Integrated Evaluation of Closed Loop Air Revitalization System Components

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Acknowledgement

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

Contractor Report

Integrated Evaluation of Closed Loop Air Revitalization System Components

1 Introduction

NASA's vision and mission statement include an emphasis on human exploration of space, which requires environmental control and life support technologies. As the target destination becomes more distant and the target mission duration longer, closed loop life support systems become increasingly necessary for feasibility and success.
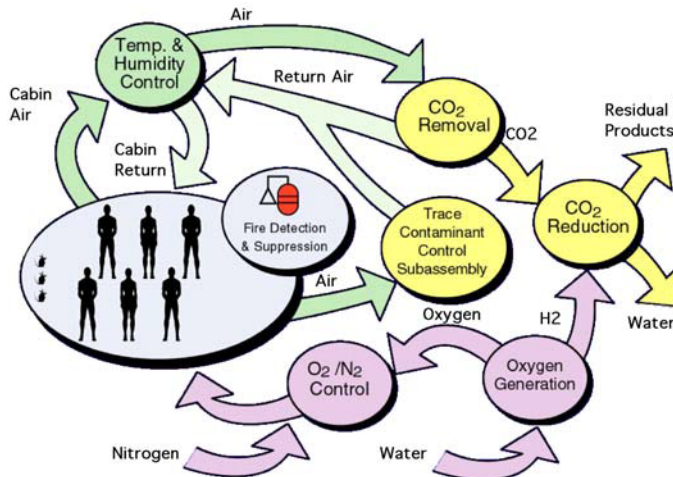
Figure 1 – Closed Loop Air Revitalization System

An air revitalization system (ARS) includes temperature and humidity control, oxygen and nitrogen supply and control, carbon dioxide and trace contaminant removal and carbon dioxide reduction for oxygen recovery. These processes also interact with the water recovery system. Crew oxygen is produced by the electrolysis of water. The hydrogen by-product of electrolysis is utilized by the carbon dioxide reduction assembly along with the waste carbon dioxide to re-form water. This last step, carbon dioxide reduction, is a necessary step for loop closure that minimizes the resupply needed for crew support.

This paper describes the development of components for a closed loop ARS, modeling and simulation of the components and integrated hardware testing, with the goal of better understanding the capabilities and limitations of this closed loop system. The integrated testing included a carbon dioxide removal assembly (CDRA), carbon dioxide reduction assembly (CRA), and two different compressor technologies that provided the necessary link between the CDRA and CRA.

1.1 What did we do

The overall test objective was to integrate the carbon dioxide removal assembly with the carbon dioxide reduction assembly. Two distinct compressor technologies were developed to provide the function of collecting and storing CO2 from the CDRA before it is consumed by the CRA. The systems were tested over a range of conditions that represented both ISS and Lunar surface activities. The test program was conducted from November 2004 through March 2006 in the Laboratory Module Simulator facility at the NASA Marshall Space Flight Center (building 4755).

1.2 Why did we do it

The purpose of the integrated testing was to operate the two configurations of ARS components to determine any limitations or requirements imposed on each component by the interfacing components. Each of the hardware assemblies (CDRA, mechanical compressor, Temperature Swing Adsorption Compressor (TSAC), and Sabatier Reactor Subassembly (SRS)) has been tested independently, and computer simulations have been run of the integrated system. Testing was required to evaluate the performance of the 4-bed molecular sieve (4BMS, another name for CDRA), compressor and Sabatier performance when integrated together and to verify the results from the engineering analysis. Specifically, the testing was intended to:
- Provide understanding of transients and integration issues;
- Validate baseline operation/control logic for the compressors;
- Validate FORTRAN integrated model of the 4BMS, compressors and Sabatier; and
- Validate the mechanical compressor and TSAC computer models.

1.3 What did we learn

The testing described herein was the first integrated test of a Four-Bed Molecular Sieve and Sabatier Carbon Dioxide Reduction Assembly with the interfacing CO2 compressor. Two compressor technologies were tested, a mechanical oil-free piston compressor and a temperature swing adsorption compressor (TSAC). The mechanical compressor was tested under simulated International Space Station parameters. The TSAC was tested under both ISS and Lunar Base parameters. Both sets of tests provided enhanced understanding of nominal steady operation and dynamic, transient scenarios that can be expected to occur in an integrated Environmental Control and Life Support System.

In general, the 4BMS, Sabatier and both compressor technologies were proved compatible and able to perform their intended functions for a wide range of input conditions. It is feasible, using these technologies to recover oxygen in the form of water, to make the next step toward oxygen loop closure. These technologies are ready to be advanced to the next Technology Readiness Level (TRL) level and put in service in a flight mission.

1.4 What do we want to do next

This test program showed not only that water recovery is feasible using CO2 reduction, but it also identified areas where each of the technologies could be improved. These improvements include upgrades to hardware components, changes to control logic and the implementation of artificial intelligence or smart controls. Additional testing should be performed with these systems to better define the proposed modifications to arrive at the best possible solution.

2 Integrated Test Configuration

Integrated testing of carbon dioxide removal and reduction assemblies was performed at MSFC over the period from 2004 through 2006. This testing was performed to understand the interactions between the different subassemblies in order to plan for future phases of subsystem development. This section details the hardware used in the integration testing, test configurations and operating parameters, and test results.

Figure 1 below depicts three main elements of an Air Revitalization System (ARS). These systems and their interactions were the focus of this test program. The three systems shown below are the carbon dioxide removal assembly (CDRA), the oxygen generation assembly (OGA) and the carbon dioxide reduction assembly (CRA). The CDRA collects and concentrates carbon dioxide and feeds it to the CRA. The OGA electrolyzes water for crew oxygen and feeds the by-product hydrogen to the CRA. The CRA reacts hydrogen and carbon dioxide to form methane and water. The water is returned to the OGA, thus partially closing the oxygen loop. The OGA/CRA interaction has been separately studied by Hamilton Sundstrand, the supplier of the ISS OGA, and is not reflected in this report. This report focuses on the interaction of the CDRA with the CRA.
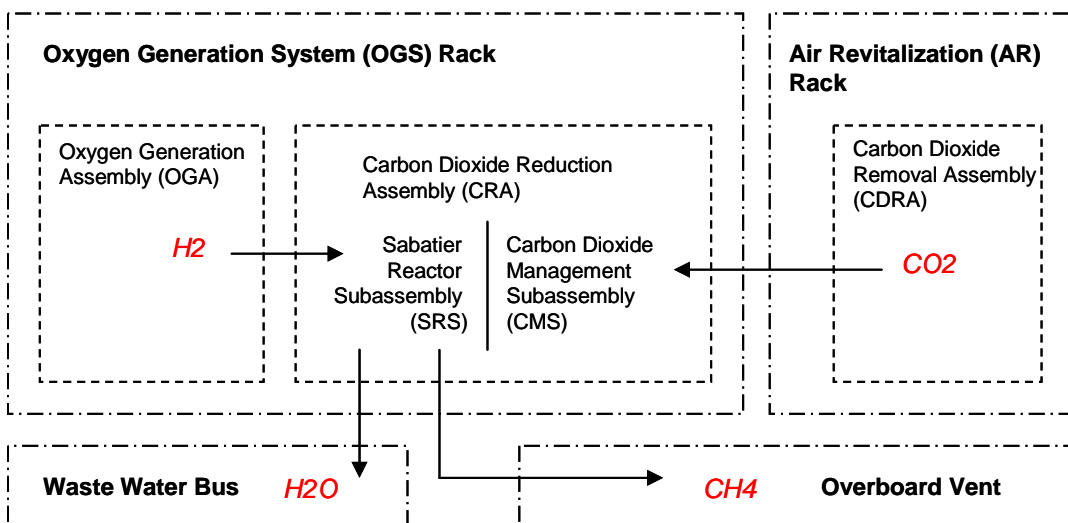
Figure 2 – Overall block diagram of the Air Revitalization System (ARS) sub-systems.

The CRA is further separated into two sub-assemblies, the Sabatier Reactor Subassembly (SRS) and the Carbon dioxide Management Subassembly (CMS). The CMS includes the compressor and accumulator. The focus of this test program, therefore, is the insertion of different compressor technologies into the CMS role supporting the requirements of the CDRA and Sabatier in their respective roles in the overall Air Revitalization System.

The 4BMS, Sabatier and compressors have each been independently tested over a range of operating conditions. These isolated tests are not covered in this test report, but are discussed in references [ ], with the focus of this study being to understand the subsystem interactions. The previous liquid and water-cooled versions of the TSAC were also tested in conjunction with the 4BMS. These tests are not reported here but are detailed in references [ ]. The sequence of test configurations presented here were planned to develop a working ARS originally for use on the International Space Station, and later as a potential solution for lunar missions. The test configurations are described below as they were conducted chronologically:

1. 4BMS with mechanical compressor and accumulator – (November, December 2004)
2. 4BMS, mechanical compressor, accumulator and Sabatier – (February, March 2005)
3. 4BMS with air-cooled TSAC – (November 2005)
4. 4BMS, air-cooled TSAC and Sabatier – (January 2006)

Referring back to Figure 1 of the Air Revitalization System, the Carbon Dioxide Reduction Assembly (CRA) consists of both the Carbon Dioxide Management Subassembly (CMS) and the Sabatier Reactor Subassembly (SRS). In these tests we evaluated two hardware configurations for the CMS. The mechanical compressor requires a separate accumulator; the TSAC serves as both compressor and accumulator. Regardless of which compressor technology was installed as CMS, the CMS would operate when required based on CO2 availability from the 4BMS, regardless of the operating state of the SRS. Since the compressor and 4BMS are so closely linked, each compressor was initially tested with the 4BMS prior to addition of the Sabatier.

2.1 Description of Equipment – Subsystems and Support Hardware

This section describes each of the subsystems used in the integration testing. The summary includes the 4-bed molecular sieve (4BMS) carbon dioxide removal assembly (CDRA), the Sabatier reactor subassembly (SRS), the mechanical compressor and accumulator (the 1st evaluated compressor), and the temperature swing adsorption compressor (the 2nd evaluated compressor).

2.1.1 4-Bed Molecular Sieve (4BMS) Carbon Dioxide Removal Assembly (CDRA)

Throughout this paper different terminology will be used to reference the hardware that was tested. The term Carbon Dioxide Removal Assembly (CDRA) refers to any system that removes carbon dioxide from the breathing atmosphere of a spacecraft. This function can technically be performed by a variety of technologies, however the name CDRA was given to the CO2 removal system aboard the International Space Station, which is a 4-bed molecular sieve (4BMS) technology.

2.1.1.1 4BMS Hardware Description

The carbon dioxide removal assembly tested in this development project is the same technology and configuration as the hardware currently installed and operating on the International Space Station (ISS). The ISS CDRA, developed by Honeywell (1), uses a four-bed molecular sieve process that consists of two desiccant beds and two CO_2 sorbent beds. Ancillary components include a blower, air-save pump, heat exchanger, valves, and sensors. Figure 3 is a schematic representation of the major components of the four-bed molecular sieve process. Cabin air is drawn through one desiccant bed to remove the moisture then through one CO_2 sorbent bed to remove the CO_2. This processed air is then sent through the second, heated desiccant bed to re-humidify the stream before returning the air back to the cabin. At the same time, the second CO_2 sorbent bed, which is loaded with CO2, is heated and evacuated to desorb the CO_2. Prior to exposing the loaded bed to vacuum the air save pump removes ullage air out of the desorbing bed and vacuum circuit and pumps it to the cabin. This is done in the first 10 minutes of the desorption half-cycle. The vacuum circuit runs from the desorbing bed check valve to space vacuum, shown as the yellow line in Figure 3. A half-cycle refers to the timed period in which one bed is doing all of the CO2 removal function. At the start of the next half-cycle, all beds switch to the opposite mode and cabin air flow 'swings' to the other set of adsorbent beds; the alternate bed then performs the CO2 removal function. In this manner continuous CO_2 removal is achieved.

The Performance and Operational Issues System Testbed (POIST) 4BMS unit located in the ISS Laboratory Module Simulator (LMS) at MSFC was used for this testing. This system has been extensively modified to achieve functionally flight-like performance for ISS sustaining engineering ground support testing (2).

The CDRA uses a pressure and temperature swing adsorption cycle to remove carbon dioxide from the crew breathing air. The CO2 removal beds are filled with 5A molecular sieve that is packed between heater plates. At the start of an adsorption cycle, the mass fraction of CO2 on the desiccant is very low and therefore the equilibrium concentration of CO2 in the air returned to the cabin is practically zero. With prolonged exposure to CO2, the bed adsorbs CO2 and 'fills', and the return air may contain small but increasing amounts of CO2. At the end of the half-cycle, it is desorbed with both heat and vacuum. The bed is heated electrically to 400°F during daytime operation when power on the ISS

is plentiful, but during nighttime operation, the heaters are turned off. The length of the ISS orbit is approximately 90 minutes with the "day" portion running from 90 minutes maximum to 53 minutes minimum, depending on the inclination of the orbit. For all day/night cyclic testing, the worst case 53 minute day was used. The 5A molecular sieve material has a high affinity for water vapor, which preferentially adsorbs and displaces CO2. Because of this phenomenon, the two desiccant beds are included in the 4-bed design. One desiccant bed removes water prior to the air stream entering the 5A bed, while the other bed, previously loaded, replenishes the water to prevent over-drying of the cabin air.
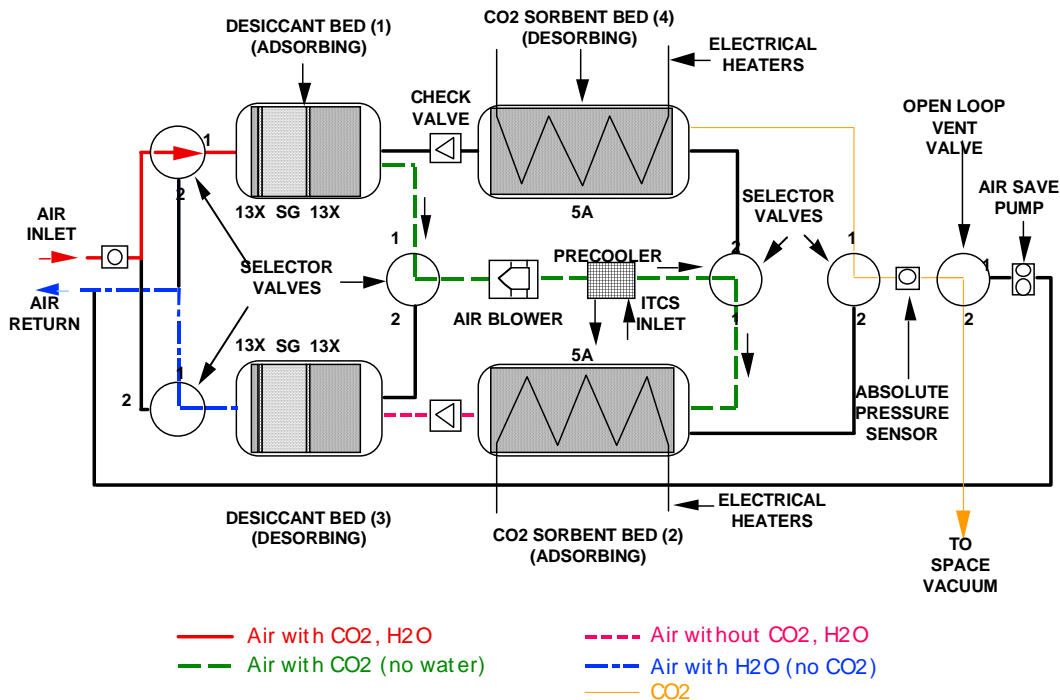
Figure 3 - 4-Bed Molecular Sieve Schematic

2.1.1.2 4BMS Integration Characteristics

One of the peculiarities of the 4BMS CDRA is that it is designed to operate on a 144 minute half cycle (10 cycles per 24-hour day). This becomes an issue only when integrating CDRA with other systems designed to operate in synch with the 90 minute diurnal orbit of the International Space Station. The 4BMS operates on the physics of adsorption isotherms of 5A molecular sieve. As such, the temperature and pressure achieved during the desorption period affects the capacity for air scrubbing on the following cycle. This becomes an important factor when integrating with a downstream system that affects the desorption pressure and when nighttime power saving protocols limit the temperature the bed reaches. The two molecular sieve beds must have sufficient capacity such that the high efficiency periods can carry it through the times when the pressure and temperature are not so favorable for good desorption.
The 5A molecular sieve material also has adsorptive capacity for chemicals other than CO2 and water. Some trace contaminants in the cabin atmosphere will be adsorbed on the zeolite and desorbed along with the carbon dioxide. Some of these chemicals have been

shown to affect the operation of downstream systems, specifically the Sabatier reactor. A summary of contaminant testing that was performed on the Sabatier catalyst is detailed in J.D. Tatara and J.L. Perry; *International Space Station Trace Contaminant Injection Test, Revision A, NASA Test Requirements Document*, January 1997.

2.1.2 Mechanical Compressor Engineering Development Unit and Accumulator

2.1.2.1 Mechanical Compressor Hardware Description

A compressor is needed to provide a vacuum for 4BMS desorption as well as compression of CO2 for efficient storage and controlled delivery to the Sabatier. The first compressor design tested was a mechanical two-stage, reciprocating piston compressor design with three in-line cylinders, which was developed by Southwest Research Institute. There are two first stage pistons and one second stage piston. The compressor is an oil-free design so that no oil contamination is introduced to the downstream Sabatier reactor. A 2-micron filter on the inlet suction line traps any dust particles generated by the 4BMS beds. The compressor is cooled with 65°F chilled water representative of the medium temperature loop (MTL) on ISS. At median pressures of 4 psia suction and 70 psia discharge, the compressor delivers approximately 17.7 scfh (1.9 lb/hr) of CO2.

To reduce compressor run time, the operating rules in Table 1 were established and programmed into the integrated control system. P_{ACCUM} is the compressor discharge or accumulator pressure while $P_{SUCTION}$ is the compressor suction or 4BMS desorbing bed pressure. These rules set the pressure limits for compressor activation and deactivation. For example, when the accumulator is almost full, at 110 psia, the compressor will not activate until the bed pressure exceeds 7.5 psia. These operating rules were developed with the goal of minimizing the compressor operating time, minimizing compressor power consumption and preventing starvation of the Sabatier. Starvation is defined as any time when hydrogen is produced by the OGA, but no CO2 is available for reaction. The performance goals are achieved by limiting the compressor operation to periods when CO2 is plentiful or the pressure rise is low. These operating rules were established during the model development period (described later) and were verified during this test activity. The compressor rules successfully minimize Sabatier starvation.

Table 1 – Compressor Operating Rules

Compressor Transition	Transition Conditions		
	P_{ACCUM} (psia)		$P_{SUCTION}$ (psia)
Standby to Operate	>=100 AND <120	AND	> 7.5
	>25 AND <100	AND	> P_{ACCUM}/58 + 3.6
	<=25	AND	> 1.0
Operate to Standby	> 40	AND	< P_{ACCUM}/58 + 1.5
	<= 40	AND	< 0.5
	>130		NA

2.1.2.2 Accumulator

Due to the chromatographic nature of CO2 desorption from molecular sieves resulting in short duration 'waves' of CO2 flow, and the Sabatier requirement for constant inlet CO2 flow, a buffering capacity is needed to integrate a 4BMS and a Sabatier when using a mechanical compressor. This is accomplished with a 0.73 ft3 accumulator. Due to space limitations within the OGA rack where the CRA hardware would be located on orbit, the total accumulator volume is achieved by ganging several small vessels together. The accumulators used for this test matched those being installed in the OGS rack.

2.1.2.3 Mechanical Compressor / Accumulator Integration Characteristics

Since the mechanical compressor has no storage capacity, an accumulator is required to buffer the short duration, high rate production of CO2 from the CDRA into the long duration, low flow rate consumption of the Sabatier. The initial sizing of the accumulator was to be one cubic foot. This resulted in an ultimate pressure of 90 psia needed to store adequate CO2 to prevent starvation. This pressure level is under the 100 psia threshold that requires additional analysis on pressure vessels. Due to the space limitations in the OGS rack, the maximum volume accumulator that could be packaged was 0.73 ft3. This results in a need for 120 psia storage pressure to prevent starvation.

The CDRA desorbs carbon dioxide from the molecular sieve first, followed by a wave of water. Water vapor in the mechanical compressor could pose problems if condensation occurs in either the compressor or the accumulator tank. A series of tests were conducted to analyze the desorption flow from the CDRA for the concentration of water in the carbon dioxide. The details of this test series are given in section 2.2.2.5. The results indicated that there is not enough water vapor desorbed by the CDRA during the normal desorption cycle to cause condensation in the compressor at pressures up to 120 psia.

2.1.3 Temperature Swing Adsorption Compressor (TSAC)

2.1.3.1 TSAC Hardware Description

The TSAC is a solid-state device that compresses CO_2 using a temperature swing adsorption process on a CO_2 selective molecular sieve. The TSAC combines the functions of a compressor and accumulator in one device.

2.1.3.1.1 Operating principle

Fundamental operating principles and designs of adsorption compressors have been applied in adsorption refrigeration cycles and heat pumps. Similar to the heat pumps, the TSAC operates based on thermal-swing adsorption compression.
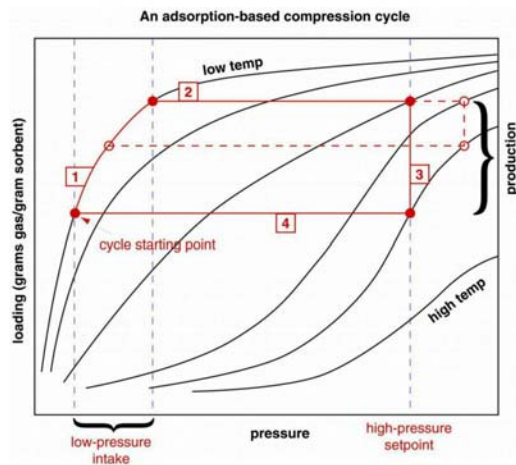
Figure 4. Work cycle of the TSAC

The typical work cycle of the TSAC is shown in **Figure 4**. The cycle includes four steps. [Ref. 1]

STEP1: Adsorption of the gas (or gas component from a gas mixture) of interest at a low pressure and temperature. Adsorption is an exothermic process. Heat of adsorption is removed during this step by cooling the sorbent bed.

STEP 2: Compression of the adsorbed gas by heating the sorbent. The bed volume is isolated during this step. The set point pressure of the process determines the temperature limit. The loading of the gas on the sorbent is reduced during heating, raising the pressure in the bed.

STEP 3: Release of the compressed gas at the desired flow rate and pressure as required by the processor downstream. Heat must be applied to maintain production as the sorbent is depleted of the adsorbed gas.

STEP 4: Decompression of the gas is achieved by cooling the sorbent. The bed volume is again isolated during this step. Temperature is reduced and gas pressure declines to the initial point in the work cycle.

2.1.3.1.2 Process Description

The process flow diagram for the air-cooled TSAC is shown in **Figure 5**. To obtain continuous operation, two identical adsorption chambers (beds) are used.
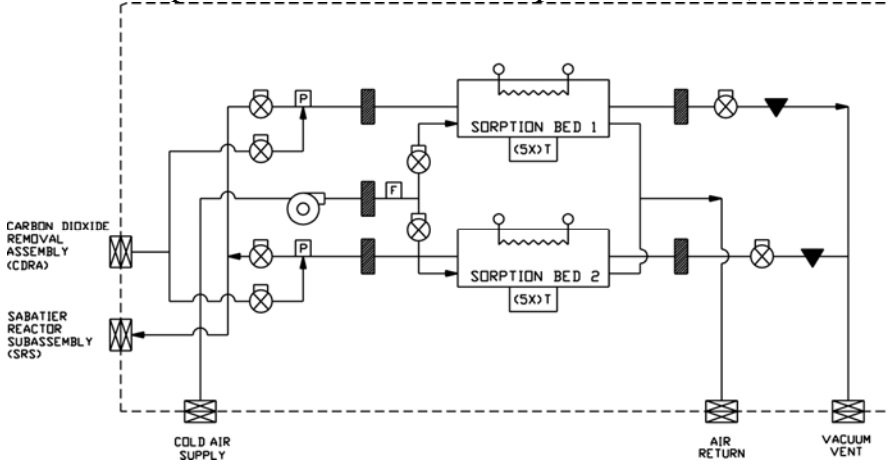
Figure 5 **- Flow diagram of the air-cooled TSAC**

The basic function of the TSAC is to remove the carbon dioxide from the CDRA at a pressure varying roughly from vacuum to 12 psia and deliver the gas to the Sabatier reactor at 21 psia. The carbon dioxide removal assembly (CDRA) includes two CO_2 adsorption beds for removing the carbon dioxide vapor from the cabin air. Like the TSAC, these beds function cyclically to switch between their adsorption and desorption processes to ensure a continuous operation. The TSAC must be synchronized with the CDRA's operation cycle to maintain complete regeneration of the CDRA beds and to supply compressed CO_2 to the Sabatier reactor. The synchronization schedule for the 4BMS and the TSAC is shown in Table 2.

Table 2 – TSAC and 4BMS Synchronization Table

		Half Cycle 1			Half Cycle 2	
Time (min)	0 10 134 144			154 278 288		
4BMS Bed A	Adsorb CO2 from Cabin Air			Air-Save	Desorb to TSAC A	Desorb to space
TSAC Bed A	Produce CO2			Cool	Adsorb	Compress
4BMS Bed B	Air Save	Desorb to TSAC B	Desorb to space	Adsorb CO2 from Cabin Air		
TSAC Bed B	Cool	Adsorb	Compress	Produce CO2		
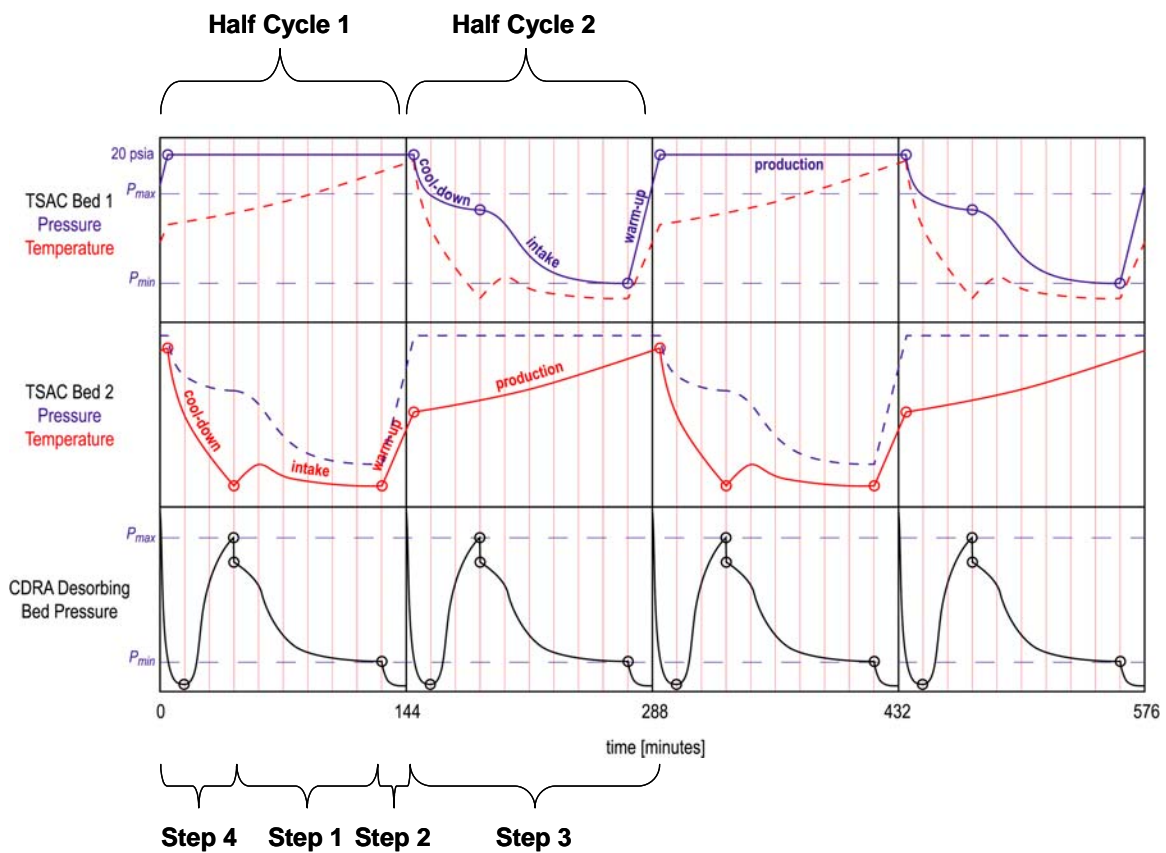
Figure 6 – TSAC and 4BMS beds temperature and pressure profiles.

The correspondence for TSAC Bed 2 between Figure 6 and Figure 4 is as follows: Step 4, cooling/decompression in preparation for the CO2 intake, occurs from 0 to 10 minutes. Step 1 where the TSAC adsorbs CO2 from the 4BMS occurs from 20 to 134 minutes. Step 2, compression in preparation for the production step runs from 134 minutes to 144 minutes. Finally, Step 3, the production step, runs from 144 minutes to 288 minutes. Referring to the 4BMS desorbing bed in Figure 6, the segments are as follows: From 0 to 10 minutes is segment 1, when the desorbing bed is being evacuated to cabin via the air save pump and the primary heater is energized. Segment 2 is from 10 to 134 minutes; here primary and secondary heaters are energized. The bed is isolated for the first ten minutes of segment 2 to allow cooling of the TSAC bed. For the remainder of the segment, it is desorbing to the TSAC. Finally, during segment 3, the bed communicates with space vacuum for more complete desorption at low pressure.

2.1.3.1.3   TSAC Development History

13

Development of the TSA CO2 compressor at NASA ARC was originally started under the Mars In-Situ Resource Utilization (ISRU) program. An Engineering prototype of a CO2 compressor was developed and tested at NASA ARC under the payload proposal PROMISE, which was intended to fly in the 2005 Mars Surveyor Lander. The CO2 compressor prototype was designed to extract and separate atmospheric gases from the Mars environment to produce buffer gases and pure, compressed CO2 for rocket propellant production. The CO2 compressor operates based on the TSA technology to separate, compress and produce CO2 at a specified rate. The concept of a CO2 compressor for closing the air loop of an ECLS system was spun-off from the Mars CO2 compressor design. Three different TSAC compressors were sequentially developed during this program with process and equipment improvements implemented in each successive build.

2.1.3.1.4   Water Cooled TSAC

The first compressor developed utilized water as the cooling medium. This compressor was designed with a concept of using three sorbent beds to cyclically adsorb and desorb, thus providing a constant sink for the 4BMS to exhaust to, and also a constant source of CO2 for the Sabatier. These beds were synchronized to the 90 minute Sabatier cycle. A single prototype bed of this configuration was fabricated and tested at NASA Ames Research Center in August 2000.

The operation of each bed is scheduled such that when one bed is available for adsorption of CO2 from CDRA, another is ready to produce CO2 for the CRA, and the third bed is in a standby or a cooling mode. A flow diagram for the proposed three bed processor is shown in Figure 7.

The complete cycle of this TSAC is 270 minutes, with each desorption cycle taking 90 minutes. Each TSAC bed is designed to accommodate the full load of CO2 required by the CRA, which in this example is one-half the CO2 available from the CDRA.
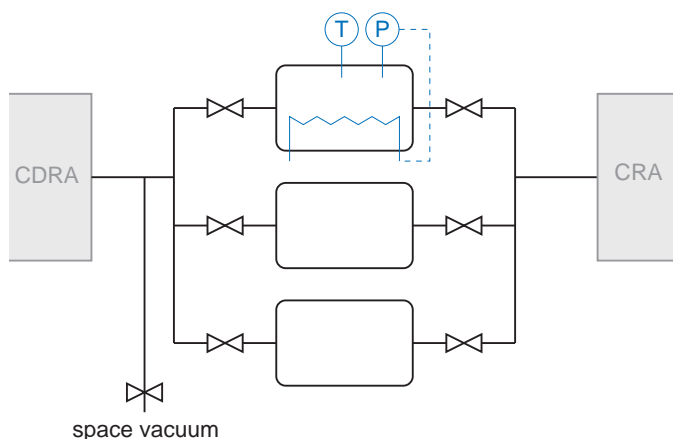
Figure 7 - Flow diagram of a three-bed TSAC device. Internal pressure is controlled through a feedback loop to the heater. Inert gas vent tubes are not shown.

The baseline design for the TSAC uses a zeolite adsorbent and a working cycle that is shown in Figure 8. The intake cycle begins at a pressure of about 2.7 kPa (0.4 psi) and ends at 27 kPa (3.9 psi). The spacecraft coolant loop is used to maintain the temperature near 30°C during this step. During pressurization, the coolant flow is shut off and the sorbent is heated to approximately 60°C; production occurs at a pressure of 100 kPa (14.5 psi) and temperatures rising to about 90°C. For depressurization, the coolant is again allowed to flow through the device to bring the temperature back to about 30°C.
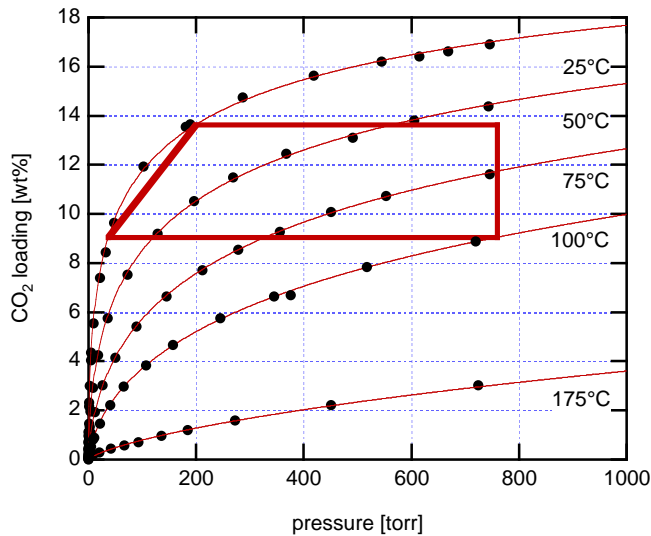
Figure 8 - Adsorption isotherms and compression cycle.

This cycle provides a working capacity of about 4.6 wt%. From it, a three-bed TSAC was sized to meet CDRA and CRA interface requirements for vacuum, CO2 pressure, and buffering capacity.
A summary of the TSAC requirements is shown in Table 3.

Table 3 - Production rates and resource requirements of TSAC sized for two kilograms CO_2 production per day at 100 kPa.

Resource	Requirement
Production level	2 kg CO_2 / day
Production pressure	100 kPa
Total mass	22.5 kg
Average power	150 W
Peak power	300 W
Average heat rejection	150 W
Total volume	25 L

2.1.3.1.5   Liquid Cooled TSAC

The next development in the TSAC design was a change of the cooling medium from water to a heat transfer fluid known as Paratherm. This heat transfer fluid allowed the bed operating temperature to increase thus increasing the working capacity. This comes at the expense of added equipment to handle the heat transfer fluid, namely a pump, heat exchanger and reservoir. The operating schedule was also modified to reduce the number of beds to two. Rather than synchronizing with the Sabatier, the beds were synchronized with the 4BMS beds. One TSAC bed was sized to absorb the entire capacity of one 4BMS bed.

The two-bed, liquid-cooled, TSAC consists of two identical sorption beds equipped with a heater in the middle and cooling coils brazed on the outer surface of the canister. The compressor canisters also contain multiple temperature sensors and pressure sensors. Pictures of the compressor canister with heating and cooling assemblies are shown in Figure 9.

Figure 9 - **Heating and cooling assemblies of the TSAC**

A flow diagram for the 2-bed, liquid-cooled TSAC is shown in Figure 10.
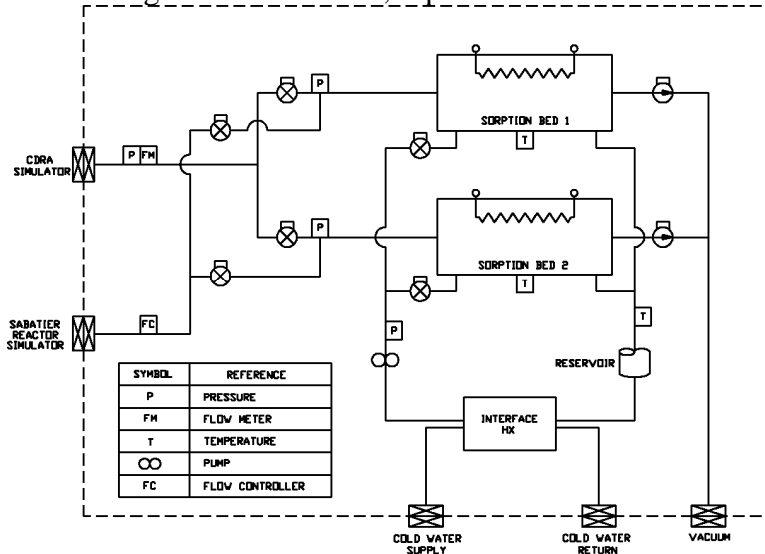
Figure 10 - **Schematic of 2-bed, liquid-cooled TSAC**

The compressor beds are conservatively designed for handling about 2 kg of CO2 per day, which is half of the requirement of ISS. Similar to the CDRA, the TSAC beds operate in a cyclical fashion. While one bed produces or desorbs CO2 for the Sabatier reactor, the other bed continues to adsorb or extract CO2 from the desorbing CDRA bed.

2.1.3.1.6 Air Cooled TSAC

The most recent TSAC design iteration was the development of an air cooled bed. Air is a safe and practical cooling medium in a spacecraft environment and eliminates all of the extra hardware mentioned previously that was needed for the liquid cooled bed. The disadvantage of the air cooled bed is that the bed itself is larger to accommodate the air cooling passages. However, the bed temperature can be operated up to 250 degrees C yielding higher working capacity.

The air-cooled TSAC design consists of multiple air slots and heaters spaced within the sorbent bed. A schematic of the TSAC design structure is shown in Figure 3.
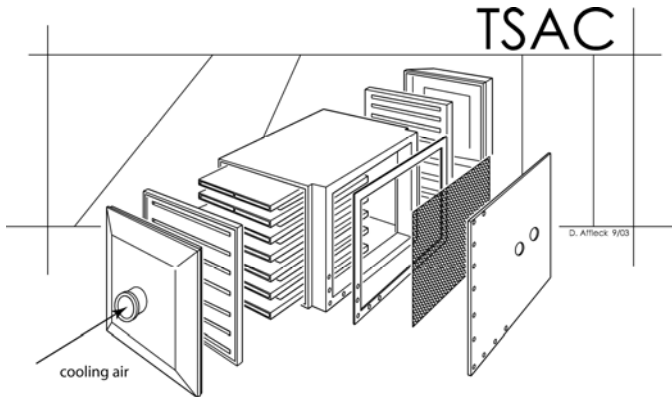
Figure 11. **Schematic of the air-cooled TSAC prototype**

The air-cooled TSAC prototype was designed to produce compressed CO_2 at a rate of 8.8 lb/day at a CO_2 loading pressure of about 4psia. The loading pressure of 4psia for TSAC is the minimum downstream pressure required for CDRA to regenerate completely within the scheduled cycle time (144 minutes). This is only a conservative estimate, derived from the characterization data of the CDRA sorbent material.

The key objective that guided the design and material selection for the TSAC was to minimize the heat loss from the compressor to the surroundings and maximize the heat transfer from the heated sorbent core to the cooling surface.
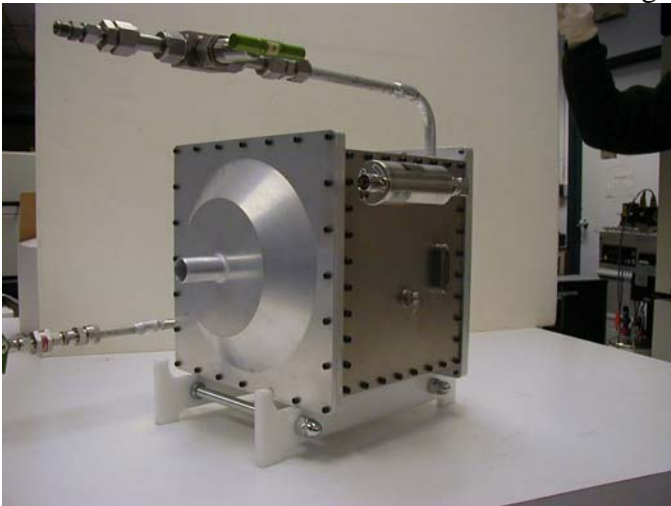
Figure 12**. Air-cooled TSAC prototype**

The mechanical design of the TSAC was facilitated with a thermal model to finalize the size, material selection and coolant flow rate.

2.1.3.2 TSAC Integration Characteristics

In contrast to the mechanical compressor, the TSAC compresses and stores the carbon dioxide at the same time, eliminating the need for an accumulator. The CO2 is delivered to the Sabatier at a fixed pressure, which is controlled by regulating the temperature of the desorbing bed. This fixed delivery pressure eases the requirements on the Sabatier for CO2 flow control; i.e. the CO2 modulating valve would have only a 4:1 turndown requirement rather than 4:1 on flow and 6:1 on pressure.

The 4BMS produces a high purity CO_2 stream, but it will be contaminated by a small amount of nitrogen and oxygen. Because the TSAC is not a flow-through system, there is a potential for a buildup of non-adsorbing gases in the compressor. These could form a barrier to CO_2 adsorption during the intake step. This situation is prevented by periodically venting this small amount of non-adsorbing gas to space vacuum via tubing between the TSAC beds and the CO_2 vent line.

2.1.4 Sabatier Carbon Dioxide Reduction Subassembly

2.1.4.1 Sabatier Hardware Description

The Sabatier Engineering Development Unit (EDU), developed by Hamilton Sundstrand, was designed to simulate the proposed flight configuration of the Carbon Dioxide Reduction Assembly (CRA) for ISS. As described previously, the CRA is an integral part of a closed loop air revitalization system and makes use of waste products, CO_2 from a 4BMS/CDRA and H_2 from the OGA, which would otherwise be vented. The CO_2 and H_2 combine to produce methane (CH_4) and water (H_2O) as shown in the reaction below. The water and methane may then be used for other processes. In the case of ISS, the water would be sent to the wastewater bus and processed to potable quality for use by the crew. The methane would be vented overboard as a waste product. In future exploration missions, the waste methane could be used as a fuel source, or further reduced to carbon and hydrogen.

Equation 1

$$CO_2 + 4\,H_2 \quad \Leftrightarrow \quad CH_4 + 2\,H_2O$$
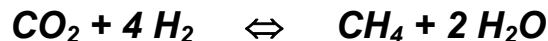
The Sabatier EDU consists of a Sabatier methanation reactor, a condensing heat exchanger, a phase separator and accompanying valves and sensors necessary for safe operation. The Sabatier EDU was modified substantially after being tested with the mechanical compressor and before being tested with the TSAC. The overall function of the system was not changed, but the individual component fidelity was improved. The

most current Sabatier EDU schematic is shown here in Figure 13. A description of the differences between the two test series is given in the appendix.
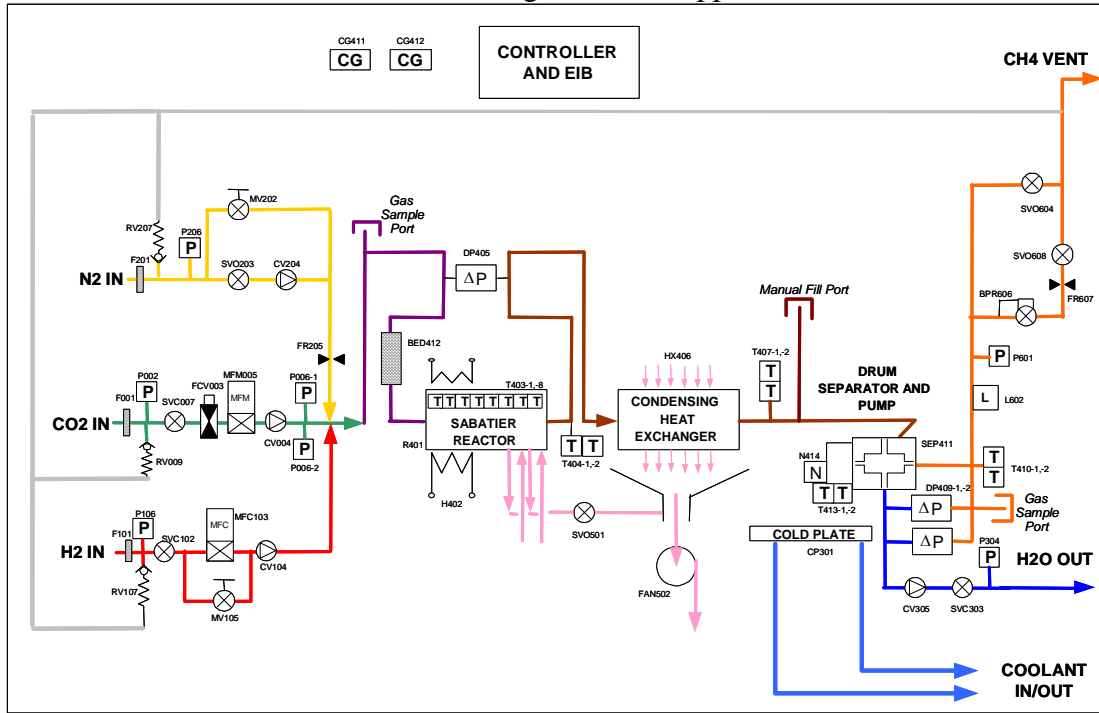
Figure 13 – Sabatier Engineering Development Unit Schematic

The Sabatier EDU has two primary modes of operation: process and standby. In process mode, inlet gasses flow through the system and methane and water are produced. In standby mode, supply gasses are isolated, coolant air is stopped, the unit is evacuated to below 1 psia, and the system is isolated. Reactor heaters cycle as required maintaining a reactor temperature of approximately 300ºF. The Sabatier EDU is operated with excess CO2 (approximately 14%) to ensure that all hydrogen is reacted. The nominal molar ratio (MR) is 3.5 to 1, H2 to CO2. A hydrogen cylinder and a flow controller were used to simulate the delivery of hydrogen from an OGA. An operator sets the hydrogen flow rate, and the Sabatier system controller calculates the required carbon dioxide and controls the flow to achieve the desired molar ratio.

The inlet CO2 and H2 gasses react in the catalytic reactor to produce methane and water vapor. This is an exothermic reaction that is self limiting at about 1000 F. The aft end of the reactor is air cooled to reduce the product exit temperature in order to achieve higher reactant conversion. Water vapor in the product stream is condensed in an air-cooled heat exchanger. The methane gas and liquid water are separated in a rotary drum phase separator. The rotation of the drum imposes an artificial gravity field that efficiently separates the two phases. When the delta pressure in the phase separator indicates a high level of liquid in the drum, the system controller increases the separator speed and the separator pumps the accumulated water to a pressurized water storage tank. The methane and excess, un-reacted gasses are vented to a facility combustible gas vent through a

combustible gas compatible vacuum system. The Sabatier system is operated at sub-ambient pressures, as planned for the flight design, to ensure that combustible gasses do not leak out to the surrounding atmosphere.

2.1.4.2 Sabatier Hardware Changes between Tests

The first series of fully integrated tests included the four bed molecular sieve, the mechanical compressor and accumulator, and the Sabatier engineering development unit. The Sabatier EDU, in its original configuration, matched the schematic shown here in Figure 14. Some of the more prominent features that were upgraded between the first and second test series are listed below:

- Addition of the rotary drum separator and pump with two differential pressure sensors for level monitoring. The original Sabatier used a tank as a 1-g separator and a small gear pump to transfer the water to the water storage device when the separator tank was full. The rotary separator included in the upgrade is of flight-like quality and is the design basis that would be used for a flight installation of Sabatier technology.
- Addition of a liquid sensor in the methane vent line. The original Sabatier had no liquid sensor. This sensor was included as a means to gather operational test data on the liquid sensor design.
- Incorporation of a multi-point thermocouple in the reactor bed for data collection. The original Sabatier had only two temperature sensors that were used for heater control and over-temperature protection. A flight system would rely on only the two or three sensors in the hot end of the bed. The Sabatier EDU was upgraded to include a multi-point thermocouple in order to gather additional reactor performance data during operation, which will lead to improved reactor designs in the future.
- Addition of a flight like modulating valve for CO2 control. The original Sabatier EDU used a commercial modulating valve with a stepper motor to control the CO2 flow. While this technology performed adequately, it could not be considered flight-like. The EDU was upgraded with a flight-like modulating valve that uses a variable solenoid to position the valve stem to control the flow. This valve was designed and manufactured with flight requirements in mind, including redundant seals and manifold mounting.
- Upgrade of the back pressure regulator to a flight-like design. Again, the original back pressure regulator was a commercial-off-the-shelf design. The new regulator was designed and manufactured to meet flight requirements including a welded diaphragm, manifold mounting and double seals.
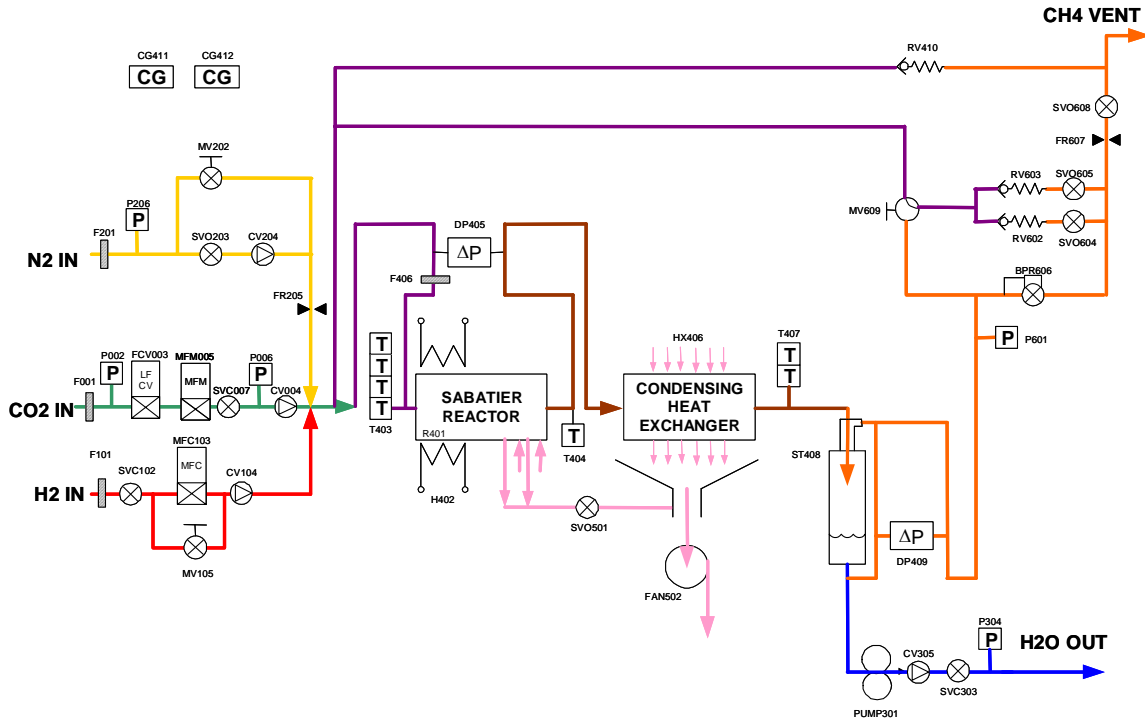
Figure 14 – Original Sabatier EDU Hardware Configuration

2.1.4.3 Sabatier Integration Characteristics

The Oxygen Generation Assembly delivers its hydrogen byproduct to the Sabatier. The OGA has two hydrogen valves, one that goes directly to the vacuum vent of the ISS and the other that interfaces directly with the Sabatier. The control software includes a handshake between the OGA and CRA, which requires that both systems have to be ready to interact before the valve to the Sabatier is opened. This control software was not part of this test series, but has been independently verified. The Sabatier requires carbon dioxide pressurized at 18 psia or higher in order to operate. If the CO2 pressure available at the interface is too low, or the OGA is not ready, the Sabatier system will transition to Standby mode.

The Sabatier CRA is designed to operate below ambient pressure. This prevents leakage of flammable gas to the cabin atmosphere after two failures. In order to test the system, a vacuum must be drawn on the methane vent line. This vacuum source must be compatible with methane and hydrogen and pose no explosion hazard. A water ejector setup was used in this integrated testing to simulate the vacuum source. The water ejector could only achieve about 4 psia under maximum flowing conditions; however, this did not seem to affect the system operating parameters elsewhere in the Sabatier system.

2.1.5 Support Hardware Configuration

2.1.5.1 4-BMS Inlet ppCO2 Control – Metabolic Load Simulation

The metabolic load contribution to the integrated tests was created by injecting CO2 according to a mass flow schedule into the air stream at the inlet to the 4-bed molecular sieve. Some of the testing was done with constant CO2 concentration, while other tests were designed to mimic the time profile predicted for a volume with crew performing various activities.

During testing, CO2 was injected into the 4BMS inlet per the test matrices in the two following tables: Table 4 lists the conditions used for the mechanical compressor test and Table 5 lists the conditions used for the TSAC test. Test conditions ranged from a 2.3-person crew to an 8.3 person crew (CO2 partial pressure of 1.5 to 5.3 mmHg respectively).

Table 4 - Test conditions for mechanical compressor test.

TP	4BMS CO2 Inlet Concentration (mmHg)	EP total	Vozdukh Operation (on=25% CO2 load)	Russian Elecktron Load (EP)	US H2 Feed Rate (slpm)*	H2/CO2 Molar Ratio	CO2 Feed Rate (slpm)	Day/night Cyclic or Continuous	Min. Number HC Required	Comp Speed (rpm)	Modeling CDRA Location	Day/night Duration (min)
1**	1.5	3	off	0	2.461	3.5	0.703	cont	3	1000	-	53/37
2**	1.5	3	off	0	4.179	3.5	1.194	day/night	4	1000	-	53/37
3**	1.5	3	off	0	4.179	3.5	1.194	day/night	4	800	-	53/37
4	3.5	7.25	on	2	4.289	3.5	1.225	continuous	3	1000	-	53/37
5	3.5	7.25	on	2	7.282	3.5	2.081	day/night	4	1000	-	53/37
6	3.5	7.25	on	2	7.282	3.5	2.081	day/night	4	800	-	53/37
8	met profile	6	off	0	8.724	3.5	2.493	day/night	50 hrs	1000	Node3	53/37
10	met profile	7.25	on	2	7.282	3.5	2.081	day/night	50 hrs	1000	Node 3	53/37
11	met profile	7.25	on	2	7.282	3.5	2.081	day/night	48 hrs	1000	Lab	53/37
*includes air leakage compensation of 0.24 lb/day air ** tests repeated after air leakage detected												

Table 5 – Test conditions for the TSAC test.

Test Point Description	Test Point #	4BMS CO2 Loading kg/day (lb/day)	4BMS Inlet CO2 Conc. MmHg (%)	Equiv. Pers. EP	TSAC Loading Pressure kPa (psia)	TSAC Production Pressure kPa (psia)	US H2 Feed Rate slpm (lb/hr)	H2/CO2 Molar Ratio	Sabatier CO2 Feed Rate slpm (lb/hr)
Integrated 4BMS/TSAC baseline test	1	8 (17.6)	--	8	27.6 (4)	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading	2	5 (11)	--	5	27.6 (4)	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading	3	4 (8.8)	--	4	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading	4	4 (8.8)	--	4	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading	5	3 (6.6)	--	3	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading pressure	6	5 (11)	--	5	41.4 (6)	133 (19.3)	--	--	--
Integrated 4BMS/ TSAC/ Sabatier at TSAC baseline conditions for TSAC health check	7	--	5.3 (0.7%)	8.3	--	124 (18)	6.766 (0.0798)	3.5	1.933 (0.502)
Integrated 4BMS/ TSAC/ Sabatier for comparison to mechanical compressor test point #2	8	--	3.5 (0.46%)	5.46	--	124 (18)	4.459 (0.053)	3.5	1.274 (0.331)
Integrated 4BMS/ TSAC/ Sabatier for comparison to mechanical compressor test point #3	9	--	1.5 (0.2%)	2.34	--	124 (18)	1.925 (0.023)	3.5	0.550 (0.143)
Integrated 4BMS/ TSAC/ Sabatier Lunar night scenario, non-optimal TSAC shutdown/ startup	10	--	2.52 (0.33%)	4	--	124 (18)	3.273 (0.037)	3.5	0.935 (0.243)
Integrated 4BMS/ TSAC/ Sabatier EVA full crew departure scenario, CO2 regenerated to cabin	11	--	Per profile	4	--	124 (18)	3.273 (0.039)	3.5	0.935 (0.243)

The test points in Table 4 reflect the test conditions used for the mechanical compressor testing. During cyclic operation (all test points except 1 and 3), the system mimics ISS protocols for power savings during orbital night. During the "night" cycle the 4BMS desorbing bed heaters are turned off and the OGA goes to standby, stopping H_2 production and signaling the Sabatier to transition into standby as well.

For test points 1 through 6, the CO2 load was constant and was set at the average metabolic load generation rate for the number of crew listed in the table. For test points 8, 10, and 11 in Table 4, 4BMS inlet CO2 levels were varied to simulate variations in ISS atmosphere, which result from changes in crew locations and activities. These transient

cabin CO2 levels, or metabolic profiles, were generated using an integrated model developed at NASA JSC. The model allows for atmosphere mixing and air revitalization hardware analysis of multiple integrated modules as configured on ISS [3] or as a potential Lunar base. Crewmember location and metabolic activity levels were based on the location of sleep stations, work stations, galley, and exercise equipment. The CO2 metabolic generation rate was defined by NASA document SSP41000 [4].

The model provided transient cabin CO2 levels, or metabolic profiles, for the United States Operating Segment (USOS) modules that will contain carbon dioxide removal units (Lab and Node 3) when ISS assembly is complete. Testing was conducted to evaluate integrated performance for the two different ISS CDRA locations. A generalized representation of the model is shown below.
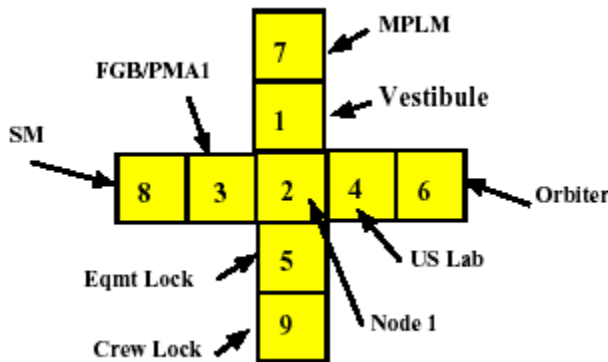
Figure 15 - Nodal representation of ISS for CO2 concentration prediction.

Figure 13 is an example of a predicted crew metabolic profile including sleep, waking and exercising periods. This graph represents the gross overall CO2 load generated within the ISS for the 6 crew members. Figure 14 illustrates the predicted atmosphere concentration resulting from the crew activities and the calculated injection flow rate needed to simulate the mission profile.

Metabolic Profiles - Max Crew Size
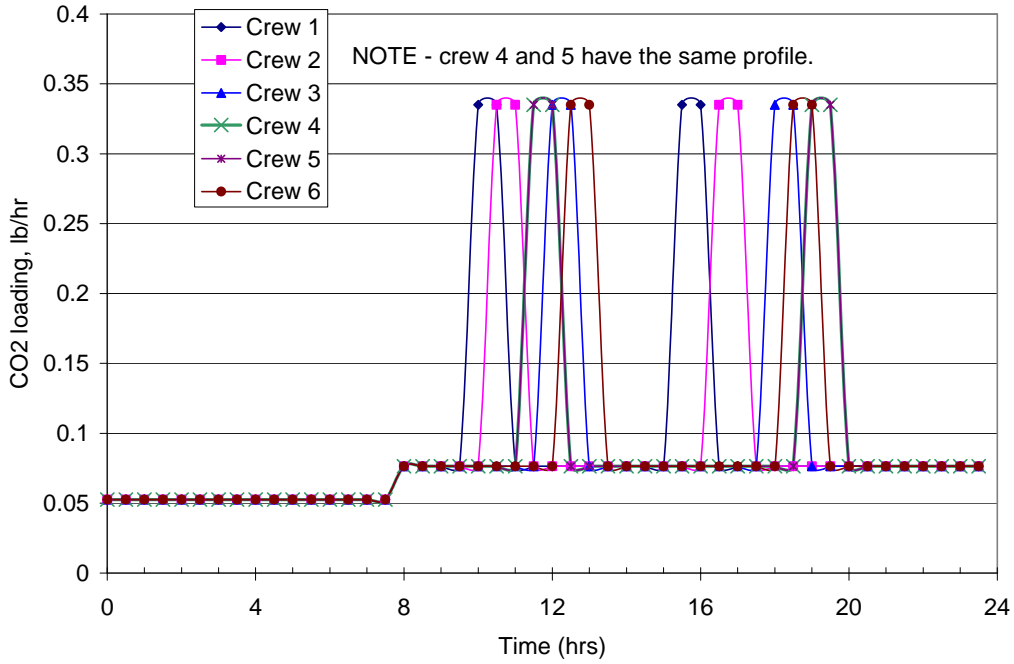
Figure 16 - Example metabolic load profile

CO2 Injection Rate to Simulate Metabolic Profile
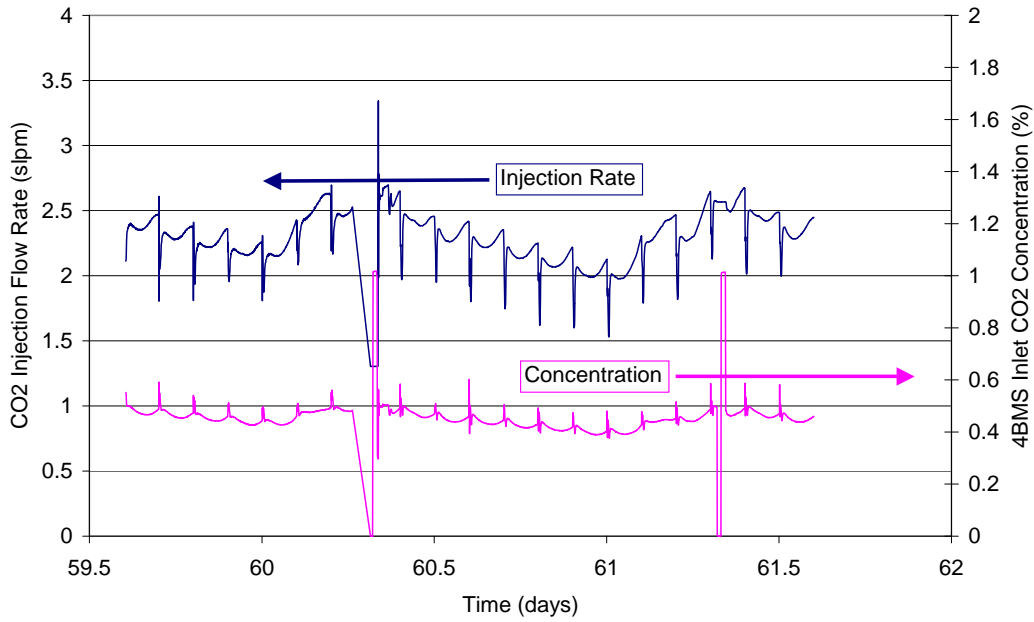
Figure 17 - Example of Metabolic Load Profile CO2 Injection Rate

The data in Table 5 reflects the test conditions used for the TSAC testing. For the TSAC testing, the system was configured to be always in "daylight", in other words, there was no nighttime disabling of heaters and idling of the hydrogen generation. These conditions were set to simulate a Lunar habitat. For test points 10 and 11, 4BMS inlet CO_2 levels were varied to simulate variations in a lunar habitat atmosphere based on crew locations and activities. The model used for ISS CO_2 concentrations was modified to represent a Lunar habitat. Figure 16 shows the resulting CO_2 concentration profile for the simulation of the Lunar EVA activity.

TSAC CO2 Injection Rate
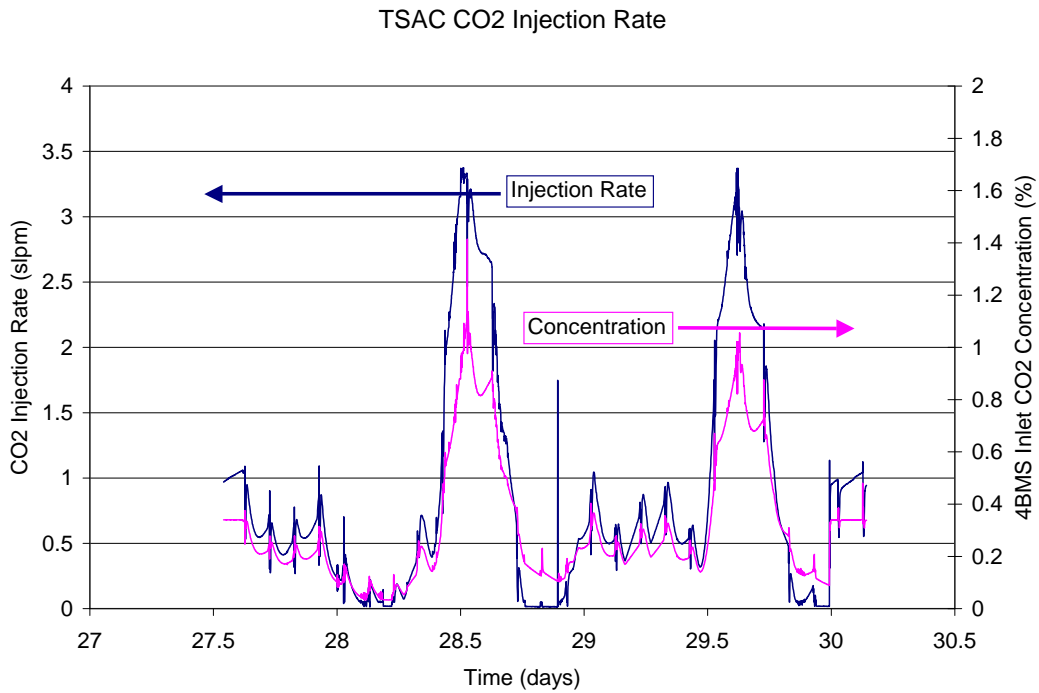
Figure 18 - CO2 Concentration for Siumulated Lunar EVA Profile

2.1.5.2 4BMS venting

When a 4BMS bed is desorbing, the compressor operation is governed by a set of operating rules based on the suction and discharge pressure. These rules have been established to optimize the compressor operation, including minimizing compressor power and compressor operating time without causing starvation of the Sabatier. These compressor rules allow the compressor to turn off while the 4BMS bed is still desorbing. Within the 4BMS, there are check valves that are closed when the bed is under vacuum and open when the bed is flowing cabin air. These check valves will crack open and leak CO2 back to the cabin atmosphere if the bed pressure gets too high. To prevent the check valves from opening, the standoff vacuum valve is used to vent the bed pressure when the compressor is not operating. The rules governing the operation of this valve are shown in Table 6.

The desorbing sorbent bed pressure must remain low enough to maintain closing force on the flapper-style check valve. (Refer back to Figure 2 in Section 2.1.1) This pressure was set at 8 psia during the mechanical compressor testing and 12 psia during the TSAC testing. During 4BMS venting, the valve V2, shown in Figure 17 below, functions as the vent CO_2 valve listed in the table.

During high metabolic load cases, the accumulator often becomes full and the vent valve has to open to relieve the pressure in the 4BMS desorbing bed. Figure 18 shows how the vent valve is activated multiple times during each 4BMS half cycle. This would cause unnecessary wear on the valve. The actual Space Station implementation of this venting control will open the valve and leave it open until the end of the half cycle. This keeps the number of valve cycles at one actuation per half cycle. More CO2 is vented to vacuum, however, as seen in the chart, when the CO2 loading is high, there is more than enough CO2 available and it is not necessary to capture all of the CO2 from the 4BMS.

Simplified Schematic of Ground Test Hardware
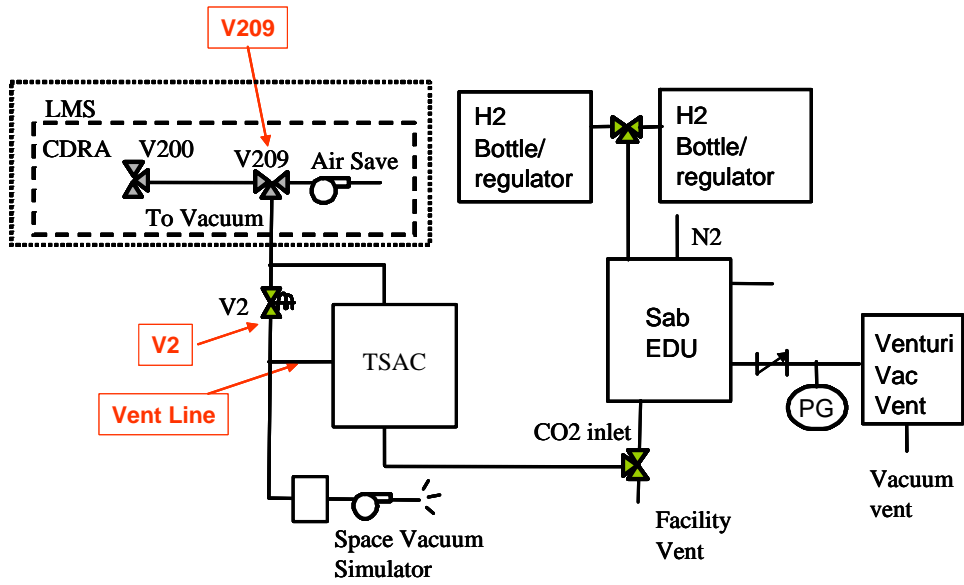
Figure 19 - Integration of ARS Components

Table 6 – Standoff Valve Operating Rules

Time in Cycle (minutes)	Decision Criteria	Vent Valve Command	
		Integrated Test	ISS Implementation
0-10	ALWAYS	CLOSED	CLOSED
10-134	$P_{suction}$ <8 AND Compressor OFF	CLOSED	CLOSED
	$P_{suction}$ < 10 AND Compressor ON	CLOSED	CLOSED
	$P_{suction}$ > 8 AND Compressor OFF	OPEN for 20 sec	OPEN until end of half cycle
	$P_{suction}$ > 10 AND Compressor ON	OPEN for 20 sec	OPEN until end of half cycle
134-144	ALWAYS	OPEN	OPEN

Vent Valve Operation at High CO2 Rates
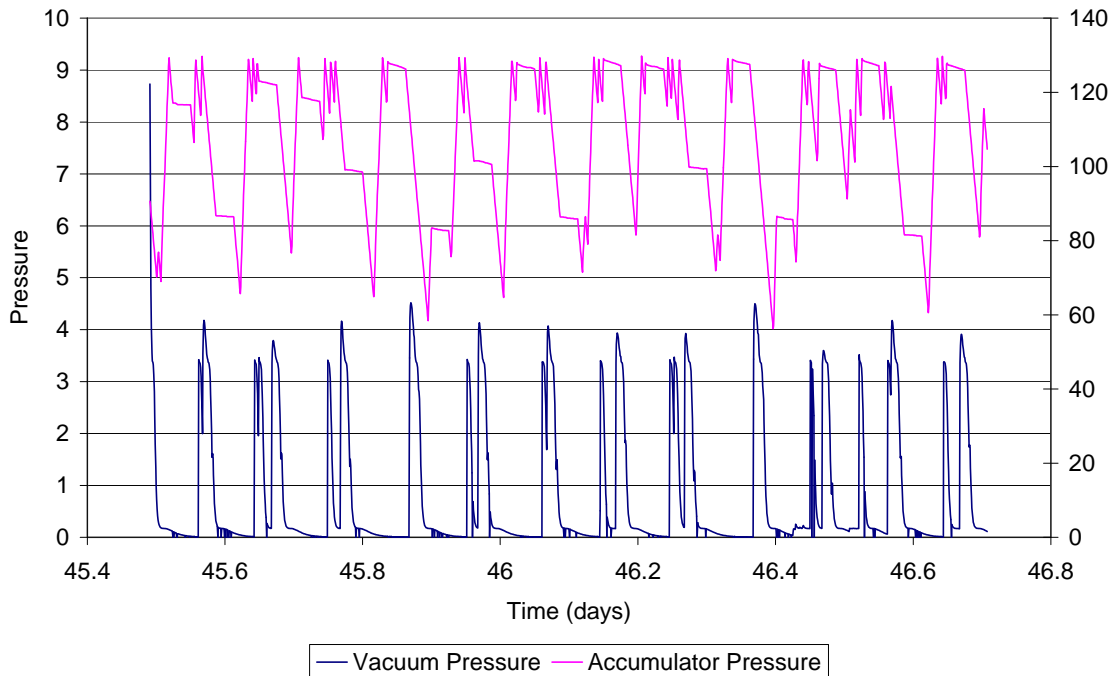
Figure 20 - High CO2 rate requires excessive activation of vent valve.

2.1.5.3 Sampling

Influent CO2 and product Sabatier gasses were sampled at least once per test point and measured for purity. Sabatier product water was also collected once per test point for analysis. Gas samples were taken of the CDRA inlet, Sabatier reactor inlet and reactor outlet. Table 7 lists the test parameters for each sample type. This data is detailed in the results section for each test configuration.

Table 7 - Fluid Composition Analysis

Sample Type	Analysis
Sabatier Inlet Concentrated CO2	CO2. O2. N2 (%)
Sabatier Product Outlet	CO2, CH4, H2, O2, N2 (%)
Sabatier Product Water	Total Carbon, Total Inorganic Carbon, Total Organic Carbon, pH, Conductivity

2.1.5.4 CO2 Moisture Content

Moisture content of the concentrated CO2 from the 4BMS is a concern for the mechanical compressor since the moisture can condense in the chambers of the compressor. Two independent tests were conducted to quantify the amount of moisture in the CO2 from this test equipment.

One test used a low moisture analyzer to measure the quantity of water vapor in the CO2 as it was evolved from the 4BMS desiccant. The instrument is a tunable infrared diode laser differential absorption spectrometer (TILDAS) provided by the NASA Glenn Research Center. A schematic of the moisture measurement test setup is shown in Figure 21. The box labeled "Moisture Measurement" indicates the location where the TILDAS instrument was connected to the system. The TILDAS was used to measure moisture concentration in the CDRA product carbon dioxide during both continuous day and day/night simulated operation.
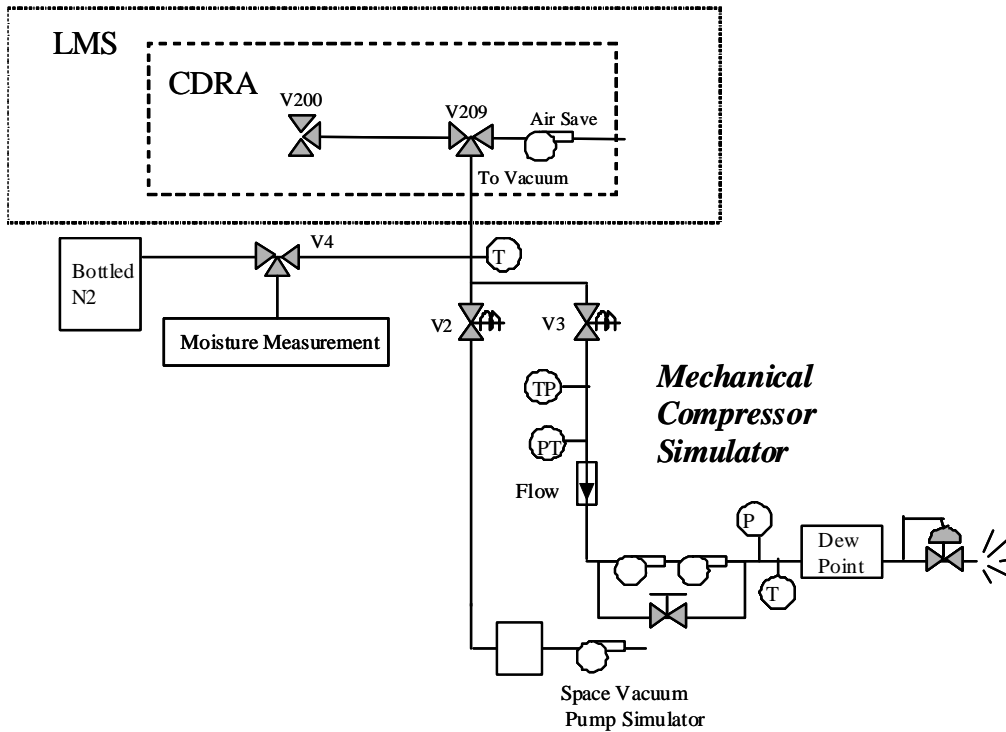
Figure 21 – Test setup of CDRA product CO2 moisture measurement using TILDAS.

The other test involved running the compressor from the desorbing CDRA to various fixed discharge pressures and measuring the resulting dew point. The discharge pressure was set to 20, 47.5, 75, 102.5 and 130 psia during different test points. The compressor on/off operation was still controlled based on the Compressor Operating Rules defined in Table 1 of Section 2.1.3.

2.2 Integrated Test Using the Mechanical Compressor

2.2.1 Overall Test Plan Objectives

The integration tests using the mechanical compressor were designed specifically to determine how the hardware would operate in the Space Station configuration. The Space Station currently has a 4BMS CDRA installed in the Lab Module. An Oxygen Generator was launched July 2006 and activated in July 2007. The OGA is also installed in the Lab Module. The operating conditions of the Space Station were used to develop the test matrix in Table 1.

In addition to the missions operations described below, test parameters were also established as a result of modeling of the systems that was being conducted in parallel to the test program. A FORTRAN program was developed by the NASA Johnson Space Center to simulate the 4BMS, mechanical compressor and accumulator. During the course of testing, the test data was correlated to the model predictions.

2.2.1.1 Test Requirements Based on ISS Implementation

The Sabatier design points detailed in Table 8 define operating conditions that serve as a simple baseline around which the Sabatier was designed to optimize water recovery performance. The Sabatier must be capable of responding to the variability of the full flow regime of both feed gases and continue operating robustly without compromising the life of any components. The interface conditions described next set the boundary conditions for the operation of the different subsystems and were used to define the test conditions.

The following assumptions were used as the basis for the flow rates and settings used in the test points:

Oxygen / Hydrogen Generation Rates

The OGA is required to produce oxygen for the station at a commanded rate between 0.212 and 0.85 lb/hr. The command to the OGA will be from the station level controller that will request 25% to 100% of the maximum power setting. Crew consumption of oxygen is nominally 1.84 lb O_2/crew-day. This translates to 0.23 lb/crew-day of hydrogen that is delivered by the OGA to the Sabatier. Air leakage from the station is also made up by oxygen from the OGA and nitrogen from storage tanks. A nominal leakage rate of 0.24 lb/day of air (0.05 lb/day O_2) was assumed, which translates to an additional 0.0063 lb/day of hydrogen delivered. The nominal crew size expected when the Sabatier is initially installed on station is 3 crew, the max expected is 6 crew plus 1.25 EP worth of animals.

Since the OGA is a high power user, it will likely only operate during the daylight time of the Space Station orbit. At the worst case azimuth, the available operating time is 53 minutes out of a 90 minute period. The daily average hydrogen flow rate is therefore multiplied by 90/53 to arrive at the instantaneous flow rates given in Table 8.

CO2 Generation / Removal

CO_2 generation by the crew is 2.2 lb CO_2/crew-day. CO_2 is desorbed from the 4BMS and is compressed by the compressor into an accumulator. The beds of the TSA compressor act as an accumulator and no external device is necessary. The mechanical compressor stores CO_2 in a tank so that the wave of CO_2 desorbed from the 4BMS over a short time span can be delivered to the Sabatier at a fixed rate over a longer duration. The CO_2 feed rates given in Table 8 are based on the crew size and the operating schedule (continuous or day/night). The day/night flow rates are 90/53 times the continuous rates per crew member. The contribution of CO_2 lost due to station leakage is considered insignificant and not included in the calculations.

The concentration of CO_2 at the inlet of the 4BMS to achieve the desired rate of CO_2 removal was obtained from a Fortran model of the 4BMS. The model and CO_2 inlet control are described in more detail in Section 2.1.5.1. The model predicted the

atmospheric steady state concentration given a specific crew size and the actual operating conditions of the 4BMS. The model did not include adsorption/desorption of CO_2 onto the desiccant beds. The initial prediction of 1.5 mmHg for a crew size of 3 turned out to be low, and the CO_2 removal rate did not match the flow rate of hydrogen available to the Sabatier for the first three test points. These test points were later repeated with a different CO_2 feed concentration.

The graph below shows the CO_2 concentration at the inlet of the 4BMS for one of the metabolic load cases. The concentration is calculated from the predicted crew activity and location coupled with the effectiveness of the 4BMS. The tall spikes in concentration are the result of the daily sensor calibration. The small spikes are due to the valves changing position between adsorbing bed cycles.

Metabolic Profile CO2 Concentration to 4BMS
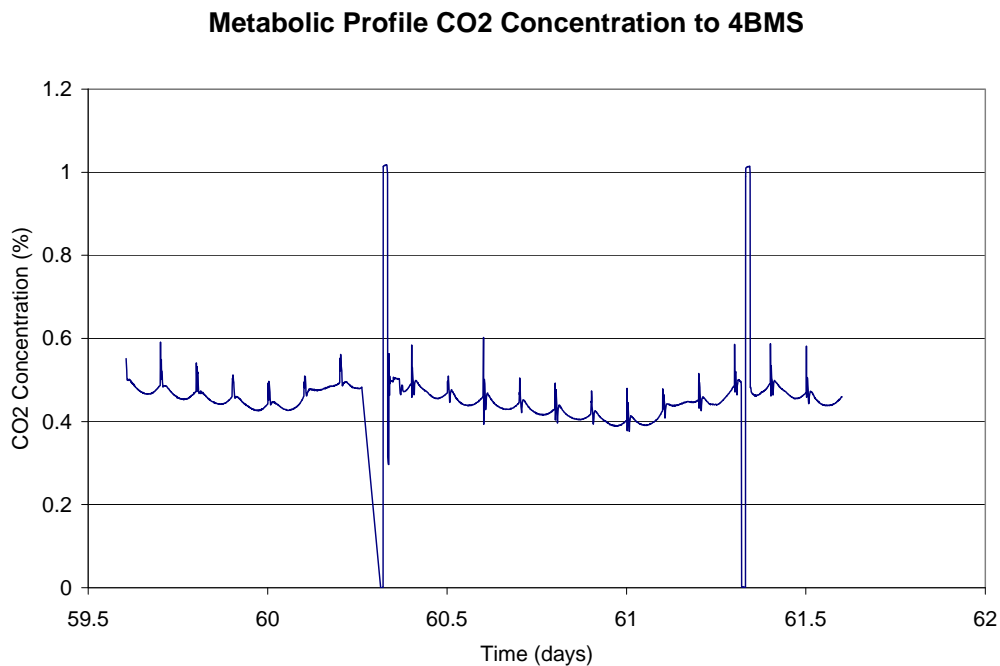
Figure 22 – CO2 inlet concentration fed to 4BMS for metabolic load profile case.

Load Sharing between US and Russian Hardware

Some assumptions had to be made to establish the load sharing of Russian and US life support equipment on the Space Station. Since the Russian and US CO_2 removal devices will be operating from the same mixed atmosphere aboard the Space Station, the split of CO_2 concentrated by each system is a function of each one's removal efficiency and the total amount of CO_2 available. The Russian CO_2 removal system (Vozdukh) specification requires that the CO_2 partial pressure be maintained at 5.3 mmHg with a CO_2 load of 3 EP. This can be considered the worst case performance point as actual Station data indicates that the CO_2 partial pressure with the Vozdukh only operating is between 3.5 and 4.0 mmHg. The Station CDRA performance gives 3.0 mmHg pCO2

34

with a 5.29 EP CO2 load. The following equation is used to calculate the removal split when both systems are operating at a given metabolic load:

$$\text{metabolic load} = \left[\text{flow rate} \times \text{removal rate} \times \text{molar fraction of CO2} \right]_{\textbf{Vozdukh}} + \left[\text{flow rate} \times \text{removal rate} \times \text{molar fraction of CO2} \right]_{\textbf{CDRA}}$$

Solving for the removal fraction yields approximately 25% Vozdukh and 75% CDRA, given the previous minimum Vozdukh performance. At actual performance levels of the Vozdukh, the split is really about 32.5% and 67.5%.

Crew Size

The crew sizes selected for ISS simulation testing include the current 3 person crew, a future planned 6 person crew when the station assembly is completed and a load of 7.25 EP which reflects 6 crew plus animals.

2.2.2 Description of Test Plan Details

2.2.2.1 Integrated Test Schematic

Simplified Schematic of ISS Life Support Hardware
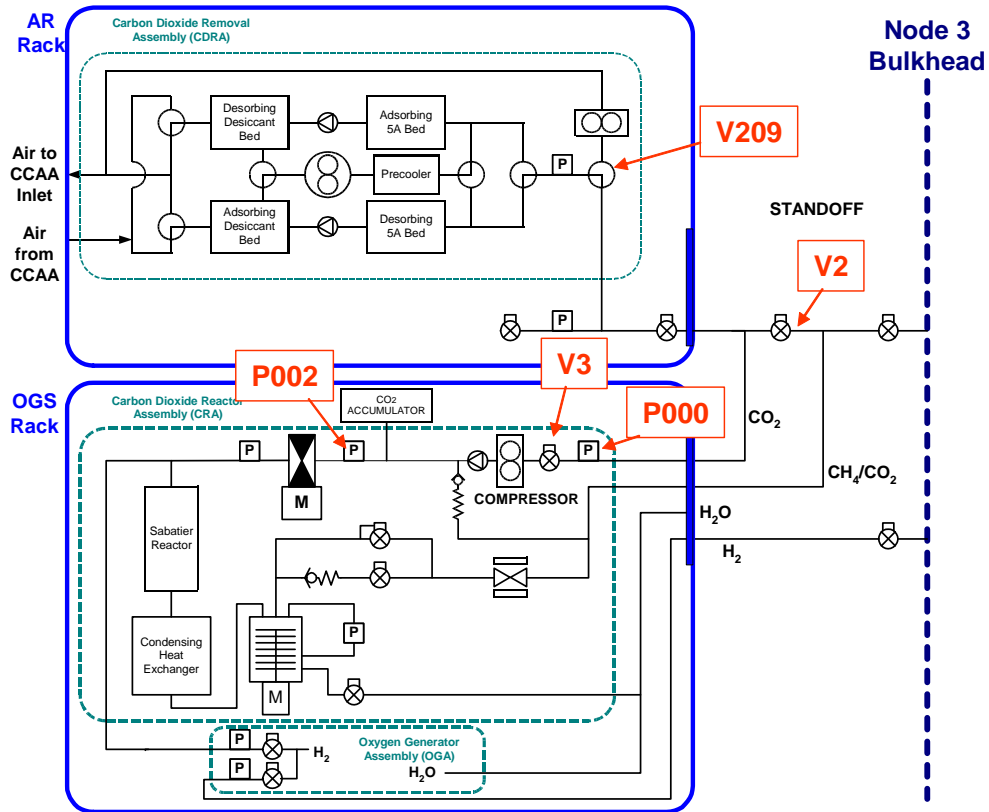
Figure 23 – Simplified Schematic of CDRA and CRA as intended to be integrated on ISS.

Figure 23 above shows simplified schematics of the CDRA and the CRA as they would be installed on the International Space Station. The highlighted components are shown with the component numbers as used in the ground integration testing. Figure 24 below is a schematic of the ground-integrated system with the same control components highlighted.

Simplified Schematic of Ground Test Hardware
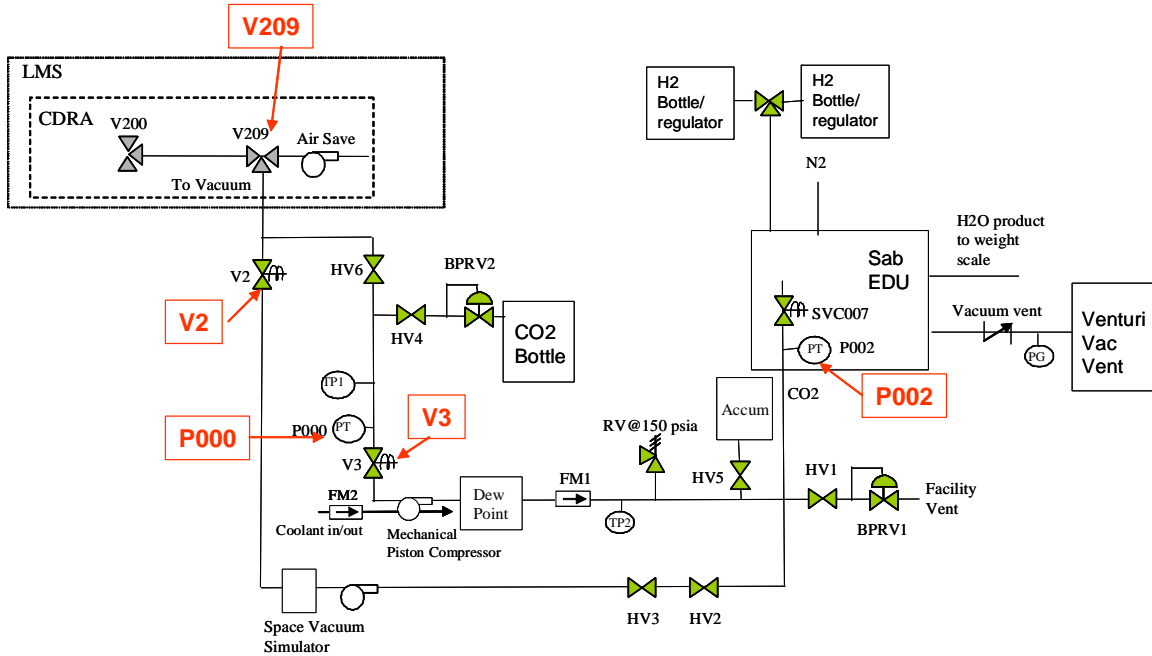
Figure 24 – Integrated Test Schematic – 4BMS, Mechanical Compressor, Accumulator, Sabatier

These components control the interaction between the different systems as follows:

- V209 – this 3-way valve switches the desorbing 4BMS bed from air-save to vent. Air save is the first 10 minutes of the desorbing half cycle before CO2 is evolved from the bed. After air save, the valve switches to deliver CO2 to the vent line.
- V2 – this shut-off valve is in the standoff of the space station. When this valve is open, the desorbing CO2 is vented to space vacuum. This valve must be commanded closed by the supervisory controller in order for the compressor to be able to draw the CO2 from the bed. If there is excess CO2 in the 4BMS that is not removed by the compressor, this valve opens to direct the excess to vent.
- P000 – this pressure sensor is located within the CO2 Management Subsystem (CMS) within the CO2 Reduction Assembly (CRA). This sensor measures the pressure of the desorbing bed, which is also the compressor suction pressure.
- V3 – this valve is also in the CMS portion of the CRA on the suction side of the compressor. Whenever the compressor is commanded to operate, V3 is opened.
- P002 – this pressure sensor is in the CRA and is used by both the CO2 Management Subsystem (CMS) and Sabatier Reactor Subsystem (SRS). This sensor measures the quantity of CO2 in the accumulator. It is used to tell the compressor when to turn on and off, and also tells the Sabatier when there is enough CO2 in the accumulator to process.
- SVC007 - Valve SVC007, inside the Sabatier, opened to allow CO2 to flow when the Sabatier was in its processing state.
- CO2 Bottle – for tests that did not utilize the 4BMS (compressor mapping, for example), bottled CO2 was used as the source by closing HV6 and opening HV4.

37

- Accumulator - The compressor delivered CO2 to the Sabatier/Accumulator inlet. The accumulator is simply a buffer volume that fills and empties when the compressor flow is greater or less than the Sabatier usage rate.

The 4BMS was operated in the nominal ISS CDRA mode. Half-cycle time was 144 minutes and process air flowrate was 95 lbs/hour average. For the last 10 minutes of the desorb cycle, the desorbing bed was exposed directly to the space vacuum simulator pump. This would be the recommended operating procedure for ISS in order to fully desorb the 4BMS bed prior to its next adsorption cycle. The CO2 loading profile to the 4BMS is described in Section 2.1.5.1.

2.2.2.2 Single Component Tests

2.2.2.2.1   4BMS

The 4 bed molecular sieve system was tested alone to verify that it met the removal capability that had been demonstrated in prior baseline cases. The test conditions are listed in the table below. The baseline testing was repeated throughout the project to ensure that there was no performance degradation as a result of the integration.

Test Case #	ppCO2 Inlet torr	CO2 Removal Rate Lb/hr	Test Duration
4BMS Baseline, 3 EP	1.48	0.23	8 hour min
4BMS Baseline, 6 EP	3.39	0.52	8 hour min

2.2.2.2.2   Mechanical Compressor

This configuration tested the compressor as a stand-alone item. The test results would be compared to the vendor test results prior to delivery of the compressor to NASA. This testing is referred to in the test plan as "Compressor Health Check." The Table below list the test conditions.

Test Point	Suction Pressure (psia)	Discharge Pressure (psia)	Pump Speed (RPM)
1	4	20	1000
2	4	130	1000
Each test point will last a minimum of 5 minutes.			

2.2.2.2.3 Sabatier

Sabatier stand alone tests were performed to generate a baseline of the Sabatier efficiency for comparison to previous Sabatier testing and to compare to the performance achieved during the integrated tests. The test conditions used are listed in the table below.

Test Point	JSC Test Point Reference	CO2 Supply Pressure (psia)	Day Cycle Time (min)	Night Cycle Time (min)	US H2 Feed Rate (lb/hr)	US H2 Feed Rate (slpm)	H2/CO2 Molar Ratio	Sabatier CO2 Feed Rate (lb/hr)	Sabatier CO2 Feed Rate (slpm)	Cyclic or Continuous
1	3	85	-	-	0.031	2.660	3.5	0.197	0.760	Continuous
2	7	25	53	10	0.106	9.000	3.5	0.567	2.570	Cyclic

2.2.2.3 4BMS + Mechanical Compressor + Accumulator

Two test objectives were completed in this configuration. The purpose of the first test was to measure the dew point of the product CO2 to determine if there would be condensation in either the compressor or the accumulator during operation. The 4BMS was operated with constant 0.2% CO2 inlet concentration. The compressor operated with the varying inlet pressure as produced by the 4BMS and with fixed outlet pressures and set by a backpressure regulator. The outlet pressures were set to 20, 47.5, 75, 102.5, and 130 psia.

Simplified Schematic of Ground Test Hardware
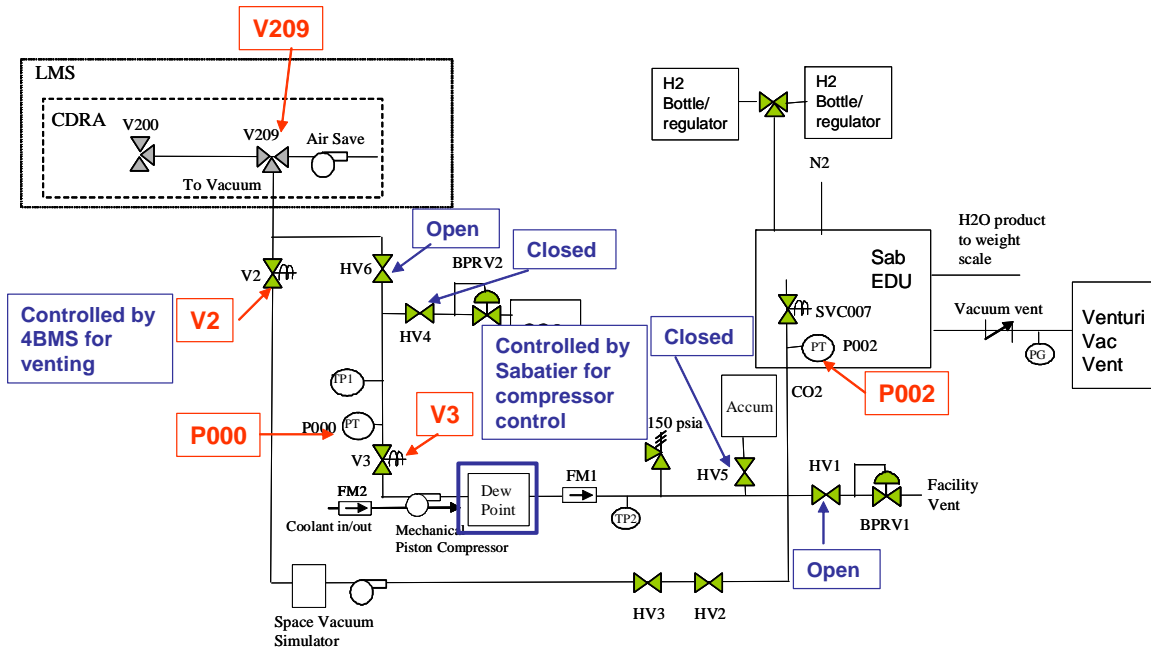
Figure 25 – Hardware configuration for 4BMS and compressor only tests.

In this test configuration, the 4BMS and compressor were integrated together with no other systems operating. The hand valves that connect the CO2 tank (HV4) and the accumulator (HV5) were closed. The Sabatier was powered on, but not processing so that it could monitor the compressor inlet (P000) and outlet (P002) pressures, and operate the compressor and inlet valve (V3). The back pressure regulator (BPRV1) was set to varying pressures according to the test plan. A closed hand valve isolated the accumulator.

The other test was to start up the compressor under vacuum. Normally, the compressor discharge pressure ins never less than 18 psia, however a system self check is being considered that would evacuate the accumulator and compressor exit. The purpose of the test was to determine if there were any operational issues with the compressor.

2.2.2.3.1   4BMS + Mechanical Compressor + Accumulator +

Sabatier

Table 8 below details the test conditions used for the integration of the mechanical compressor with the 4BMS and the Sabatier. The column data in the table is as follows:

- Column 1 is the test point number used for recording test conditions and resulting data.
- Column 2 is the constant CO2 concentration fed to the 4BMS at the cabin air flow inlet. These tests were run open loop, therefore the feed concentration to the 4BMS was set by a CO2 mass flow controller with measured CO2 concentration feedback to the mass flow control setpoint.
- Column 3, EP, is Equivalent Persons. Early mathematical modeling of the 4BMS predicted that 1.5 mmHg partial pressure of CO2 fed to the inlet of the 4BMS would result in the equivalent CO2 removal rate of 3 EP generation rate. After testing this condition and analyzing the data, it was found that 1.5 mmHg inlet resulted in only 2.3 EP worth of CO2 collected and delivered to the Sabatier for processing. The correction to the inlet feed rate was made in later tests.
- Column 4 indicates the status of a virtual Vozdukh, the Russian CO2 removal system. When the Vozdukh is off, all of the CO2 from the entire crew is collected and concentrated by the US CRDA equipment and available for processing by the Sabatier. When the Vozdukh is on, 25% of the crew load of CO2 is collected by the Russian equipment and therefore not available to the Sabatier.
- Column 5 indicates the status of a virtual Elektron, the Russian oxygen generator. The contributing level of the Elektron is given in EP of oxygen delivered by the Elektron. When the Elektron is producing oxygen, the US OGA production level is lowered by the same amount and therefore the hydrogen available to the Sabatier for processing is decreased. These contributions from other hardware become important when determining the amount of water recovery available from the Sabatier system.
- Column 6 is the US hydrogen feed rate to the Sabatier. This value is the amount of hydrogen generated along with the rate of oxygen generated to make up for losses. The oxygen consumption rate is calculated from the crew size, the contribution supplied by the Elektron (subtracted out) and a component for make up oxygen for station air leakage amounting to 0.24 lb/day. The value of hydrogen in column 6 is used as the set point of the hydrogen mass flow controller in the Sabatier EDU.
- Column 7 is the set point for hydrogen/CO2 molar ratio. While this number is a variable in the Sabatier control program, it was set to a constant 3.5 for these tests. The Sabatier calculates the control set point for its CO2 control valve based on the hydrogen feed rate and the molar ratio.
- Column 8 is the CO2 feed rate. This is the average feed rate of CO2 that the Sabatier should be calculating for the set point of its control valve.
- Column 9 indicates day/night cyclic or continuous operation. When the integrated system is operating in day/night mode, the OGA transitions to a standby mode when the space station is in the dark side of the orbit and power is scarce. When the station is back in the daylight side of the orbit, the OGA transitions back to Process mode. Hydrogen is only available to the Sabatier when the OGA is in Process mode. The times used for the duration of the day and night portions of the orbit are given in Column 13.

- Column 10 indicates the minimum number of half cycles (HC) required to reach nominal steady state conditions for the test point. These values were used to schedule the test point in order to complete the series.
- Column 11 is the compressor speed. Determining the correct size for the mechanical compressor was one of the objectives of this test program. Adjusting the speed of the compressor was a simple method of adjusting the compressor capacity to see its effect on integration. A compressor designed for the flight application of this system would be made with smaller pistons if necessary rather than slower speed. Motor speeds under 1000 rpm have major impacts on sizing of EMI filters in the controller.
- Column 12 indicates the location of the CDRA (the station 4BMS) in the model used to develop the metabolic profile. The location of the CO_2 removal equipment with respect to the location of crew members during different activities affects the instantaneous concentration of CO_2 seen at the 4BMS inlet.
- Column 13, as described previously, is the duration in minutes of the daylight and night portions of the space station orbit.

Table 8 – Integrated Test Matrix Input Parameters, Mechanical Compressor Test

TP	4BMS CO2 Inlet Concentration (mmHg)	EP total	Vozdukh Operation (on=25% CO2 load)	Russian Elecktron Load (EP)	US H2 Feed Rate (slpm)*	H2/CO2 Molar Ratio	CO2 Feed Rate (slpm)	Day/night Cyclic or Continuous	Min. Number HC Required	Comp Speed (rpm)	Modeling CDRA Location	Day/night Duration (min)
1**	1.5	3	off	0	2.461	3.5	0.703	cont	3	1000	-	53/37
2**	1.5	3	off	0	4.179	3.5	1.194	day/night	4	1000	-	53/37
3**	1.5	3	off	0	4.179	3.5	1.194	day/night	4	800	-	53/37
4	3.5	7.25	on	2	4.289	3.5	1.225	continuous	3	1000	-	53/37
5	3.5	7.25	on	2	7.282	3.5	2.081	day/night	4	1000	-	53/37
6	3.5	7.25	on	2	7.282	3.5	2.081	day/night	4	800	-	53/37
8	met profile	6	off	0	8.724	3.5	2.493	day/night	50 hrs	1000	Node3	53/37
10	met profile	7.25	on	2	7.282	3.5	2.081	day/night	50 hrs	1000	Node 3	53/37
11	met profile	7.25	on	2	7.282	3.5	2.081	day/night	48 hrs	1000	Lab	53/37
*includes air leakage compensation of 0.24 lb/day air ** tests repeated after air leakage detected												

2.2.3 Discussion of Test Results

2.2.3.1 Description of Result Metrics for Fully Integrated Tests

Table 2.2-2 lists the parameters used to evaluate the performance of the subsystems during the integration tests. The parameters are listed as Set points or Performance. Set points are input parameters that are established for each test case. They are the input variables to which the systems respond. Parameters are the responses of the subsystems. The input parameters include the items discussed in Section 2.2.3.2 as well as some additional items not included on the previous tables. Some of the additional parameters were not changed between test points, but would have to be considered in the development of an Air Revitalization System for other exploration mission scenarios.

Summary plots of each Test Point are assembled in Appendix A.

Table 2.2-9 – Integration Test Metrics

Integration Test Parameters	
Set point	**Performance**
Overall System Test	
Test Duration	Frequency of Vacuum Vent
Day/Night or Continuous	Sabatier Starvation
Crew Size	
4BMS	
CO2 Inlet Concentration or Feed Rate	CO2 Removal Efficiency
Half Cycle Duration	Power
Mechanical Compressor	
Compressor Speed	Power
Accumulator Working Pressure Range	Number of Start/Stop Cycles
Accumulator Volume	Duty Cycle
Sabatier	
Hydrogen Feed Rate (based on crew size)	Water Recovery Efficiency
Molar Ratio	Actual Water Production
Day/Night Cycle Times	Power
Theoretical Water Production (based on H2 available)	Reactor Temperatures
	Reactor Pressure Drop

The significance of the Set points and Performance parameters are discussed in detail below:

Overall System Test

- Test Duration – the duration of each test was pre-established to attempt to reach steady state operation within the 4BMS. The tests with constant CO2 concentration fed to the 4BMS were run for three or four half cycles. The tests that incorporated a metabolic profile to simulate the movement of crew within the habitat were run for 50 hours or more to include repetition of the profile.

- Day/Night or Continuous – Day/night vs. continuous operation affects the availability of power. It is assumed that when the ISS is in the night portion of the orbit that power consuming devices must be tuned down or off. This affects the Sabatier operation and the heater power allowed in the 4BMS.

- Crew Size – crew size is used as an indicator of overall load on the systems. Crew consumption of oxygen (reflected in hydrogen flow rate) and crew production of carbon dioxide drive the sizing requirements for the subsystems.

- Frequency of Vacuum Vent – the vacuum vent is controlled at the system level based on what is going on with the 4BMS. Excessive venting is an indication of poor CO2 management and likely is associated with Sabatier starvation.

- Sabatier Starvation – the overall goal of the system integration is to recover as much water as possible. Sabatier starvation means that there is hydrogen produced ready to be converted, but there is not enough carbon dioxide available to run the reaction. The overall mass balance of hydrogen and carbon dioxide is such that there is always excess CO2 available, so starvation is another indicator of poor CO2 management.

4BMS

- Inlet CO2 concentration or feed rate – The feed rate of CO2 to the 4BMS falls out of the crew size parameter and sets the operating envelope for the integrated systems.

- Half Cycle Duration – A half cycle refers to the length of time that all beds of the 4BMS system are in either adsorb or desorb. The length of the half cycle affects how well the molecular sieve beds adsorb and desorb CO2. The integration tests were all performed with a 144 minute half

cycle, however some of the stand alone tests were done with 155 minute half cycles to compare to the manufacturer's baseline tests. Shorter half cycle times increase the CO2 removal performance.

- CO2 Removal Efficiency – CO2 removal efficiency is a measure of the amount of CO2 actually captured by the 4BMS compared to the amount fed to it. Most of the tests were done open loop, which means that the scrubbed air from the 4BMS was not returned to the inlet. Because the testing was open loop, there was no buildup of CO2 concentration that would otherwise be seen with a poor performing 4BMS. CO2 removal efficiency is affected by the desorption pressure, a significant artifact of integration with a compressor instead of space vacuum venting.

- Power – The 4BMS heaters consume power to desorb CO2 and water from the zeolite. The power requirement is a function of the CO2 loading isotherms. The lower the vacuum pressure available for desorption, the lower the power requirement to drive off the CO2.

Mechanical Compressor

- Compressor Speed – In this series of testing, the compressor speed was varied to effectively change the flow rate capacity of the compressor. In reality, the piston size and stroke would be optimized to achieve the desired volumetric flow rate. The speed change allowed an easy way to change flow conditions and observe the results.

- Accumulator Working Pressure Range – The accumulator used in the mechanical compressor tests was restricted to operation between 18 and 120 psia. There are several factors that influence this range that could change for other than and ISS application. The low set point pressure is based on the pressure drop allocation for the control components in the Sabatier at maximum flow rate. This pressure drop is added to the reactor inlet pressure and the minimum pressure of 18 psia is achieved. The actual pressure drop of the EDU hardware was lower than the allocation because there were no filters installed in the lines. The upper pressure limit is based on pressure ratio achievable by the compressor, inlet dew point and the resulting dew point of the gas once compressed, and the pressure rating of the downstream components. The accumulator vessel can withstand over 2000 psia, however, not all of the shutoff valves can be exposed to that pressure. The maximum operating pressure selected for these tests was 120 psia, which was sufficiently low enough to prevent condensation.

- Accumulator Volume – The accumulator volume for the ISS application is 0.73 ft3. This is the largest volume of accumulator bottles ganged together that could fit in the Space Station rack designated for Sabatier installation. All of the integration tests using an accumulator used similar size bottles to simulate the ISS available volume.

- Power – Power is one of the key performance variables of the mechanical compressor. The power consumption is based on the work done to compress the carbon dioxide and also the mechanical and electrical efficiency of the compressor and motor.

- Number of Start/Stop Cycles – The number of start/stop cycles resulting from the integration dynamics is an important factor in the life of the compressor. The number of start/stops affects wear of moving parts and life of electronic components.

- Duty Cycle – Duty cycle is the most important factor affecting life of the compressor. The life limiting component of the compressor is the piston rings, and their life is directly attributed to run time.

Sabatier

- Hydrogen Feed Rate – The hydrogen feed in these tests was delivered from gas cylinders. In a real ARS application, the hydrogen would come from an oxygen generator and would be a function of the oxygen produced for crew consumption. The hydrogen feed rate can be any value for other mission scenarios.

- Molar Ratio – Molar ratio is the ratio of hydrogen to carbon dioxide fed to the Sabatier reactor. The stoichimetric ratio is 4 moles hydrogen to 1 mole CO2. In these tests, the molar ratio was set to 3.5. In the space station application, CO2 is in excess of hydrogen. The reactor works more efficiently when the molar ratio is not at the stoichiometric value. In other applications, Mars for example, the reactor might be run at molar ratios greater than 4.

- Day/Night Cycle Times – The day night cycle time for most of the tests was set to 52 minutes day, 37 minutes night. This corresponds to the longest night duration of the ISS orbit. The length of the night cycle affects how much the reactor cools off before being restarted.

- Theoretical Water Production – This value is the amount of water that could be generated by the Sabatier if every mole of hydrogen was consumed, and all of the water was collected. The molar ratio of water generated to hydrogen consumed is 1:2.

- Actual Water Production – This is actual mass of water collected over each test duration. The water production is affected by the reactor efficiency, the separator waste heat and the number of shutdown cycles for night time operation.

- Water Recovery Efficiency –This is the ratio of actual water to theoretical water. It is the most telling of the Sabatier performance metrics for overall system performance.

- Power – Power is consumed by the Sabatier to preheat the reactor and to operate the separator, in addition to valves and sensors.

- Reactor Temperatures – The reactor temperatures indicate the general health of the Sabatier reaction and vary with different inlet feed rates and molar ratios.

- Reactor Pressure Drop – Reactor pressure drop varies with feed flow rate, unless there is excessive water condensation in the reactor bed. A high value would indicate a performance issue that would require adjustment.

2.2.3.2 4BMS Baseline Test

The table below lists the results of 4-BMS stand alone testing that was performed after the integrated tests were completed.

Test Case #	ppCO2 Inlet torr	CO2 Removal Rate Lb/hr	In – Out CO2 Removal Efficiency
4BMS Baseline	3.79	0.52	74%
4BMS Baseline TP2 Conditions	1.48	0.23	84%
4BMS Baseline TP4 Conditions	3.39	0.52	81.5%
4BMS Baseline TP5 Condition	3.40	0.52	81.8%

2.2.3.3 Mechanical Compressor Baseline Test

The mechanical compressor was tested in a stand-alone configuration to compare its performance against the baseline data recorded by the manufacturer. The compressor was tested at 4 psia inlet pressure, 130 psia outlet pressure and produced about 2 lb/hr. The compressor was also tested at 4 psia inlet pressure and 20 psia outlet pressure. The flow rate varied between the three runs, with approximate averages of 1.2, 1.4, and 2 lbs/hr. Large variations in inlet pressure were observed.

Test Point	Suction Pressure (psia)	Discharge Pressure (psia)	Pump Speed (RPM)	Flow Achieved
1	4	20	1000	1.2-2 lb/hr
2	4	130	1000	2 lb/hr
Each test point will last a minimum of 5 minutes.				

2.2.3.4 4BMS + Mechanical Compressor

The purpose of these integrated tests was to measure the dew point of the product CO_2 to determine if there would be condensation in either the compressor or the accumulator during operation. The 4BMS was operated with constant 0.2% CO_2 inlet concentration. The compressor operated with the varying inlet pressure as produced by the 4BMS and with fixed outlet pressures set by a back pressure regulator. The outlet pressures were set to 20, 47.5, 75, 102.5, and 130 psia. Dew point of the compressed CO_2 remained below 31 F for all conditions tested. During extended compressor operation, the dew point remained around 0 F. CO_2 removal from the 4BMS using the mechanical compressor was the same as using the space vacuum simulator within the measurement accuracy of the tests.

Test Case #	ppCO2 Inlet torr	CO2 Removal Rate Lb/hr	In – Out CO2 Removal Efficiency
4BMS CEDU	1.48	0.24	87%
4BMS CEDU	3.37	0.54	85%
4BMS CEDU	3.38	0.58	92%
4BMS Stand Alone	1.48	0.23	84%
4BMS Stand Alone	3.39	0.52	81.5%
4BMS Stand Alone	3.40	0.52	81.8%

Dew Point Data

Test Day	Compressor outlet pressure	Max Dew Point
Day 7	20	31 F

Day 8	50, 75, 100	30, 29, 27
Day 9	130	31

2.2.3.5 Mechanical Compressor Startup Under Vacuum

One of the safety checks envisioned for the Sabatier CRA system required vacuum venting of the entire Sabatier system including the mechanical compressor and accumulator. The mechanical compressor was tested by starting it with vacuum at both the inlet and outlet to determine if there were any performance issues. Three successive tests were conducted with no problems encountered. No unusual noises or other unusual behavior were observed.

2.2.3.6 4BMS + Mechanical Compressor + Accumulator + Sabatier

This section describes the test results for the 4BMS, Mechanical Compressor/Accumulator and Sabatier integration test series. Eleven different test points were run, each with a different set of operating conditions. The summary of test results is given below in Table 2.2-3.

Test points 1,2 and 3 were conducted at the minimum crew loading of 3 Equivalent Persons, with all of the CO_2 removal performed by the 4BMS (no Vozdukh simulation). Test Point 1 was continuous operation, or no day/night cycling. This means the Sabatier and the 4BMS heaters were allowed to operate all of the time. Test Points 2 and 3 used a 53 minute day/37 minute night cycle. Test Point 3 was run with the slower compressor speed (800 rpm) compared to 1 and 2 with the 1000 rpm speed. Test Points 4,5 and 6 mimicked 1,2, and 3 except they were run at the maximum crew loading of 7.25 Equivalent Persons with simulation of 2 EP of CO_2 removal and H_2 production by Russian hardware. Test Points 8, 10 and 11 were run with metabolic profile inputs for the CO_2 feed to the 4BMS. Test Point 8 was 6EP with no Russian hardware, 10 and 11 were 7.25 EP with 2 EP of Russian hardware. Test Points 8 and 10 were simulated with the ARS components installed in the Node 3 location of the ISS. Test Point 11 was simulated with the components in the Laboratory Module of ISS.

Table 2.2-10 – Mechanical Compressor CO2 Capture Performance Data

Test Point	CO2 EP	Time Period Evaluated (hrs)	Number of 4BMS Half Cycles	Number of Sabatier Day/Night Cycles	Number of Compressor ON/Off Cycles	Compressor Cycles per Half Cycle	Total Compressor Run Time (min)	Average Compressor Run Tim per Half Cycle (min)	Compressor Duty cycle (%)	Total Sabatier Starvation Time (min)
1	3	16.10	6.75	-	21	3.11	168	25	17	15
2	3	3.78	1.5	2.75	5	3.33	42	28	19	9

3	3	22.50	9	15	25	2.78	324	36	25	9
4	5.4	7.80	3.25	-	11	3.38	67	21	15	0
5	5.4	14.43	6	9.75	23	3.83	136	23	16	0
6	5.4	27.35	11.5	18	42	3.65	251	22	15	0
8	6 (met)	40.78	17	27.5	68	4.00	399	23	16	0
10	5.4 (met)	28.78	12	19	50	4.17	235	20	14	0
11	5.4 (met)	43.20	18	28.5	80	4.44	355	20	14	0

Test Point	CO_2 EP	Total Number of 4BMS Vent Cycles	Average 4BMS Vent Cycles per Half Cycle	Accumulator Average Minimum Pressure (psia)	Accumulator Average Maximum
1	3	0	0	20	60
2	3	0	0	20	40
3	3	0	0	20	55
4	5.4	6	1.85	50	130
5	5.4	7	1.17	50	130
6	5.4	13	1.13	60	130
8	6 (met)	11	0.65	50	130
10	5.4 (met)	9	0.75	60	130
11	5.4 (met)	23	1.28	55	130

The number of compressor cycles and compressor duty did not vary greatly from between test conditions. The greatest difference noted is at the lower CO2 loading, there is a marked difference between the low and high speed compressor tests. As expected, the lower speed had a higher duty cycle. This difference is not seen in the higher CO2 loading cases. The compressor rules are less demanding on the compressor when the accumulator is near its full mark, and therefore the compressor operation is nearly the same for both cases. Some of the test periods evaluated were quite short and therefore there is significant round off error associated with the results.

The minimum EP cases (1, 2 and 3) experienced periods of Sabatier starvation when H2 was being produced by the OGA but there was not enough CO2 in the accumulator for processing. The accumulator pressure dropped to the minimum operating pressure of 20 psia and only reached to a maximum pressure of 60 psia. There were no vent cycles, which indicates that no CO2 was wasted. At these low rates, the impact of leakage is more significant, and it may not be possible to avoid starvation.

The higher EP cases (test points 4, 5 and 6) did not experience any starvation. There were numerous vent cycles and overall high accumulator pressures. The overall water production efficiency was generally higher, since all of the hydrogen was processed.

The compressor duty cycle for all cases was on the order of 13-21% with the higher CO2 loading cases having the lower duty cycle. There was not a large difference in duty cycle between the cases with the different compressor speeds (Test points 2 vs. 3 and 5 vs. 6).

Figure 2.2-26 below is a typical example of performance data collected during the mechanical compressor integration tests. The performance data described above is shown in this plot of one CDRA half cycle. The top purple line is the accumulator pressure. In this test case, the accumulator is regularly near the upper limit of 130 psia. When the accumulator pressure is at this maximum value, the compressor rules do not allow the compressor to turn on to pump CO2 from the CDRA. In time, the CDRA bed pressure, indicated by the pink line, reaches the maximum allowable pressure of 8 psia and the vacuum vent valve is opened. The vent valve opening is noted by the sharp increase in pressure of the vacuum tank indicated by the dark blue line. The aqua line indicates when the Sabatier is in Process mode, and the green line indicates when the compressor is activated. For this test case, the compressor activates between 3 and 4 times per CDRA half cycle.
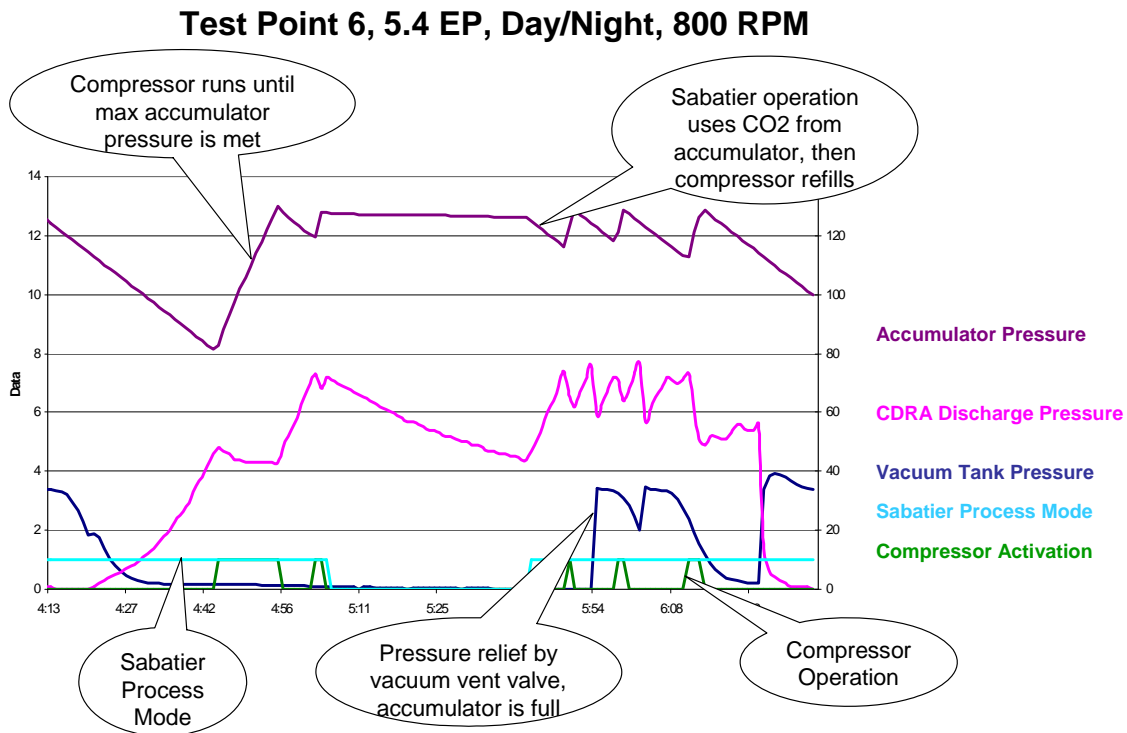

Figure 2.2-26 – Typical Performance Data for Mechanical Compressor Integration Tests

The following four plots show the characteristic water recovery data for some of the test points. In Test Point 4, the overall water recovery was 95%. This test point was at continuous operation at the higher CO2

loading. There was no starvation of the Sabatier during this test point. This is the highest water recovery expected from the Sabatier system at these operating conditions. In contrast, Test Point 1, which was continuous at the lower CO2 loading, showed signs of Sabatier starvation and yielded only 89% water recovery. The offset of the blue line with the two small steps from the straight gray line is the loss of water due to insufficient CO2 available to the Sabatier. The water recovery of the Sabatier based on its operating time is 91%, the two percent difference is due to starvation.

Test Point 6 is a cyclic day/night case. The water recovery suffers more in this mode due to the cyclic operation. Each time the Sabatier transitions to and from Standby, the system is evacuated and steam is lost to the vacuum vent. The reactor also is not at the optimal temperature due to the constant change of flow rate. The efficiency drops from the high of 94% in Test Point 4 down to 89% in Test Point 6 due to cyclic operation. Further, the recovery worsens in Test Point 3, which is cyclic at the lower CO2 loading. Starvation occurs in this scenario dropping the water recovery to 82% overall.

The three metabolic load cases (Test Points 8, 10 and 11) did not experience any Sabatier starvation. Their water recovery numbers are slightly lower than the equivalent fixed CO2 feed cyclic case (Test Point 6).

Test Point 6, 5.4 EP, Day/Night, 800 RPM
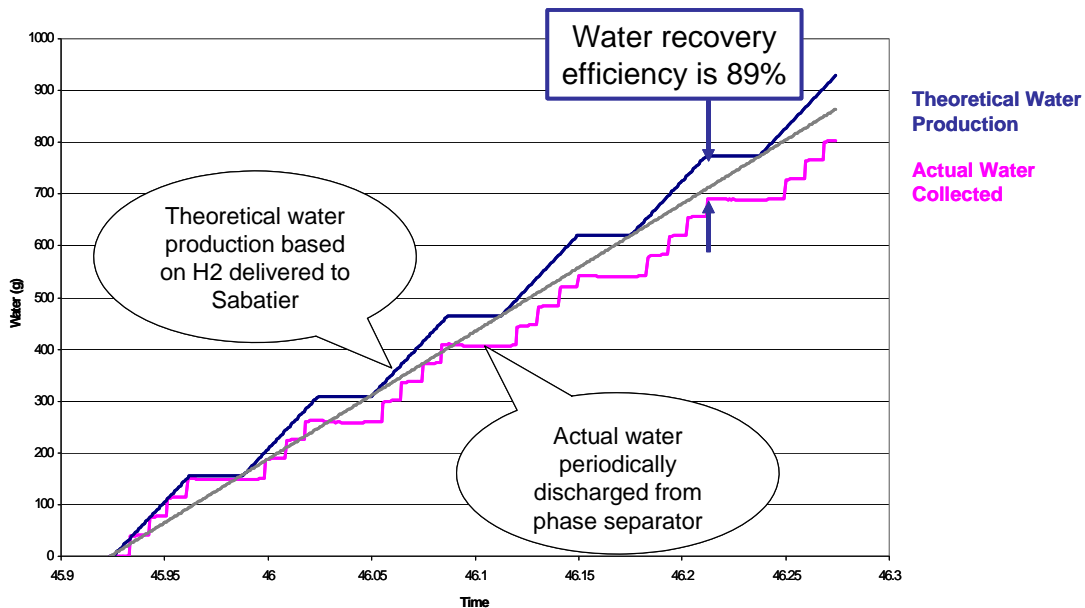
Test Point 4, 5.4 EP, Continuous, 1000 RPM
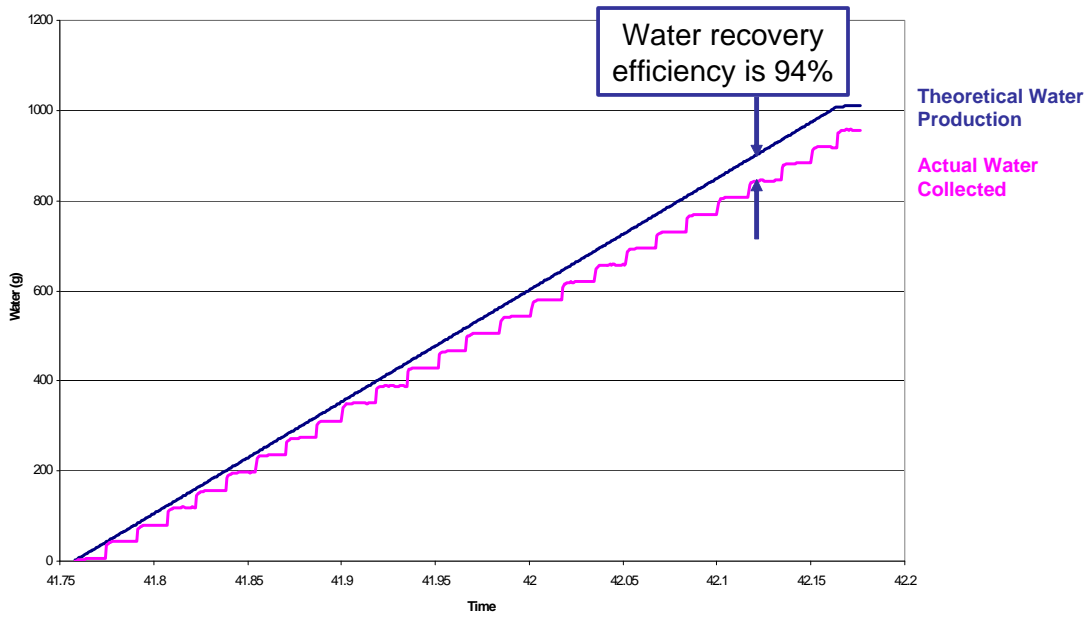
Test Point 1, 3 EP, Continuous, 1000 RPM
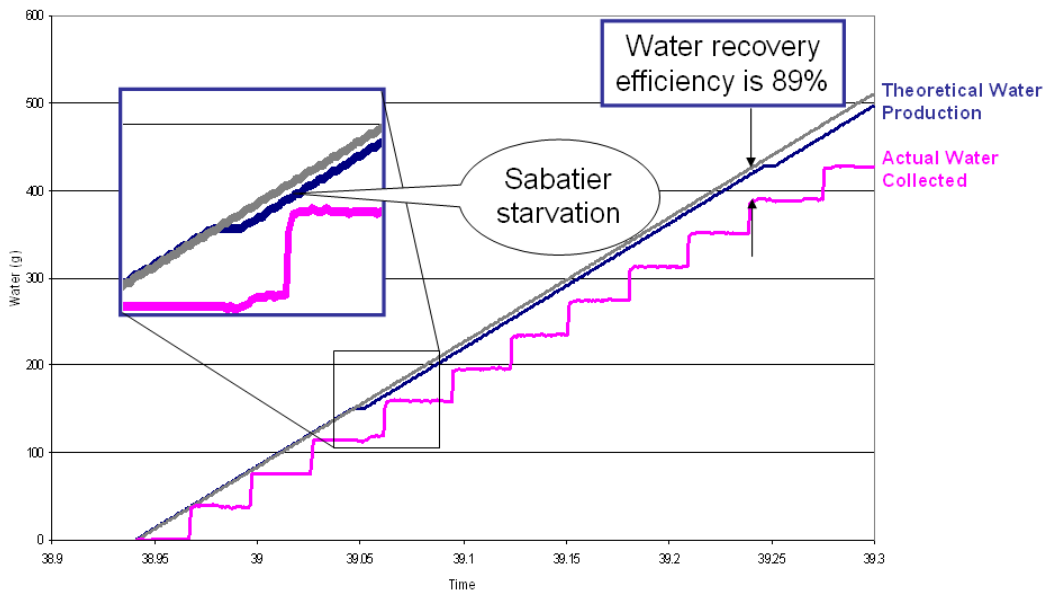
Test Point 3, 3 EP, Day/Night, 800 RPM
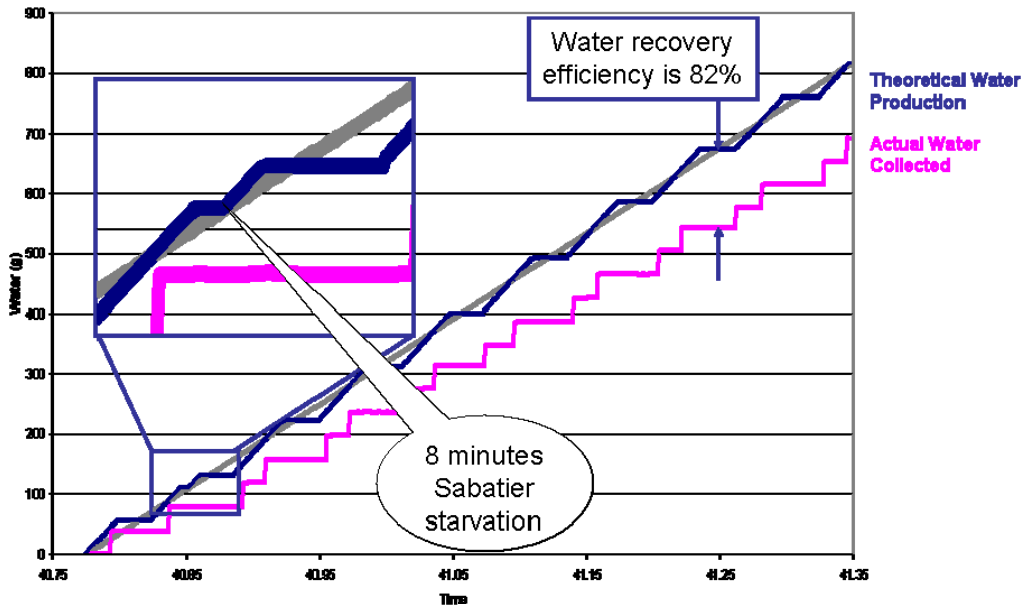
Table 2.2-11 - Sabatier Water Production Rate Efficiencies

Test Point	CO2 EP	Time Period Evaluated (hrs)	Actual Water Collected (gm)	Theoretical Water Production Rate (gm/min)	Actual Water Production Rate (gm/min)	Water Production Efficiency
1	3	16.10	876.3	0.99	0.85	89%
2	3	3.78	197.1	0.99	0.85	84%
3	3	10.85	574.6	0.99	0.81	82%
4	5.4	5.97	576.0	1.72	1.6	94%
5	5.4	6.65	637.7	1.72	1.6	93%
6	5.4	15.05	1341.8	1.72	1.5	89%
8	6 (met)	14.90	1590.3	2.06	1.8	88%
10	5.4 (met)	19.97	1836.6	1.72	1.4	87%
11	5.4 (met)	19.98	1713.9	1.72	1.5	86%

The water production performance is presented in Table 2.2-4. As expected, the steady state cases (Test Points 1 and 4) had the highest water recovery rates as there was no water vapor lost due to venting during Standby operation. The higher EP cases had slightly higher water recovery as there were no periods of Sabatier starvation.

54

2.2.4 Conclusions from This Test Section

The integration test of the 4-Bed Molecular Sieve, Mechanical Compressor and Accumulator and Sabatier was a successful test program. The testing showed that these systems could be properly integrated together. There is no significant, detrimental impact on the 4-Bed CO_2 removal system when desorbed with a compressor instead of space vacuum. 4-BMS CO_2 removal efficiency was well above requirements for the wide range of CO_2 inlet concentrations tested. The compressor control logic in place during this test program supported the wide range of conditions tested. Modifications were made in the flight CO_2 compressor control logic to accommodate pressure sensor accuracy requirements. Also, the 4-BMS vent valve flight control strategy is different than what was tested and results in fewer valve cycles.

As a result of this testing, the compressor simulation model was modified to better predict flow at low suction pressures. The 4-BMS model was also updated to incorporate a leakage factor to estimate air leakage into the system components that operate at vacuum.

2.3 Integration Test Using the TSA Compressor

2.3.1 Description of Tests

2.3.1.1 4BMS + TSAC

The TSAC integration tests were conducted in three phases at MSFC. The first phase included the integration test of the 4BMS and TSAC only with constant 4BMS CO_2 loading. Phases 2 and 3 included the Sabatier with constant and variable CO_2 loading of the 4BMS. The primary objective of the first phase was to demonstrate the TSAC performance in a realistic environment where the CO_2 flow and pressure from the 4BMS varied with time. The objectives of these tests were to gather data for the validation and optimization of the air-cooled TSAC design, and for development of a low power CO_2 removal system that incorporates the functions of the 4BMS and the TSAC.

Figure 1 below shows a simplified schematic of the 4BMS and the TSAC configured for the initial phase of the stand alone tests. The Sabatier simulator was a mass flow controller set to draw a fixed flow rate of CO_2 from the TSAC.
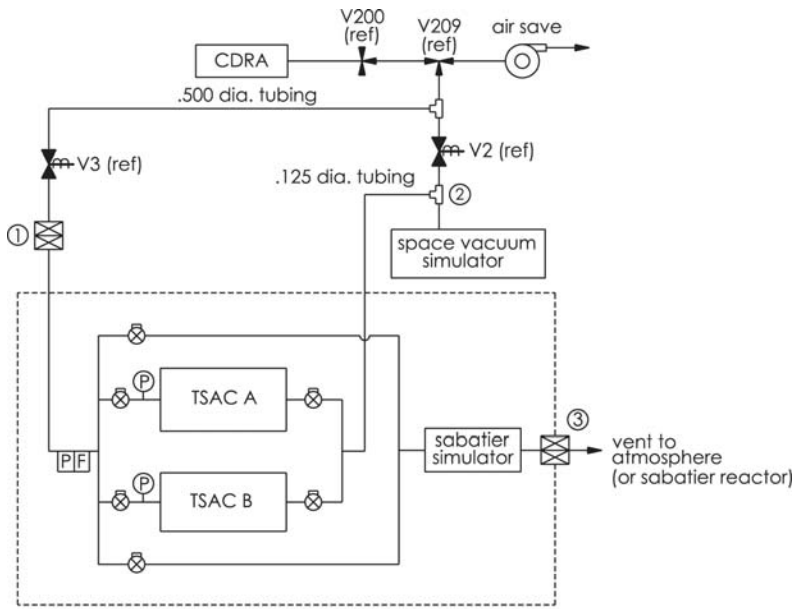
Major interfaces between CDRA, TSAC & Sabatier reactor			
Interfaces		ARC	MSFC
CO2 inlet	①	.50 SS tubing	.50 SS tubing
Vacuum	②	.125 SS tubing	.125 SS tubing
CO2 outlet	③	.250 SS tubing to vent	

Note: Room air will be used for cooling. (Interfaces are not shown)

Figure 27 - Simplified Schematic of 4BMS and TSAC Integration Test

2.3.1.2 4BMS + TSAC + Sabatier

Simplified Schematic of Ground Test Hardware
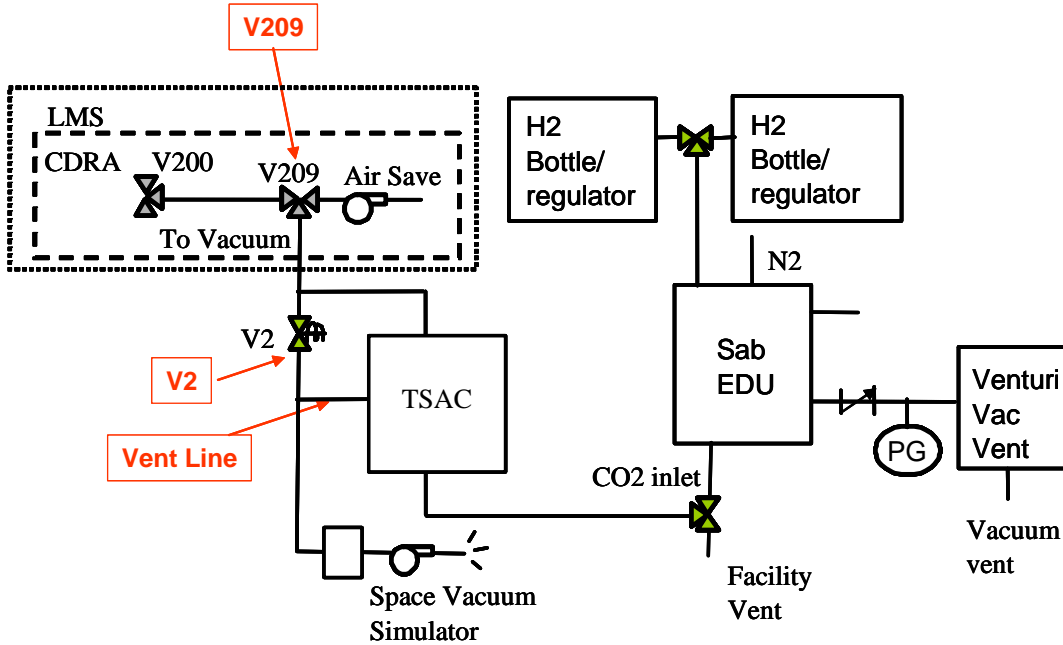
Figure 28 – Integrated Test Schematic – 4BMS, TSAC, Sabatier

Figure 2 above is a simplified schematic of the 4BMS integrated with the TSAC and the Sabatier. The same V209 and V2 valves were used as with the mechanical compressor test. The two beds of the TSAC and the associated valves that allow switching are not shown in this diagram. These are all contained in the box labeled TSAC. The V209 valve again is used to allow the desorbing 4BMS bed to first perform the air-save function (removing ullage air volume back to the cabin). This valve then switched to the vent direction (to compressor or vacuum) once air-save was completed. The V2 valve, again was used to pressure relieve the 4BMS beds if the desorbing CO_2 pressure was too high. The logic for this valve operation is described in Section 2.1 (Hardware Description). The integrated hardware shown above in Figure 2 operated as follows:

- During bed desorption, the 4BMS (labeled CDRA in the figure) delivers CO_2 through valve V209.
- Excess CO_2 is vented through valve V2 to the space vacuum simulator. The venting logic is described in more detail in Section 2.1.5.2, 4BMS Venting.
- CO_2 for processing is delivered through valve V3 to the suction of the TSAC. The TSAC controlled all of the valves necessary to switch between the two sorbent beds and isolate the TSAC from the 4BMS and Sabatier. The Sabatier controller did not perform this function.
- A separate vent line from the TSAC to the space vacuum simulator was used to allow the TSAC beds to bleed diluent gases (nitrogen and oxygen) from the beds.

57

Without the bleed stream, these diluents would build up and the compression capacity would diminish.

- The compressor delivered CO2 to the Sabatier inlet. The TSAC sorbent beds act as both accumulator and compressor. A separate accumulator is not needed with this compressor configuration.
- Valve SVC007, inside the Sabatier (not shown), opened to allow CO2 to flow when the Sabatier was in its processing state.

As with the mechanical compressor integration, during the TSAC integration the 4BMS was operated in the nominal ISS CDRA mode. Half-cycle time was 144 minutes and process air flow rate was 95 lbs/hour average. For the last 10 minutes of the desorb cycle, the desorbing bed was exposed directly to the space vacuum simulator pump. The CO2 loading profiles for the different test points are described in detail in Section 2.0.

2.3.1.3 Test Conditions

Table 5 below details the test conditions used for the integration of the TSA compressor with the 4BMS with and without the Sabatier. The column data in the table is as follows:
- Column 1 is a description of the conditions being simulated.
- Column 2 is the test point number for recording test parameters and resulting data.
- Column 3 is the target CO2 loading on the 4BMS for the TSAC/4BMS parametric tests without the Sabatier.
- Column 4 is the target CO2 inlet concentration to the 4BMS for fully integrated tests with the Sabatier. These tests were run open loop, therefore the feed concentration to the 4BMS was set by a CO2 mass flow controller with measured CO2 concentration feedback to the mass flow control set point.
- Column 5 is the number of equivalent persons in the crew. The test points used for comparison of the two compressors were set with the same number of crew. For the test points that simulated a Lunar Base, the crew was set to 4. The compressor parametric tests used various crew sizes to achieve the desired loading values.
- Column 6 is the TSAC loading or suction pressure. This value is controlled in each test.
- Column 7 is the TSAC production or discharge pressure. The pressure was set at 19.3 psia for the 4BMS/TSAC only tests. The pressure was set at 18 psia for the 4BMS/TSAC?Sabatier tests.
- Column 8 is the US H2 feed rate. This designation was carried over from the ISS simulation tests even though there currently is no concept of multiple life support hardware components for Lunar operations. The H2 feed rate is calculated from the crew O2 consumption with an allotment of 0.24 lb/day of air leakage.
- Column 9 is the H2/CO2 molar ratio. While this value is a variable in the Sabatier control logic, it was set to a constant value of 3.5 for all tests.

- Column 10 is the feed rate of CO2 from the compressor to the Sabatier. This value is calculated by the Sabatier controller from the indicated hydrogen flow rate and the desired molar ratio.

The following describes the different test points and objectives:

- Test Points 1 through 5 were performed with the 4BMS and TSAC only, without the Sabatier
- Test Point 1 was a maximum loading test with 8 kg/day loading on the 4-BMS and TSAC loading at 4 psia. The TSAC production rate was 4.2 kg/day.
- Test Point 2 was to determine the maximum TSAC production capacity at 5 kg/day 4-BMS loading.
- Test Point 3 was to determine the maximum TSAC production capacity at 4 kg/day 4-BMS loading .
- Test Point 4 was to determine the maximum TSAC production capacity with the 4-BMS loaded to 4 kg/day, but the 4-BMS was not desorbed to vacuum at the end of the half cycle. This test would provide data pertinent to LPCOR development.
- Test Point 5 was to determine the maximum TSAC production capacity at 3 kg/day 4-BMS loading.
- Test Point 6 was a parametric test with the TSAC loading pressure intended to be 6 psia.
- Test Points 7 through 11 were integrated tests including the Sabatier.
- Test point 7 was a baseline configuration that mimicked conditions of a previously run 4BMS/TSAC only test. The purpose of this test was to verify that the integration of the Sabatier did not impact the performance of the TSAC and 4BMS.
- Test points 8 and 9 were designed to mimic previous integration tests with the 4BMS/Mechanical Compressor and Sabatier. The purpose of these tests was to obtain direct comparisons of the compressor technologies as they relate to the integration requirements.
- With the current focus on the Vision for Space Exploration, the team decided to develop test conditions that would reflect possible future exploration mission scenarios. These missions simulate a manned outpost at the Lunar south pole. Test Point 10 simulated the extended Lunar night and Test Point 11 simulated EVA activities. The basis for these test points is described in more detail in the next section.

In all of these tests, the objectives also included measurement of the effects of integration on the efficiencies of the stand-alone components.

Table 12 - Integrated Test Matrix – TSAC Test

Test Point Description	Test Point #	4BMS CO2 Loading kg/day (lb/day)	4BMS Inlet CO2 Conc. MmHg (%)	Equiv. Pers. EP	TSAC Loading Pressure kPa (psia)	TSAC Production Pressure kPa (psia)	US H2 Feed Rate slpm (lb/hr)	H2/CO2 Molar Ratio	Sabatier CO2 Feed Rate slpm (lb/hr)
Integrated 4BMS/TSAC baseline test	1	8 (17.6)	--	8	27.6 (4)	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading, 5 kg/day	2	5 (11)	--	5	27.6 (4)	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading, 4 kg/day	3	4 (8.8)	--	4	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading and no vacuum desorb ot 4BMS	4	4 (8.8)	--	4	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading, 3 kg/day	5	3 (6.6)	--	3	TBD	133 (19.3)	--	--	--
Integrated 4BMS/TSAC at reduced CO2 loading pressure	6	5 (11)	--	5	41.4 (6)	133 (19.3)	--	--	--
Integrated 4BMS/ TSAC/ Sabatier at TSAC baseline conditions for TSAC health check	7	--	5.3 (0.7%)	8.3	--	124 (18)	6.766 (0.0798)	3.5	1.933 (0.502)
Integrated 4BMS/ TSAC/ Sabatier for comparison to mechanical compressor test point #2	8	--	3.5 (0.46%)	5.46	--	124 (18)	4.459 (0.053)	3.5	1.274 (0.331)
Integrated 4BMS/ TSAC/ Sabatier for comparison to mechanical compressor test point #3	9	--	1.5 (0.2%)	2.34	--	124 (18)	1.925 (0.023)	3.5	0.550 (0.143)
Integrated 4BMS/ TSAC/ Sabatier Lunar night scenario, non-optimal TSAC shutdown/ startup	10	--	2.52 (0.33%)	4	--	124 (18)	3.273 (0.037)	3.5	0.935 (0.243)
Integrated 4BMS/ TSAC/ Sabatier EVA full crew departure scenario, CO2 regenerated to cabin	11	--	Per profile	4	--	124 (18)	3.273 (0.039)	3.5	0.935 (0.243)

2.3.1.4 Mission scenario development

This section describes the operating conditions set for each series of integration tests. Section 0 explains the reasons for choosing the test point in the matrices and how each series of tests relates to future missions. Section 2.3.1.3 details the input parameters in terms of crew size, processing duration, etc.

Specific, quantitative test conditions, like any requirement, must be traceable back to some realistic higher level requirement, which in turn is traceable to a mission scenario. Rather than starting "at the bottom" with candidate test points the test point definitions

can be derived "top down" from the mission scenarios. This process ultimately links the tests and the data produced to the mission need.

Because of the configuration of the Sabatier scar in the OGS rack, the TSAC compressor is a less likely candidate for the ISS application, however its technical merits make it a viable candidate for other space exploration missions where interface conditions have not already been set. The TSAC test conditions were based on possible Lunar mission operating parameters. Various scenarios were explored that taxed the systems' capabilities over a range of conditions. These Lunar mission scenarios were used to develop the input parameters of Table 5.

Lunar Base CRA Installation
With the current focus on the VSE, it was decided that test points should be included to reflect possible future mission scenarios. Three basic mission scenarios were developed: 1) Impact of lunar day/night cycles at the south pole, 2) Lunar mission EVA, and 3) Reduced pressure cabin atmosphere. For this test series, the third mission scenario was ruled out since time constraints would not allow the reconfiguration of test hardware for sub-ambient operation.
Impact of Lunar Day/Night Cycles at the South Pole
Lunar missions will operate with very different power cycle availability than the more familiar ISS power-cycle profile. Due to a reduction in resupply water capability, the use of a CDRA/TSAC/Sabatier system is most advantageous as part of an Outpost life support system, which will most likely be positioned at the Lunar South Pole. At the South Pole, solar power is available nearly continuously for most of the month, with periods of 24 to 48 hrs where no solar power is available and stored battery power is required. Reduced power operations will probably be necessary during this night period. Since OGA provides hydrogen to Sabatier, one test point included shutting down the Sabatier production during what would be the Lunar night. With the Sabatier shut down during Lunar night, TSAC need not operate to produce CO_2. Depending on the TSAC state when the system shuts down, the start-up could be simple or more complex. The CDRA would continue operating to maintain CO_2 levels in the habitat.

Due to time constraints, the most challenging scenario was selected where the lunar night cycle begins relatively early in a CDRA half cycle and ends towards the end of a CDRA half cycle. This results in the TSAC shutting down when only a fraction of the adsorbing bed has been loaded and only a fraction of the desorbing/producing bed has been unloaded. Hence, when the lunar night is over and the TSAC/Sabatier re-started, for the first TSAC cycle after the half cycle change, there is too much CO_2 on the adsorbing TSAC bed for the CDRA to fully desorb.

Preliminary testing found that by approximately 70-80 min into the 4BMS 144 min cycle, about 25% of the available CO_2 was adsorbed onto TSAC. Hence for this test point, Lunar night or TSAC/Sabatier shutdown occurred at this time. Due to time constraints, the Lunar night cycle was reduced to a minimum of 6 hrs, about the time it takes to fully cool down the TSAC and Sabatier systems. After the lunar night cycle, the TSAC and

Sabatier were started back up at roughly 120 min into the current 4BMS cycle. Since there is almost no CO2 remaining on the 4BMS desorbing bed at this time, the TSAC was not able to adsorb any additional CO2. Since the TSAC requires roughly 20 min to heat up before it can provide CO2 to the Sabatier, the desorbing TSAC bed at first was not able to unload any additional CO2 to Sabatier. Hence, when the CDRA half cycle change occurred, the TSAC was essentially in a worst-case configuration with both beds partially loaded with CO2. The results of this test configuration will be discussed below.

Lunar Mission EVA
Lunar Exploration missions will be highly EVA intensive, with crews of two to four making trips on the lunar surface multiple times in a week. The number of crewmembers actually in the habitat can change significantly during the day or the week, changing the load on each of the air systems. It was assumed that if an OGA were used for oxygen generation, it would also be used to generate oxygen that is stored for consumption during EVAs resulting in continuous H2 availability. It was also assumed that the CDRA would remain operational even if all crew were on EVA since this is the most likely flight configuration due to its simplicity.

Multiple possible EVA scenarios were evaluated. These included: 1) 4 crew EVA where CO2 exhausted on EVA is stored and later regenerated back to the cabin, 2) 4 crew on EVA but CO2 is vented during EVA, 3) 4 crew on EVA but depart habitat in groups of two offset by 4 hrs, and 4) 2 crew on EVA and 2 remain in habitat. METOX regeneration was used as a model for the regenerable EVA CO2 removal technology.

Overall, approximately ten different possible EVA scenarios were developed. Several of the configurations were modeled in JSC's integrated model discussed previously. In comparing the predicted cabin ppCO2 profiles, it was concluded that the most dynamic and therefore worst case test scenario was defined as a 4 crew, single departure EVA where CO2 is stored and later regenerated to the cabin. Based on modeling, the most realistic EVA CO2 regeneration scenario involved 2 crew worth of CO2 being regenerated starting 2 hours post EVA followed by the remaining 2 crew's worth of CO2 regenerated the following day. Figure 3 depicts the cabin ppCO2 results of this scenario.
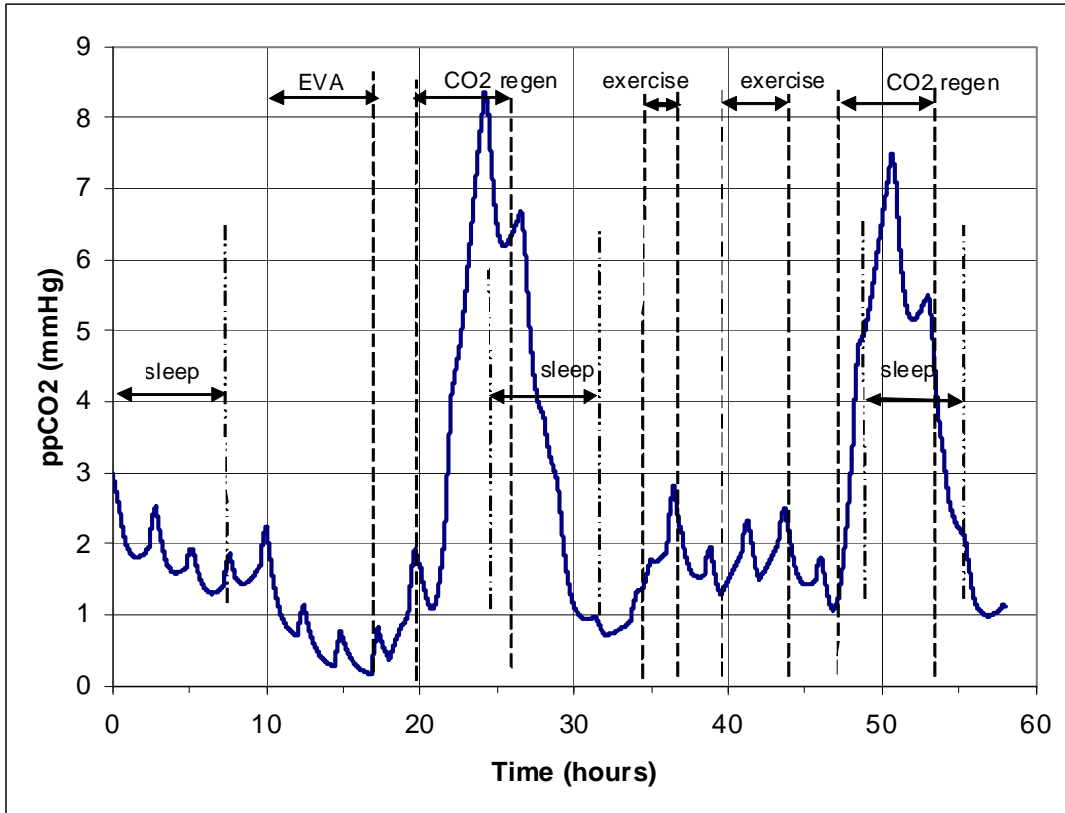
Figure 29 - Lunar EVA Mission Scenario Cabin ppCO2

2.3.2 Discussion of Test Results – Integration Test with TSAC

2.3.2.1 Results - 4BMS + TSAC

The 4BMS and TSAC were tested together over a range of CO2 feed rates to better define the TSAC operating envelope and to provide data for further design improvements. In order to understand the impact of the TSAC on the 4BMS, a test plan was developed to compare operating effects. The 4BMS was operated in a stand-alone open loop mode, and then integrated with the TSAC under similar input conditions. Table 2 below lists the test conditions and the results for the two different operating modes. The CO2 removal efficiency of the 4BMS was an average of 2.75% less when integrated with the TSAC than in open-loop mode, desorbing to vacuum. The worst effect was in the middle of the range of input CO2 concentration, 2.6 mmHg ppCO2, where the efficiency dropped 5% when the TSAC was added. Figure 4 below shows the difference between the two sets of operating conditions.

Table 13 - Operating parameters for 4BMS / TSAC comparison tests

Data File	Inlet CO2 Concentration	CO2 Removal	4BMS CO2 Removal	Efficiency Loss with

	(mmHg)	Rate (lb/hr)	Efficiency (%)	TSAC
4BMS Compare #1	5.30	0.73	69	2%
TSAC Test #1	5.27	0.71	67	
4BMS Compare #3	3.31	0.56	85	3%
TSAC Test #2	3.28	0.54	82	
4BMS Compare #4	2.63	0.44	84	5%
TSAC Test #3	2.65	0.41	79	
4BMS Compare #5	1.96	0.32	84	1%
TSAC Test #4	1.94	0.32	83	

Effect of Adding TSAC to 4BMS CO2 Removal Efficiency
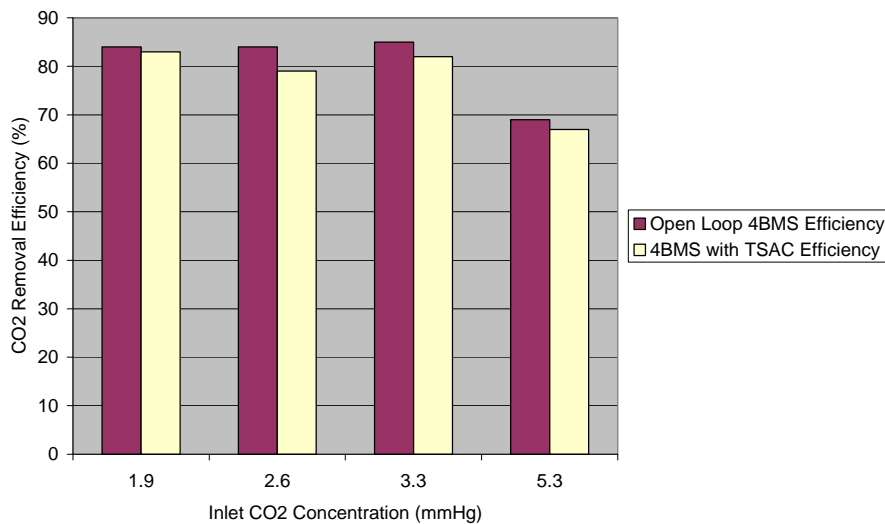
Figure 30 - Graphical presentation of integration effects on 4BMS efficiency

One objective of the 4BMS / TSAC testing was also to obtain parametric data for the TSAC for sizing and evaluation. Table 3 lists the test parameters for these tests along with the performance targets and actual results. These tests were described in the ICES paper 2006-01-2271 "Integrated Test and Evaluation of a 4-Bed Molecular Sieve, Temperature Swing Adsorption Compressor, and Sabatier Engineering Development Unit."

Table 14 - TSAC Performance Target and Actual Results

Test Point Description	Test #	4 BMS Inlet ppCO2 mmHg	4 BMS CO2 Removal kg/day Target / Result	TSAC Loading Pressure psi Target / Result	TSAC Production Rate kg/day Target / Result	TSAC Delivery Pressure mmHg Target / Result	Comments
Integrated 4BMS/TSAC	1	5.27	8 / 7.7	4 / ??	4.2 / 4.24	1000 /	This

baseline test						1002	condition is not listed in the ICES paper
Integrated 4BMS/TSAC at reduced CO2 loading, 5 kg/day	2	3.28	5 / 5.39	4 / ??	Max / 4.24	1000 / 1002	ICES Test #1 4.2 kg/day
Integrated 4BMS/TSAC at reduced CO2 loading, 4 kg/day	3	2.65	4 / 4.5	4 / ??	Max / 4.07	1000 / 1004	ICES Test #3 11/18/05 9:06 AM to 11/19/05 6:13 AM
Integrated 4BMS/TSAC at 4 kg/day and no vacuum desorb of 4BMS	4	2.58	4 / 4.16	4 / ??	Max / 2.89	1000 / 1004	ICES Test #4 11/21/05 9:06 AM to 11/22/05 7:12 AM
Integrated 4BMS/TSAC at reduced CO2 loading, 3 kg/day	5	1.94	3 / 3.49	4 / ??	Max / 3.99	1000 / 1003	ICES Test #5 11/19/05 4:28 PM to 11/20/05 11:41 AM
Integrated 4BMS/TSAC at increased CO2 loading pressure	6	3.26	5 / 5.96	6 / ??	Max / 4.75 /	1000 / 1004	ICES Test #2 4.8 kg/day

2.3.2.2 Results - 4BMS + TSAC + Sabatier

This section describes the test results for the 4BMS, Temperature Swing Adsorption Compressor and Sabatier integration test series. Five different test points were run, each with a different set of operating conditions. The summary of test results is given below in Table 3 along with the summary data from 4BMS + TSAC parametric testing.

2.3.2.2.1   Integrated Test Results - Nominal Steady State Operation

Some of the TSAC integration tests were conducted at nominal steady state inlet conditions to baseline the performance of the systems together. These first three test points were conducted with steady CO2 feed flow to the CDRA and continuous operation of the Sabatier. These cases resulted in sufficient CO2 capture by the TSAC so that there were no periods of Sabatier starvation. The excess CO2 not needed by the Sabatier was

vented by the CDRA directly to the vacuum vent. Figure 5 below illustrates typical TSAC performance for Test Point #1. This test point was run with very high CO2 loading, 8.3 EP. The pink and blue lines are the alternating TSAC bed pressures. There is instrumentation error between the pressure sensor measuring the 4BMS bed and the pressure sensor measuring the TSAC bed. The CDRA discharge pressure must be higher in order to flow to the TSAC. The saw tooth lines at about 10 psia are the equilibrium pressures when each TSAC bed has completed adsorbing CO2 from the desorbing CDRA bed. The saw tooth pressure is the result of the 4BMS bed heater cycling to maintain temperature while the CO2 is desorbing. The smooth lines at about 20 psia are each of the desorbing TSAC beds providing continuous flow to the Sabatier. As long as the green line at the top of the graph (Sabatier inlet CO2 pressure) remains above 18 psia, then the Sabatier is allowed to operate (shown by the purple line at the bottom of the graph). The brown line is the vacuum tank pressure. The large spike at each TSAC bed change is from the CDRA going into the 10 minute space vacuum desorb portion of its operating cycle. The smaller peaks in the middle of each half cycle are from the vent valve opening to relieve the CDRA pressure.
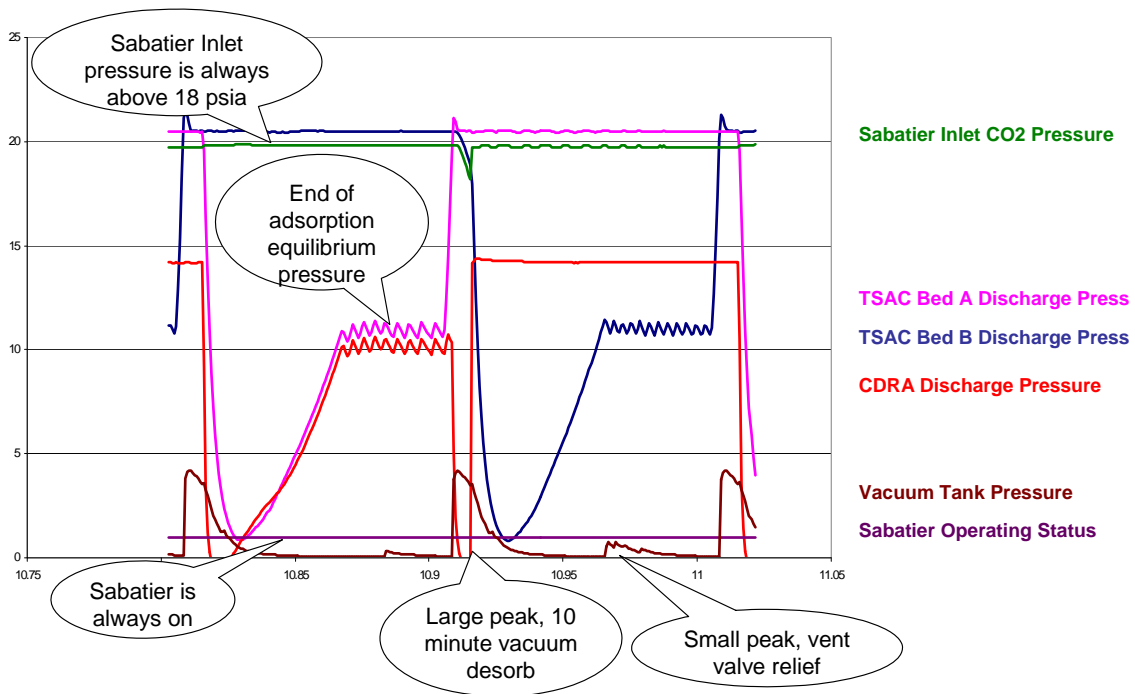
Test Point 1 4BMS/TSAC Comparison

Figure 31 - Typical TSAC Performance Data

Table 15 - Test results for 4BMS / TSAC / Sabatier integrated testing

Test Point	Objective of Test Point	4BMS CO2 Loading (kg/day)	4BMS Inlet CO2 Conc. (mmHg)	4BMS Removal (kg/day) (lb/hr)	TSAC Loading (Suction) Pressure at End of Cycle (kPa) (Torr)	TSAC Production Pressure at End of Cycle (kPa) (Torr)	TSAC Production (Sabatier Demand) Rate (kg/day) (slpm)	Sabatier H2 Feed Rate (slpm)	Sabatier Reactor Inlet Pressure (kPa) (psia)	Sabatier Reactor Hot Zone Temp (°C)(°F)	Sabatier Reactor Outlet Temp (°C)(°F)	Sabatier Starvation Period (min)	Number of 4BMS Vent Cycles in Integrated Operation	Sabatier Water Production Efficiency	Cabin CO2 Utilization
1	Steady State Load Conditions, 8.3 EP	10.90	5.21	7.57 (0.72)	72.79 (10.56)	141.09 (1058.26)	5.23 1.85	6.76	72.48 10.51	534 993	74 166	0		93%	70%
2	SS 5.46 EP	7.51	3.42	6.20 (0.57)	42.75 (6.20)	141.11 (1058.42)	3.43 1.21	4.45	69.21 10.04	527 981	74 165	0		93%	55%
3	SS 2.34 EP	3.27	1.48	2.46 (0.23)	26.28 (3.81)	141.15 (1058.69)	1.49 0.53	1.91	65.05 9.43	472 882	69 157	0		92%	61%
4	Lunar Night	5.56	2.52	4.50 (0.41)	32.36 (4.69)	141.15 (1058.74)	2.53 0.90	3.26	67.50 9.79	518 965	73 163	41	0	95%	45%
5 Part 1	Lunar EVA Exit	2.91	1.34	0.54 0.18	31.61 4.59	141.17 1058.87	2.51 0.89	3.2	67.32 9.76	517 962	72 162	14		95%	71%
5 Part 2	Lunar EVA Return	6.07	2.74	4.27 0.39	42.30 6.14	137.38 1030.45	2.37 0.84	3.16	64.59 9.37	512 953	71 100	174	23	92%	62%

Test points 2 and 3 were designed to copy the operating conditions of the previously completed mechanical compressor integrated tests. The 3 and 5.4 EP CO2 loading cases with continuously operating Sabatier were chosen to replicate (refer to cases 1 and 4 of the Mechanical Compressor tests). As expected, the equilibrium pressure of the adsorbing TSAC bed for each case is related to the CDRA inlet CO2 concentration. This equilibrium data is summarized below in Table 5 and illustrated in Figure 6.
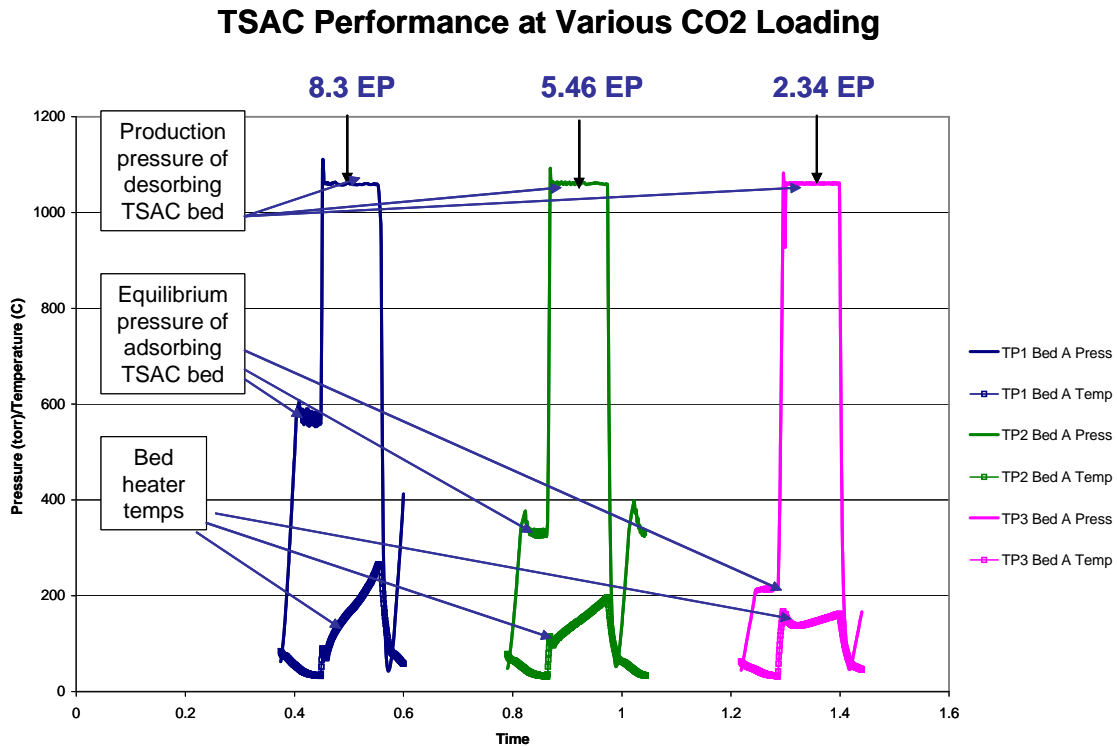

Figure 32 - TSAC equilibrium loading pressure is dependent on CO2 feed to CDRA.

Table 5 below lists water production efficiency data for the various scenarios tested with the 4BMS, TSAC and Sabatier. The Sabatier was upgraded from the previous configuration that was tested with the mechanical compressor, so the efficiency data cannot be directly compared. The upgraded Sabatier EDU has a rotary phase separator, which spins all the time to separate the gas and liquid phases in micro-gravity. Some of the excess heat from the separator motor goes into evaporating the product water, which lowers the recovery efficiency. The previous version of the Sabatier EDU had a tank separator with a pump that only operated when the tank was emptied. For a gravity based mission, such as a lunar habitat, a tank and pump would be the preferred separator.

Table 16 - Sabatier Efficiency Data when Integrated with TSAC

Test Point	Description	Sabatier H2 Feed Rate (slpm)	Sabatier Starvation Period (min)	Sabatier Reactor Hot Zone Temperature (C) (F)	Sabatier Water Production Efficiency	Sabatier Hot Zone Temperature with Mechanical Compressor (C) (F)	Sabatier Water Production Efficiency in Equivalent Mechanical Compressor Test
1	Compare to 4BMS/TSAC baseline	6.76	0	534 993	94%		
2	Compare to Mech. Comp TP4	4.45	0	527 981	92%	510 950	94%
3	Compare to Mech. Comp TP1	1.91	0	472 882	87%	454 850	89%
4	Lunar night scenario	3.26	41	518 965	89%		
5 Part 1	Full crew EVA departure	3.20	14	517 962	96%		
5 Part 2	Full crew EVA return and regenerate	3.16	174	512 953	86% (peak 91%)		
NA	Stand alone Sabatier EDU Test prior to Mech Comp. Integration	9.0	NA	535 995	92%		
NA	Stand alone Sabatier Upgrade EDU test prior to TSAC Integration	2.65	NA	504 940	92%		

2.3.2.2.2 Integrated Test Results - Simulated Mission Profiles

In addition to the steady state tests, lunar mission cases described previously in Section 2.2.3.1.2 were tested. The simulated cabin CO2 concentration profile, which was the result of the cabin atmosphere simulation model, was used as the input profile of CO2 fed to the CDRA.

Test point number 4 was a lunar night scenario. At the South Pole, the lunar night lasts 24 to 48 hours straight, once per month. Since operations would depend on battery power when no solar power is available, it is likely that the oxygen generator would be turned off. Without hydrogen, the Sabatier would also shut down and the TSAC compressor, likewise. A scenario was simulated in which the TSAC and Sabatier were turned off part-way through a CDRA cycle, and allowed to completely cool down before restarting. Figure 7 below shows the results of the simulation when the systems were turned off, allowed to cool, then turned back on.

Lunar Night Cycle Simulation with CDRA/TSAC/Sabatier

Sabatier should have turned on here

32 minutes into Bed B adsorb cycle CDRA turned off

After turning back on, Bed B doesn't have enough CO2 for full cycle
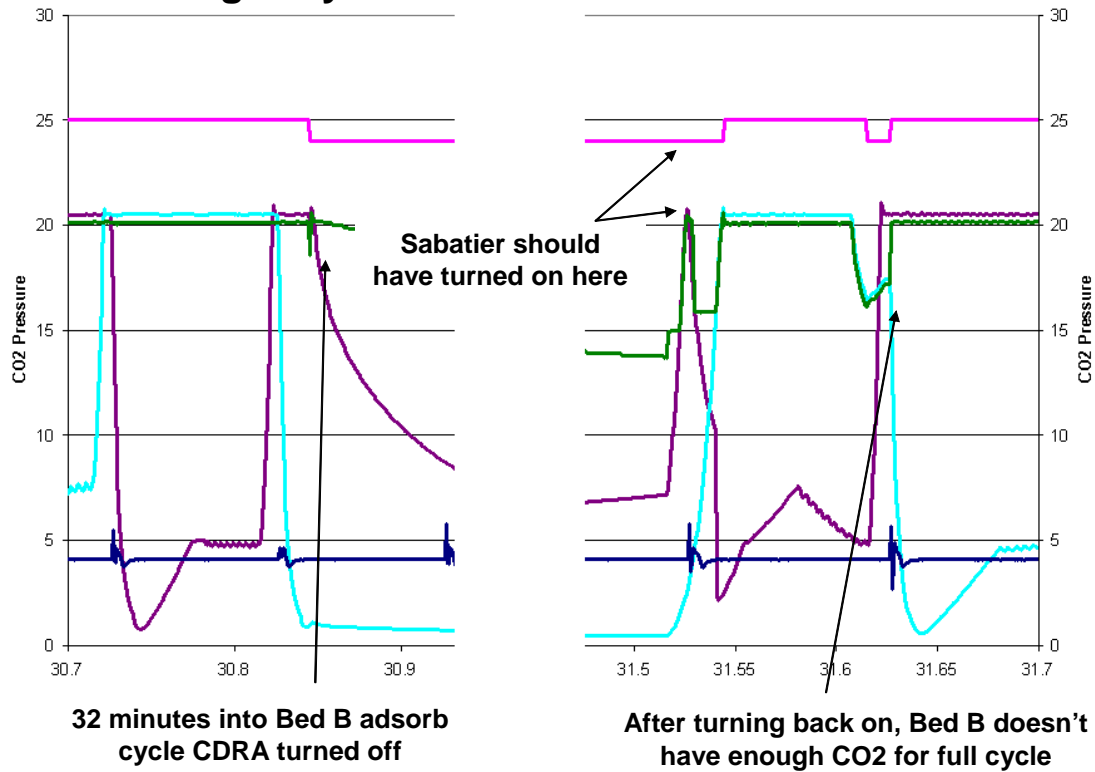
Figure 33 - Results of simulated Lunar night

During the simulation, the CDRA continued to operate as it would be required to properly maintain the atmosphere in the habitat. The CO2 desorbed from the CDRA was vented to the vacuum system as long as the TSAC was turned off. The systems were turned back on 120 minutes into the CDRA cycle, when there was essentially no more CO2 to transfer to the TSAC. The bed that had been adsorbing during the shutdown had only received a partial fill and during the following cycle there was not enough CO2 captured to operate the Sabatier continuously. The systems recovered to normal operation following one full CDRA cycle. The starvation effect could be minimized by starting up the TSAC one half cycle ahead of the oxygen generator and Sabatier as long as the atmosphere oxygen concentration would allow further delay.
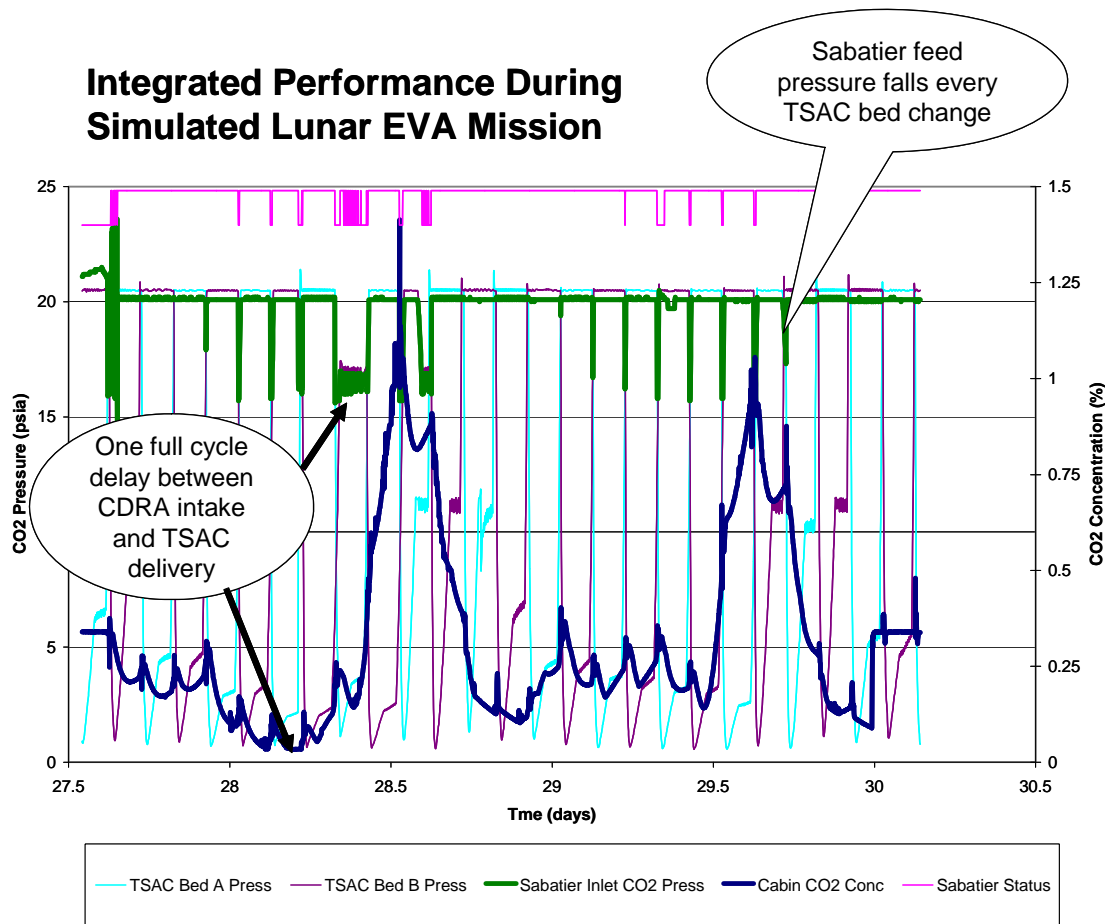
Figure 34 - Simulated Lunar EVA Excursion profile results in long periods of Sabatier starvation.

Figure 8 above shows the results of a simulated lunar EVA mission. The CO2 concentration feeding the CDRA is the result of a simulation of a habitat with 4 crewmembers with periods of EVA followed by regeneration of the EMU CO2 collection canisters in the habitat. There is a time delay of one CDRA cycle (4.8 hours) between when the CO2 concentration in the cabin drops and when the CO2 delivered to the Sabatier is insufficient. This effect could possibly be corrected with intelligent software that lowers the O2 production rate (therefore lowering the Sabatier processing rate) during periods when the TSAC bed loading is low. The final loading pressure of the TSAC bed in its previous half cycle is an indicator of the total bed loading and what the delivery capability will be in the next half cycle.

2.3.3 Conclusions from This Test Section

The testing described herein was the first integrated test of a 4-Bed Molecular Sieve, Temperature Swing Adsorption Compressor, and Sabatier Reactor. Five successful tests were completed with these three systems. These tests provided enhanced understanding

of both nominal, steady-state operation and dynamic, transient scenarios that can be expected to occur on a Lunar base. Six additional 4BMS-TSAC tests explored widely varying 4BMS loading conditions and the corresponding response of the TSAC. In general, the three systems were proved compatible and able to perform their intended functions for a wide range of input conditions.

These specific conclusions are drawn from these test results:

- The dynamic transients expected in a Lunar EVA scenario were played out in Test Point 5. The CO_2 concentration changes due to crew movement into and out of the habitat. The response of the systems is delayed, one system to the next, as each system progresses through half cycles. The hydrogen generation rate (by-product from oxygen generation) is current with crew activity. The CO_2 delivery rate is delayed by one half cycle. This mismatch results in Sabatier starvation. Adaptive software may be a solution to better match the hydrogen and CO_2 rates to feed the Sabatier. There should be sufficient oxygen concentration buffer to allow delayed oxygen production while waiting for the CO_2 to be concentrated.
- Large variations between half cycles were noted during the Lunar EVA scenario. The causes for these variations need to be understood and rectified.
- The TSAC had, on average, less than 5% negative impact on the 4BMS performance. However, much higher deviation was noted at 2.6 torr inlet $ppCO_2$ and bears further review.
- A 4BMS heater ramp control algorithm can save about 50 watts (time averaged power). However, refinements to the TSAC operation will be required to prevent gaps in the CO_2 production to the Sabatier.
- Additional work is required to prevent TSAC exposure to humidity from room air. The TSAC material's sensitivity to humidity required it to be extensively purged after inadvertent exposure to room air. Isolation mechanisms should be implemented and tested to prevent air leakage during 4BMS shutdowns.
- Additional refinements to the overall control software are required for better communication between the 4BMS, TSAC and Sabatier.
- The Sabatier software performed a vacuum leak check during every transition to Standby. If the water level was sufficiently high, the separator would be instructed to pump out the water during the vacuum leak check. The separator cannot create enough pressure rise when at vacuum to satisfy the pump out requirement, which then causes a system shutdown. An adjustment to the Sabatier control is required to prevent separator triggered shutdowns during standby mode.
- The Sabatier required CO_2 pressure deadband should be a minimum of 3 psi when integrated with a TSAC. The low pressure for Standby should be 16 psia and the high pressure should be 19 psia when operating at the conditions used in this test program. A smaller deadband results in valve chatter while the TSAC is heating up and generating pressure.
- The TSAC and 4BMS need sufficient communications to synchronize their half cycles and to signal each when shutdowns and initiated.

3 Conclusions

The testing described herein was the first integrated test of a Four-Bed Molecular Sieve, Sabatier Carbon Dioxide Reduction Assembly with the interfacing CO2 compressor. Two compressor technologies were tested, a mechanical oil-free piston compressor, and a temperature swing adsorption compressor. The mechanical compressor was tested under simulated International Space Station parameters. The TSAC was tested under simulated Lunar Base parameters. Both sets of tests provided enhanced understanding of both nominal steady operation and dynamic, transient scenarios that can be expected to occur in an integrated Environmental Control and Life Support System.

Additionally, the compressors were tested independently and with only the 4BMS over varying CO2 loading conditions. The corresponding compressor response to changing conditions was observed.

In general, the 4BMS, Sabatier and both compressor technologies were proved compatible and able to perform their intended functions for a wide range of input conditions.

3.1 Overall Conclusions from the Integration Test Experience

The integration test of the 4-Bed Molecular Sieve with two different compressors and a Sabatier reactor was a successful test program. The testing showed that these systems could be properly integrated together. There is no significant, detrimental impact on the 4-Bed CO2 removal system when desorbed with a compressor instead of space vacuum. 4-BMS CO2 removal efficiency was well above requirements for the wide range of CO2 inlet concentrations tested. The different systems' control logic in place during this test program supported the wide range of conditions tested. These tests provided enhanced understanding of both nominal, steady-state operation and dynamic, transient scenarios. In general, the three systems were proved compatible and able to perform their intended functions for a wide range of input conditions.

3.2 Summary of Observation from the Integration Test

These specific conclusions are drawn from the test results:

- Both compressors (TSAC and mechanical) had a small but measurable effect on the CO2 removal performance of the 4BMS. Since the vacuum level is not as low as space vacuum, some residual CO2 remains on the CO2 removal beds, which in turn reduces their capacity on the next adsorb cycle. During the mechanical compressor testing, the performance reduction was 5.4%. During the TSAC testing, the performance reduction ranged from 1-9% with an average of 4.2%. The integrated

performance may be improved with longer space vacuum desorb time or higher temperature. This subject is a candidate for further testing.

- As a result of this testing, the mechanical compressor simulation model was modified to better predict flow at low suction pressures.

- The 4-BMS model was also updated to incorporate a leakage factor to estimate air leakage into the system components that operate at vacuum.

- The dynamic transients expected in a Lunar EVA scenario were evaluated in the TSAC testing. The test results showed a significant time delay from crew activity to system performance. Adaptive software may be a solution to better anticipate system changes and to alter production rates to maintain system balance.

- Both compressors had, on average, less than 6% negative impact on the 4BMS performance.

- A modified 4BMS heater ramp control algorithm was tested and resulted in power savings, however gaps in CO2 delivery occurred. The prospect of power improvements is likely and future testing of modifications to the heater schedule is warranted.

- Additional work is required to prevent TSAC exposure to humidity from room air by implementing isolation mechanisms.

- Additional refinements to the overall control software are required for better communication between the 4BMS, TSAC and Sabatier.

- The TSAC and 4BMS need sufficient communications to synchronize their half cycles and to signal each other when shutdowns are initiated.

- The current compressor operation/control logic appears to support a wide range of test conditions, but modifications may need to be made in order to reduce starvation during the low EP cases as well as reduce the number of brief operation cycles during high EP loading.

- Also, the impact of increased cycles on the 4BMS vacuum vent valve should be evaluated to determine if these operating rules could be improved.

- The data collected over the course of integrated testing is currently being compared with predictions from existing models to validate the model against test data. The model is being adjusted as required to duplicate test results. Thus far it has been determined that the current compressor model does not adequately predict flowrate through the compressor at low suction pressures. A curve fit has been added to the compressor model based on test results. In addition, the impact of vacuum circuit in-leakage has become very evident upon comparison of test results with model

predictions. Efforts are underway to estimate the current bed leak rates and incorporate them into the model as a "worst case". An operational flight system, once leakage due to sorbent dusting is eliminated, is expected to have a much lower leak rate.

- The impact of in-leakage on the system and its operating rules cannot be ignored since in-leakage results in increased compressor run time as well as decreased Sabatier efficiency. While it may be difficult to implement, any future plans regarding the integration of a flight CDRA with a CRA should also involve re-evaluating existing protocols for verifying CDRA as well as CRA leak rates. As observed in this test, current CDRA/4BMS leak test procedures could result in significant in-leakage that impacts CRA performance.

- The dynamic transients expected in a Lunar EVA scenario (TP 5) provided insight on the delayed response of both the 4BMS and TSAC. Consideration of adaptive software to better utilize large influxes of CO_2 is suggested.

- Large variations between half-cycles were noted during the Lunar EVA scenario. The specific causes for this trend need to be understood and rectified.

- The TSAC had, on average, less than 5% negative impact on the 4BMS performance. However, much higher values were measured at about 2.6 torr inlet pp CO_2, and bear further review.

- A 4BMS heater ramp control algorithm can save about 50 watts (time-averaged power). However, refinements to the TSAC operation will be required to prevent gaps in CO_2 production to the Sabatier.

- Additional work is required to prevent TSAC exposure to room air. An isolation valve, or other appropriate solution, should be implemented and tested.

- Additional refinements to the overall control software are required for better communication between the 4BMS, TSAC, and Sabatier.

- An adjustment to the Sabatier control is needed to prevent separator-triggered shutdowns following standby mode.

- 4BMS performance was well above requirements for the range of inlet CO2 concentrations tested.

- In general, the current TSAC operation/control logic appears to support a range of test conditions, but a more robust test matrix should be explored in future.

- Upgraded components within the Sabatier EDU performed as expected.

- Lessons learned from this test can, should, and will be incorporated into future revisions of the CDRS hardware.

3.3 Lessons Learned

3.3.1 Lessons Learned from the Integration Testing

This section documents the Lessons Learned, Anomalies and Resolutions that were implemented as part of the integrated testing.

- Hydrogen flow rate inconsistent across various measurement means, system mass balance not in check. Sabatier water production efficiency calculation is based on hydrogen flow rate.
  - *Critical parameters that are used to evaluate system performance against requirements must be accurate and verified against accepted standards.*
- Loss of network communication from the Sabatier system led to a crash of the overall control computer, which in turn led to shutdown of the other subsystems.
  - *Control systems need to be designed such that subsystems can continue to operate independently if they lose contact with the main controller. In the case of the ARS, the CDRA is considered critical life support and needs to have the capability to continue operation in the absence of higher level commands. The Sabatier software must be designed to not propagate errors outside its boundaries.*
- The Sabatier system rapidly cycled from Process to Standby during operation with the TSAC compressor during low CO2 production rates. The transition was keyed off of CO2 supply pressure limits. The Sabatier operating bands designed initially for the mechanical compressor operation were too tight for TSAC operation. Pressure bands were widened to allow smoother, slower mode transitions and avoid rapid cycling.
  - *System triggers that initiate logic decisions (such as changing operating mode, activating control loops, etc) must be examined and exercised over the widest range of operating conditions possible. The problem during the testing was resolved by changing the set points for the transition commands. These type of set points should also be variable in the control software so they can be adjusted to optimize operation.*
- The Sabatier phase separator pump attempted to pump water out of the system when in standby while the pressure was very low. The pump could not overcome the differential pressure to pump out water when the system pressure was so low.
  - *The Sabatier flight software was designed to prevent the separator from pumping water during any low-pressure conditions. The software also performs a pump-out prior to transitioning to Standby while there is still pressure in the system to aid the pumping.*
- The Sabatier system rapidly between Standby and Process such that the Standby evacuation was not completed. Valves were chattering during the transition. The

action of the valves cause pressure changes that in turn changed status in the software that caused the valves to change position again. This was another artifact of control ranges set too close together. The transitions were taking place prior to completion of purge steps and the software ended up caught in an indeterminate state.

- o *Software logic should be designed such that sequences are completed before subsequent operating state changes are allowed to occur. Checks should be incorporated to verify that procedures (such as purges) are completed.*

- If the Sabatier had gone through a shutdown and was still hot, upon restart it would go directly to Process without performing the required purge in Standby first. Apparently the temperature requirement was met and the software did not wait for the purge requirement to be met.
  - o *Software must be written to ensure that all requirements are met, not just the first requirement. Careful testing is often needed to flush out these types of errors in code, as it is often only a unique set of circumstances will create the right conditions for these anomalies.*

- Sabatier reactor thermal soak back – when flow to the reactor stops (as in Process to Standby transition) the heat of the reactor soaks back to the inlet. This was accommodated in the Sabatier EDU by increasing high temperature shutdown limits. The flight reactor design also acknowledged this phenomenon and designed the inlet end instrumentation to tolerate high temperature.
  - o *Component and controls design must consider all conditions, including non-operational conditions.*

- 4MBS heater ramp rate – during the TSAC testing, the 4BMS heater control was modified from a fixed temperature setpoint control to a ramp rate in which the temperature linearly increased from 60 to 400 F. The result of this test was a savings of 50 W time averaged over the desorption cycle, however, less CO2 was desorbed from the 4BMS to the TSAC during the cycle. The overall integration result was starvation of the Sabatier reactor for steadily increasing durations. Due to the potential power savings, further evaluation of modified desorption schedules is warranted.

- TSAC sensitivity to leaks – during testing, the TSAC was inadvertently exposed to room air several times. Since the adsorbent material is very sensitive to humidity, the TSAC had to be taken offline and purged for an extended period of time before resuming testing.
  - o *Future integrated designs must include means of isolating the TSAC to prevent accidental exposure to cabin air. Subsystem design must consider operating and non-operating states that may be damaging to the hardware.*

- Integrated TSAC / Sabatier control pressure – as a result of the testing, it was determined that a minimum of 3 psid is needed for the Sabatier setpoints for CO2 pressure. When the Sabatier transitions to Process, the initial draw of CO2 lowers

the TSAC pressure by more than 2 psid. If the transition setpoints are too close together, the systems will cycle rapidly between Process and Standby.

- Air effects on Sabatier performance – temperature anomalies were noted in the Sabatier profile during the mechanical compressor testing. It was concluded that the temperature spike at the reactor inlet was due to higher than normal concentration of air during a 4BMS bed switching event. The Sabatier reactor is robust to the presence of air and its known temperature profile proved to be a good indicator of altered operating conditions.
    - *A future test item would be to determine if the reconfigured Sabatier reactor temperature sensors are as sensitive to detecting air inclusion as the EDU Sabatier.*

- Sabatier Phase Separator operation at vacuum – testing determined that the rotary phase separator cannot pump water out when the gas pressure is at vacuum. The flight operating control is configured to empty the separator at the beginning of a Standby transition when the gas pressure in the system is still relatively high.

- CDRA leak check – A significant observation made during integrated testing was that hardware leakage could be masked if the hardware is leak checked while not in operation. For example, during initial integration testing, the 4BMS passed leakage testing, yet significant air in-leakage was observed during testing. The root cause was a selector valve that was cold-soaked during operation that caused the soft goods to shrink and allow leak paths. The valve was not cold during the static system leak check, and therefore passed the test.
    - *Systems need to be leak checked in their operating environment to ensure trouble free operation.*

3.3.2 Lessons Learned from the Sabatier Flight Program

This section documents Lessons Learned that were incorporated into the flight Sabatier design as a result of the integration testing.

3.3.2.1 Hardware Changes Required

- Hydrogen Vent Tee – the space station OGS rack was initially designed with a scar for the Sabatier Assembly to be added at a later date to the Oxygen Generation Assembly, but the Sabatier design was not very far advanced at the time the rack was launched. The initial plan was for the Sabatier to vent in the same line as the CDRA. This was later changed to having the Sabatier use the hydrogen vent from the OGA instead.
    - *The implementation of this change required the addition of a tee line that would be inserted at the interface panel quick disconnect. The change also*

imposed restrictions on the rate of discharge of the Sabatier to meet the restrictions of the shared vent line.

3.3.2.2 Software Changes Required

- CDRA Control Software – the flight CDRA software did not have provisions for interface commands related to a Sabatier system. The software had to be modified to keep the bulkhead vent valve closed so that the Sabatier could extract the CO2 from the desorbing CDRA beds. The CDRA venting logic, as noted earlier, is different for the flight system than the ground test system. Once the flight system bed pressure exceeds 8 psi, indicating that the compressor has not been activated, the vacuum vent valve is opened and left opened for the remainder of the desorption cycle. The loss of recovered CO2 is acceptable at this point since the accumulator is likely full or the system is not operational. This modification keeps the total number of cycles on the vacuum vent valve the same as that for which they were originally designed.

- OGA Evacuation Check – the OGA will check the pressure in the Sabatier hydrogen delivery line before opening the valve to deliver hydrogen. If the pressure is high, the Sabatier could potentially have air in it. The OGA will not deliver if the pressure is too high to avoid a potentially hazardous condition. The pressure limit was initially 0.3 psia. This limit was too low, as the Sabatier pressure would at least be that of the vapor pressure of water in the phase separator, plus any instrumentation error in the pressure sensor. The limit was raised to 3.0 psia and the change made to the OGA software.

- Phase separator pumpout – as a result of the integrated testing, the flight Sabatier software included provisions to pump out the phase separator at the very beginning of a transition to Standby while there is still sufficient gas pressure in the separator. The software then does not allow the separator to pump out any other time in Standby.

3.4 Recommendations for Subsystem Modification if Designing a New System

- CDRA/TSAC combined design

Can there be weight/power/volume savings if the CDRA and TSAC were designed as a single system? LPCOR

- CDRA / OGA cycle mismatch

  The ARS system on ISS is designed with the OGA operating on a 90 minute diurnal cycle, which matches the station orbit. The OGA would be powered and producing hydrogen during the "day" when power is plentiful and in standby during the "night" when power is scarce. The CDRA operated on a 144 minute half cycle. The mismatch in cycle times requires the use of storage volume to collect CO_2 when hydrogen is not available to process.

  This would be a good area to investigate in the future, either through modeling or testing, to see if matched cycles results in less starvation or smaller accumulator volume.

- CDRA Power Usage – Desorption Rate

  The current design of the 4MBS has the heaters turn on full power during the desorption phase if the station is in the daylight portion of the orbit. Testing with both compressors has shown that the 4BMS can retain CO_2 in the bed for a significant period of time as long as the bed is evacuated to space vacuum for the final 10 minutes of the cycle. The 4BMS may possibly be operated such that the bed is pressure controlled instead of temperature controlled to save power when the compressor is not ready to receive CO_2. This would prevent venting of the CO_2 from the 4BMS to space vacuum.

  Investigate by modeling or testing.

- CO_2 tank proof pressure

  During the period of time leading up to the Integration Test program, the OGA for the International Space Station was designed and built. Coincidental development of the Sabatier led to incorporation of accumulator tanks into the OGS rack prior to its launch. The volume available for these tanks was smaller than desired, but development testing of the mechanical compressor showed that the compressor could meet the higher pressure demand required to offset the smaller volume. Although these tanks were designed and manufactured to accommodate very high pressures, they were only proof tested to 160 psia. The application of sensor inaccuracies and control bands to the operating system requirements resulted in a usable maximum operating pressure of only 115 psia. In practice, this lower operating pressure will result in greater venting of CO_2 overboard and likely associated Sabatier starvation. Interfacing systems should be proofed to as high a pressure as possible per the results of trade studies. The CO_2 accumulator for ISS was proofed to 145 psig (160 psia), but the application of sensor accuracies to overpressure protection reduces the actual maximum operating pressure to 100 psig (115 psia).

- Shared Vent Lines - Restriction on flow, temperature, MDP,

  In the ISS design, the Sabatier shares the vent line with the OGA. The vent line was sized and proof tested to meet the requirements of the OGA alone. During integrated operation, there are times when both systems must be able to vent gases

through this line at the same time. The line is not sized to accept this much flow without creating excessive back pressure. The Sabatier must therefore restrict the rate at which it allows venting gases to flow into the line.

Future integrated designs must consider all operating scenarios, including startup and shutdown, as input to designing interfacing systems (i.e. vent line).

- Coolant Interface

  The coolant temperature directly affects the percent of water recovery of the Sabatier system by setting the dew point temperature at the phase separator. Coolant temperature should certainly be included in any trade study for future ARS designs. The additional water recovery would have to be traded against issues of external condensation on coolant lines if installed in a habitable volume of the spacecraft or habitat.

- OGA Interface – Pressure Check

  The design of the ISS controls requires that the OGA verify that the Sabatier had been vented prior to allowing hydrogen to flow to the system. This is done for system safety to prevent introduction of hydrogen to the Sabatier if it was full of air. The target pressure value had been set to 0.1 psia to verify evacuation. However, this value is not achievable when the Sabatier system has water in the phase separator. When evacuated, the inlet pressure will be something more than the vapor pressure of water at the phase separator temperature. For ISS installation, a modification will have to be made to the OGA software to raise the pressure limit used for the interface check.

  This system check also requires that the Sabatier be evacuated during every standby. This results in some product water loss. The water recovery gained by not venting would have to be traded against other methods of preventing flammable mixtures.

- Waste Water Bus MDP

  The waste water bus on ISS has a MDP of about 90 psig. The Sabatier system was designed with an MDP of 268 psig to provide containment as a final means of protection against damage due to detonation. The interface of the phase separator to the waste water bus was an area of concern due to the possibility of transmitting a pressure wave through the water lines. I will get the details on how this was resolved.

- Location in Habitable Volume

  The ISS ARS is designed with all components in the habitable volume. This then requires that all of the components that contain flammable gas have either secondary containment (the OGA dome) or be operated at sub-ambient pressure to prevent leakage of gas out into the cabin. The sub-ambient operation results in a water recovery penalty, as the lower system pressure increases the volume fraction of water vapor that is vented with the methane product gas. For exploration systems, locating the flammable gas components outside the habitable area would allow operation at higher pressure, and therefore increase water recovery. There may be other benefits of volume and mass savings achieved by operating at higher pressure.

- Acoustics and EMI Restrictions

  Acoustics and EMI are not insurmountable requirements, but add weight and volume to systems for attenuation. Location of the system outside the habitable volume may lessen the burden of acoustic and EMI requirements.

4 Recommendations

4.1 Recommended Future Testing

This integrated test program has shown that a closed loop Air Revitalization System is achievable and practical. However, there is insufficient data from either integrated test to draw conclusions about the long term effects of each compressor on the 4BMS operation, and vice-versa. The testing uncovered possible areas for improvement, and areas where more information is needed. The testing has shown that the systems can be integrated with acceptable reduction of performance of the 4BMS and the resulting water recovered is as much as 90% of what is theoretically possible. Long duration experiments under controlled conditions, in terms of 4BMS loading, TSAC loading, compressed CO2 production, CO2 purity, vacuum levels, etc.., should be performed to better understand long term performance.

4.1.1 Recommended Test Objective

Any future development should focus on improving the systems' equivalent system mass (ESM - weight, power and volume), efficiency and reliability. Many observations were made of potential improvements in ESM and reliability. These potential improvements should be the focus of follow on testing or modeling work.

Due to software control limitations, the integrated tests to date were performed at preset operating schedules. Upon adding a more sophisticated and flexible control system, the integrated systems should be tested under dynamic operating conditions where the system parameters such as CO2 inlet, cycle time, standby time, etc are varied in a non-uniform pattern (that are realistic to mission-specific scenarios).

4.1.2 Specific Recommended Tests

The following specific test recommendations are made with a focus on discovering potential areas for improvement to system weight, power, volume, efficiency or reliability.
- Test integrated combinations of compressors and the 4BMS with different lengths of vacuum desorb time and different desroption temperatures to determine if the

4BMS CO_2 removal efficiency can be improved. The integrated testing showed an average loss of CO_2 removal efficiency of about 4-5%. This loss may be recovered by modifying operating times.

- Test adaptive software for the overall ARS system to better match CO_2 and hydrogen availability. This would lead to minimizing instances of Sabatier starvation and improved overall water recovery.
- Test variations of heater ramp algorithms to determine if power savings can be achieved in both 4BMS and TSAC components.
- Test the TSAC with lower pressure cooling air (as might be a design requirement for a Lunar base or future spacecraft) or with alternate cooling medium (liquid) as might be available in future application. Each will have design impacts on the cooling rate and overall efficiency.
- Use the ground based hardware to verify protocols for evaluating leakage rates of in-flight hardware to improve flight system reliability.
- Further test variable loads, such as the Lunar EVA scenario tested here, to flush out the reason for the large variations noted between half cycles. This will lead to better understanding of the system operations and ultimately improve efficiency and reliability.
- Investigate the large performance impact noted at 2.6 torr inlet CO_2 pressure and not at other CO_2 concentrations during TSAC/4BMS testing. Perform addition tests if warranted. It remains unknown whether this stems from a testing anomaly, analysis error, or is indicative of a true performance sensitivity. Additional testing will provide a basis for overall system repeatability and measurement accuracy.
- Review test results to determine specific combinations of factors that cause subsystem shutdowns and make necessary control modifications. An example is the Sabatier separator attempt to empty at vacuum pressure. This protocol was corrected in the Sabatier flight software.
- Perform testing over a more robust range of operating conditions. The wider the acceptable operating range, the more flexibility for future loop closure.

4.2 Recommended Future Hardware Development

4.2.1 Subsystem Development

These are some possible development tasks that would result in improvements in ESM and reliability based on the results of the completed testing. Additional improvements may be discovered as a result of additional future testing outlined above.

- Develop a heater ramp algorithm for the 4BMS that will save power, yet accomplish the CO_2 desorption needed.

- Develop isolation mechanism and associated control to prevent room air humidity from entering TSAC beds.
- Improve heat transfer design of the TSAC and the 4BMS in order to reduce power usage by investigating the following factors:
    - Arrangement of heaters and cooling ducts to minimize the thermal mass;
    - New adsorbents or adsorbent structures with reduced thermal resistance;
    - Improved package insulation; and
    - Flexibility in design to allow utilization of waste heat.
- Design TSAC for moisture management which may include system isolation, moisture sensing and on-line regeneration.
- Improve TSAC controls which allow flexibility in startup, operation and shutdown, and allow better subsystem communication and synchronization.
- Implement adaptive software which will allow optimization of product delivery based on previous cycle loading, purge control, compression time, and available power.
- Develop subsystems that are modular, that operate more efficiently at reduced loading and can be stacked for higher loading.
- Develop low volume, lightweight, high temperature components.
- Continue development of the LPCOR system that combines the CO2 removal and CO2 compression functions of the 4BMS and TSAC.
- Through modeling or testing, evaluate the impact of different cycle times for the 4BMS and Sabatier. Determine if there is an optimum cycle time for each that minimizes the accumulator volume and/or overall system power.
- Evaluate the impact of powering the 4BMS heaters to control bed pressure rather than temperature.
- Evaluate the length of vacuum desorb time needed to fully clear the 4BMS beds if the bed is pressure controlled prior to desorption.
- Determine the water recovery cost/benefit as a result of higher or lower Sabatier operating pressure, and the associated system level impacts.

4.2.2 Component Development

- Consider all operating and non-operating conditions (such as temperature and pressure extremes) when designing components.
- Test flight-like Sabatier reactor to determine if the temperature sensors are sensitive enough to detect excessive air in the CO2 as was noted with the EDU reactor.
- Develop a liquid cooled Sabatier phase separator for maximum water recovery.

4.2.3 Controls Development

- Improve communication links between integrated subsystems for synchronizing cycles and reporting system anomalies and shutdowns.
- Improve mechanical compressor operating logic to minimize short cycles and reduce starvation at low CO2 loading.

- Improve operating rules for 4BMS vent valve to minimize cycles on the valve.
- Develop protocols for verification of accuracy of key measurement sensors.
- Develop software protocols that prevent propagation of failures to other systems, and the ability to operate independently if needed.
- Evaluate system triggers that initiate logic decisions and exercise them over the widest practical range of operating conditions. This will prevent issues such as rapidly cycling caused by pressure dead bands.
- Develop controls protocols that can be adjusted by crew intervention or by "smart" controls. This will allow a system to acclimate to its environment (for example, microgravity) and make necessary adjustments.
- Design software logic such that sequences are completed before subsequent operating state changes are allowed to occur. Checks should be incorporated to verify that procedures (such as purges) are completed.
- Design software such that all conditions are met before transitions occur. Careful testing over a wide range of operating conditions is needed to locate errors in code.
- Optimize Sabatier/TSAC pressure control logic and operating limits for transitions between Process and Standby that are based on TSAC delivery pressure.
- Develop protocols for leak checking components in their operating environment so that so that non-operating conditions (temperature or pressure) do not mask the detection of leakage.

5 Appendices

Calculations

This section details the calculations used to evaluate the performance of the subsystems during the Integrated Test Program.

Raw Data – Sensor for Mechanical test only in green, for TSAC test only in red, for both tests in black.

Tag	Name	Units
CDPGas124	4BMS Inlet Air CO2 Concentration	%CO2
CDPGas125	4BMS Outlet Air CO2 Concentration	%CO2
AFCGas126	Lab Air CO2 Concentration	%CO2
CDPDP_120	4BMS Inlet Air Dewpoint	F
CDPDP_121	4BMS Outlet Air Dewpoint	F
AFcDP_120	Lab Air Dewpoint	F
CDPTmp120	4BMS Inlet Air Temperature	F
CDPTmp121	4BMS Outlet Air Temperature	F
AFcTmp120	Lab Air Temp. Middle	F
CDPmt13	5A Bed 308 Heater Temp A	F
CDPmt14	5A Bed 308 Heater Temp B	
CDPmt16	5A Bed 309 Heater Temp A	F
MSAFlw022	Lab CO2 Inject Flowrate	SLPM
CDPMpde	4BMS Operating Mode 0OF 1SH 2A1 3A2 4A3 5B1 6B2 7B3 8WP	
CDPmw12	5A Bed 308 Primary Heater Power	Watt
CDPmw13	5A Bed 309 Primary Heater Power	Watt
CDPmw14	5A Bed 308 Secondary Heater Power	Watt
CDPmw15	5A Bed 309 Secondary Heater Power	Watt
CDPFlw121	4BMS Inlet Air Flowrate (TSI Meter)	SCFM
CDPTmp086	4BMS Precool Inlet H2O Temp	F
CDPFlw080	4BMS Precooler Inlet H2O Flow	GPM
CDPPrs120	4BMS Inlet Air Pressure	PSIA
CDPPrs122	4BMS Outlet Air Pressure	PSIA
CDPDP_023	Dessicant Bed Outlet Air Dewpt	F
MSAMas020	Facility CO2 Tank Weight	Lbs
CDPPrs021 CDPPrs023	Fac Vacuum Tank Air Inlet Pressure	Torr
CDPPrs022 CDPPrs024	Fac Vacuum Tank Air Pressure	Torr
CDPmt11	Desiccant Bed Outlet Temperature	F
THCFlw120 VenFlw120	THC CHX Outlet Air Flowrate	SCFM
CDPPrs123	Sorbent bed 308 pressure	PSIA
CDPTmp125	Desiccant bed 104 Outlet Air Temp	F
CDPFlw120	4BMS Inlet Air Flowrate (Sierra Meter)	SCFM
CDPFacClk	4BMS cycle Elapsed Time	
CDPmdns	4BMS Day/Night Status	
AfcPrs120	Lab Pressure	PSIA
MSAFlw023	Lab High CO2 Inject Flowrate	LBS/HR
CDPPrs121	Precooler Outlet to Ambient	PSIA
CDPTemp133	Precooler Inlet Air Temp	Deg F
MSA3WV020	0 is Inlet 1 is THC	
CDPmp12	Pump Inlet Air Pressure	PSIA
CDPVlt120	2-Stage Pump (Air Save) Voltage	Volts
CDPCur120	2-Stage Pump (Air Save) Current	Amps
CDPmp10	Blower Delta Pressure	In H2O
CDPmz16		
CDPTmp640		

Tag	Name	Units
CDPSpr003		
MEDDP_020	Mechanical Compressor Outlet Dewpoint	F
MEDFlw020	Compressor Outlet Flow after DP	lb/hr
MEDPrs020	Compressor Inlet Pressure	PSIA
MEDTmp020	Manifold Outlet or Crankcase HX inlet	F
MEDTmp021	Crankcase HX Outlet or CP HX inlet	F
MEDTmp022	Manifold Inlet	F
MEDTmp023	Cold Plate Outlet	F
MEDTmp024	Crankcase External Motor End	F
MEDTmp025	Lower Guide Cylinder Stage 1 Motor End	F
MEDTmp026	Crossover Head Stage 1 Motor End	F
MEDTmp027	Crossover Head Stage 2	F
SEDCO2 cmd	Sabatier CO2 Command	SLPM
MEDFlw021	Sabatier CO2 Flow	SLPM
SEDMFM006		
SEDCompressor	Compressor command	1=on 0=off
TSAF prod	TSAC outlet CO2 flowrate	Sccm
TSAP1	Bed A Internal pressure	Torr
TSAP2	Bed B internal pressure	Torr
TSAExtWalA	Bed A External Wall Temperature	C
TSAHA1	Bed A Heater 1 Temperature	C
TSAHA3	Bed A Heater 3 Temperature	C
TSATouchA	Bed A Touch Temperature	C
TSAExtWalB	Bed B External Wall Temperature	C
TSATouchB	Bed B Touch Temperature	C
TSAHB1	Bed B Heater 1 Temperature	C
TSAHB3	Bed B Heater 3 Temperature	C
TSAPower	Heater power for Bed A and Bed B	Watts
TSAF cdra	TSAC Inlet CO2 flowrate	Sccm
TSAAirInA	Bed A Cooling Air Inlet Temperature	C
TSAAirInB	Bed b Cooling Air Outlet Temperature	C
TSAAirOutA	Bed A Cooling Air Inlet Temperature	C
TSAAirOutB	Bed A Cooling Air Outlet Temperature	C
TSAP cdra	Inlet pressure	Torr
SEDP106	H2 Inlet pressure	Psia
SEDH2_SP_ent	OGA H2 setpoint	
SEDP002	CDRA pressure	psia
SEDCRA READY	Status	1=on 0=off
SEDCurrent	Current from OGA 0-4095 counts 0-100 Amps	
SEDDP405	Reactor Delta Pressure	PSID
SEDDP409	Separator Delta Pressure	"H2O PSID
SEDEOGAREADY	Ethernet write 1=on 0=off	
SEDH2 cmd		SLPM
SEDHtr A	1=on 0=off (Y20)	
SEDHtr B	1=on 0=off (Y21)	
SEDMas020	Sabatier EDU Water	Grams
SEDMFC	H2 Mass Flow	SLPM
SEDMolar	User selected molar ratio	
SEDOGA READY	Status 1=on 0=off	
SEDP000	Compressor suction Pressure CDRA Pressure	PSIA
MEDPrs021	Accumulator Pressure or CO2 inlet	PSIA
SEDP006	Reactor inlet pressure	PSIA
SEDP206	Nitrogen inlet pressure	PSIA
SEDP304	Product water pressure	PSIA
SEDP601	Reactor outlet pressure	PSIA
SEDProcess	Process Mode (C102)	
SEDPUMP301	Water pump 1=on 0=off	
SEDSEP_run		
SEDPurge	Purge Mode	
SEDstby_purge		
SEDReactCool	501 Cooling Air Valve 1=closed 0=open	
SEDSVO501		
SEDShutdown	Shutdown Mode	
SEDStandby	Standby Mode	

Tag	Name	Units
SEDStop SEDASD	Stop Mode	
SEDT CHXout A SEDT407-1	Heat Exchanger Outlet Temperature	degF
SEDT CHXout B SEDT407-2	Heat Exchanger Outlet Temperature	degF
SEDT React A SEDT403_1	Reactor Hot Zone Reacto Temperature 1	degF
SEDT React B SEDT403_2	Reactor Hot Zone Reacto Temperature 2	degF
SEDT React C SEDT403_3	Reactor Inlet Reacto Temperature 3	degF
SEDT React D SEDT403_4	Reactor Inlet Reacto Temperature 4	degF
SEDT React Out SEDT404_1	Reactor Outlet	degF
CDPSV_160	Vacuum Solenoid	
CDPSV_640	(0 Closed 1 Open) TSAC	
CDPSV_641	(0 Closed 1 Open) Space Vacuum	
CDPSV_642	(0 Closed 1 Open) MPC	
CDPmz16	Valve Pos. 209 (T = Ener. = B Pos.) Volt	
CDPTmp640	Re-positional Instr. Cluster Temp	F
CDPSpr003	Sabatier Inlet Hydrogen Flowrate	SLPM
SEDFCV003_cmd	CO2 flow command	SLPM
SEDsep_spd	Separator speed	Rpm
SEDfan	Cooling fan status	
SEDMFC103_cmd	H2 flow command	
SEDH402_1	Heater status	
SEDsep_curr	Separator current	Amps
SEDMas020	Sabatier EDU Water	Grams
SEDMFC103	Actual hydrogen flow	SLPM
SEDmolar_ratio	User selected molar ration	

Calculated Data for Mechanical Compressor Test

Name	Units	Calculation
Time	Hours	(current time – initial time) *24
FMG62 4BMS Inlet Air CO2 Pressure	mmHg	(inlet air CO2 concentration/100 * inlet air pressure) *760/14.7
CO2 in	lb/hr	(inlet CO2 pressure/air pressure) * (flow*60) * 14.7*144 *44 / (R * (T+460))
FFG69 4BMS Outlet Air CO2 Pressure	mmHg	(outlet air CO2 concentration/100 * inlet air pressure) *760/14.7
CO2 out	lb/hr	(outlet CO2 pressure/air pressure) * (flow*60) * 14.7*144 *44 / (R * (T+460))
4BMS CO2 Removal Rate	lb/hr	CO2 rate in – CO2 rate out
FMG10 Lab Air CO2 Pressure	mmHg	(lab air CO2 concentration/100 * inlet air pressure) *760/14.7
4BMS CO2 Removal Fraction		1-CO2 out/CO2 in
Total Heater Power	Watts	Sum of 4 heaters, bed 308, 309 primary and secondary
Total	Watts	Sum of 4 heaters plus air save pump power
FMD13 Desiccant bed outlet	mmHg	Dew point converted to saturation pressure
H2O lost	lb/min	Air flow rate * sat pressure * 18 * 14.7 * 144 / (760 * R * (T +460))
Air-Save Pump Power,	Watts	Pump voltage * current (> 0)
CO2 Injection	scfm	CO2 injection (slpm) * 0.035315
Flow Rate from CO2 injection	Scfm	(CO2 injection flow * (1- outlet CO2 %))/((inlet – outlet CO2%)/100)
CDPmp12 Pump Inlet Air Pressure corrected	torr	Pump inlet air pressure / 2
CDPPrs123 Sorbent bed 308 pressure	torr	Bed 308 pressure psi * 760 / 14.7
CDPmp12 Pump Inlet Air Pressure	torr	Pump inlet pressure psi *760 / 14.7
CDPDP_023 Dessicant Bed Outlet Air Dewpt	C	Dewpoint degrees F converted to C
CDPDP_120 4BMS Inlet Air Dewpoint	C	Dewpoint degrees F converted to C
CDPTmp120 4BMS Inlet Air Temperature	C	Dewpoint degrees F converted to C
CRA Ready (11=on 10=off)		CRA ready status + 10
OGA Current/10		SEDH2_SP_ent / 10
TSAC Power/10		TSAPower / 10
OGA Ready (9=on 8=off)		OGA ready status + 8
Compressor Status (13=on 12=off)		Compressor status + 12
Calc MR from Actual Flow		Corrected H2 flow / Sabatier CO2 flow
H2 Rate adjusted, (@0°C)	SLPM	Recorded data * slope + offset
Calc H2O Prod @ 100% Eff	gram	H2 flow/ 22.4 / 2 * 18 * timestep + previous summed value
Calc H2O Prod @ 90% Eff	gram	Calculated 100% efficient water * 0.9
Calc H2O Prod @ 80% Eff	gram	Calculated 100% efficient water * 0.8
H2O Prod Efficiency (valid with W/D calc)	%	Actual water produced / calculated 100% efficient water * 100
H2O Production	grams	Current mass water (scale) – initial mass water
H2 Useage Rate	Liters	H2 flow * timestep + previous summed value
Day/Night Status (7=day, 6=night)		Day night status + 6
Desired CO2 Flow	(SLPM)	H2 flow / selected molar ratio
Starvation (Standby when OGA Ready)		=1 when OGA ready is true and Sabatier is standby
4BMS CO2 Dump in A2 (mp12>7.95 and segment=A2)		=1 if 4BMS mode is 3 and pump inlet pressure > 11.5

Name	Units	Calculation
4BMS CO2 Dump in A2 (mp12>7.95 and segment=B2)		=1 if 4BMS mode = 6 and pump inlet pressure > 11.5
CEDU Cycle Counter (flag step changes)		Checks for change in CEDU status from one time step to next
Water Dump Event		Checks for water mass change > 17 grams from one time step to next

Subsystem Efficiency Calculations

4BMS
4BMS CO2 Removal Rate (lb/hr) = CO2 Inlet (lb/hr) – CO2 Outlet (lb/hr)
4BMS CO2 Removal Efficiency = 1- CO2 Inlet (lb/hr)/CO2 Outlet (lb/hr)

Sabatier
H2 Usage = Average H2 Flow * Total time of test
Theoretical Water Production Rate = H2 Usage / 22.4 / 2 * 18
Actual Water Production Rate = Scale reading at end of test – scale reading at beginning of test
Sabatier Water Recovery Efficiency = Actual Water Production / Theoretical Water Production *100

5.2 Appendix Data Plots

5.2.1 Introduction

This document describes the test data collected from the integrated test program. Data was collected from all of the operating systems. Different data sets are plotted for different combinations of systems. The following graphs are representative data sets from the different cases that were run.

91
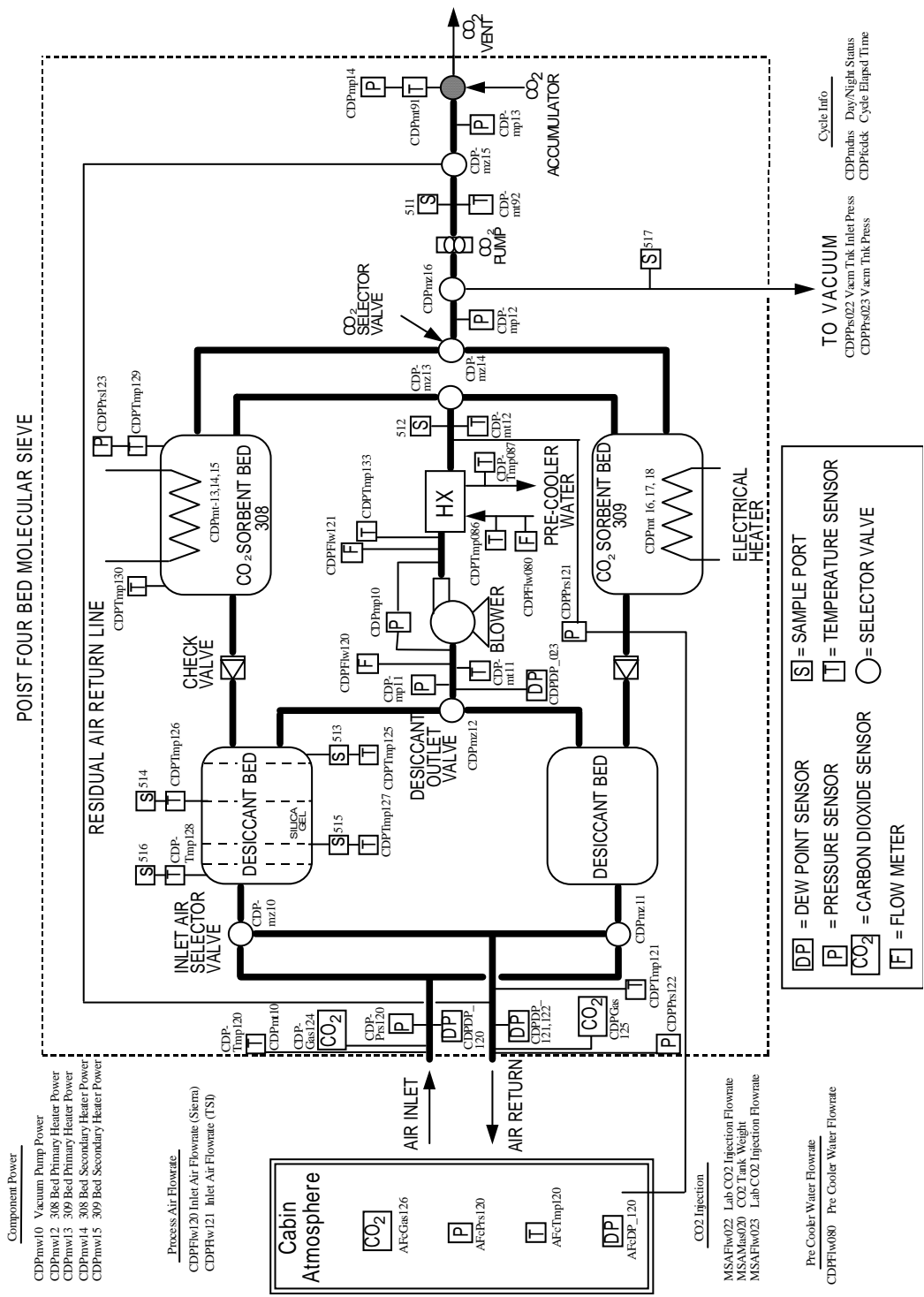
Figure 1 - Detailed Schematic of 4BMS with sensor locations identified.

Sabatier Engineering Development Unit
SVL18383
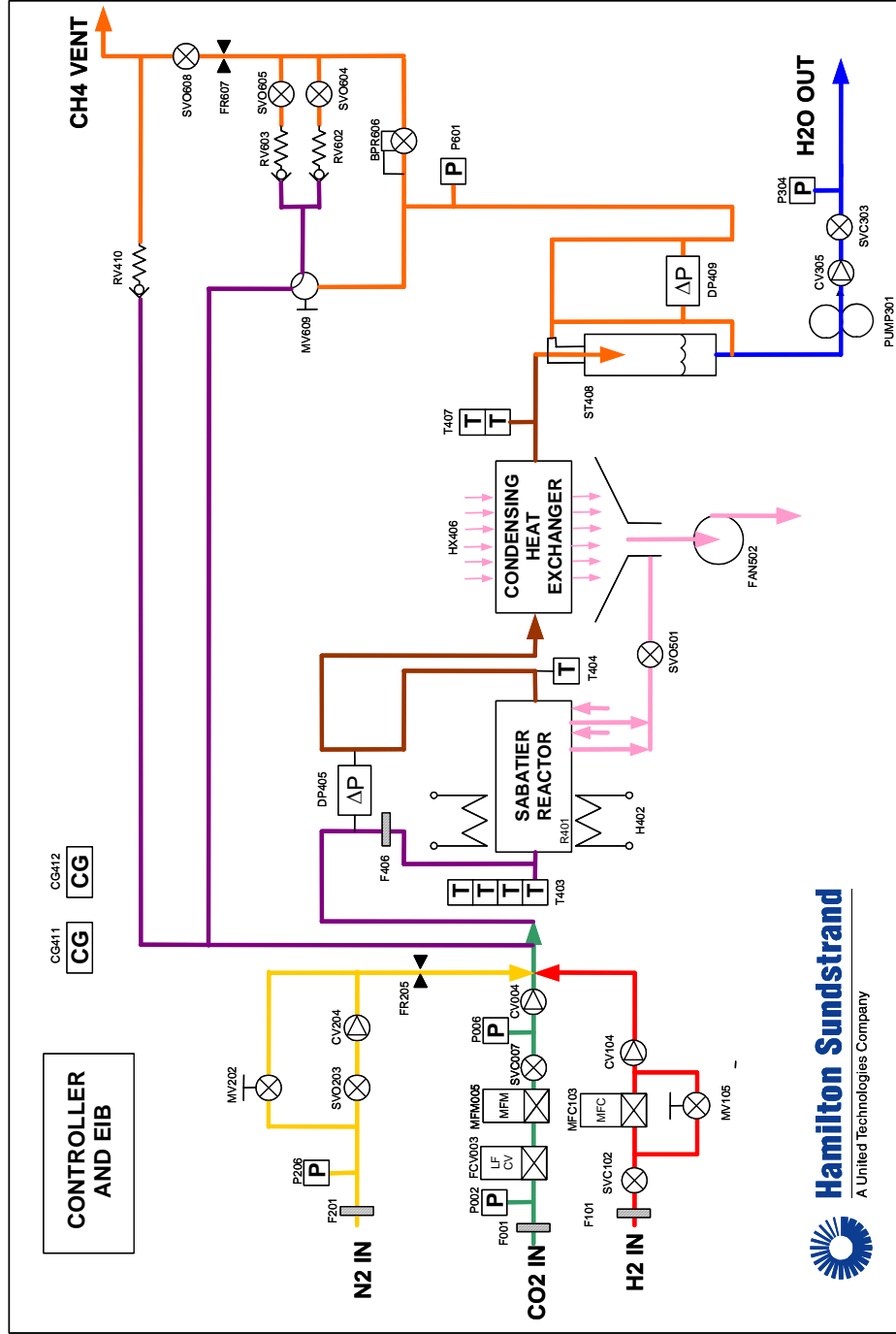
Figure 2 - Detailed Schematic of Sabatier EDU used in Mechanical Compressor Test with sensor locations identified.

6/25/04
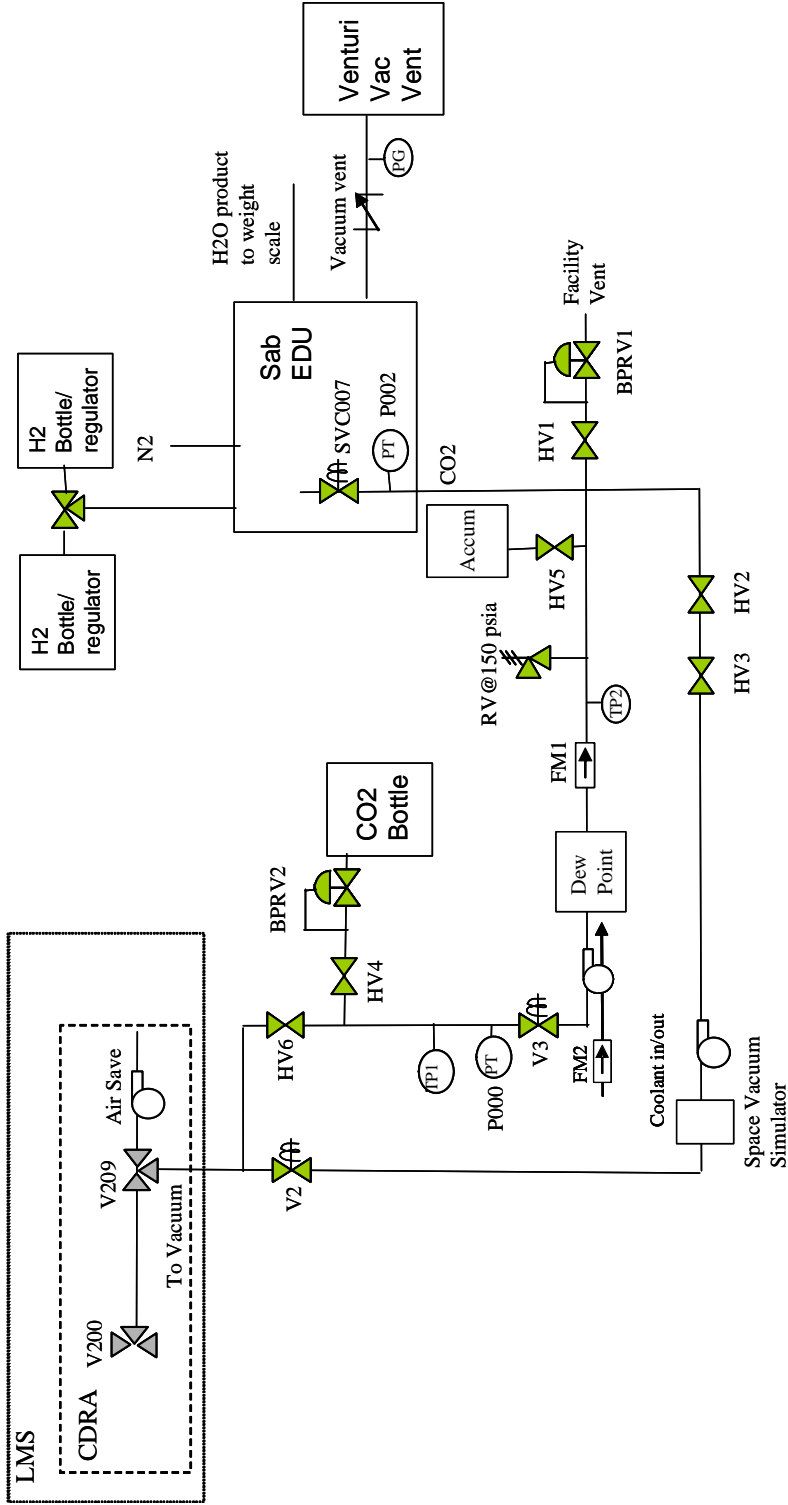
Figure 3 - Schematic of Integrated Test with Mechanical Compressor with sensor locations identified.
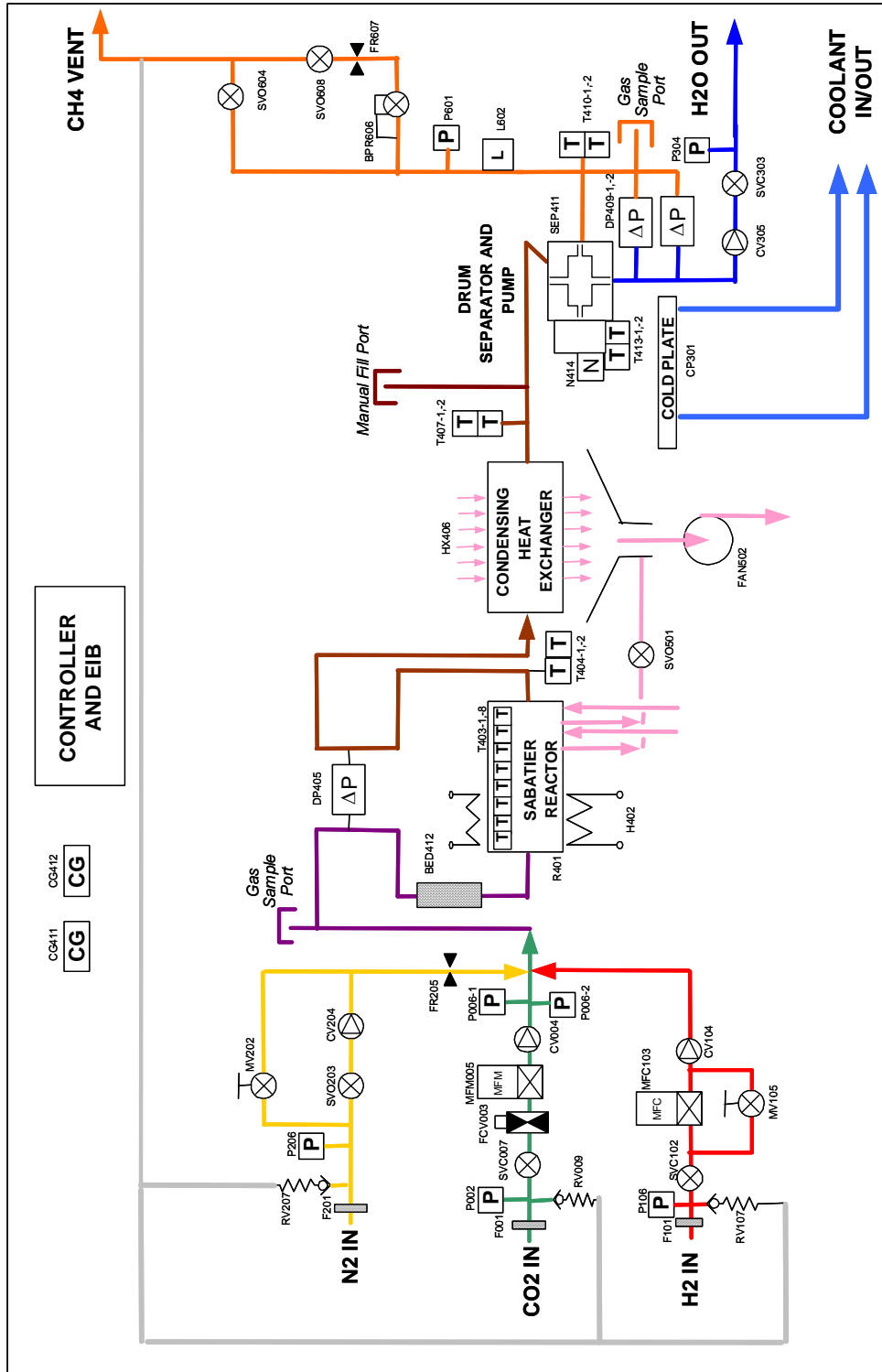
Figure 4 - Schematic of Sabatier EDU used with TSAC testing with sensor locations identified.
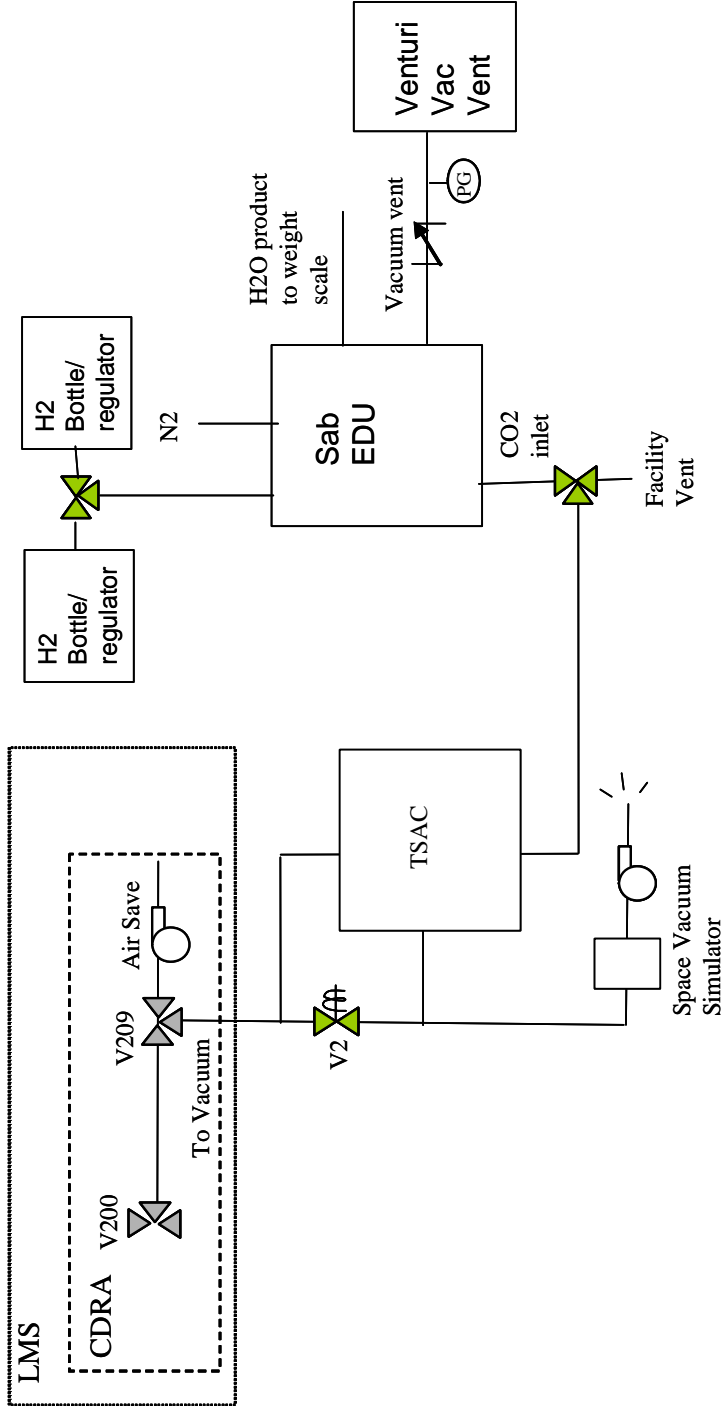
Figure 5 - Schematic of Integrated Test with TSAC with sensor locations indentified.

Table 1 – Sensors in the 4BMS

Sensor Designation	Sensor Description
CDPDP_023	Dessicant Bed Outlet Air Dewpt
CDPDP_120	4BMS Inlet Air Dewpoint
CDPFlw080	4BMS Precooler Inlet H_2O Flow
CDPFlw120	4BMS Inlet Air Flowrate (Sierra)
CDPFlw121	4BMS Inlet Air Flowrate (TSI)
CDPmw12	5A Bed 308 Prim. Heater Power
CDPmw13	5A Bed 309 Prim. Heater Power
CDPmw14	5A Bed 308 Sec. Heater Power
CDPmw15	5A Bed 309 Sec. Heater Power
CDPPrs021	Fac Vacuum Tank CO_2 Inlet Pressure
CDPPrs022	Fac Vacuum Tank CO_2 Pressure
CDPPrs120	4BMS Inlet Air Pressure
CDPPrs121	Precooler Outlet to Ambient
CDPPrs122	4BMS Outlet Air Pressure
CDPTmp086	4BMS Precooler Inlet H_2O Temp
CDPTmp120	4BMS Inlet Air Temp.
MSAFlw022	Lab Low CO_2 Inject Flowrate
MSAFlw023	Lab High CO_2 Inject Flowrate
MSAMas020	Facility CO_2 Tank Weight
THCFlw120	THC CHX Outlet Air Flowrate
CDPTmp121	4BMS Outlet Air Temp.
AFcTmp120	Lab Air Temp. Middle (1)
CDPCur120	CO_2 Pump Current
CDPVlt120	CO_2 Pump Voltage
CDPmp10	Diff. Fan 303
CDPPrs123	Sorbent bed 308 pressure
CDPTmp087	CDRA Chill H_2O Out
CDPTmp121	4BMS Outlet Air Temp.
CDPTmp125	Desiccant bed 104 Outlet Air Temp

Sensor Designation	Sensor Description
CDPTmp126	Port 514 Internal Desiccant Bed 1 Temp.
CDPTmp127	Port 515 Internal Desiccant Bed 1 Temp.
CDPTmp128	Port 516 (mt98) Desiccant Bed 1
CDPTmp129	Port 503 Sorbent Bed Internal Temp.
CDPTmp130	Port 504 Sorbent Bed Internal Temp.
CDPTmp133	Precooler Inlet Air Temp
MSAFT_022	Total CO_2 Added L
MSAFT_023	Totalize CDPFlw023
AFcDP_120	Lab Air Dewpoint (1)
CDPPrs020	feedback delta pressure
CDPTmp020	Space Simulator Tank In
THCTmp084	THC HX Chill In
THCTmp085	THC HX Chill Out
THCTmp120	THC CHX Inlet Air Temp.
THCTmp121	THC CHX Outlet Air Temp.
AFcPrs120	Module Pressure (1)
AFcTmp120	Lab Air Temp. Middle (1)
AFcTmp121	CABIN FRONT TEMP (1)
AFcTmp122	CABIN BACK TEMP (1)
HB_Prs220	High Bay Pressure (1)
HB_Tmp220	High Bay Temp. (1)

Table 2 - Sensors in the Sabatier EDU

Sensor Designation	Sensor Description
SEDCO2_cmd_003	CO_2 Command 0-4095 counts
SEDCO2_Flow_005	CO_2 Mass Flow (V1414)
SEDCompressor	Compressor command 1=on 0=off (Y24)
SEDCRA READY	CRA Status 1=on 0=off (Y23)
SEDCRAREADY	CRA Status 1=on 0=off (C131)3
SEDCurrent f OGA	0-4095 counts 0-100 Amps (V1551)
SEDDP405	Reactor Delta Pressure (V1400)
SEDDP409	Separator Delta Pressure (V1401)
SEDEOGAREADY	Ethernet write 1=on 0=off (C135)
SEDH2_cmd_103	H_2 Command 0-4095 counts (V1420)
SEDHtr_A	Heater A 1=on 0=off (Y20)
SEDHtr_B	Heater B 1=on 0=off (Y21)
SEDMas020	Sabatier EDU Water
SEDMFC_103_data	H_2 Mass Flow (V1415)
SEDMolar ratio_	User selected molar ratio (V1660)
SEDOGA READY	OGA Status 1=on 0=off (X104)
SEDOGAREADY	OGA Status 1=on 0=off (C130)
SEDP000	Compressor suction Pressure (V1554)
SEDP002	Accumulator Pressure or CO_2 inlet (V1402)
SEDP006	Reactor inlet pressure (V1403)
SEDP206	Nitrogen inlet pressure (V1404)
SEDP304	Product water pressure (V1405)
SEDP601	Reactor outlet pressure (V1406)
SEDProcess	Process Mode (C102)

Sensor Designation	Sensor Description
SEDPUMP301	Water pump 1=on 0=off (Y22)
SEDPurge	Purge Mode (C104)
SEDReactCool_501	Cooling Air Valve 1=closed 0=open (Y31)
SEDShutdown	Shutdown Mode (C100)
SEDStandby	Standby Mode (C101)
SEDStop	Stop Mode (C103)
SEDT CHXout_A	Heat Exchanger Outlet Temperature (V1435)
SEDT CHXout_B	Heat Exchanger Outlet Temperature (V1436)
SEDT React_A	Reactor Hot Zone (V1430)
SEDT React_B	Reactor Hot Zone (V1431)
SEDT React_C	Reactor Inlet (V1432)
SEDT React_D	Reactor Inlet (V1433)
SEDT React_Out	Reactor Outlet (V1434)
	Product water weight scale

Table 4 - Sensors in the Temperature Swing Adsorption Compressor

TSAF prod	TSAC outlet CO2 flowrate
TSAP1	Bed A Internal pressure
TSAP2	Bed B internal pressure
TSAExtWalA	Bed A External Wall Temperature
TSAHA1	Bed A Heater 1 Temperature
TSAHA3	Bed A Heater 3 Temperature
TSATouchA	Bed A Touch Temperature
TSAExtWalB	Bed B External Wall Temperature
TSATouchB	Bed B Touch Temperature
TSAHB1	Bed B Heater 1 Temperature
TSAHB3	Bed B Heater 3 Temperature
TSAPower	Heater power for Bed A and Bed B
TSAF cdra	TSAC Inlet CO2 flowrate
TSAAirInA	Bed A Cooling Air Inlet Temperature
TSAAirInB	Bed b Cooling Air Outlet Temperature
TSAAirOutA	Bed A Cooling Air Inlet Temperature
TSAAirOutB	Bed A Cooling Air Outlet Temperature
TSAP cdra	Inlet pressure

Table 3 - Sensors in the Mechanical Compressor

Sensor Designation	Sensor Description
MEDDP_020	Mechanical Compressor Outlet Dewpoint, F
MEDFlw020	Compressor Outlet Flow after DP, lb/hr
MEDPrs020	Compressor Inlet Pressure, PSIG
MEDTmp020	Manifold Outlet or Crankcase HX inlet, F
MEDTmp021	Crankcase HX Outlet or CP HX inlet, F
MEDTmp022	Manifold Inlet, F
MEDTmp023	Cold Plate Outlet, F
MEDTmp024	Crankcase External Motor End, F
MEDTmp025	Lower Guide Cylinder Stage 1 Motor End, F
MEDTmp026	Crossover Head Stage 1 Motor End, F
MEDTmp027	Crossover Head Stage 2, F

4BMS Baseline Case	Test Day 58	6/27/05	Page 11
Additional 4BMS Case	Test Day 17	2/6/05	Page 23
Mechanical Compressor Stand Alone Case	Test Day 4	11/2/04	Page 27
4BMS/CEDU Baseline Case	Test Day 9	12/1/04	Page 36
Sabatier Standalone Case	Test Day 16	2/4/05	Page 44
4BMS/TSAC Baseline Case		11/20/05	Page 57
4BMS/CEDU/Sabatier Fully Integrated Case	Test Day 16	2/4/05	Page 63
4BMS/TSAC/Sabatier Fully Integrated Case		1/27/06	Page 77

5.2.2 4BMS Baseline Case

POIST 4BMS/Compressor EDU Testing - 4BMS B/L with TP1 Conditions - Elapsed Time from 6/27 -- Test Day 58 2005

Plot 1 -- Status for 4BMS, CRA, OGA and Compressor (offset for clarity)
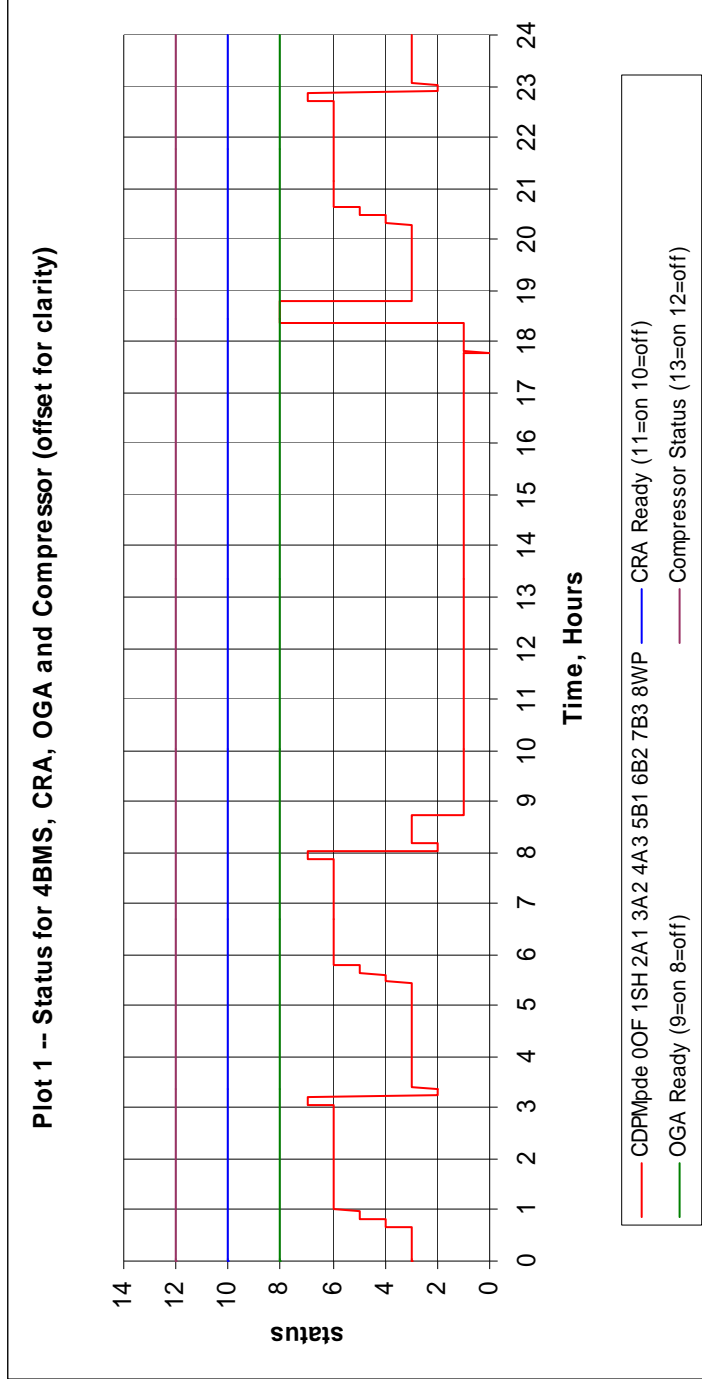
This plot gives the status of each of the operating systems against a timeline. For this case, only the 4BMS is operating. The integer values correspond to the different processing cycles of the 4BMS. 0=Off, 1=SH??, 2=Bed A Air Save, 3=Bed A Desorb, 4=Bed A Vacuum Vent, 5=Bed B Air Save, 6=Bed B Desorb, 7=Bed B Vacuum Vent. The compressor and Sabatier are both off.

Plot 2 -- Carbon Dioxide Partial Pressures at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator
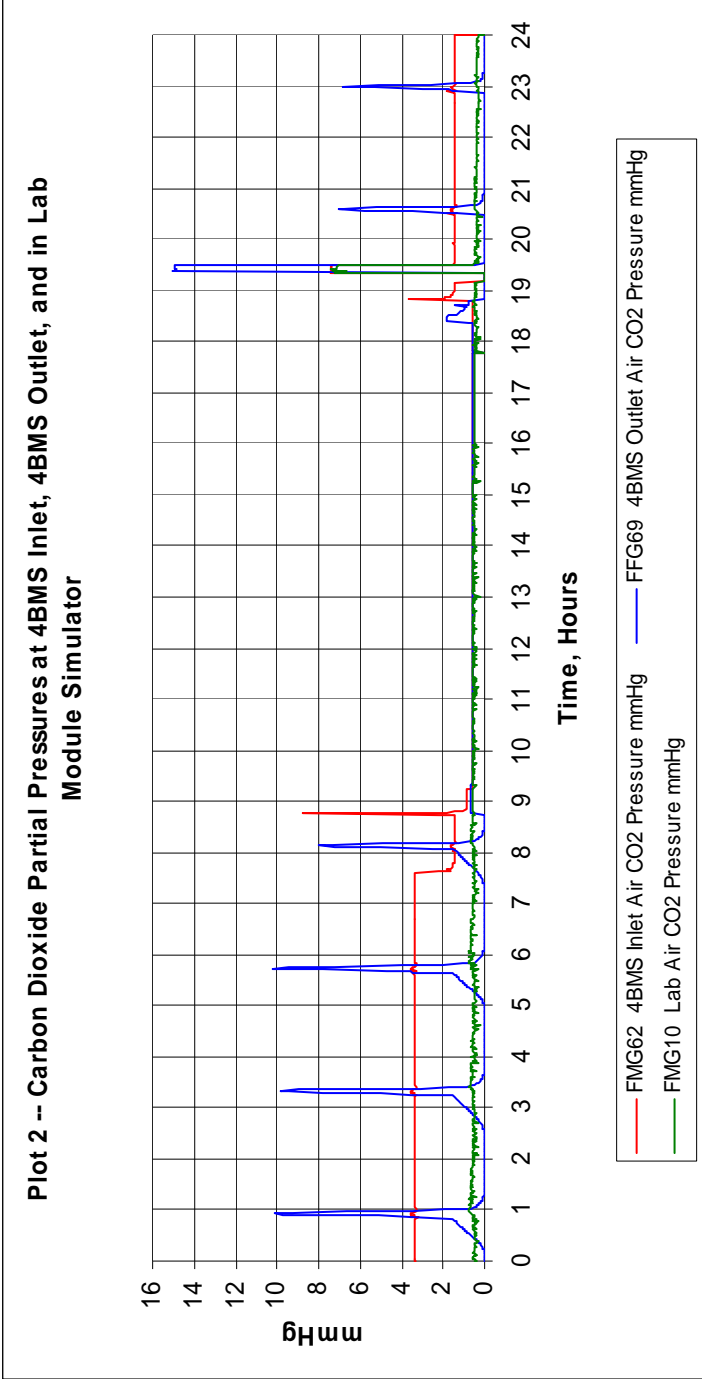
This plot shows the CO2 concentration in and out of the 4BMS. The outlet concentration spikes every time the beds switch because there is residual CO2 in the lines from the desorbing bed that goes to the 4BMS outlet once that desorbing bed comes on-line and air starts flowing through it again.

Plot 3 -- Air Dewpoint at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator
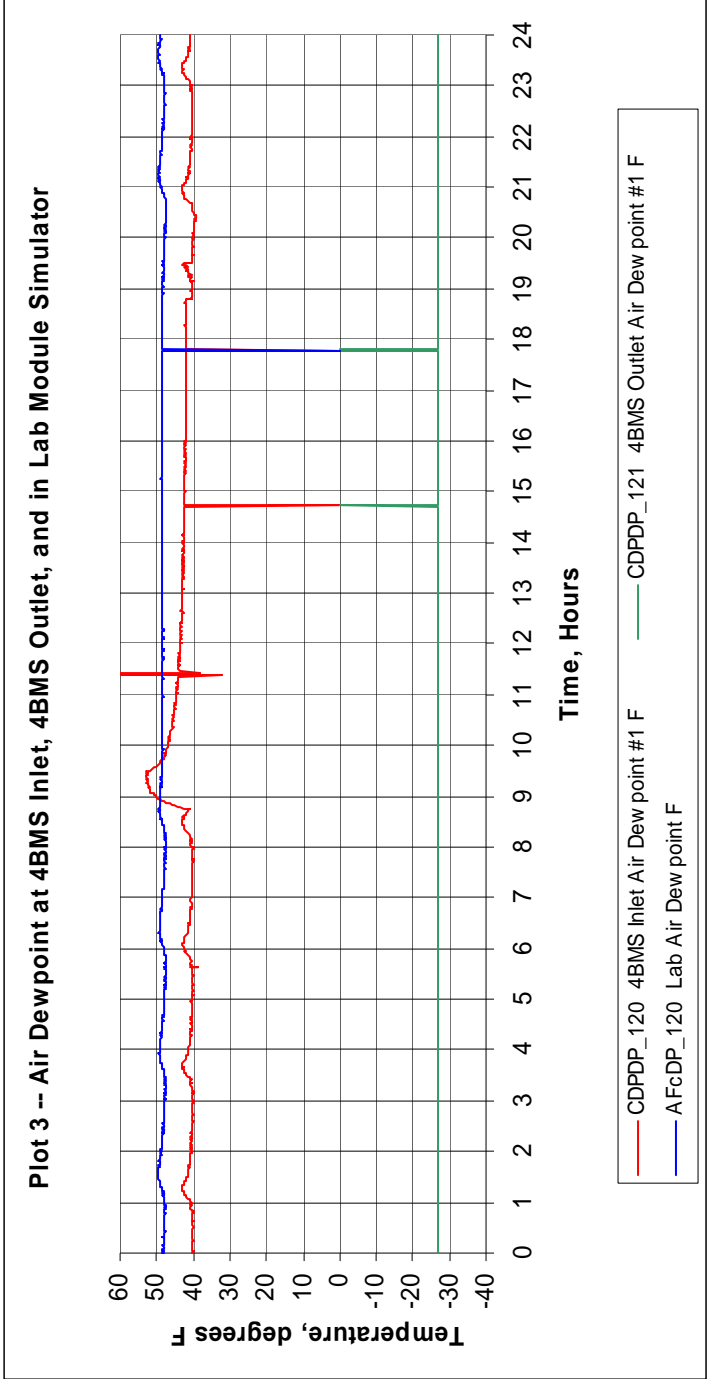
This plot shows the dew point of the air entering the 4BMS and the bulk air in the Lab Module simulator. The outlet dew point sensor was not working during the test.

Plot 4 -- Air Temperature at 4BMS Inlet, 4BMS Outlet, in Lab Module Simulator, and Water Temperature at Precooler Inlet

Temperature, degrees F

Time, Hours

CDPTmp120 4BMS Inlet Air Temperature F
AFcTmp120 Lab Air Temp. Middle F
CDPTmp121 4BMS Outlet Air Temperature F
CDPTmp086 4BMS Precool Inlet H2O Temp #1 F
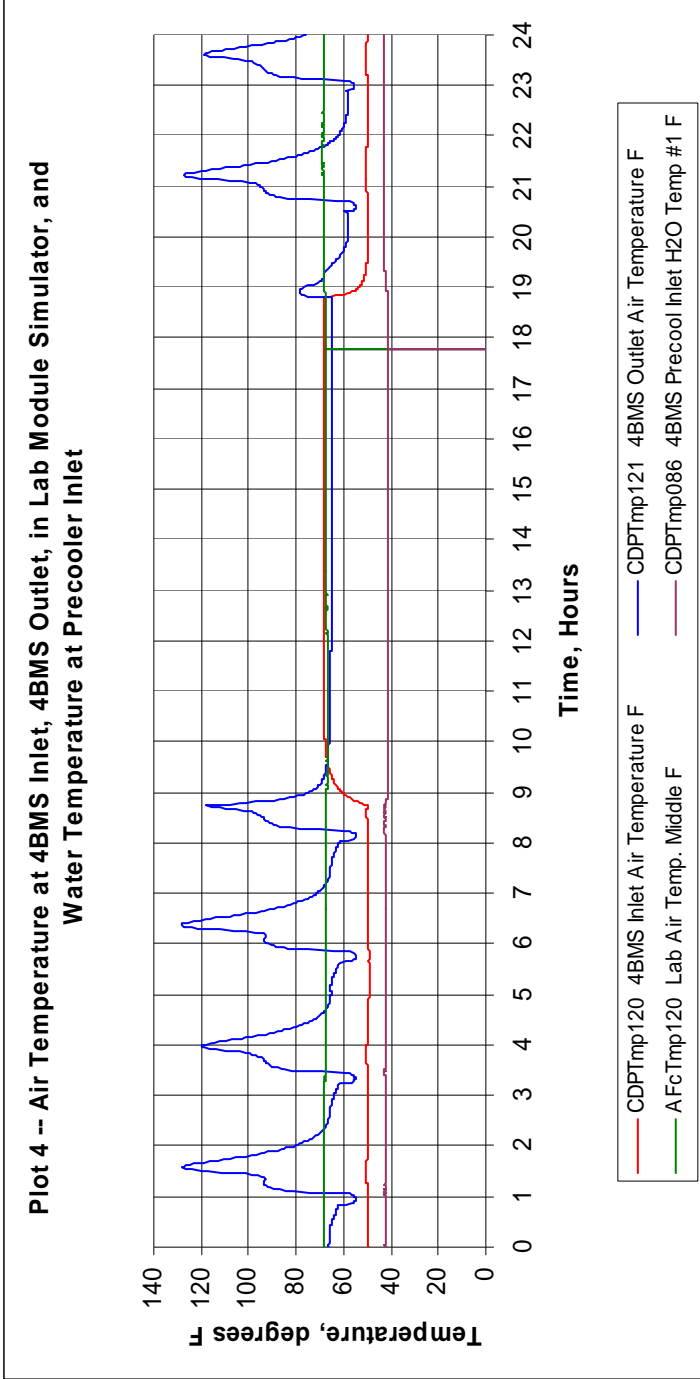
This plot shows air temperatures throughout the 4BMS. At the start of a bed change (at 25.5 hours above) the previously desorbed bed that is still hot becomes the adsorbing bed. The air flowing through the bed picks up the heat from the bed, topping out at about 130 F. This hot air then flows through the spent desiccant bed and regenerates it by picking up the water and returning it to the cabin.

Plot 5 -- Sorbent Bed Heater Temperatures

CDPmt13 5A Bed 308 Heater Temp A F
CDPmt16 5A Bed 309 Heater Temp A F
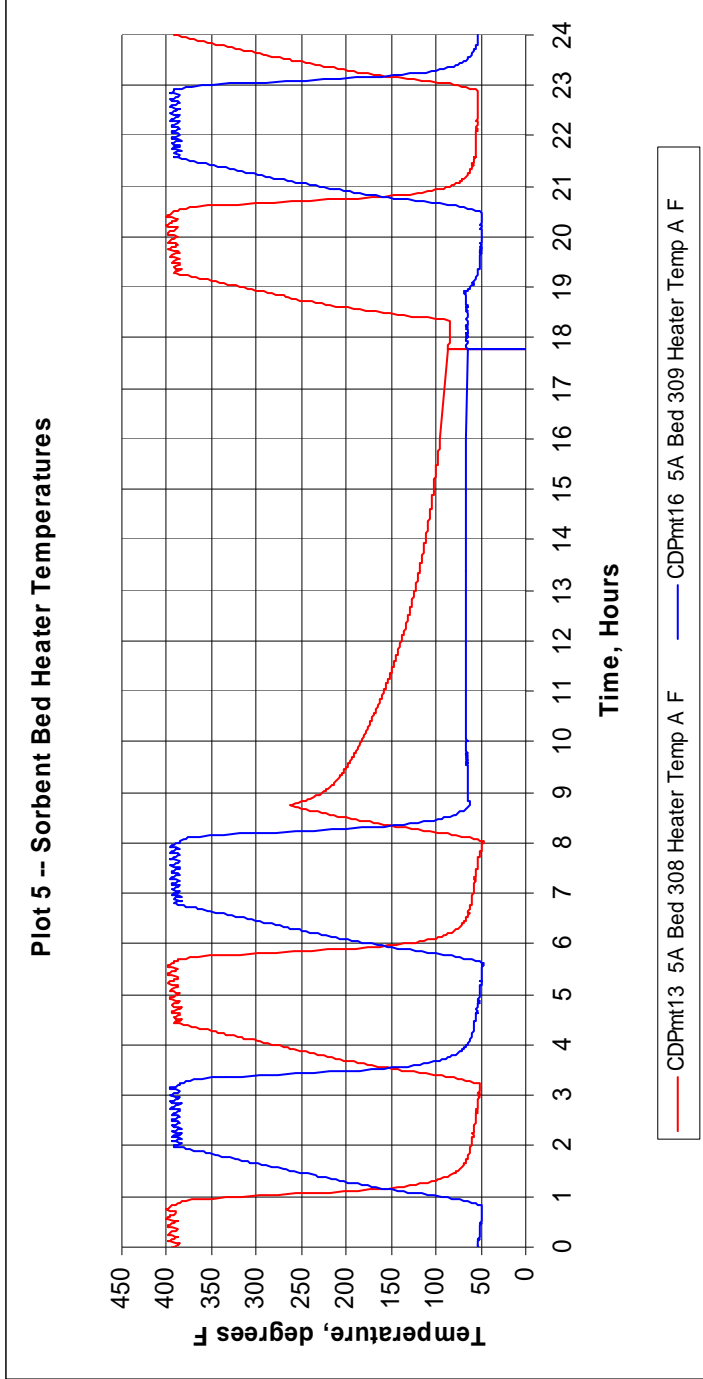
This plot shows the temperatures of the molecular sieve beds. The desorbing bed heaters are fully on until the temperature reaches 400 F and then an ON/OFF control is used to maintain the temperature at 400 until the end of the cycle.

105

Plot 6 -- Desiccant Bed Inlet and Outlet Air Temperatures
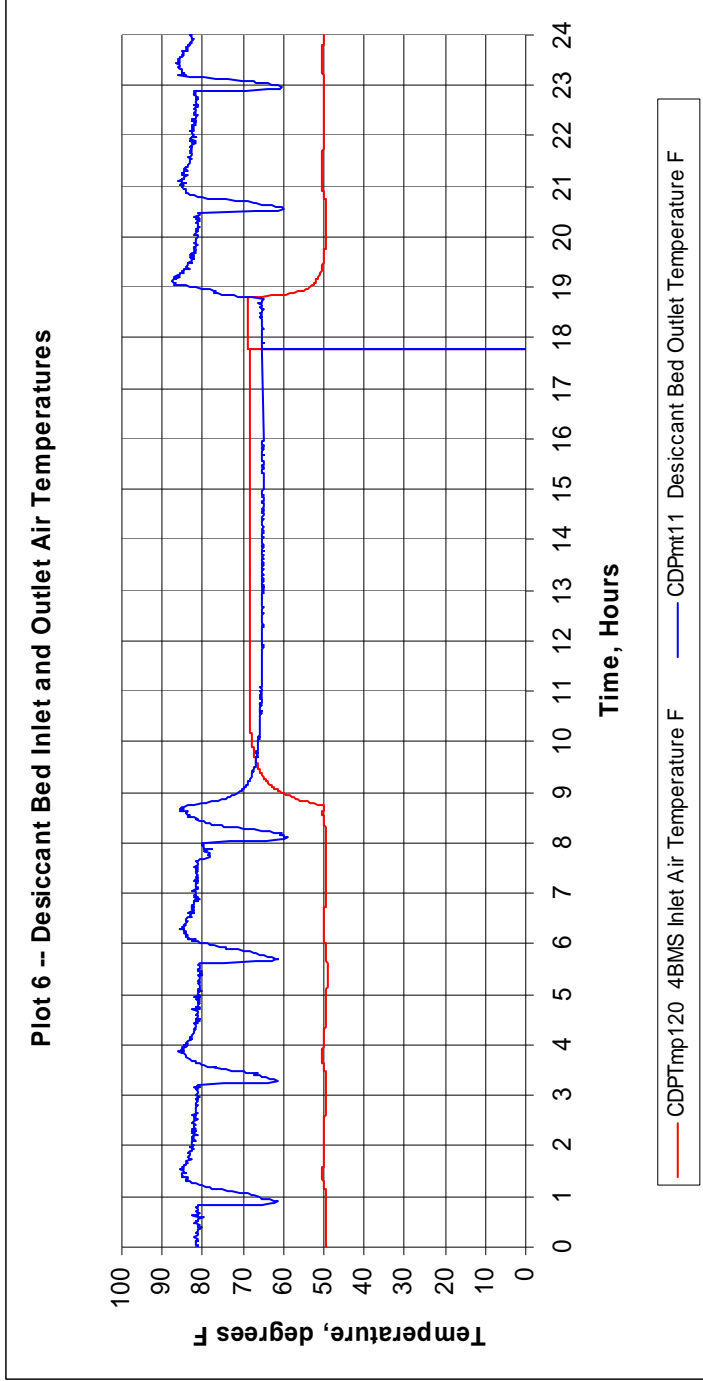
This plot shows the temperatures of the desiccant bed. The air leaving the desiccant is warmed by the heat of adsorption of water onto the desiccant material.

Plot 7 -- Desiccant Bed Outlet Air Dewpoint Temperature

CDPDP_023 Dessicant Bed Outlet Air Dew pt F
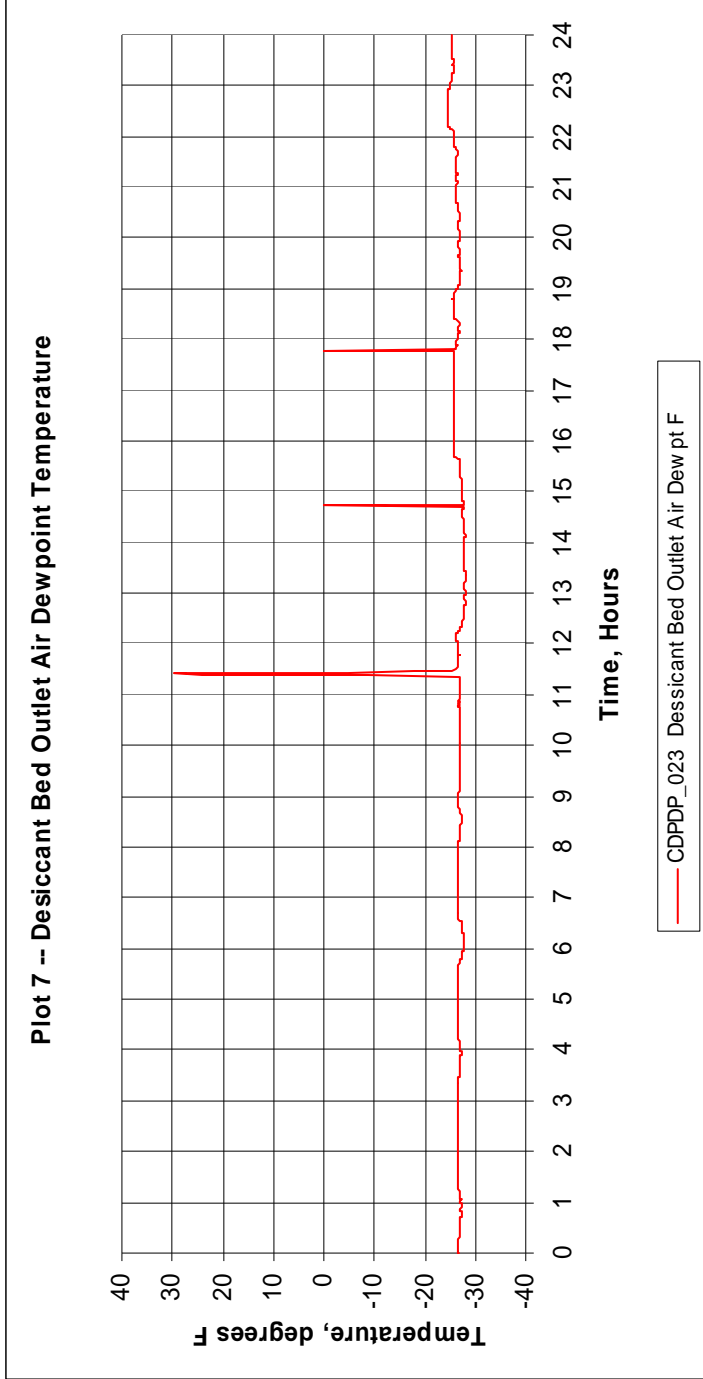
This plot shows how the dew point of the air leaving the desiccant and entering the molecular sieve bed remains very dry. Water will contaminate the molecular sieve and require high temperature regeneration. The spikes in the dew point signal are due to calibrations of the sensor.

Plot 8 -- 4BMS Process Air Flow Rate

Legend:
- CDPFlw 120 4BMS Inlet Air Flow rate SCFM (Sierra)
- CDPFlw 121 4BMS Inlet Air Flow rate SCFM (TSI)
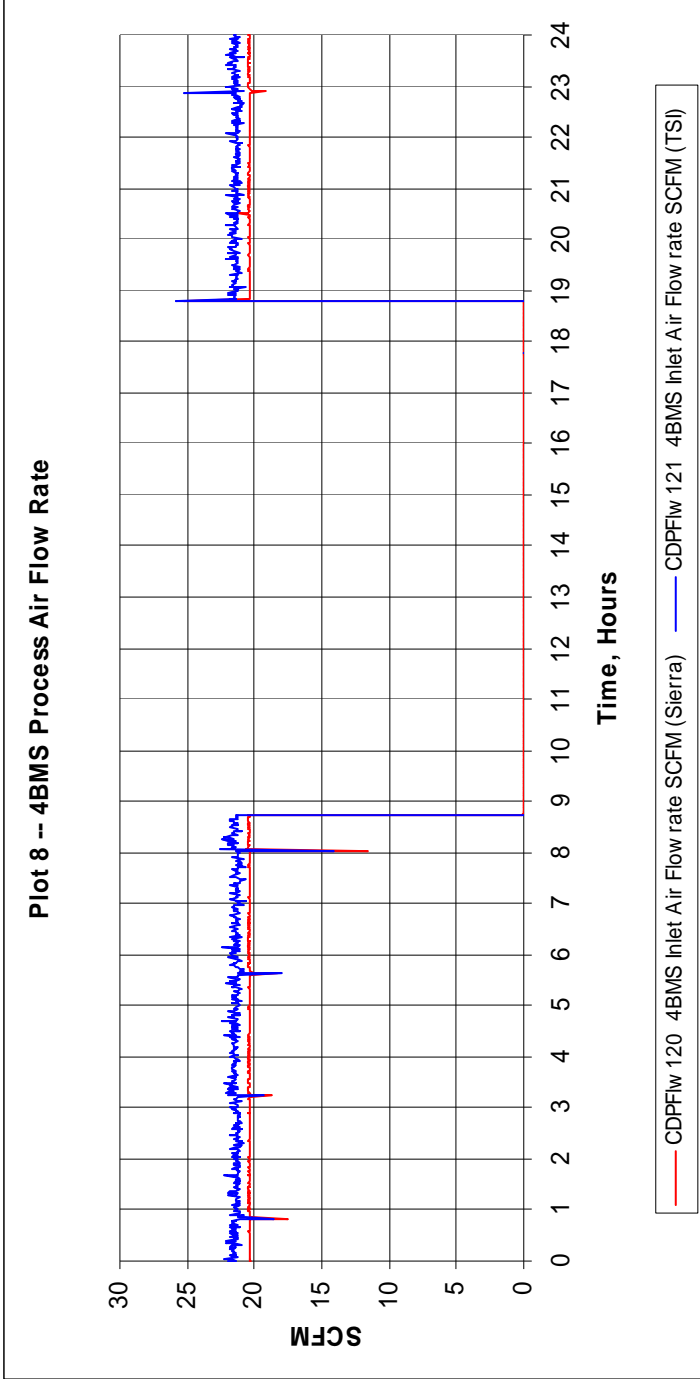
Two different air flow instruments were used to monitor the process air flow.

Plot 9 -- 4BMS Vacuum System Pressures

Legend:
- CDPPrs123 Sorbent bed 308 pressure PSIA
- CDPPrs021 Fac Vacuum Tank Air Inlet Pressure Torr
- CDPmp12 Pump Inlet Air Pressure PSIA
- CDPPrs022 Fac Vacuum Tank Air Pressure Torr
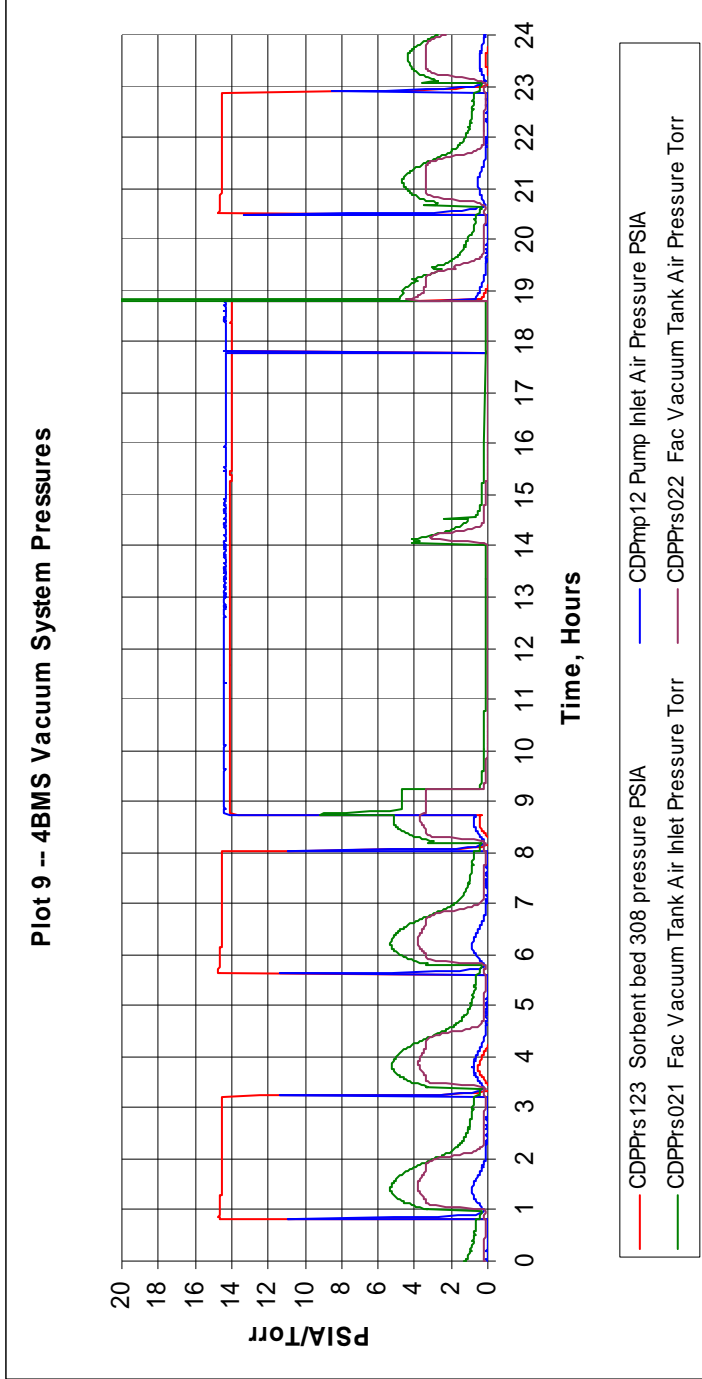
This plot shows the pressures throughout the 4BMS. The bed pressure (red square wave shown in PSIA) cycles between ambient pressure during adsorption and vacuum during desorption. The vacuum system pressures spike up initially when the bed begins desorbing and then returns to vacuum levels as the CO2 is exhausted from the bed.

109

Plot 10 -- 4BMS Component Power
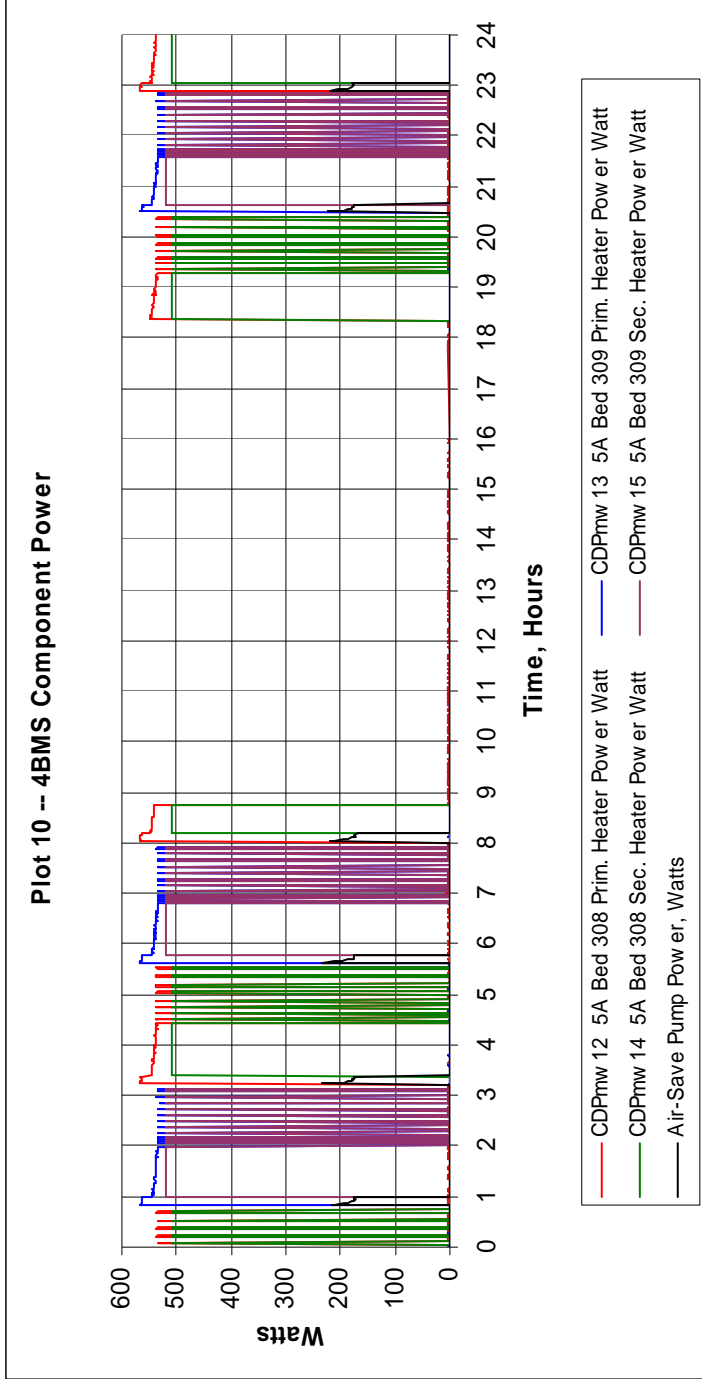
This plot shows the power summary for the system. The primary and secondary heaters are on full until the bed reaches 400 F and then cycle to maintain the temperature. The air save pump is activated for 10 minutes of each half cycle.

Plot 11 -- 4BMS CO2 Injection and Coolant Water Flow Rate

Legend:
- MSAFlw 022 Lab CO2 Inject Flow rate SLPM
- MSAFlw 023 Lab High CO2 Inject Flow rate LBS/HR
- CDPFlw 080 4BMS Precooler Inlet H2O Flow GPM
- MSAMas020 Facility CO2 Tank Weight Lbs
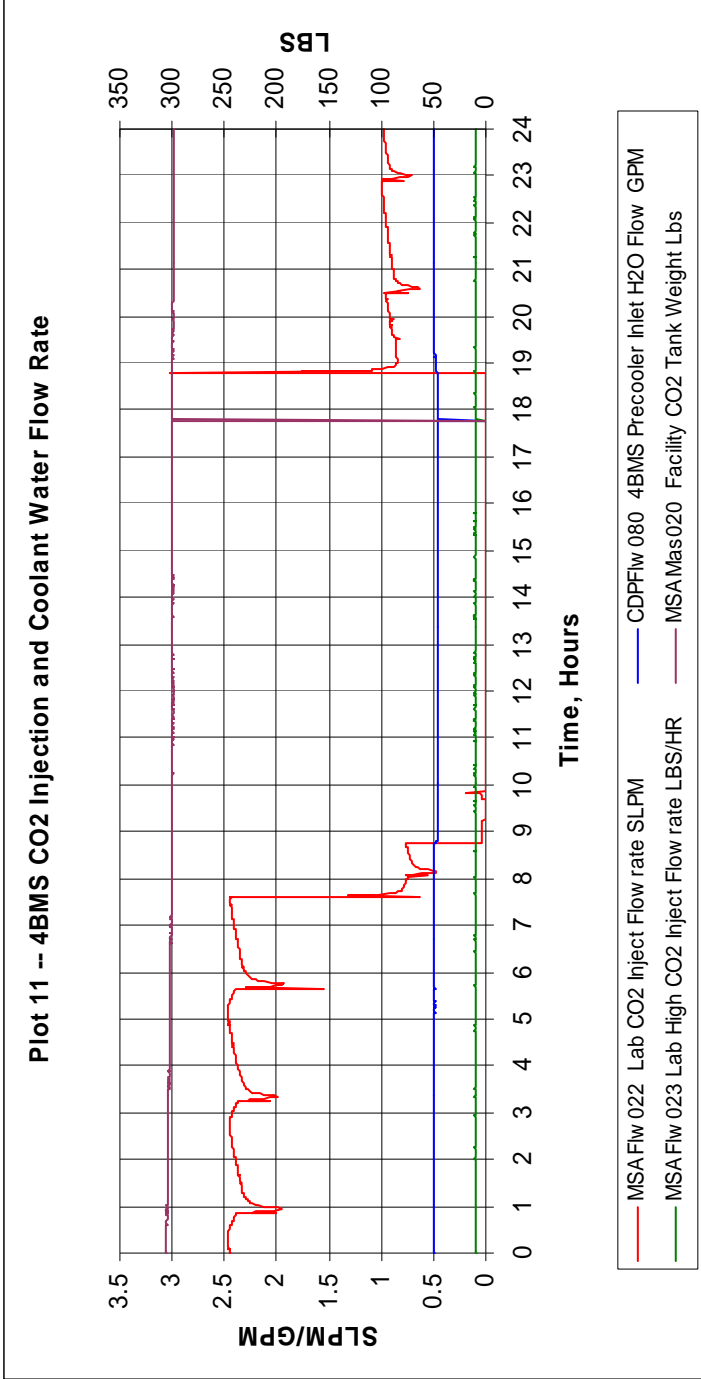
This plot shows the CO2 injection rate into the 4BMS. The CO2 injection rate is based on a closed loop algorithm to maintain a constant CO2 concentration at the inlet of the 4BMS as shown in plot 2 and plot 12. The CO2 tank weight is a means of performing a mass balance on CO2 to verify the accuracy of the measurements.

111

Plot 12 -- Percent Carbon Dioxide at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator

CDPGas124 4BMS Inlet Air CO2 Concentration %CO2 — CDPGas125 4BMS Outlet Air CO2 Concentration %CO2

AFCGas126 Lab Air CO2 Concentration %CO2
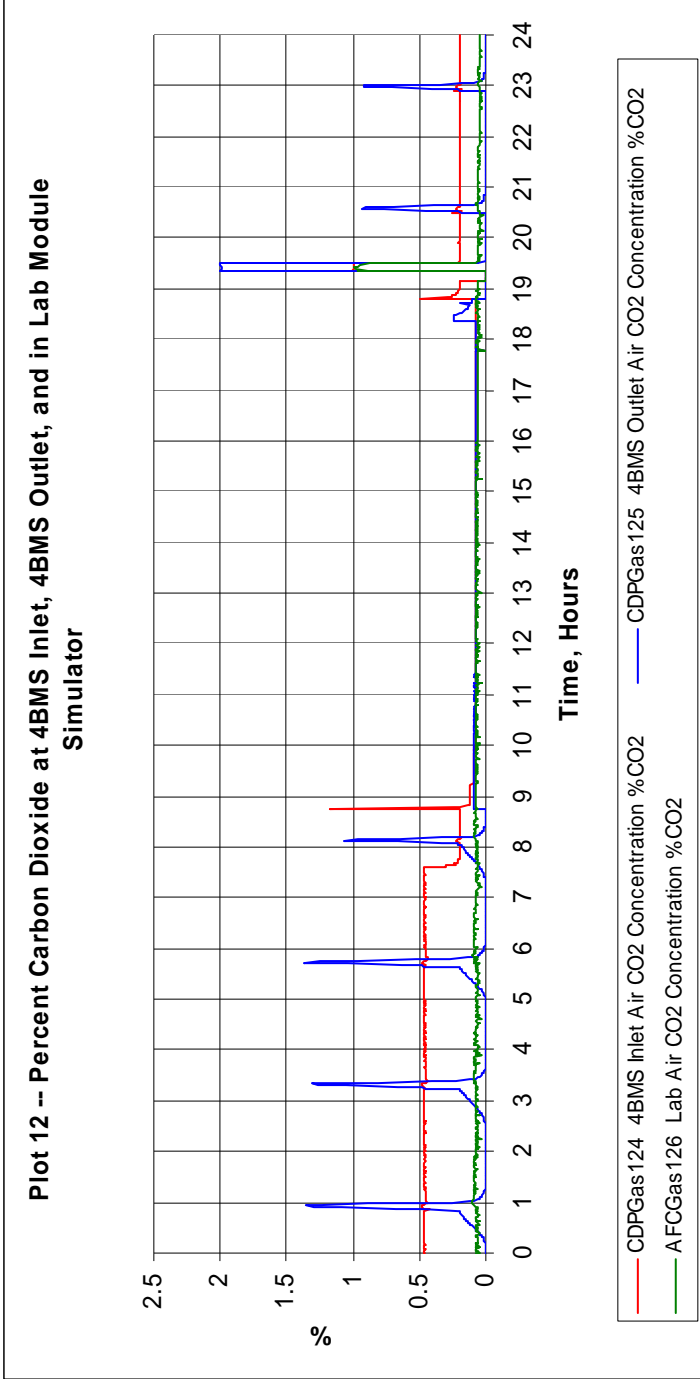
This plot is the same as Plot 2 except it is reported in % concentration instead of mmHg.

5.2.3 Additional 4BMS Baseline Case

Another example of 4BMS Baseline test conditions:

POIST 4BMS/Compressor EDU Testing - 4BMS Baseline - Elapsed Time from 2/6 -- Test Day 17 2005

Plot 1 -- Status for 4BMS, CRA, OGA and Compressor (offset for clarity)

CDPMpde 00F 1SH 2A1 3A2 4A3 5B1 6B2 7B3 8WP — CRA Ready (11=on 10=off)
OGA Ready (9=on 8=off) — Compressor Status (13=on 12=off)

Plot 2 -- Carbon Dioxide Partial Pressures at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator

FMG62 4BMS Inlet Air CO2 Pressure mmHg — FFG69 4BMS Outlet Air CO2 Pressure mmHg
FMG10 Lab Air CO2 Pressure mmHg

Plot 3 -- Air Dewpoint at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator

CDPDP_120 4BMS Inlet Air Dew point #1 F — CDPDP_121 4BMS Outlet Air Dew point #1 F

Plot 4 -- Air Temperature at 4BMS Inlet, 4BMS Outlet, in Lab Module Simulator, and Water Temperature at Precooler Inlet

CDPTmp120 4BMS Inlet Air Temperature F — CDPTmp121 4BMS Outlet Air Temperature F
AFcTmp120 Lab Air Temp. Middle F — CDPTmp086 4BMS Precool Inlet H2O Temp #1 F

Plot 5 -- Sorbent Bed Heater Temperatures

CDPmt13 5A Bed 308 Heater Temp A F ——— CDPmt16 5A Bed 309 Heater Temp A F

Plot 6 -- Desiccant Bed Inlet and Outlet Air Temperatures

CDPTmp120 4BMS Inlet Air Temperature F ——— CDPmt11 Desiccant Bed Outlet Temperature F

Plot 7 -- Desiccant Bed Outlet Air Dewpoint Temperature

CDPDP_023 Dessicant Bed Outlet Air Dew pt F

Plot 8 -- 4BMS Process Air Flow Rate

CDPFlw120 4BMS Inlet Air Flow rate SCFM (Sierra) ——— CDPFlw 121 4BMS Inlet Air Flow rate SCFM (TSI)

114

Plot 9 -- 4BMS Vacuum System Pressures

CDPPrs123 Sorbent bed 308 pressure PSIA
CDPPrs021 Fac Vacuum Tank Air Inlet Pressure Torr
CDPmp12 Pump Inlet Air Pressure PSIA
CDPPrs022 Fac Vacuum Tank Air Pressure Torr

Plot 10 -- 4BMS Component Power

CDPmw 12 5A Bed 308 Prim. Heater Pow er Watt
CDPmw 14 5A Bed 308 Sec. Heater Pow er Watt
Air-Save Pump Pow er, Watts
CDPmw 13 5A Bed 309 Prim. Heater Pow er Watt
CDPmw 15 5A Bed 309 Sec. Heater Pow er Watt

Plot 11 -- 4BMS CO2 Injection and Coolant Water Flow Rate

MSA Flw 022 Lab CO2 Inject Flow rate SLPM
MSA Flw 023 Lab High CO2 Inject Flow rate LBS/HR
CDPFlw 080 4BMS Precooler Inlet H2O Flow GPM
MSAMas020 Facility CO2 Tank Weight Lbs

Plot 12 -- Percent Carbon Dioxide at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator

CDPGas124 4BMS Inlet Air CO2 Concentration %CO2
AFCGas126 Lab Air CO2 Concentration %CO2
CDPGas125 4BMS Outlet Air CO2 Concentration %CO2

115

5.2.4 Mechanical Compressor Stand Alone Case

POIST 4BMS/Compressor EDU Testing – CEDU Baseline - Elapsed Time from 11/22 -- Test Day 4 2004

Plot 1 -- Status for 4BMS, CRA, OGA and Compressor (offset for clarity)

CDPMpde 0OF 1SH 2A1 3A2 4A3 5B1 6B2 7B3 8WP —— CRA Ready (11=on 10=off)
—— OGA Ready (9=on 8=off) —— Compressor Status (13=on 12=off)

This plot is the same as the status plot for the 4BMS stand alone test. Each line represents the status of each piece of equipment. The 4-bed mol sieve was operated under its normal operating mode, and the compressor was only activated three times. The Sabatier and OGA were not involved in this test.

Plot 2 -- CEDU Overview
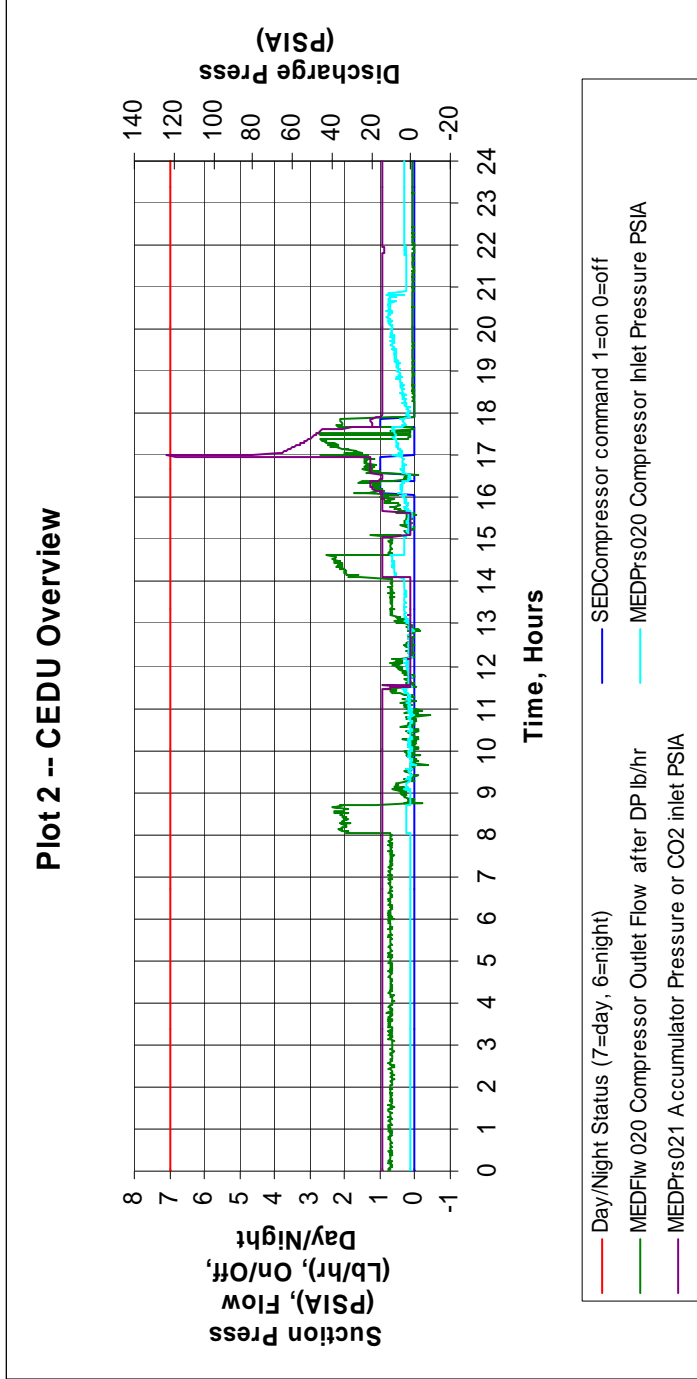
This plot shows multiple data items on one plot: compressor flow, inlet and outlet pressure and the compressor command. These same data are shown in separate plots following for better clarity.

117

Plot 3 -- CEDU Outlet Flow Rate, On/Off
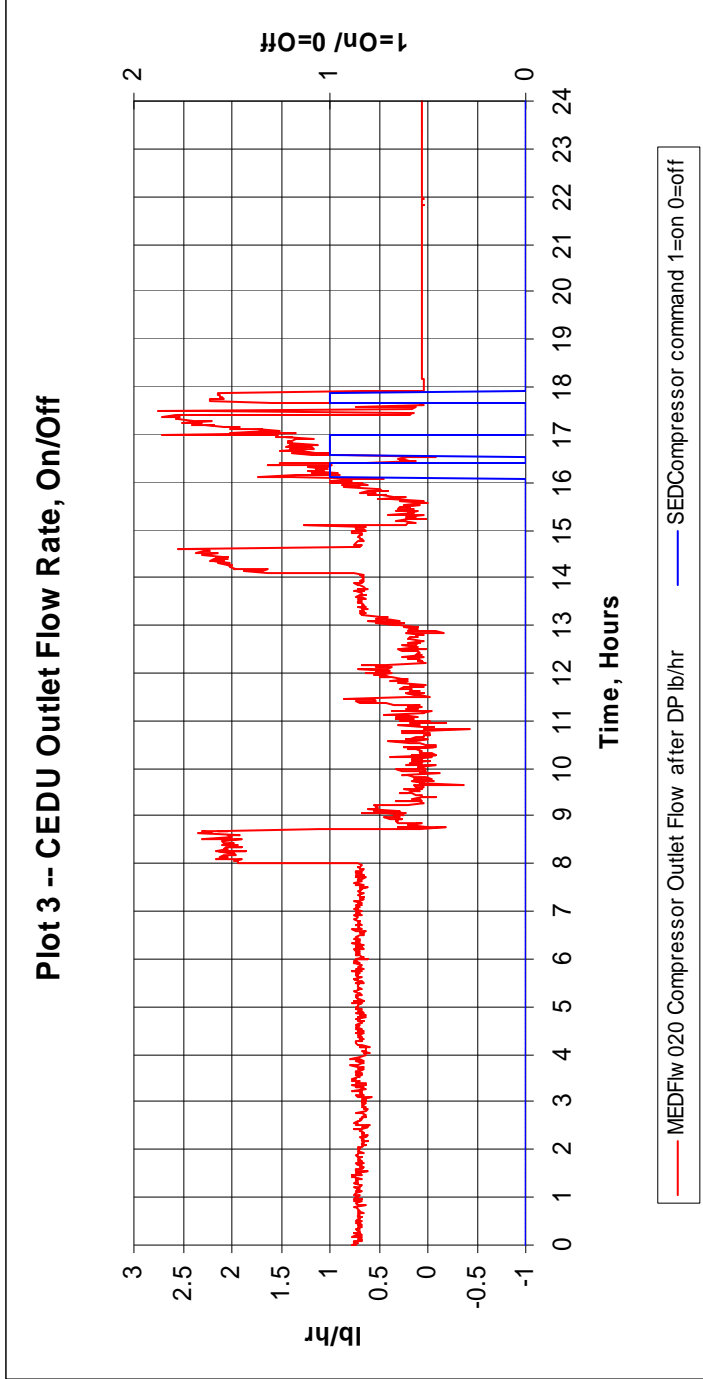
This plot shows the flow rate at the compressor exit. This data, along with the inlet and outlet pressure, is used to verify the flow rate model of the compressor.

Plot 4 -- CEDU Inlet Pressure
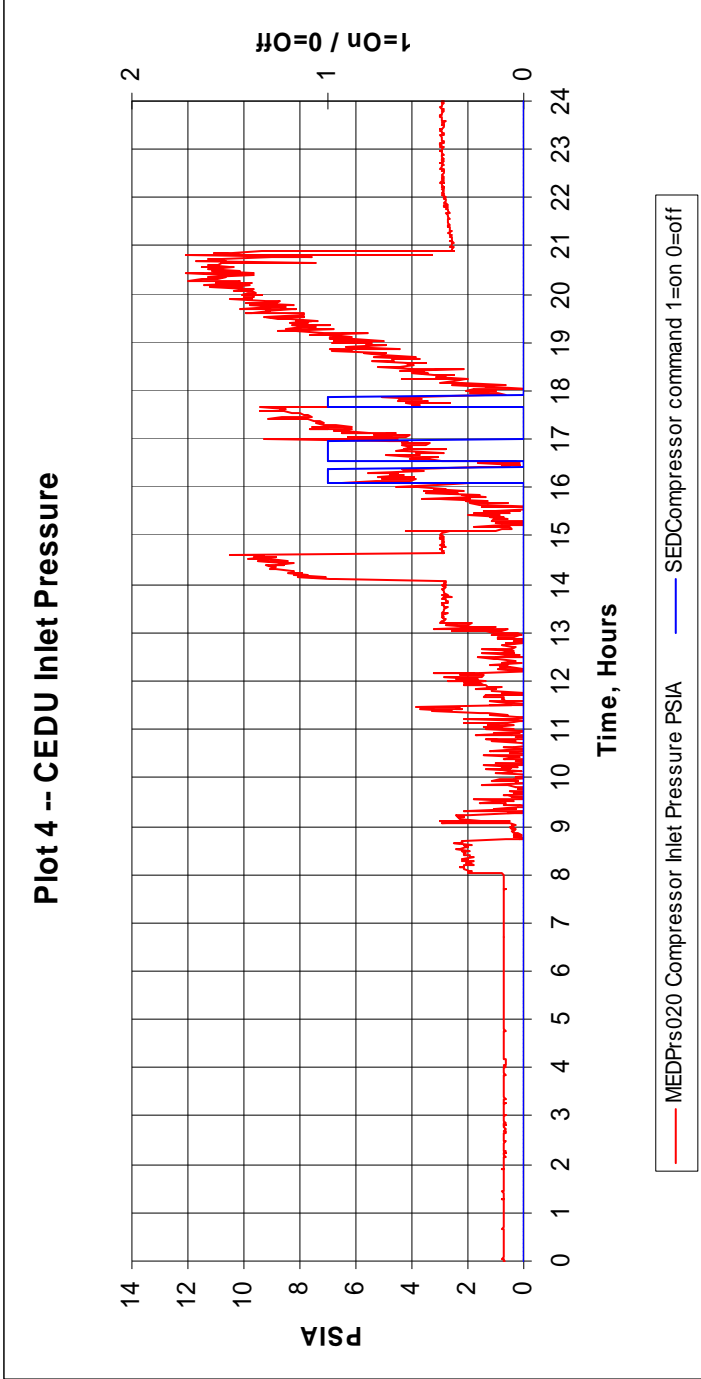
This plot shows the compressor inlet pressure. The inlet pressure varies as the 4-bed mol sieve is transitioning through its operating modes.

119

Plot 5 -- CEDU Outlet Dew Point
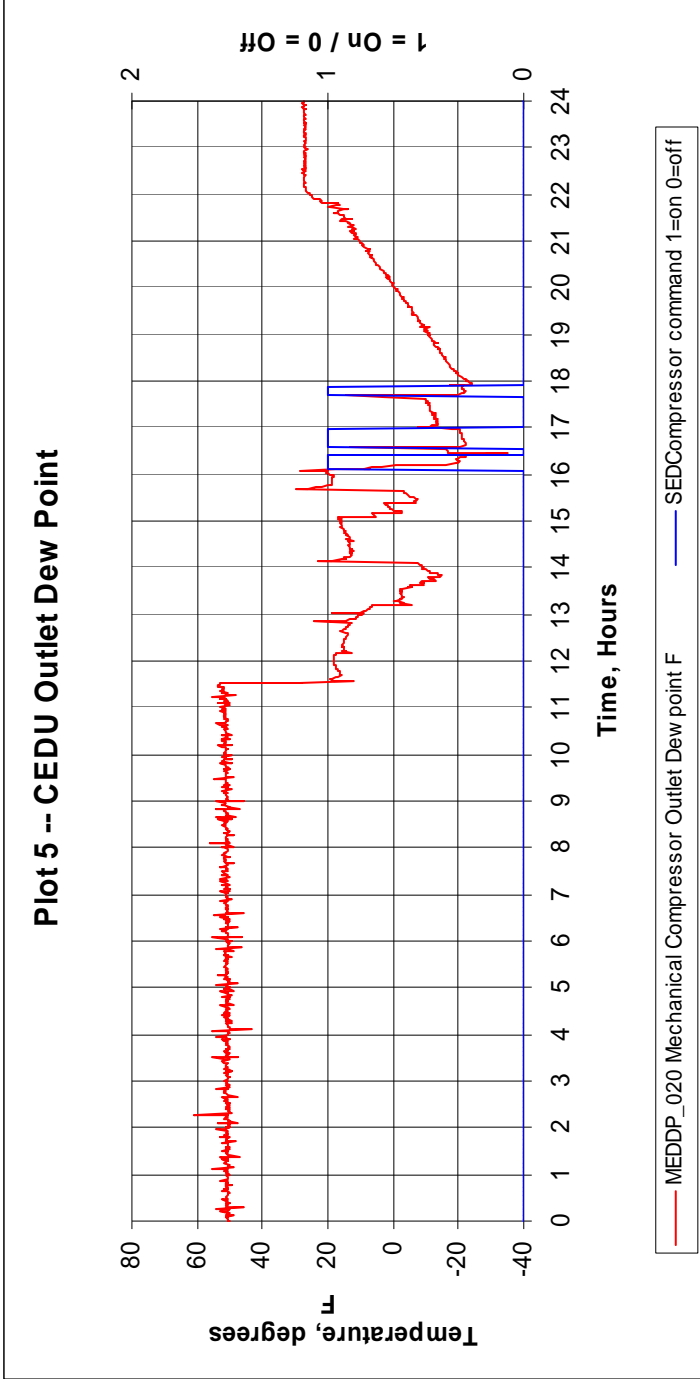
This plot shows the outlet dew point of the compressor. The dew point was anticipated to be high enough to cause condensation in the compressor, but as shown in the plot, the dew point remained low throughout the test.

Plot 6 -- CEDU Outlet Pressure
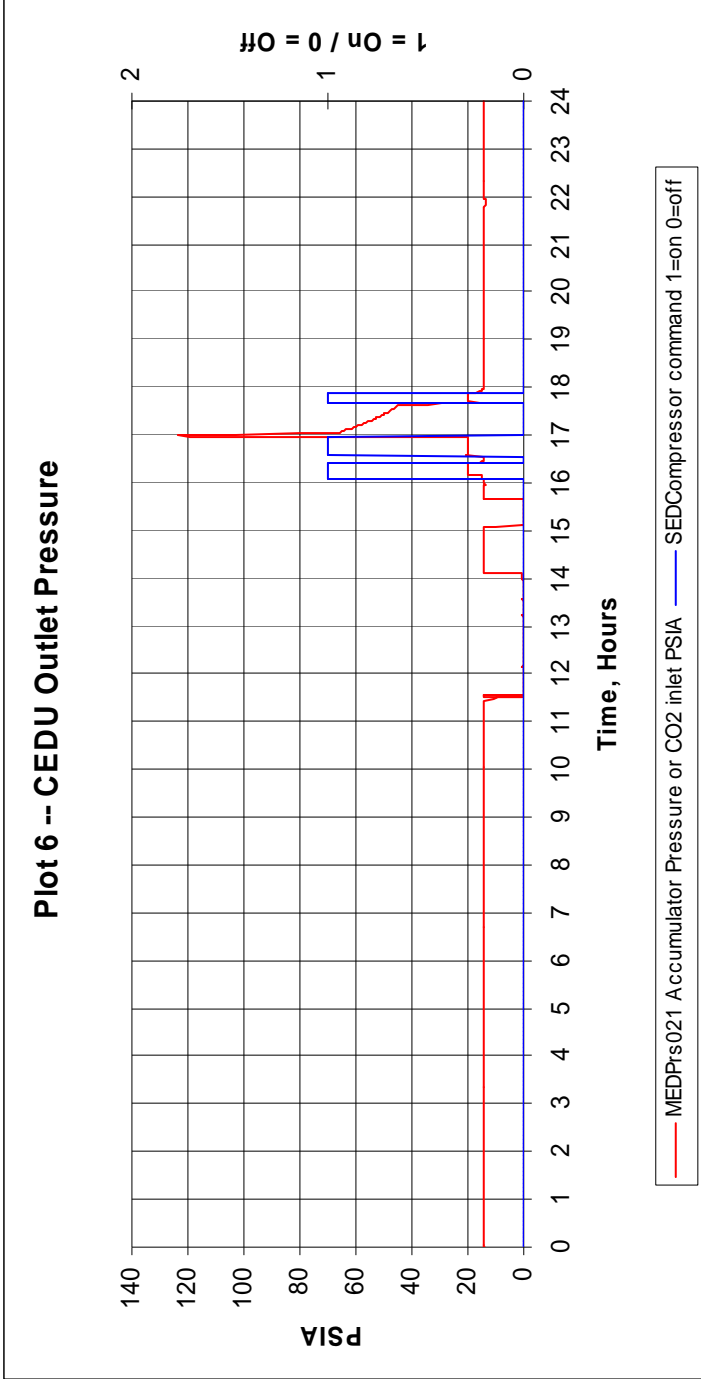
This plot shows the compressor discharge pressure. The compressor was tested at varying discharge pressures by incorporating a pressure regulator into the downstream plumbing.

Plot 7 – CEDU Temperatures (1 of 3)
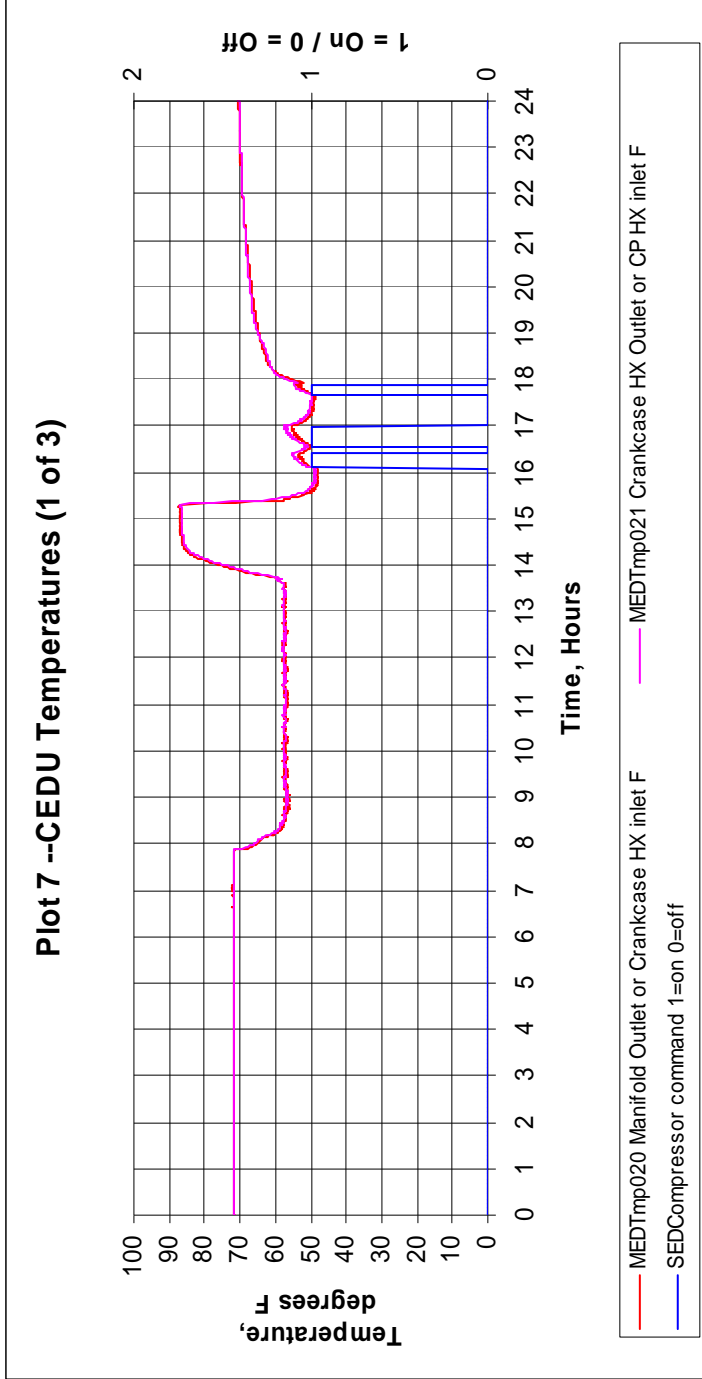
This plot and the next two show the temperatures at various locations within the compressor. The temperatures are measured in the cooling water throughout the compressor. The large temperature increase at 14-15 hours was due to thermocouples being removed from the coolant and not relevant to the specific test results.

Plot 8 -- CEDU Temperatures (2 of 3)

Temperature, degrees F

Time, Hours

1 = On / 0 = Off

MEDTmp022 Manifold Inlet F
MEDTmp024 Crankcase External Motor End F
MEDTmp023 Cold Plate Outlet F
SEDCompressor command 1=on 0=off

Plot 9 -- CEDU Temperatures (3 of 3)

MEDTmp025 Low er Guide Cylinder Stage 1 Motor End F — MEDTmp026 Crossover Head Stage 1 Motor End F
MEDTmp027 Crossover Head Stage 2 F — SEDCompressor command 1=on 0=off

124

5.2.5 4BMS/CEDU Baseline Case

POIST 4BMS/Compressor EDU Testing -- CEDU/4BMS BL #5 - Elapsed Time from 12/1 -- Test Day 9 2004

Plot 1 -- Carbon Dioxide Partial Pressures at 4BMS Inlet and 4BMS Outlet, and 4BMS, CEDU and SEDU Status
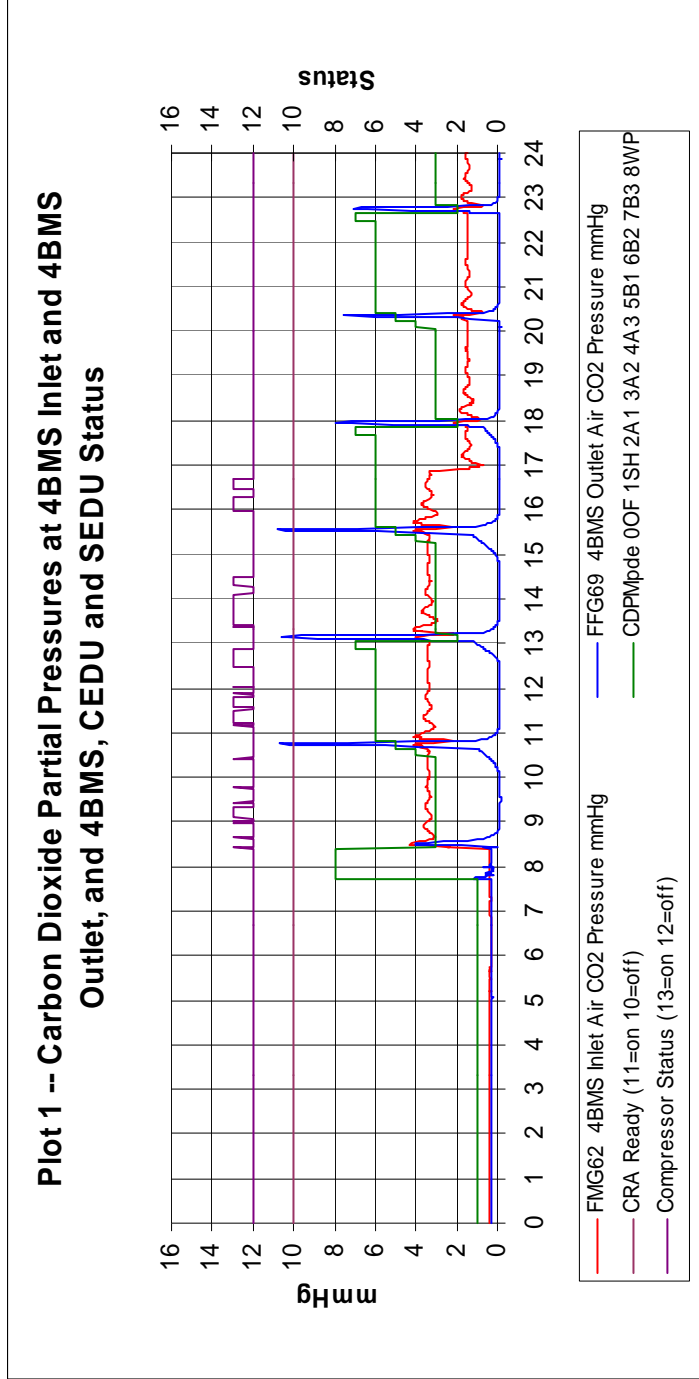
This plot shows the status of the 4BMS and the compressor and the carbon dioxide concentration into and out of the CO2 removal system. The compressor was operated in the middle part of the day for this test series, as indicated by the purple line changing from 12 to 13. For this test, the inlet CO2 concentration (indicated by the red line above) was set to 3 mmHg for half of the test and 1.5 mmHg for the remainder.

Plot 2 -- CEDU Status

Legend:
- Day/Night Status (7=day, 6=night)
- MEDFlw 020 Compressor Outlet Flow after DP lb/hr
- MEDPrs021 Accumulator Pressure or CO2 inlet PSIA
- SEDCompressor command 1=on 0=off
- MEDPrs020 Compressor Inlet Pressure PSIA

Y-axis (left): Suction Press (PSIA), Flow (lb/hr), On/Off, Day, Night
Y-axis (right): 0, 20, 40, 60, 80, 100, 120, 140
X-axis: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

This plot shows some of the key data for the mechanical compressor. The inlet and outlet pressures are both shown on this plot along with flow and the compressor command. The following plot shows the same data on a magnified time scale.

Plot 2 -- CEDU Status

Legend:
- Day/Night Status (7=day, 6=night)
- MEDFlw 020 Compressor Outlet Flow after DP lb/hr
- MEDPrs021 Accumulator Pressure or CO2 inlet PSIA
- SEDCompressor command 1=on 0=off
- MEDPrs020 Compressor Inlet Pressure PSIA

Y-axis (left): Suction Press (PSIA), Flow (lb/hr), On/Off, Day, Night
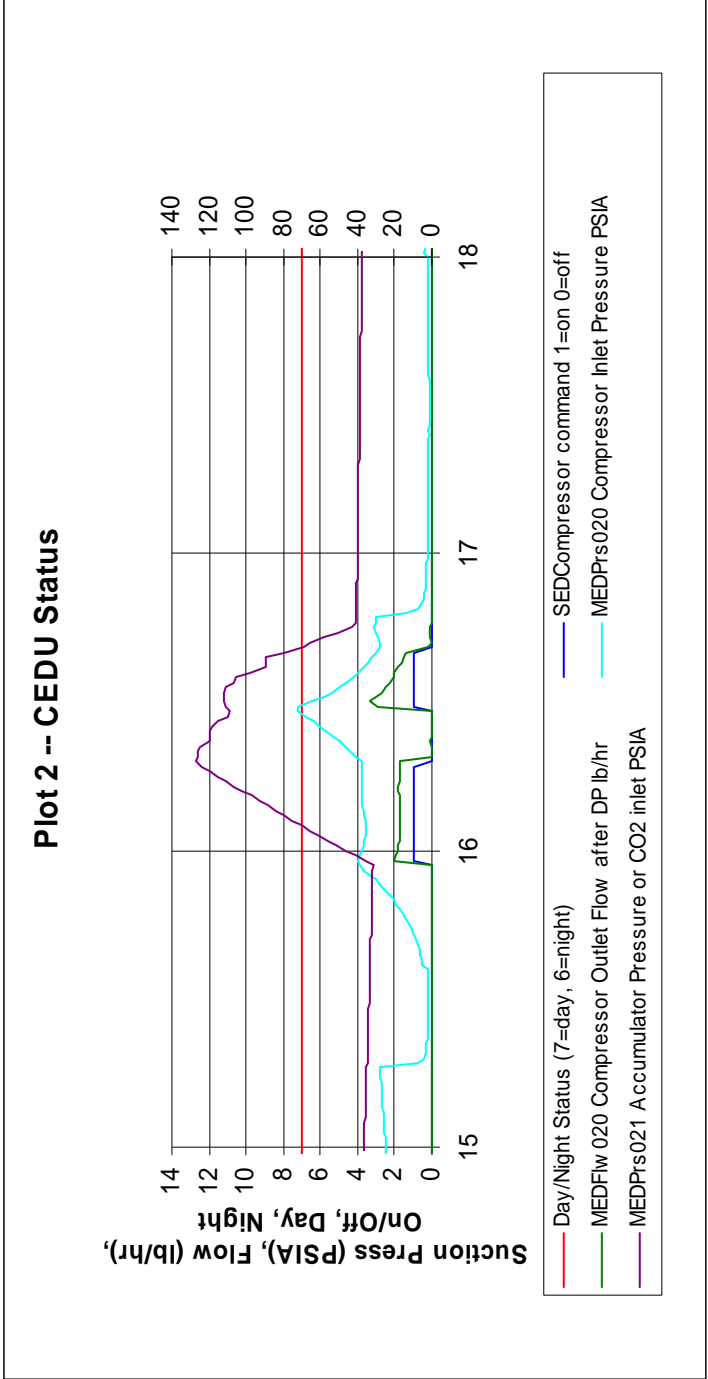
This plot shows the magnified time scale of the previous plot. The light blue line above is the compressor inlet pressure, which is the same as the molecular sieve bed pressure as it is being desorbed. The purple line is the accumulator pressure into which the compressor is pumping the CO2. The green line shows the mass flow rate of CO2 from the compressor.

127

Plot 3 -- 4BMS Vacuum System Pressures

Legend:
- CDPPrs123 Sorbent bed 308 pressure PSIA
- CDPmp12 Pump Inlet Air Pressure PSIA
- CDPPrs021 Fac Vacuum Tank Air Inlet Pressure Torr
- CDPPrs022 Fac Vacuum Tank Air Pressure Torr

Y-axis: PSIA/Torr
X-axis: Time, Hours
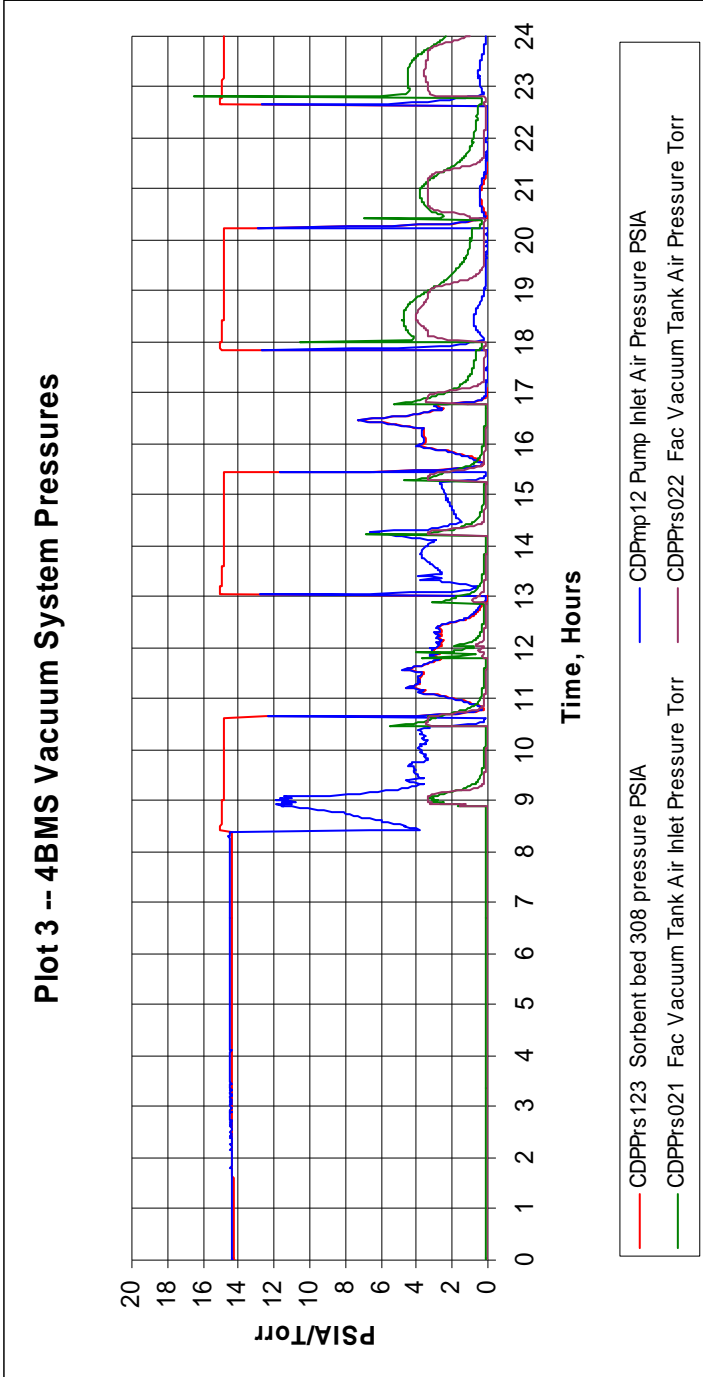
This plot summarizes the vacuum system pressures for the integrated test. The vacuum pressures indicate when the 4BMS is venting to vacuum. The plot is shown again with a magnified time line on the next page.

Plot 3 -- 4BMS Vacuum System Pressures

Time, Hours

PSIA/Torr

CDPPrs123 Sorbent bed 308 pressure PSIA
CDPmp12 Pump Inlet Air Pressure PSIA
CDPPrs021 Fac Vacuum Tank Air Inlet Pressure Torr
CDPPrs022 Fac Vacuum Tank Air Pressure Torr
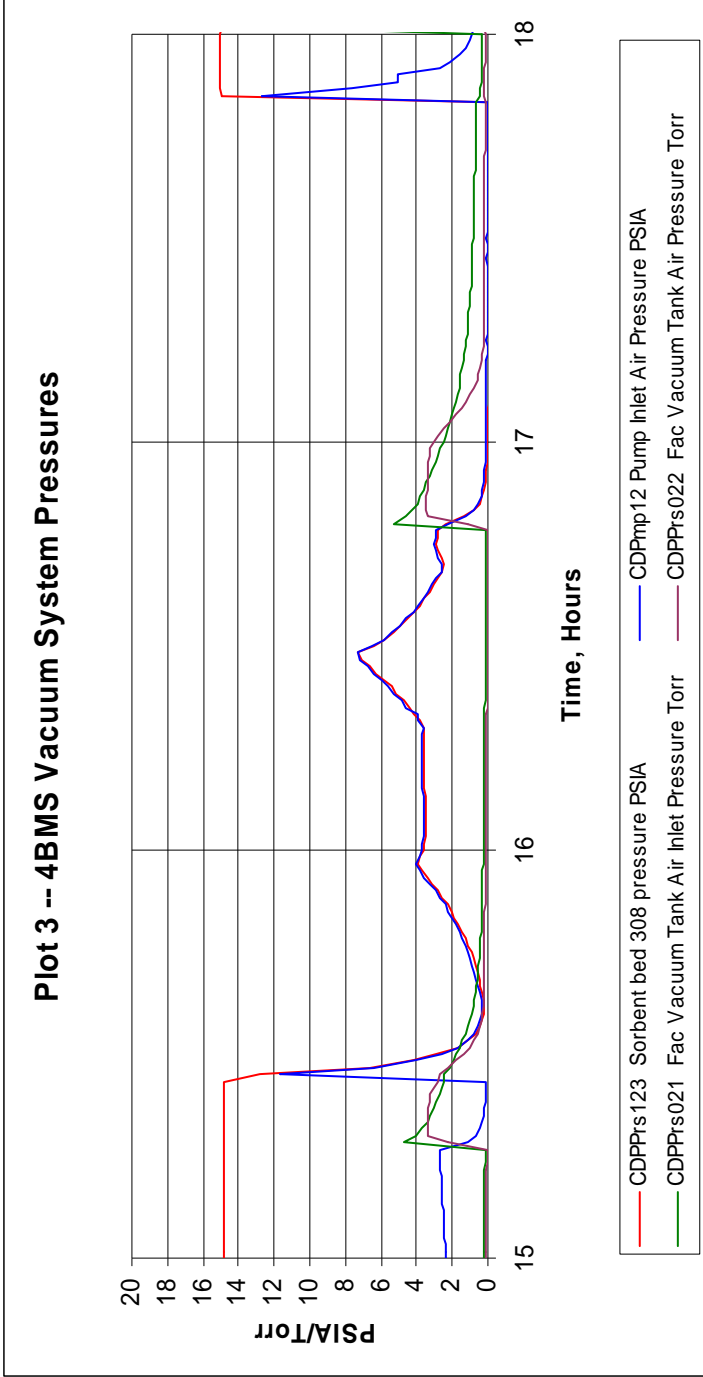
This plot details the system vacuum pressures in more detail. The red and blue lines are the bed pressure and compressor inlet pressure, respectively. The pressures are basically the same during the desorption phase. The green and brown lines are the vacuum pressures. The bed is desorbed directly to the space vacuum simulator during the last 10 minutes of the desorption cycle, as indicated by the increase in the two vacuum pressures. During integrated testing, there are occasions when the accumulator is full, and the bed must therefore desorb to space vacuum instead of activating the compressor.

129

Plot 4 -- CEDU Inet and Outlet Pressures, Outlet Dew Point
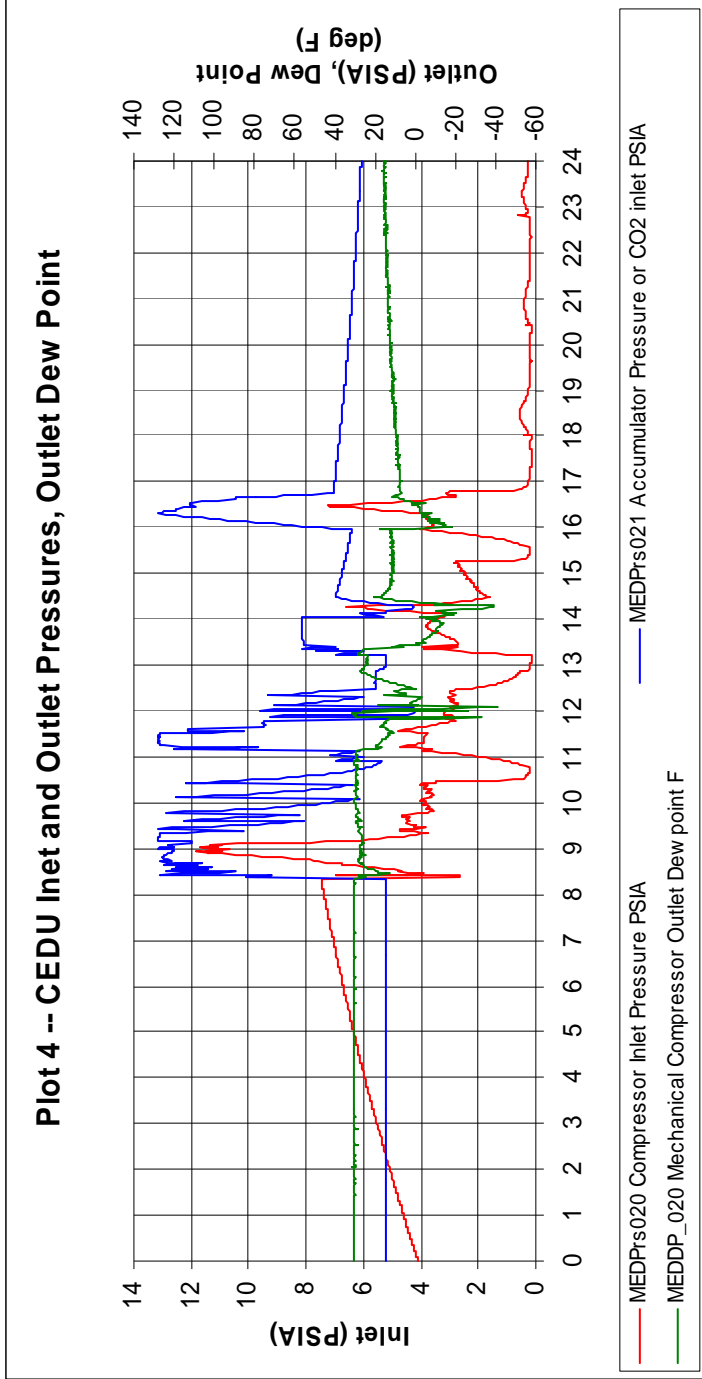
This plot again shows the compressor inlet and outlet pressure, and also the dew point of the product CO2. The data shows that the dew point never exceeds 30 F, even at high accumulator pressure. There is, therefore, little risk of condensation in either the compressor or the accumulator.

Plot 5 -- Sorbent Bed Heater Temperatures

Legend: CDPmt13 5A Bed 308 Heater Temp A F, CDPmt16 5A Bed 309 Heater Temp A F

X-axis: Time, Hours (0 to 24)

Y-axis: Temperature, degrees F (0 to 450)
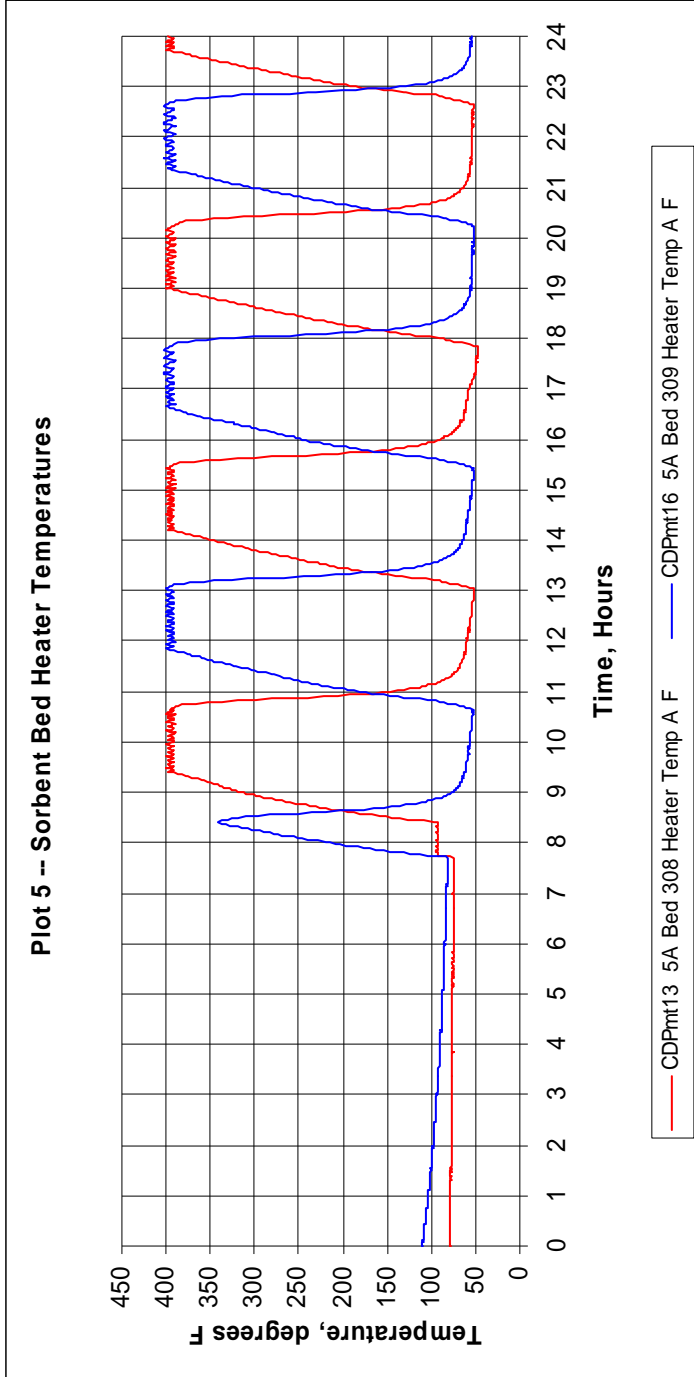
This plot shows the temperature of the two molecular sieve beds. The heater for the desorbing bed is turned on full power until the bed reaches 400 F. The heater is then cycled to maintain the bed temperature while the CO_2 is desorbed.

Plot 6 -- Desiccant Bed Outlet Air Dewpoint Temperature

CDPDP_023 Dessicant Bed Outlet Air Dew pt F

132
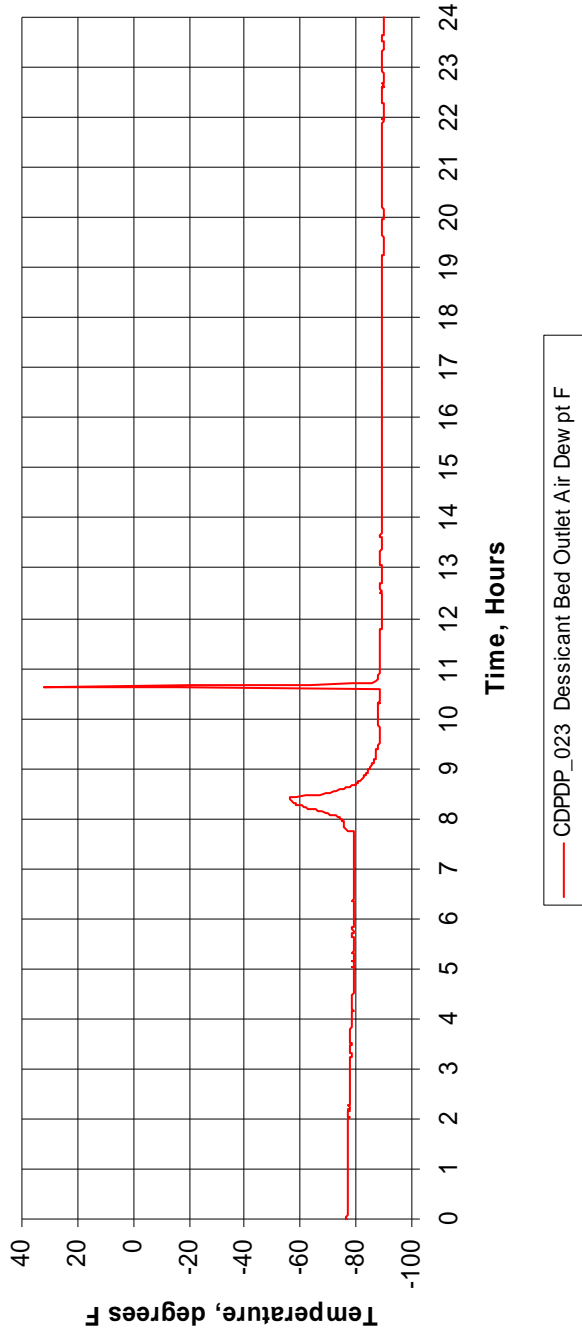
5.2.6 Sabatier Standalone Baseline Case

POIST 4BMS/Compressor EDU Testing – Sabatier Baseline Pt #1 - Elapsed Time from 2/4 -- Test Day 16 2005

Plot 1 -- Status for 4BMS, CRA, OGA and Compressor (offset for clarity)
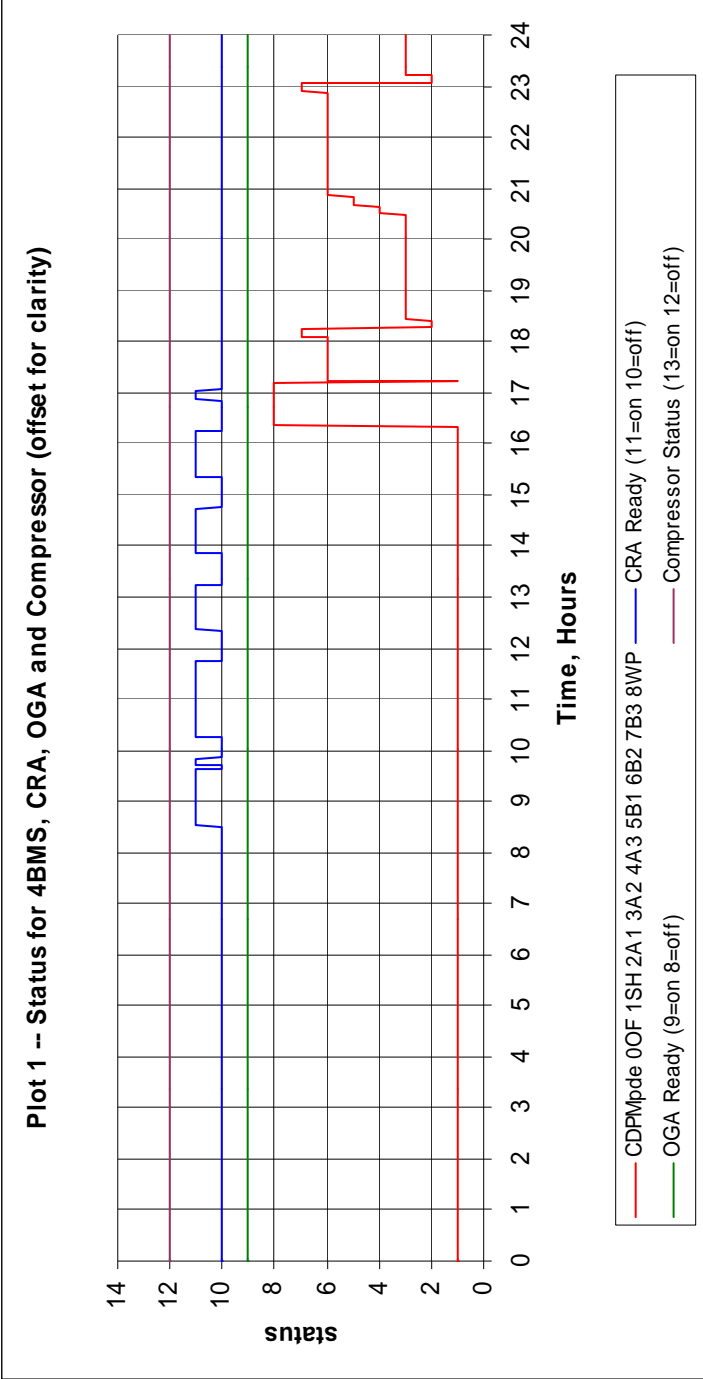
This plot shows the operating status of the components. In this test, the Sabatier was operated alone.

Plot 2 --SEDU Reactor Cooling Control
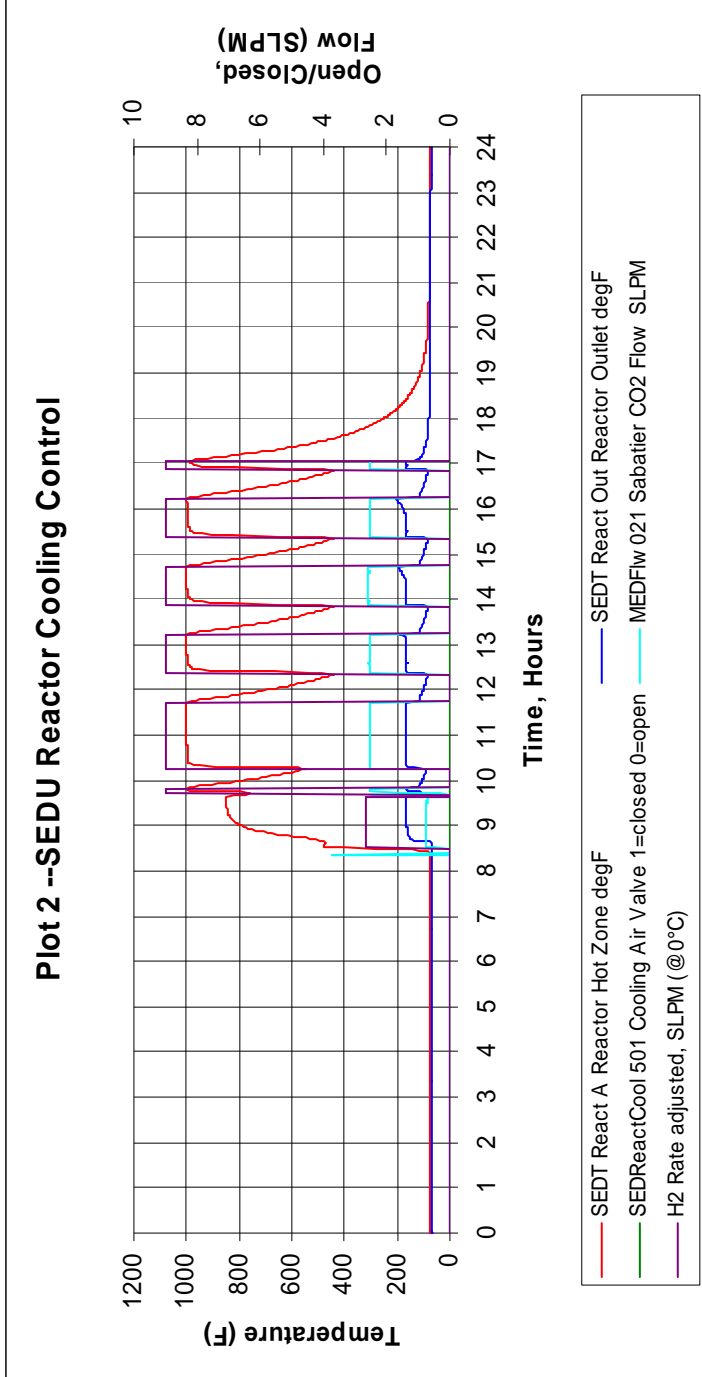
This plot shows the hydrogen and carbon dioxide flow rates along with the temperatures of the reactor. This case was run at full flow, 9 slpm hydrogen and 2.7 slpm CO2, in cyclic operation. The reactant flow is on for about 53 minutes and off for 37 minutes. The hot zone of the reactor peaks out at 1000 F while reactants are flowing and cools down to about 500 F when the flow is stopped. The reactor outlet flow is below 200 F during the entire run.

Plot 3 -- SEDU Separator Level Control
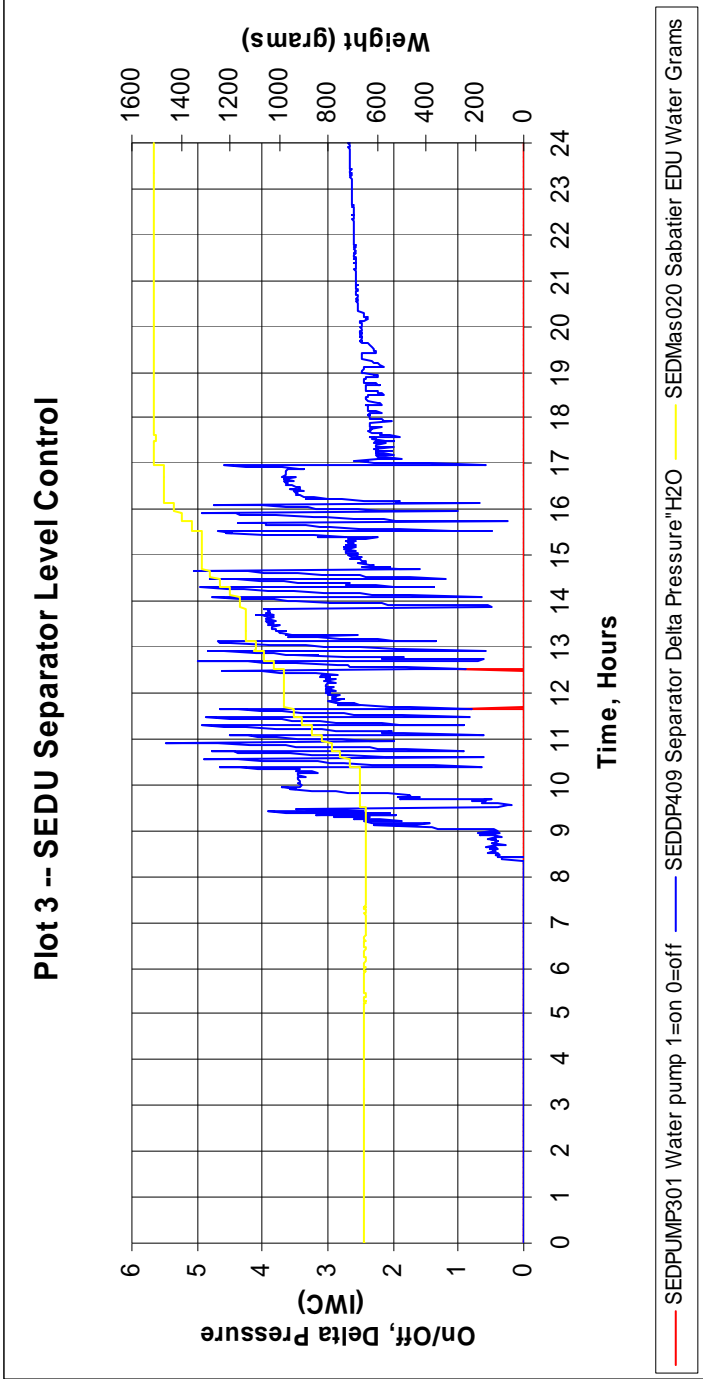
This plot shows the operation of the water collection tank and pump. The data is shown magnified in the next plot.

135

Plot 3 -- SEDU Separator Level Control
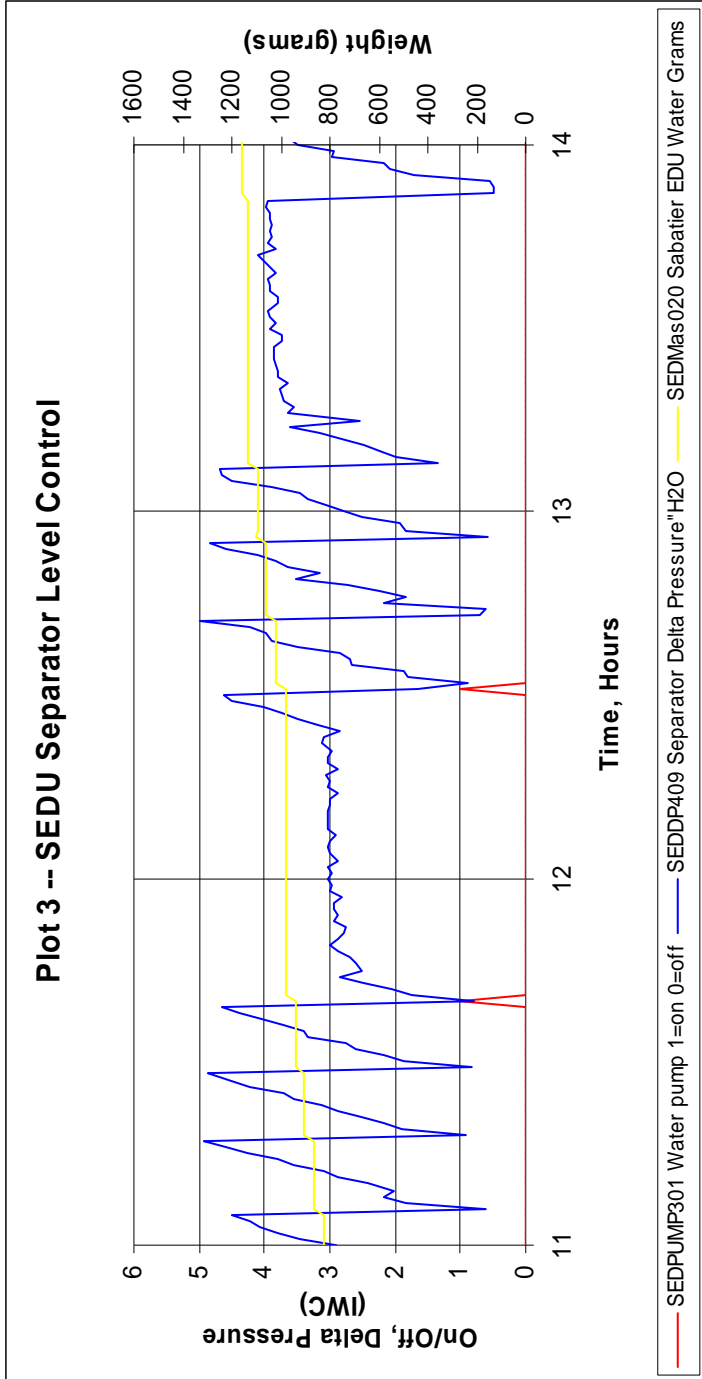
This plot shows the operation of the water separator in more detail. The saw tooth line is the level in the separator as measured with a differential pressure sensor. When the level reaches a high limit, the pump is activated for about 5 seconds. The data collection for these tests was one reading per minute. Many times, the reading did not catch the activation of the pump, which is why only a few activations are shown on the graph. The water weight is measured with an electronic scale. The time period around hour 12 with no increase in water weight is a Standby period for the Sabatier system.

Plot 4 -- SEDU System Pressures
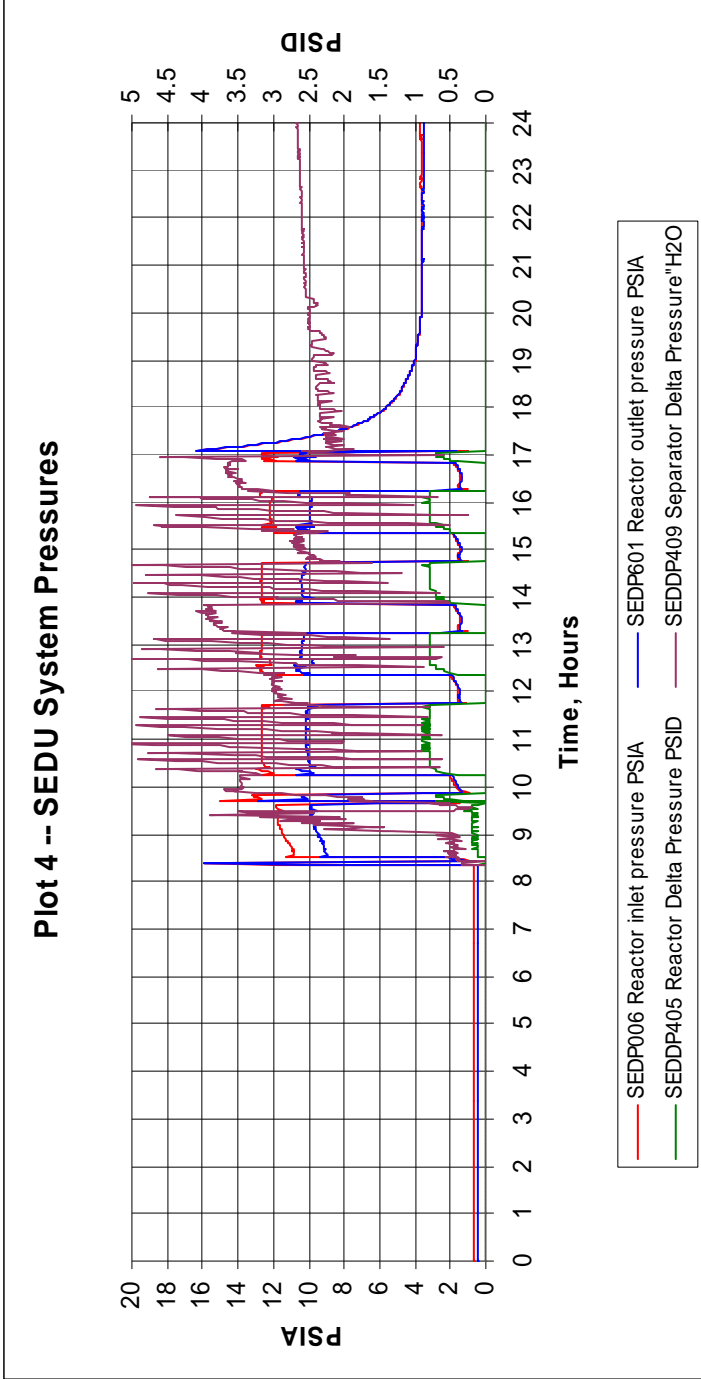
This plot shows the pressures throughout the Sabatier system. The maroon, spiked lines are the same separator differential pressure reading shown in the previous plot. The red and blue lines are the reactor inlet and outlet pressures, respectively. The reactor is evacuated to low pressure (<2 psia) every time the system transitions to Standby. The green line is the reactor differential pressure. The differential pressure is related to flow rate, and is less than 1 psid at full flow.

137

Plot 5 -- SEDU System Efficiency

Legend:
- Calc H2O Prod @ 100% Eff, gram
- Calc H2O Prod @ 90% Eff, gram
- Calc H2O Prod @ 80% Eff, gram
- H2O Production, grams
- H2 Useage Rate, Liters

Y-axis: Weight (grams), Usage (lites)

X-axis: Time, Hours
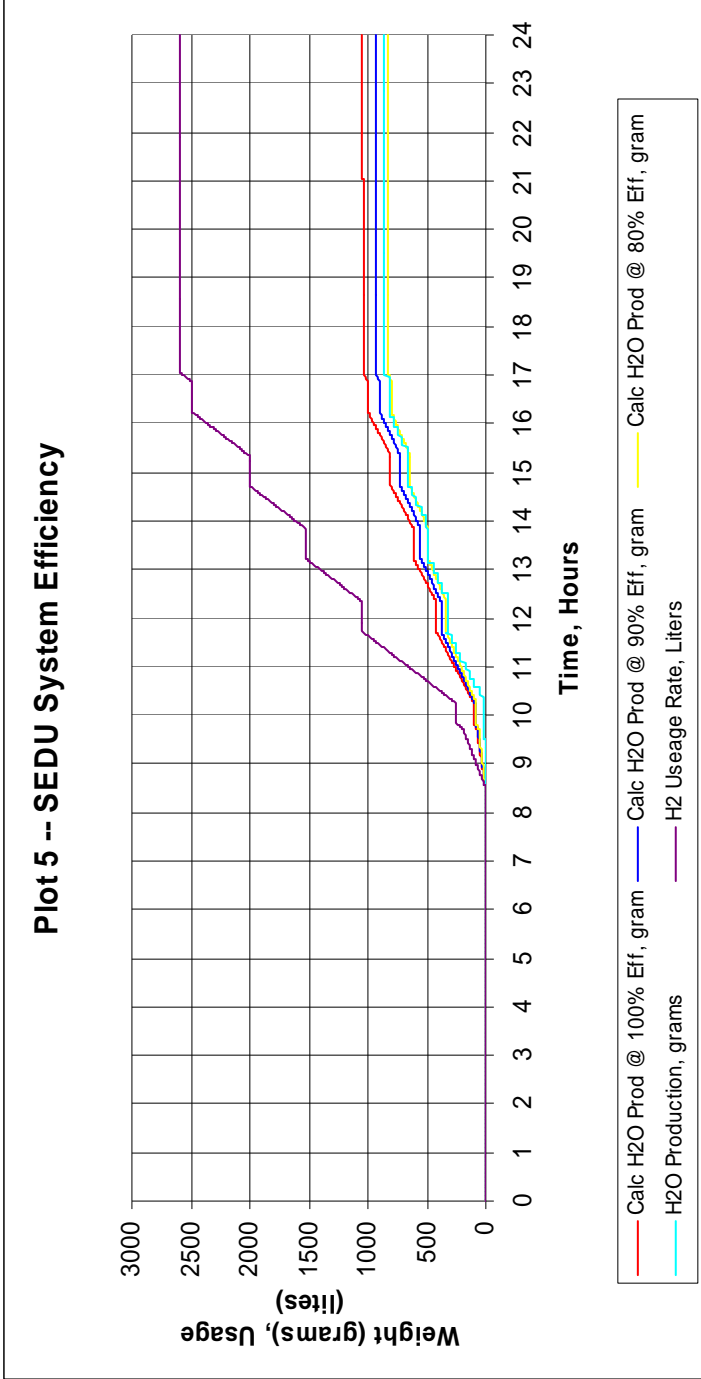
This plot shows the Sabatier water production rate plotted with calculated efficiency targets. The efficiency is calculated from the usage rate of hydrogen. This plot shows the efficiency to be about 80%. This plot is a little misleading for efficiency because the water weight is not recorded until the first dump out by the pump, and therefore the inventory of water in the system is not fully accounted.

138

Plot 6 -- SEDU Molar Ratio
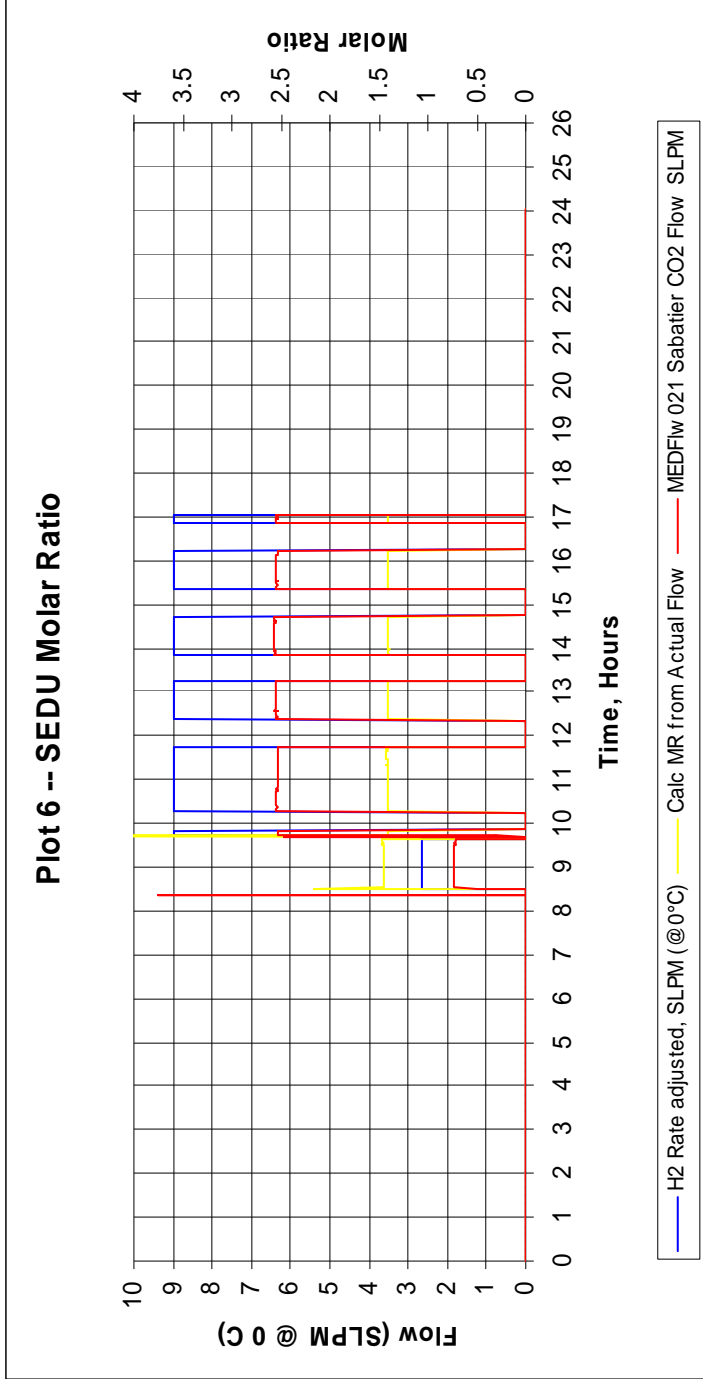
This plot shows the hydrogen and carbon dioxide flows to the Sabatier reactor and the calculated molar ratio. The stoichiometric ratio for the reaction is 4 moles hydrogen per mole of carbon dioxide. Since the ISS life support closed loop mass balance is carbon dioxide rich, the reactor is controlled to a molar ratio of 3.5 to ensure that all of the available hydrogen is used in the reaction.

Plot 7 -- SEDU CO2 and H2 Flow

Legend: MEDFlw 021 Sabatier CO2 Flow SLPM — Desired CO2 Flow (SLPM) — SEDMFC H2 Mass Flow SLPM
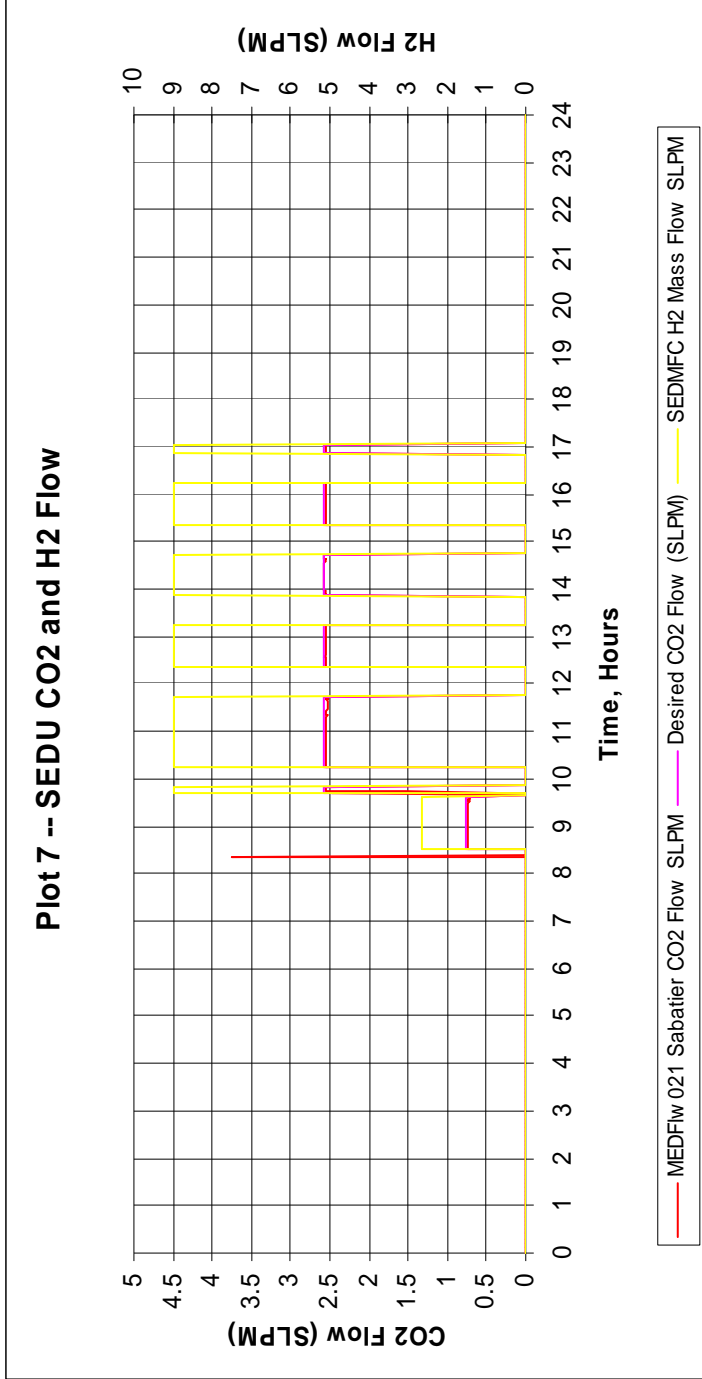
This plot shows the CO2 and H2 flow feeds to the reactor. In this test, the Sabatier was operated in cyclic mode, therefore the flows are turned on and off for every Process/Standby mode.

Plot 8 -- SEDU Temperatures
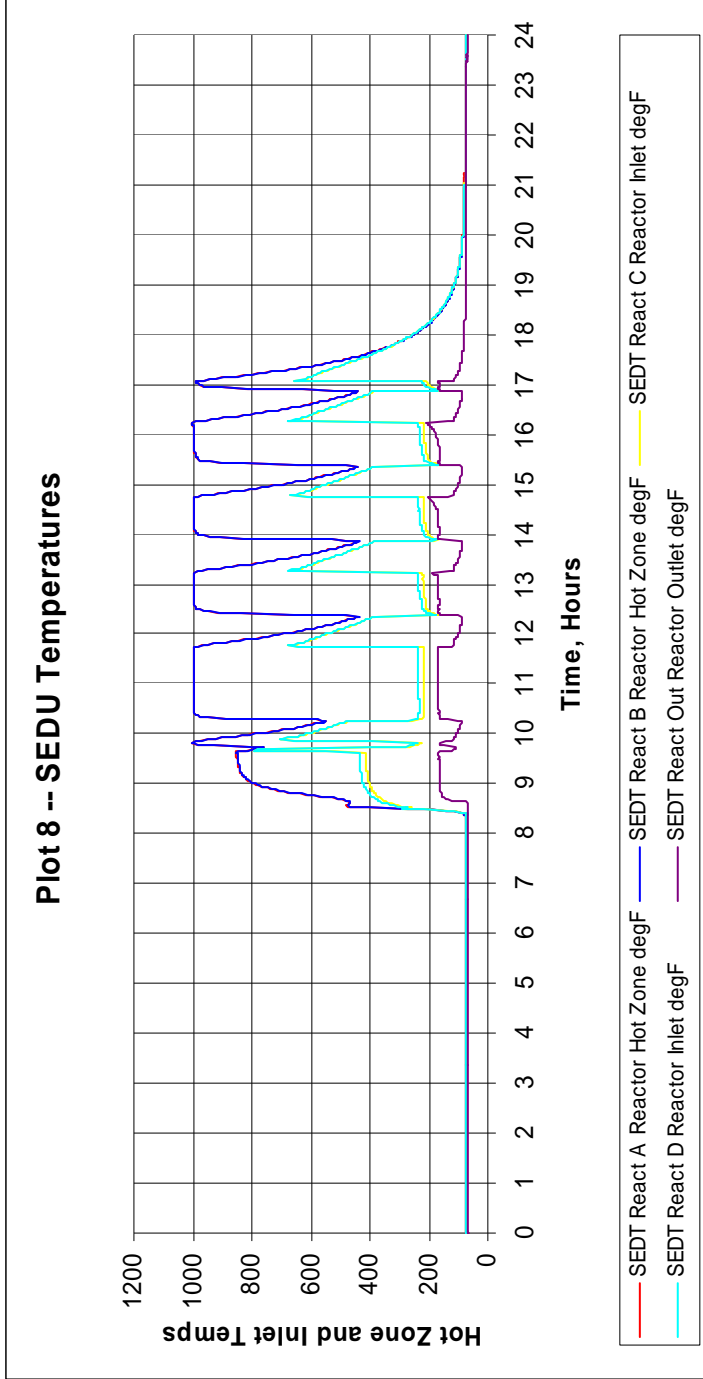
This plot details the temperatures in the Sabatier reactor. Temperatures A and B are in the hot zone of the reactor, which is about three inches from the inlet end. Temperatures C and D are closer to the inlet end and intended to be used to detect the presence of air in the inlet CO2 stream. While the reactants are flowing into the reactor, the heat from the reaction is continuously pushed toward the aft end of the reactor bed. When the flows stop (around 11.75 hours, 13.25 hours, 14 hours, etc) the hottest part of the reaction zone starts to cool down, but the inlet end of the reactor immediately starts to heat up due to conduction of heat from the hot zone. The outlet of the reactor follows the same cooling trend as the hot zone when the reactants are removed.

141

Plot 9 -- SEDU Water Production Rate

Legend: H2O Production, grams — SEDStandby Standby Mode — SEDProcess Process Mode (C102)
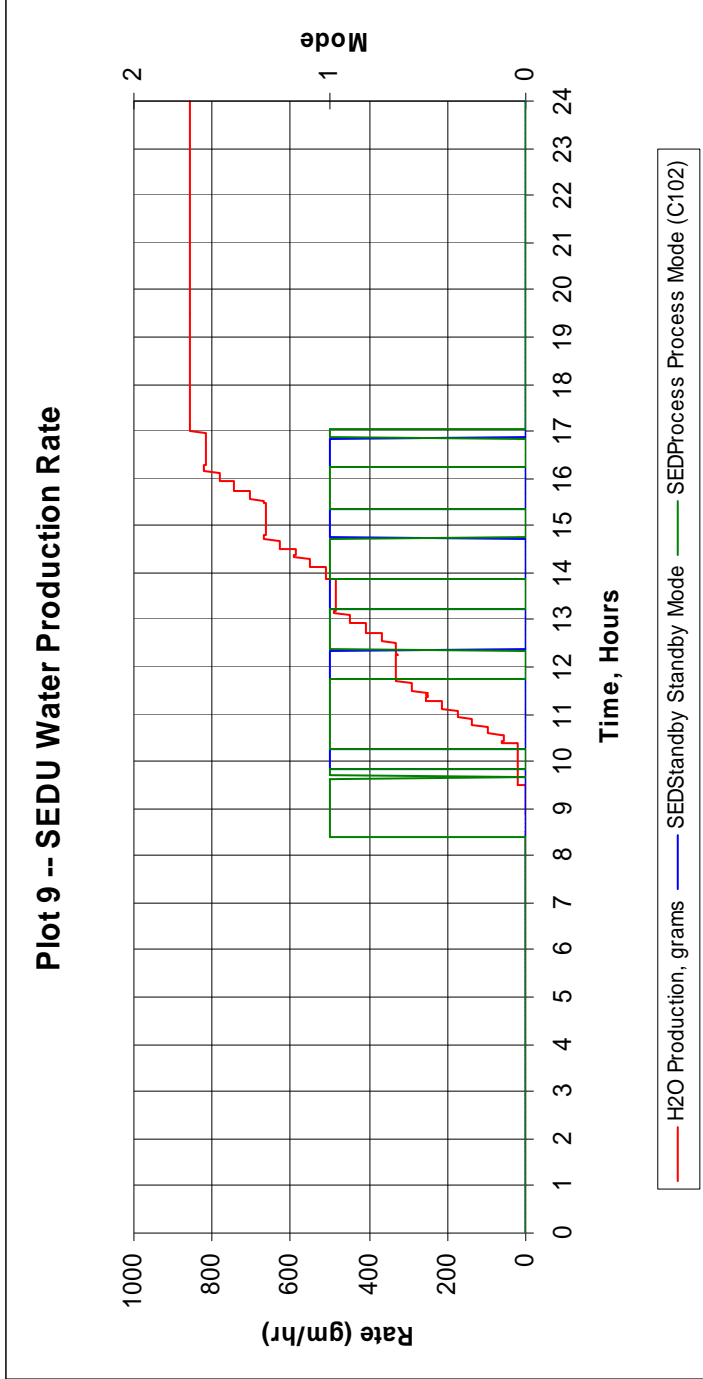
This plot details the water production rate. The water product is recorded on a digital scale, which is incremented every time the product water pump turns on to empty the separator. During Standby (when the blue line is 1 and the green line is 0) there is no additional water production, and the red line is flat for the duration. Once Process mode starts again, the water production starts again.

Plot 10 -- SEDU Overview
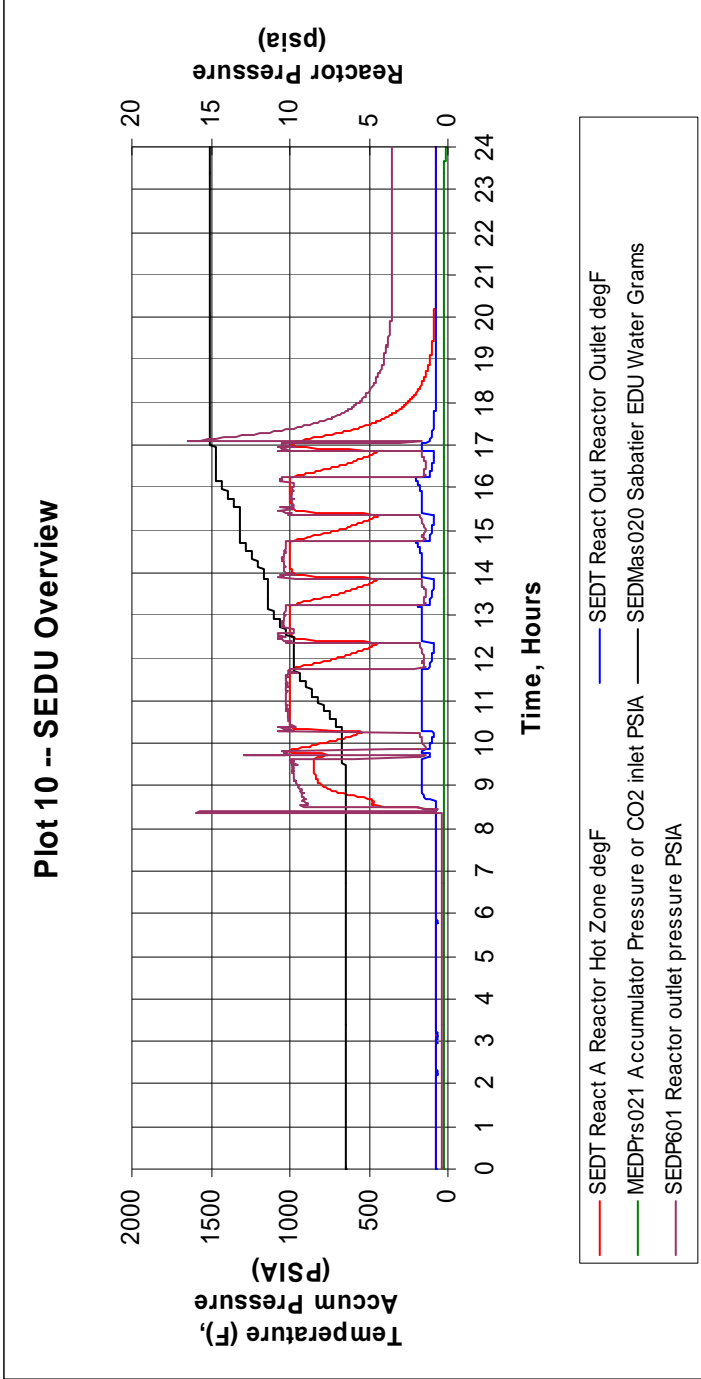
This plot is an overview of the Sabatier system operation, and gives analysts a quick glance at the state of the system. The reactor pressure and temperatures show readily that the system is operating in a cyclic mode, since the temperature and pressure are alternating. The water production line shows that the system is operating well, with no major problems. The CO2 accumulator pressure is also listed on this graph. In this test case, the CO2 feed was operated on a fixed 25 psia feed source. For the integrated tests, the CO2 pressure rises and falls and the compressor fills the accumulator and the Sabatier empties it.

Plot 11 -- SEDU Status

Legend:
- OGA Ready (9=on 8=off)
- SEDStandby Standby Mode
- MEDPrs021 Accumulator Pressure or CO2 inlet PSIA
- CRA Ready (11=on 10=off)
- SEDProcess Process Mode (C102)
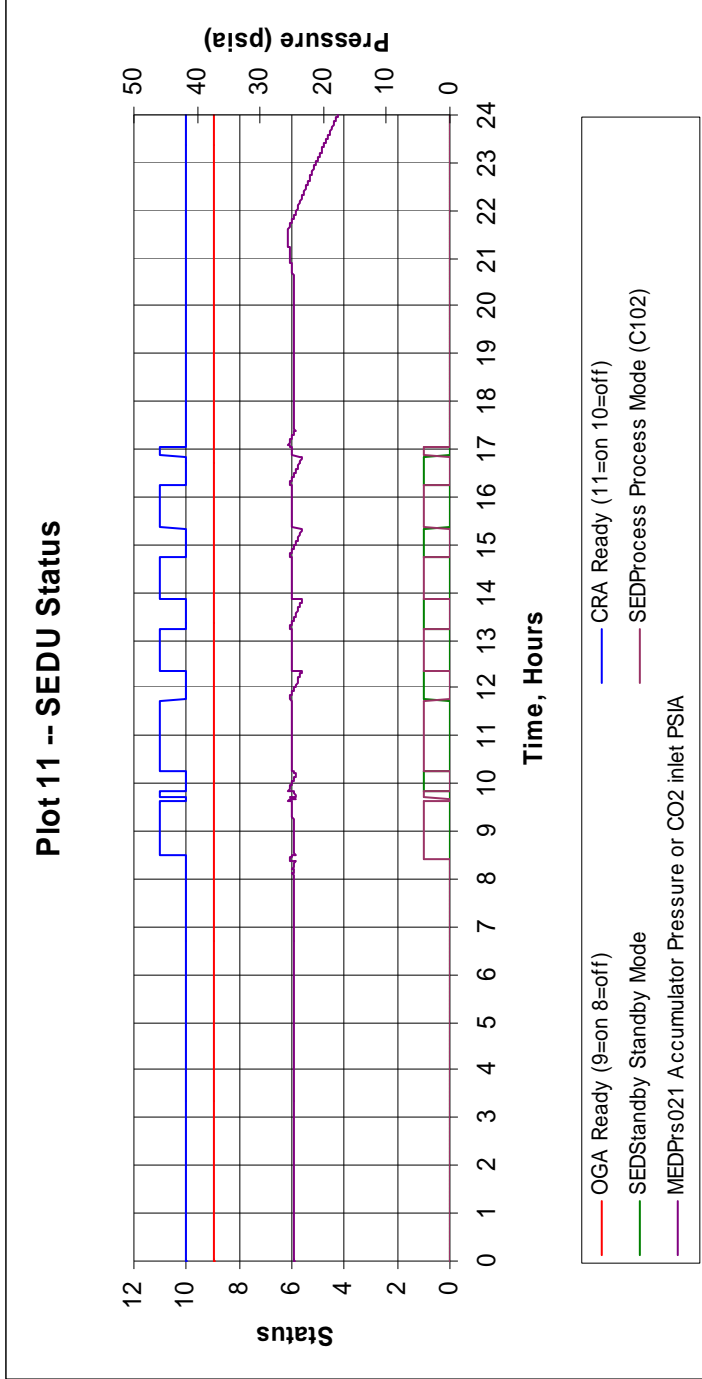
This plot shows the status of some of the systems in the integrated test. The OGA status (off for this stand alone test) is given along with the Sabatier Process or Standby modes. The accumulator pressure is given here as well, which is more informative for the integrated tests.

Plot 12 -- SEDU CO2 Flow Control Accuracy
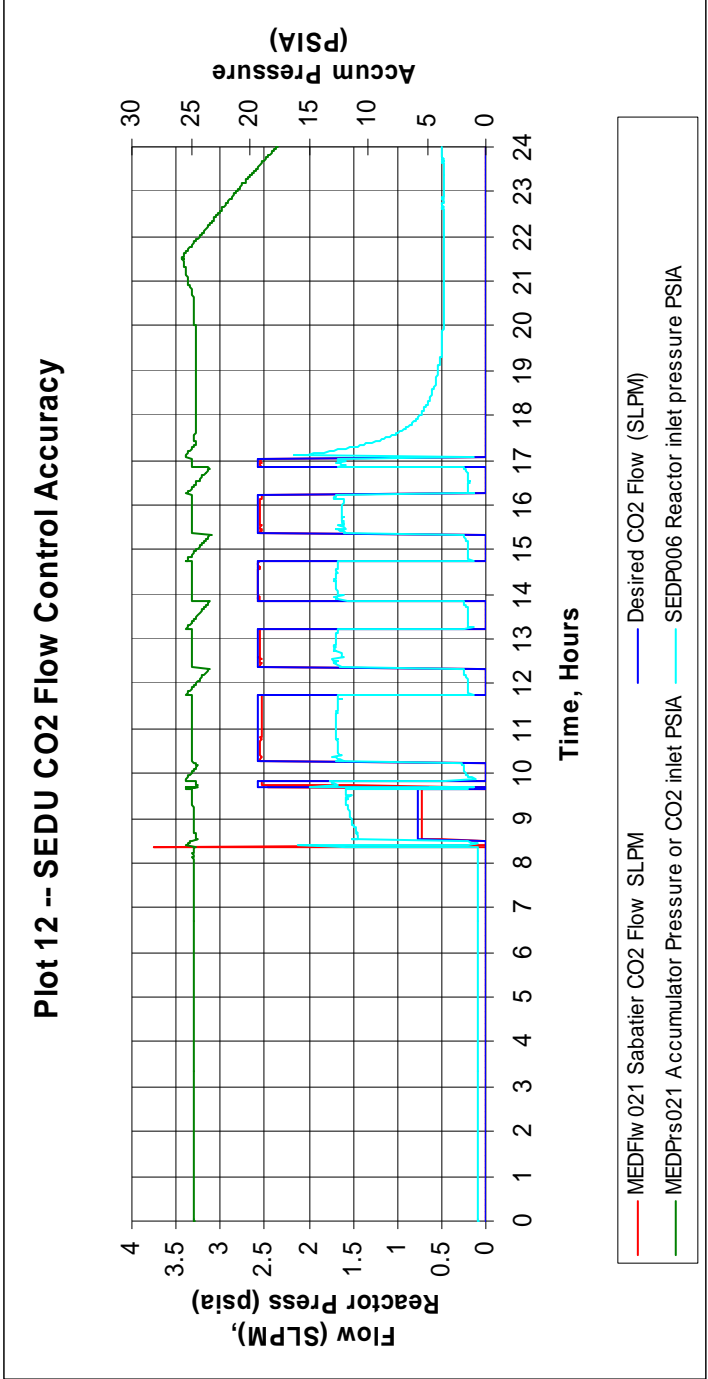
This plot shows the accuracy of the CO2 flow control. The Sabatier required development of a flow control for space flight use. The Sabatier EDU incorporated a motor drive control valve. This plot shows that the actual flow met the desired flow over the range of inlet pressures used for this test.

4BMS/TSAC Baseline Case

POIST 4BMS/TSAC/Sabatier Testing – 4BMS-TSAC Test #4 - Elapsed Time from 11/20/2005

Plot 1 -- Status for 4BMS and TSAC

CDPMpde 0OF 1SH 2A1 3A2 4A3 5B1 6B2 7B3 8WP ———— TSAFprod TSAC Outlet CO2 Flow rate sccm
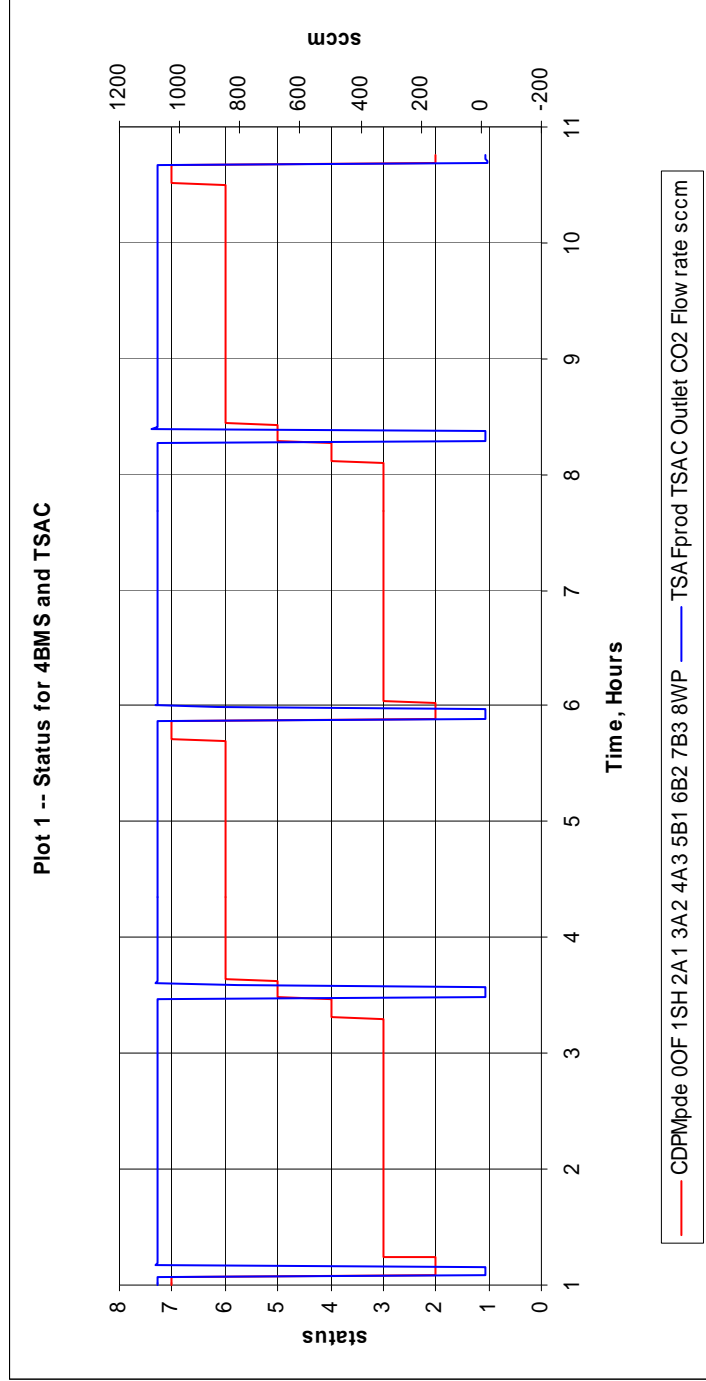
This plot is, again, the familiar status plot, which shows the operating mode of the 4BMS. The TSAC does not have a mode designation data element, but the plot of output flow gives a good indication of the operating state. Each bed is in a "Deliver" state when the output flow is constant.

Plot 13 -- TSAC Internal Pressures
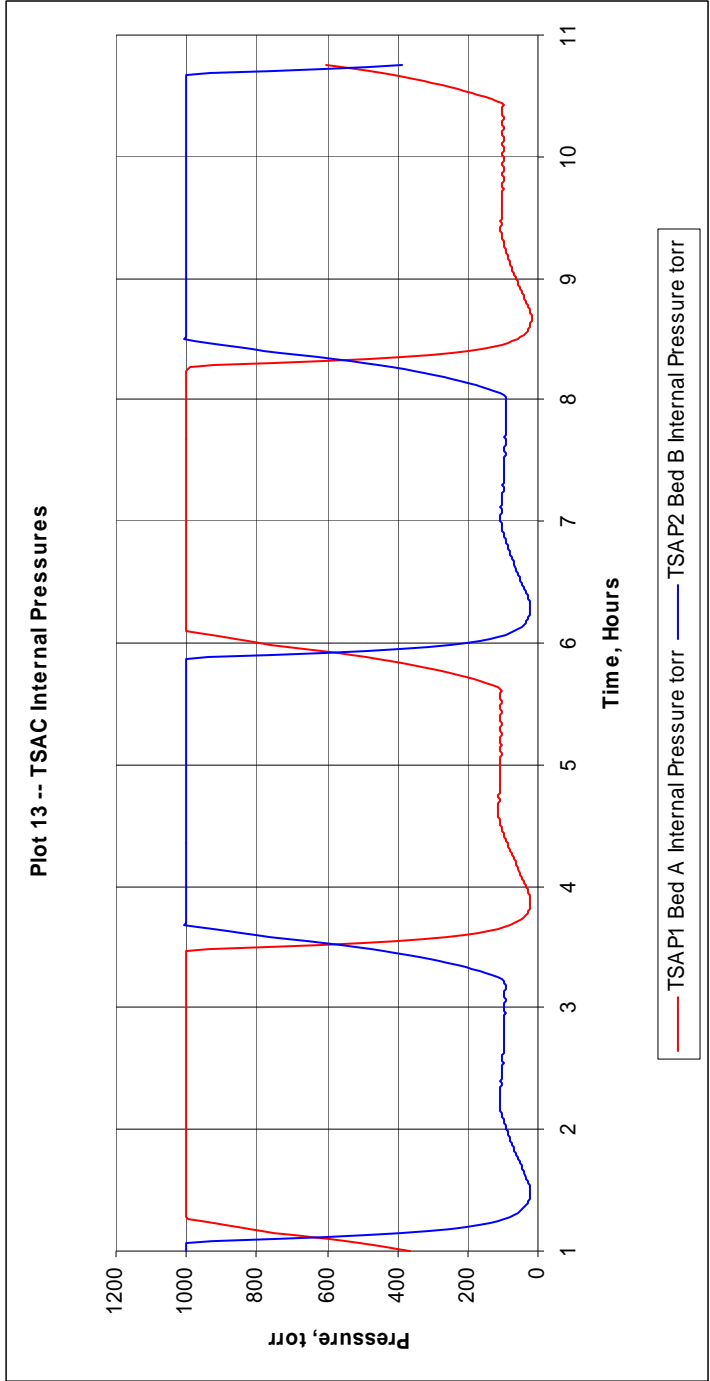
This plot shows the pressures of the CO2 product in each of the two TSAC beds. When the beds are desorbing, the pressure is maintained at 1000 torr for the duration of the desorb cycle.

Plot 14 -- TSAC Bed A Temperatures

Legend:
- TSAHA1 Bed A Heater 1 Temperature C
- TSAHA3 Bed A Heater 3 Temperature C
- TSAExtWalA Bed A External Wall Temperature C
- TSATouchA Bed A Touch Temperature
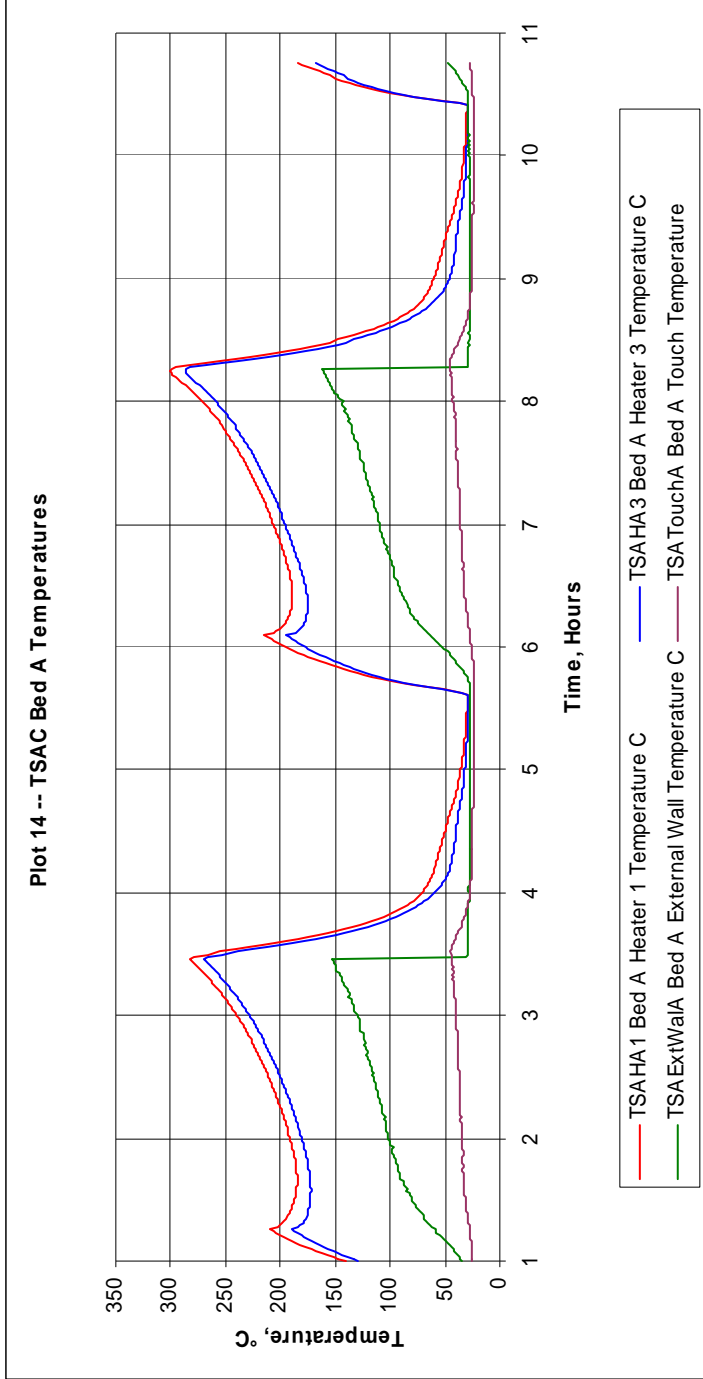
This plot shows the temperature profile for Bed "A". The significance of the curves is explained for plot number 16 which shows temperatures and pressures together.

Plot 15 -- TSAC Bed B Temperatures

TSAHB1 Bed B Heater 1 Temperature C
TSAHB3 Bed B Heater 3 Temperature C
TSAExtWalB Bed B External Wall Temperature C
TSATouchB Bed B Touch Temperature C

This plot shows the temperature profile for Bed "B".
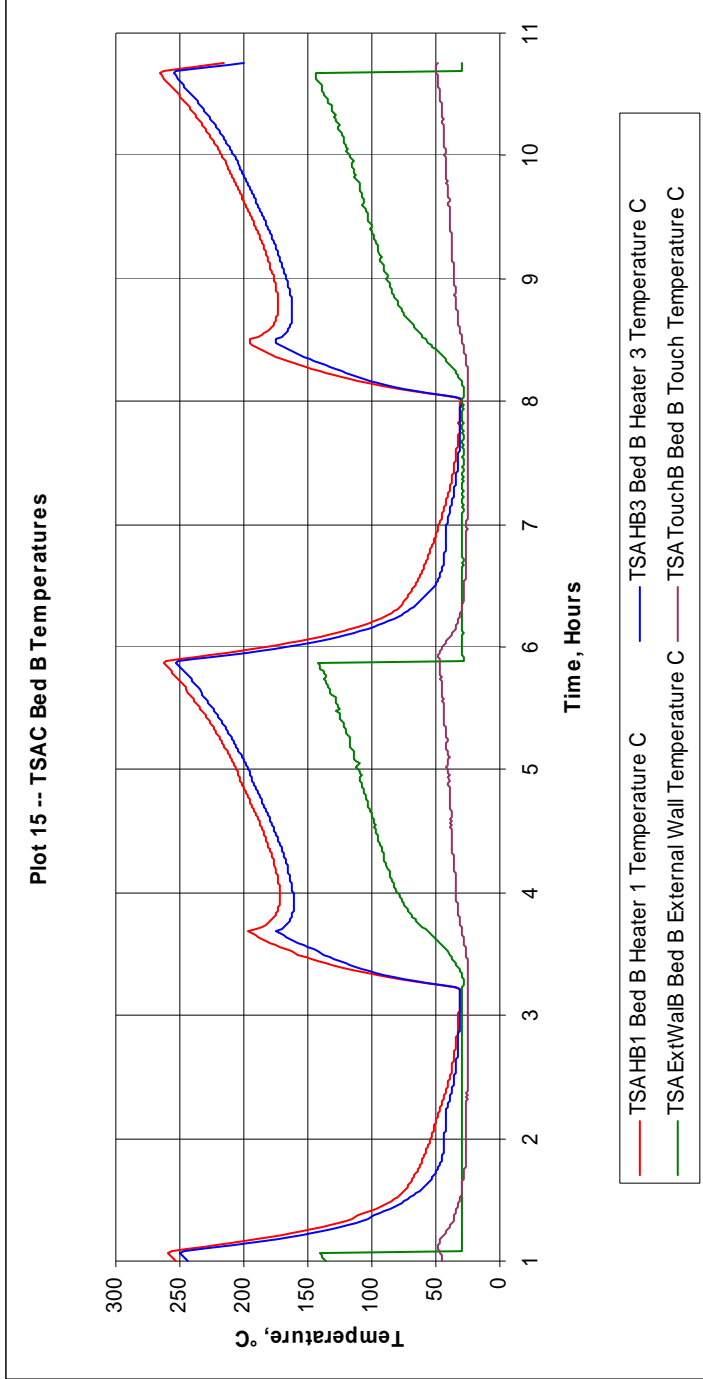
Plot 16 -- TSAC Bed A Pressures and Temperatures
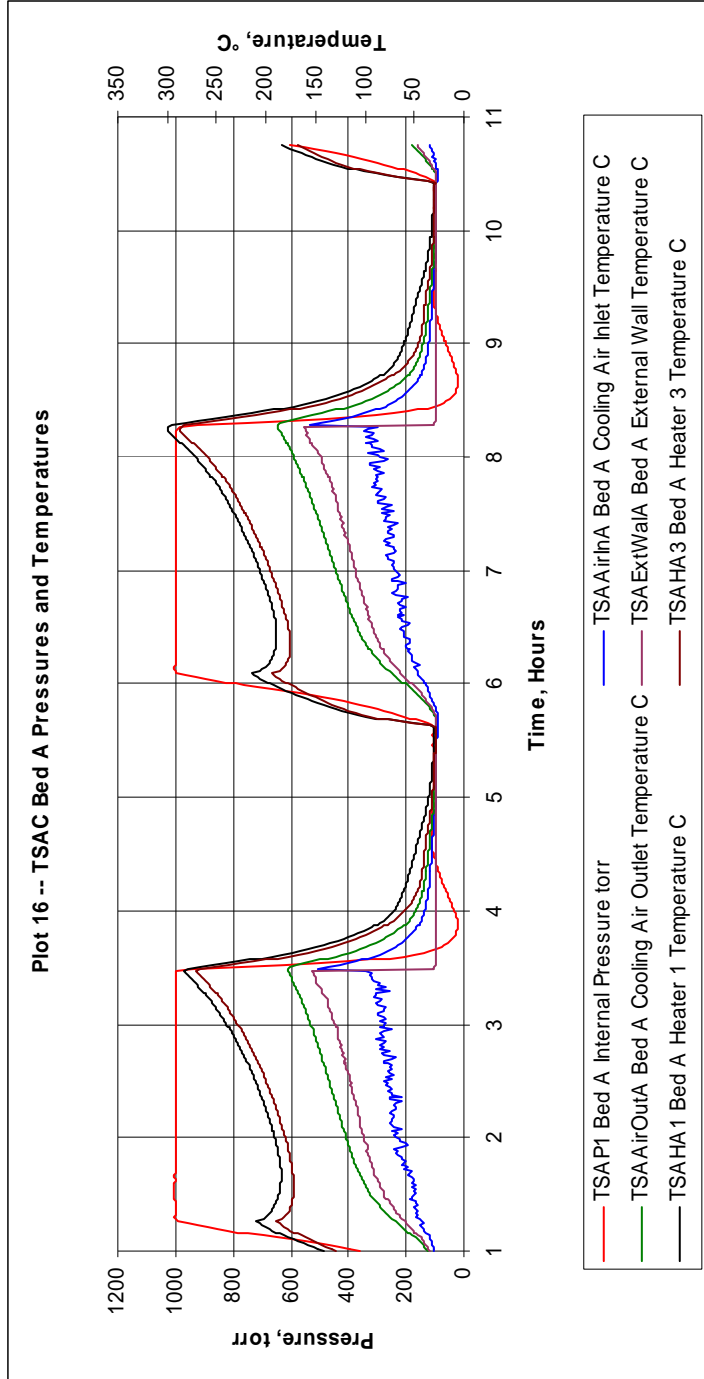
This plot shows the temperatures and pressures together. When Bed A transitions into desorb mode (about 5.5 hours on the plot) the heaters are turned on and the temperature and pressure of the bed quickly rise. Even though the bed temperature and pressure are not at the maximum at hour 6.0, the bed is capable of delivering full flow at this time (see plot 1). The temperature and pressure continue to rise until the delivery pressure of 1000 torr is reached and delivery is initiated. Once the delivery pressure is met, the heater power is reduced to maintain the pressure and the temperature momentarily drops. As CO2 is drawn off the bed, the temperature is increased to maintain pressure until the end of the cycle (hour 8.5 on the plot). Upon switching beds, the bed that was previously desorbing is isolated and cooled to reduce the internal pressure, preparing it for adsorption from the 4BMS.

Plot 18 -- TSAC Inlet Flow Rate
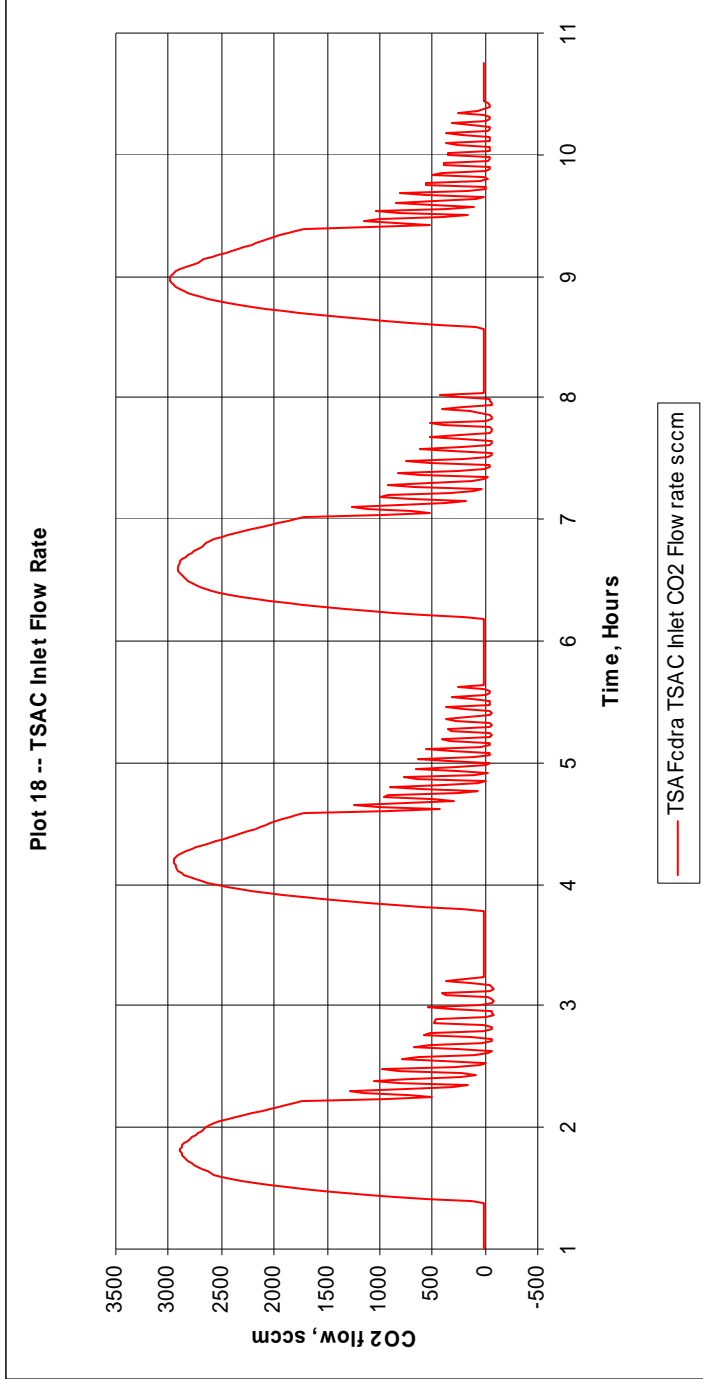
This plot shows the flow rate of CO_2 from the 4BMS into the TSAC. The CO_2 comes off the 4BMS in a wave, and the saw tooth flow pattern at the end of each cycle is due to the oscillating heater control in the 4BMS as the last of the CO_2 is desorbed from the 4BMS bed.

151

5.2.7 4BMS/CEDU/Sabatier Fully Integrated Case

POIST 4BMS/CEDU/Sabatier Testing – TP 3 – Elapsed Time from 2/4 – Test Day 16 2005

Plot 1 -- Status for 4BMS, CRA, OGA and Compressor (offset for clarity)
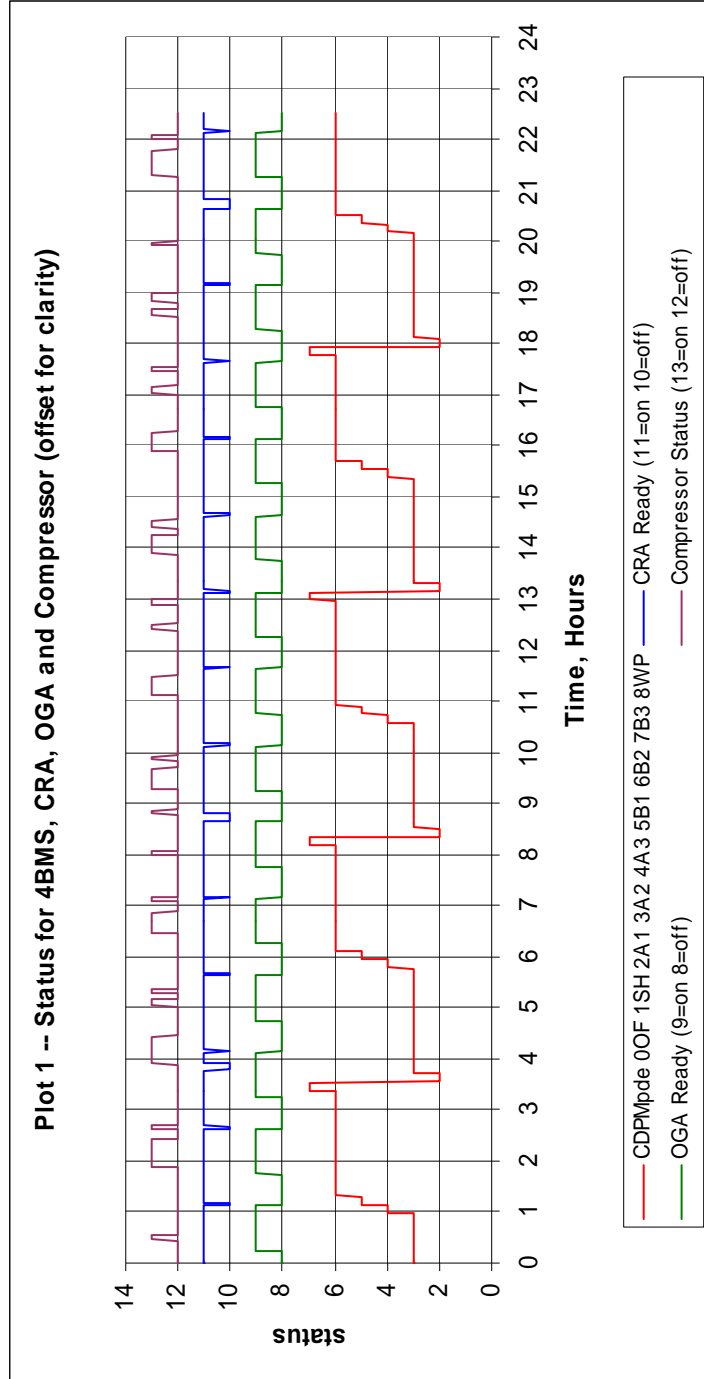
This first plot shows the status of the different subsystems. In this test point, the Sabatier was operated cyclically. There was no real Oxygen Generation Assembly in the integrated test, but the test control system sent a signal to the Sabatier representing the OGA status, to which the Sabatier operation would respond. When the OGA signaled that it was Off, the Sabatier went to Standby or Not Ready status. Once the Sabatier had completed its health checks it would return a Ready status even though the OGA was not yet on. The Sabatier would wait for the OGA ready signal before going back to Process mode. The 90 minute OGA cycle was completely independent of the 4BMS 144 minute half cycle.

Plot 2 --SEDU Reactor Cooling Control
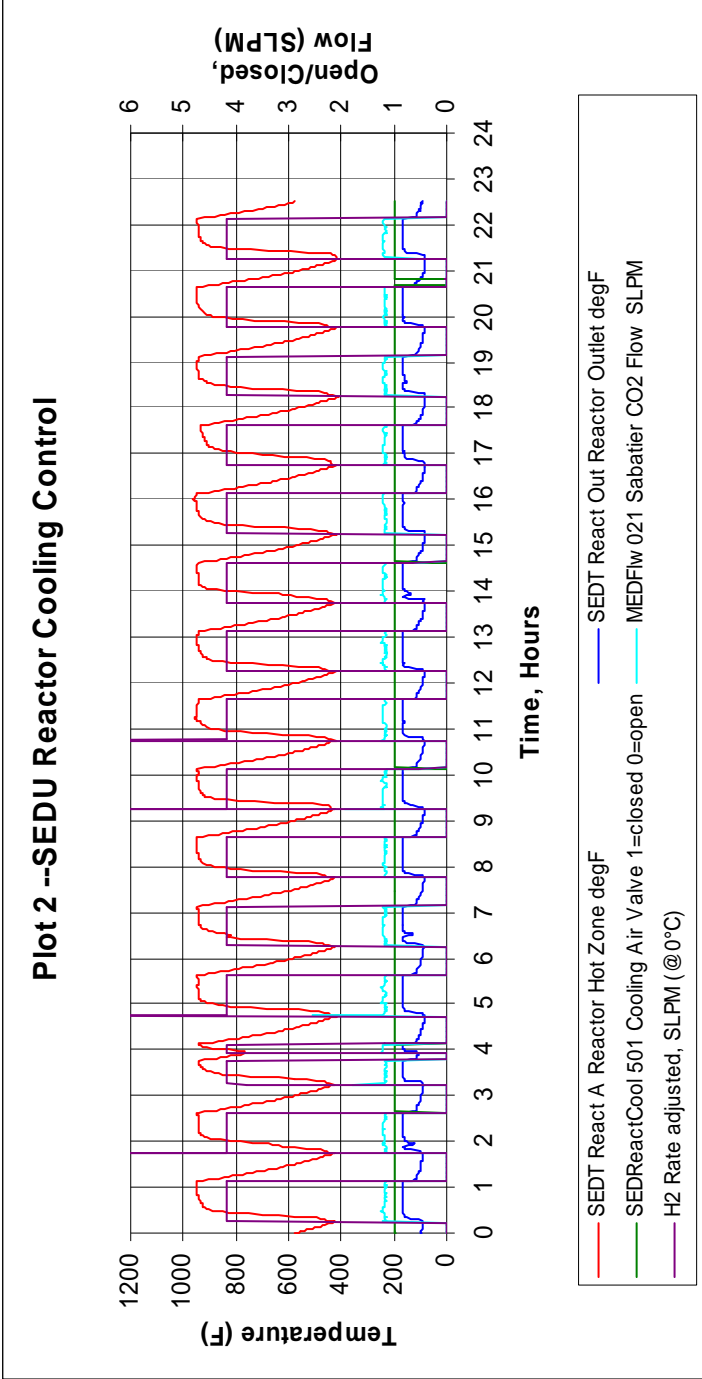
This plot shows the reactor temperatures and cooling control operation. The cooling air valve was set to open to maintain the reactor exit temperature below 300 F. Since this case was cyclic operation at 3 crew rate of hydrogen flow, the temperature was always below 300 F and the cooling air valve was always kept closed. As the Sabatier cycled from Process to Standby, the hydrogen and CO2 flow to the reactor was stopped and the reactor would naturally cool off until the next Process cycle began and the reactor heated itself up again.

Plot 3 -- SEDU Separator Level Control
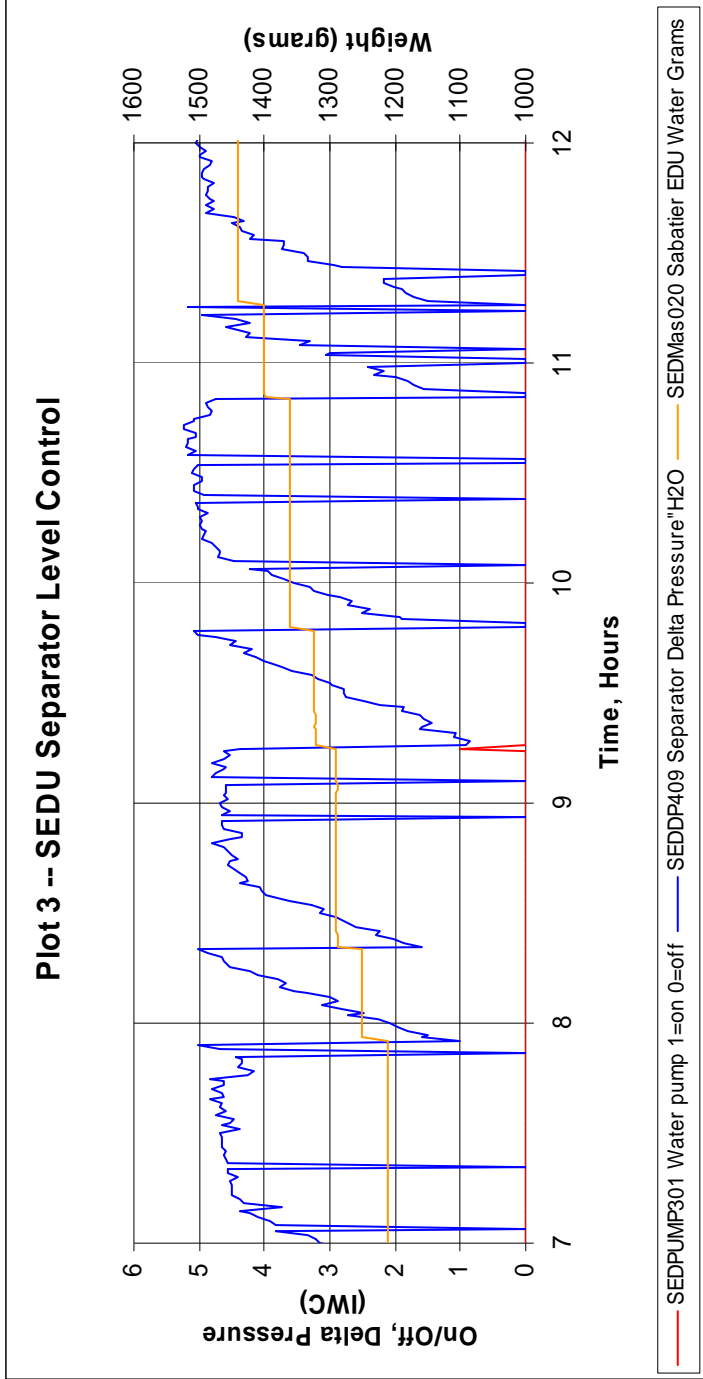
This plot shows the level control in the phase separator of the Sabatier. Since the system is operating cyclically, there are periods when the level in the separator stops increasing. This is the time when the Sabatier is in Standby and water generation ceases. The gradually increasing slope of the blue line is when water is generated at a constant rate during Process mode. The sharp vertical lines are simply irregular data from the differential pressure sensor. The orange line represents the accumulated water product that is recorded by a digital scale. The total increases in steps as the water from the separator is periodically pumped out to the reservoir on the scale. Each time the water is pumped out, the level decreases and then starts slowly building again. The data collection is once per minute, and the pump operation only lasts 5 seconds, so rarely is the pump activity captured by the data stream.

154

Plot 4 -- SEDU System Pressures
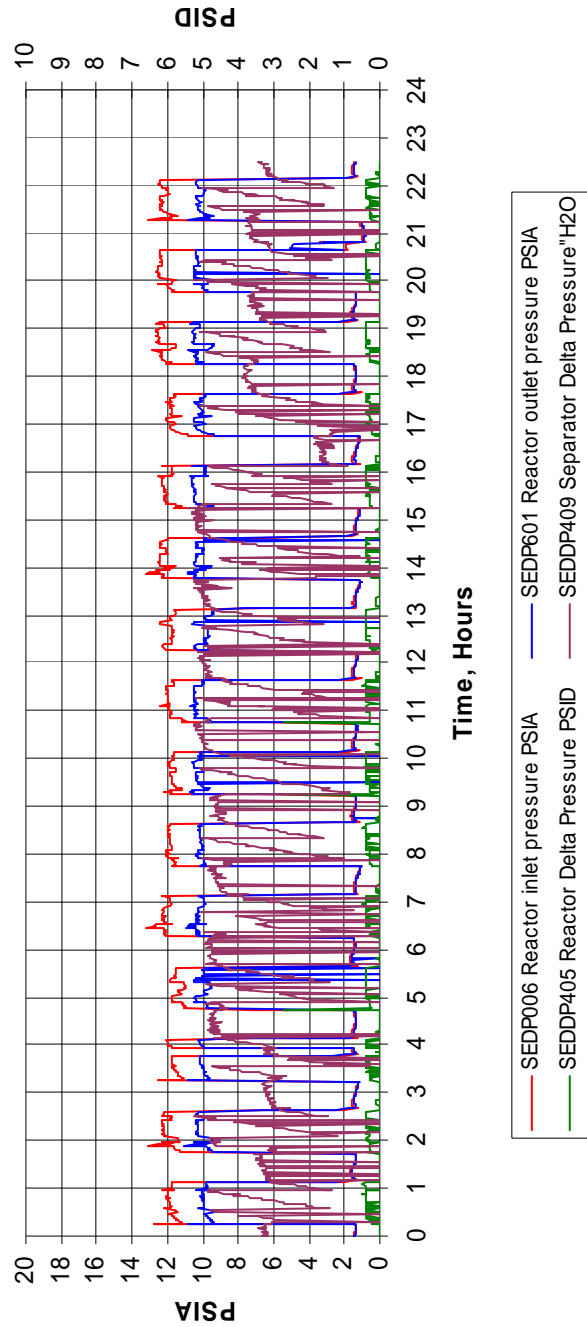
This plot shows the different pressures within the Sabatier system. The reactor inlet and outlet pressures vary from 12 and 10 psia (respectively) during the Process mode to about 1 psia during the Standby period. During each Standby period, the reactor is evacuated to space vacuum to exhaust the potentially flammable gases. While the pressure is low, the system does a self check to determine if there are any leaks. The reactor differential pressure is about 1 psid while gas is flowing, and it goes to zero during the Standby period of no flow.

Plot 5 -- SEDU System Efficiency

Weight (grams), Usage (lites)

Time, Hours

— Calc H2O Prod @ 100% Eff, gram   — Calc H2O Prod @ 90% Eff, gram   — Calc H2O Prod @ 80% Eff, gram
— H2O Production, grams   — H2 Useage Rate, Liters
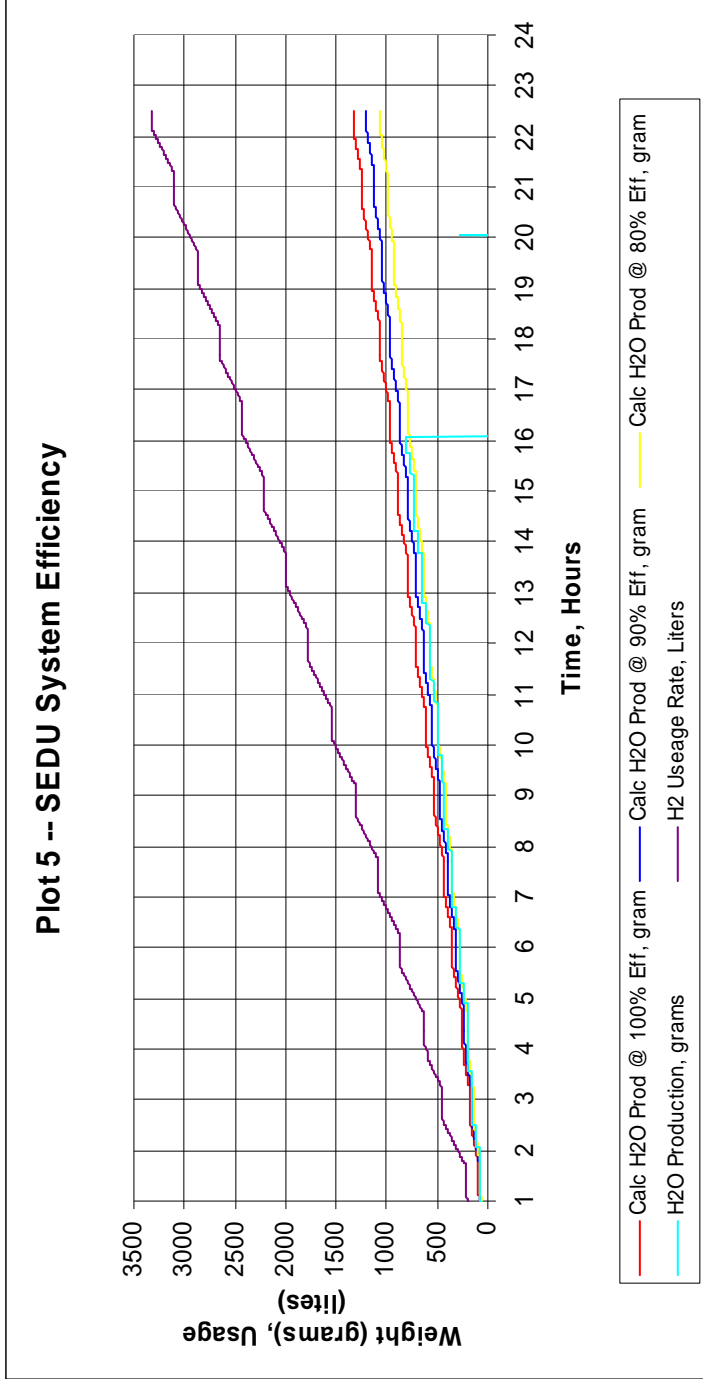
This plot shows the actual water production and the calculated production based on different efficiency rates. The top line is the hydrogen usage, and it levels off every time the system switches into standby. The H2O Production line is the same value from the digital scale as was shown on the level control plot (#3). The calculated production values are the amount of water that would be collected if the system operated at the stated efficiency. For 100% efficiency, the water generation rate is 0.4 grams water per standard liter of hydrogen consumed.

Plot 6 -- SEDU Molar Ratio
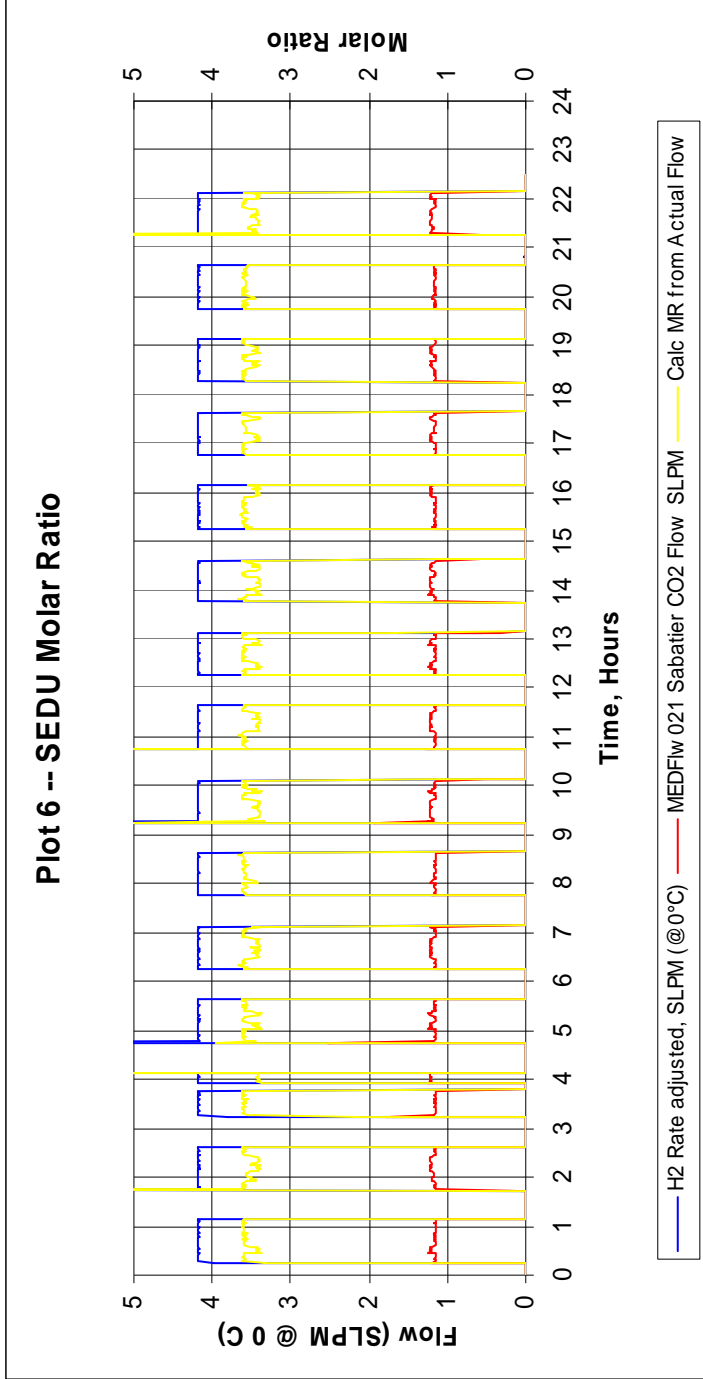
This plot shows the flow control of the hydrogen and carbon dioxide. The hydrogen is controlled by a mass flow controller and is therefore very constant. The CO2 is controlled by a motorized valve and must respond to the changing CO2 accumulator pressure. The CO2 flow control is not as constant as the hydrogen, but the molar ration remains very close to 3.5 throughout the test.
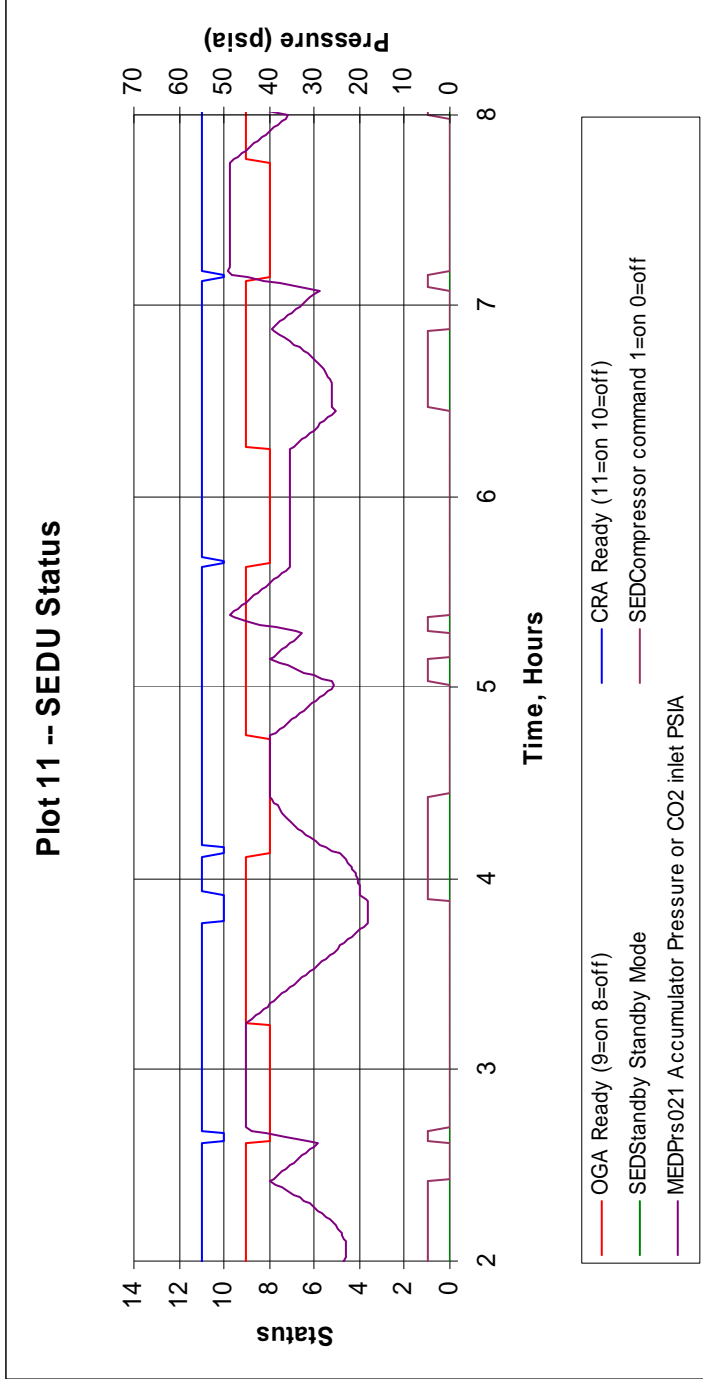
Plot 8 -- SEDU Temperatures
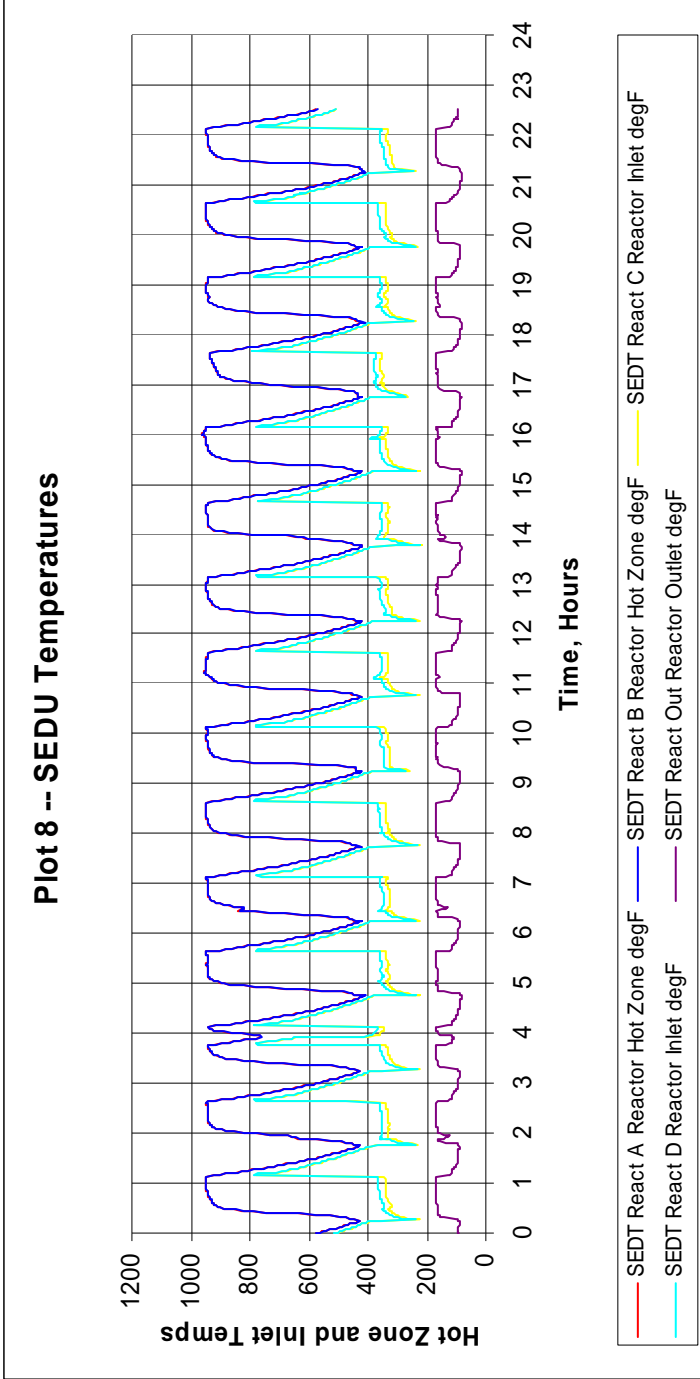
This plot shows the Sabatier reactor temperatures during testing. It is the same characteristic as the Sabatier stand alone testing.

158

Plot 9 -- SEDU Water Production Rate
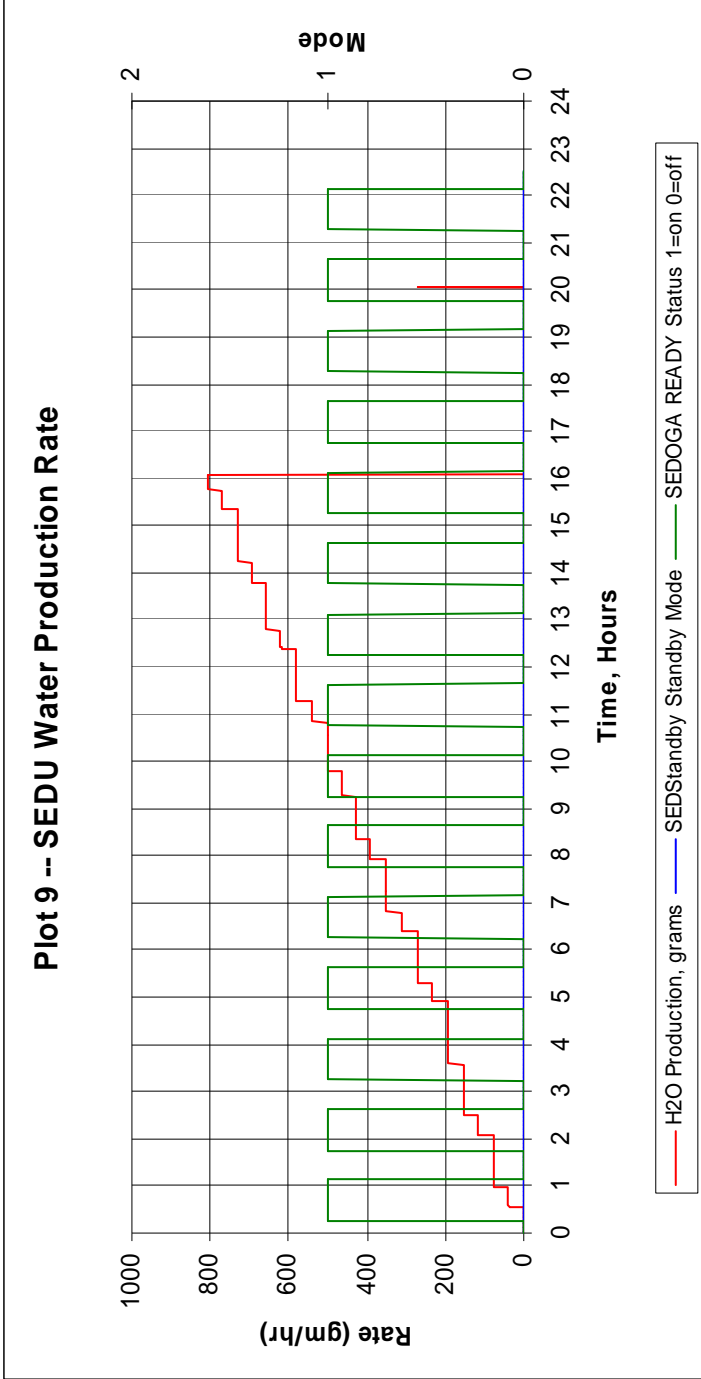
This plot shows the water production rate overlaid with the Sabatier Ready status. The water collected increases only while the system is in Process mode and not in Standby.

159

Plot 10 -- SEDU Overview
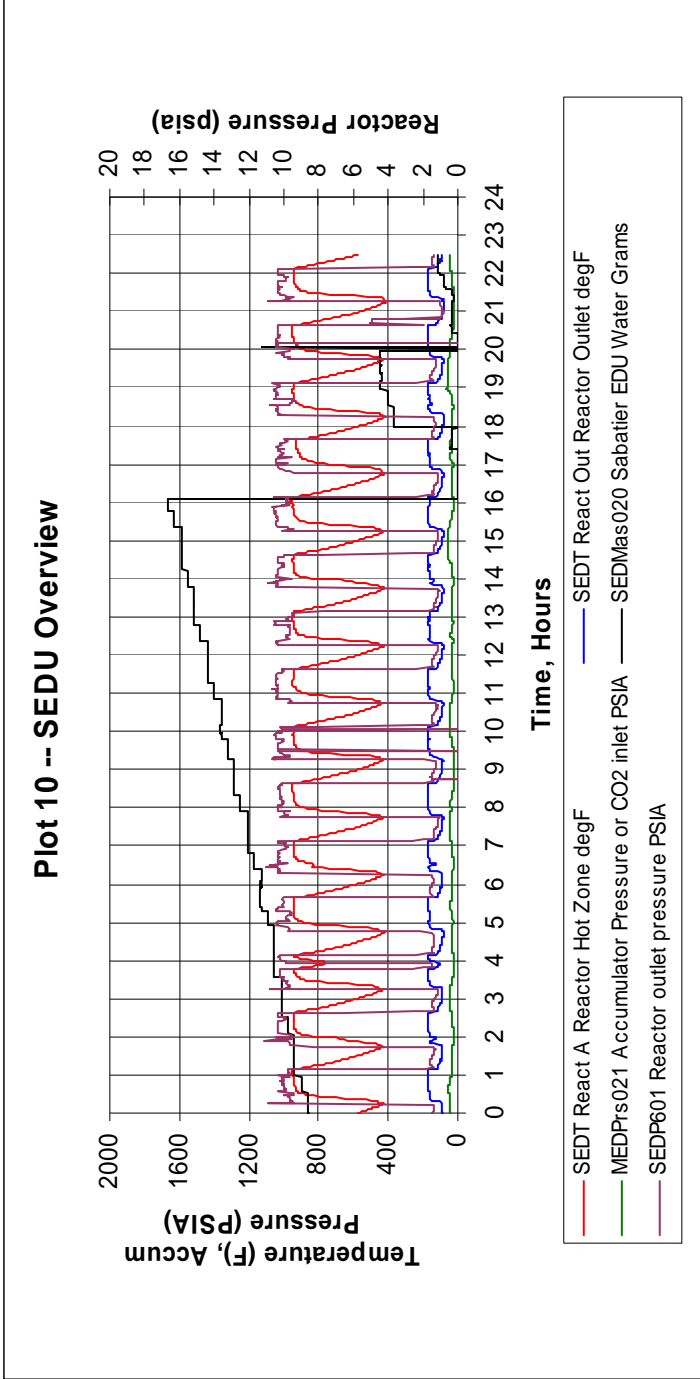
This plot is an overview of the Sabatier system operation. It shows the accumulator pressure, system pressure, reactor temperatures and the cumulative water product collected. With this one plot, one can tell that the system is operating in cyclic more, the temperatures are stable and the outlet temperature is cool enough to not need cooling air. The accumulator pressure is relatively low (about 50 psi) throughout the cycles.

Plot 11 -- SEDU Status

Legend:
- OGA Ready (9=on 8=off)
- SEDStandby Standby Mode
- MEDPrs021 Accumulator Pressure or CO2 inlet PSIA
- CRA Ready (11=on 10=off)
- SEDCompressor command 1=on 0=off

This plot shows the status of the different operating systems and the accumulator pressure with the time scale magnified. At about 3.8 hours, the pressure in the accumulator dips below 20 psia. The Sabatier has to transition to Standby mode during this time that there is insufficient CO2, and therefore the Sabatier status is Not Ready. Each time the compressor turns on (bottom line) the pressure in the accumulator increases. When the OGA is operating and the Sabatier is in Process (red line) the pressure in the accumulator decreases as CO2 is drawn out.

161

Plot 12 -- SEDU CO2 Flow Control Accuracy
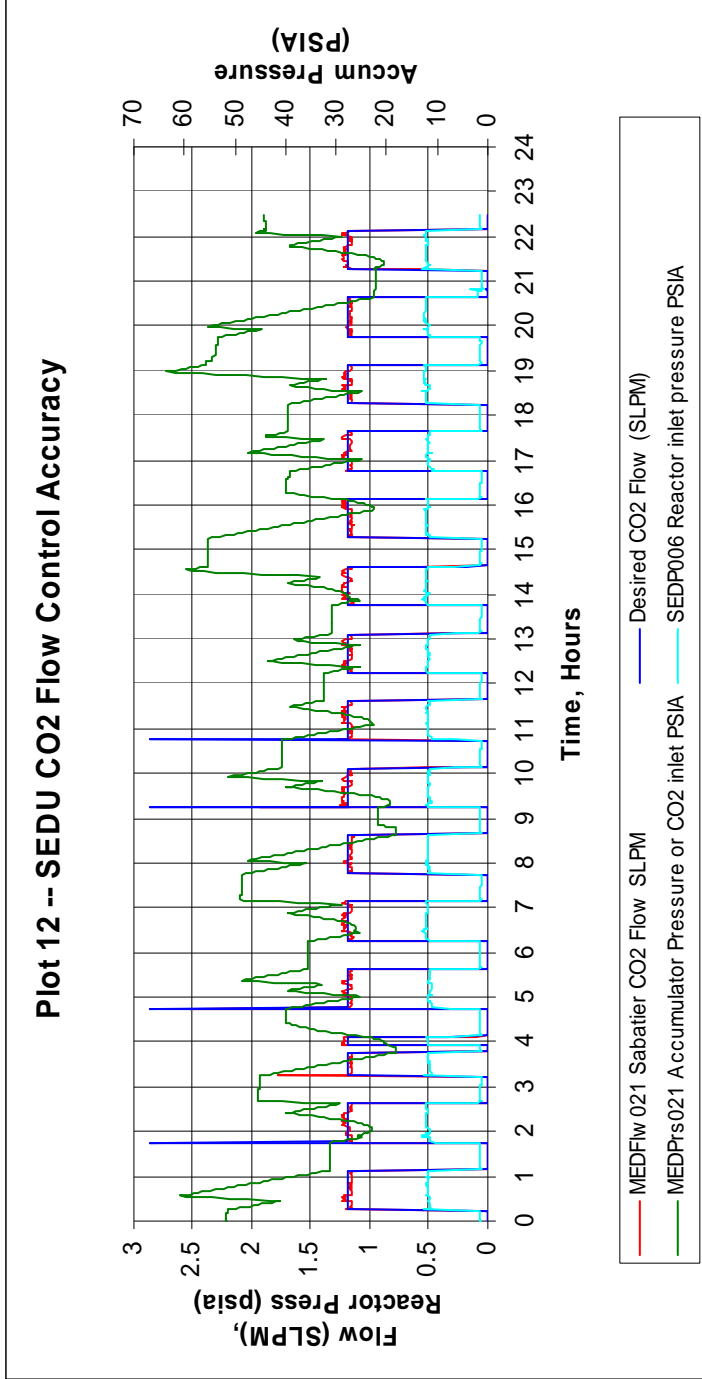
This plot shows the control accuracy of the CO2 modulating valve. The accumulator pressure is the upstream pressure to the valve. The reactor pressure is the downstream pressure. The valve must control flow over 4:1 flow turndown and 6:1 pressure turndown. The dark blue line is the desired flow and the red line over it is the actual flow as measured by a mass flow meter. The actual flow is within 4% of the desired flow.

Plot 2 -- CEDU Status
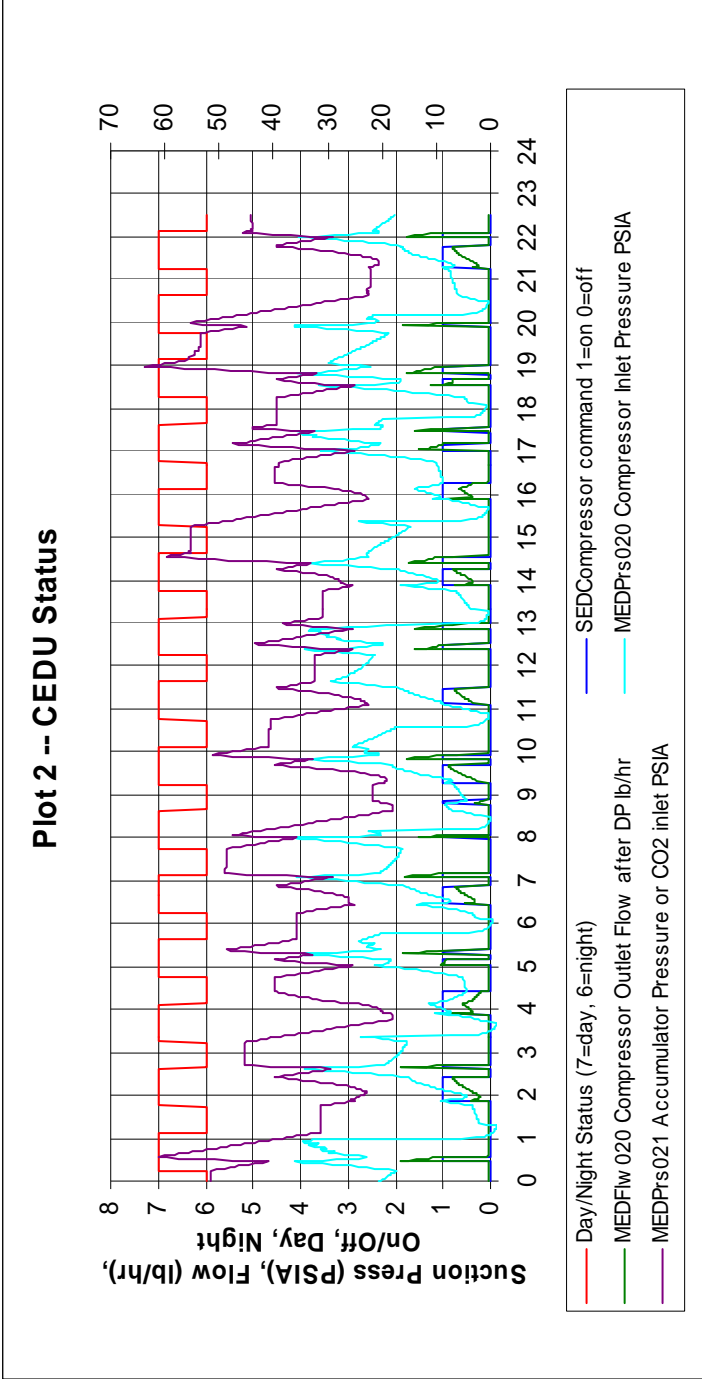
This plot shows the status of the mechanical compressor when integrated with the 4BMS and Sabatier. It shows the compressor inlet and outlet pressures and flow rate. This information is used to fine tune the compressor operating logic to minimize power and maximize CO2 recovery.

Plot 4 -- CEDU Inet and Outlet Pressures, Outlet Dew Point
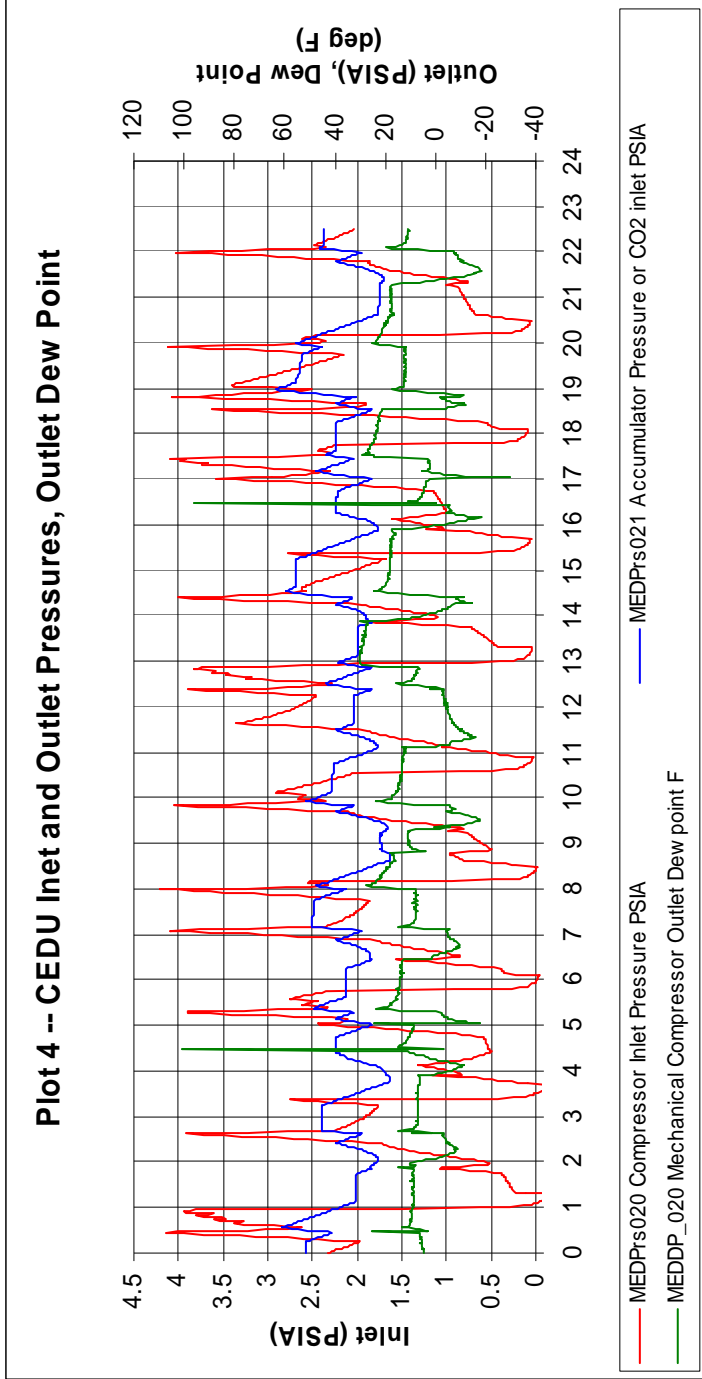
This plot additionally shows the dew point of the CO2 leaving the compressor. The tall spikes at 4.5 and 16.4 hours are calibration runs of the dew point sensor. The dew point never exceeds 30 F, therefore condensation in the compressor or accumulator is not an issue.

164

Plot 5 -- Sorbent Bed Heater Temperatures
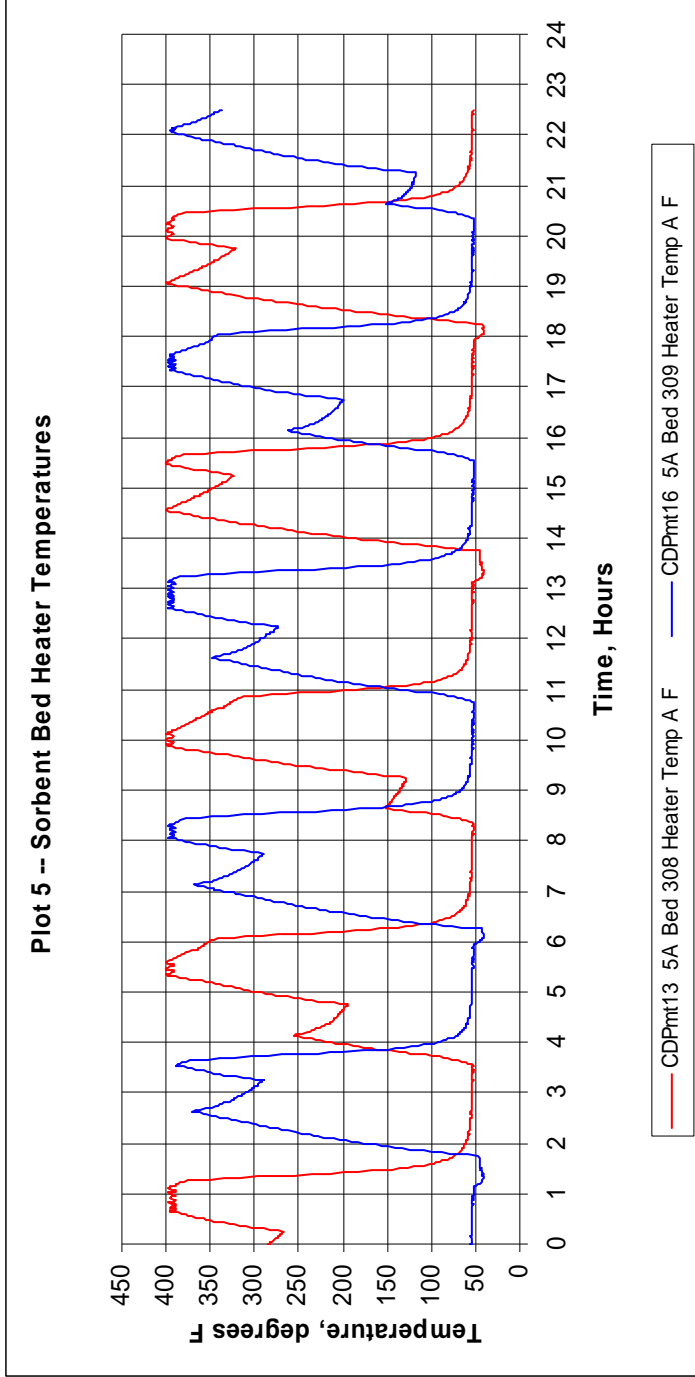
This plot shows the variation of 4BMS operation when the system test is simulating a day/night cycle. The heaters in the 4BMS are turned off during the night portion of the cycle resulting in temperature decrease of the desorbing bed. The cycle at hour 3 does not produce enough CO2 and results in a short period of CO2 starvation for the Sabatier (noted in plot # 11 above).
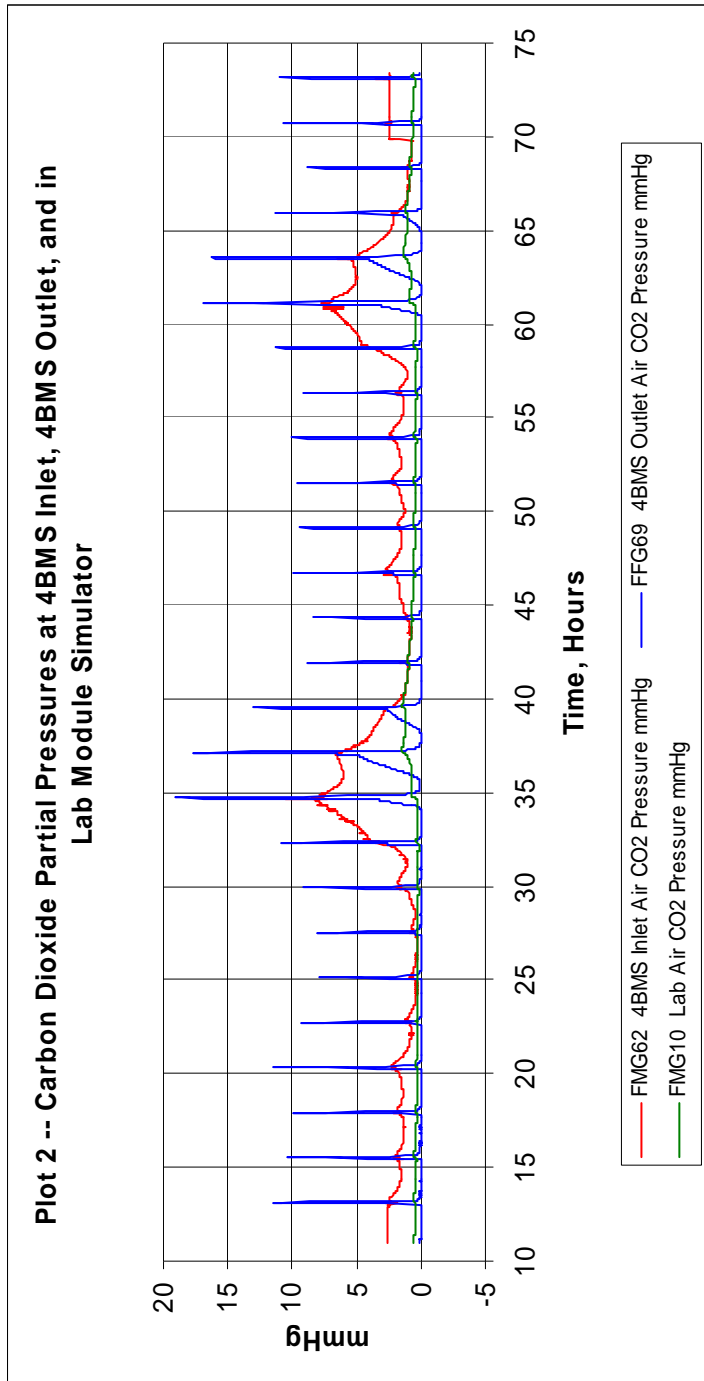
5.2.8 4BMS/TSAC/Sabatier Fully Integrated Case

POIST 4BMS/TSAC/Sabatier Testing – Lunar Night 1C – Elapsed Time from 1/27/2006

The following plots are from one of the tests with the TSAC and the 4BMS and Sabatier. The conditions were set to simulate a Lunar mission with 4 crew all leaving for EVA together and returning together. The CO2 from 2 crew members is regenerated two hours after return from EVA, and the CO2 from the remaining 2 crew members is regenerated the next day.


Plot 1 -- Status for 4BMS, TSAC and Sabatier
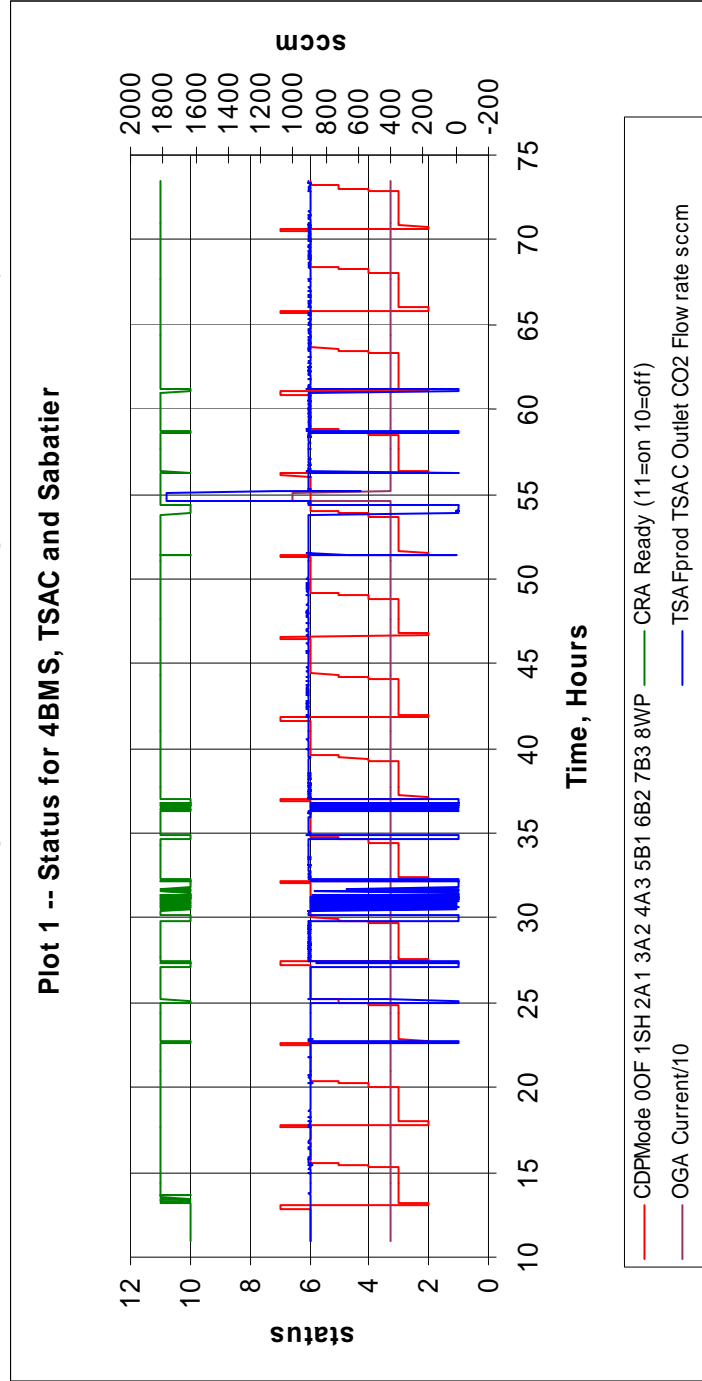
This plot shows the status of the different subsystems in the test. The Lunar mission is assumed to be in daylight all the time, therefore there is no Day/Night cycling as in the ISS Mission scenarios used in the mechanical compressor tests. There are a few false starts at the beginning of the test, then at hours 22, 25 and 27 there are periods where the Sabatier switched to Standby. Later plots will show that the mission scenario resulted in periods of CO2 starvation for the Sabatier subsystem. Around 30 hours, there is a period where the Sabatier rapidly switched from Process to Standby. This occurred because the deadband on the pressure setpoint to turn the

166

Sabatier on and off was too narrow, and the normal operation caused the pressure to cross that span quickly. One of the recommendations for future modifications is to broaden that deadband.
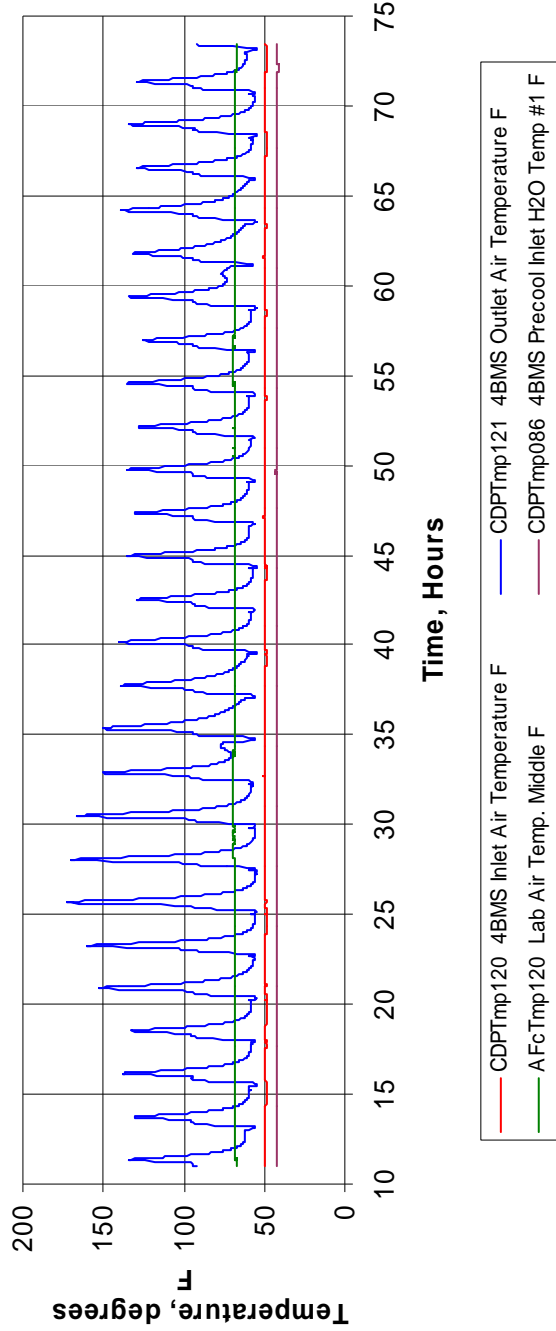

Plot 2 -- Carbon Dioxide Partial Pressures at 4BMS Inlet, 4BMS Outlet, and in Lab Module Simulator

Legend: FMG62 4BMS Inlet Air CO2 Pressure mmHg — FFG69 4BMS Outlet Air CO2 Pressure mmHg — FMG10 Lab Air CO2 Pressure mmHg

This plot shows the CO2 concentration at the inlet of the 4BMS. This concentration profile was the output result of modeling the Lunar habitat with the crew activities and location. This profile includes the 4 crewmember EVA with the staggered regeneration. The outlet CO2 is almost zero except for the sharp spikes at the bed changes. There is an increase in CO2 at the output between hours 35 and 40. This is the time period when the first two EVA CO2 packs are regenerated and the 4BMS in the habitat cannot keep up with the additional CO2 load during regeneration. This effect is seen again between hours 60 and 65 when the next two EVA packs are regenerated.

**Plot 3 -- Air Dewpoint at 4BMS Inlet and in Lab Module Simulator**
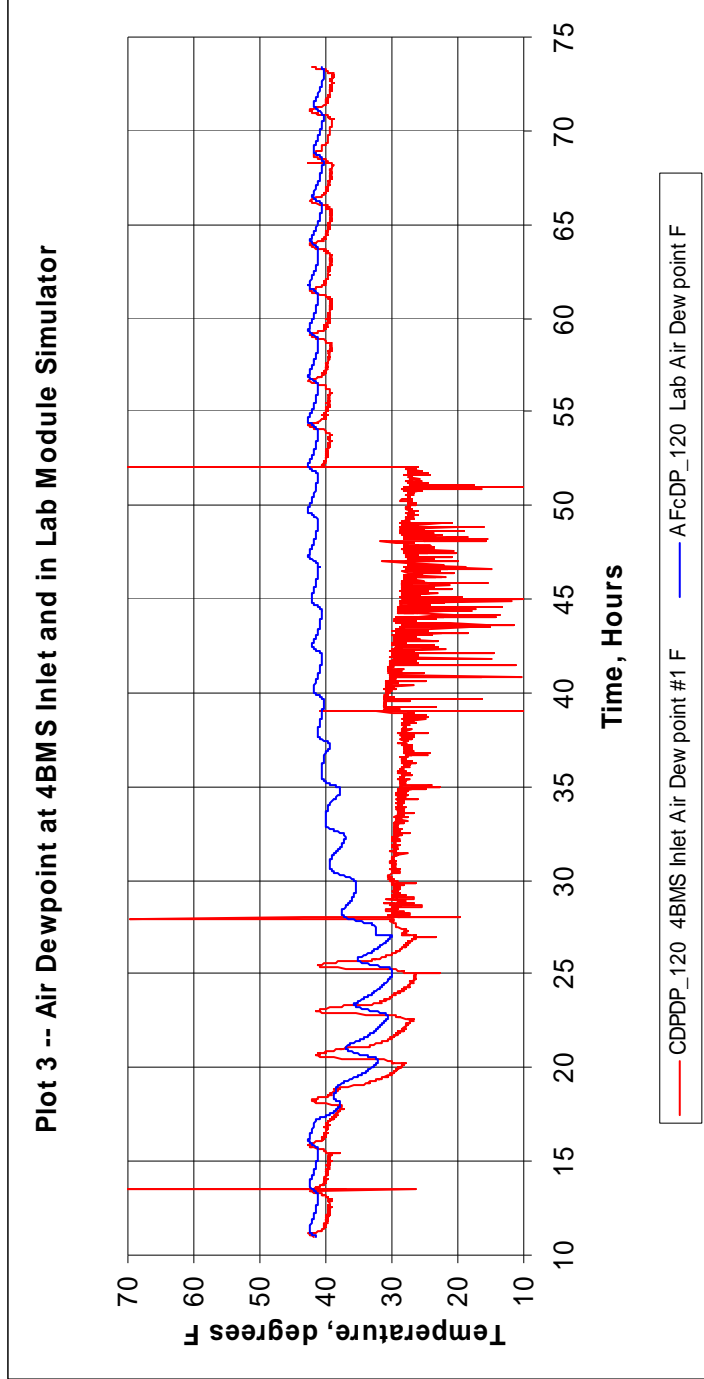
This plot shows dew point readings at the 4BMS inlet and in the Lab Module simulator. The section between hour 30 to 50 is an apparent bad sensor reading. The tall spikes are calibration runs of the sensor. During each cycle, a dump of humid air from the desorbing bed is returned to the inlet of the condensing heat exchanger, which in turn feeds back to the inlet of the 4BMS. The red line shows the small spike in inlet humidity at each bed change, which is then reduced as the cycle completes its course. The blue line is the lab module average humidity, which follow the trend of the inlet humidity. Water is continuously injected into the lab module to make up for the water lost to the vacuum simulator. The inlet, being downstream of the condensing heat exchanger, is typically at a lower dew point than the lab module average.

Plot 4 -- Air Temperature at 4BMS Inlet, 4BMS Outlet, in Lab Module Simulator, and Water Temperature at Precooler Inlet
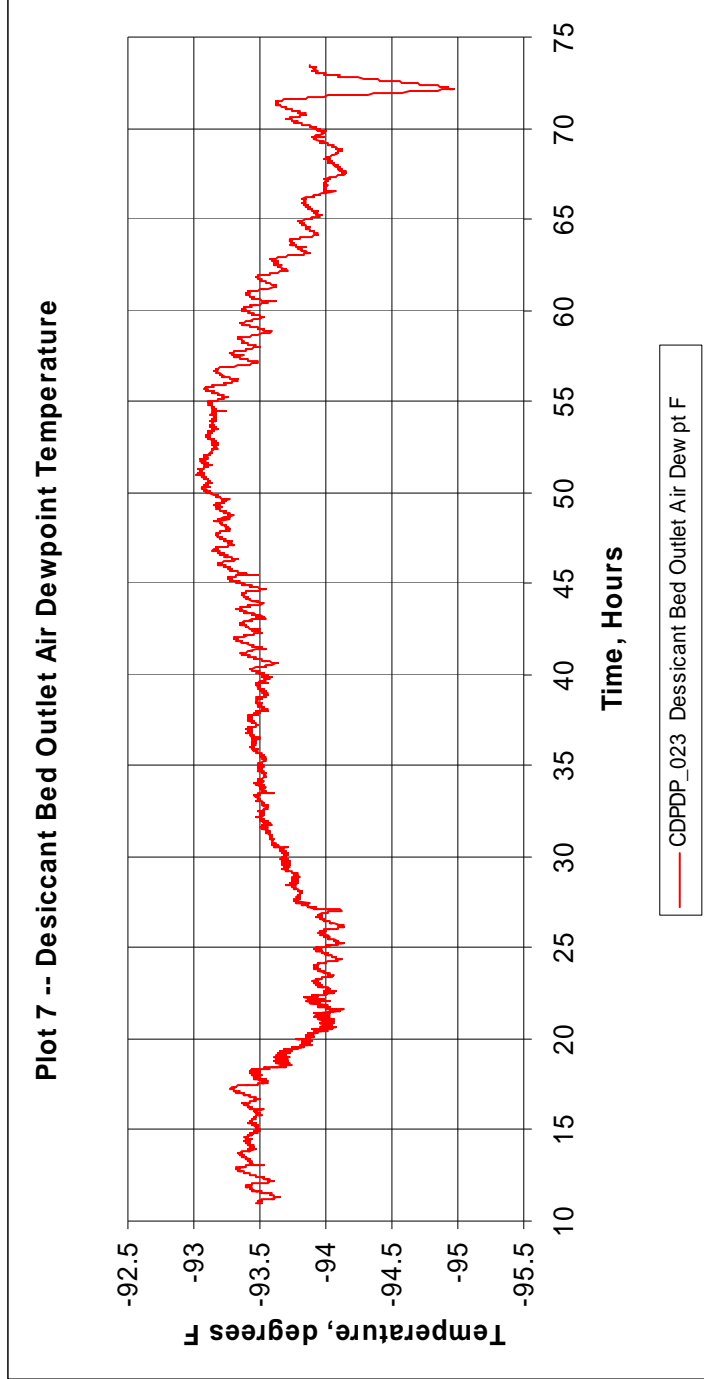
Temperature, degrees F

Time, Hours

CDPTmp120 4BMS Inlet Air Temperature F
AFcTmp120 Lab Air Temp. Middle F
CDPTmp121 4BMS Outlet Air Temperature F
CDPTmp086 4BMS Precool Inlet H2O Temp #1 F

This plot shows the air and cooling water temperatures at the 4BMS. When the beds switch, the air exiting is initially very high temperature as it is flowing through the bed that was just recently heated to 400 F. This hot air is used to desorb the desiccant bed that is full of water. The air temperature quickly returns to normal temperatures as the bed cools down and begins adsorbing CO2. The air inlet temperature is cooler than the average Lab Module temperature since it has been cooled by the condensing heat exchanger.
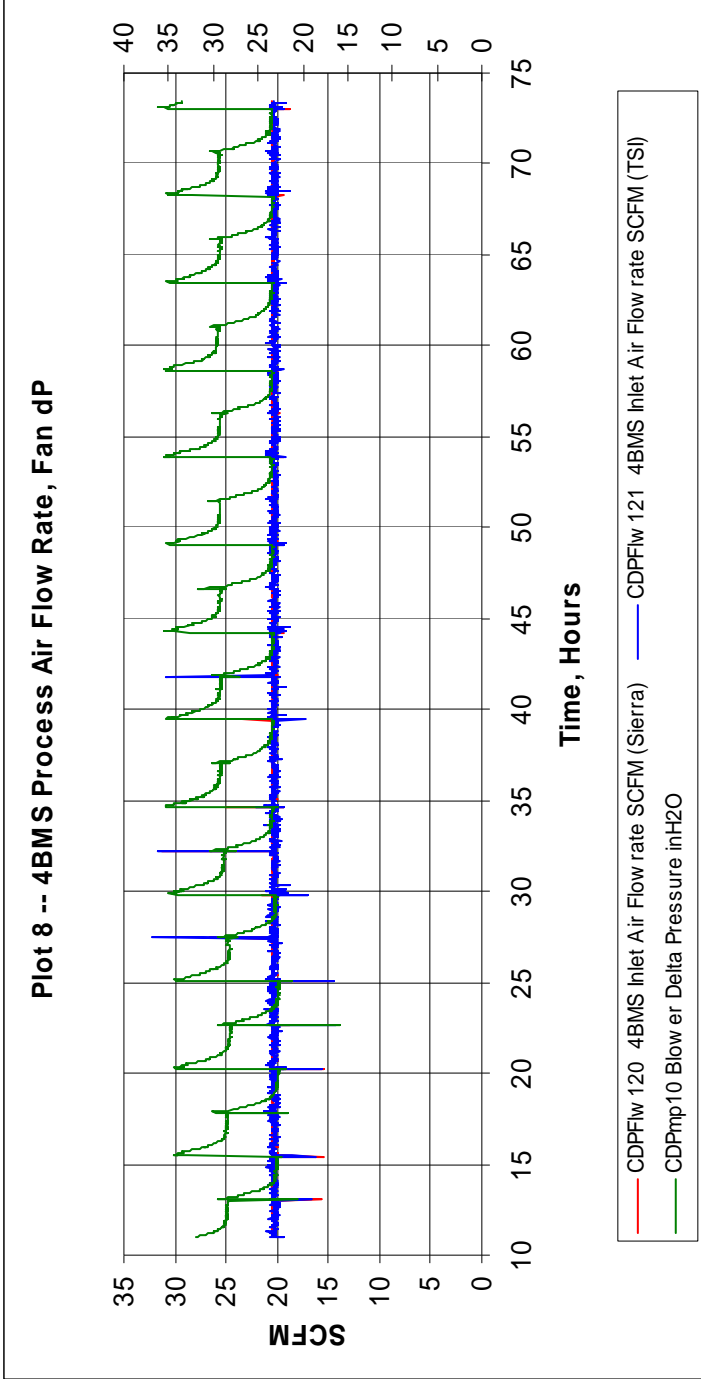
Plot 5 -- Sorbent Bed Heater Temperatures
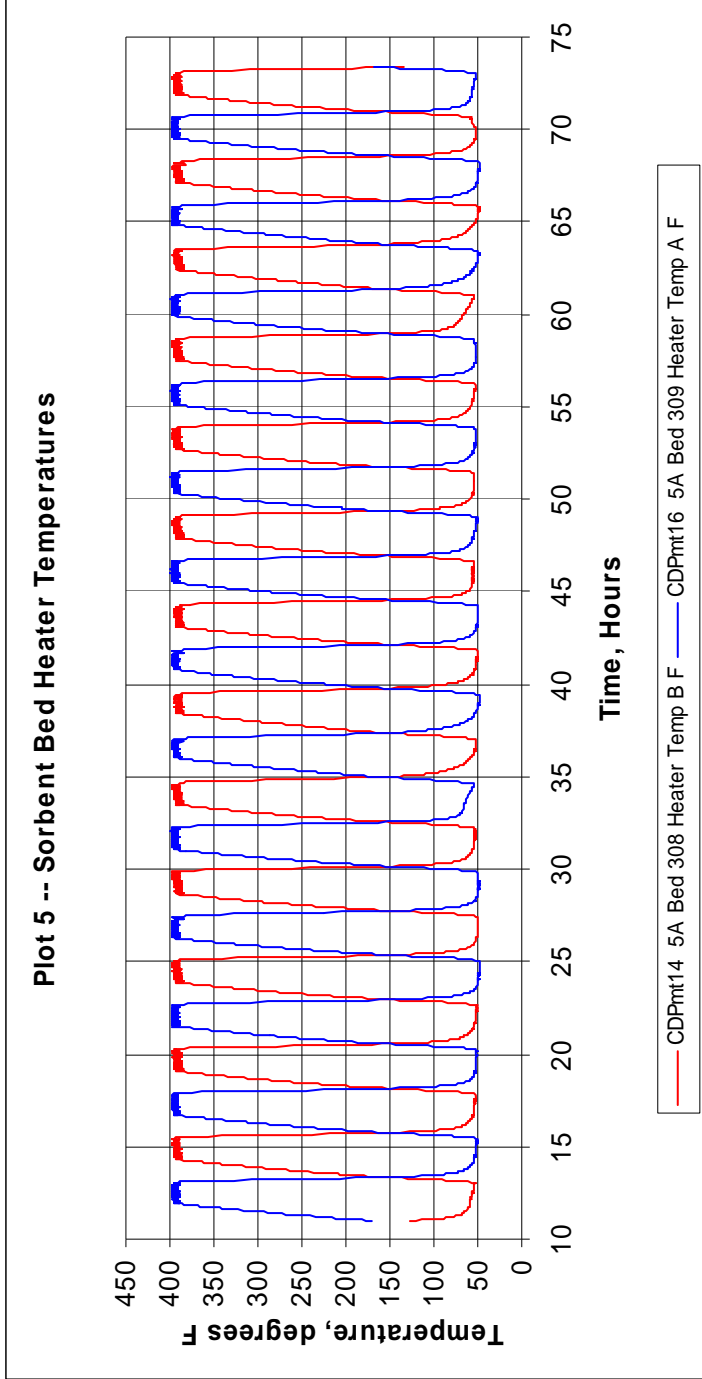
This plot shows the 4BMS bed heater temperatures. Since the simulation is always daytime, the heaters of the 4BMS are kept on full power according to the normal processing schedule, i.e., there is no power save mode that turns heaters off. Each bed is heated to 400 F to desorb the CO2.

Plot 6 -- Desiccant Bed Inlet and Outlet Air Temperatures
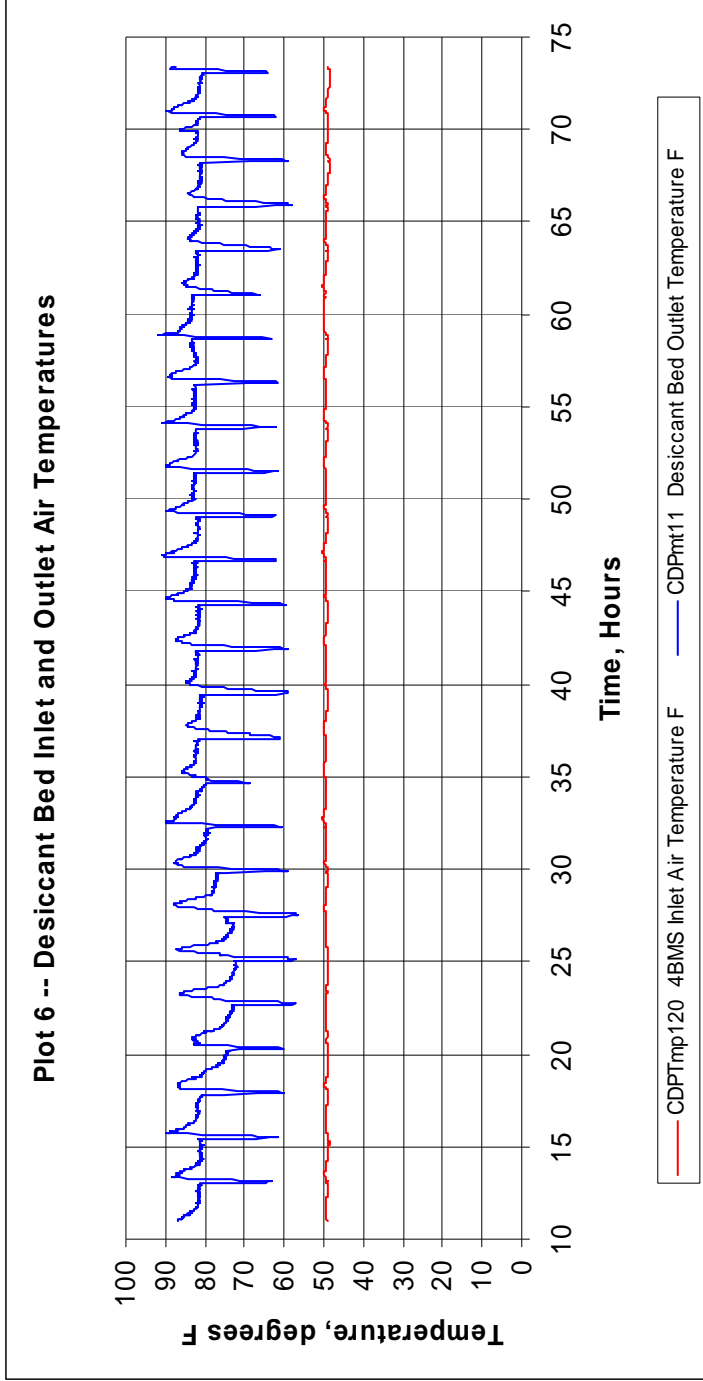
This plot shows the temperature of the air into and out of the adsorbing desiccant bed. The temperature rises due to the heat of adsorption of water onto the desciccant.

Plot 7 -- Desiccant Bed Outlet Air Dewpoint Temperature

CDPDP_023 Dessicant Bed Outlet Air Dew pt F

This plot shows the dew point of the air leaving the desiccant and entering the CO_2 adsorption bed. This dew point is monitored for breakthrough. Water that escapes the desiccant bed will interfere with the adsorption of CO_2 onto the CO_2 sorbent bed. The bed would then have to be regenerated at high temperature to remove the water.

Plot 8 -- 4BMS Process Air Flow Rate, Fan dP

Legend:
- CDPFlw 120 4BMS Inlet Air Flow rate SCFM (Sierra)
- CDPFlw 121 4BMS Inlet Air Flow rate SCFM (TSI)
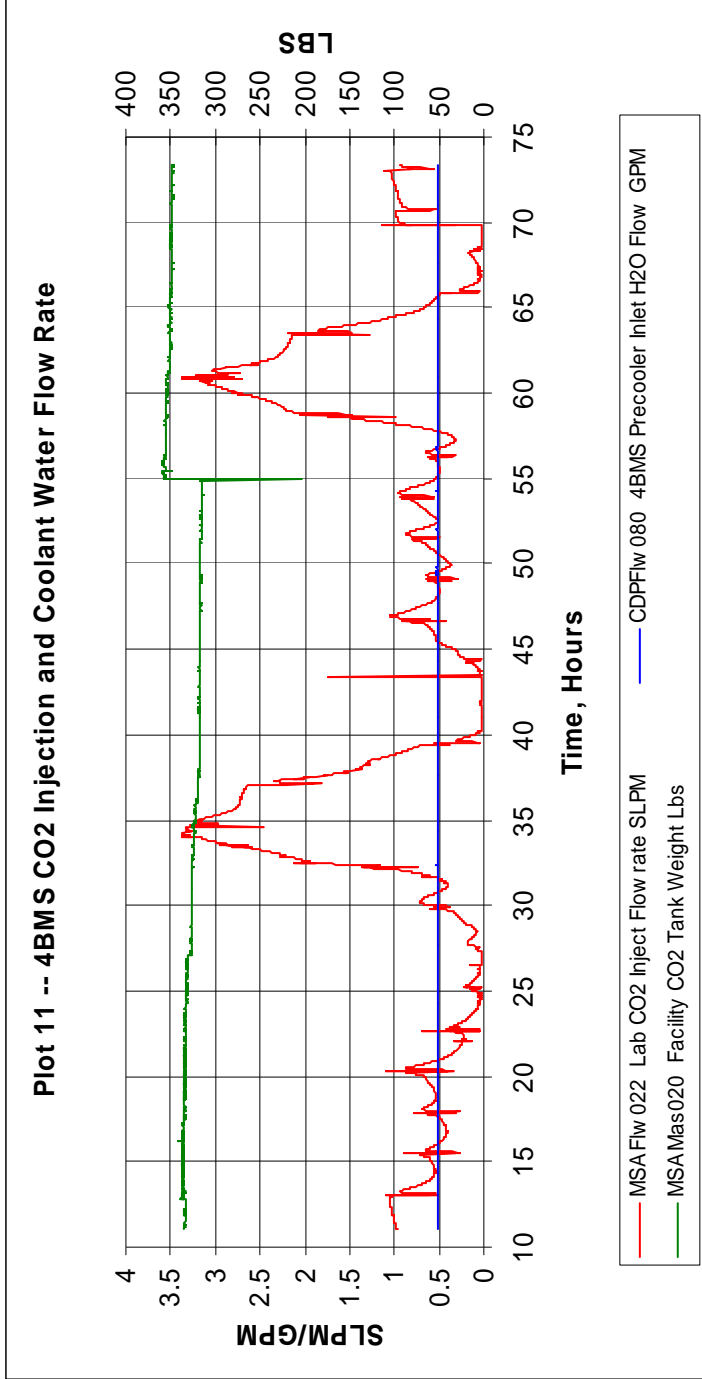- CDPmp10 Blower Delta Pressure inH2O

This plot shows the air flow rate to the 4BMS and the blower pressure drop. The pressure drop rises quickly while the air temperature is high from the desiccant. (Refer back to plot 6). The air flow was measured with two different devices, which showed very good agreement.

173

Plot 9 -- 4BMS Vacuum System Pressures
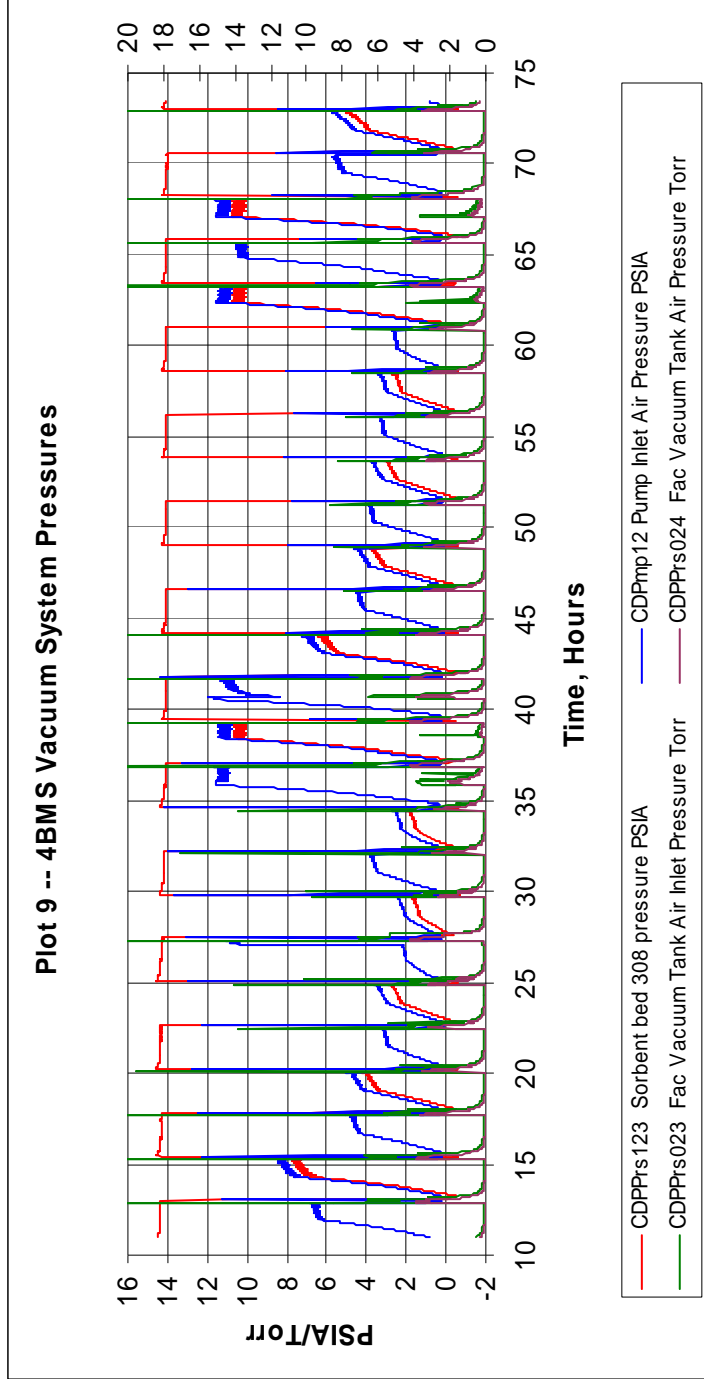
This plot shows vacuum pressures of the 4BMS. The 4BMS desorbing bed (bed 308) and the TSAC inlet pressure (Pump Inlet Air Pressure) are almost the same except for the pressure drop between the two systems. The spikes in the Facility Vacuum pressures indicate when either the 4BMS is performing its 10 minute space vacuum desorb, or the bed pressure is excessive and the 4BMS must vent early. Between hours 35 and 40, when the EVA CO2 canisters are regenerated, there is excess CO2 in the habitat that the TSAC cannot deliver to the Sabatier, therefore, the 4BMS must vent some of the CO2 when its bed pressure increases. This happens again between hours 60 and 65.

**Plot 10 -- 4BMS Component Power**
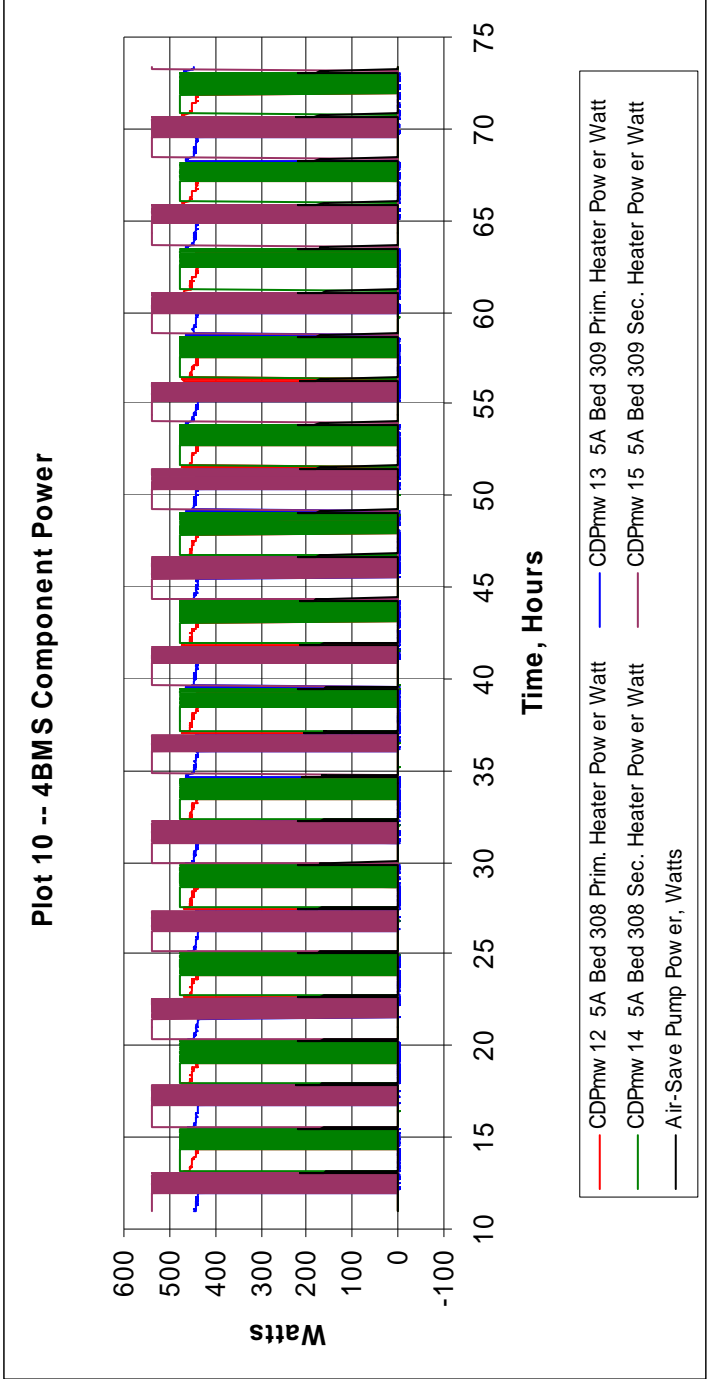
This plot shows the power usage of the 4BMS. The thick bars are the bed heaters cycling on and off when the bed is at temperature. The heater control is on/off control, which gives the temperature profile the characteristic saw tooth pattern.

175

Plot 11 -- 4BMS CO2 Injection and Coolant Water Flow Rate

Legend:
- MSAFlw 022 Lab CO2 Inject Flow rate SLPM
- CDPFlw 080 4BMS Precooler Inlet H2O Flow GPM
- MSAMas020 Facility CO2 Tank Weight Lbs

Axes:
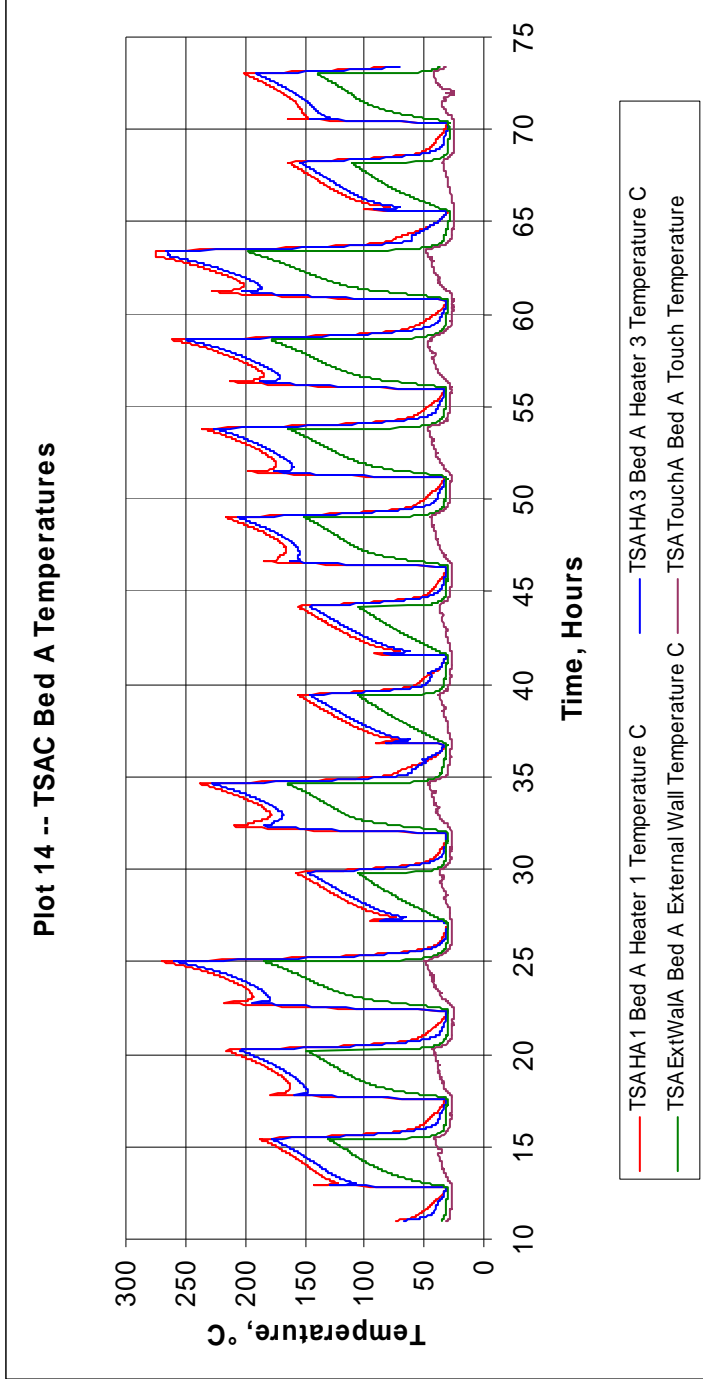- Left: SLPM/GPM
- Right: LBS
- Bottom: Time, Hours

This plot shows the CO2 injection rate. This injection rate is a result of the Lunar habitat model with the crew activity, including the EVA scenario previously discussed. The CO2 tank weight is also recorded as a backup to the injection flow rate recording. The coolant flow rate, which is constant at 0.5 gpm, is monitored for system health.

176

Plot 12 -- TSAC Product Flow Rate
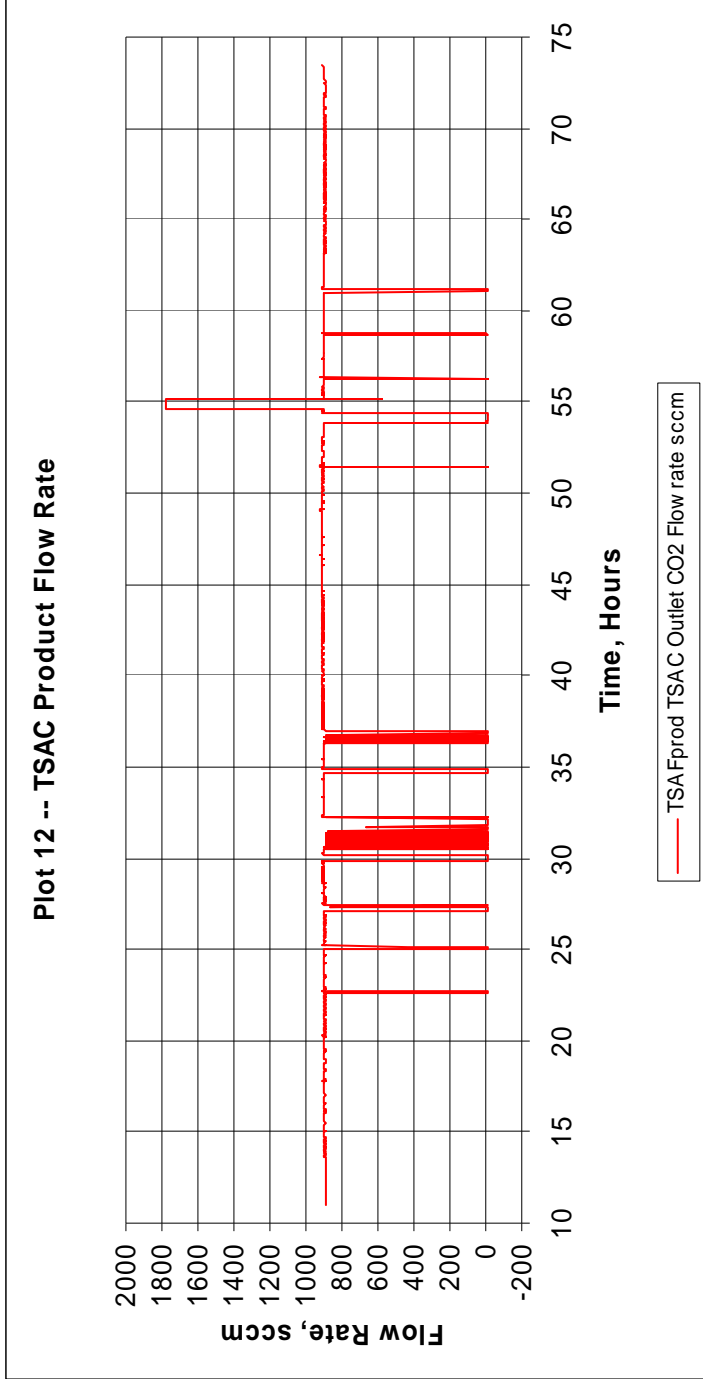
This plot shows the TSAC CO2 delivery flow rate to the Sabatier. The delivery is fairly constant until the periods of starvation begin at hour 22, 25 and 27. Then at hour 30, the period begins when the Sabatier repeatedly tried to start and the pressure deadband caused it to shut down. At hour 55 the hydrogen flow setpoint was temporarily set to twice the normal rate. The TSAC was momentarily able to keep up, but then later a period of starvation resulted at hour 57.

Plot 13 -- TSAC Internal Pressures
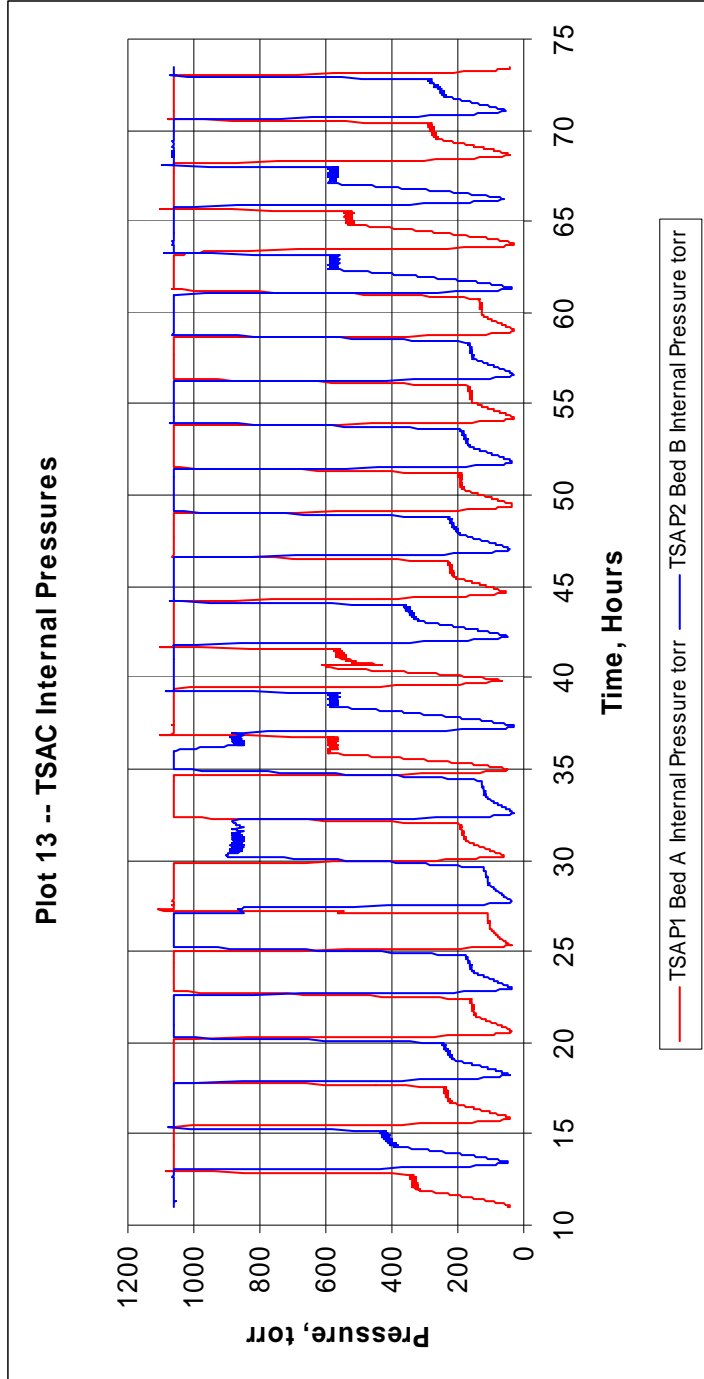
This plot shows the pressures of the TSAC beds. During periods of starvation (hour 30 to 35), the TSAC bed pressure falls short because there was insufficient CO_2 available from the 4BMS. This is seen again at hour 60-65.

178

Plot 14 -- TSAC Bed A Temperatures

Temperature, °C
Time, Hours

TSAHA1 Bed A Heater 1 Temperature C
TSAHA3 Bed A Heater 3 Temperature C
TSAExtWalA Bed A External Wall Temperature C
TSATouchA Bed A Touch Temperature

This plot shows the temperatures of the TSAC Bed A. The detailed description is given for plot 16.

179

Plot 15 -- TSAC Bed B Temperatures
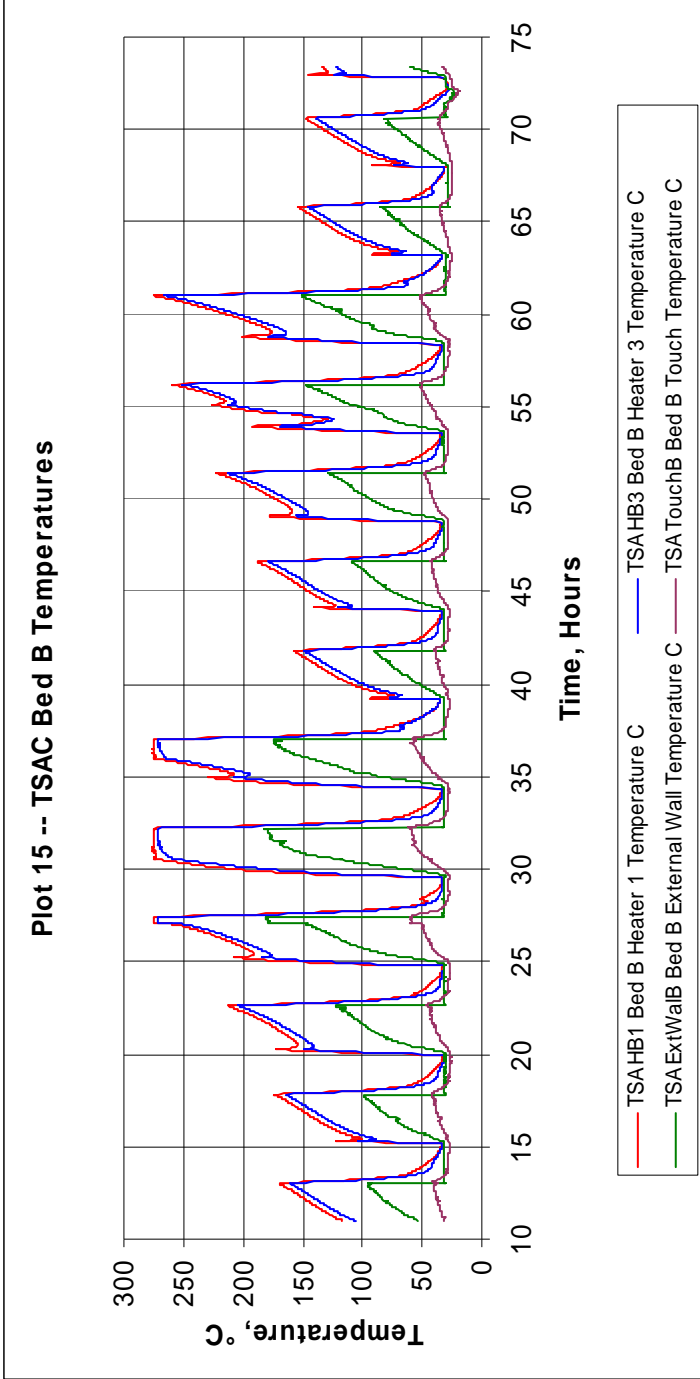
This plot gives the temperatures for the TSAC Bed B. The detailed description is given for plot 17.

180

Plot 16 -- TSAC Bed A Pressures and Temperatures
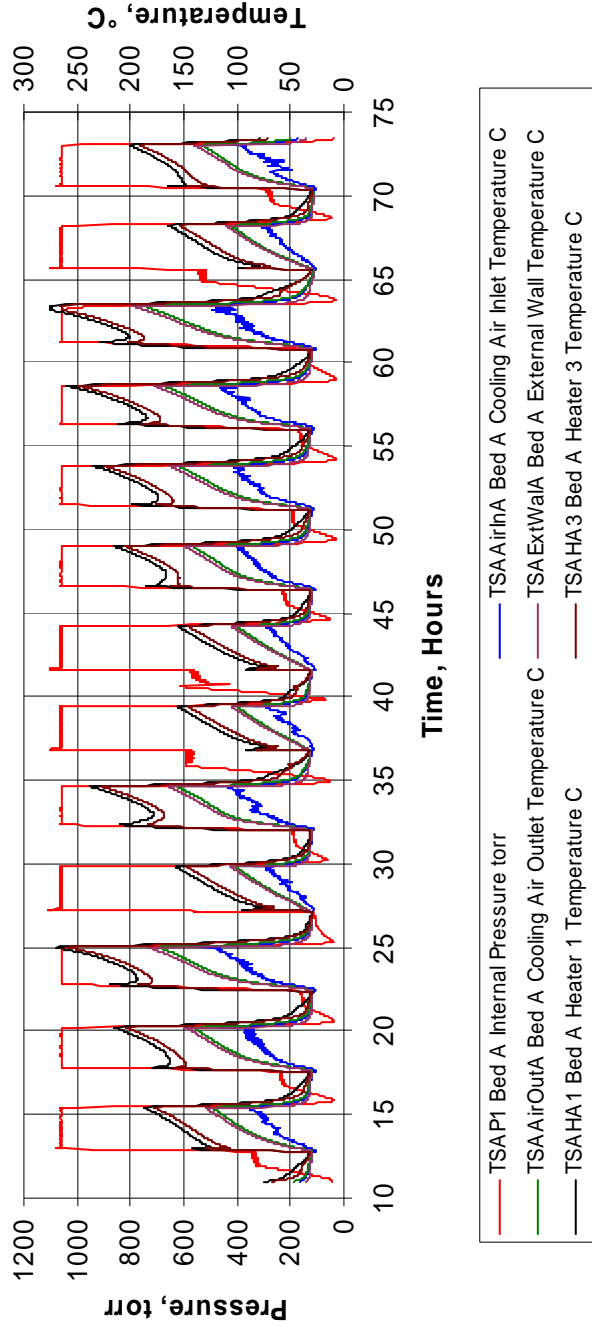
This plot shows the pressure and temperature profile of the A bed. In each cycle, the bed is heated until the delivery pressure is achieved. Heating continues as delivery begins until the temperature reaches a maximum setpoint. In the first cycle, pressure is maintained with the bed temperature below 200 C. In the next cycle, the temperature is increased a little over 200 C and in the third cycle the temperature reaches the maximum setpoint of 275 C. In each of these cycles the CO2 input from the 4BMS was less and less, as noted in Plot 18 below. Around hour 35-40 there is too much CO2 from the 4BMS and the TSAC could not deliver it all to the Sabatier so the bed started the adsorb cycle half full. This is noted in the vacuum system pressure plot back on Plot 9.

181

Plot 17 -- TSAC Bed B Pressures and Temperatures
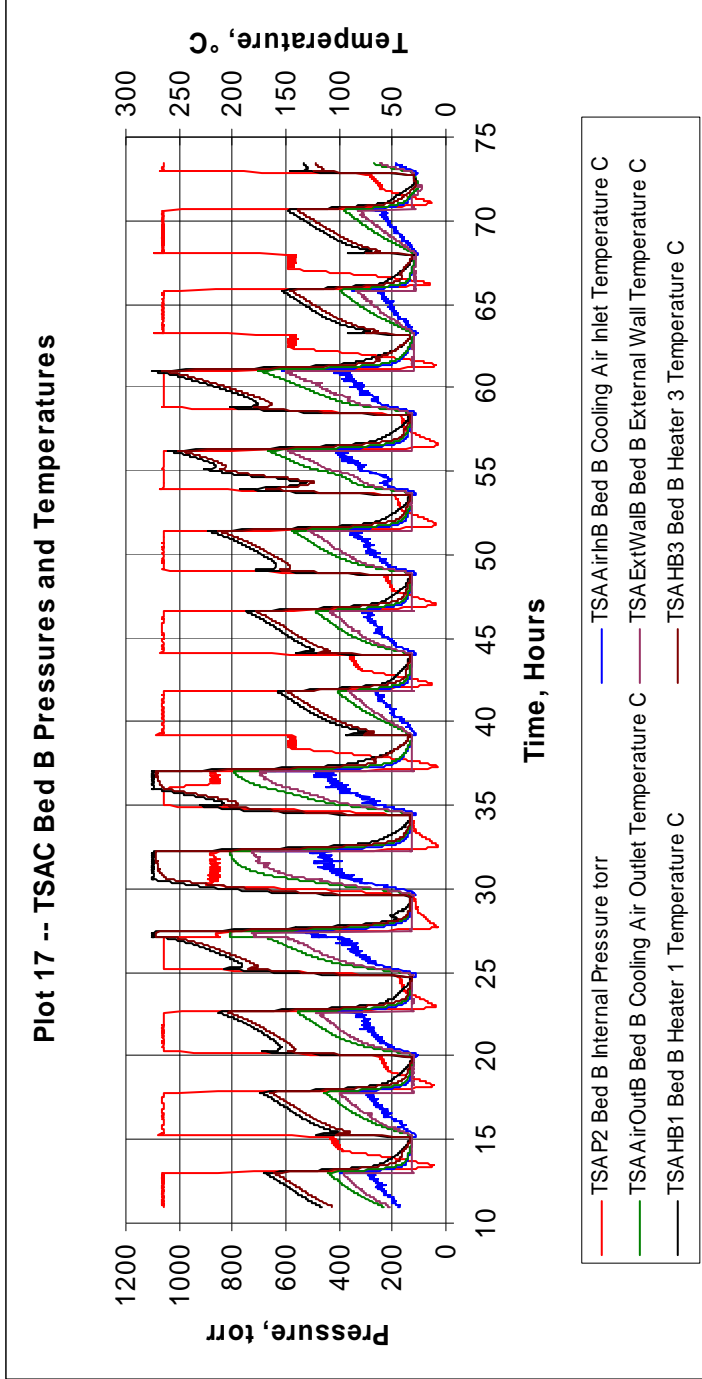
This plot of Bed B pressure and temperature shows a couple of instances of the TSAC running out of CO2 pressure for delivery to Sabatier. Between hour 25 and 30, the bed loses pressure before the end of the cycle. The following cycle the bed pressure is low for the full cycle, and again the next cycle the bed pressure fall short before the end of the cycle. This is the result of too little CO2 available from the 4BMS the preceding cycle.
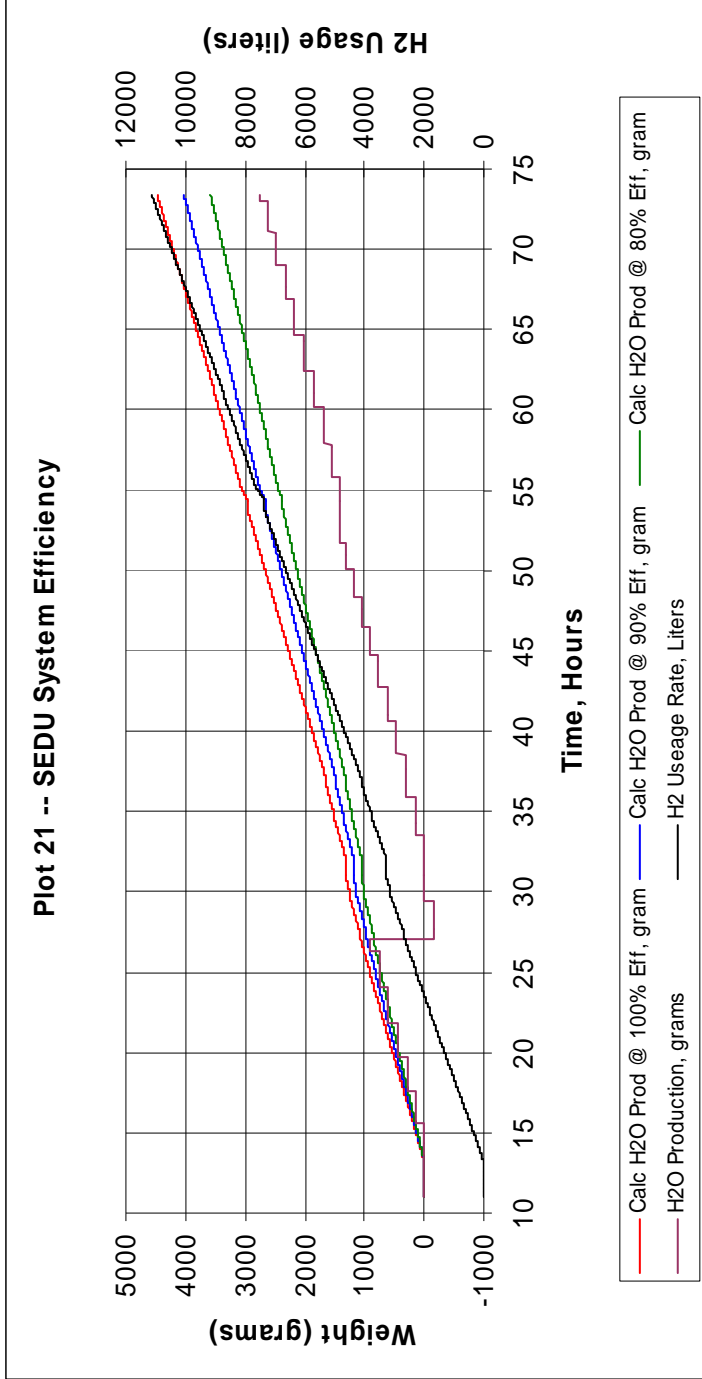
Plot 18 -- TSAC Inlet Flow Rate
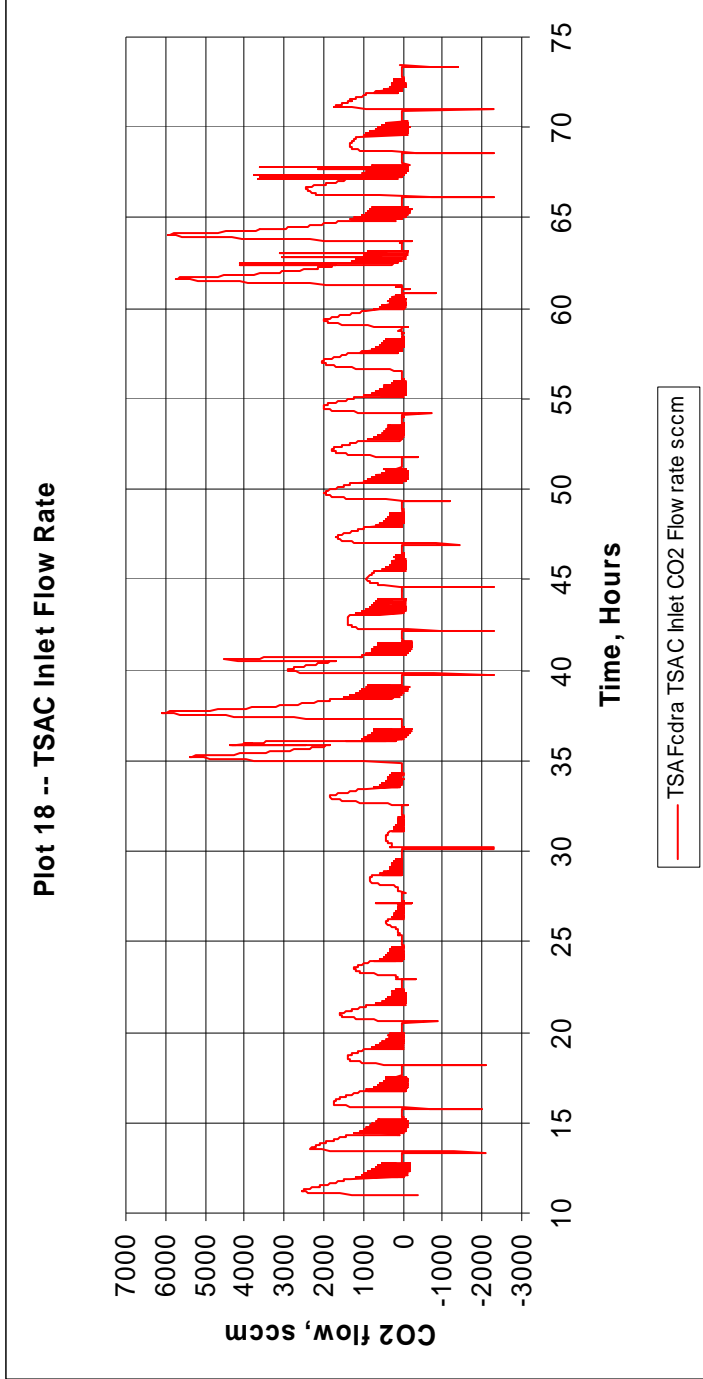
This plot shows the CO2 flow rate from the 4BMS to the TSAC. The CO2 comes off the CO2 adsorbent bed in a wave. Most of the flow comes off as the bed temperature is climbing. Once the bed reaches its setpoint temperature, the heaters start turning on and off to maintain the setpoint. Each time the heaters turn on, more gas is released, and when the heaters turn off, the flow rate decreases. This profile could potentially be improved with a variable power heater control instead of the on/off control.
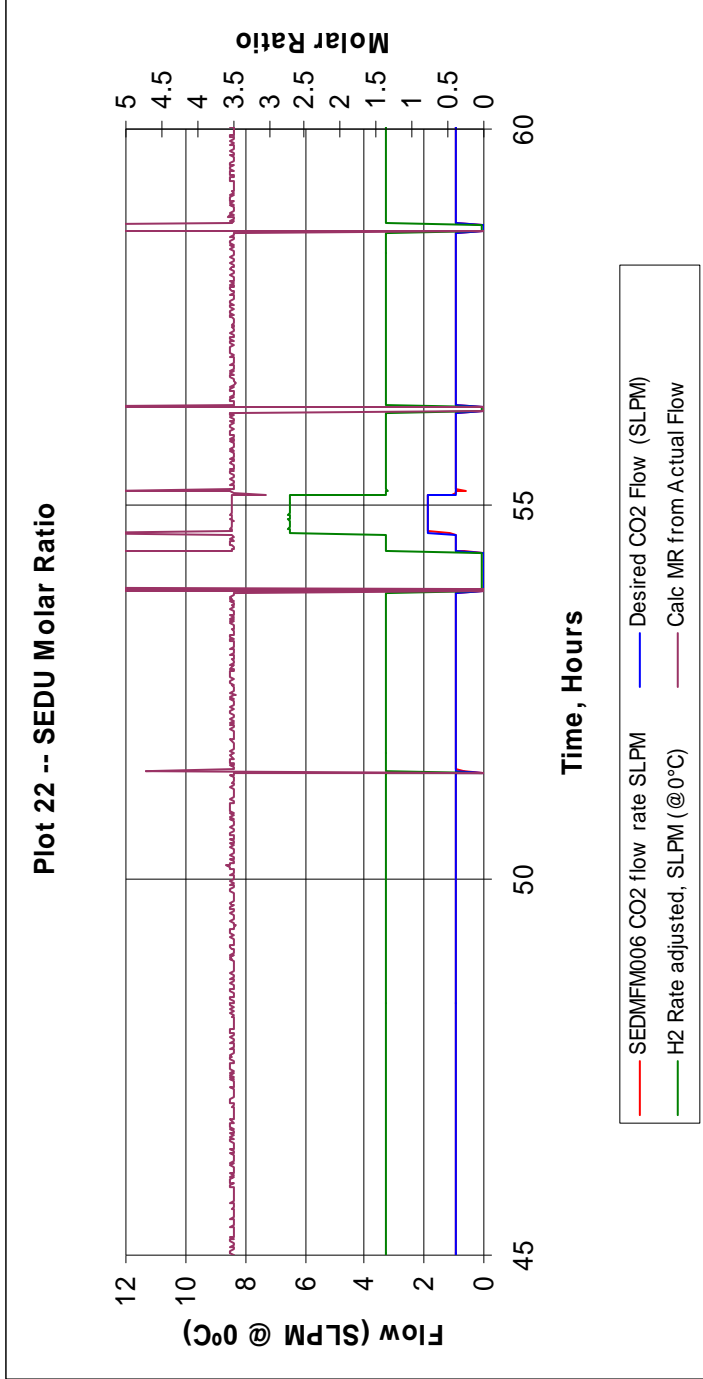
Plot 19 -- SEDU Separator Level Control
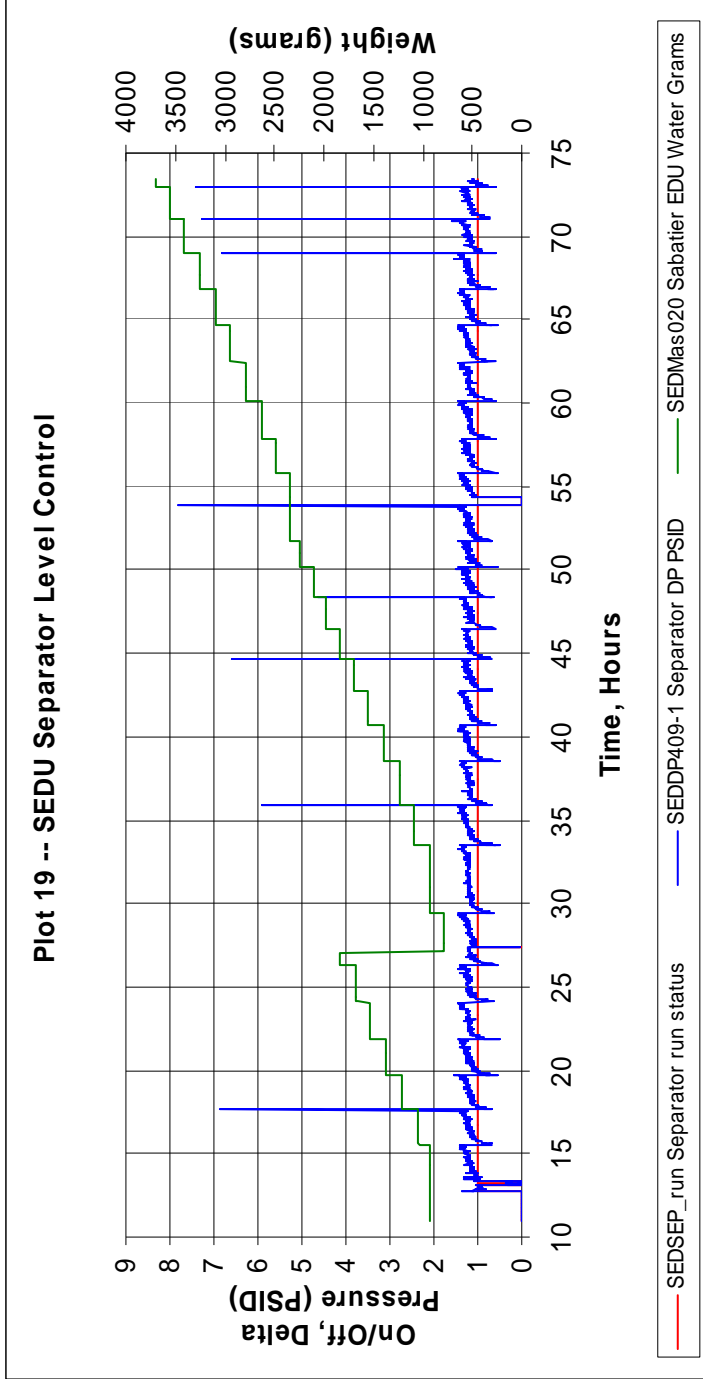
This plot shows the operation of the rotary phase separator in the Sabatier system and the water collection rate. The rotating bowl of the separator gradually fills with water that is condensed in the heat exchanger. The differential pressure between the liquid at the bottom of the bowl and the gas pressure slowly rises as more liquid is accumulated. When the pressure reaches a setpoint, the speed is increased to pump the liquid out, dropping the differential pressure as the liquid is removed. During this test, the separator collected about 140 grams of water between each pumpout over a time period of about 116 minutes. This equates to 1.2 grams/minute of water generation. At the hydrogen inlet flow rate of 3.26 slpm, the maximum water recovery possible is 1.3 grams/minute. The Sabatier achieved 92% recovery during the steady state portions of this test.

Plot 20 -- SEDU System Pressures
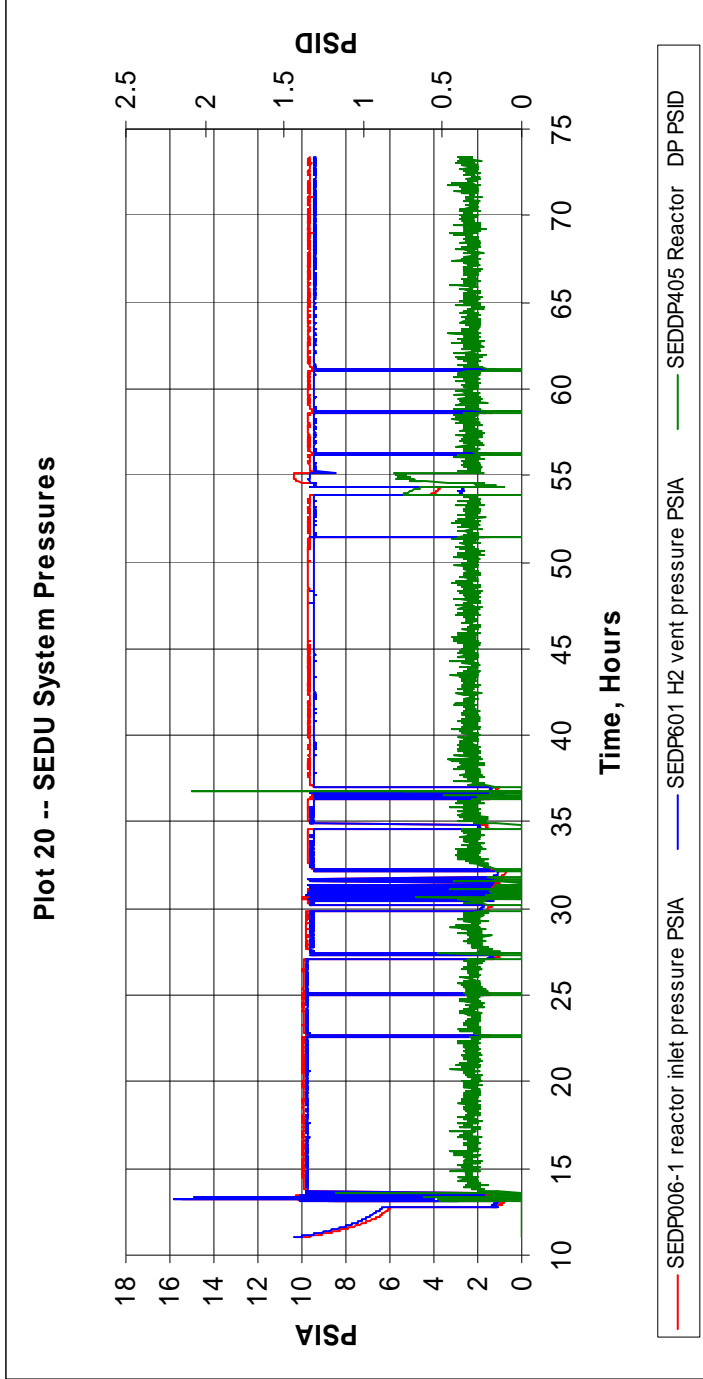
This plot shows the Sabatier system pressures. During steady state operation, the reactor pressure is about 10 psia. Operating at sub-ambient pressure is a safety feature of the system that prevents leakage of flammable gas to the cabin environment. Any time the Sabatier transitions to Standby the system is evacuated to vacuum to remove the gases. The downward spikes in the plot indicate the times that the Sabatier went to Standby due to starvation.

Plot 21 -- SEDU System Efficiency

Legend:
— Calc H2O Prod @ 100% Eff, gram
— Calc H2O Prod @ 90% Eff, gram
— Calc H2O Prod @ 80% Eff, gram
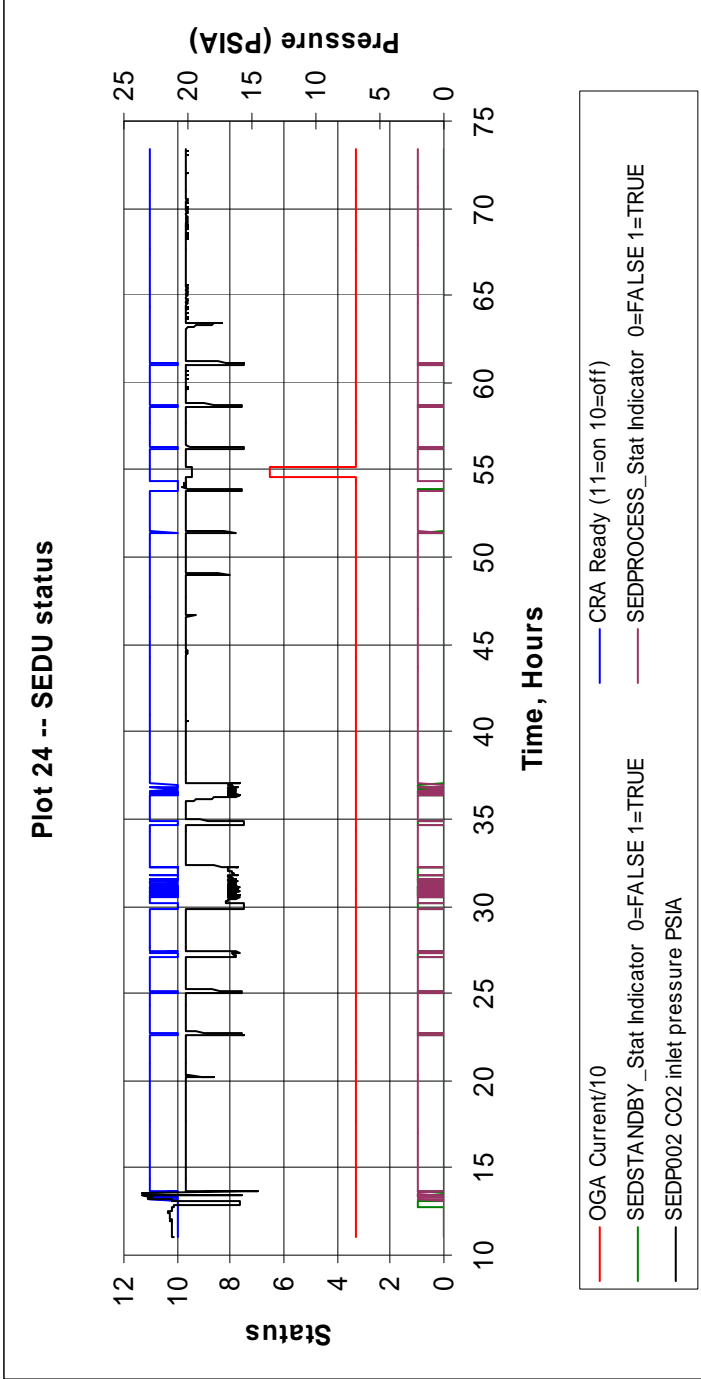— H2O Production, grams
— H2 Useage Rate, Liters

This plot shows the actual water collection compared to the theoretic production rate. At 100% recovery efficiency, the Sabatier reaction created 0.4 grams of water for each standard liter of hydrogen consumed. The overall water generation during this entire test was about 86%.

Plot 22 -- SEDU Molar Ratio

Legend:
- SEDMFM006 CO2 flow rate SLPM
- H2 Rate adjusted, SLPM (@0°C)
- Desired CO2 Flow (SLPM)
- Calc MR from Actual Flow

This plot shows the molar ratio of hydrogen to CO2 during the test. The stoichiometric ratio for the Sabatier reaction is 4 moles hydrogen per mole CO2. The Sabatier is typically operated at a molar ratio of 3.5 because there is usually excess CO2 available in a partially closed loop Air Revitalization System. At one point in the test (hour 55) the hydrogen flow rate was temporarily increased and the CO2 flow increased to match it at the same ratio of 3.5. The molar ratio value is undefined when the hydrogen and CO2 flows are both zero.

Plot 23 -- SEDU Temperatures

Legend:
- SEDT403_1 Reactor Temperature 1 deg F
- SEDT403_3 Reactor Temperature 3 deg F
- SEDT404_1R Reactor Outlet Temperature deg F
- SEDT403_2 Reactor Temperature 2 deg F
- SEDT403_4 Reactor Temperature 4 deg F
- SEDT407_2R Heat Exchanger Outlet Temperature 2 deg F
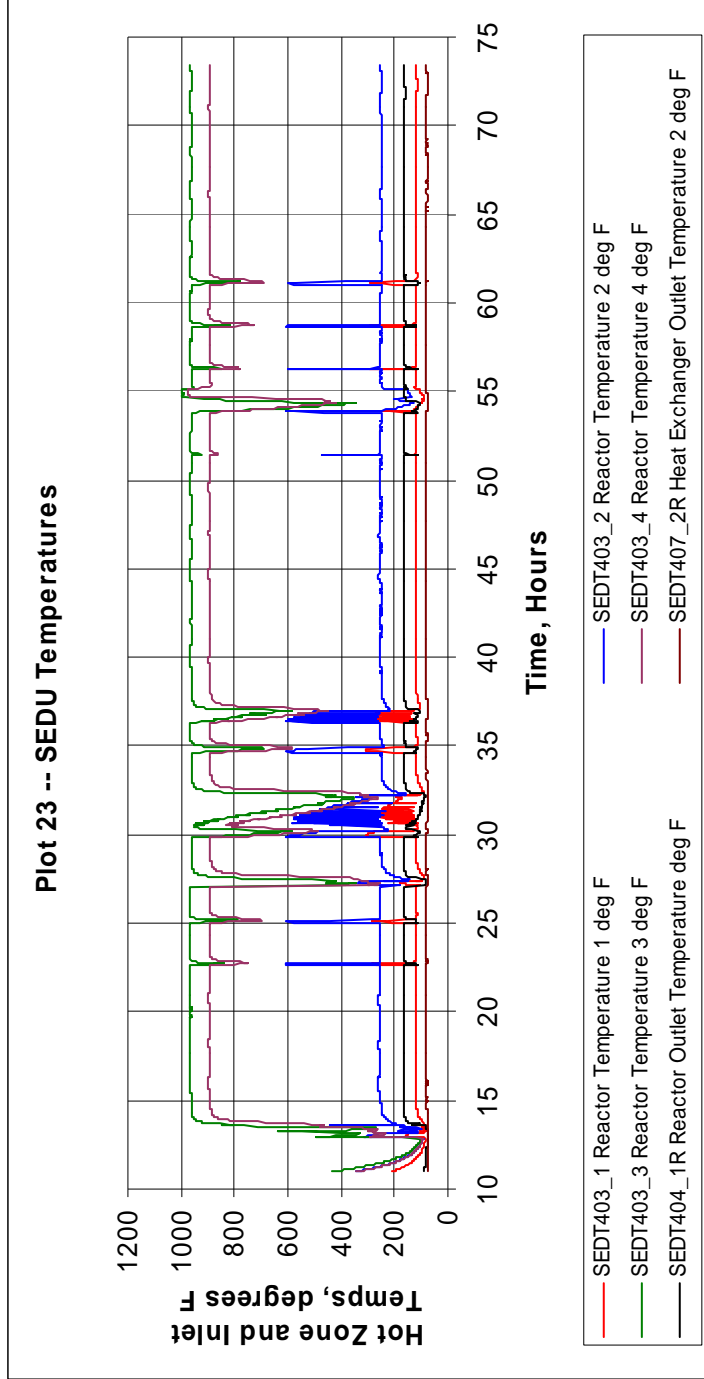
This plot shows the Sabatier reactor temperatures during the test. The top line is the hot zone of the reactor. The reactor cools quickly any time the system transitions to Standby. Each time the reactor temperature dips in the plot is an indication that there was CO2 starvation.

Plot 24 -- SEDU status

Legend:
- OGA Current/10
- SEDSTANDBY_Stat Indicator 0=FALSE 1=TRUE
- SEDP002 CO2 inlet pressure PSIA
- CRA Ready (11=on 10=off)
- SEDPROCESS_Stat Indicator 0=FALSE 1=TRUE

This chart shows the status of the Sabatier system and the CO2 inlet pressure. CO2 availability and OGA ready are the two key indicators that determine if the Sabatier can operate. This mission scenario had OGA ready all the time, therefore the CO2 inlet pressure was the cause for the Sabatier being unable to operate.

189

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[14]		International Space Station Trace Contaminant Injection Test, Revision A, NASA Test Requirements Document, January 1997	J. D. Tatara J. L. Perry

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14. ABSTRACT

NASA's vision and mission statements include an emphasis on human exploration of space, which requires environmental control and life support technologies. This Contractor Report (CR) describes the development and evaluation of an Air Revitalization System, modeling and simulation of the components, and integrated hardware testing with the goal of better understanding the inherent capabilities and limitations of this closed loop system. Major components integrated and tested included a 4-Bed Modular Sieve, Mechanical Compressor Engineering Development Unit, Temperature Swing Adsorption Compressor, and a Sabatier Engineering and Development Unit. The requisite methodolgy and technical results are contained in this CR.

15. SUBJECT TERMS

Environmental Control and Life Support Technologies, Air Revitalization System, Closed Loop Air Revitalization System, 4-Bed Modular Sieve, Mechanical Compressor Engineering Development Unit, Temperature Swing Adsorption Compressor, Sabatier Engineering and Development Unit

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