the TCCS inlet air port. A new hose material required to get the CDRA-4EU leak tight was suspected. EChamber pressure fluctuated wildly corresponding to temperature variances. Damper proportional/integral/derivative (PID) control was a suspected contributor. CO levels ran high in the afternoon and the injection rate was decreased from 0.15 ml/min to 0.11 ml/min.

7/26/14 – Test Day 2 – A scheduled power outage occurred at 0747. Everything connected to uninterruptible power supply (UPS) stayed up. However, the hazardous gas pump could not be connected to UPS because of its high amperage. When it went down, the Sabatier CRA went to Purge/Hold. The OGA was held in Standby until the power outage was over. It took about 20 minutes to notice that the hazardous gas pump was down. Overall a routine 15 minute changeover from facility H_2 to OGA H_2 for the Sabatier CRA took 90 minutes. All other operations were nominal.

7/27/14 – Test Day 3 – Nominal day with no anomalies noted.

7/28/14 – Test Day 4 – There was a PACRATS crash at approximately 1400. This caused the TCCS M-COA, CDRA-4EU to go down. The Sabatier CRA continued to process until the CO_2 Accumulator ran out while program recovery was occurring. The OGA went to Standby. It took approximately 45 minutes to return the system to integrated operations.

7/29/14 – Test Day 5 – Nominal day with no anomalies noted. The Horiba CO_2 monitors could not be calibrated due to a N_2 (zero gas) regulator failure.

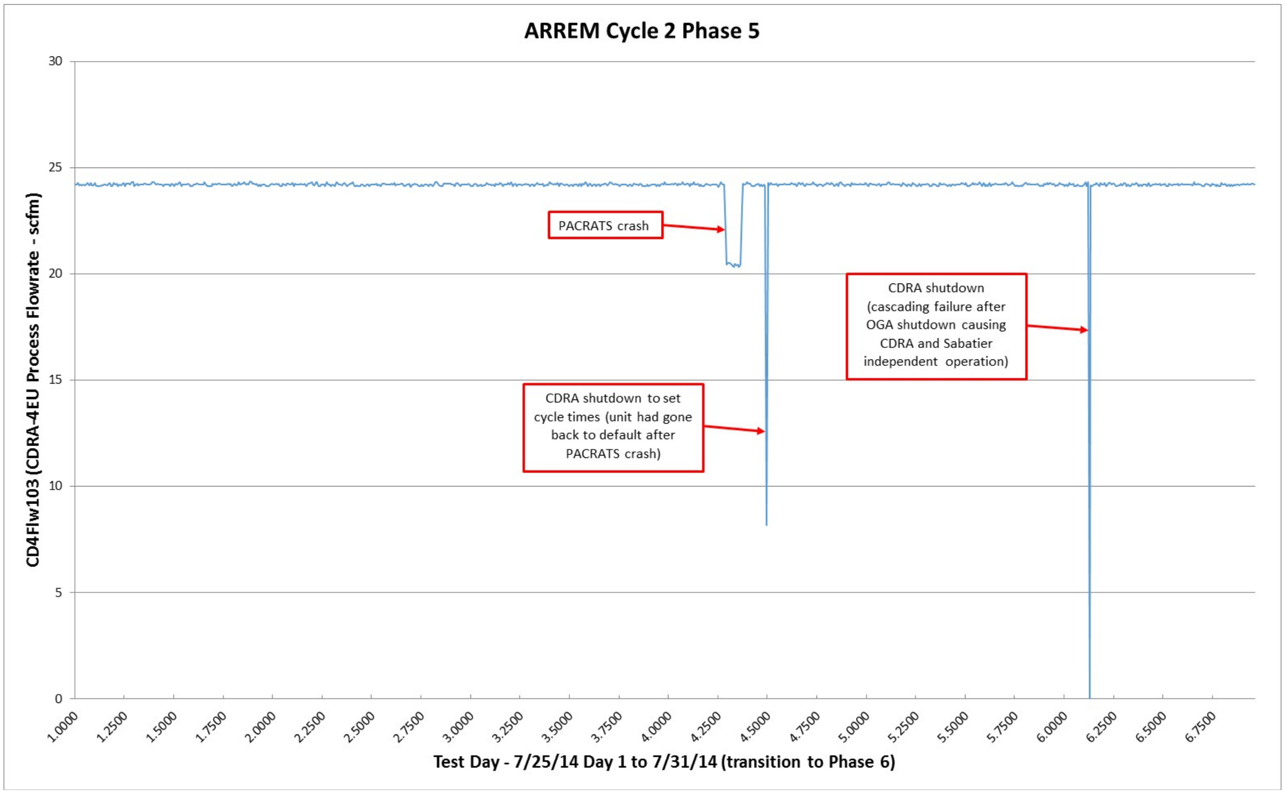
7/30/14 – Test Day 6 – At 1024, an OGA shutdown occurred. Data review indicated a shutdown circuit in the Power Supply Module (PSM). Sabatier CRA went to Standby for about 2 hours and then back to Process with facility H_2. An attempt to re-activate the OGA (non-integrated with the Sabatier CRA) was unsuccessful. A CDRA-4EU shutdown occurred just after 1200 because of a buildup in CO_2 accumulator pressure (a possible program issue with dumping to space vacuum while the other hardware issues were being resolved). CDRA-4EU was re-started and a CO_2 dump to space vacuum occurred via the pump rules and operations returned to normal. The N_2 regulator on the Horiba calibration lines was replaced and the monitors re-calibrated.

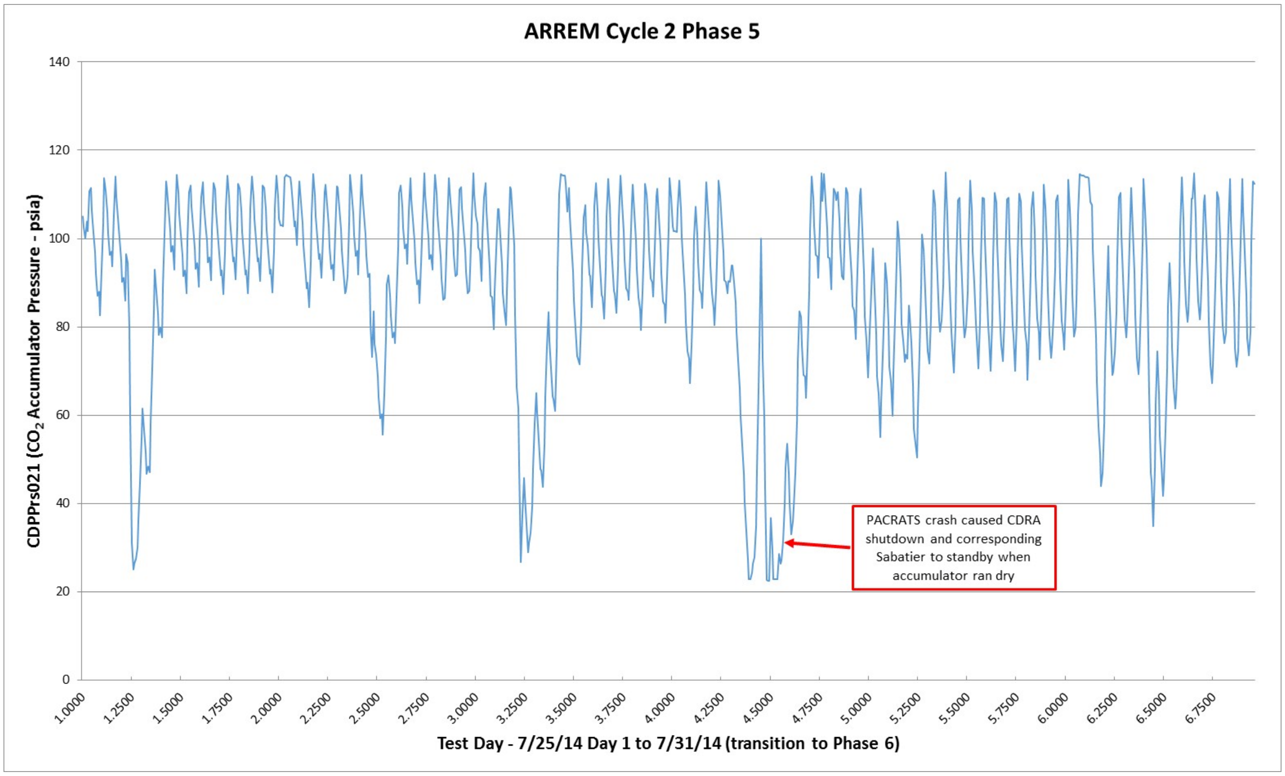
Phase 5 Test Results The EChamber atmosphere ethanol concentration slowly rose from an initial concentration of 2 ppm to just over 6 ppm by the end of Day 6 which is still well below the 180 day Station Maximum Allowable Concentration (SMAC) of 1000 ppm. The same can be said for CH_4 (topping out at 55 ppm with a 180 day SMAC of 5300 ppm). CO exhibited the same slow rise topping out at 17 ppm which is still below the 55 ppm 7-day SMAC but above the 15 ppm 30-day/180-day/1000-day SMAC. The latter SMAC of 15 ppm is the target for exploration missions. The ACFB, TCCS M-COA, and the Condensing Heat Exchanger were the removal components for Phase 5. The TCCS M-COA's performance was compromised somewhat by a lower than expected throughput (0.85 scfm .vs. 2 scfm) and possible siloxane contamination of the catalyst. For further analysis of the TCCS M-COA's performance see "Evaluation of an Atmosphere Revitalization Subsystem for Deep Space Exploration Missions" (J. L. Perry et al, 44th International Conference on Environmental Systems, July 2015). Post-test evaluation found that thermal control of the M-COA is more difficult below 1 scfm when using deadband control logic for regulating catalytic reactor temperature. As a result, the M-COA unit operated at an average lower temperature yet evaluation found 94% single pass oxidation efficiency for CO. The thermal dynamics observed may be corrected by implementing proportional-integral-derivative (PID) control rather than the typical deadband control logic. The increasing CO concentration is attributed to an injection rate into the EChamber higher than targeted. The CO_2 Management Assembly worked according to the updated control logic. The larger working amount (along with attention paid as to when to sample the CO_2 Accumulator) allowed for no CRA standbys (except for anomalies) during Phase 5. There were also very few, if any, instances of the CDRA-4EU dumping CO_2 to space vacuum because the CO_2 Accumulator was full. The Metabolic Simulator CO_2 injection, H_2O injection, and O_2 removal functions performed nominally at the 3-, 4-, and 6-person rates. The highest delta between expected and actual (10.7%) amount occurred with the O_2 removal. The O_2 concentrator was assumed to deliver 93% purity and the expected amount was based on that. Variations probably originated with the purity of the stream accounting for the delta. The EChamber O_2 level was maintained much better than in Cycle 1 with only a 0.6% variance during Phase 5. The EChamber dewpoint sensor (AFcDwp100) read in the low to mid 60's ºF which is comparable to Cycle 1 data. The EChamber CO_2 sensor (AFcCO2100) also compared favorably to Cycle 1 data ranging between 0.3% and 0.5% indicating that CDRA-4EU was performing nominally. Humidity condensate data is in Table 1 below.

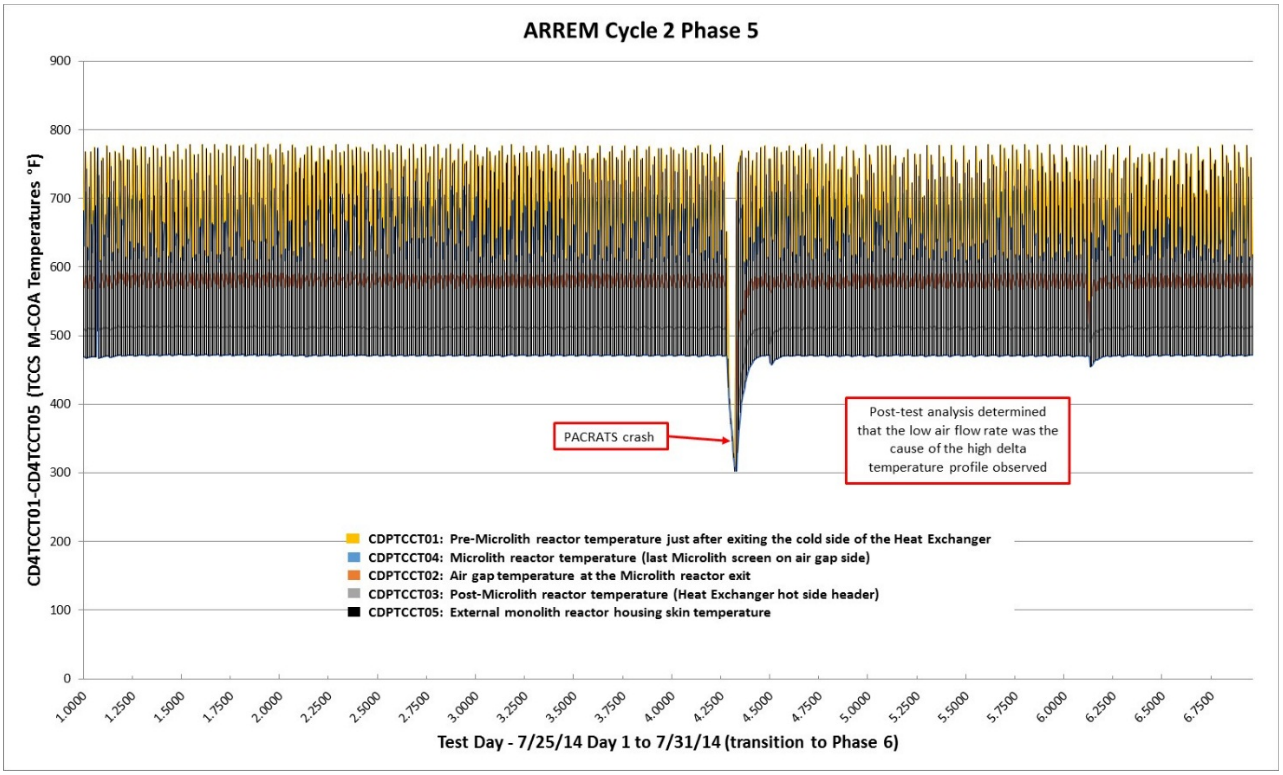
Table 2: Cycle 2 Phase 5
Humidity Condensate
(NOTE: ND is Not Detected)

Analyte	Test Day					
	1	2	3	4	5	6
Condensate (lb)	11.15	12.35	15.8	N/A (no data recorded)	20.85	23.2
Methanol (ppm)	17.7	24	32	46.2	42.8	46
Ethanol (ppm)	41	50	60.8	73.8	86.4	90
Acetone (ppm)	<1	<1	0.9	<1	<1	<1
1-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-propanol (ppb)	<1	<1	<1	<1	<1	0.97
2-methyl 2-propanol (ppm)	ND	ND	ND	ND	ND	ND
2-butanol (ppm)	ND	ND	ND	ND	ND	ND
Trimethylsilanol (ppb)	<5	2.25	7.28	<5	5.71	4
Hexamethylcyclotrisiloxane (ppb)	<700	<700	<700	<700	<700	<700
Total Organic Carbon (ppm)	39.3	50.5	61.7	72.1	79	82.8

Note that additional analysis found dimethylsilanediol (DMSD) in the condensate samples. The concentration ranged between 510 ppm and 1300 ppm with an average of 725 ppm. The DMSD reporting limit was 500 ppm.

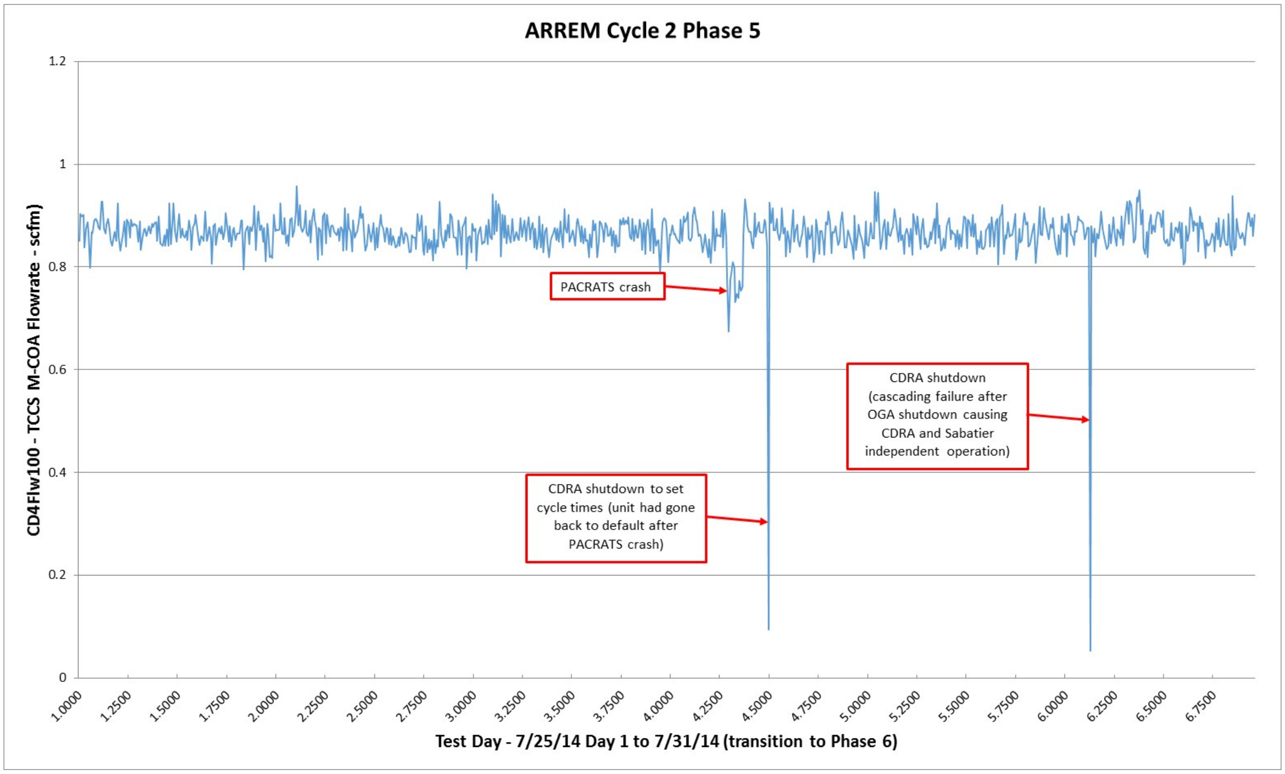

ARREM Cycle 2 Phase 5
CD4Flw103 (CDRA-4EU Process Flowrate - scfm)
30
25
20
15
10
5
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)
PACRATS crash
CDRA shutdown to set cycle times (unit had gone back to default after PACRATS crash)
CDRA shutdown (cascading failure after OGA shutdown causing CDRA and Sabatier independent operation)


ARREM Cycle 2 Phase 5
CDPPrs021 (CO_2 Accumulator Pressure - psia)
140
120
100
80
60
40
20
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)
PACRATS crash caused CDRA shutdown and corresponding Sabatier to standby when accumulator ran dry


ARREM Cycle 2 Phase 5

PACRATS crash

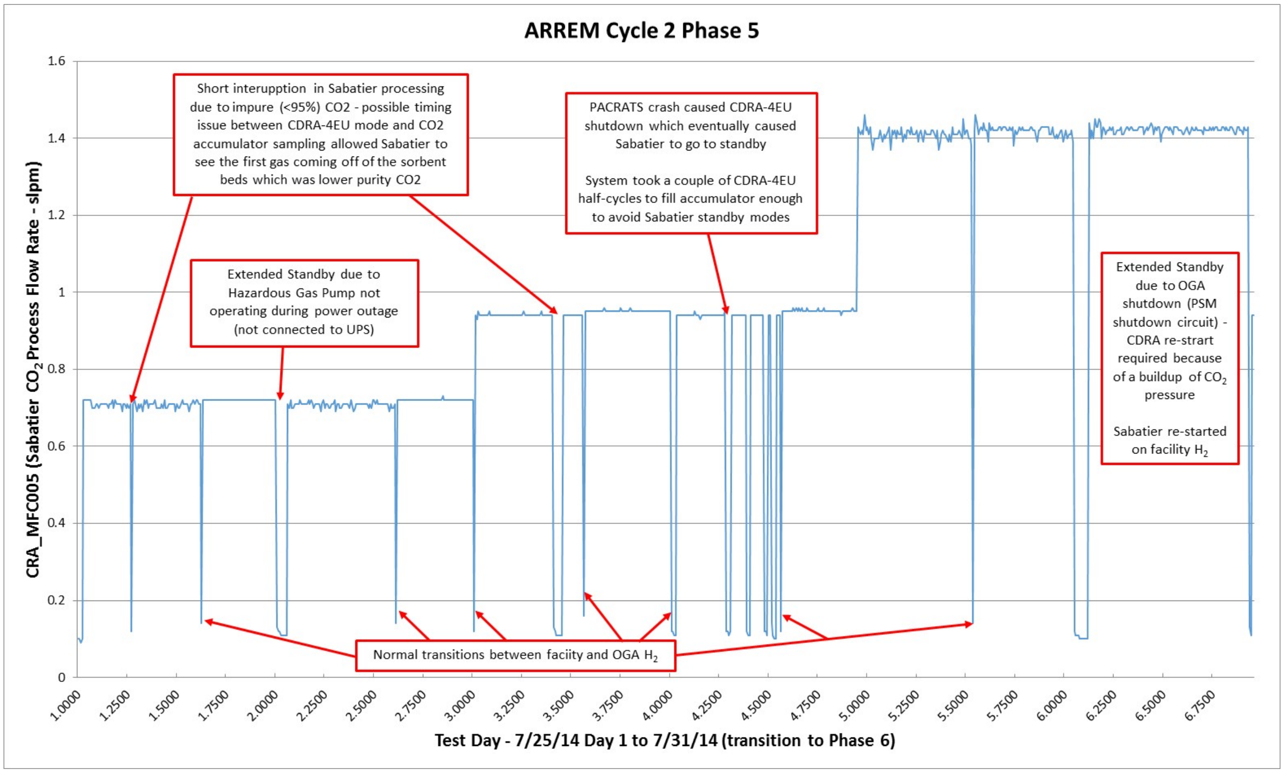
Post-test analysis determined that the low air flow rate was the cause of the high delta temperature profile observed


ARREM Cycle 2 Phase 5

PACRATS crash

CDRA shutdown (cascading failure after OGA shutdown causing CDRA and Sabatier independent operation)

CDRA shutdown to set cycle times (unit had gone back to default after PACRATS crash)


ARREM Cycle 2 Phase 5

Short interupption in Sabatier processing due to impure (<95%) CO2 - possible timing issue between CDRA-4EU mode and CO2 accumulator sampling allowed Sabatier to see the first gas coming off of the sorbent beds which was lower purity CO2

PACRATS crash caused CDRA-4EU shutdown which eventually caused Sabatier to go to standby

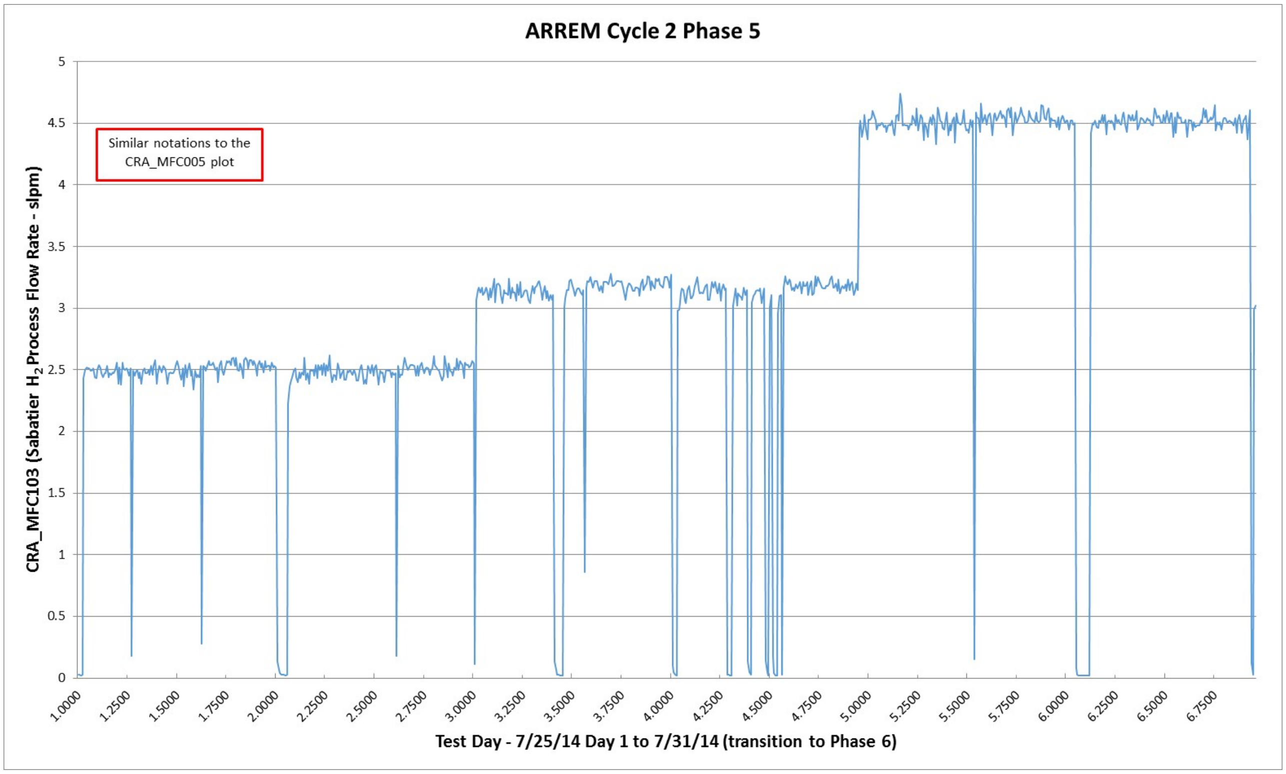
System took a couple of CDRA-4EU half-cycles to fill accumulator enough to avoid Sabatier standby modes

Extended Standby due to Hazardous Gas Pump not operating during power outage (not connected to UPS)

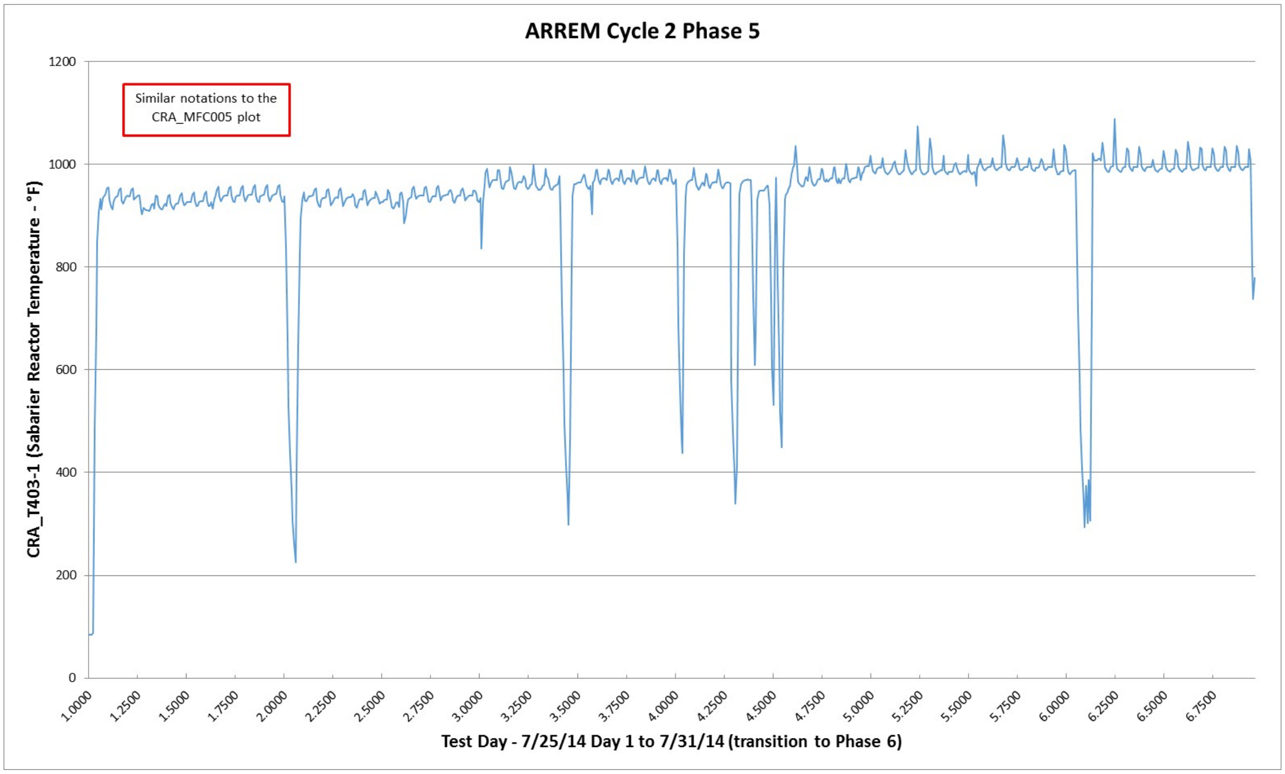
Extended Standby due to OGA shutdown (PSM shutdown circuit) - CDRA re-strart required because of a buildup of CO_2 pressure

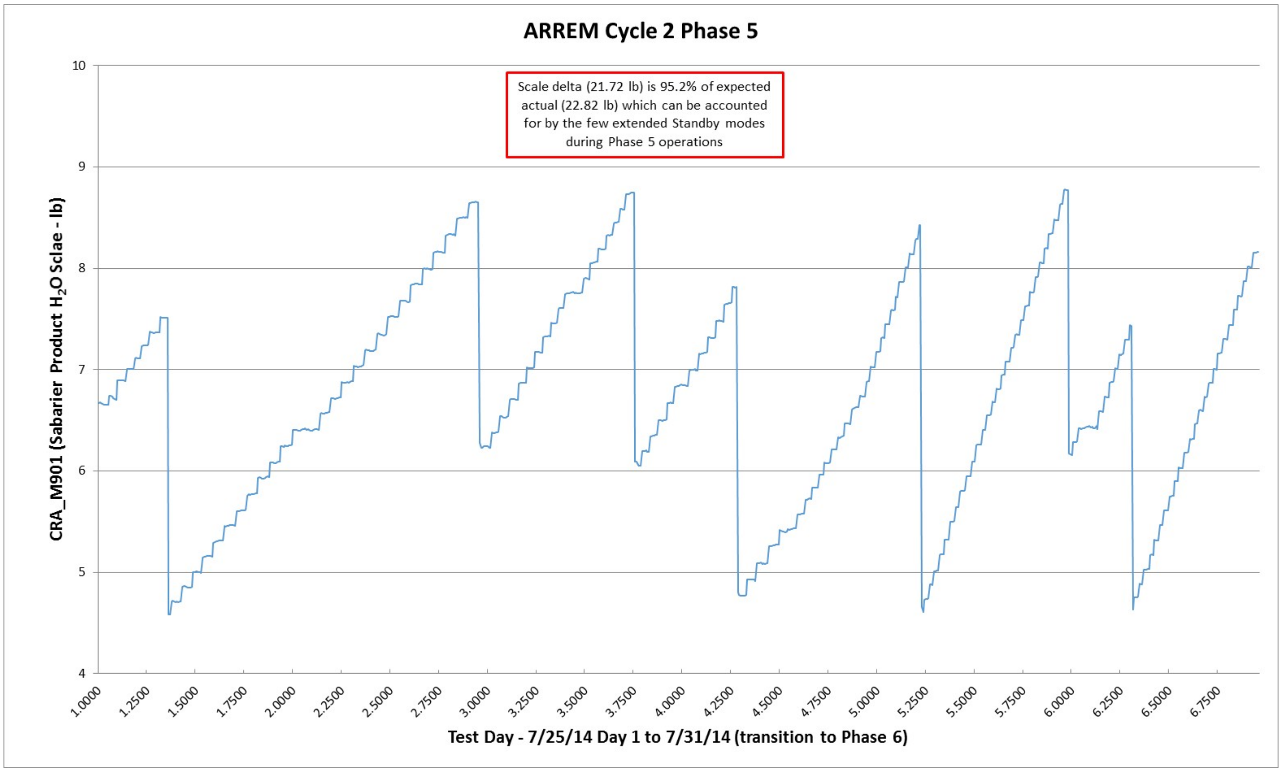
Sabatier re-started on facility H_2

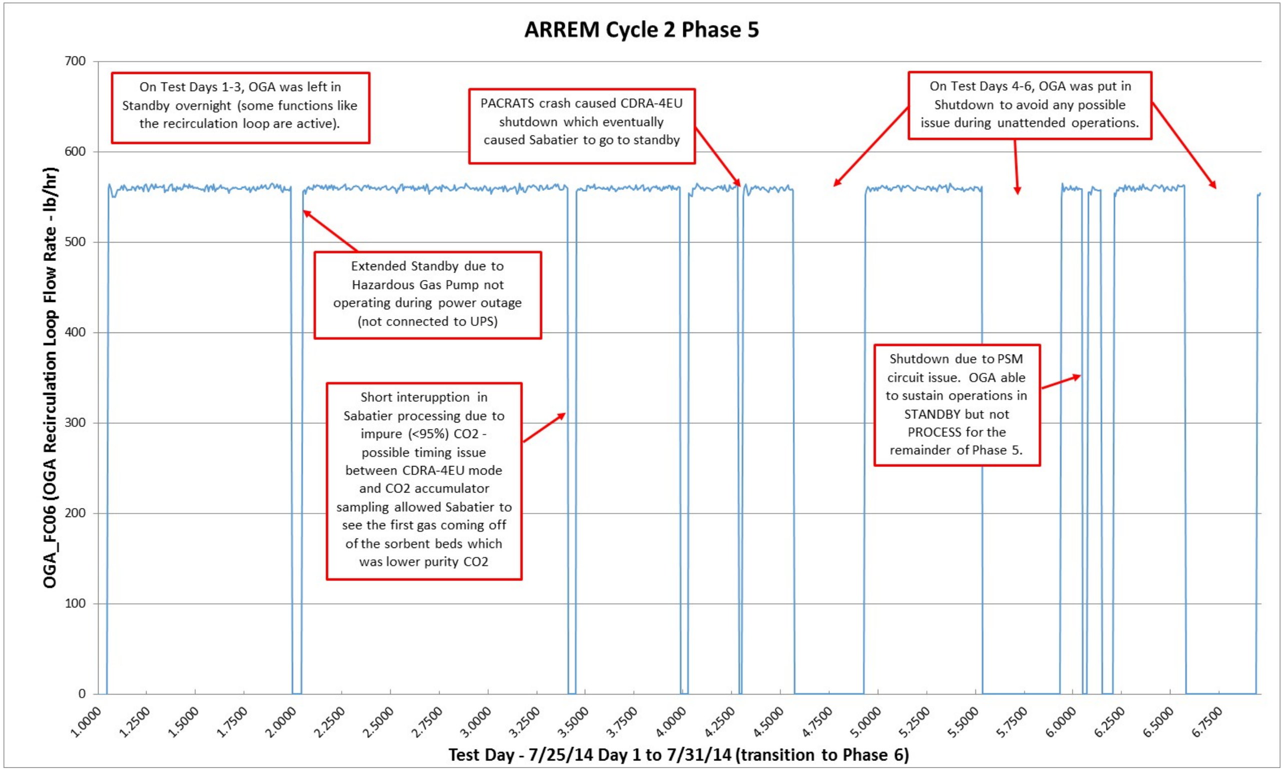
Normal transitions between faciity and OGA H_2


ARREM Cycle 2 Phase 5

Similar notations to the CRA_MFC005 plot


ARREM Cycle 2 Phase 5
Similar notations to the CRA_MFC005 plot
CRA_T403-1 (Sabarier Reactor Temperature - °F)
0
200
400
600
800
1000
1200
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)


ARREM Cycle 2 Phase 5
Scale delta (21.72 lb) is 95.2% of expected actual (22.82 lb) which can be accounted for by the few extended Standby modes during Phase 5 operations
CRA_M901 (Sabarier Product H_2O Sclae - lb)
4
5
6
7
8
9
10
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)



ARREM Cycle 2 Phase 5

On Test Days 1-3, OGA was left in Standby overnight (some functions like the recirculation loop are active).

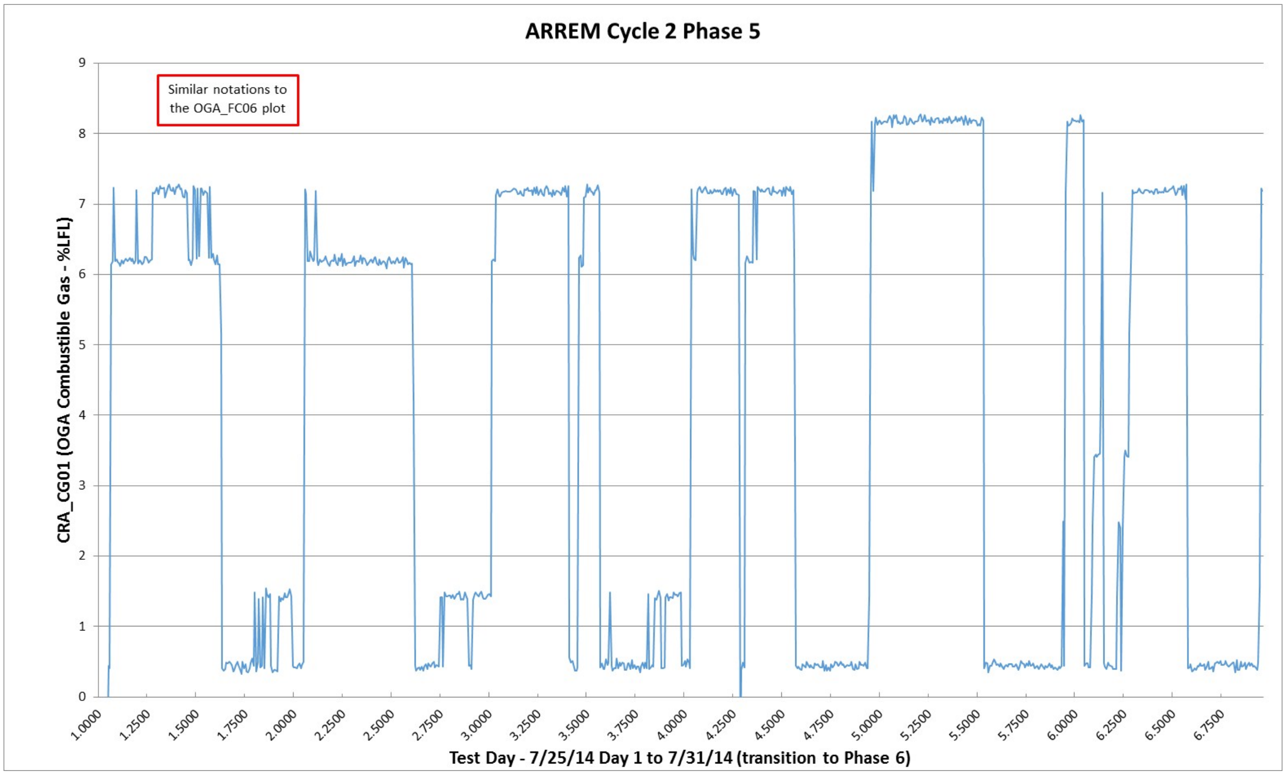
PACRATS crash caused CDRA-4EU shutdown which eventually caused Sabatier to go to standby

On Test Days 4-6, OGA was put in Shutdown to avoid any possible issue during unattended operations.

Extended Standby due to Hazardous Gas Pump not operating during power outage (not connected to UPS)

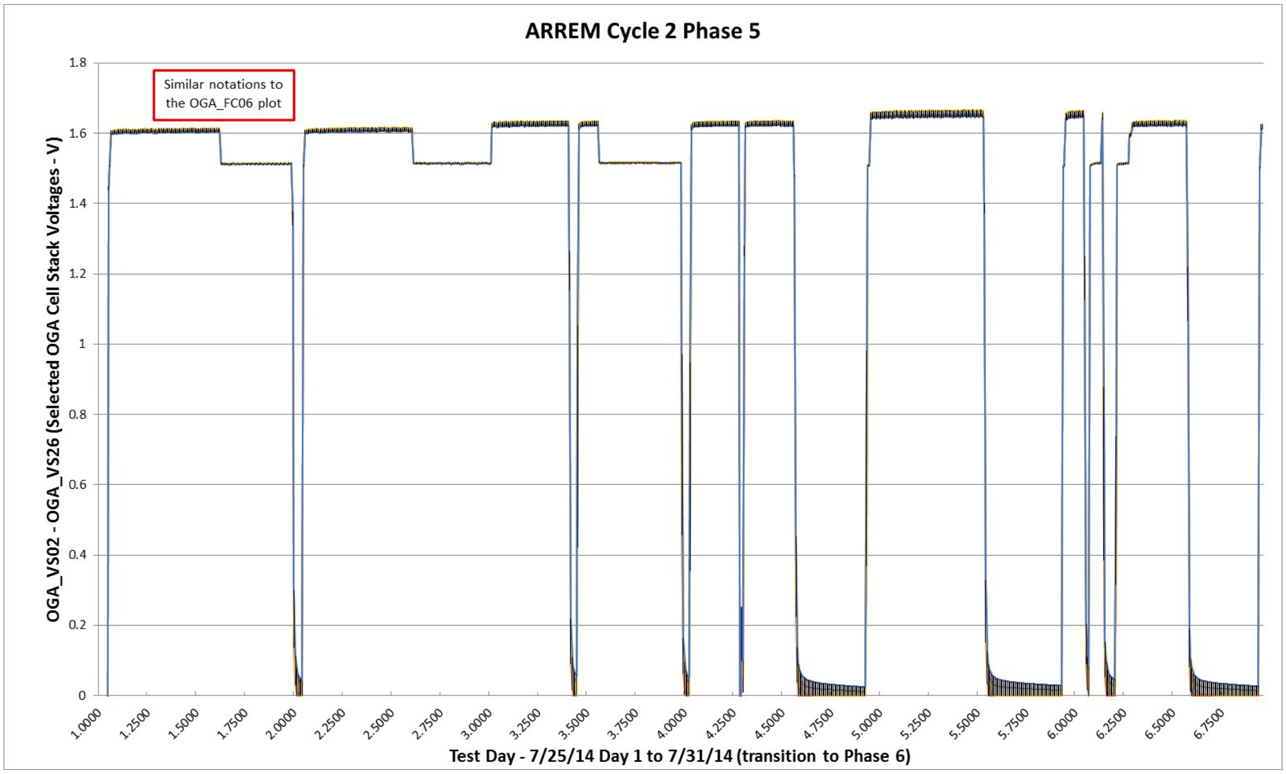
Short interupption in Sabatier processing due to impure (<95%) CO2 - possible timing issue between CDRA-4EU mode and CO2 accumulator sampling allowed Sabatier to see the first gas coming off of the sorbent beds which was lower purity CO2

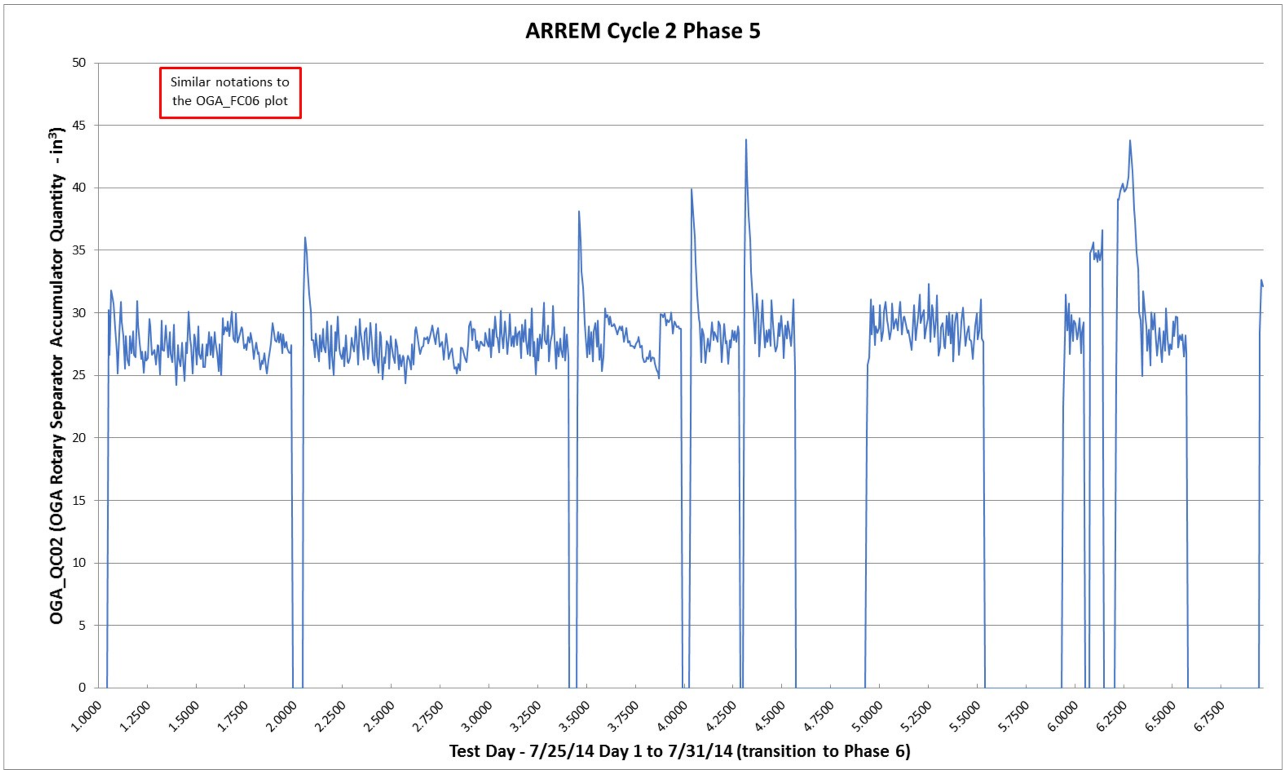
Shutdown due to PSM circuit issue. OGA able to sustain operations in STANDBY but not PROCESS for the remainder of Phase 5.

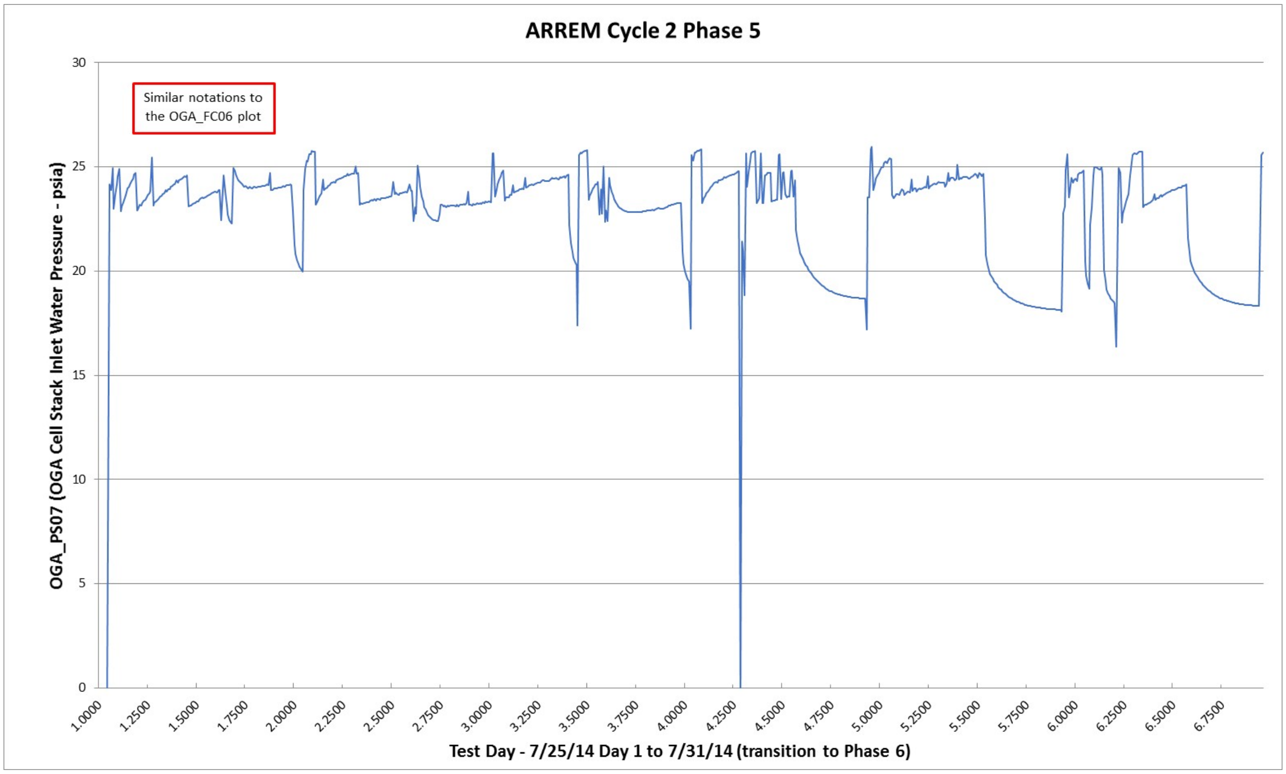


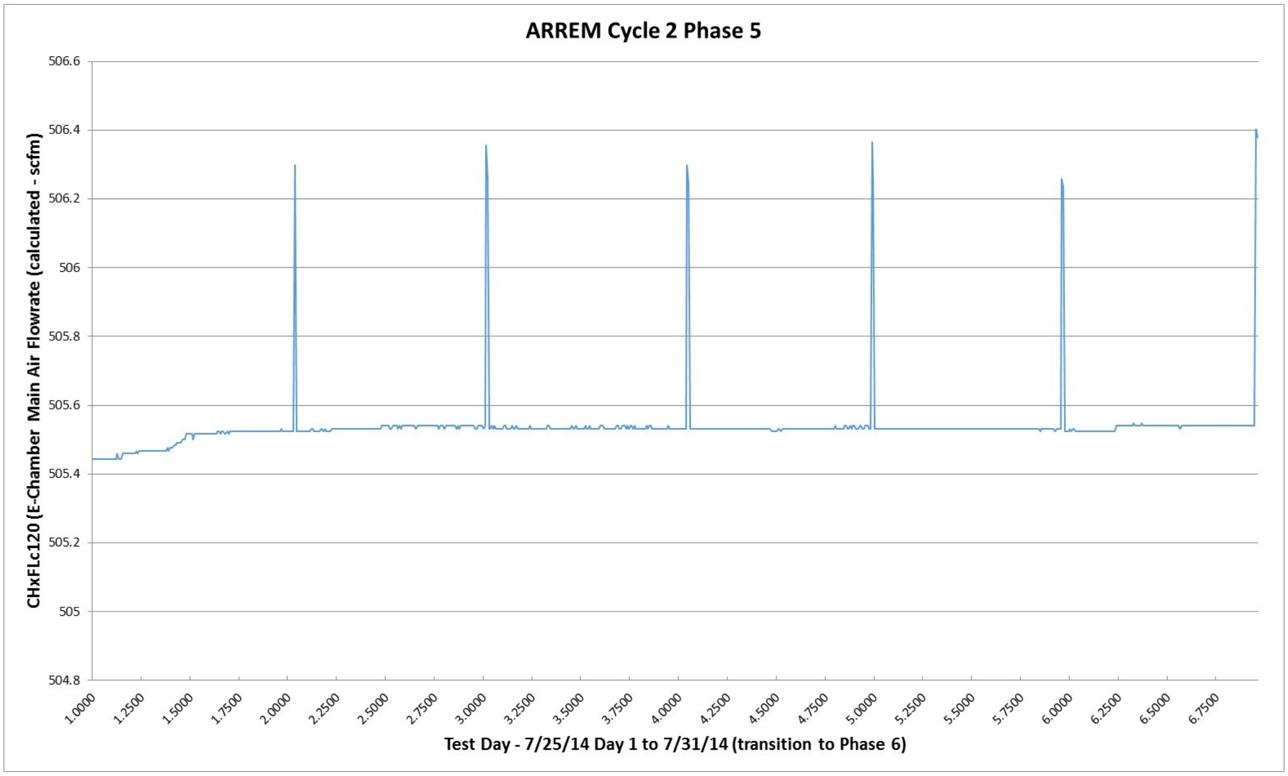
ARREM Cycle 2 Phase 5

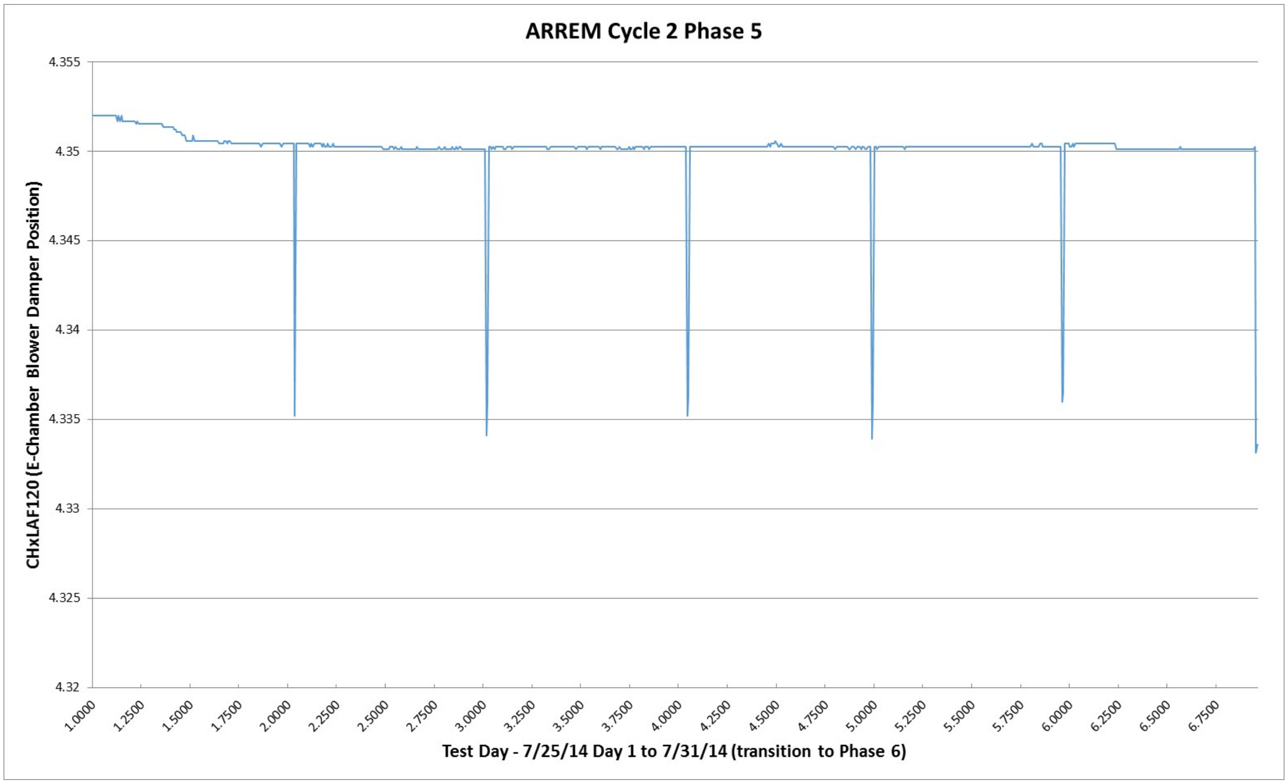
Similar notations to the OGA_FC06 plot


ARREM Cycle 2 Phase 5
Similar notations to the OGA_FC06 plot
OGA_VS02 - OGA_VS26 (Selected OGA Cell Stack Voltages - V)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)

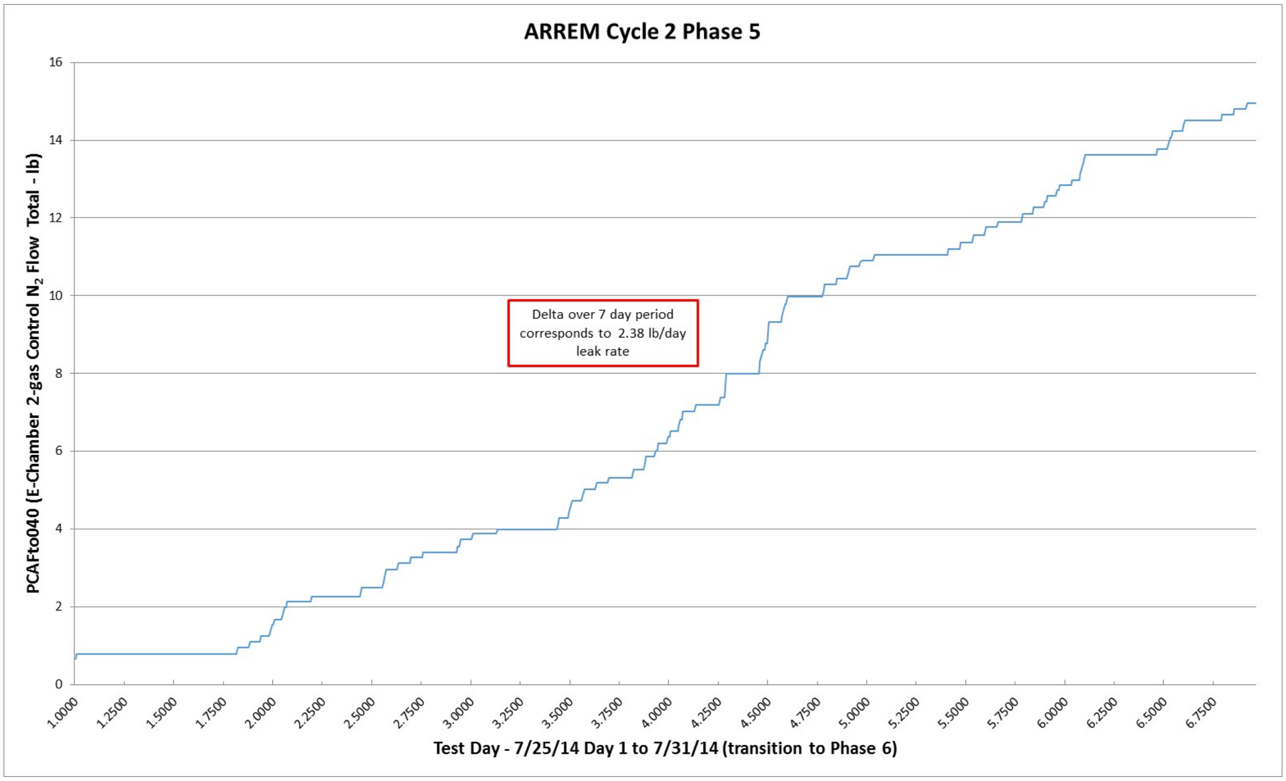

ARREM Cycle 2 Phase 5
Similar notations to the OGA_FC06 plot
OGA_QC02 (OGA Rotary Separator Accumulator Quantity - in³)
50
45
40
35
30
25
20
15
10
5
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)


ARREM Cycle 2 Phase 5
Similar notations to the OGA_FC06 plot
OGA_PS07 (OGA Cell Stack Inlet Water Pressure - psia)
0
5
10
15
20
25
30
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)


ARREM Cycle 2 Phase 5
CHxFLc120 (E-Chamber Main Air Flowrate (calculated - scfm)
504.8
505
505.2
505.4
505.6
505.8
506
506.2
506.4
506.6
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)

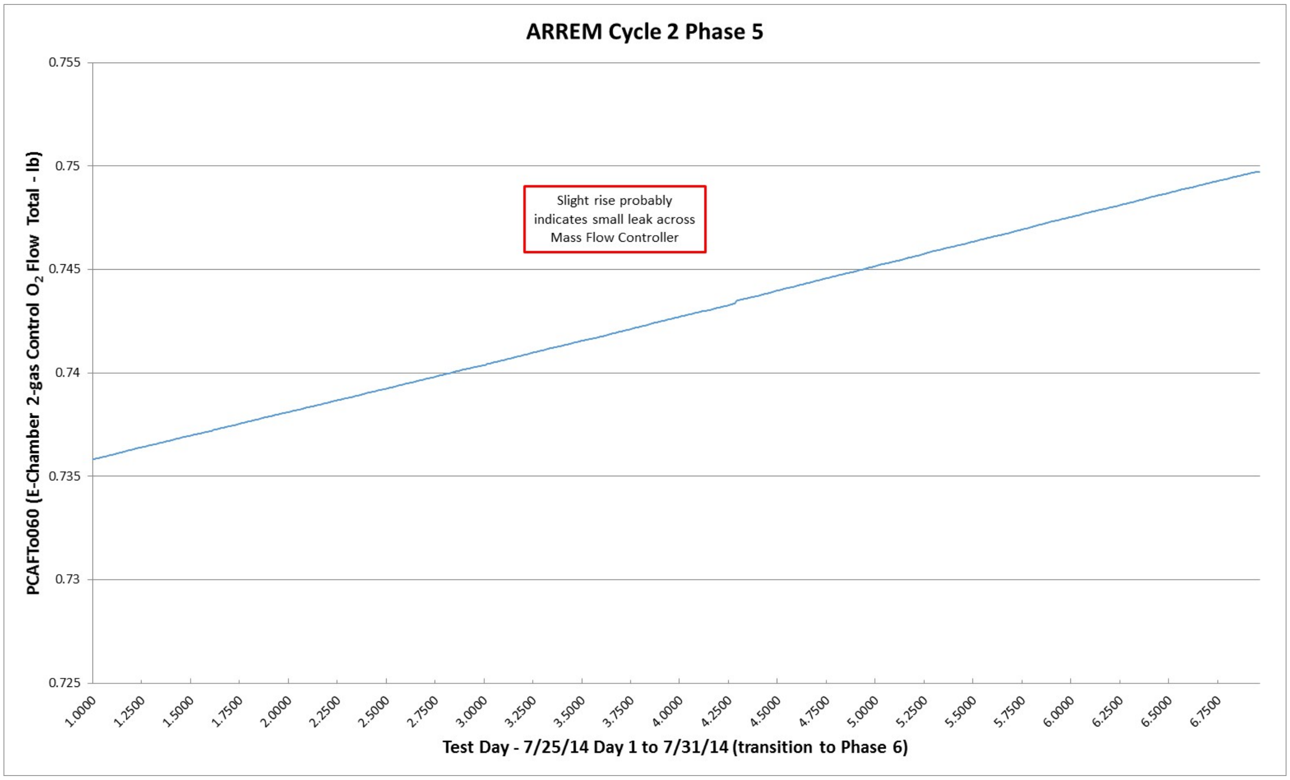


ARREM Cycle 2 Phase 5

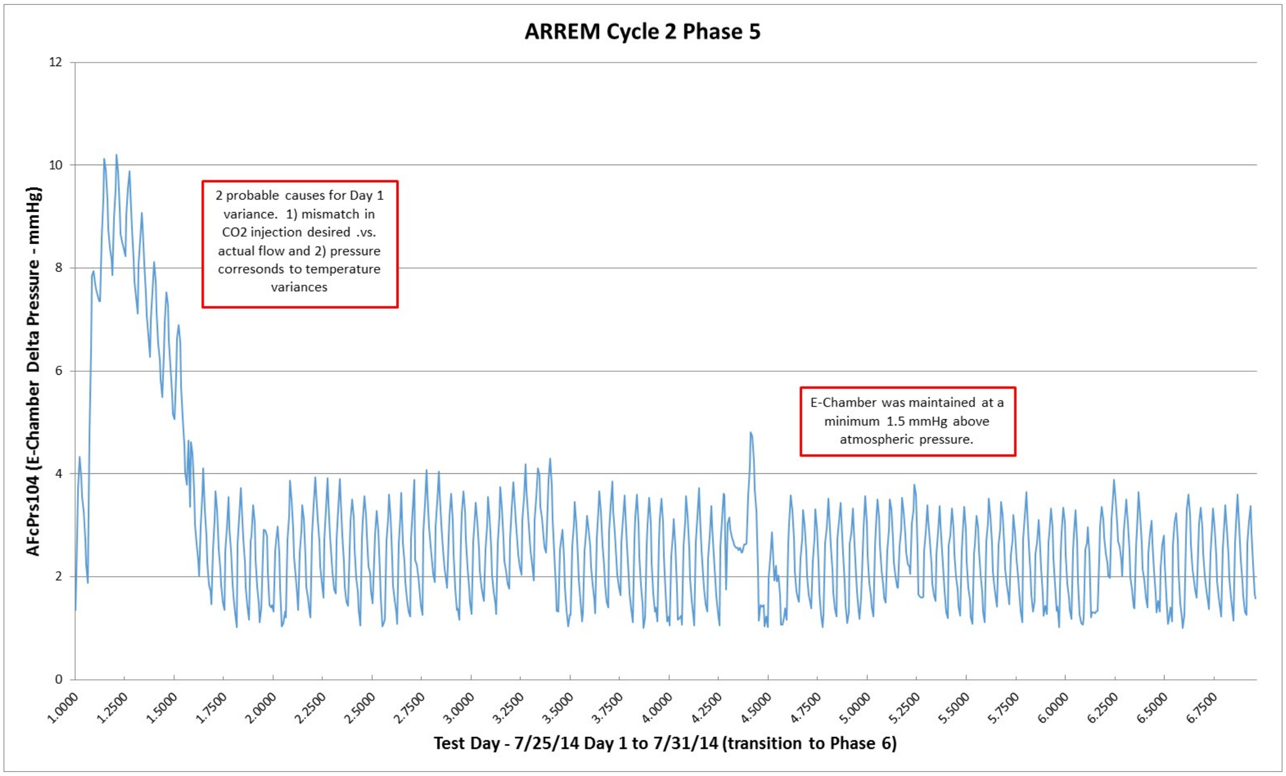


ARREM Cycle 2 Phase 5

Delta over 7 day period corresponds to 2.38 lb/day leak rate

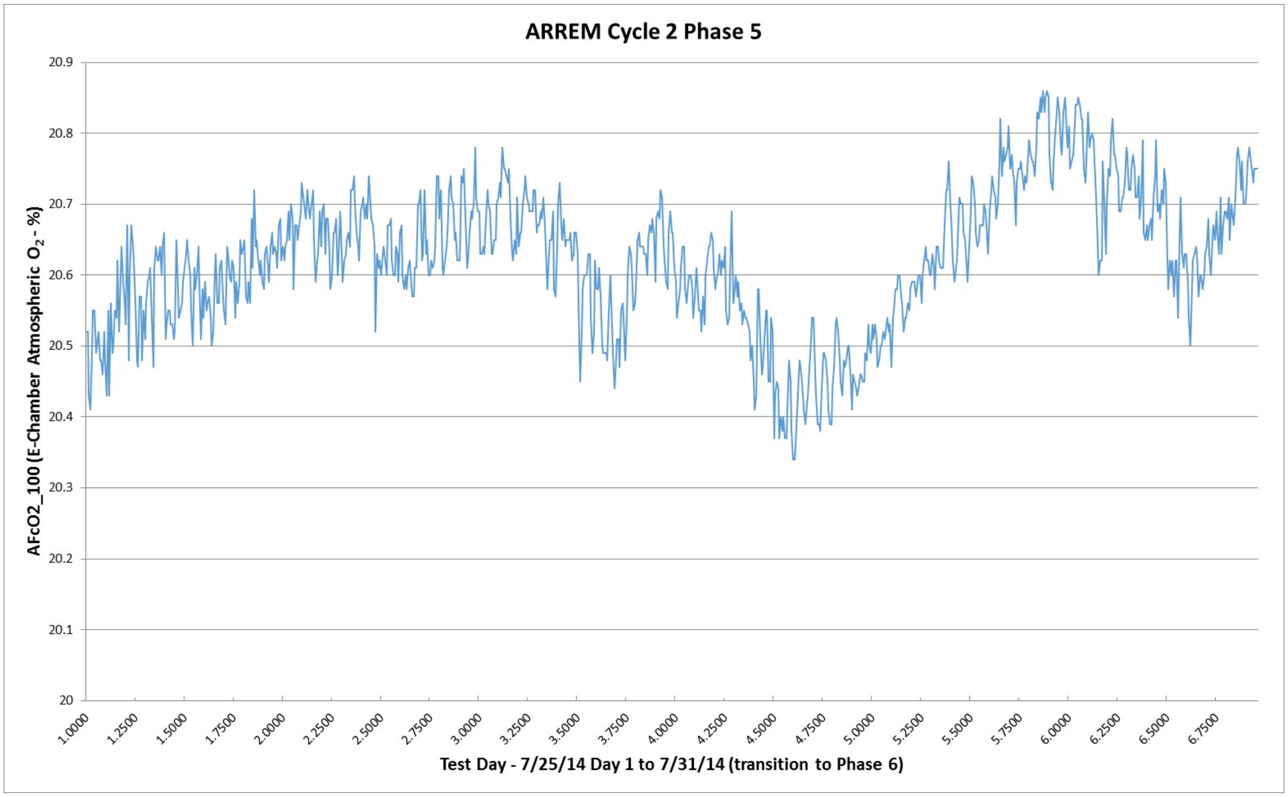


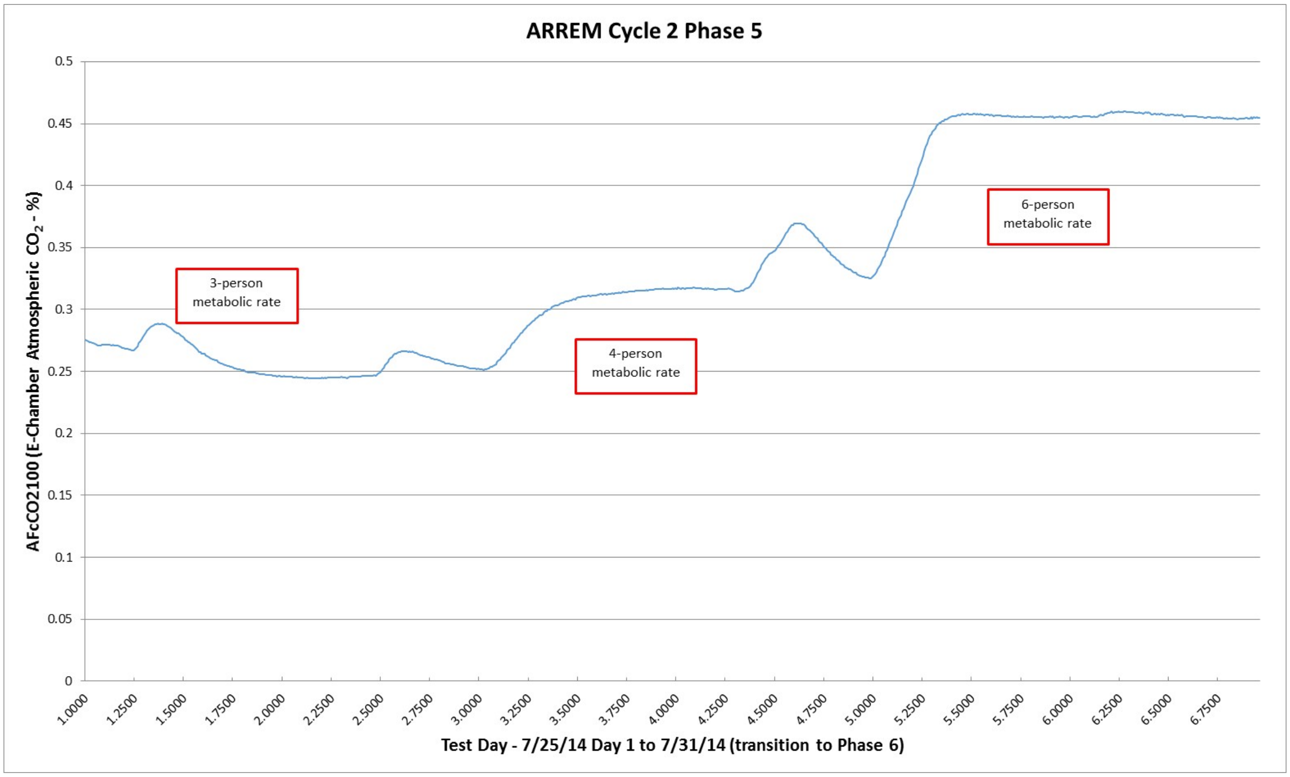
Slight rise probably indicates small leak across Mass Flow Controller

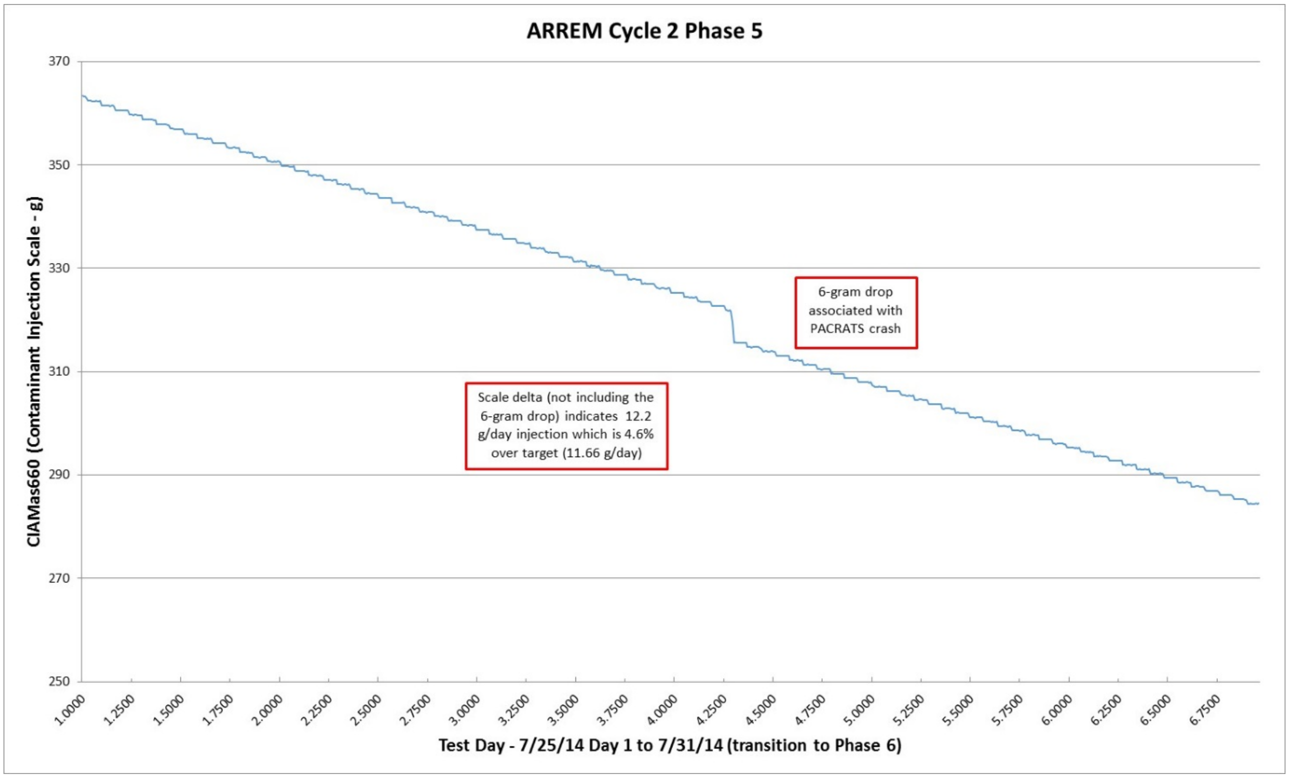


2 probable causes for Day 1 variance. 1) mismatch in CO2 injection desired .vs. actual flow and 2) pressure corresonds to temperature variances

E-Chamber was maintained at a minimum 1.5 mmHg above atmospheric pressure.

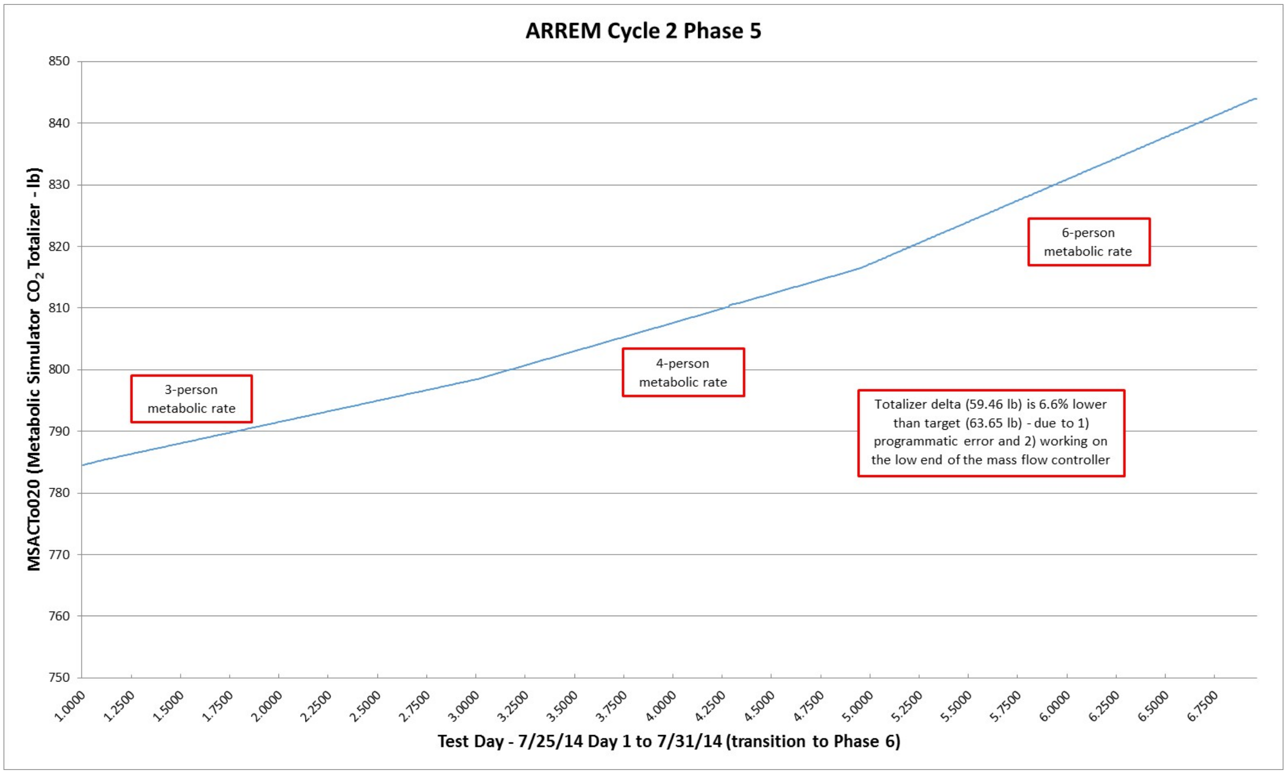

ARREM Cycle 2 Phase 5
AFcO2_100 (E-Chamber Atmospheric O$_2$ - %)
20.9
20.8
20.7
20.6
20.5
20.4
20.3
20.2
20.1
20
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)


ARREM Cycle 2 Phase 5
AFcCO2100 (E-Chamber Atmospheric CO$_2$ - %)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3-person metabolic rate
4-person metabolic rate
6-person metabolic rate
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)

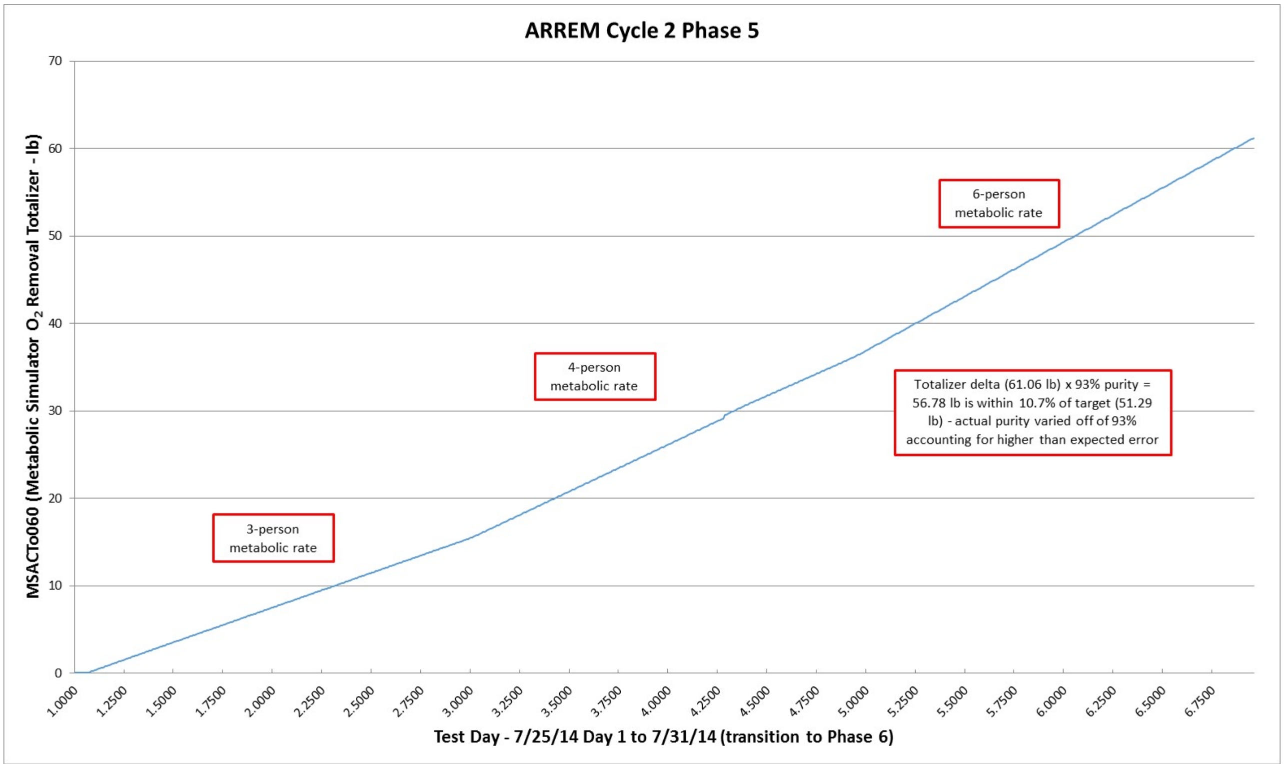


6-gram drop associated with PACRATS crash

Scale delta (not including the 6-gram drop) indicates 12.2 g/day injection which is 4.6% over target (11.66 g/day)



Totalizer delta (59.46 lb) is 6.6% lower than target (63.65 lb) - due to 1) programmatic error and 2) working on the low end of the mass flow controller



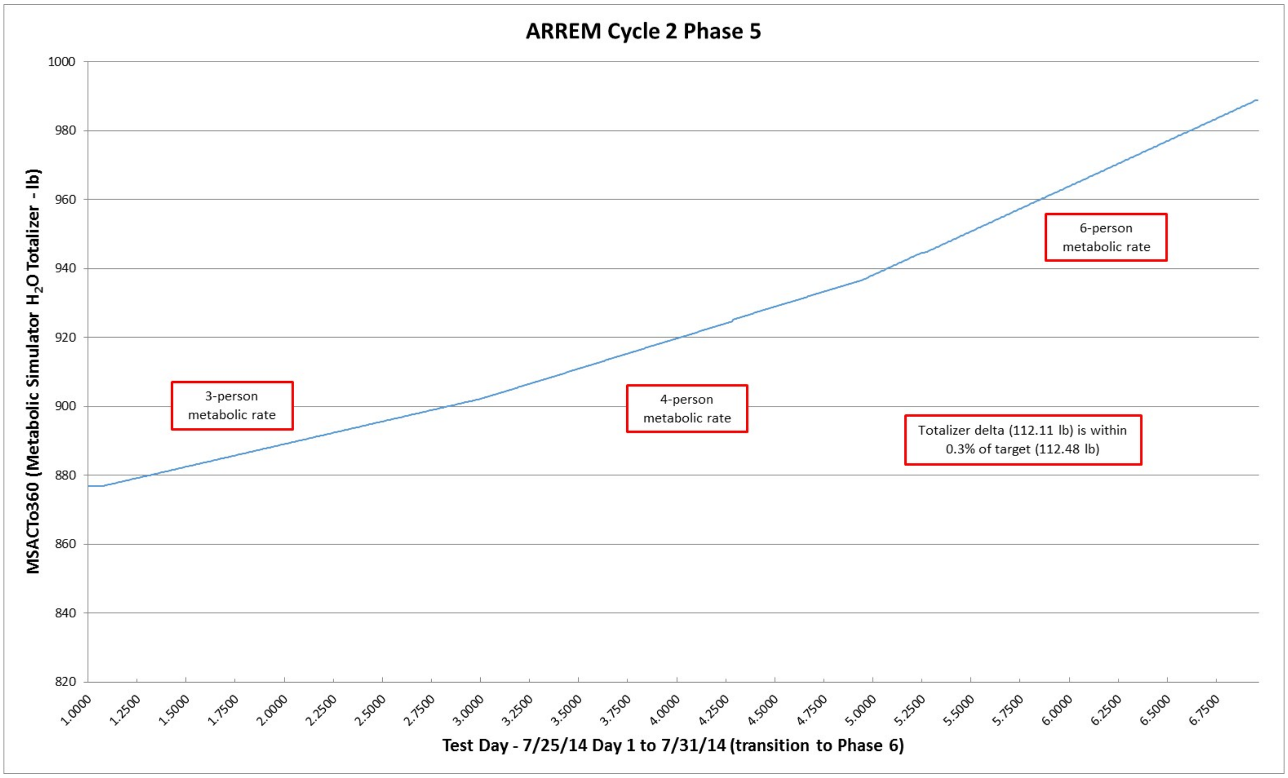
ARREM Cycle 2 Phase 5

6-person metabolic rate

4-person metabolic rate

3-person metabolic rate

Totalizer delta (61.06 lb) x 93% purity = 56.78 lb is within 10.7% of target (51.29 lb) - actual purity varied off of 93% accounting for higher than expected error



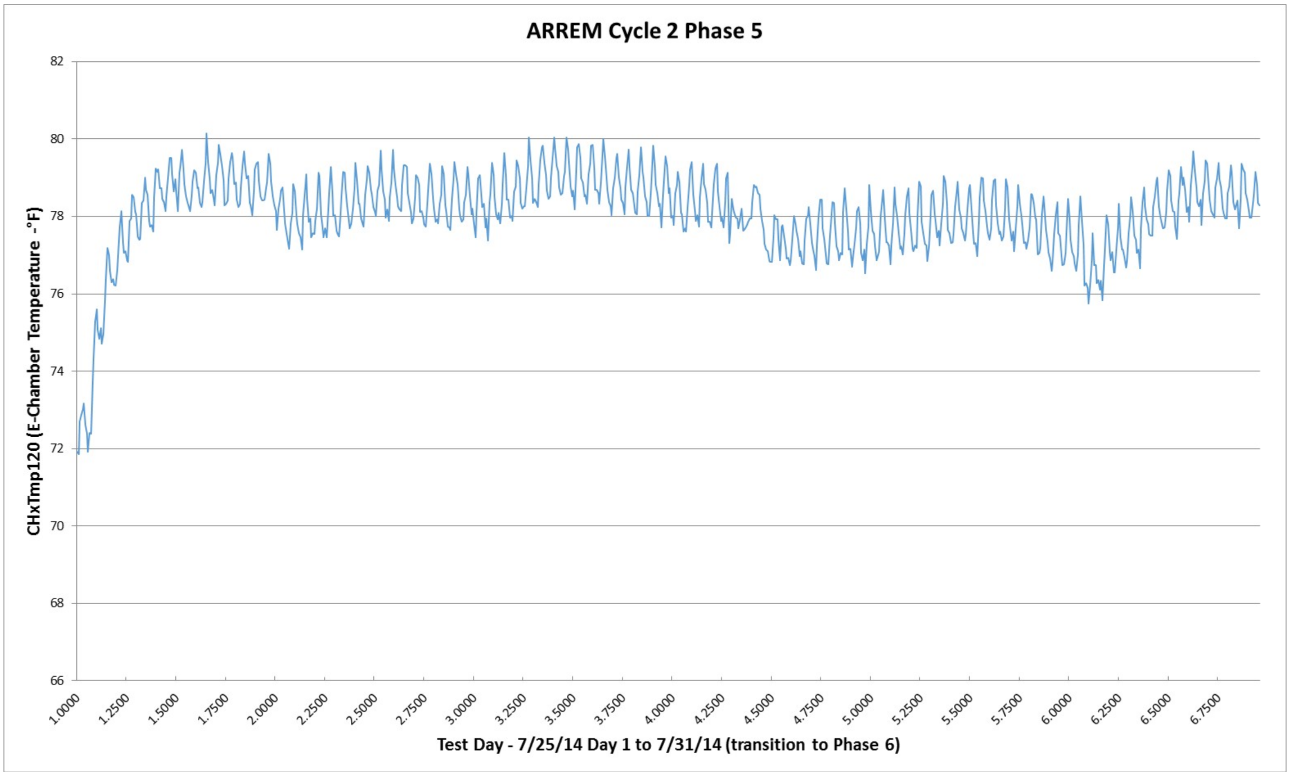
ARREM Cycle 2 Phase 5

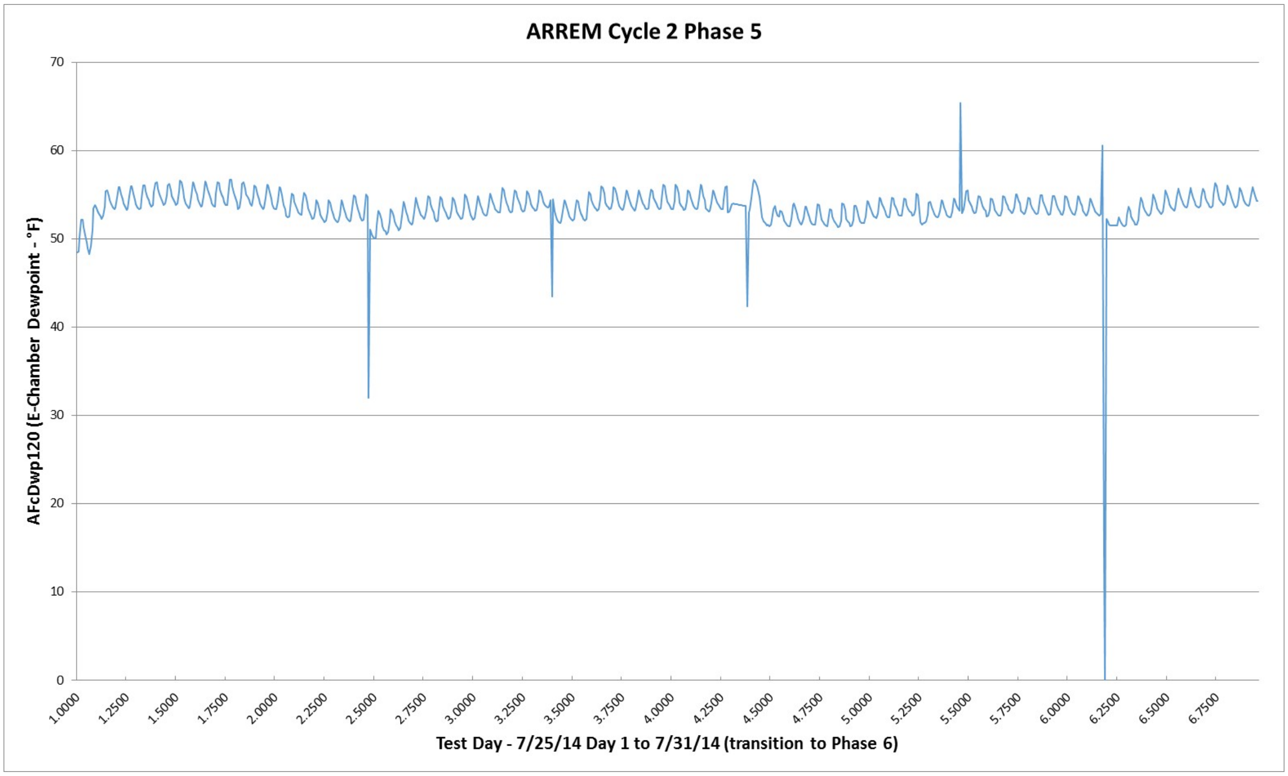
6-person metabolic rate

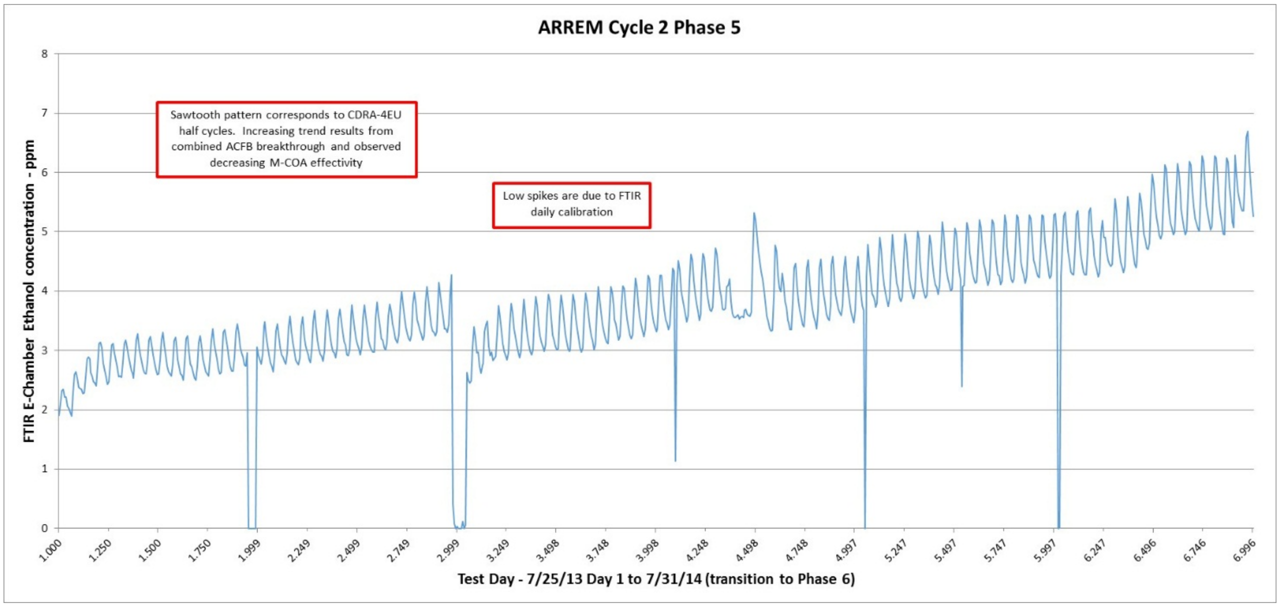
3-person metabolic rate

4-person metabolic rate

Totalizer delta (112.11 lb) is within 0.3% of target (112.48 lb)

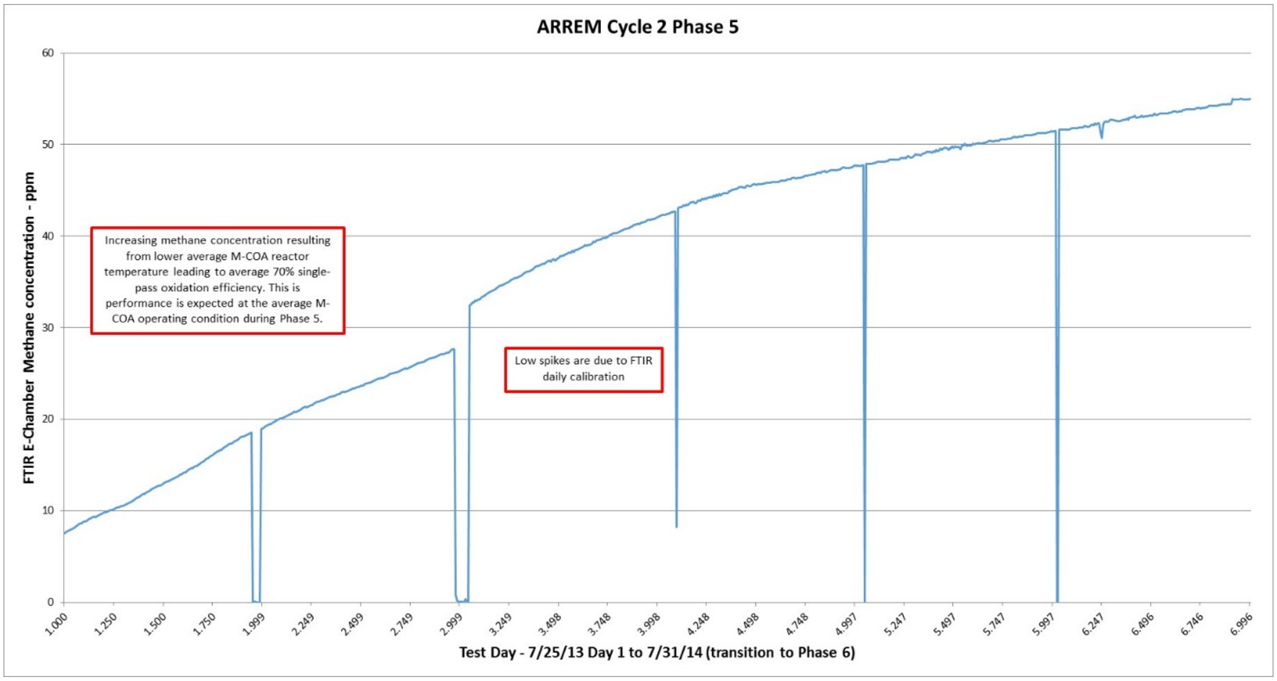

ARREM Cycle 2 Phase 5
CHxTmp120 (E-Chamber Temperature - °F)
82
80
78
76
74
72
70
68
66
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)


ARREM Cycle 2 Phase 5
AFcDwp120 (E-Chamber Dewpoint - °F)
70
60
50
40
30
20
10
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
4.2500
4.5000
4.7500
5.0000
5.2500
5.5000
5.7500
6.0000
6.2500
6.5000
6.7500
Test Day - 7/25/14 Day 1 to 7/31/14 (transition to Phase 6)



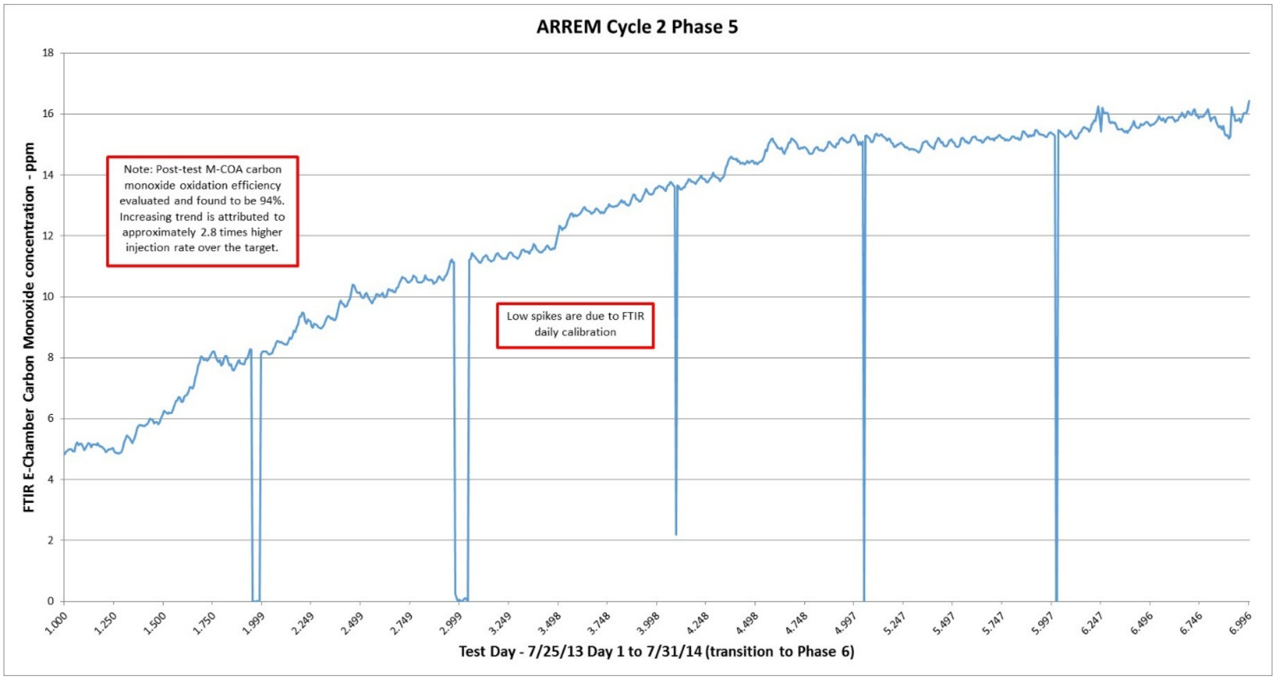
Sawtooth pattern corresponds to CDRA-4EU half cycles. Increasing trend results from combined ACFB breakthrough and observed decreasing M-COA effectivity

Low spikes are due to FTIR daily calibration



Increasing methane concentration resulting from lower average M-COA reactor temperature leading to average 70% single-pass oxidation efficiency. This is performance is expected at the average M-COA operating condition during Phase 5.

Low spikes are due to FTIR daily calibration



Phase 6 (Dynamic Metabolic Profile) Overview (7/31/14 to 8/3/14 – ES62-TCP-ARS-14-005): Phase 6 was a direct follow-on test from Phase 5. The difference from Phase 5 to Phase 6 was that Phase 6 was run with a dynamic metabolic load based on 4-crew members. Because of this lower demand, the OGA, which had suffered a Power Supply Module circuit shutdown at the 6-crew member metabolic load was tried again. However, it was only able to complete about 15 hours of run-time before the same circuit shutdown re-occurred.

Phase 6 Event Summary 7/31/14-8/1/14 – Transition from Phase 5 and Test Day 1 – The original intent was to immediately transition from Phase 5 into Phase 6 by just implementing setpoints for the dynamic metabolic loading requirement of Phase 6. However, the computer that controlled the FTIR shut down early on 7/31. The main control computer began slowing down execution times because of the FTIR issue and eventually main program execution stopped. Both computers had to be re-started. EChamber pressure control was lost as a result and an N_2 boost back to 1.5 mmHg above ambient pressure was required. There was also a minor issue with re-starting contaminant injection which was quickly resolved. CDRA-4EU and TCCS had to be re-started but OGA and Sabatier ran through the computer problems without incident. This delayed the transition by about 2 hours. Further delays were encountered when EChamber CO_2 sensors diverged after injection was stopped in order to set the dynamic metabolic profile. Eventually AFcCO2101 was determined to be accurate while AFcCO2100 was dropped from consideration (possibly slow to respond due to flow path issues). One final delay happened because the oxygen removal rate required by the dynamic profile was higher than the oxygen concentrator could match. The EChamber door was opened to verify that the local oxygen flow setting for the concentrator was as high as it could be. Once that was determined the profile was changed to match the maximum achievable by the concentrator for portions of the dynamic profile with higher removal rates. Time 0 for Phase 6 was set at 1301, 7/31 once the settings for the dynamic profile were completed in the control program.

8/1-2/14 – Test Day 2 – The OGA again suffered the PSM circuit shutdown at 1148 on 8/1. From that point, O_2 and H_2 were supplied by the facility. All other operations were nominal.

8/2-3/14 – Test Day 3 – Nominal day with no anomalies noted. The Principal Investigator declared that after 72 hours of dynamic metabolic profile testing Phase 6 would be considered complete.

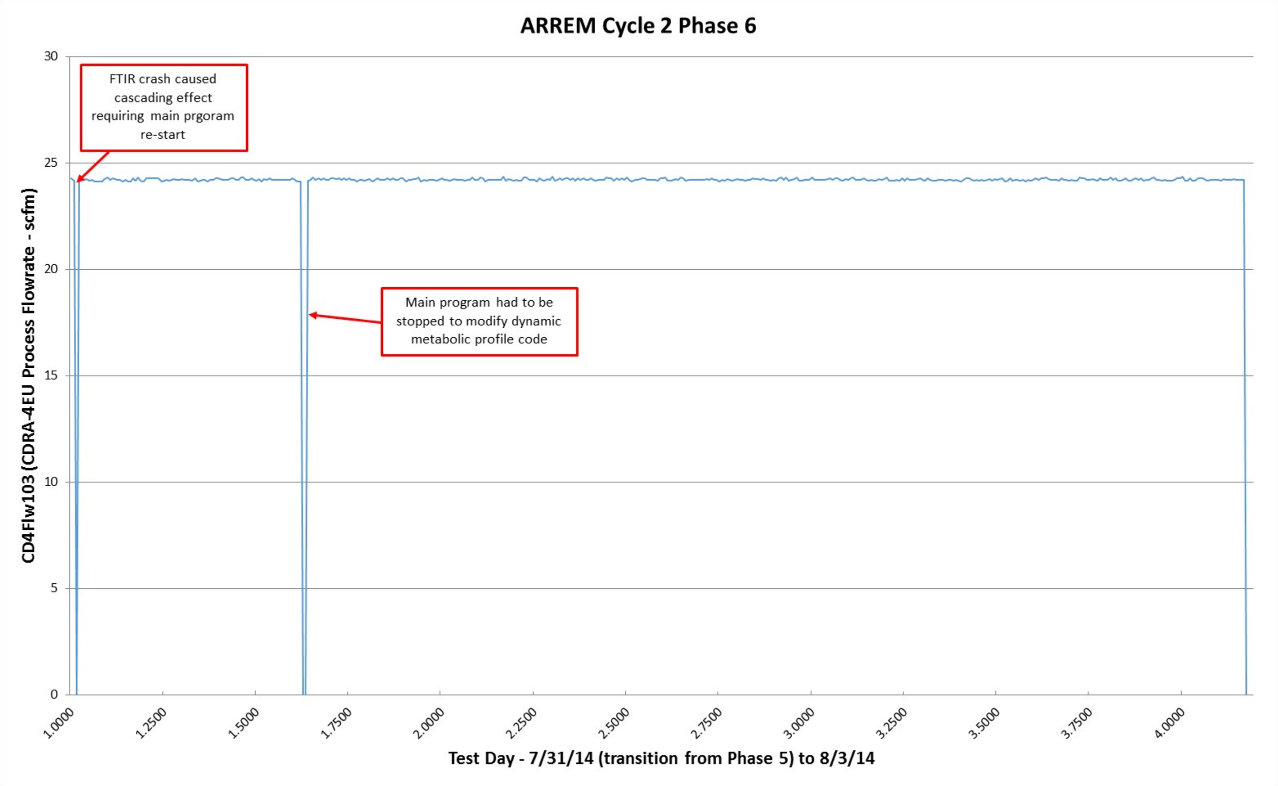
Phase 6 Test Results The EChamber atmosphere ethanol concentration settled into a range of 4-8 ppm which is well below the 180 day SMAC of 1000 ppm. Methane concentration was lost at the beginning of Phase 6 because the EChamber door was opened to verify that the Oxygen Concentrator was running at the maximum achievable rate. It built back up from about 16 ppm to about 33 ppm over the 3 days of Phase 6 (well below the 180 SMAC of 5300 ppm). Carbon Monoxide also showed the initial drop followed by a same slow rise topping out at just under 12 ppm. This level is below the 55 ppm 7-day SMAC as well as below the 15 ppm 30-day/180-day/1000-day SMAC. The ACFB, TCCS M-COA, and the Condensing Heat Exchanger were the removal components for Phase 6 as they were in Phase 5. For further analysis of the TCCS M-COA's performance see "Evaluation of an Atmosphere Revitalization Subsystem for Deep Space Exploration Missions" (J. L. Perry et al, 44th International Conference on Environmental Systems, July 2015). Data indicates that the test articles and facility environmental effectors (mainly metabolic simulation) handled the dynamic metabolic load without anomaly or excursion outside habitable limits. Humidity condensate data is in Table 2 below.

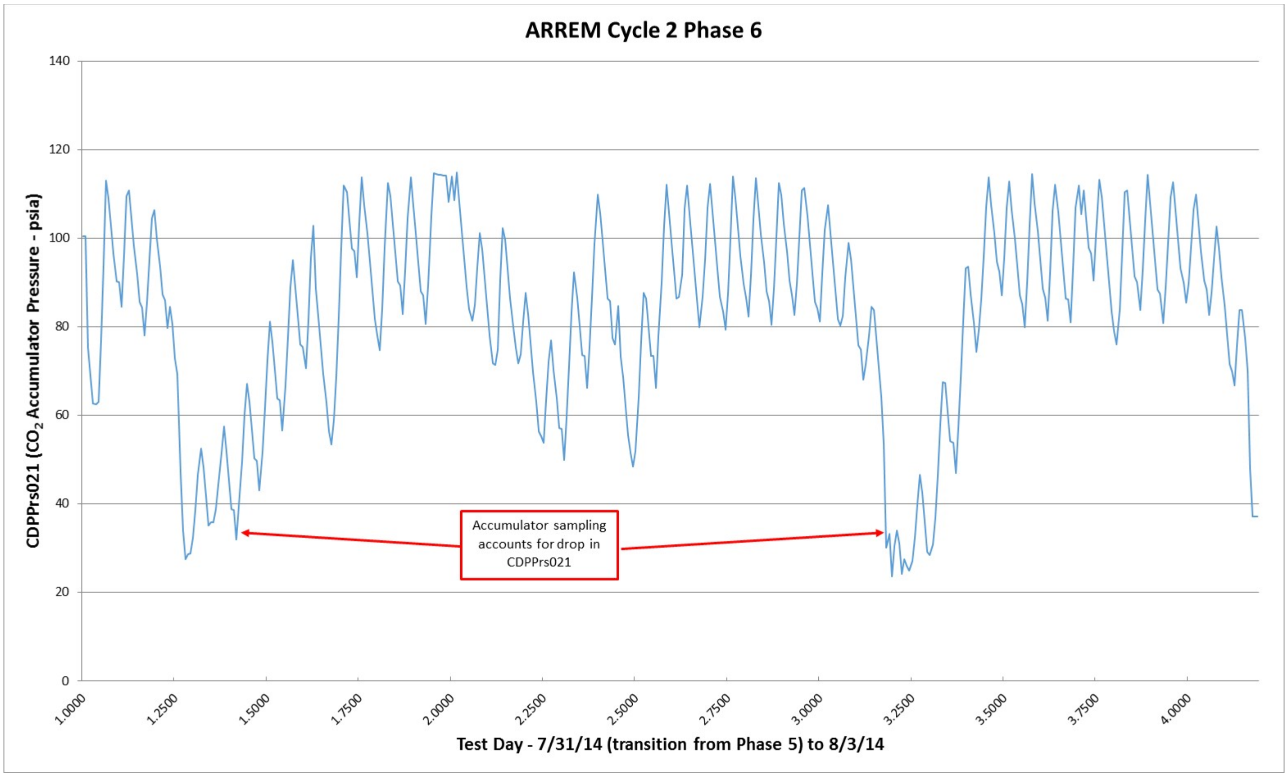
Table 3: Cycle 2 Phase 6
Humidity Condensate
(NOTE: ND is Not Detected)

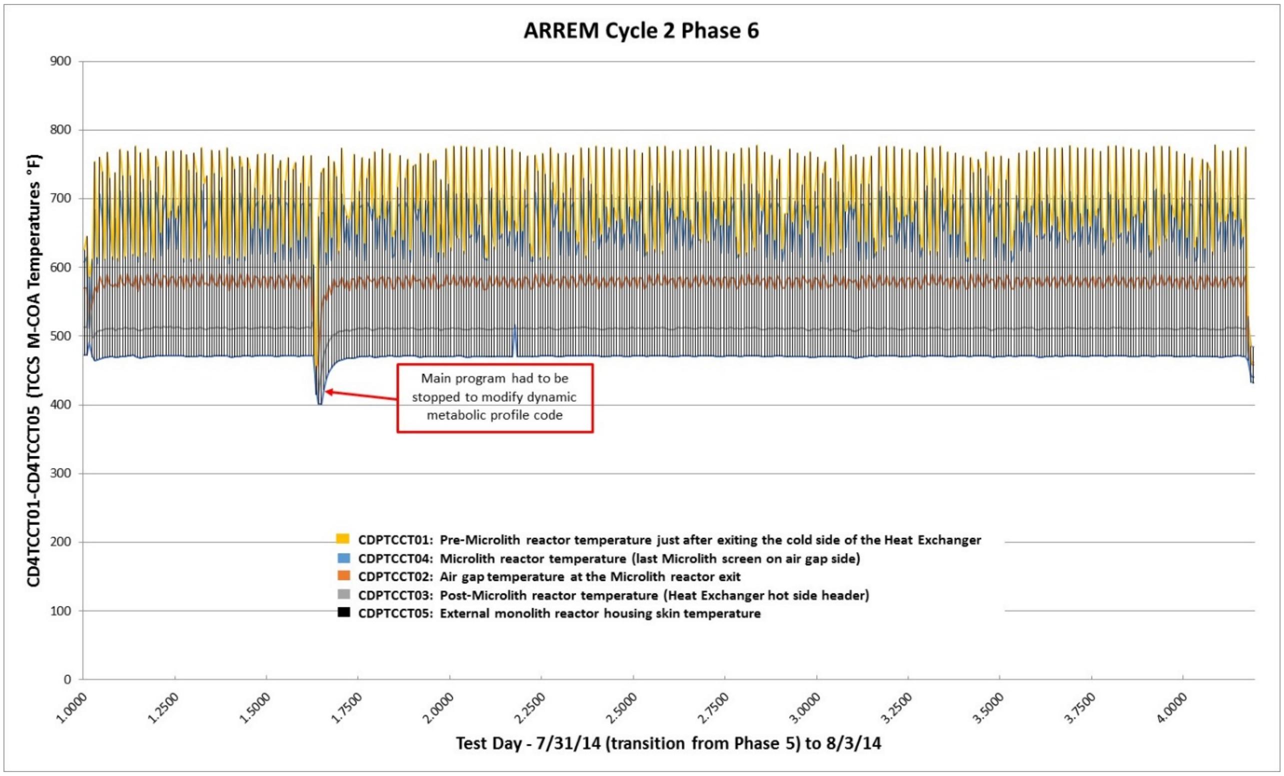
Analyte	Test Day		
	1	2	3
Condensate (lb)	N/A	35.19 (2-day aggregate)	16.05
Methanol (ppm)	36	36	41
Ethanol (ppm)	86	86	96
Acetone (ppm)	<1	<1	1
1-propanol (ppm)	ND	ND	ND
2-propanol (ppb)	<1	<1	<1
2-methyl-2-propanol (ppm)	ND	ND	ND
2-butanol (ppm)	ND	ND	ND
Trimethylsilanol (ppb)	10.7	8.33	<5
Hexamethylcyclotrisiloxane (ppb)	<700	<700	<700
Total Organic Carbon (ppm)	78.2	81.2	93.1

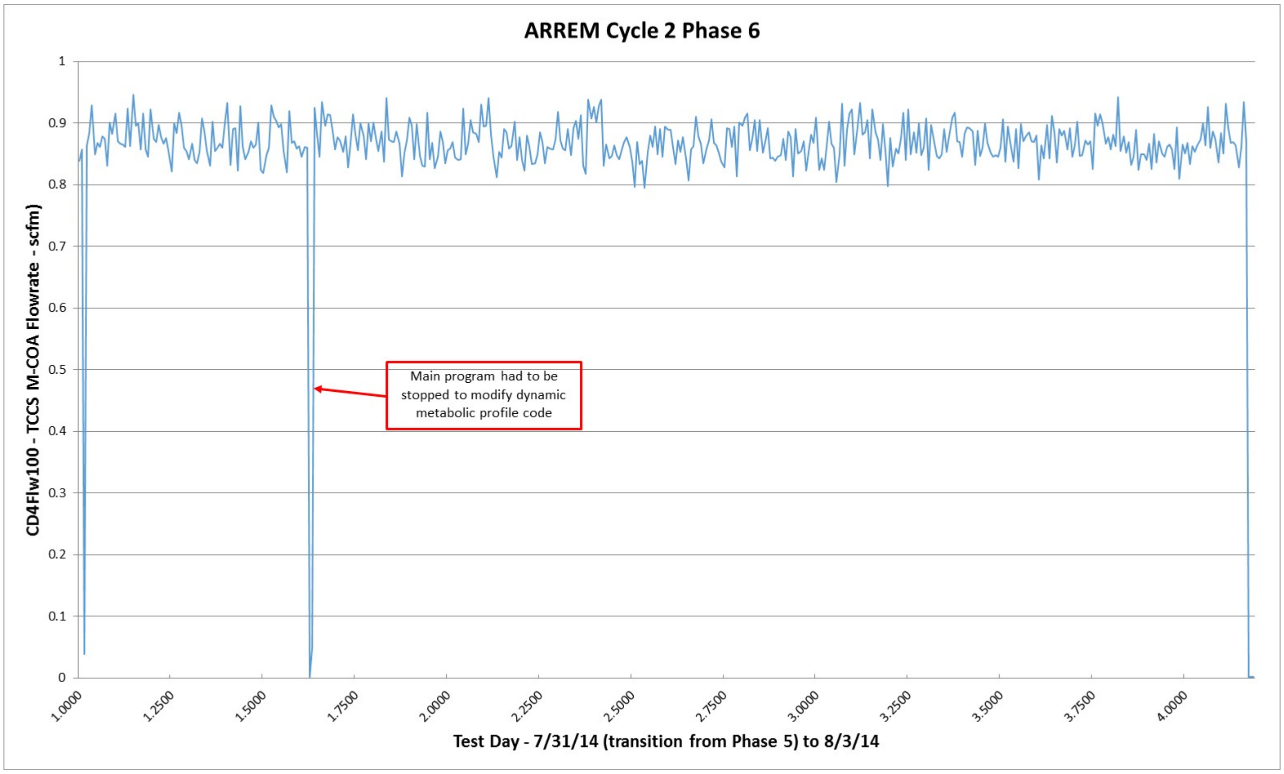
Note that additional analysis found dimethylsilanediol (DMSD) in the condensate samples. The concentration ranged between 510 ppm and 1300 ppm with an average of 725 ppm. The DMSD reporting limit was 500 ppm.

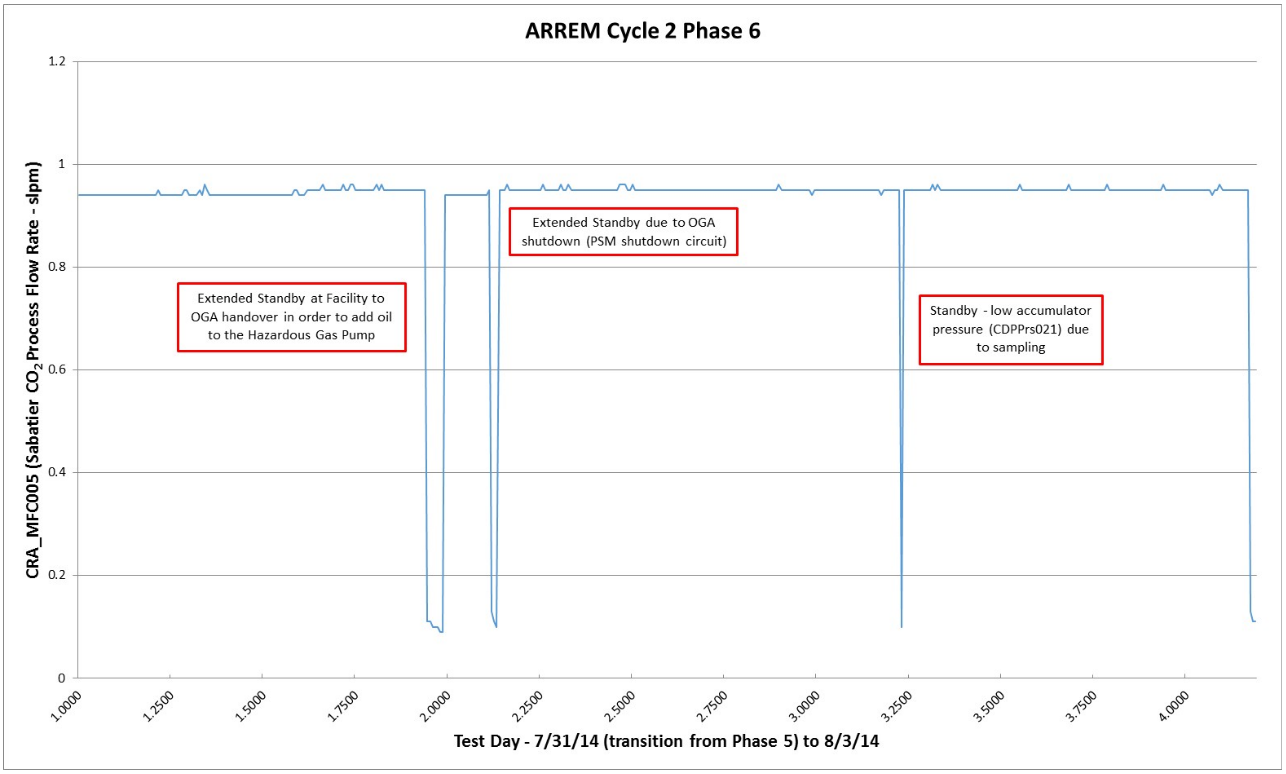
NOTE: Cycle 2 Phase 6 plots start at the transition from Phase 5 (0800, 7/31). Time zero for Phase 6 was 1301, 7/31 which corresponds to Test Day 1.209.






ARREM Cycle 2 Phase 6
CD4TCCT01-CD4TCCT05 (TCCS M-COA Temperatures °F)
900
800
700
600
500
400
300
200
100
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
Test Day - 7/31/14 (transition from Phase 5) to 8/3/14
Main program had to be stopped to modify dynamic metabolic profile code
CDPTCCT01: Pre-Microlith reactor temperature just after exiting the cold side of the Heat Exchanger
CDPTCCT04: Microlith reactor temperature (last Microlith screen on air gap side)
CDPTCCT02: Air gap temperature at the Microlith reactor exit
CDPTCCT03: Post-Microlith reactor temperature (Heat Exchanger hot side header)
CDPTCCT05: External monolith reactor housing skin temperature

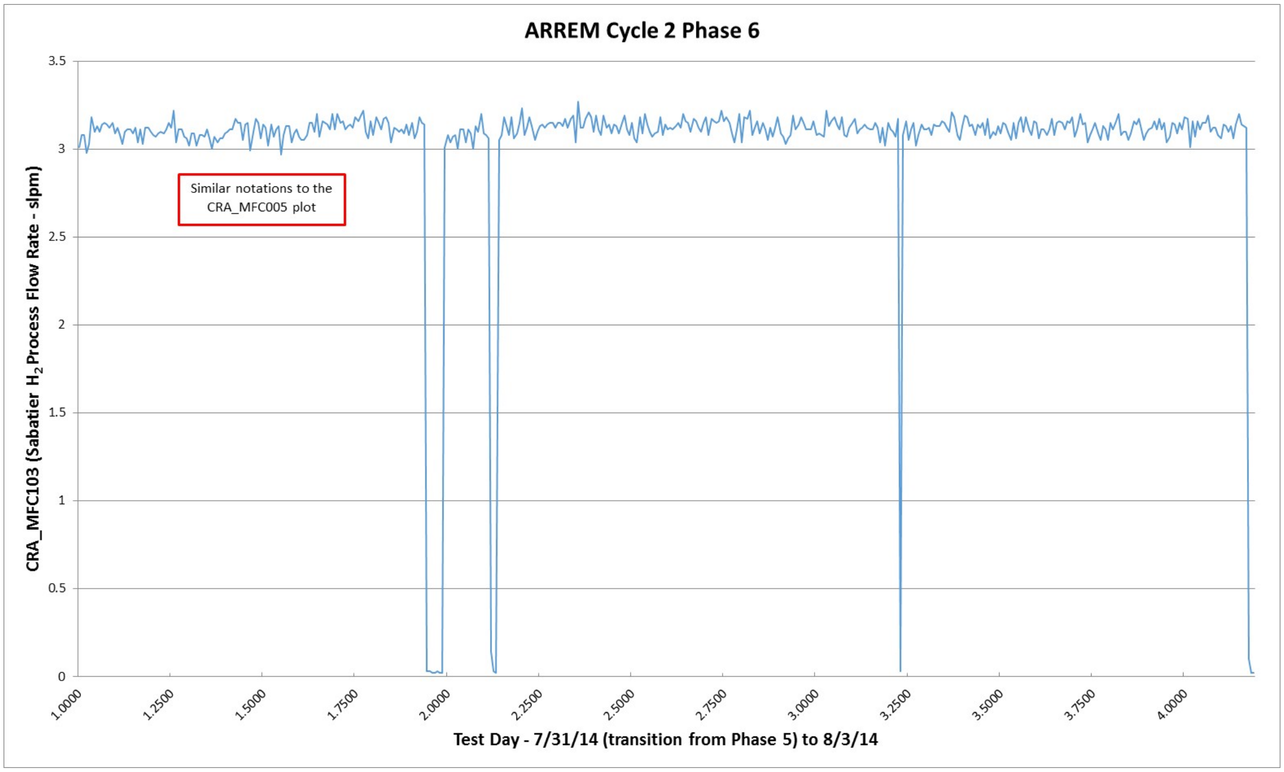

ARREM Cycle 2 Phase 6
CD4Flw100 - TCCS M-COA Flowrate - scfm
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
Test Day - 7/31/14 (transition from Phase 5) to 8/3/14
Main program had to be stopped to modify dynamic metabolic profile code



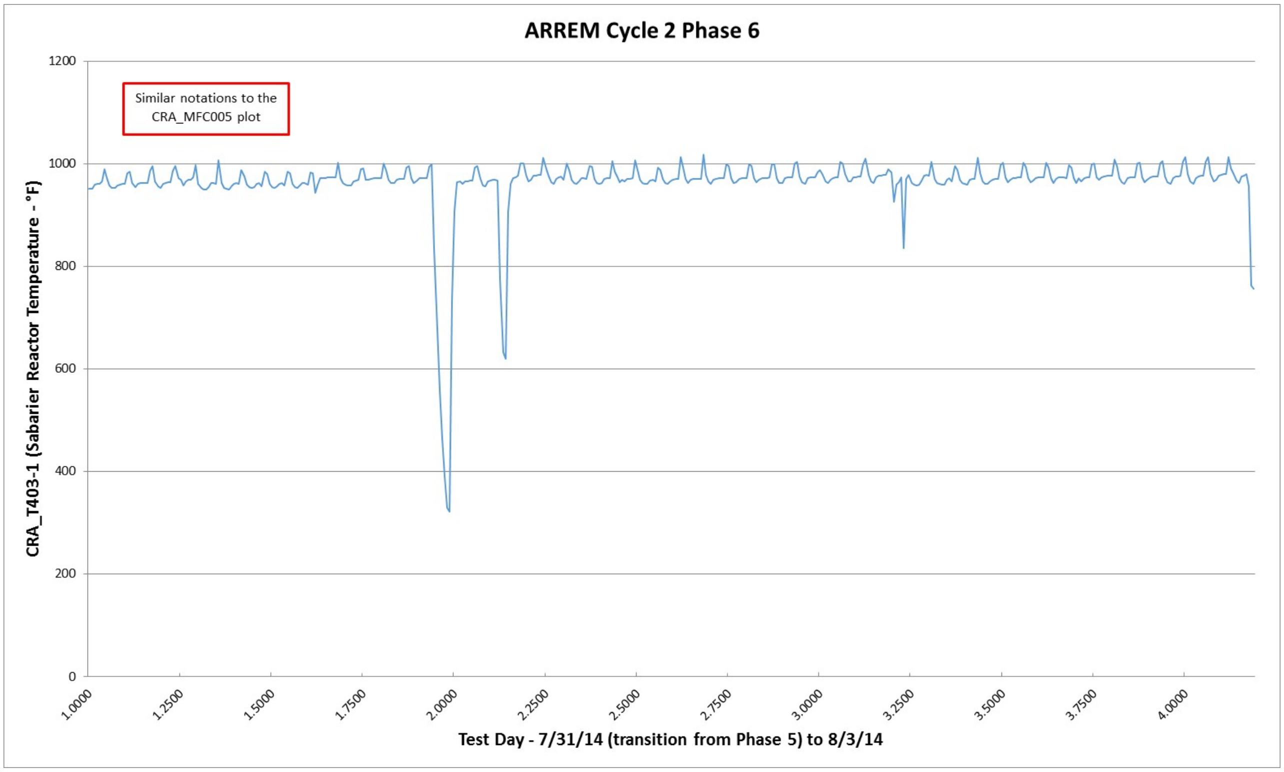
Extended Standby due to OGA shutdown (PSM shutdown circuit)

Extended Standby at Facility to OGA handover in order to add oil to the Hazardous Gas Pump

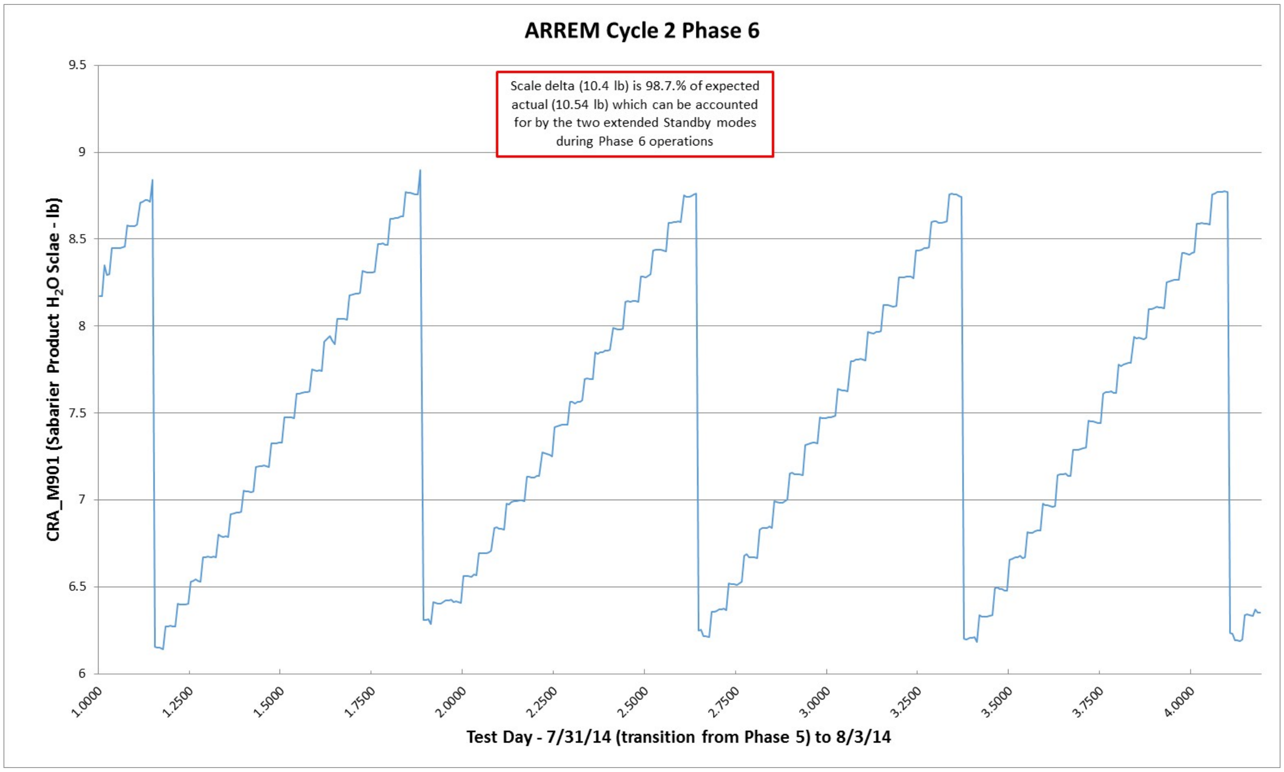
Standby - low accumulator pressure (CDPPrs021) due to sampling



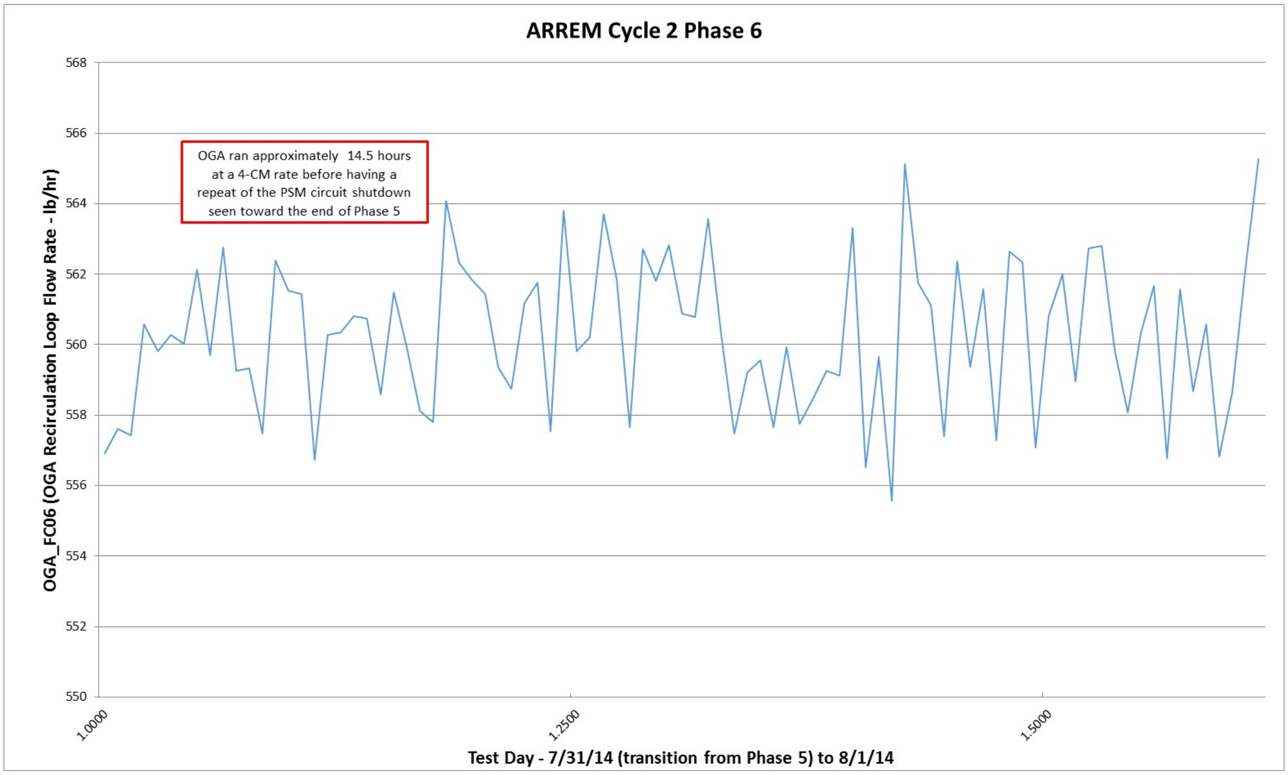
Similar notations to the CRA_MFC005 plot

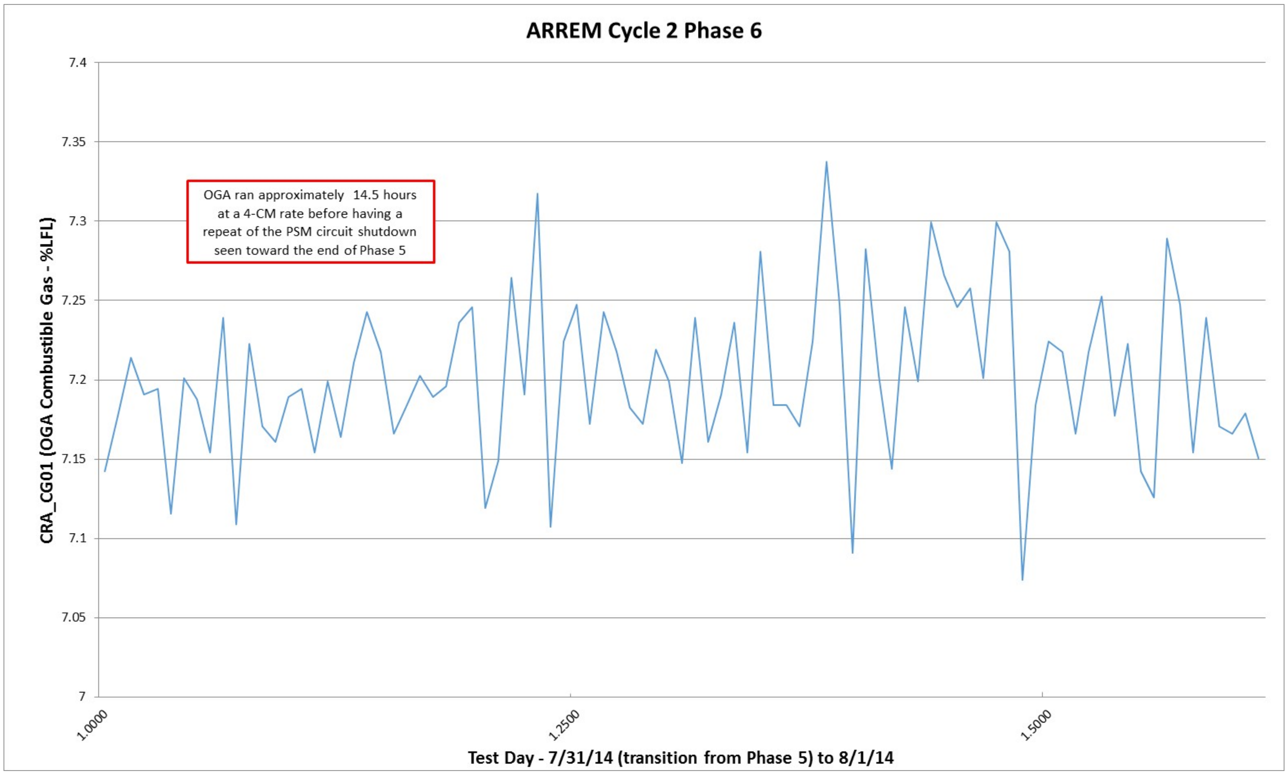


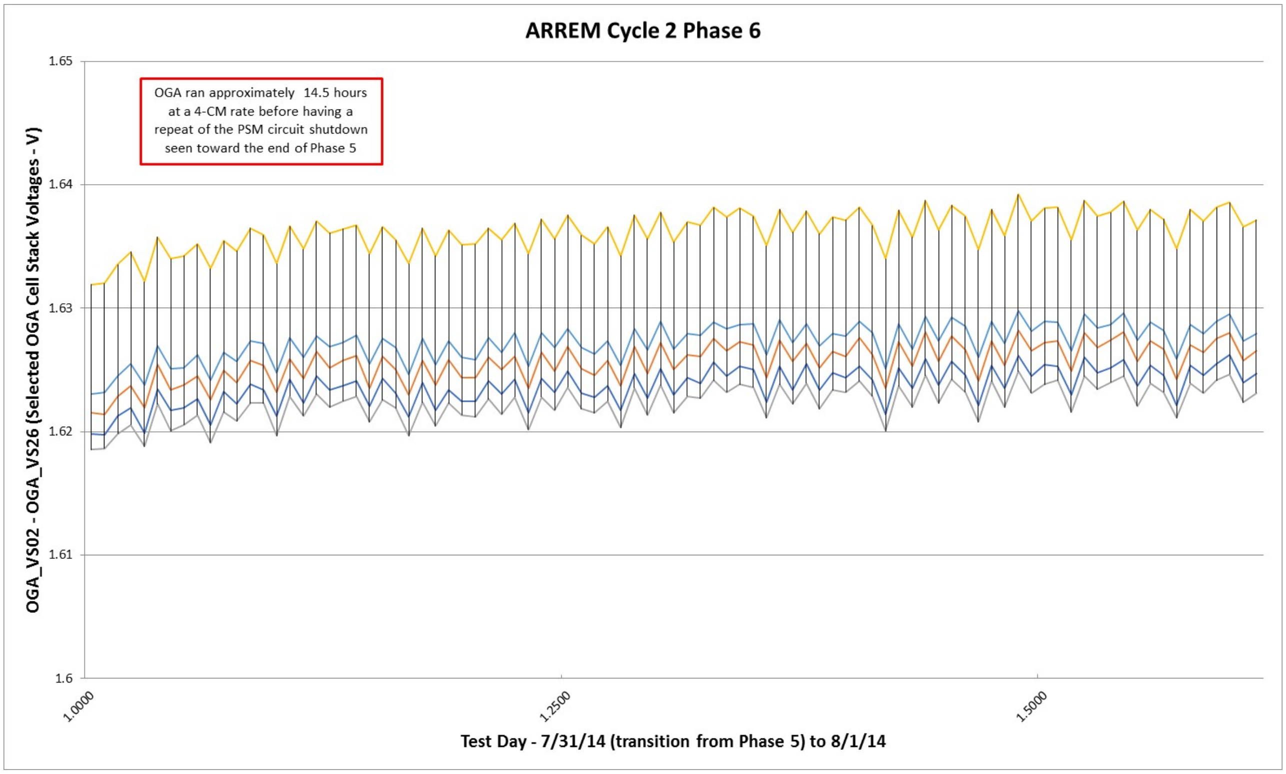
Similar notations to the CRA_MFC005 plot



Scale delta (10.4 lb) is 98.7.% of expected actual (10.54 lb) which can be accounted for by the two extended Standby modes during Phase 6 operations

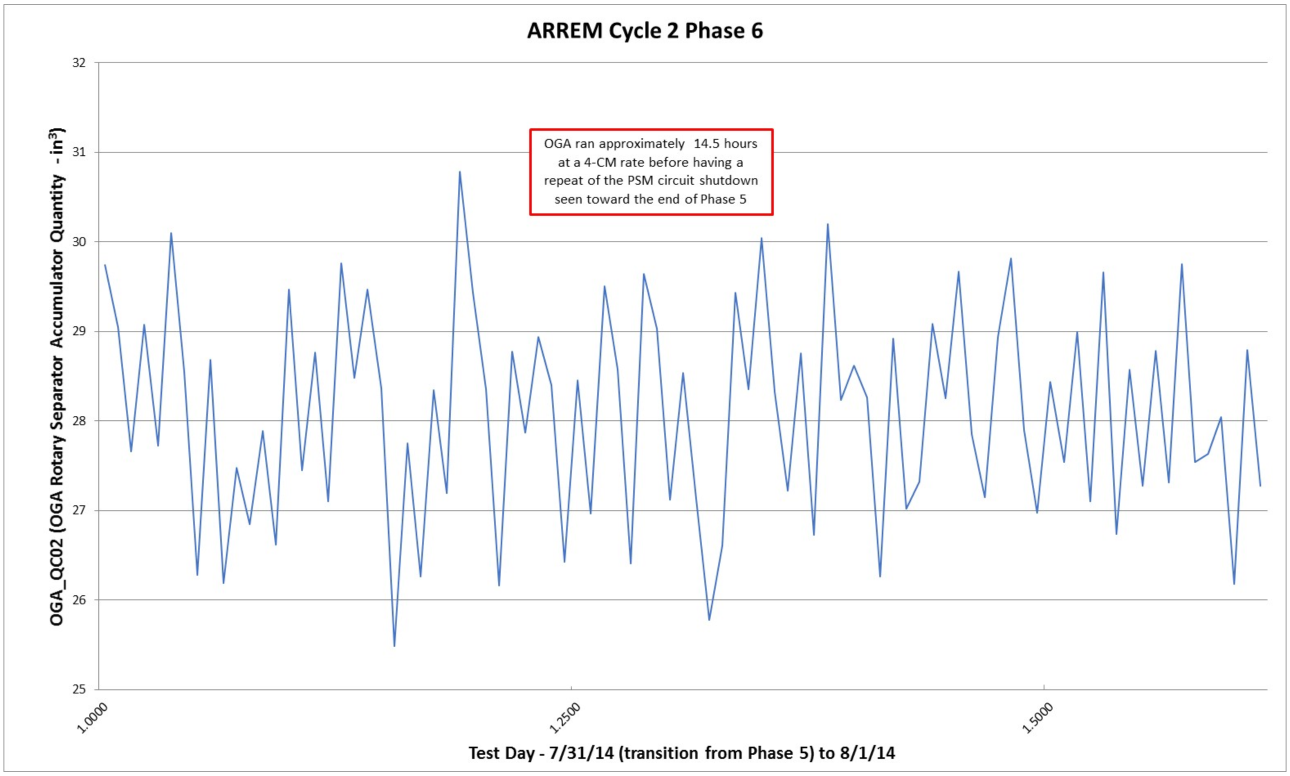

ARREM Cycle 2 Phase 6
OGA_FC06 (OGA Recirculation Loop Flow Rate - lb/hr)
568
566
564
562
560
558
556
554
552
550
1.0000
1.2500
1.5000
Test Day - 7/31/14 (transition from Phase 5) to 8/1/14
OGA ran approximately 14.5 hours at a 4-CM rate before having a repeat of the PSM circuit shutdown seen toward the end of Phase 5


ARREM Cycle 2 Phase 6
CRA_CG01 (OGA Combustible Gas - %LFL)
7.4
7.35
7.3
7.25
7.2
7.15
7.1
7.05
7
1.0000
1.2500
1.5000
Test Day - 7/31/14 (transition from Phase 5) to 8/1/14
OGA ran approximately 14.5 hours at a 4-CM rate before having a repeat of the PSM circuit shutdown seen toward the end of Phase 5



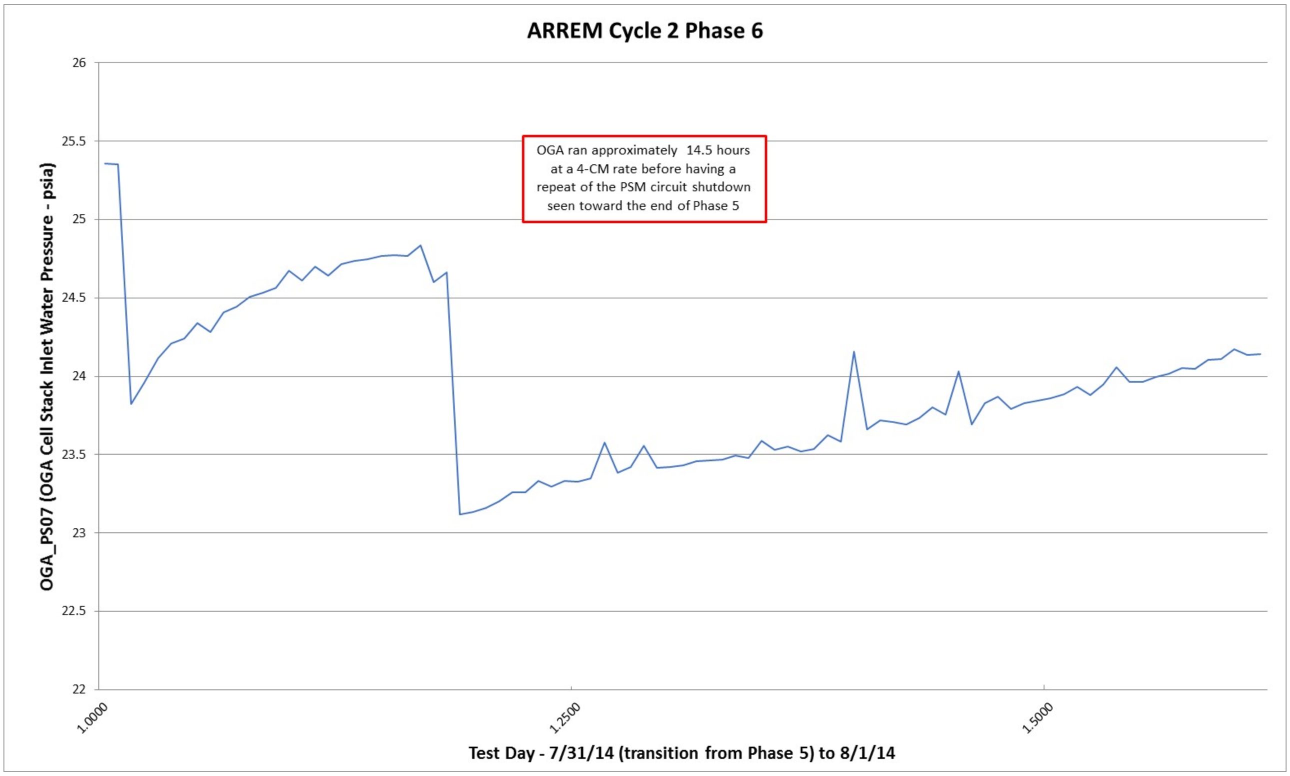
ARREM Cycle 2 Phase 6

OGA ran approximately 14.5 hours at a 4-CM rate before having a repeat of the PSM circuit shutdown seen toward the end of Phase 5

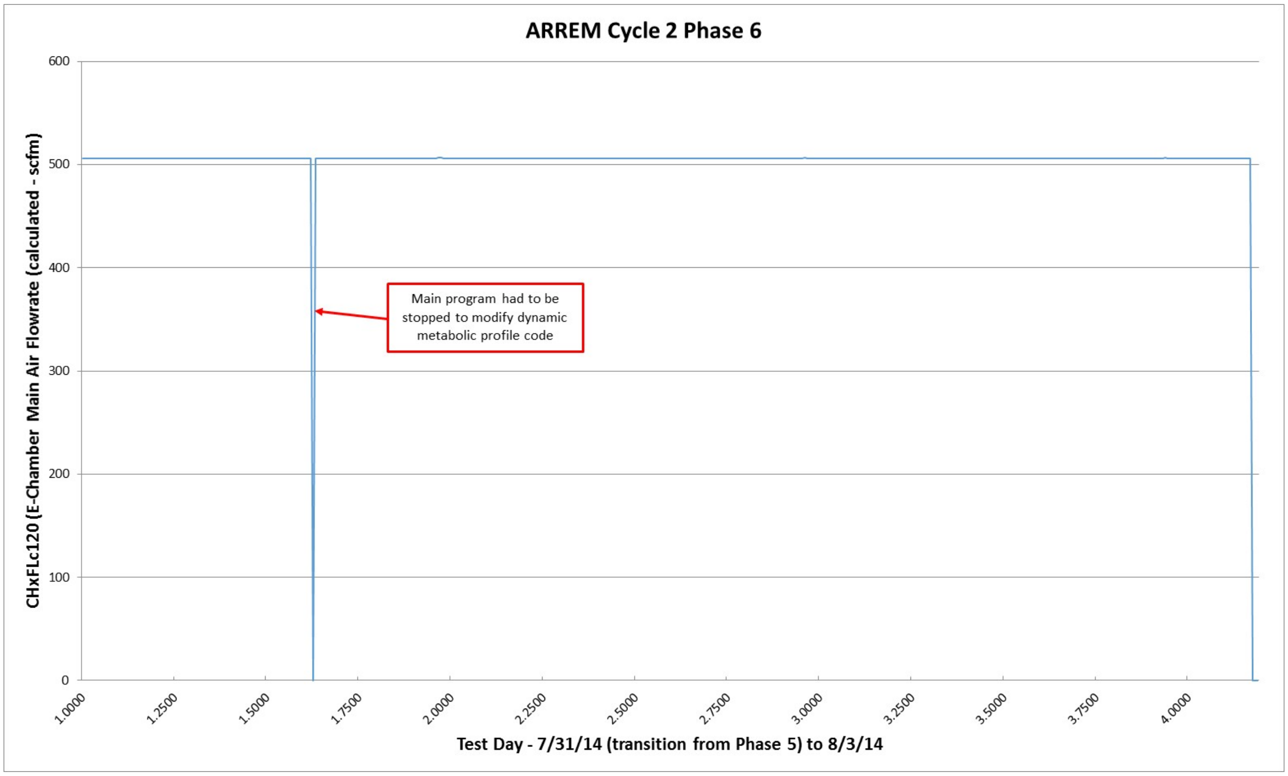


ARREM Cycle 2 Phase 6

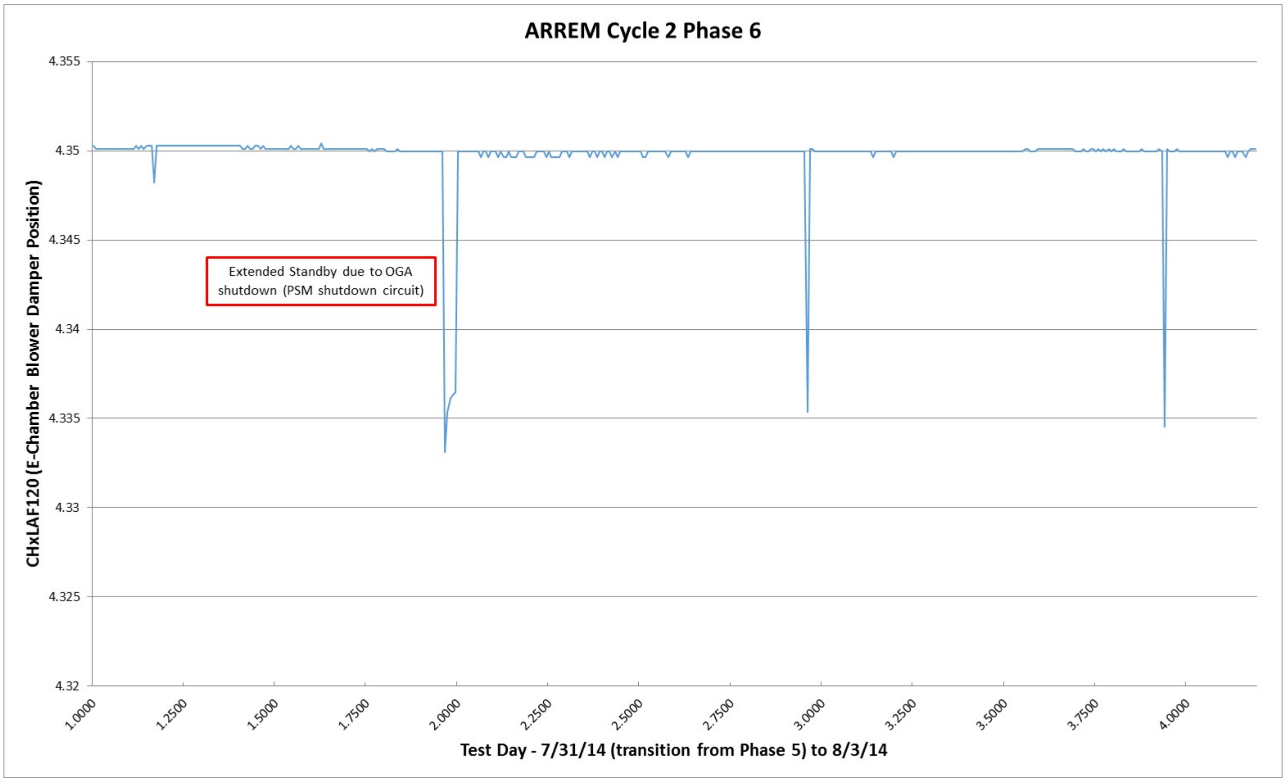
OGA ran approximately 14.5 hours at a 4-CM rate before having a repeat of the PSM circuit shutdown seen toward the end of Phase 5



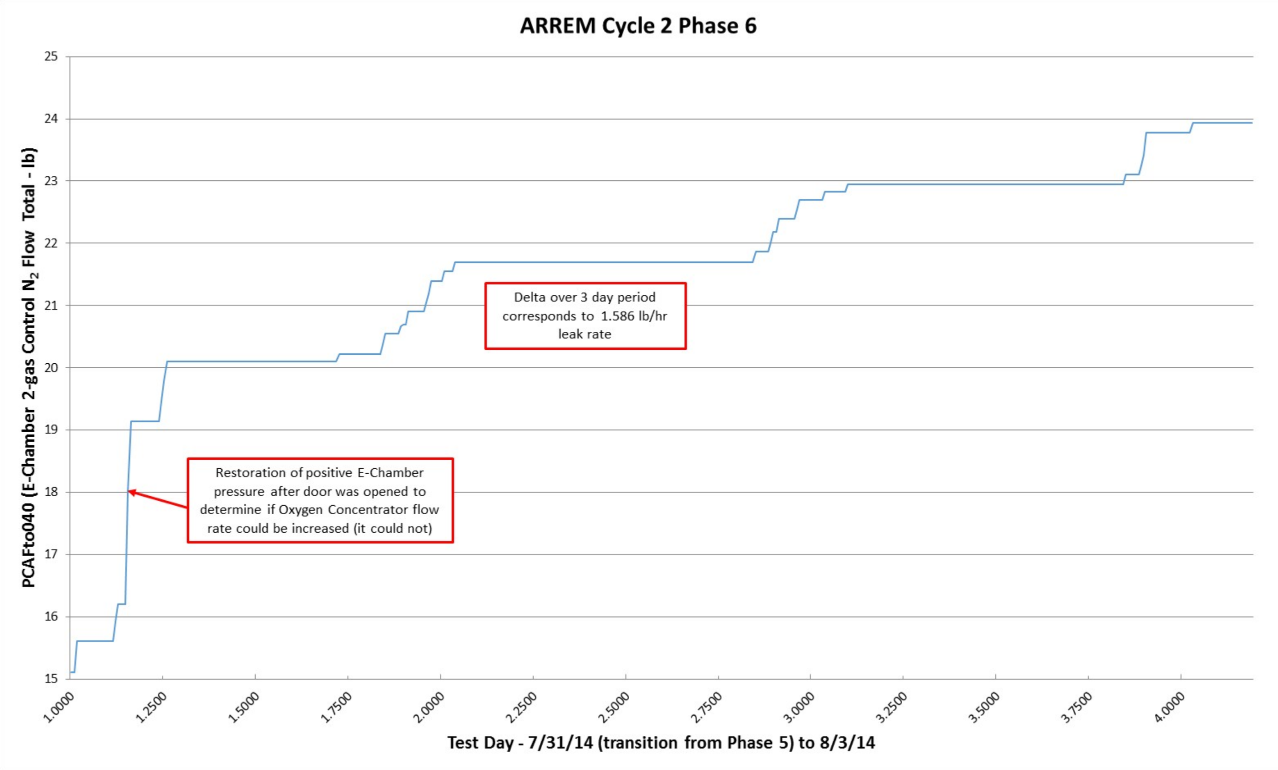
OGA ran approximately 14.5 hours at a 4-CM rate before having a repeat of the PSM circuit shutdown seen toward the end of Phase 5



Main program had to be stopped to modify dynamic metabolic profile code

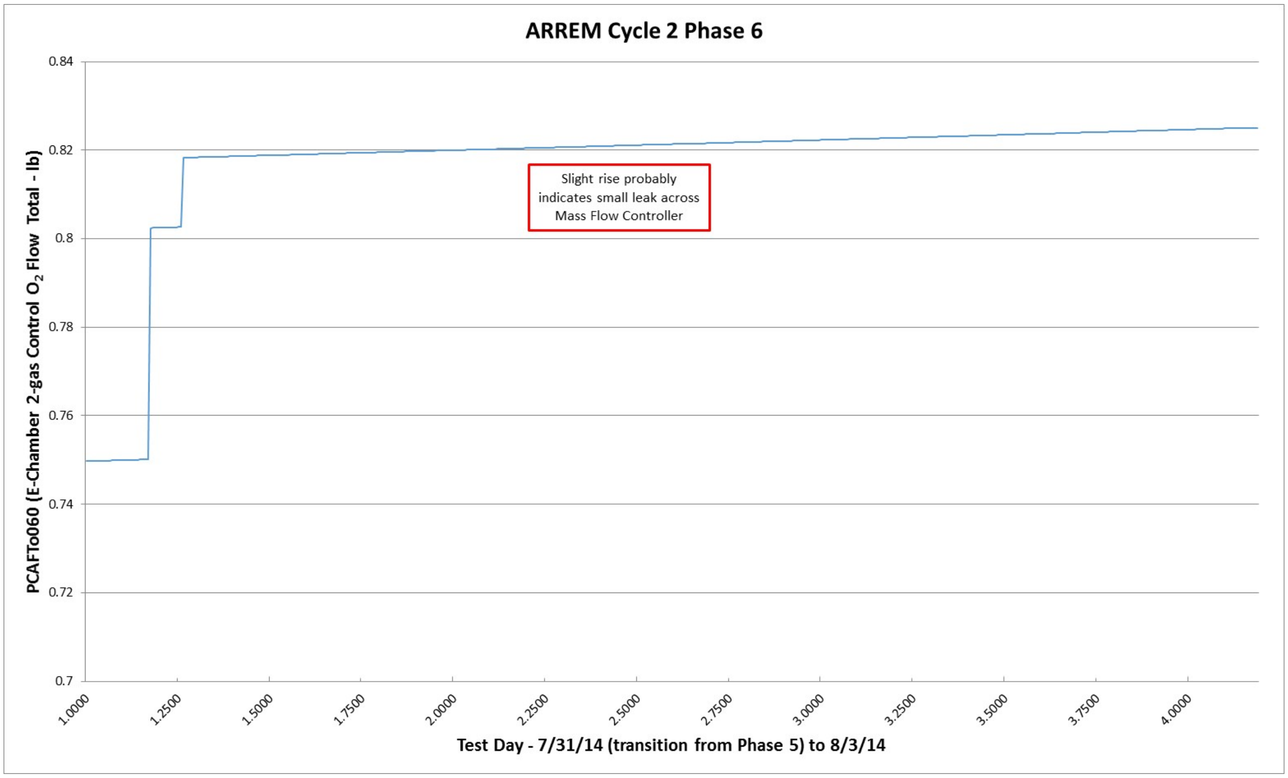


Extended Standby due to OGA shutdown (PSM shutdown circuit)

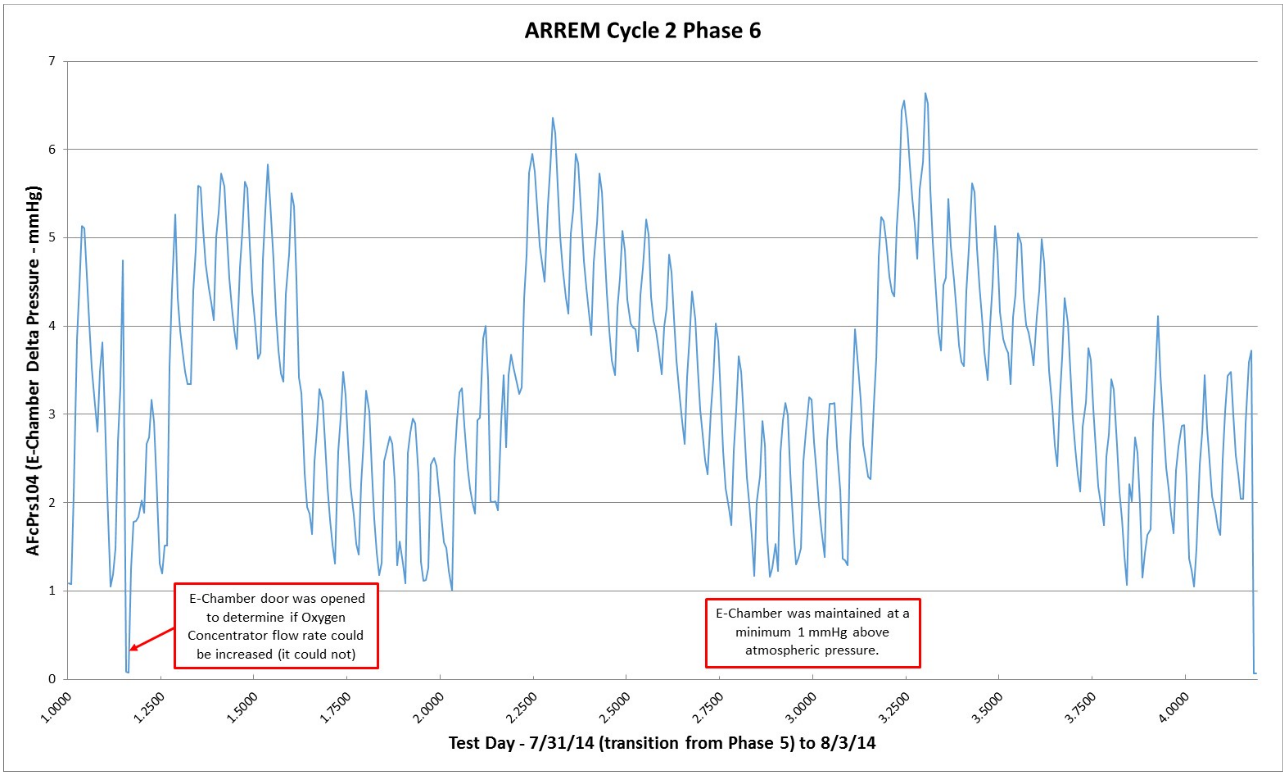


Delta over 3 day period corresponds to 1.586 lb/hr leak rate

Restoration of positive E-Chamber pressure after door was opened to determine if Oxygen Concentrator flow rate could be increased (it could not)

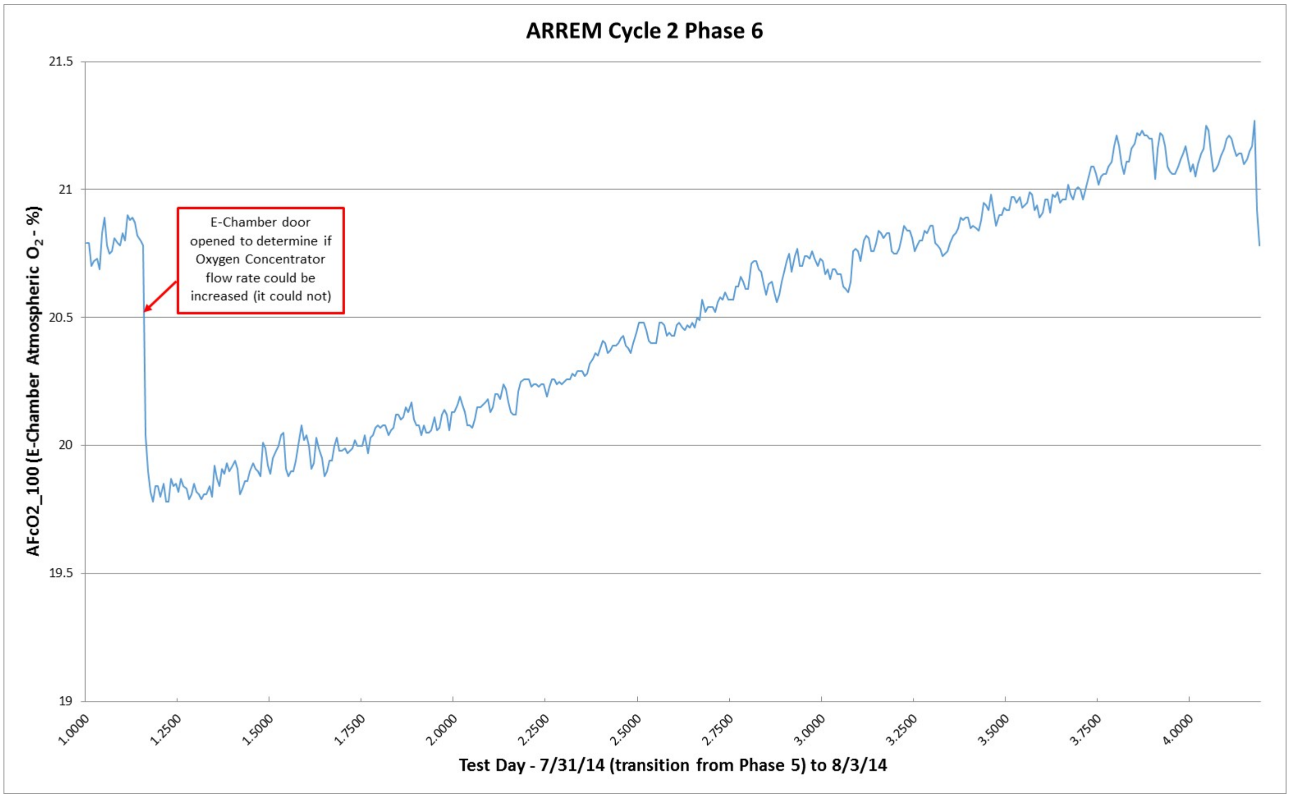


Slight rise probably indicates small leak across Mass Flow Controller

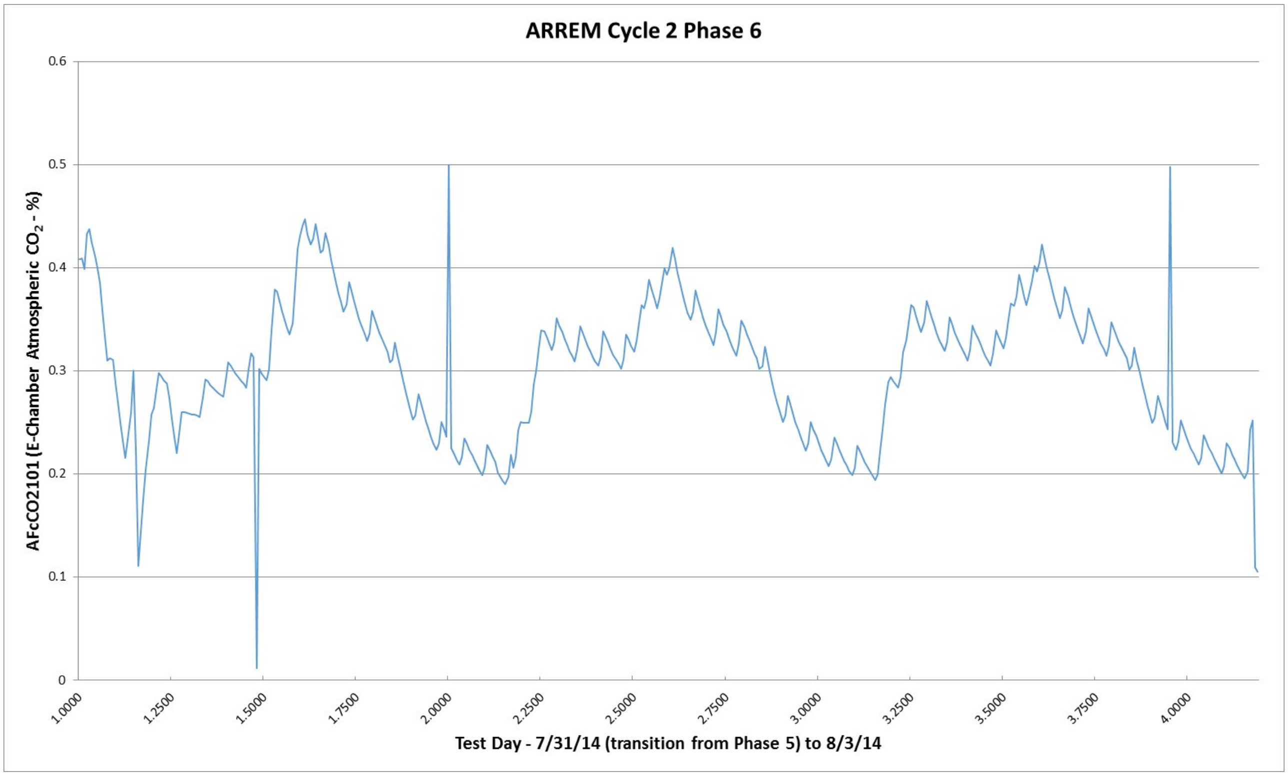


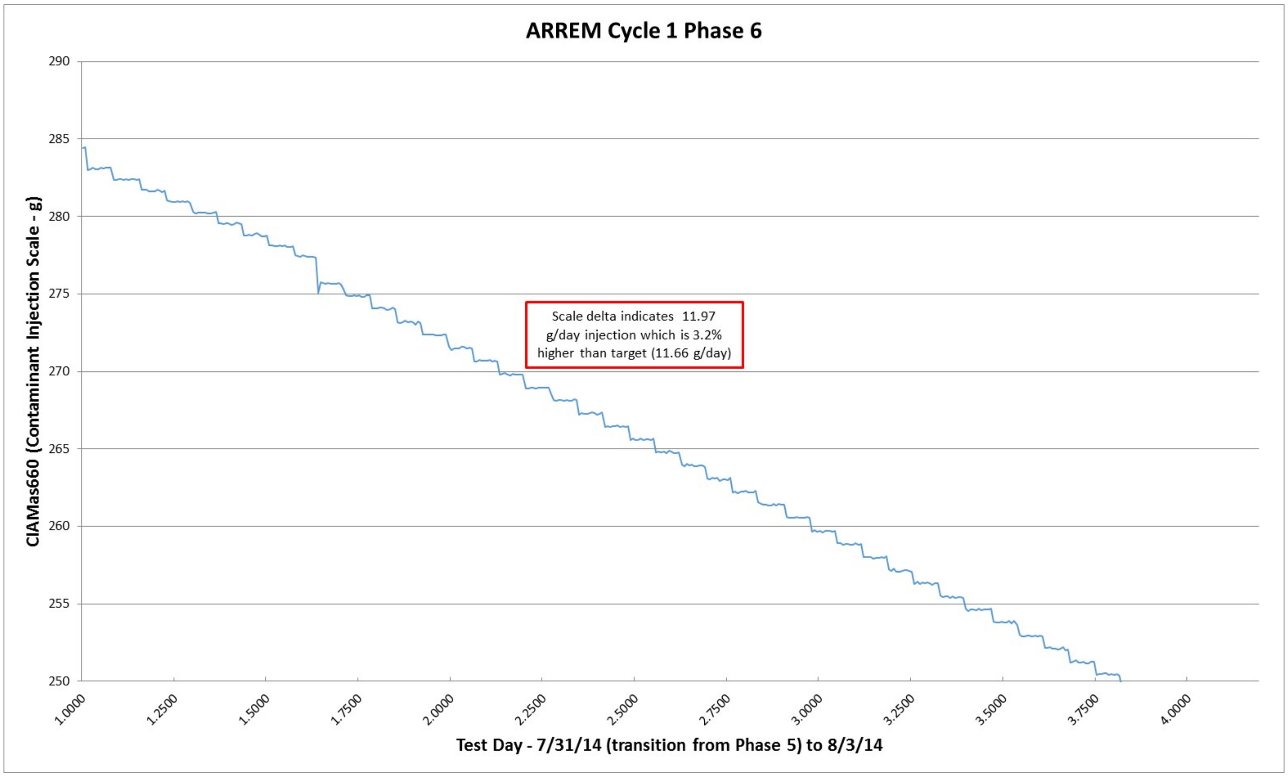
E-Chamber door was opened to determine if Oxygen Concentrator flow rate could be increased (it could not)

E-Chamber was maintained at a minimum 1 mmHg above atmospheric pressure.

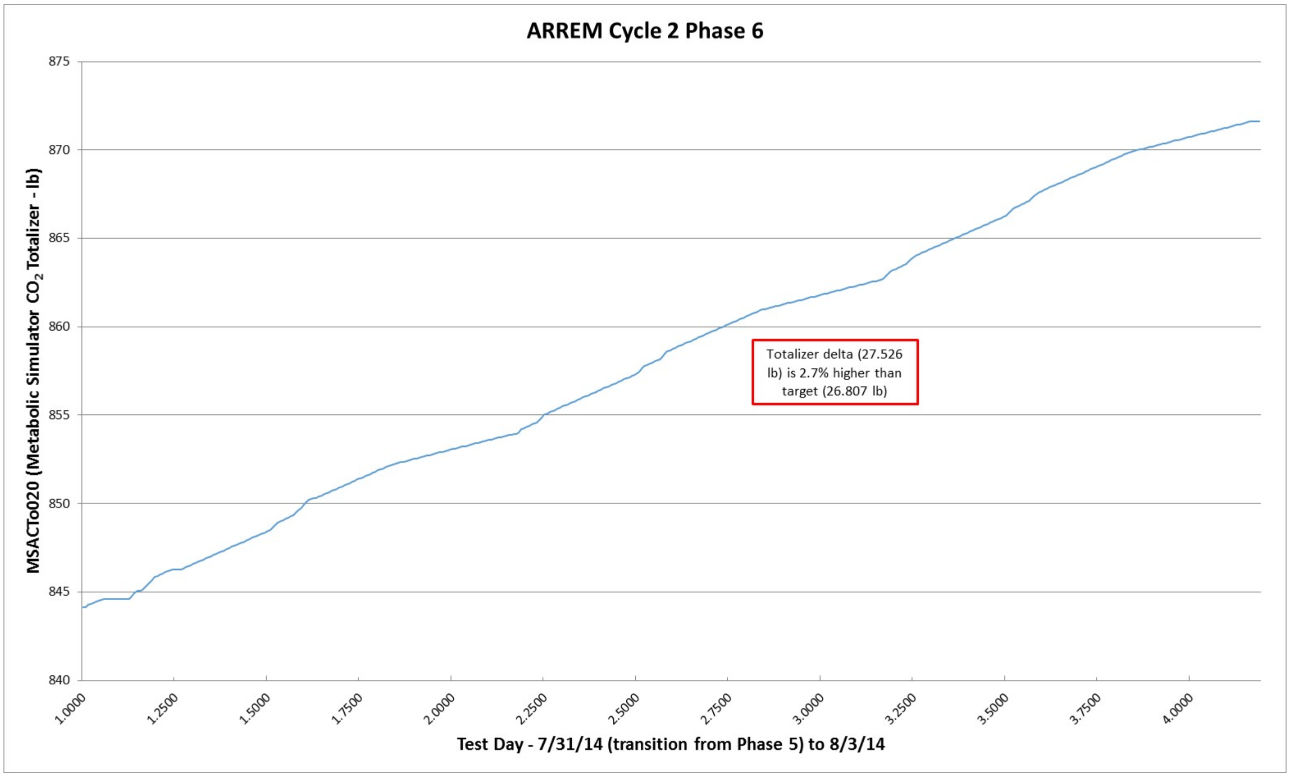


E-Chamber door opened to determine if Oxygen Concentrator flow rate could be increased (it could not)

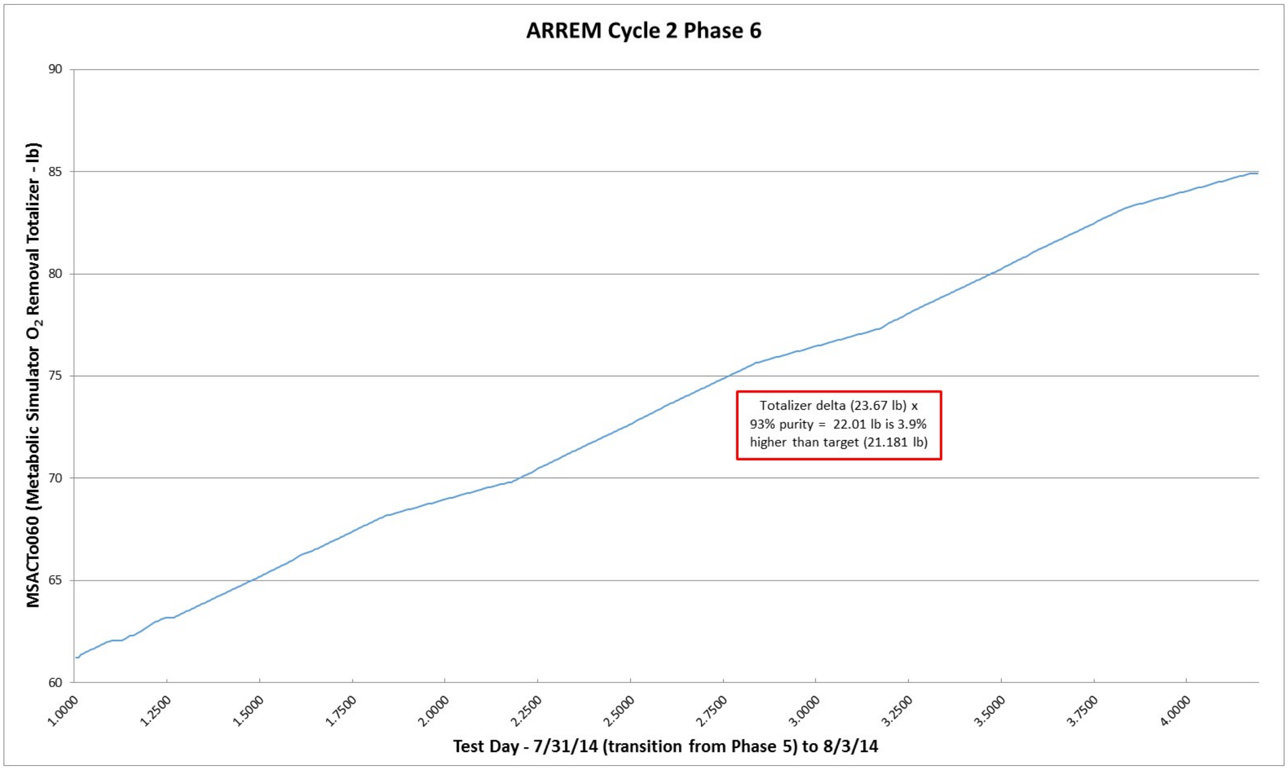




Scale delta indicates 11.97 g/day injection which is 3.2% higher than target (11.66 g/day)

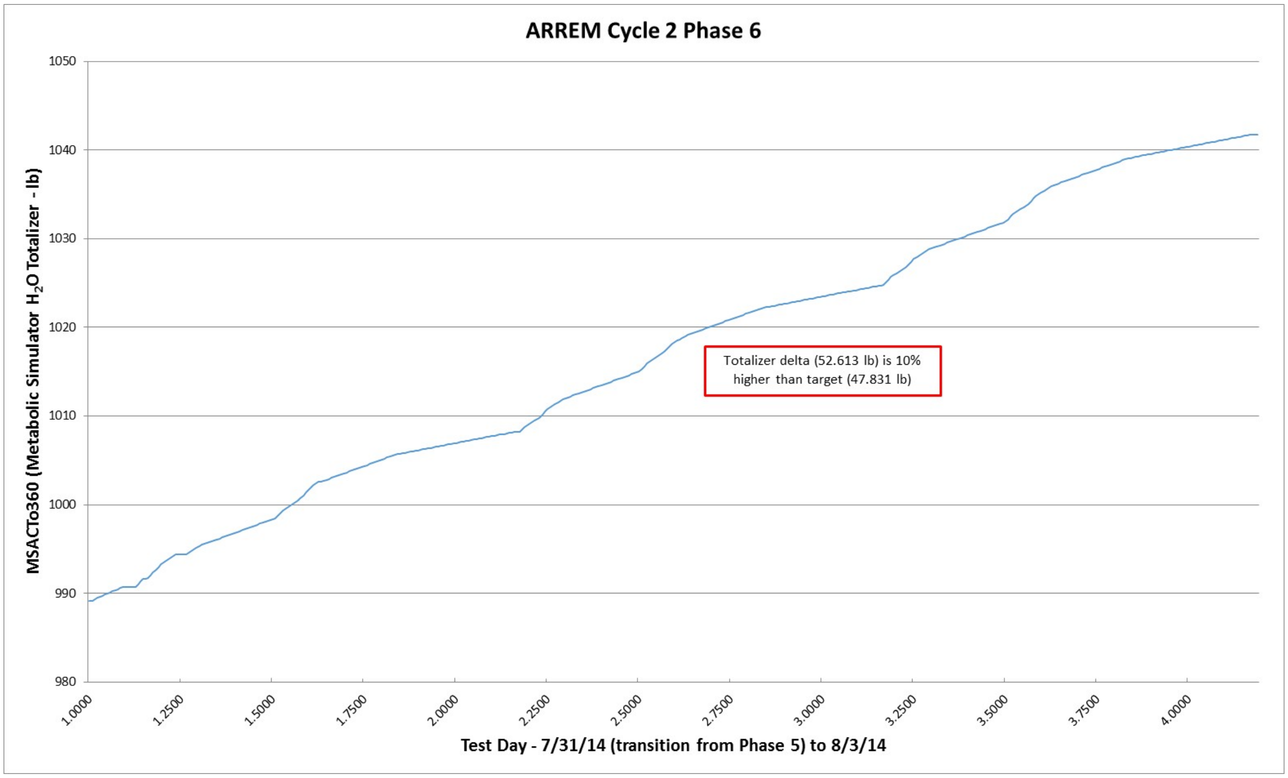


Totalizer delta (27.526 lb) is 2.7% higher than target (26.807 lb)



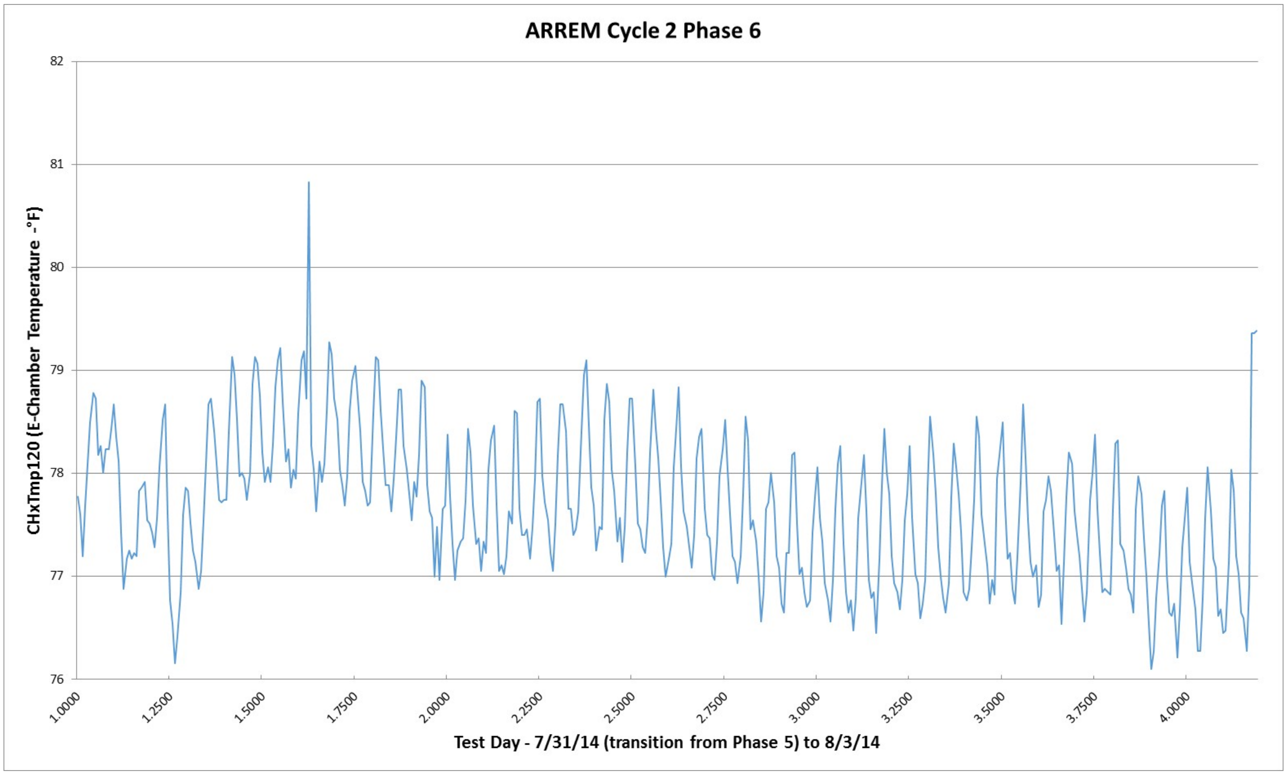
ARREM Cycle 2 Phase 6

Totalizer delta (23.67 lb) x 93% purity = 22.01 lb is 3.9% higher than target (21.181 lb)

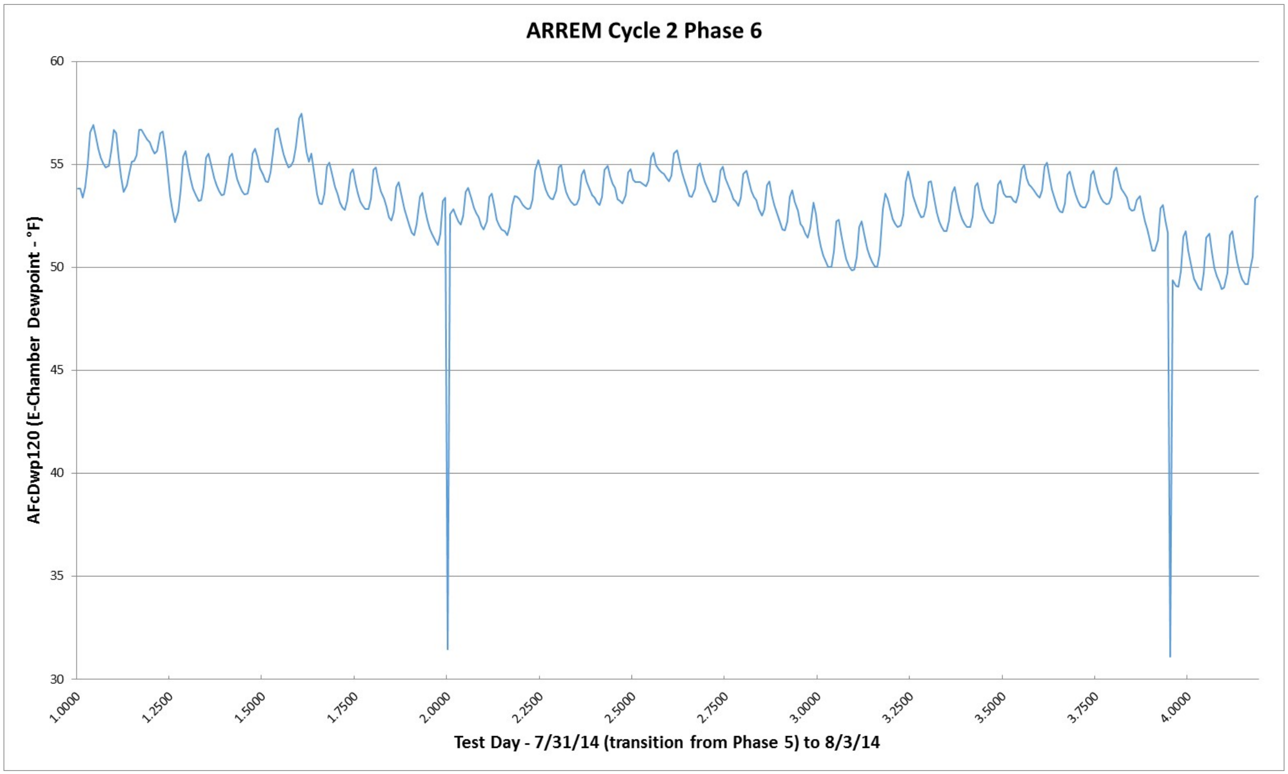


ARREM Cycle 2 Phase 6

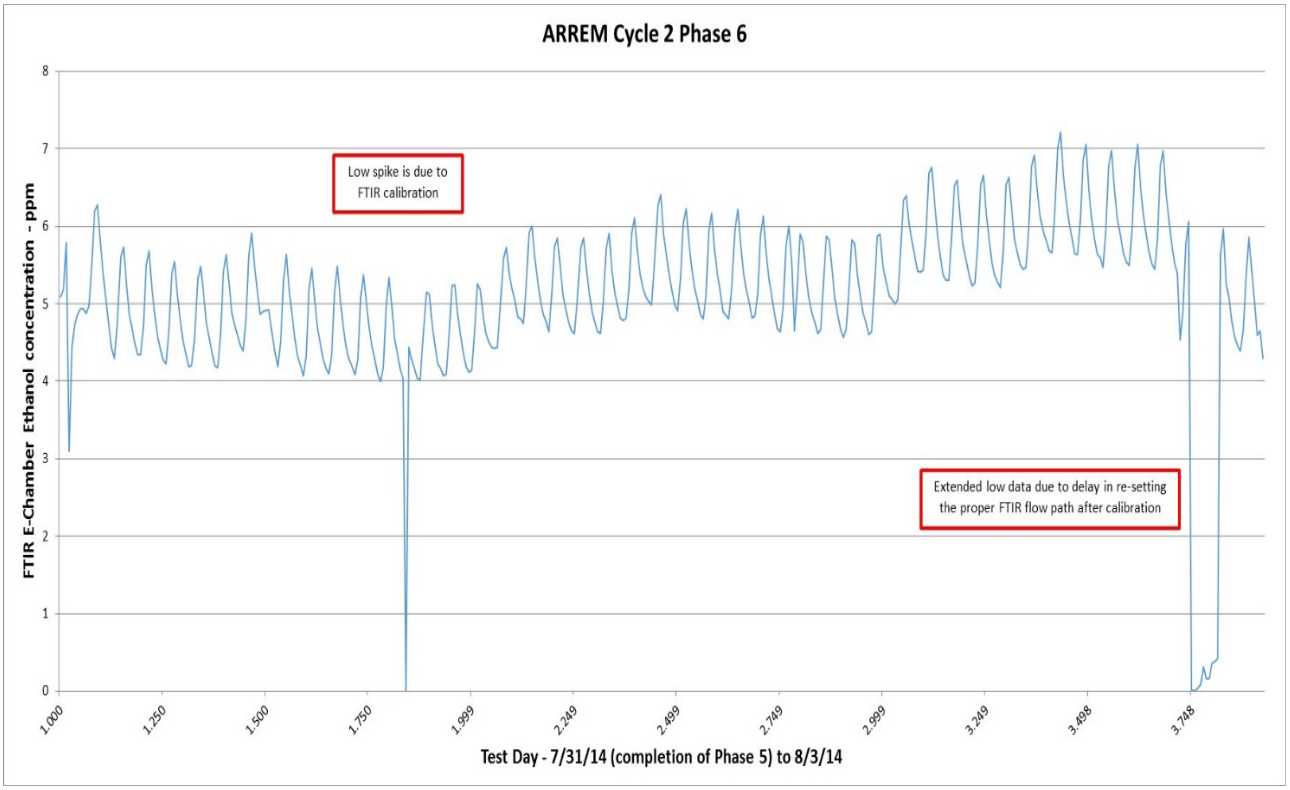
Totalizer delta (52.613 lb) is 10% higher than target (47.831 lb)

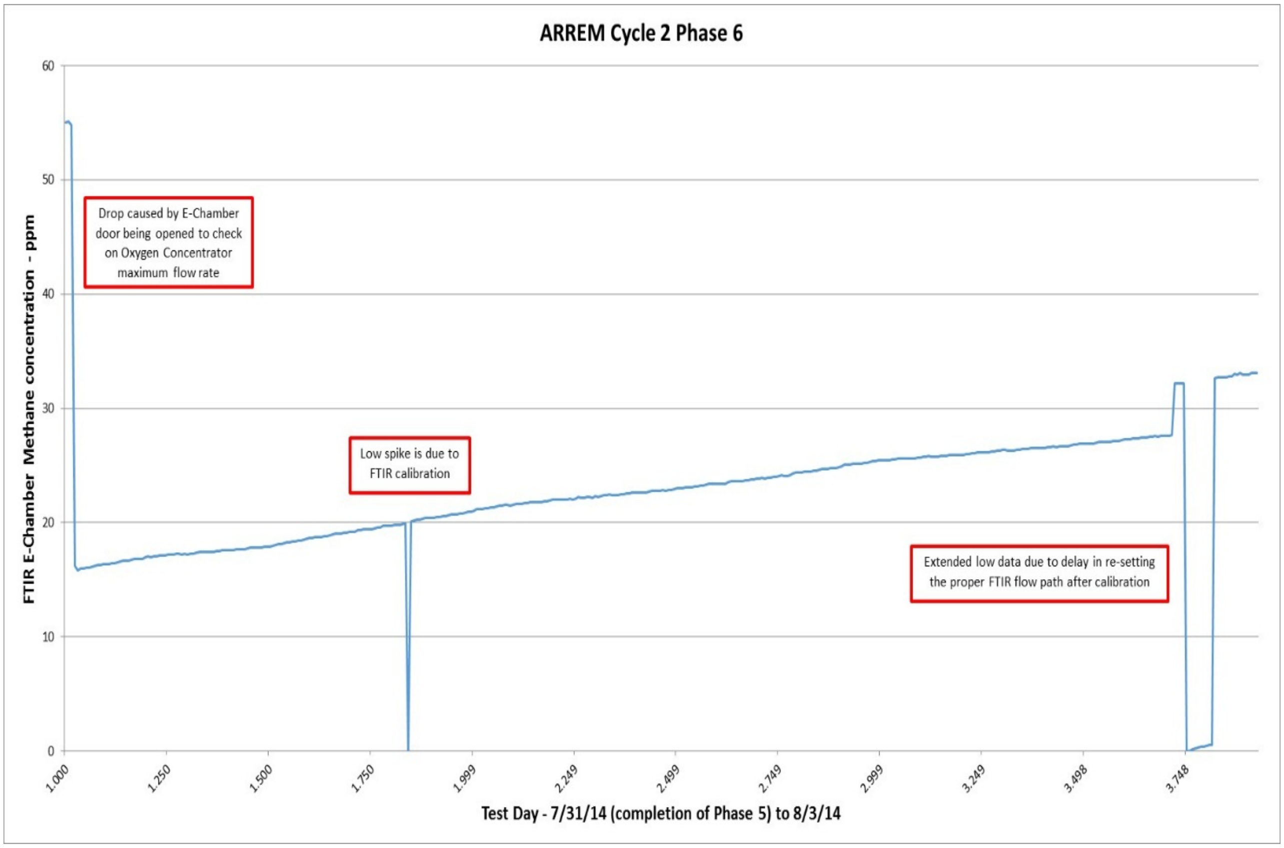


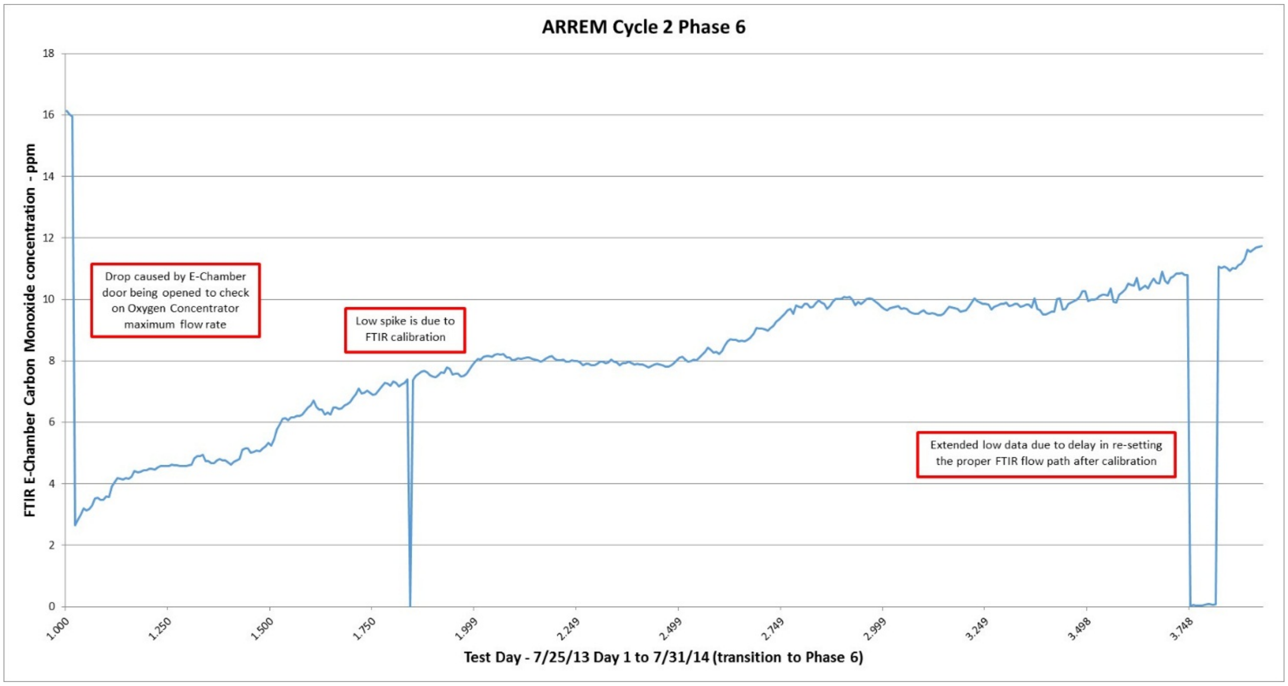
ARREM Cycle 2 Phase 6
CHxTmp120 (E-Chamber Temperature - °F)
82
81
80
79
78
77
76
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
Test Day - 7/31/14 (transition from Phase 5) to 8/3/14



ARREM Cycle 2 Phase 6
AFcDwp120 (E-Chamber Dewpoint - °F)
60
55
50
45
40
35
30
1.0000
1.2500
1.5000
1.7500
2.0000
2.2500
2.5000
2.7500
3.0000
3.2500
3.5000
3.7500
4.0000
Test Day - 7/31/14 (transition from Phase 5) to 8/3/14


ARREM Cycle 2 Phase 6
FTIR E-Chamber Ethanol concentration - ppm
8
7
6
5
4
3
2
1
0
1.000
1.250
1.500
1.750
1.999
2.249
2.499
2.749
2.999
3.249
3.498
3.748
Test Day - 7/31/14 (completion of Phase 5) to 8/3/14
Low spike is due to FTIR calibration
Extended low data due to delay in re-setting the proper FTIR flow path after calibration


ARREM Cycle 2 Phase 6
FTIR E-Chamber Methane concentration - ppm
60
50
40
30
20
10
0
1.000
1.250
1.500
1.750
1.999
2.249
2.499
2.749
2.999
3.249
3.498
3.748
Test Day - 7/31/14 (completion of Phase 5) to 8/3/14
Drop caused by E-Chamber door being opened to check on Oxygen Concentrator maximum flow rate
Low spike is due to FTIR calibration
Extended low data due to delay in re-setting the proper FTIR flow path after calibration



Phase 7 (Environmental Monitoring) Overview (8/18/14 to 8/22/14 & 9/22/14 to 9/26/14 – ES62-TPS-RRR-14-008): The purpose of Cycle 2 Phase 7 was to test Environmental Monitoring equipment and compare the results to facility monitors. The test articles were: Tunable Environmental Laser Spectrometer (TELS), Rapid Self Calibrating (RaSCal), Vehicle Environmental Monitor (VEM) Water Module, and a uGC "LunchBox". All of the articles were provide by the Jet Propulsion Laboratory (JPL). The EChamber provided the contaminant injection capability and controlled environment for the sensors.

Phase 7 Event Summary 8/18/14 Test Day 1 – After several facility issues (FTIR and host control computer communication problem, MSFC uGC computer problem, implementing a TELS software update), a dry run day was performed with a 1 minute injection of CO into the EChamber. Snapshots from 4 different monitors recorded the following data:

MSFC uGC – 107 ppm, FTIR – 101.6 ppm, AFcCO_100 – 101 ppm, and TELS 8.7 ppm

At this point, a facility scrubber was activated and left overnight to clean the EChamber atmosphere.
8/19/14 – Test Day 2 – Cleaning the EChamber atmosphere proved more difficult than expected. Internal sensors were still reading 52 ppm at 0745 on 8/19. A High Purity Air purge was initiated which further lowered the CO to 42.1 mmHg after an hour. A power outage (with no generator backup) took attention away from the issue for a couple of hours. Finally, with the CO below 50 ppm and no further easy remedy in reach, the EChamber door was opened. The CO reading inside immediately dropped to 0 ppm and hand-held CO monitors outside the EChamber did not measure any increase so it was almost immediately dispersed into the 4755 North High Bay atmosphere. The rest of the day was spent preparing for the VEM Water Module and the RaSCal. Some troubleshooting was done for TELS without success. Eventually it was returned to JPL for repair. The repair centered on a wiring issue (see 9/22/14 – Test Day 5 for further TELS data) and software modifications related to the processing of CO absorption spectra.

8/20/14 – Test Day 3 – DI water was flushed through the VEM Water Module and the chiller was set to 65 °F (non-condensing mode). Humidity injection was started in error and stopped about an hour later. Then a 10 ml contaminant mix injection was done. After about 90 minutes the EChamber ethanol reading had not stabilized so the manifold heater was activated at 120 °F. It still took 2 more hours for a stable reading: FTIR – 20 ppm, and GC – 17 ppm. 2 more injections with lengthy stabilization periods resulted in FTIR – 80 ppm, and GC – 60 ppm. The chiller was set to condensing mode and humidity injection was started at 2200, 8/20. The VEM Water Module responded but a qualitative analysis is all that can be offered from the data presented by JPL.

8/21/14 – Test Day 4 – On the morning of 8/21, humidity injection was stopped and the chiller was set back to non-condensing mode. The scrubber was started along with the LfFB to clean up the EChamber atmosphere. By 0903, the ethanol concentration in the EChamber was down to 27 ppm. The plan was to stop the scrubbers and inject contaminant mix in 20 ml increments until reaching 100 ml total. However, while performing this the reason that the stabilization periods were so long was discovered. The contaminant injection manifold blower controller had malfunctioned. Any ethanol that was making it into the EChamber atmosphere was virtually unaided in doing so. This portion of the test was aborted in order to fix this problem.

9/22/14 – Test Day 5 – By 9/22, the TELS had been repaired and returned to MSFC from JPL. This time the TELS data was within about 10% of facility measurements at 50, 100, and 150 ppm increments. This is acceptably accurate considering that the expected usage of TELS is to monitor for a fire which would produce CO in greater quantities than this.

9/24/14 – Test Day 6 – With testing for the other environmental monitors complete, the attention turned to the uGC "Lunch Box". The contaminant of choice for testing this unit was m-xylene. On 9/24, 25 ml of m-xylene was injected in 4 increments (one 10 ml and then three 5 ml) over a 3 hour period. MSFC FTIR responded up to 24.41 ppm for m-xylene.

9/25/14 – Test Day 7 – m-xylene concentration dropped overnight to 14.44 ppm as read on the MSFC FTIR. Two more 5 ml injections were done that morning (boosting the FTIR reading to 28.59 ppm) for further data gathering before activating the EChamber scrubbers to clean the atmosphere. The EChamber door was opened before noon on 9/25 after the EChamber m-xylene concentration had dropped to 16.85 ppm. The FTIR was re-baselined for the contaminant mix and the EChamber door was closed again at 1642. 15 ml of contaminant mix was injected with an FTIR response up to 36.53 ppm ethanol.

9/26/14 – Test Day 8 – Overnight the EChamber concentration of ethanol dropped to 23.11 ppm (m-xylene 2.04 ppm). A final 5 ml contaminant mix injection was done at 0840. The EChamber scrubber was activated at 1100 and the EChamber door was opened at 1200 signaling the end of Phase 7 and therefore, Cycle 2.

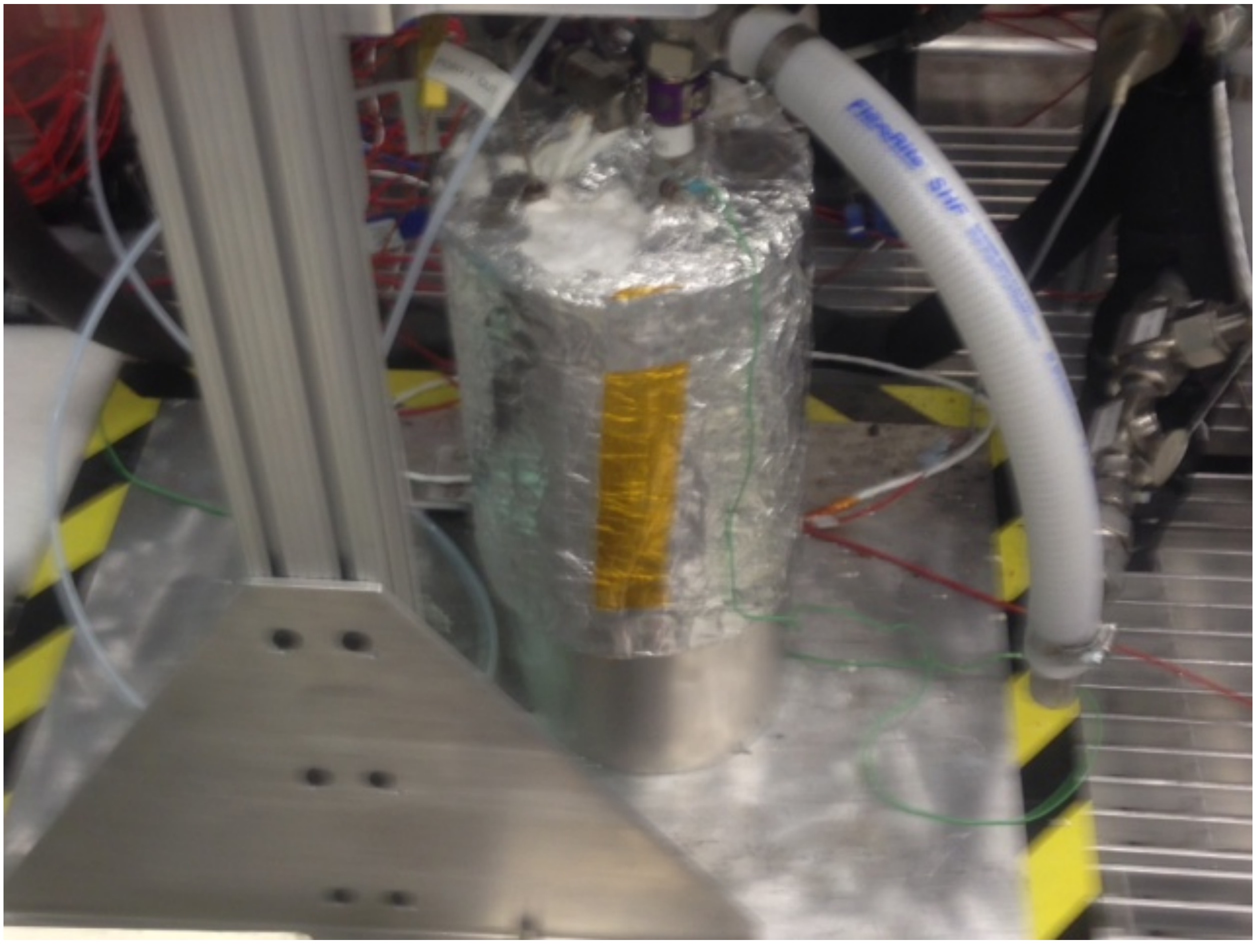
All MSFC generated environmental monitor data was delivered to the various Principal Investigators for Phase 7 for analysis and comparison to data generated by the test articles. MSFC personnel have not yet received any analytical reports back from the Phase 7 PI's.

Additional data, such as raw PACRATS data for other sensors and tabulated Gas Chromatograph data not included in this report, is available on the ES62 server at the following location: \\msnaf01\es62\1Echamber\Engineering Documents\Cycle2\Cycle2TestData.

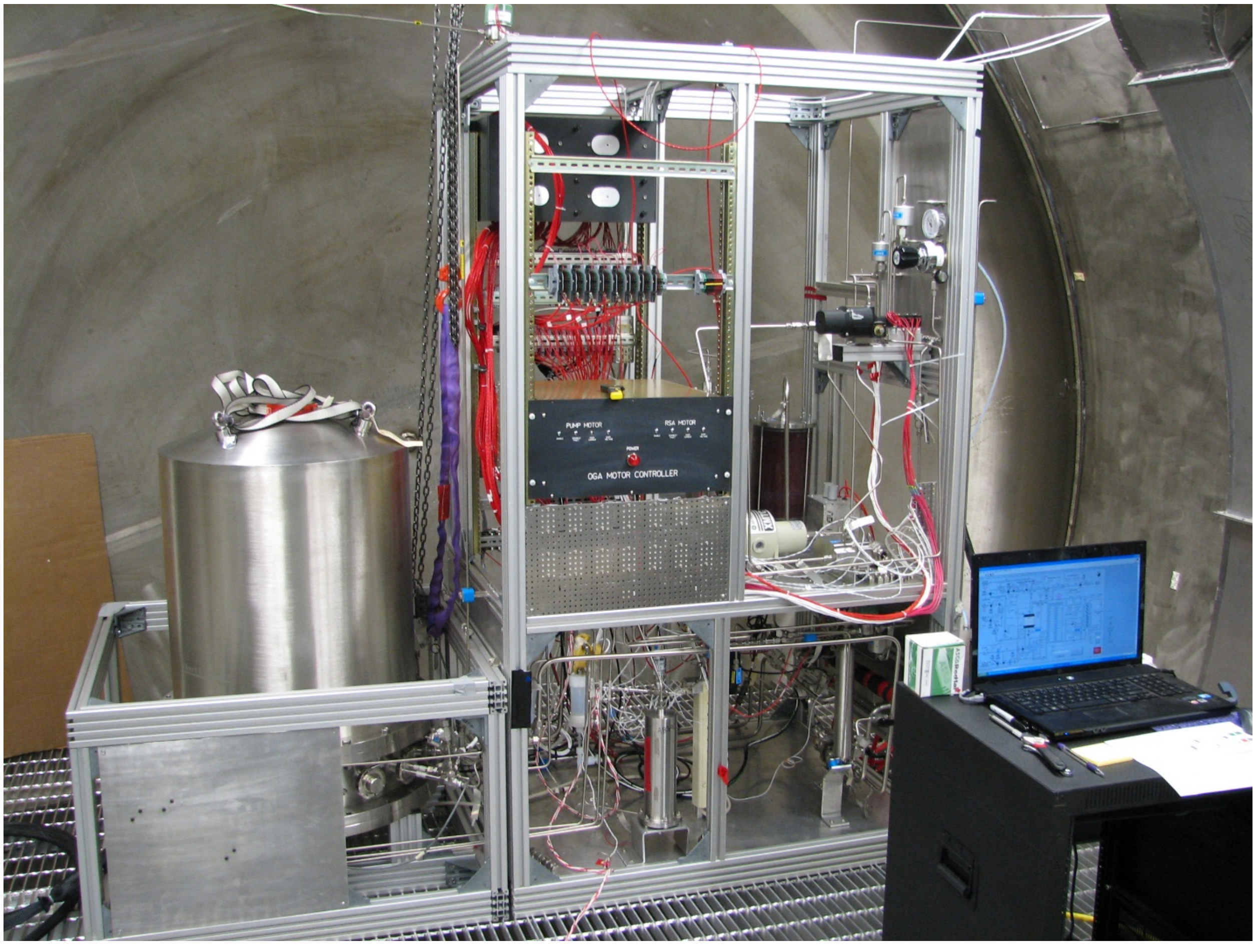
Appendix A: Pictures of Test Hardware used in ARREM Cycle 2. NOTE: schematics for the subsystems and the integrated facility are not suitably sized for inclusion in this report but are available on the ES62 server at the following location: \\msnaf01\es62\1Echamber\Schematics.

TCCS Adsorbent Cartridge Fixed Bed (ACFB)

TCCS Low-flow Fixed Bed (LfFB). NOTE: the LfFB was not used after the Phase 4 evaluation showed that the ACFB would provide the required contaminant removal for Phases 5 and 6

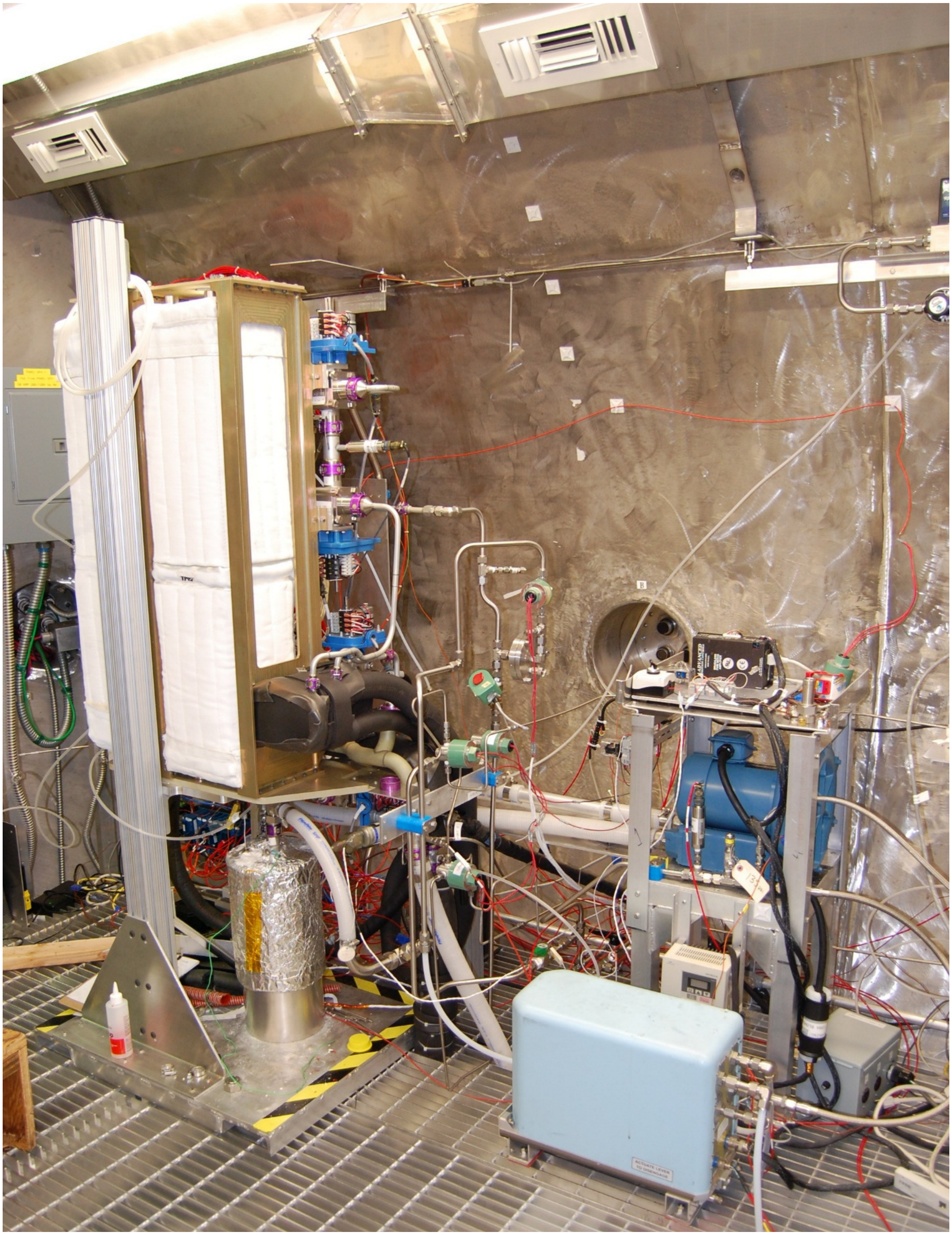


TCCS Monolith-Catalytic Oxidizer Assembly (M-COA)



Oxygen Generator Assembly (OGA)

Sabatier Carbon Dioxide Reduction Assembly (CRA)



Carbon Dioxide Removal Assembly -4 Engineering Unit (CDRA-4EU)

Appendix B: EChamber 2-gas Control System Logic Diagram

Chamber Total Pressure Control

Total pressure control was maintained between 0.40 and 0.93 kPa (3 and 7 mmHg) above the prevailing barometric pressure (gauge pressure). Chamber venting occurred if the pressure reached 1.6-kPa (12-mmHg) gauge pressure. At less than 0.40-kPa gauge pressure, nitrogen injection was 17 initiated. Injection stopped at 0.93-kPa gauge pressure. This control approach ensured that no dilution from the ambient atmosphere occurred and that the atmospheric composition inside the test chamber was purely the result of ARS subassembly operations. Figure 11 summarizes the CMS total pressure control logic.

Oxygen Partial Pressure Control

The oxygen partial pressure control range was set between 20.3 and 20.9 kPa (2.95 and 3.03 psia). To achieve this control, the oxygen partial pressure signal from the MCA was conditioned by the host computer and used to open and close a facility-provided valve that allowed oxygen to flow into the chamber at 0.0454 to 0.0907 kg/min (0.1 to 0.2 lb/min). Oxygen partial pressure could also be regulated by using this same conditioned MCA oxygen partial pressure signal to control the OGA oxygen production rate; however, technical difficulties prevented the OGA from being used in the test. In the event that oxygen partial pressure became too high, additional nitrogen would be injected into the chamber to dilute it. This approach is shown schematically by figure 11.

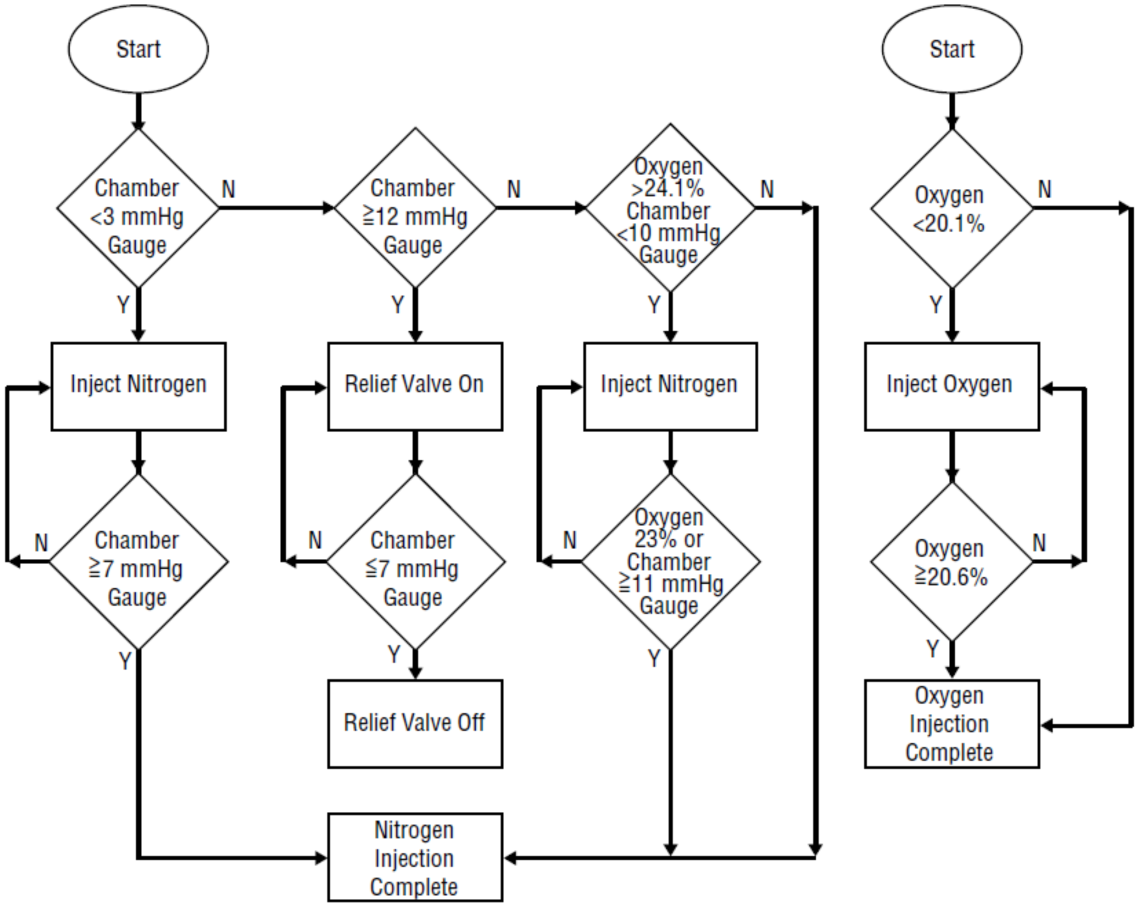


FIGURE 11.—CMS total pressure and oxygen partial pressure control logic.

Ref. NASA TM-108541, 1997, pp. 16-17.

REFERENCES

1. Moore, C.L.; and Peri, F.: "The Exploration Technology Development Program," AIAA 2007-136, 45th AIAA Aerospace Sciences Meeting and Exhibit, January 8–11, 2007, Reno, NV, 2007, doi.org/10.2514/6.2007-136.

2. NASA Strategic Space Technology Investment Plan, NASA Headquarters, December 2012.

3. NASA Systems Engineering Processes and Requirements, NPR 7123.1B, pp. 100–102, April 18, 2013.

4. NASA Space Flight Program and Project Management Handbook and the Standing Review Board Handbook, NPR 7120.5E, August 14, 2012.

5. NASA Technology Roadmaps TA6: Human Health, Life Support, and Habitation Systems NASA Headquarters 2015.

6. Drake, B.G. (Ed.): "Human Exploration of Mars Design Reference Architecture 5.0," NASA/SP—2009–566, NASA Johnson Space Center, Houston, TX, July 2009.

7. Drake, B.G. (Ed.): "Human Exploration of Mars Design Reference Architecture 5.0, Addendum," NASA/SP—2009–566-ADD, NASA Johnson Space Center, Houston, TX, July 2009.

8. Drake, B.G.; and Watts, K.D. (Eds.): "Human Exploration of Mars Design Reference Architecture 5.0, Addendum #2," NASA/SP–566-ADD2, NASA Johnson Space Center, Houston, TX, March 2014.

9. "NASA Exploration Destinations, Goals, and International Collaboration," Conference Report (House Report 112-284) accompanying the FY 2012 Consolidated and Further Continuing Appropriations Act (P.L. 112-55), August 2012.

10. Perry, J.L.; Carrasquillo, R.L.; and Harris, D.W.: "Atmosphere Revitalization Technology Development for Crewed Space Exploration," AIAA 2006-140, 44th AIAA Aerospace Sciences Meeting and Exhibit, January 9–12, 2006, Reno, NV, 2006, doi.org/10.2514/6.2006-140.

11. Perry, J.L.; and Howard, D.F.: "Spacecraft Life Support System Process Technology Maturation using Stage Gate Methodology," SAE Technical Paper 2007-01-3045, International Conference on Environmental Systems, doi: 10.4271/2007-01-3045, 2007.

12. Perry, J.L.; Abney, M.B.; Knox, J.C.; et al.: "Integrated Atmosphere Resource Recovery and Environmental Monitoring Technology Demonstration for Deep Space Exploration," AIAA

2012-3585, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, 2012, doi.org/10.2514/6.2012-3585.

13. Roman, M.; Perry, J.L.; and Jan, D.: "Design, Development, Test, and Evaluation of Atmosphere Revitalization and Environmental Monitoring Systems for Long Duration Missions," AIAA 2012-5120, *AIAA Space and Astronautics Forum and Exposition*, Pasadena, California, 2012.

14. Perry, J.L.; Bagdigian, R.M.; and Carrasquillo, R.L.: "Trade Spaces in Crewed Spacecraft Atmosphere Revitalization System Development," AIAA 2010-6061, 40th International Conference on Environmental Systems, July 11–15, 2010, Barcelona, Spain, 2010, doi.org/10.2514/6.2010-6061.

15. Perry, J.L.; Abney, M.; Frederick, K.; et al.: "Functional Performance of an Enabling Atmosphere Revitalization Subsystem Architecture for Deep Space Exploration Missions," AIAA 2013-3421, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

16. Perry, J.L.; Conrad, R.; Frederick, K.; et al.: "Evaluation of an Atmosphere Revitalization Subsystem for Deep Space Exploration Missions," ICES-2015-107, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

17. Howard, D.; Perry, J.L.; and Roman, M.: "Lessons Learned from the Development and Implementation of the Atmosphere Resource Recovery and Environmental Monitoring Project," *AIAA Space 2014 Conference and Exposition*, Pasadena, California, August 2014.

18. Jan, D.L.; and Newton, R.: "Environmental Monitoring as a part of Life Support: Deep Space Exploration," AIAA 2012-3433, 42nd International Conference on Environmental Systems, San Diego, CA, July 15–19, 2012, doi.org/10.2514/6.2012-3433.

19. Macatangy, A.V.: "An Assessment of Environmental Health Needs," AIAA 2013-3465, 43rd International Conference on Environmental Systems, Vail, CO, July 14–18, 2013.

20. Perry, J.L.: "Elements of Spacecraft Cabin Air Quality Control Design," NASA/TP—1998–207978, NASA Marshall Space Flight Center, Huntsville, AL, May 1998.

21. Meyer, M.: "ISS Ambient Air Quality: Updated Inventory of Known Aerosol Sources," ICES-2014-199, 44th International Conference on Environmental Systems, Tucson, AZ, 2014.

22. Tatara, J.D.; and Perry, J.L.: "Performance of Off-the-Shelf Technologies for Spacecraft Cabin Atmospheric Major Constituent Monitoring," NASA/TM—2004–213392, NASA Marshall Space Flight Center, Huntsville, AL, October 2004.

23. Air Quality Monitoring Report: A Review of Responses to the NASA Request for Information on Trace Contaminant Monitoring, NASA/TM—2004–213144, July 2004.

24. Hodgson, E.; Converse, D.; Duggan, M.; and Gentry, G.: "Flexible Path Environmental Control and Life Support Technology—Possible First Steps to Move Beyond LEO," AIAA 2012-3443, 42nd International Conference on Environmental Systems, San Diego, CA, doi.org/10.2514/6.2012-3443, July 15–19, 2012.

25. Metcalf, J.; Peterson, L.; Carrasquillo, R.; and Bagdigian, R.: "National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Integrated Roadmap Development," AIAA 2012-3444, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, doi.org/10.2514/6.2012-3444.

26. NASA-HDBK-8739.19-3, Measurement Uncertainty Analysis Principles and Methods, NASA Measurement Quality Assurance Handbook—ANNEX 3, Washington, DC, July 2010.

27. Coleman, H.W.; and Steele, W.G.: *Experimentation and Uncertainty Analysis for Engineers,* John Wiley & Sons, Inc., pp. 7–14, 76–118, 1989.

28. Perry, J.L.; Tomes, K.M.; and Tatara, J.D.: "Thermal Catalytic Oxidation of Airborne Contaminants by a Reactor Using Ultra-Short Channel Length, Monolithic Catalyst Substrates," NASA/TM—2005–214061, NASA Marshall Space Flight Center, Huntsville, AL, September 2005.

29. Luna, B.; Somi, G.; Winchester, J.P.; et al.: "Evaluation of Commercial Off-the-Shelf Sorbents and Catalysts for Control of Ammonia and Carbon Monoxide," AIAA 2010-6062, 40th International Conference on Environmental Systems, July 11–15, 2010, Barcelona, Spain, doi.org/10.2514/6.2010-6062, 2010.

30. Knox, J.; Gostowski, R.; Watson, D.; et al.: "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems," AIAA 2012-3642, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, doi.org/10.2514/6.2012-3642, 2012.

31. Woods, S.: "OGA Testbed Operation with Nitrogen Purge Disabled," Hydrogen Hazards Memorandum HMEM.013, White Sands Test Facility Hydrogen Group, January 2014.

32. Mulloth, L.M.; Perry, J.L.; and LeVan, D.: "Integrated System Design for Air Revitalization in Next Generation Crewed Spacecraft," SAE 2004-01-2373, 34th International Conference on Environmental Systems, Colorado Springs, CO, doi:10.4271/2004-01-2373, 2004.

33. Varghese, M.; Mulloth, L.; Luna, B.; and Hogan, J.: "Development Status of a Low-Power CO_2 Removal and Compression System for Closed-Loop Air Revitalization," AIAA 2010-6060, 40th International Conference on Environmental Systems, July 11–15, 2010, Barcelona, Spain, doi.org/10.2514/6.2010-6060, 2010.

34. Hogan, J.; Luna, B.; Mulloth, L.; et al.: "The Low-Power CO_2 Removal and Compression System: Design Advances and Developmental Status," AIAA 2012-3587, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, doi.org/10.2514/6.2012-3587, 2012.

35. James, J.; Matty, C.; Meyers, V.; et al.: "Crew Health and Performance Improvements with Reduced Carbon Dioxide Levels and the Resource Impact to Accomplish Those Reductions," AIAA 2011-5047, 41st International Conference on Environmental Systems, July 17–21, 2011, Portland, OR, 2011, doi.org/10.2514/6.2011-5047.

36. Wheeler, R.; Hadley, N.; Dahl, R.; et al.: "Advanced Plasma Pyrolysis Assembly (PPA) Reactor and Process Development," AIAA 2012-3553, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, 2012, doi.org/10.2514/6.2012-3553.

37. Abney, M.; Mansell, J.; Long, D.; et al.: "Series Bosch System Development," AIAA 2012-3554, 42nd International Conference on Environmental Systems, July 15–19, 2012, San Diego, CA, 2012, doi.org/10.2514/6.2012-3554.

38. Jan, D.: "Environmental Monitoring as Part of Life Support for the Crew Habitat for Lunar and Mars Missions," AIAA 2010-6092, 40th International Conference on Environmental Systems, Barcelona, Spain, doi.org/10.2514/6.2010-6092, 2010.

39. "Advanced System Integration and Control for Life Support," Workshop on Advanced System Integration and Control for Life Support, Monterey, CA. <https://books.google.com/books/about/workshop_on_Advanced_system_integration.html?id=RCtEmwEACAAJ> August 2003.

40. "Advanced Life Support Systems," Workshop on Advanced System Integration and Control for Life Support, Monterey, CA. <https://books.google.com/books/about/workshop_on_Advanced_system_integration.html?id=RCtEmwEACAAJ> August 2003.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01–09–2016

2. REPORT TYPE
Technical Publication

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Advanced Exploration Systems Atmosphere Resource Recovery and Environmental Monitoring

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
J. Perry, M. Abney, R. Conrad, A. Garber, D. Howard, M. Kayatin, J. Knox, R. Newton, K. Parrish, M. Roman, and N. Toomarian*

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Huntsville, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–1419

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TP—2016–218228

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 54
Availability: NASA STI Information Desk (757–864–9658)

13. SUPPLEMENTARY NOTES
Prepared by the Space Systems Department, Engineering Directorate
*NASA Jet Propulsion Laboratory, Pasadena, CA

14. ABSTRACT

In September 2011, the Atmosphere Resource Recovery and Environmental Monitoring (ARREM) project was commissioned by NASA's Advanced Exploration Systems program to advance Atmosphere Revitalization Subsystem (ARS) and Environmental Monitoring Subsystem (EMS) technologies for enabling future crewed space exploration missions beyond low Earth orbit. The ARREM project's period of performance covered U.S. Government fiscal years 2012–2014. The ARREM project critically assessed the International Space Station (ISS) ARS and EMS architectures and process technologies as the foundation for an architecture suitable for deep space exploration vehicles. The project's technical content included technical tasks focused on improving the reliability and life cycle cost of ARS and EMS technologies as well as reducing future flight project developmental risk and design, development, test, and evaluation costs. Targeted technology development and maturation tasks, including key technical trade assessments, were accomplished and integrated ARS architectures were demonstrated. The ARREM project developed, demonstrated, and tested leading process technology candidates and subsystem architectures that met or exceeded key figures of merit, addressed capability gaps, and significantly improved the efficiency, safety, and reliability over the state-of-the-art ISS figures of merit. Promising EMS instruments were developed and functionally demonstrated in a simulated cabin environment. The project's technical approach and results are described and recommendations for continued development are provided.

15. SUBJECT TERMS
life support, exploration systems, atmosphere revitalization, environmental monitoring, resource recovery, carbon dioxide removal, oxygen supply, trace contaminant control, particulate matter filtration

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk at email: help@sti.nasa.gov
U	U	U	UU	264	19b. TELEPHONE NUMBER *(Include area code)* STI Help Desk at: 757–864–9658

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

National Aeronautics and
Space Administration
IS02
George C. Marshall Space Flight Center
Huntsville, Alabama 35812