HAMILTON STANDARD Division of UNITED TECHNOLOGIES

SVHSER 7103

NASA CR-
151146

INTERIM REPORT

BREADBOARD CO_2 AND HUMIDITY

CONTROL SYSTEM

BY

ALBERT M. BOEHM

PREPARED UNDER CONTRACT NO. NAS 9-13624

BY

HAMILTON STANDARD
DIVISION OF UNITED TECHNOLOGIES CORPORATION
WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

OCTOBER, 1976

(NASA-CR-151146) BREADBOARD CO2 AND HUMIDITY CONTROL SYSTEM Interim Report (Hamilton Standard, Windsor Locks, Conn.) 178 p HC A09/MF A01 CSCL 22B

N77-15079

Unclas
G3/16 12517

HAMILTON STANDARD Division of UNITED TECHNOLOGIES™

SVHSER 7103

INTERIM REPORT

BREADBOARD CO_2 AND HUMIDITY CONTROL SYSTEM

BY

ALBERT M. BOEHM

PREPARED UNDER CONTRACT NO. NAS 9-13624

BY

HAMILTON STANDARD
DIVISION OF UNITED TECHNOLOGIES CORPORATION
WINDSOR LOCKS, CONNECTICUT

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

OCTOBER, 1976

ABSTRACT

A regenerable CO_2 and humidity control system is being developed for potential use on Shuttle as an alternate to the baseline lithium hydroxide (LiOH)/condensing heat exchanger system. The system utilizes a sorbent material, designated HS-C, to adsorb CO_2 and water vapor from the cabin atmosphere. The material is regenerated by exposing it to space vacuum.

A half-size breadboard system, utilizing a flight representative HS-C canister, was designed, built, and performance tested to Shuttle requirements for total CO_2 and total humidity removal.

The breadboard HS-C canister was fabricated using unique design and construction techniques. The use of a new chemical matrix material allowed significant optimization of the system design by packing the HS-C chemical into the core of a heat exchanger which is manifolded to form two separate and distinct beds. The system and canister run nearly adiabatic with the heat of the adsorbing bed passing directly to the desorbing bed to balance the heat of desorption in a regenerative manner.

Breadboard system performance was proven by parametric testing and simulated mission testing over the full range of Shuttle crew sizes and metabolic loadings. Vacuum desorption testing demonstrated considerable savings in previously projected Shuttle vacuum duct sizing.

FOREWORD

This report has been prepared by Hamilton Standard, Division of United Technologies Corporation for the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center in accordance with Contract NAS 9-13624, "Breadboard and Flight Prototype CO_2 and Humidity Control Systems." The report covers work accomplished on the breadboard phase of the program between August 1, 1973 and April 30, 1976.

Appreciation is expressed to the Technical Monitors, Mr. Frank Collier, Mr. Robert J. Cusick, and Mr. L. D. Kissinger of the NASA, Johnson Space Center, for their guidance and advice.

This program was conducted under the direction of Mr. Harlan F. Brose and Mr. Fred H. Greenwood, Program Managers, and Mr. Albert M. Boehm and Mr. Arthur E. Francis, Program Engineers, with the assistance of Mr. Edward H. Tepper, Analysis, and Mr. John E. Steinback, Design.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES
(Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

SUMMARY

The breadboard system development effort was divided into the major tasks of analysis, design, fabrication, and test.

The analysis task identified an optimum flight system based on the primary requirements for four and ten man operation to fail operation-fail safe groundrules. The breadboard system was defined during this task by simplifying the projected flight system without changing its functional operation.

Two novel approaches to HS-C system operation and design were identified during the analysis task. First, the feasibility of varying the adsorption/desorption cycle time, to accommodate varying crew sizes and metabolic loadings, was selected as an alternate control scheme to varying airflow rate. Subsequent breadboard testing showed that a combination of cycle time and airflow control actually produce the overall optimum system.

A radical change in canister design and construction technique was the second novel output. The use of a new, foamed aluminum (known as duocell) was identified as an improved bed core material. The combining of two separate beds into one canister further optimized the system design by using the heat of adsorption to desorb the adjacent bed in a regenerative manner.

A small scale module test program was conducted and proved the feasibilities of both new approaches. A module was constructed using the duocell material in a regenerative two bed design. The module was tested to evaluate the effect on CO_2 and H_2O performance by the two major control variables of cycle time and airflow rate. Airflow rate testing had been extensively tested previously and served as the baseline to evaluate the unique bed design and also the effect of the variable cycle time control scheme.

Having verified the canister concept with module testing, a breadboard canister was designed and fabricated to a flight configuration. The canister was packaged with commercial components to form the breadboard system. The canister was filled with new HS-C material. The new material was produced by a revised, time saving procedure in a new fabrication setup which greatly increased the production batch size to 0.02 m^3 (20 liter) or 7.7 kg (17 lb) per batch. Test samples from each batch verified the new material to be repetitive and equal to that produced with the previous equipment.

The breadboard system was successfully tested with a Shuttle Orbiter simulated environment of volume, temperature, pressure, PCO_2, and humidity. The system was performance tested in five major phases as follows:

Performance calibration testing established the operating parameters of the baseline four and ten man crews for both timing and flow control schemes.

A parametric test phase expanded the performance calibration testing to seven man metabolic loadings.

One hundred, twenty-six hours of mission testing simulated a Shuttle mission and established the long term performance of the breadboard system.

The ullage-save compressor test phase established the feasibility of using a compressor to greatly reduce the ullage penalties of a flight system.

The vacuum desorption test phase provided considerable insight into the desorption phenomina and justified a reduction in the projected Shuttle vacuum duct size to a 89 mm (3.5 in) diameter duct.

INTRODUCTION

A regenerable CO_2 and humidity control system is being developed for potential use on Shuttle as an alternate to the baseline Lithium Hydroxide (LiOH) and condensing heat exchanger system. The system uses a sorbent material (designated "HS-C") to adsorb CO_2 and water vapor from the cabin atmosphere. The CO_2 and water vapor are subsequently desorbed overboard when exposed to the space vacuum. Continuous adsorption from the cabin and desorption to space is achieved by utilizing two beds which are alternately cycled between adsorption and desorption. The HS-C system is especially desirable because it requires no liquid loop connections, needing only space vacuum and electrical connections to perform within the cabin environment.

The HS-C material is comprised of small spherical highly porous acrylic ester pellets, 0.5 mm (.020 in) coated with a thick nonvolatile liquid, polyethylenimine (PEI). The porous substrate exposes an extremely large surface area of the PEI coating to the cabin atmosphere. The PEI is then able to chemically absorb the CO_2 and H_2O from the atmosphere.

Past development programs, NAS 1-8944, NAS 9-11971, and NAS 9-12957, have concentrated on material optimization and flight compatibility of the material. The material has been optimized for bead size and coating thickness. The quality and compatibility of the material have been proven by various tests. These include; vibration, flammability, solvent vapors, acid gas, microbiological, off-gassing, high temperature, and life.

In addition, the HS-C material has been parametrically tested to establish the effect on performance of various environmental parameters. These have included the atmospheric effects of cabin temperature, dew point, and PCO_2 levels. HS-C bed configuration testing has included the variables of bed temperature, bed thickness, and desorption pressures.

This program is the fourth in a series designed to develop HS-C to a status acceptable for consideration for Shuttle. This program was designed to develop unique HS-C components and test a flight prototype system to simulated Shuttle mission profiles. As a preliminary phase, a half-size breadboard system was designed, built, and tested to simulated mission profiles. This interim report concentrates exclusively on the breadboard system phase of the program.

The calculations in this report were made in US customary units and converted to SI metric units.

OBJECTIVES

The primary objective of the breadboard phase of this program was to demonstrate the performance of the breadboard system under simulated Shuttle requirements.

The program was divided into seven tasks:

Breadboard System Analysis
Breadboard System Design
HS-C Material Fabrication
Breadboard System Fabrication
Facility Modification
Test Setup
Breadboard System Test

The objectives of each task are listed below.

BREADBOARD SYSTEM ANALYSIS OBJECTIVES

- To define component and system sizing.
- To define the operating parameters and control methods of the system.
- To verify the analysis assumptions and conclusions with a module test program.

BREADBOARD SYSTEM DESIGN OBJECTIVES

- To formulate a design for the breadboard system that will accurately represent the flight system operation.
- To formulate a design for the breadboard canister that accurately represents the flight configuration and construction.

HS-C MATERIAL FABRICATION OBJECTIVES

- To manufacture a sufficient quantity of HS-C material for breadboard system testing.
- To expand the manufacturing capability of HS-C to batch sizes consistent with ultimate Shuttle need.
- To demonstrate the quality and repeatability of HS-C material produced by the new facility.

BREADBOARD SYSTEM FABRICATION OBJECTIVES

- To procure, manufacture and assemble the breadboard system and all its components.
- To demonstrate the ability to fabricate the flight configuration canister.

FACILITIES MODIFICATION OBJECTIVE

- To improve the vacuum capacity of the existing vacuum system, Rig 52.

TEST SETUP OBJECTIVE

- To provide a test setup adequate to test the breadboard system per the Master Test Plan.

BREADBOARD SYSTEM TEST OBJECTIVES

- To demonstrate the ability of the breadboard system to provide design compliance.
- To demonstrate acceptable CO_2 and humidity control performance on a simulated Shuttle mission.
- To demonstrate the feasibility of using a compressor to reduce ullage penalties.
- To establish the HS-C performance dependence on desorption pressures in order to minimize the vacuum duct size.

CONCLUSIONS

1. The breadboard system provided excellent performance for Shuttle Application.

2. Analytical techniques were shown to be accurate in predicting component and system sizing, performance and operating conditions. The HS-C parametric data base was sufficiently increased by the breadboard testing to allow even greater use of analytical tools to size and predict performance of an HS-C flight design.

3. The HS-C material can be fabricated in flight compatible, production batch sizes of 7.7 kg (17 lb). In addition, a minimum two year self life for the HSC material was verified during the test phase.

4. The HS-C canister can be fabricated to a flight configuration using the unique design of duocell foam and integral screens.

5. Existing facilities were modified to provide a test setup that accurately represented a Shuttle cabin and performance transients.

6. The breadboard system was tested for a total of 505 hours with no degradation in performance.

7. Cycle time adjustments were shown to be the primary parameter affecting CO_2 control.

8. Airflow rate adjustments were shown to be the primary parameter affecting H_2O control.

9. A combination of the cycle time and airflow rate control schemes was shown to allow the maximum flexibility in accommodated varying crew sizes and metabolic loadings.

10. The ullage-save compressor was shown to be a feasible method for reducing ullage penalties.

11. Desorption vacuum pressures were shown to have a negligible affect on HS-C performance at all pressures below 133.3 Pa (1,000 microns).

12. Vacuum desorption testing justified a reduction in the projected vehicle vacuum duct to a 89 mm (3.5 in) diameter.

13. The breadboard system test results are directly applicable as the design base for a full-size system.

RECOMMENDATIONS

1. The flight system should be redefined per updated Shuttle philosophies of fail-safe backup only. Such a system would invariably have one full size HS-C canister rather than the three, half size canisters which were required to meet the fail-operational/fail-safe groundrule of the breadboard system analysis task. Further savings are possible by the reduction in vacuum valves needed to support only one canister.

2. The feasibility of fabricating a full-size HS-C canister should be demonstrated by building and structurally testing a flight weight, full-size, flight prototype canister.

3. Flight prototype vacuum cycling valves should be designed, fabricated, and endurance tested to complete the development of all components unique to the HS-C system.

4. A Shuttle vehicle integration study should be conducted to establish all parameters affecting the integration of an HS-C system into the Orbiter vehicle. This comprehensive study should consider the parameters of: available packaging envelopes, mounting constraints and locations, operational performance in conjunction with the existing ARS, interfacing plumbing locations, routings, and sizes. The conclusion of this task should be an updated trade-off comparing the projected HS-C flight system with the existing Shuttle ARS.

5. The flight prototype canister and vacuum cycling valves should be installed with flight configuration air and vacuum ducting to form a flight prototype system. This system should be tested to demonstrate performance compliance on a simulated Shuttle mission.

6. The flight prototype system should be parametrically tested to minimize vacuum desorption ducting requirements with projected duct lengths and configurations.

7. The ullage-save compressor technique should be used with all four-man and seven-man test conditions.

8. The procurement of a commercially available, internally vaned, vacuum mixer would greatly facilitate any future HS-C material fabrication.

9. The phenomena of improved performance through proper conditioning of the HS-C material, as observed in the vacuum desorption testing, should be investigated thoroughly.

RESULTS

The results of analysis and design phases of the program were the definition, sizing, and packaging of the breadboard system with specific attention paid to the flight configuration of the breadboard canister.

The projected flight system is shown schematically in Figure 1. The breadboard system was generated from the flight schematic by simplifying the hardware approach to certain component functions or by making use of existing GFE components. The breadboard system is defined schematically in Figure 2.

The breadboard canister design represents the major hardware breakthrough of the program. The NASA has applied for two separate patents relating to the canister design. The first relates to the use of a regenerative heat exchanger approach to canister design. This approach combines two separate chemical beds into one canister to use the heat of adsorption passively to balance the heat of desorption in a nearly adiabatic process. The second patent application relates to the use of aluminum foam as the chemical matrix material. The aluminum foam offers the unique combination of properties desirable as a bed core matrix, including easy HS-C filling, structural support, brazeability, and thermal performance. Figure 3 shows a breakaway view of a regenerative, two bed, flight canister design. A cross section of the canister, showing the aluminum foam matrix material, is presented in Figure 4.

The results of the fabrication phase of the program are also depicted by Figure 4. This photograph shows the details of the brazed canister assembly including the aluminum foam, integral screens, parting sheets, and closure bars. The completed breadboard canister is shown in Figure 5. The completed breadboard system is shown as part of the test setup in Figure 6.

The testing of the breadboard system provided the most important results of the program. The test results verified the analysis and design conclusions, defined Shuttle operational requirements, established CO_2 and H_2O performance maps, established the feasibility of the ullage-save compressor, and minimized the vacuum duct requirements.

From the testing, it was concluded that neither the cycle time control scheme nor the airflow rate control scheme alone could optimumly handle all crew sizes and metabolic loading ranges. The final choice of cycle time and airflow rate for the different

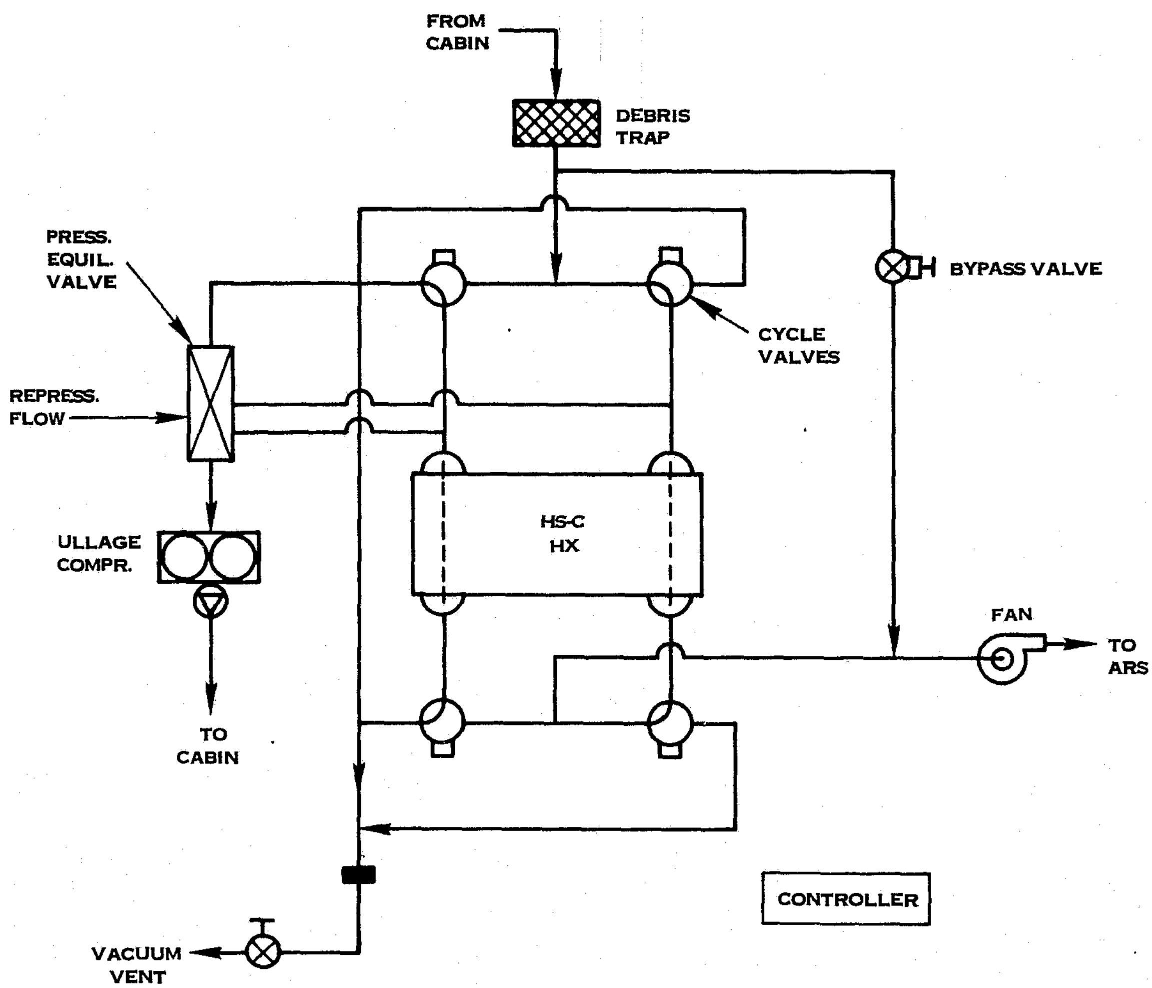


FIGURE 1 HS-C FLIGHT SCHEMATIC

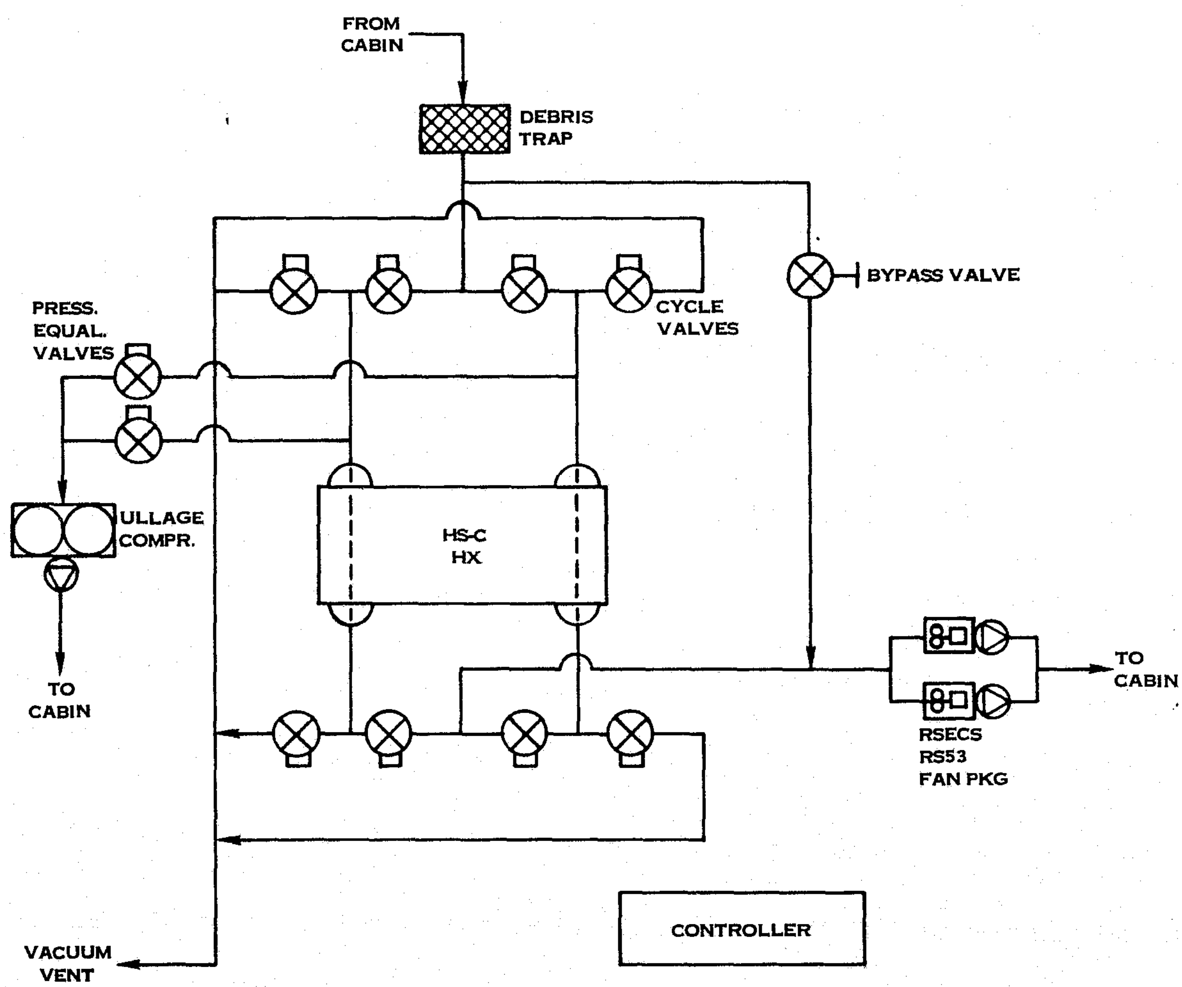


FIGURE 2 BREADBOARD SYSTEM SCHEMATIC

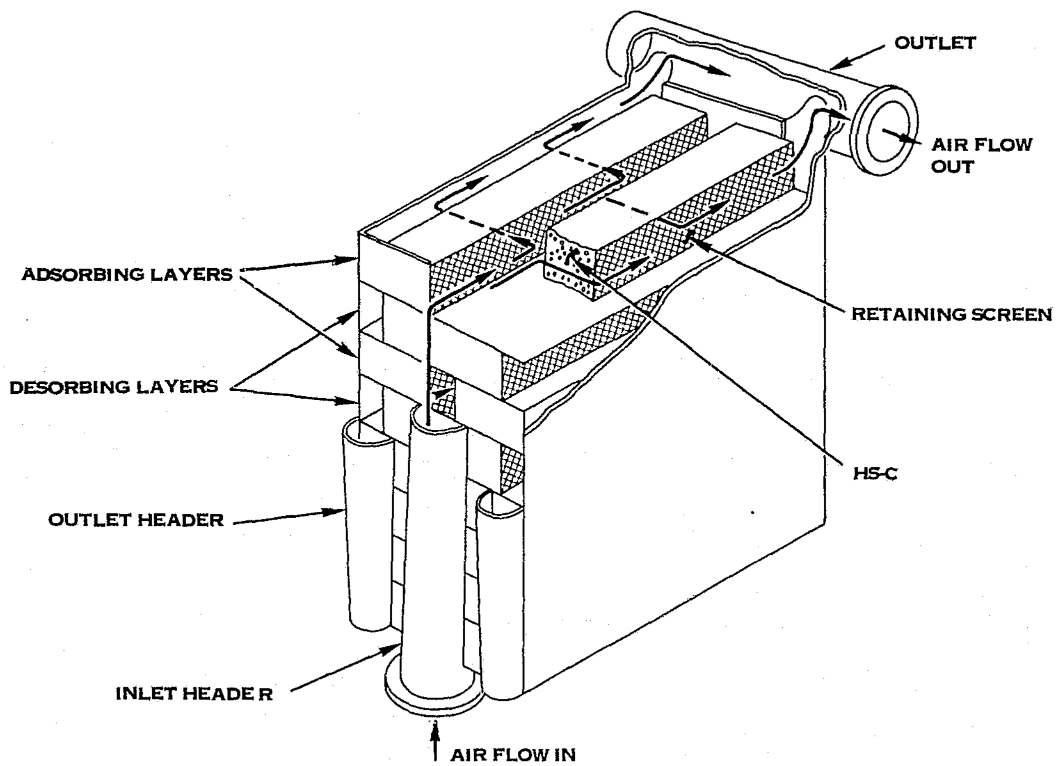


FIGURE 3 HS-C FLIGHT CANISTER CONCEPT

HAMILTON STANDARD Division of UNITED TECHNOLOGIES

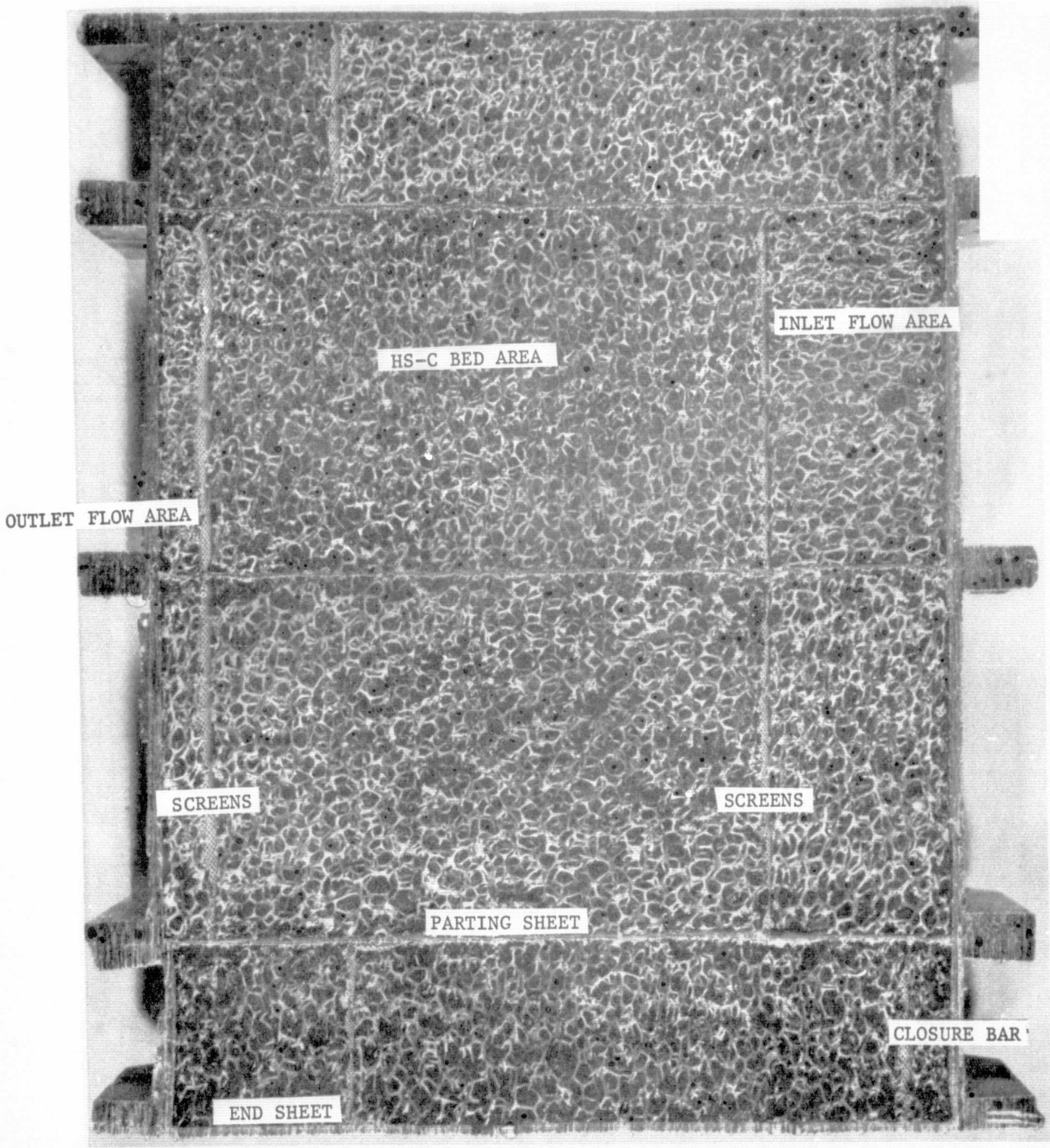


FIGURE 4 CROSS-SECTION OF SECOND MODULE

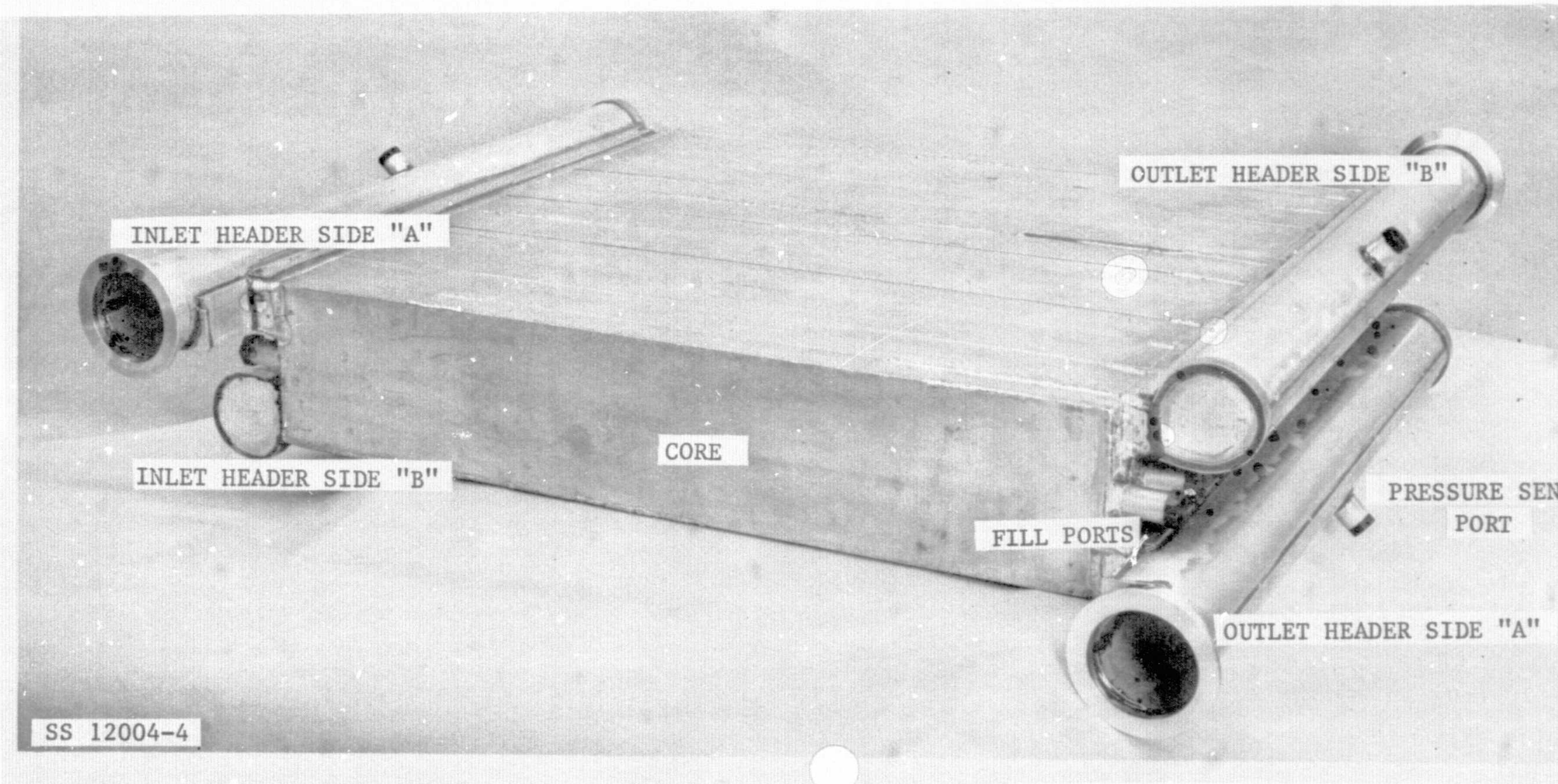


FIGURE 5 THE BREADBOARD CANISTER

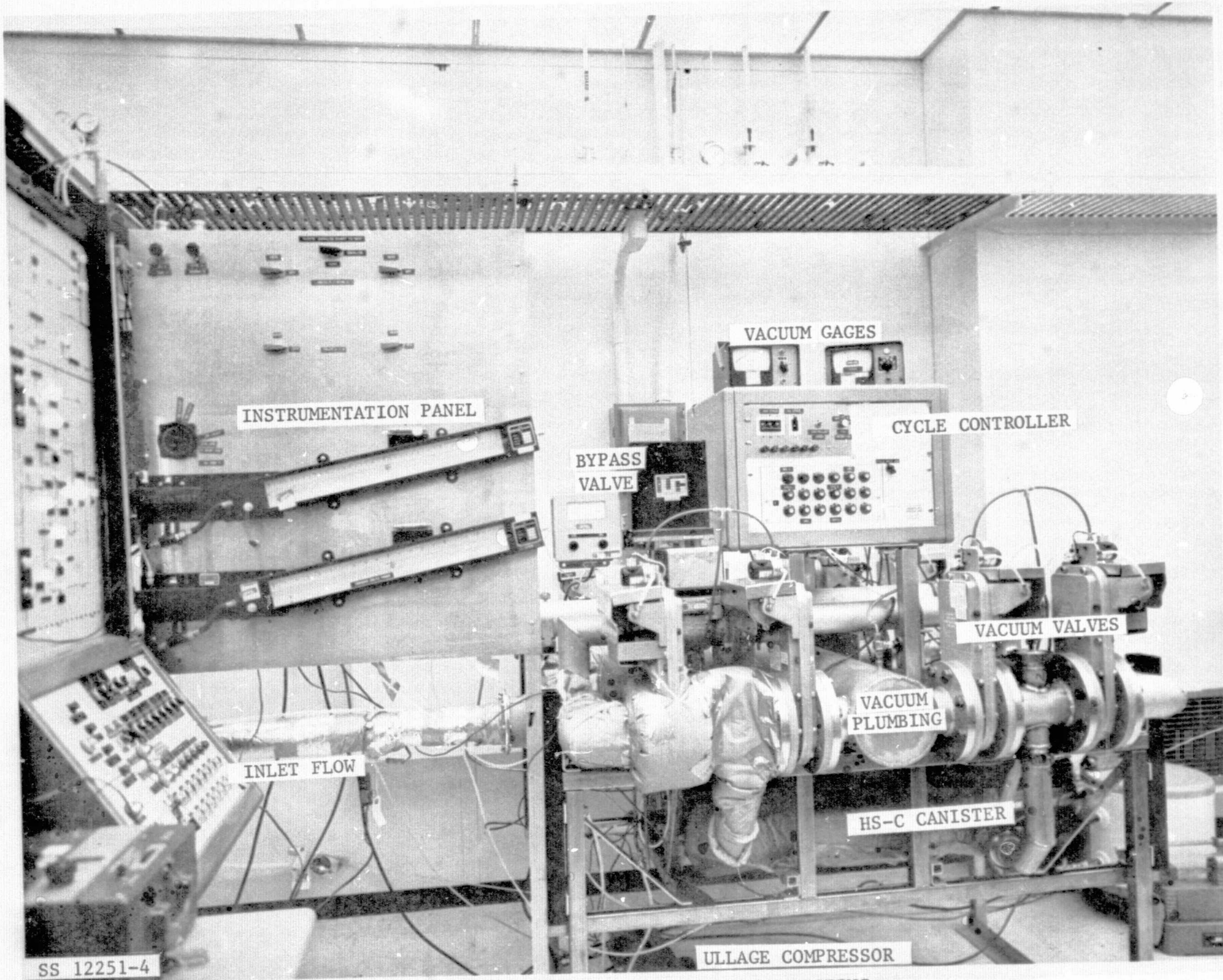


FIGURE 6 THE BREADBOARD SYSTEM DURING TESTING

crew sizes is shown in Table 1. It is recommended that three controller settings be used for all crew sizes. The controller settings pick the cycle time and fan airflow rate. The controller would then adjust the bypass valve, shown in the schematics of Figures 1 and 2, to control the actual airflow through the canister. The bypass valve would be adjusted to control the humidity level of the vehicle for varying crew sizes, temperature ranges, and metabolic loadings. CO_2 is controlled automatically for each range of crew sizes.

The testing also resulted in the CO_2 performance map of Figure 7. The CO_2 level is maintained below .67 kPa (5 mmHg) for all conditions. The top curve gives the performance for the three baseline crews at their respective control settings of fan speed and cycle time (refer to Table 1). The bottom curve shows the CO_2 levels when a four man crew is present, and the controller is on a seven man setting. The range within the two curves depicts the CO_2 levels for either a five or six man crew at the seven man setting. Similarly, crews of less than four men operating at the four man control setting would result in improved CO_2 performance depicted by the shaded flow control range of the mapping, although these crews were not specifically tested.

The CO_2 performance map, Figure 7, also shows the trend for lower PCO_2 levels at higher cabin temperatures. This is due to the operational characteristics of the HSC material. Testing has shown that the CO_2 capacity of the material improves with both increasing temperature and increasing humidity. Since humidity automatically increases with high temperatures because of the increased metabolic latent load from the crew, the improved performance of HS-C at the higher temperatures is the combined effect of both parameters.

The humidity control performance map is shown in Figure 8. These curves have been scaled up from the half-size breadboard rates and flows to be compatible with full-size Shuttle requirements. The map shows that airflow is the exclusive parameter affecting humidity control at cycle times of less than 30 minutes. Only a four man crew has a cycle time greater than 30 minutes and is specifically shown by the 40/40 cycle curve. The humidity level for any operating condition can be found from the performance map by knowing the fan speeds of Table 1. Use of the bypass valve can further reduce airflow through the canister down to 0.014 m^3/sec (30 cfm) and establishes the total operating regime of the map.

TABLE 1
BREADBOARD CONTROL SETTINGS

Controller Setting	Fan* Airflow	Cycle Time	Orbiter Crew Size
(Max Crew Size)	m^3/s (cfm)	(Min Adsorb/Min Desorb)	(Men)
4	0.024 (50)	40/40	1-4
7	0.024 (50)	19/19	5-7
10	0.033 (70)	10/10	8-10

*Bypass valve modulates air flow through the HS-C canister based upon cabin dew point.

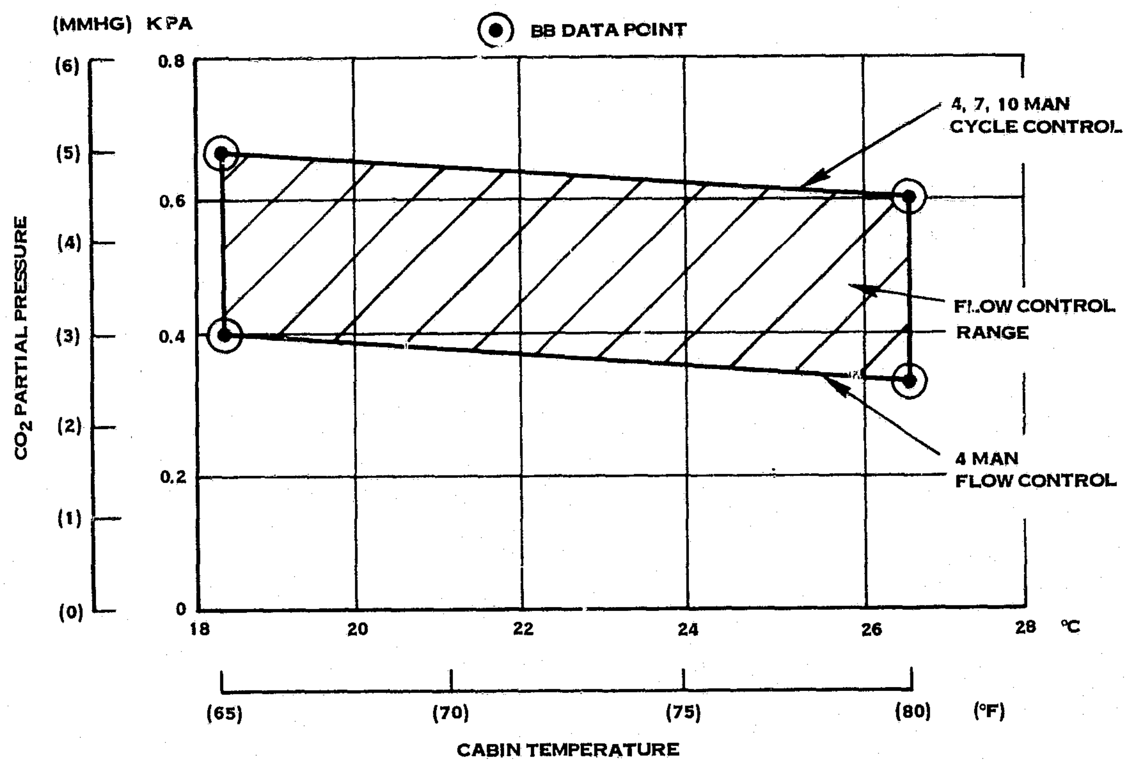


FIGURE 7 CO_2 PERFORMANCE MAP

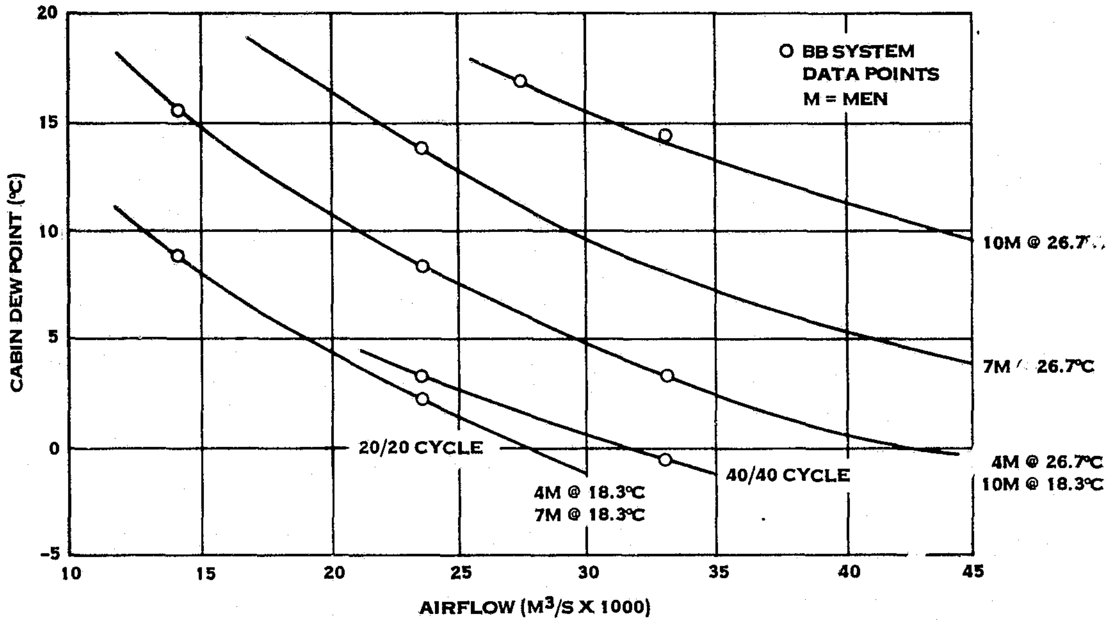


FIGURE 8A HU IDITY PERFORMANCE MAP (S.I. UNITS)

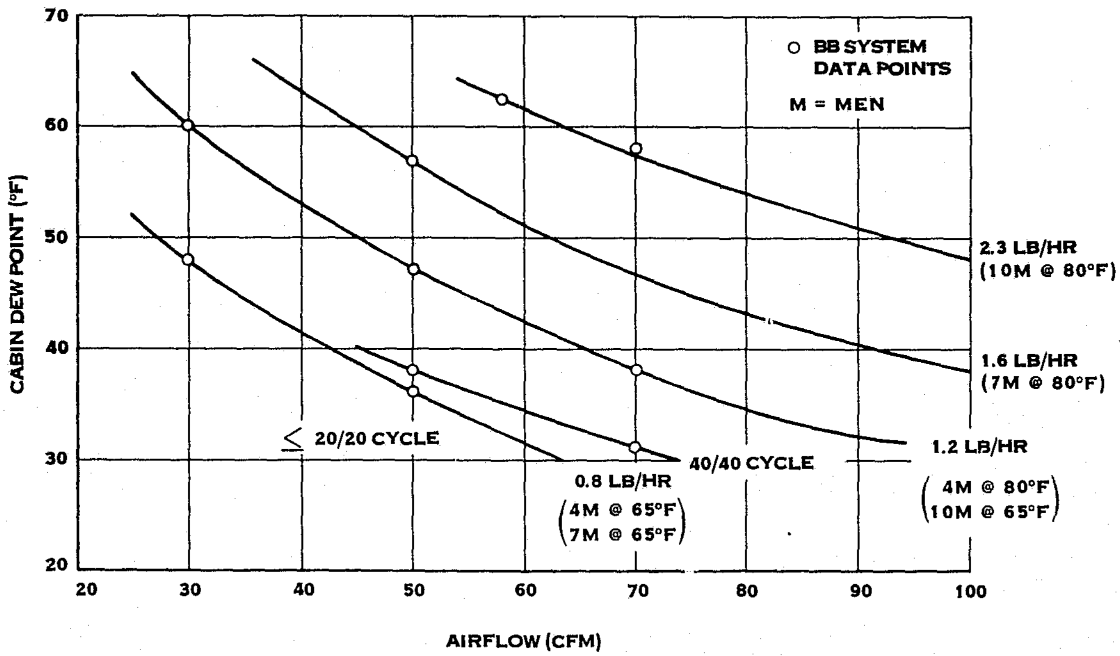


FIGURE 8B HUMIDITY PERFORMANCE MAP (U.S. UNITS)

The results of ullage-save compressor testing proved the feasibility of using a compressor to reduce ullage penalties without sacrificing performance. The test results, summarized in Table 2, show that there was no measurable effect on CO_2 performance and only a slight effect on H_2O performance. This table compares ullage-save compressor test data with data taken at the same conditions but without the ullage compressor. There was no appreciable difference in the CO_2 equilibrium pressures for either the four man or seven man crew. However, the dew point equilibrium level, which was expected to rise 1.4°C actually rose 2°C when the ullage compressor was used for both cases. This increase can be compensated by increasing the airflow rate by 0.0033 m^3/s (7 cfm) which will result in superior CO_2 performance. The final choice of airflow will depend on the operational integration of the HS-C system into Shuttle and whether that system is constrained by humidity control or by CO_2 control.

The results of the vacuum desorption testing have significant impact on the integration of an HS-C system into the Shuttle Orbiter vehicle. The effect of desorption pressures on HS-C performance is shown in Figure 9. From this graph, it can be seen that both the CO_2 and H_2O removal performances of the breadboard system did not fall off until the desorption pressure exceeded 133 Pa (1,000 microns). A 10% degradation was recorded at a pressure of 266 Pa (2,000 microns). This pressure is measured at the plumbing interface to the canister and represents the lowest pressure attained which occurred at the end of the desorption cycle. The effect of desorption pressure on projected Shuttle vacuum duct sizes is shown in Figure 10. This curve shows that a 89 mm (3.5 inch) diameter duct would provide the desired 133 Pa (1,000 microns) desorption pressure. Both Figure 10 and the desorption test parameters were based on the worst case, ten men at 26.7°C (80°F), desorption loading. Once the duct size is fixed, the desorption pressures, as shown in Figure 10, will be lower for smaller crew sizes or smaller metabolic loadings than the ten man test case.

TABLE 2
ULLAGE COMPRESSOR RESULTS

(S.I. Units)

Crew Size (Men)	Cabin Temp. (°C)	PCO_2 Level W/O USC (kPa)	PCO_2 Level USC (kPa)	Dew Point W/O USC (°C)	Dew Point USC (°C)
4	18.3	.40	.42	11	12.8
7	26.7	.60	.59	14	16

(U.S. Units)

(Men)	(°F)	(mmHg)	(mmHg)	(°F)	(°F)
4	65	3.0	3.15	52	55
7	80	4.5	4.4	57	61

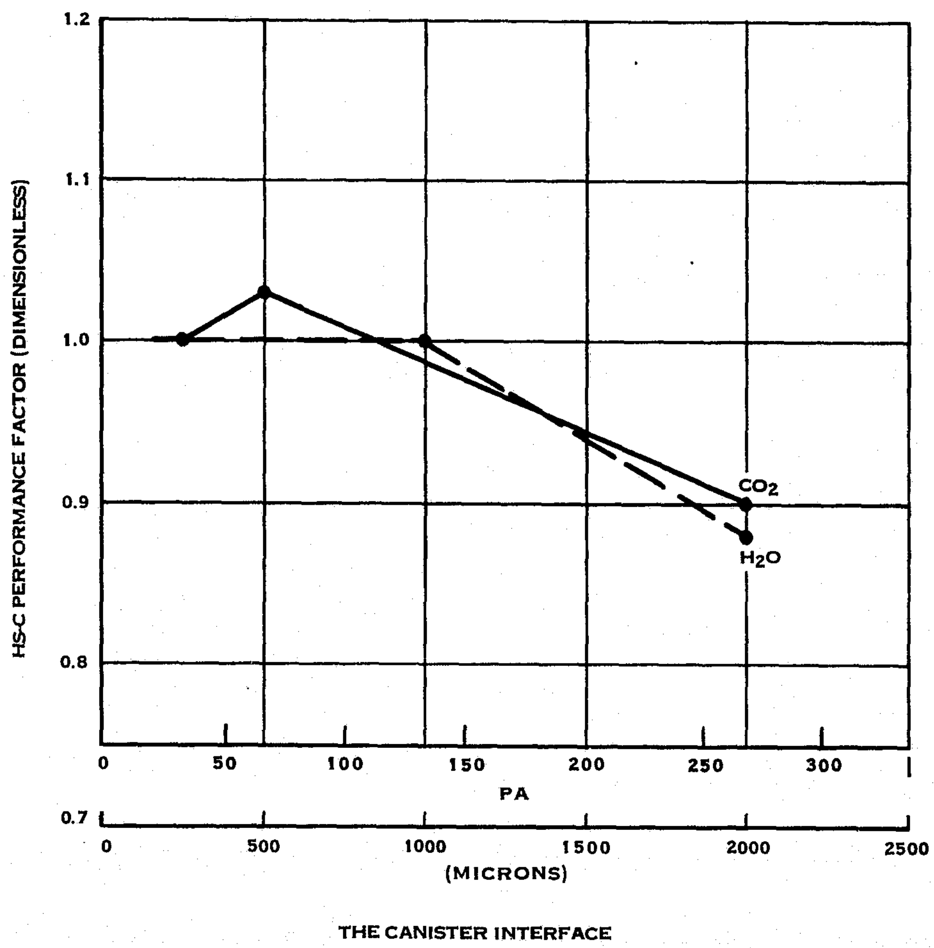


FIGURE 9 EFFECT OF DESORPTION PRESSURE ON HS-C PERFORMANCE

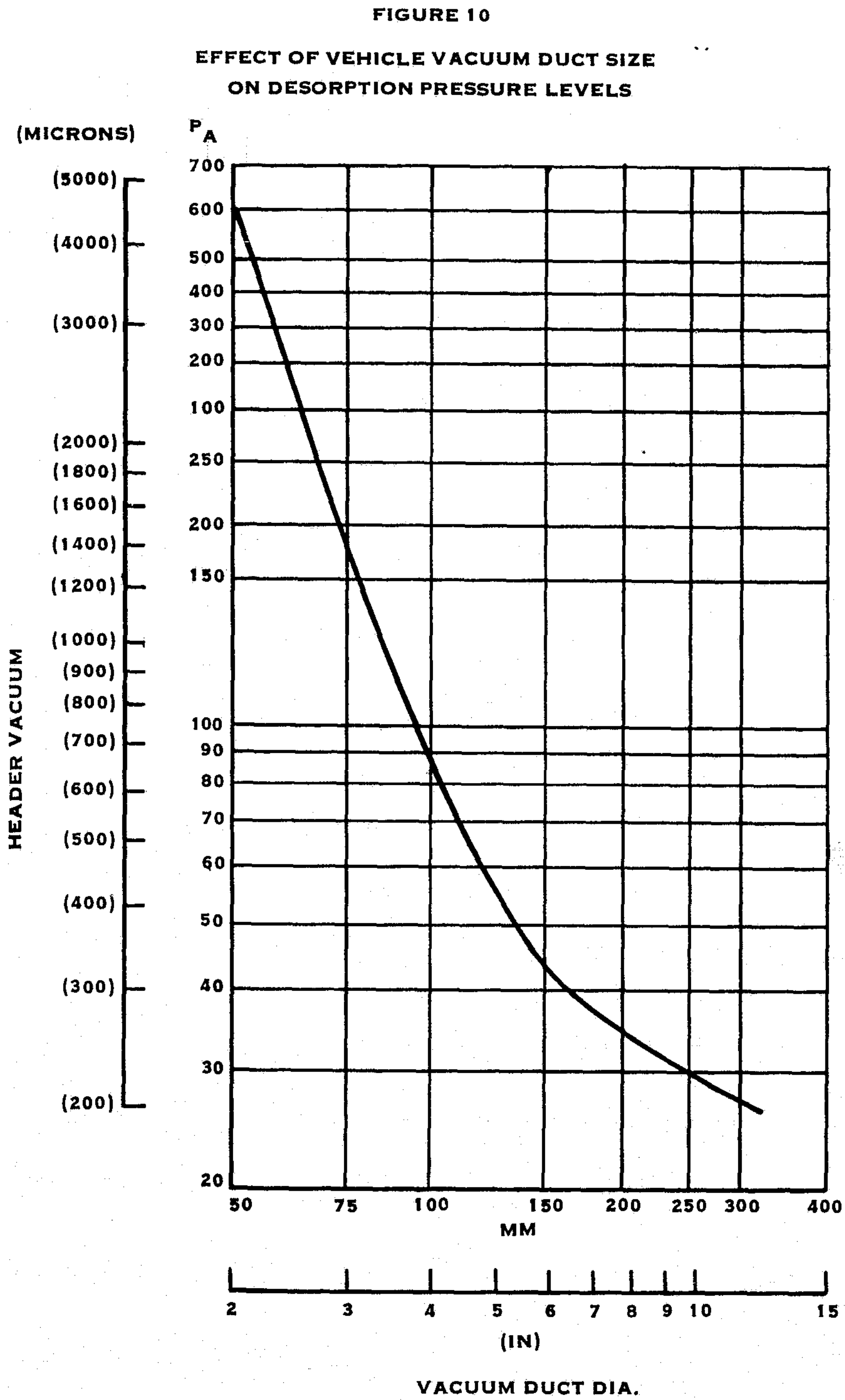


FIGURE 10 EFFECT ON DUCT SIZE ON DESORPTION PRESSURE

DISCUSSION

The NASA Statement of Work defines five major breadboard system tasks in its Work Breakdown Structure. Hamilton Standard, in preparing the Program Operating Plan (POP), expanded this list to a total of nine tasks. A comparison of both lists is shown in Table 3. The detailed presentation of this section is divided into subsections defined by the expanded Hamilton Standard list. The use of the expanded list is consistent with and allows cross referencing with all progress reports and other documents published during the program. All tasks are presented in the following subsections in their numerical order except the last two tasks, which are not specifically presented.

The Computer Program Update task (WBS 8.0) was deleted by contract modification prior to initiating the task. This task would have been, at best, a duplication of an independent NASA effort to develop a math model of the HS-C performance parameters and operation.

The final task, Management and Reporting (WBS 9.0), corresponds to the NASA WBS 5.0 task, Interim Report. Since this document is the Interim Report, there is no need to specifically describe its activity.

TABLE 3
WORK BREAKDOWN STRUCTURE

NASA Nomenclature No.	NASA Nomenclature Task	HS Nomenclature No.	HS Nomenclature Task
1.0	Breadboard System Analysis	1.0	Breadboard System Analysis
2.0	Breadboard Design	2.0	Breadboard System Design
3.0	Breadboard Fabrication	3.0	HS-C Material Fabrication
		4.0	Breadboard System Fab.
4.0	Breadboard Test	5.0	Facilities Modification
		6.0	Test Setup
		7.0	Breadboard System Test
		8.0	Computer Program Update
5.0	Interim Report	9.0	Management and Reporting

BREADBOARD SYSTEM ANALYSIS

The objective of this task was to conduct a system analysis and module test program based upon the requirements contained in the Statement of Work, section 3.2.1 and identified as WBS 1.0. The analysis was used to verify and recommend changes to the existing system requirements and to determine system performance, reliability requirements, and any specific detail constraints.

An analysis was performed for each of the following system configurations:

- A ten-man system (nominal metabolic rates) which satisfies the fail operational, fail-safe requirements.

- A four-man system (maximum metabolic rates) which satisfies the fail operational, fail-safe requirement.

- After the two analyses were completed, a parametric capability analysis was conducted. The performance of the ten-man system was determined using the maximum metabolic rates of the four-man system. Then, the performance of the four-man system was determined using the nominal metabolic rates pertaining to the ten-man system.

During the conduct of the system analyses, all Shuttle mission phases were considered, including off-design conditions such as (a) high and low moisture loads coupled with low and high CO_2 loads, (b) hot and cold cabin conditions with varying metabolic loads, and (c) varying process gas flow rates for nominal metabolic loads.

In addition, the analysis included integration of operating parameters for this program with RSECS (Contract NAS 9-13307).

The module test program consisted of the design and fabrication of a test module and the test evaluation of cycle time adsorption control. The results of this program were used to finalize the design of the full size HS-C breadboard system.

Program Modifications

Subsequent to the completion of the analysis task, certain contract Statement of Work modifications impacted the assumptions and conclusions of the task. These modifications did not impact the breadboard system. They impacted the projected flight system and the RSECS integration. As such, no updating of the analysis effort has occurred per the direction of the cognizant NASA Technical Monitor.

The major changes that should be remembered when reviewing this section are as follows:

- The fail operational-fail safe requirement has been relaxed to a fail-safe requirement only. This has a great impact on the flight schematic and system weight by no longer needing three half size canisters for redundancy. One full size canister greatly reduces the number of components, especially canisters and vacuum valves.
- The breadboard system is no longer a deliverable item and will not be tested as part of RSECS. The RSECS integration considerations presented in the analysis report are no longer applicable to the breadboard system.

Analysis Report

A comprehensive analysis report was submitted as the third progress report of this program. This report was prepared per NASA format and was considered an acceptable Interim Report covering the extensive and complex Breadboard System Analysis Task (WBS 1.0). This document was identified by the Hamilton Standard No. ECS-730024-L-006 and titled "Third Progress Report." This report identified a flight system concept, the breadboard system design requirements, and a unique design approach for the HS-C canister using a Duocel foamed aluminum material as the chemical matrix and heat exchanger core.

The unique canister design was proven out by a small-scale module test program which is presented in the following section. This test program further refined the design requirements and sizing for the breadboard system. The updating of the Analysis Report, ECS-730024-L-006, per the results of the module test program are presented in the following sections of this report.

Module Testing

A module test program was initiated to evaluate the feasibility of using Duocel foam as a chemical matrix material, to expand the data base, and to investigate the effect of cycle time and airflow on performance.

The primary result of the module program was to justify a reduction in the HS-C canister size. The water removal performance of the HS-C in the Duocell matrix was better than the previous design, allowing a reduction in the canister size to the point controlled by CO_2 loading rather than H_2O loading.

A test module was designed, and the drawing is given as Figure 11 of this report. The critical feature of this design was the use of Duocel foam, brazed to both sides of a conventional parting sheet. Use of this foam provided the development base for use in the breadboard system. The brazed joint with the parting sheet provided the heat transfer path for isothermal design.

The Duocel foam block was 6.35 cm (2 1/2 inches) wide by 7.62 cm (3 inches) in the flow direction of 2.54 cm (1 inch) high in the heat transfer direction. The 2.54 cm (1 inch) dimension was representative of the heat transfer of 1/2 the proposed air passage height, thereby providing a working model of the Analytical Design, which used 3.08 cm (2 inch) blocks in alternating absorb/desorb layers. The 7.62 cm (3 inch) flow length duplicated the Analytical Design, with the module having provisions for desorption from both sides of the 7.62 cm (3 inch) width.

The Duocel block width of 6.35 cm (2 1/2 inches) was the result of stock availability. This size held approximately 42 gm (0.1 lb) of HS-C in each bed. The air flow was proportioned to the design criteria of 11.78 x 10^{-3} m^3/sec/kg HS-C (2.5 cfm/lbm HS-C).

The test setup, illustrated in Figure 12, utilized Rig 88 to condition the process airflow. The air temperature out of the rig was maintained at 26.7°C (80°F), 16.1°C (61°F) dew point and 0.67 kN/m^2 (5 mmHg) CO_2 partial pressure. These conditions remained constant throughout the test program.

A bleed from the rig outlet fed the module at a constant rate. The module was fitted with bed selector valves on the inlet and outlet of each bed. The valves on each bed operated together, either open or closed, providing automatic switching from adsorb to desorb mode. While one bed was adsorbing (flow path), the other was exposed to vacuum from both ends of the bed.

The vacuum was supplied by Rig 52 which had parallel four inch connections controlled by vacuum gate valves. This provided the ability to bypass the test cold traps during stabilization, then place the traps on line for a measured time by closing off the bypass. The traps were isolated by two inch ball valves.

Two traps were used in series. The first, chilled by dry ice in freon, was used to collect water from the desorbing beds and is shown in Figure 13. The second trap, chilled by liquid nitrogen, was used to trap the carbon dioxide. Water measurement was attempted by weighing the collected water in the liquid state. Carbon dioxide determination was attempted by monitoring the pressure rise within the cold trap as it was warmed. The content of the expanded gases was to be verified using a gas analysis technique.

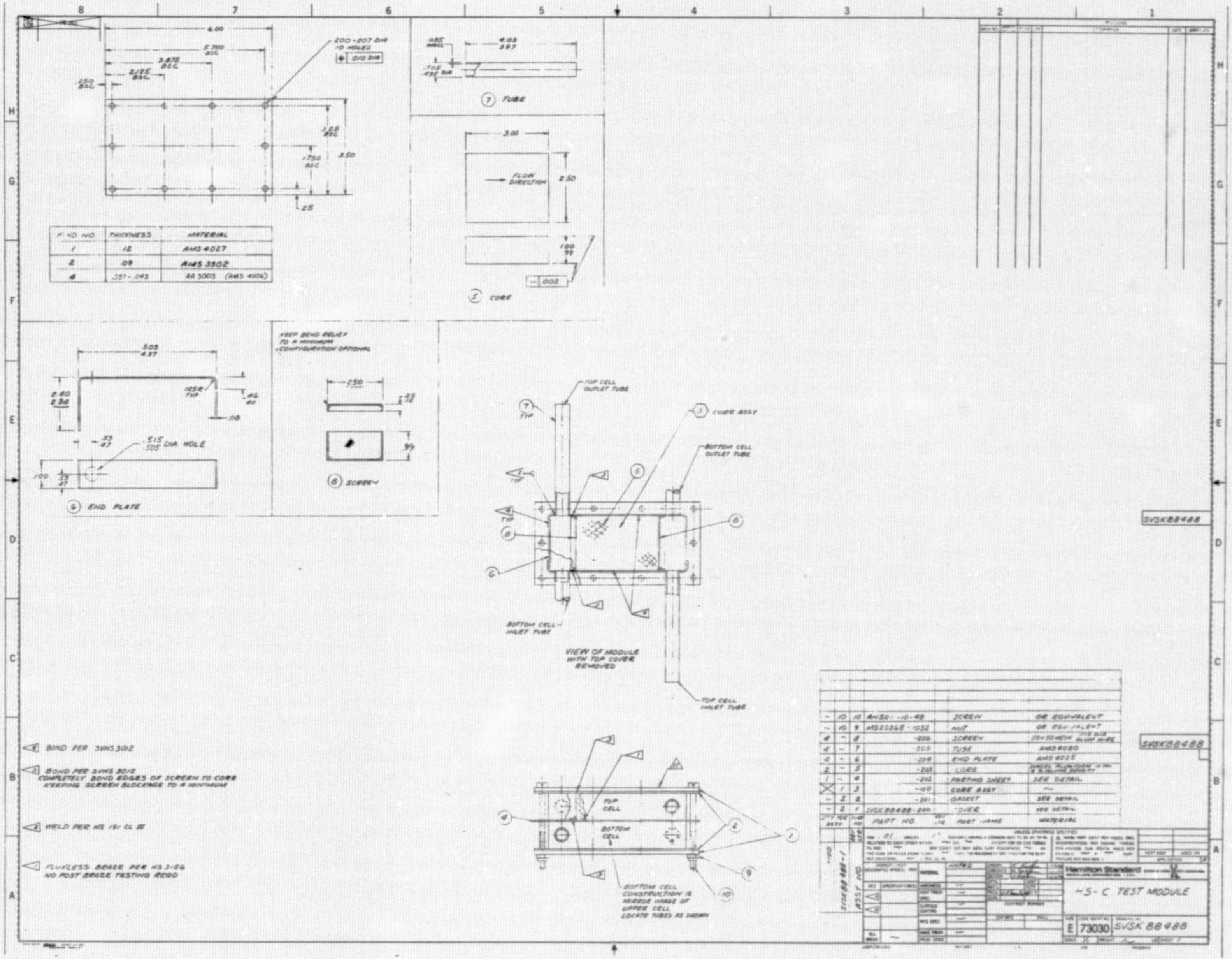


FIGURE 11 HS-C TEST MODULE

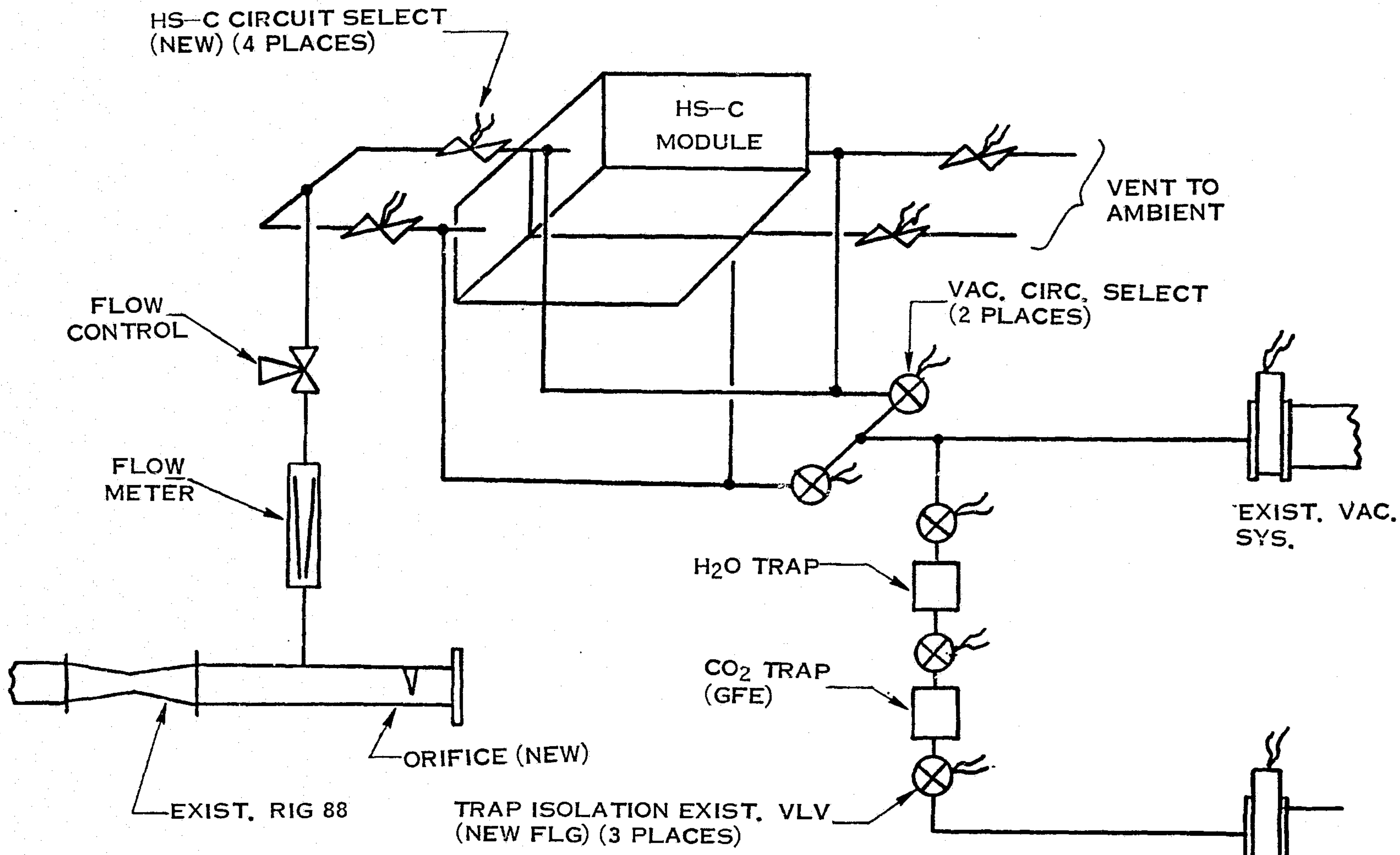


FIGURE 12 HS–C MODULE SCHEMATIC TEST SET UP

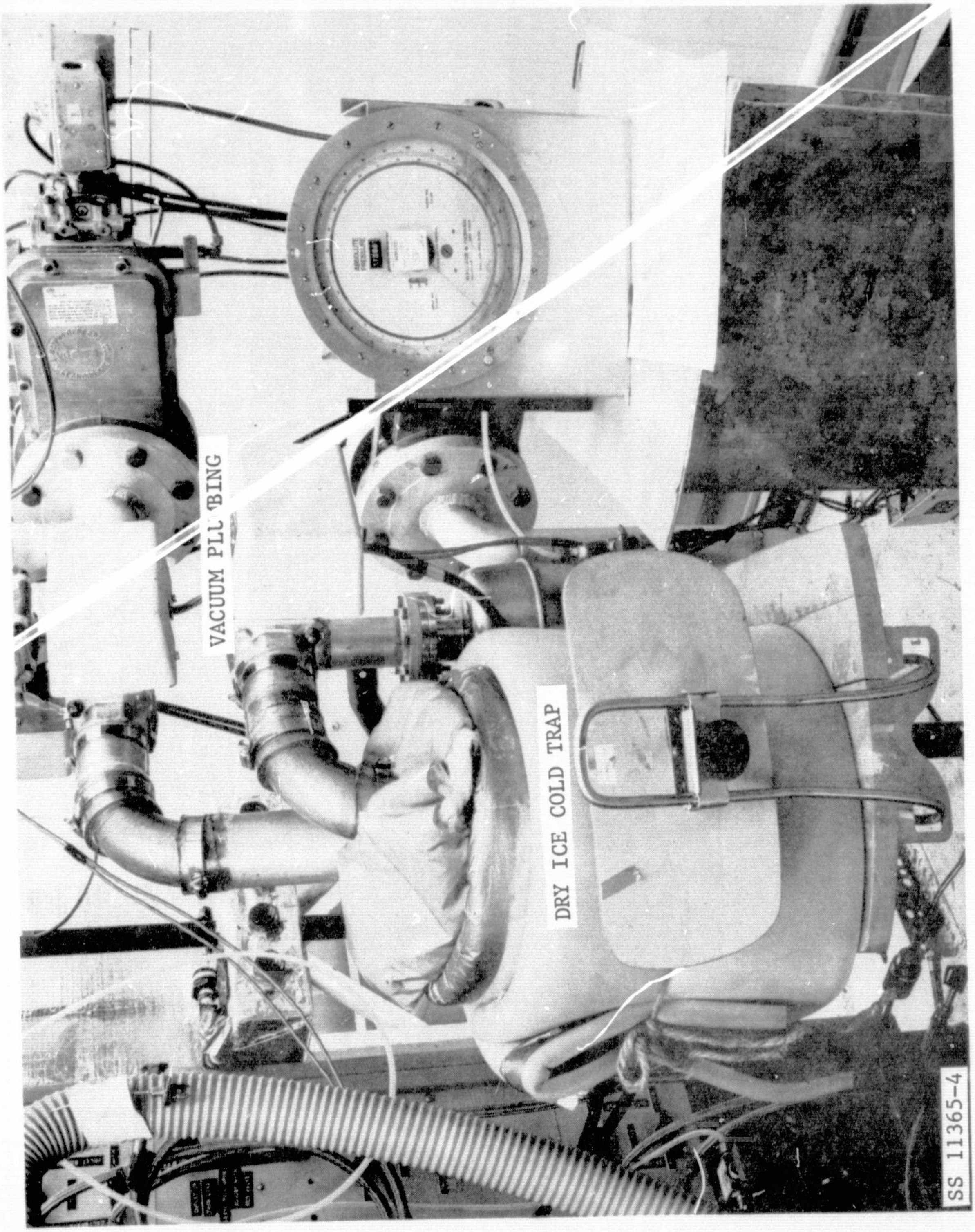


FIGURE 13 COLD TRAP SETUP

Several setup changes were required during the course of testing. The initial test setup is shown in Figure 14. The solenoid valves at the module inlet were replaced by a three-way motor driven barrel valve, since the solenoids were adding an estimated 16.7°C (30°F) to the air stream temperature. These solenoid valves then were incorporated into the vacuum system to preclude airstream bypass around the adsorbing bed. To minimize pressure drop, the vacuum plumbing was increased from 12.7 mm (1/2 inch) to 25.4 mm (1 inch) lines; and the solenoid valves, having a 9.5 mm (3/8 inch) seat and an 'S' shaped flow path, were replaced with 25.4 mm (1 inch) ball valves.

Instrumentation of the setup was increased to provide closer control of conditions. Thermocouples and vacuum pressure transducers were added at the module inlet, rather than depend on the temperature at Rig 88 and the vacuum level in the cold traps. A Lira CO_2 analyzer and Cambridge Hygrometer were connected to the module outlet to provide corroboration of module performance.

Some delays were caused by temporary breakdown of the humidity control within Rig 88 and by valve sequencing. The latter allowed full surge flow from air supply to vacuum during changeover, which was corrected. However, bed channeling was encountered resulting in poor performance. The bed was reloaded with HS-C, under NASA observation, and returned to test. The module was installed such that gravity assists in avoiding channeling, Figure 15.

With the setup done, three separate attempts were made to collect the desorbing gas and establish correlation with performance predictions. These runs were made at a thirty minute duty cycle, 10.6°C (51°F) dew points and a flow of 1.08 $mm^3/s/kg$ HS-C (2.3 scfm/lb HS-C), duplicating the design datum in the third progress report (ECS-730024-L-006).

None of these runs was successful in collecting the predicted amounts of CO_2 or H_2O, even though use of another technique provided quite close correlation. It was reasoned that the thermal mass of the setup, Figure 16, and specific design of the traps, notable surface area, were allowing gases to pass through the vacuum system. All readings obtained were below predictions. Accordingly, it was recommended that the alternative measurement system be used.

Thereafter, the use of inlet and outlet readings for CO_2 and H_2O on the adsorbing (air flow) side of the bed were the same as those described by the Test Plan, ECS-730024-L-010, for monitoring inlet conditions. Inlet and outlet data were recorded at regular intervals over the adsorb cycle phase for a total of three continuous hours.

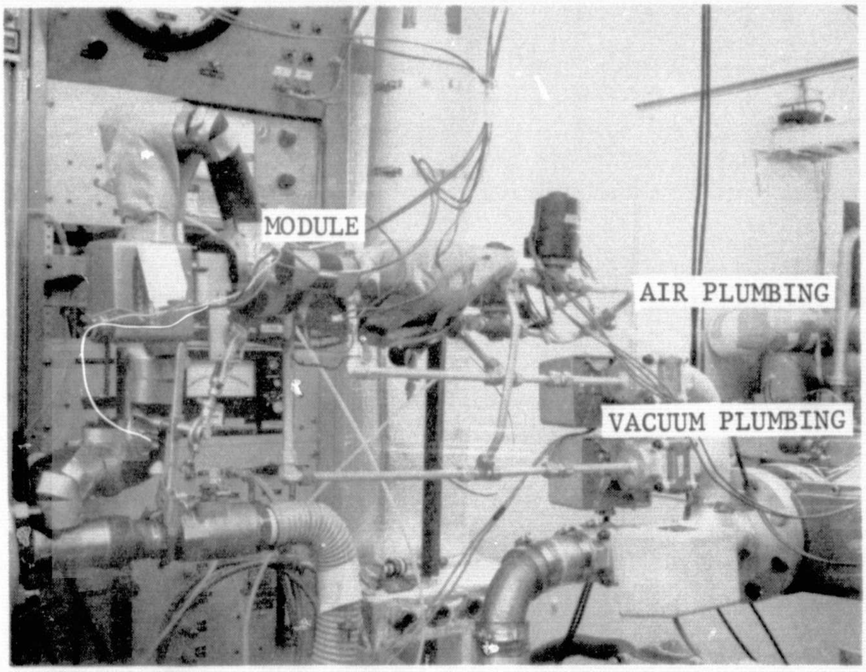


FIGURE 14 INITIAL MODULE SETUP

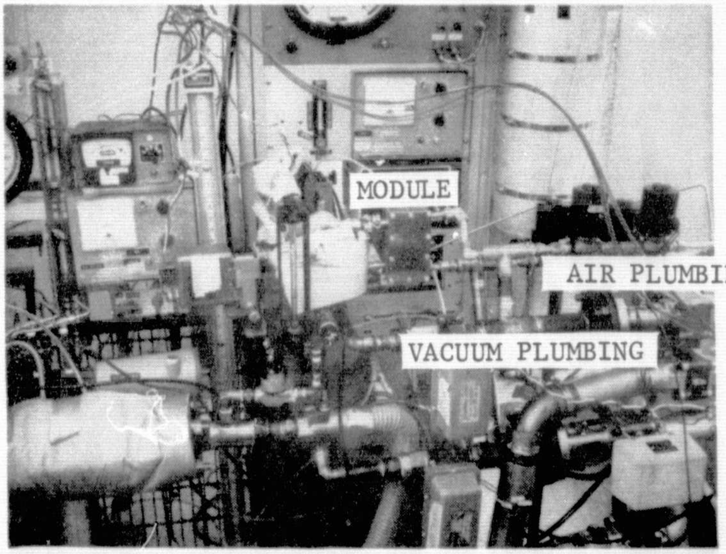


FIGURE 15 FINAL MODULE SETUP

The integration technique used was to average the readings for each adsorb cycle over the three hour period to obtain an average reading for each of the data recording points, each minute or two. These average reading values were then converted to pressure, using a calibration curve for the Lira and steam cables for the Hygrometer readings. The pressure values were then averaged to obtain the average pressure for the cycle.

Two separate runs were made to establish a correlation to the performance prediction base, both before and after rework of the vacuum system. The data from these runs is shown in Table 4.

Table 4
Correlation of Predicted and Actual Performance

Run	Performance CO_2 (mass CO_2/mass HS-C-hr)	Performance H_2O (mass H_2O/mass HS-C-hr)	Date
Prediction*	.035	.057	--
Correlation 1	.025	.048	4/17/74
Vac. Sys. Rewk.	--	--	4/20/74
Correlation 2	.032	.052**	4/21/74

*Reference ECS-730024-L-006 (Progress Report No. 3), Figure 7
**Uncorrected, air temperature 31.1°C (88°F) average

The accuracy of this technique is enhanced by the use of averaged values, minimizing the effect of instrument reading idiosyncrasies. The flow into the module was steady, recovering within fractions of a second during adsorb/desorb changeover. The inlet dew point was very stable, and inlet CO_2 reading varied $\pm$ 1.0% max at a nominal level of approximately 37% units.

The calibration curves of the Liras were established at four CO_2 concentrations, 0, 1/2, 1, and 2% using certified calibration gases. Since the gas sample is drawn from the flow streams using a vacuum pump, calibration of the Lira Analyzers is done at a regulated pressure of 89.63 kN/m^2 (13 psia). The zero and 100% points were verified before each run, using the appropriate calibration gases, dry nitrogen and 2% CO_2 respectively.

During a review of the inlet/outlet data acquisition, NASA requested the use of real time data recording for purposes of retrieval, should that be required. Accordingly, an eight channel Sanborn recorder was incorporated into the system, providing a continuous data trace. This was operated in parallel with the existing multipoint recorder during data recording times. Should gage readings be erroneous, these records will provide a means of retrieving data otherwise lost. Signal filter circuits were required to minimize noise to signal ratios but had minimal response affect, since the delay of CO_2 and dew point readings is primarily due to the sample flow rates to the measuring instruments. Unfiltered solenoid signals were used to identify which bed was receiving air flow (valve actuated) during data recording. The signal noise levels of these valves are sufficiently different so that, once identified, the flow circuit is readily recognized from the trace.

Module testing was then conducted utilizing 12 complete test runs. The data and results of these tests are summarized in Table 5. This data has been plotted in Figure 16 to show a comparison of the performance parameters. Appendix A shows the correlation between efficiency and performance as shown in Table 5.

The data point at 6.5×10^{-3} m^3/min (0.23 cfm) and a 20 minute cycle was repeated to verify the data at that point. The water point appeared to be better and was used. However, the data for CO_2 appeared anomalous and was disregarded. The curve for a 20 minute cycle for CO_2 was faired between the 15 and 30 minute points, proportional to that at 9.3×10^{-3} m^3/min (0.33 cfm). The original data at this condition was discarded.

As a check on repeatability, two other runs were repeated at 9.3×10^{-3} m^3/min (0.33 cfm) at cycles of 15 and 20 minutes. These points showed close agreement with previous water data. The CO_2 data, however, showed an appreciable variation of approximately 15%.

An examination of the CO_2 data as a group shows that either set of 15 and 20 minute points, original or rerun data, appear anomalous in the group. However, with the curve faired between the mean of these points, the data again appears orderly. Since no basis was established to discredit either set of data, the difference between the points was taken as data scatter.

Again referring to Figure 16, the water point at 6.5×10^{-3} m^3/min (0.23 cfm) and a 30 minute cycle appears anomalous. However, close examination of the data at this flow shows that adsorption 'breakthrough', that point where adsorption falls off rapidly, occurs just after the 20 minutes of the 30 minute cycle. Since this implies that none of the shorter cycles can saturate the HS-C bed at that flow, those data points should cluster, as shown, and that the 30 minute datum should be lower.

Repeated water data at 15 and 20 minute cycles and 9.3×10^{-3} m^3/min (0.33 cfm) do not exhibit the same spread as the CO_2 data. The water performance curves were faired between the points.

TABLE 5A

TEST DATA SUMMARY SHEET
S.I. UNITS

TEST DATE	DUTY CYCLE MIN/MIN.	AIR FLOW M^3/S	H_2O PRESSURE (KPA) IN	H_2O PRESSURE (KPA) OUT	H_2O PRESSURE (KPA) Δ	EFF Δ/P_{IN}	PERFORMANCE KG H_2O/HR / KG HS-C	CO_2 PRESSURE (PA) IN	CO_2 PRESSURE (PA) OUT	CO_2 PRESSURE (PA) Δ	EFF Δ/P_{IN}	PERFORMANCE KG CO_2/HR / KG HS-C
4/26	10/10	1.09×10^{-4}	1.831	0.174	1.657	0.336	0.1049	666.5	329.5	337.0	0.506	0.199
4/27	15/15	1.09×10^{-4}	1.831	0.207	1.624	0.349	0.1029	666.5	346.0	320.5	0.481	0.189
4/29	20/20	1.09×10^{-4}	1.767	0.374	1.393	0.310	0.0914	666.5	324.5	342.0	0.513	0.202
5/2	30/30	1.09×10^{-4}	1.831	0.341	1.490	0.320	0.0942	666.5	426.4	240.1	0.360	0.142
5/3	10/10	1.56×10^{-4}	1.831	0.169	1.662	0.357	0.1510	666.5	409.2	257.3	0.386	0.152
5/6	15/15	1.56×10^{-4}	1.842	0.223	1.619	0.346	0.1463	666.5	413.6	252.9	0.379	0.149
5/4	20/20	1.56×10^{-4}	1.831	0.306	1.525	0.830	0.1387	666.5	435.2	231.3	0.347	0.137
5/5	30/30	1.56×10^{-4}	1.780	0.563	1.217	0.269	0.1137	677.2	485.2	192.0	0.288	0.113
5/7	10/10	1.96×10^{-4}	1.831	0.256	1.575	0.339	0.1801	666.5	417.9	248.6	0.373	0.147
5/10	20/20	1.09×10^{-4}	1.837	0.181	1.656	0.355	0.1046	666.5	525.2	141.3	0.212	0.083
5/15	15/15	1.56×10^{-4}	1.831	0.183	1.648	0.354	0.1498	666.5	451.9	214.6	0.322	0.128
5/16	20/20	1.56×10^{-4}	1.831	0.336	1.495	0.321	0.1359	666.5	468.1	198.4	0.298	0.117

NORMALIZED CONDITIONS:

AIR TEMPERATURE	26.7°C
DEW POINT	16.1°C
CO_2 PRESSURE	0.667 KPa

* PERFORMANCE IS CALCULATED FROM EFFICIENCY PER APPENDIX A

TABLE 5B

TEST DATA SUMMARY SHEET
U.S. UNITS

TEST DATE	DUTY CYCLE MIN/MIN	AIR FLOW FT^3/MIN	H_2O PRESSURE (PSIA) IN	OUT	Δ	EFF Δ/P_{IN}	PERFORMANCE LB H_2O/HR / LB HS-C	CO_2 PRESSURE (MMHG) IN	OUT	Δ	EFF Δ/P_{IN}	PERFORMANCE LB CO_2/HR / LB HS-C
4/26	10/10	0.23	0.2655	0.0253	0.2425	0.904	0.1049	5.00	2.472	2.26	0.506	0.0507
4/27	15/15	0.23	0.2655	0.0300	0.2355	0.887	0.1029	5.00	2.596	2.404	0.481	0.0482
4/29	20/20	0.23	0.2563	0.0542	0.2021	0.788	0.0914	5.00	2.434	2.566	0.513	0.0513
5/2	30/30	0.23	0.2655	0.0499	0.2156	0.812	0.0942	5.00	3.199	1.801	0.360	0.0361
5/3	10/10	0.33	0.2655	0.0245	0.2410	0.907	0.1510	5.00	3.070	1.930	0.386	0.0555
5/6	15/15	0.33	0.2671	0.0324	0.2347	0.879	0.1463	5.00	3.103	1.897	0.379	0.0545
5/4	20/20	0.33	0.2655	0.0444	0.2211	0.833	0.1387	5.00	3.265	1.735	0.347	0.0499
5/5	30/30	0.33	0.2581	0.0817	0.1764	0.683	0.1137	5.08	3.640	1.440	0.288	0.414
5/7	10/10	0.415	0.2655	0.0372	0.2283	0.860	0.1801	5.00	3.135	1.865	0.373	0.675
5/10	20/20	0.23	0.2664	0.0262	0.2402	0.901	0.1046	5.00	3.940	1.060	0.212	0.0144
5/15	15/15	0.33	0.2655	0.0266	0.2389	0.900	0.1498	5.00	3.390	1.610	0.322	0.0463
5/16	20/20	0.33	0.2655	0.0488	0.2167	0.816	0.1359	5.00	3.512	1.488	0.298	0.0429

NORMALIZED CONDITIONS:

AIR TEMPERATURE	26.7°C (80°F)	
DEW POINT	16.1°C (51°F)	
CO_2 PRESSURE	0.667 KPa	(5 MM HG)

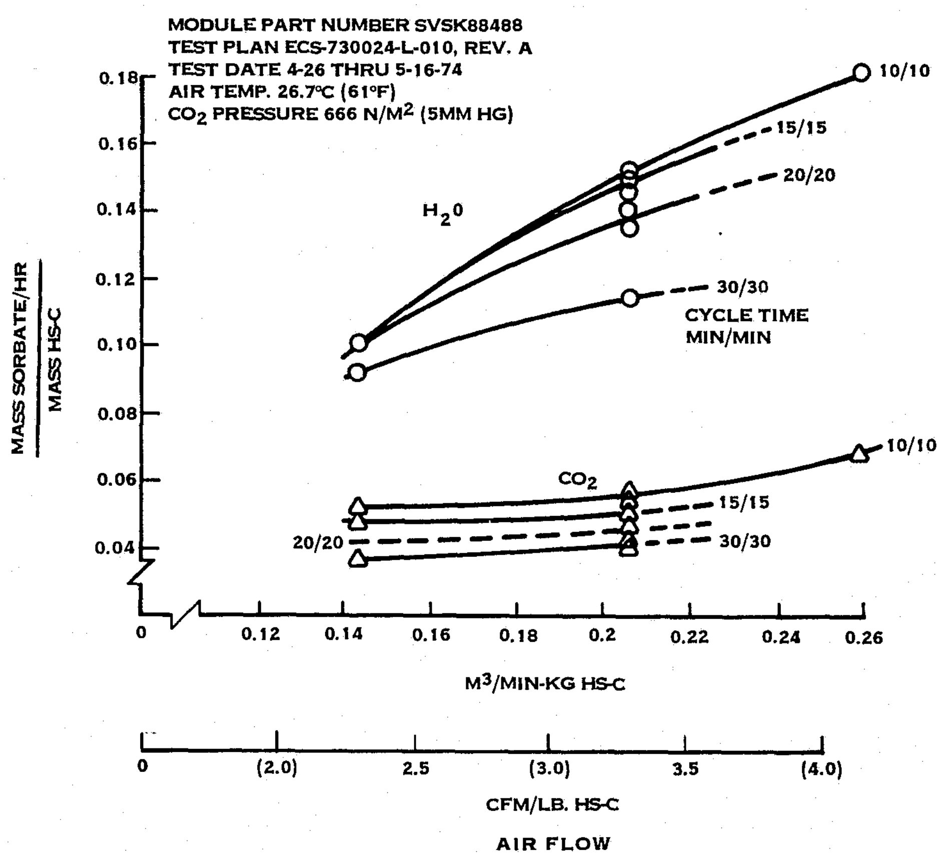


FIGURE 16 MODULE PERFORMANCE

The purpose of the module testing was to verify that cycle time could be used to regulate the adsorption of H_2O and CO_2 as proposed in the 29 November 1973 Preliminary Design Review (PDR). The test data obtained demonstrate that cycle time indeed can be used effectively to increase performance when required by increased metabolic loading.

Impact of Module Testing on Canister Design

The module test data were examined to determine what, if any, impact they had on the canister design (reference Progress Report 3, Table VI), which had been based on previous HS-C data. To accomplish this, the module data were replotted against the mass of HS-C required to meet performance requirements at the ten-man load condition.

This condition requires a removal rate of 1.04 kg/hr (2.3 lb/hr) H_2O and 0.52 kg/hr (0.879 lb/hr) CO_2. By dividing these values by the empirical removal rates at data points, on line HS-C bed weights can be determined and plotted for various cycle rates and air stream flows. These data are tabulated in Table 6 and so plotted on Figure 17. The analytical canister design for this condition, 7.35 kg (16.2 lb) HS-C at a duty cycle of 13.5 minutes, is plotted for reference.

This plot, with the exception of the two repeated data points at 9.3×10^{-3} m^3/min (0.33 cfm), indicated that the analytical bed design was adequate. The design basis, however, shifted from water limited to carbon dioxide limited.

Design Allowance for Performance Degradation

An allowance for performance degradation was defined which is based upon ammonia offgassing tests, previously reported under Contract NAS 9-12957. Using the ammonia data curve of SVHSER 6185, Figure 9 for that program, degradation to zero performance occurs in about 40,000 hours at 80°F.

To account for potential degradation, the bed size was increased by a factor of 10%. This gives an estimated margin of 4,000 hours or approximately twenty-four, seven-day missions. This margin definition assumes that ten man loading at an 26.7°C (80°F) condition prevails throughout. Reduced loading at lower temperatures would extend this margin.

TABLE 6
HS-C BED QUANTITY AS REQUIRED BY MODULE DATA

RUN		CO_2			H_2O		
CYCLE (MIN)	FLOW (REF) M^3/MIN (CFM)	CO_2 PERFORMANCE (1) (MASS CO_2/ MASS HS-C HR)	BED WEIGHT (2) KG	(LB)	H_2O PERFORMANCE (1) (MASS H_2O/ MASS HS-C HR)	BED WEIGHT (3) KG	(LB)
10	0.0065 (13.77)	0.0507	7.86	(17.33)	0.1049	9.95	(21.93)
15		0.0482	8.27	(18.24)	0.1029	10.14	(22.35)
20		—	—		—	—	
30		0.0361	11.05	(24.35)	0.0942	11.08	(24.42)
10	0.0093 (19.70)	0.0555	7.18	(15.84)	0.11510	6.91	(15.23)
15		0.0545	7.32	(16.13)	0.1463	7.13	(15.72)
20		0.0499	7.99	(17.62)	0.1387	7.52	(16.58)
30		0.0414	9.63	(21.23)	0.1137	9.18	(20.23)
20	0.0065 (13.77)	0.0065	—		0.1046	9.98	(22.0)
15	0.0093 (19.70)	0.0463	8.61	(18.98)	0.1498	6.96	(15.35)
20		0.0429	9.29	(20.49)	0.1359	7.67	(16.92)

(1) Performance data from Table 5

(2) Bed Weight required for CO_2 control = $\frac{.52 \text{ kg/hr}}{CO_2 \text{ Performance}}$

(3) Bed weight required for H_2O control = $\frac{1.04 \text{ kg/hr}}{H_2O \text{ Performance}}$

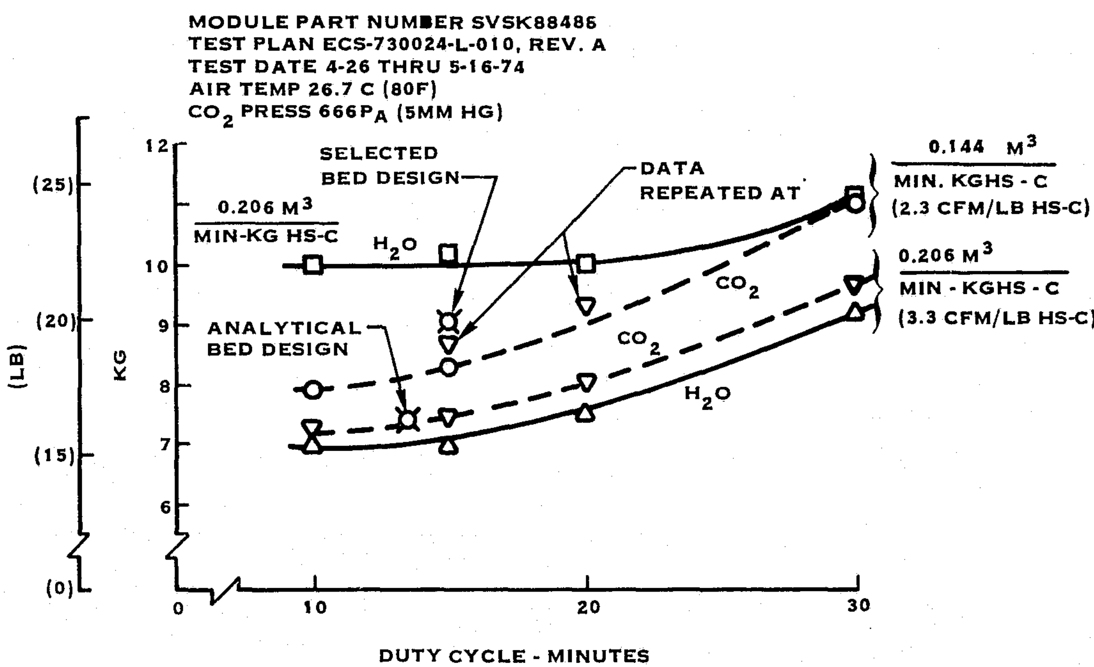


FIGURE 17. EFFECT OF CYCLE TIME AND FLOW RATE ON BED WEIGHT (10 MAN CONDITION)

System Design Analysis

Review of the data indicates the HS-C system should be sized on the basis of the last data points recorded. These data points represent the lowest performance recorded and, thus, result in a conservatively sized canister. A design on this basis has the mechanical design requirements listed in Table 7, including the performance margin described above. Table 7 was also used as the design requirements for the breadboard canister and the breadboard system.

Sizing of this bed was performed as described in ECS-730024-L-006, Third Progress Report. Calculations for this design are included as Appendix B of this report and are based on the results of the module testing.

Resulting from experience with the module tests, the system and canister duct sizes were evaluated for flow in the vacuum (desorb) mode. The design basis used was a fifteen minute duty cycle with ten man nominal loading. In addition, flow resistance in this mode was kept equivalent to or less than that used in the HS-C model.

The results of this analysis show that the canister header diameter, 63.5 mm (2.5 inches), is adequate. In the system where exhaust ducts from each canister join, the size increases to 101.6 mm (4 inches). The common vacuum header, connecting each end of the canister (double end desorb), increases to 203.2 mm (8 inches).

The bypass valve, to provide an alternative method of performance control as agreed at the PDR, November, 1973, was sized for 1.4 m^3/min (50 cfm) as a 76 mm (3 inch) valve. The size was based on flow rate per ECS-730024-L-006, Figure 22. This flow rate, with the bed selected, provides a range of 0.014 m^3/min-kg HS-C (2.2 cfm/lb HS-C) to 0.36 m^3/min-kg HS-C (5.8 cfm/lb HS-C).

The higher range of flows are achieved by using two RSECS RS-53 fans in parallel. The complete range of flow requires adjustment of the system outlet orifice to balance system pressure drop and fan input for the required flow. This relationship is given in Figure 18. The design point orifice will allow a pressure drop of approximately 0.732 kPa (2.94 inches H_2O), the exact sizing to be determined during test setup.

TABLE 7
MECHANICAL DESIGN REQUIREMENTS

Item	Requirement
HS-C/Bed	4.76 kg (10.5 lb)
2 Bed Operating in Parallel Adsorb and Desorb HS-C/System	19.05 kg (42 lb)
Air Flow Bed Depth	7.62 cm (3 in)
Max Ullage Volume	2.5 x Bed Void Volume
Bed Pressure Drop	846.5 N/m^2 (3.4 in H_2O)
Duct and Valve Pressure Drop	124.5 N/m^2 (0.5 in H_2O)
Air Flow, System	1.98 m^3/min (70 cfm)
Air Flow, Canister	0.99 m^3/min (35 cfm)
Exhaust (to Vacuum) Duct Diameter	20.3 cm (8 in)
Throttle Orifice Pressure Drop, Nominal(1)	731.6 N/m^2 (2.94 in H_2O)
Bypass Valve Diameter	7.6 cm (3 in)
Target Leakages (External), 21.1°C (70°F), 103.4 kN/m^2 (15 psid)	
Canister	1.5 x 10^{-5} cc He/sec
Breadboard System	4.1 cc He/sec
Timer Range	0 to 165 minutes
Bed Changeover Time Target	10 sec
Bypass Design Flow(1)	1.4 m^3/min (50 cfm)

(1) Variations in orifice diameter, number of fans on line, and bypass flow shall provide a flow range of .014 m^3/min kg HS-C (2.2 cfm/lb HS-C) to 0.36 m^3/min kg HS-C (5.8 cfm/lb HS-C).

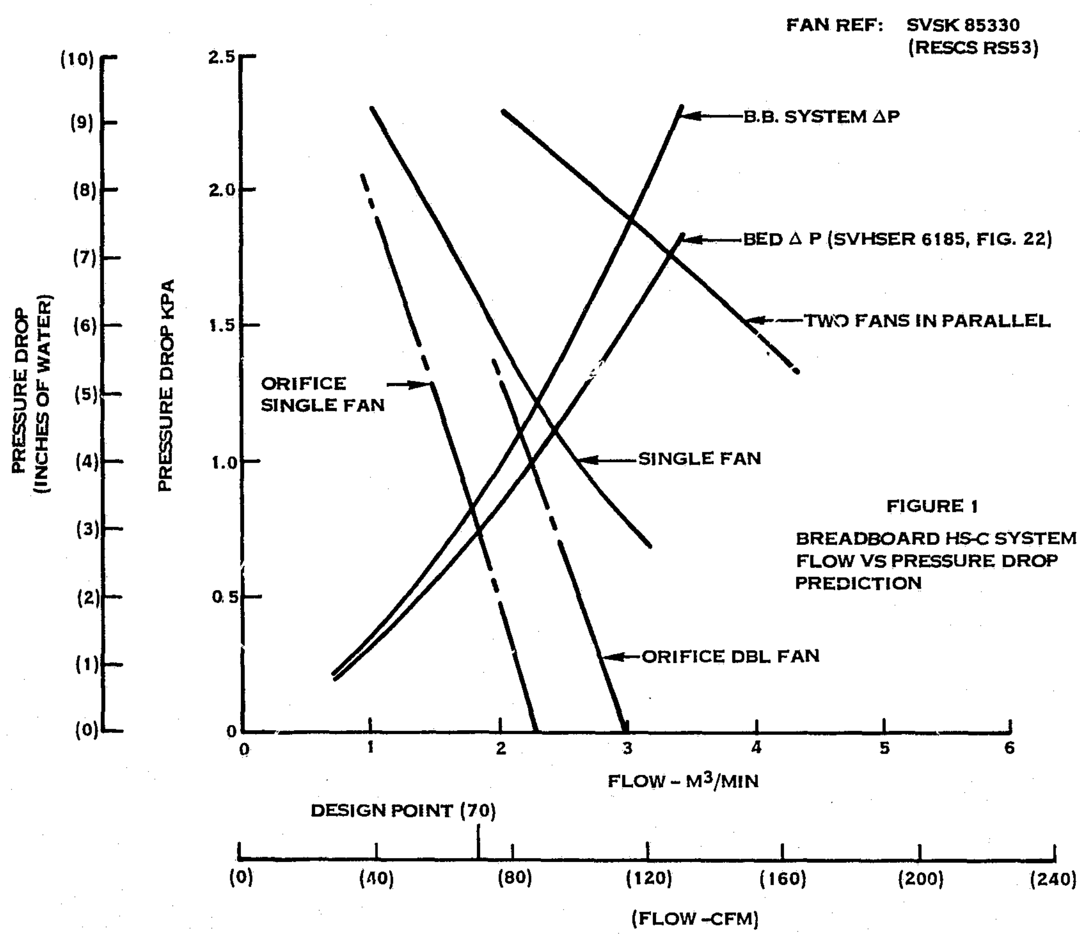


FIGURE 18 BREADBOARD SYSTEM FLOW AND PRESSURE DROP CHARACTERISTICS

During module test, changeover time was noted at approximately 30 seconds. It was recognized that during operation the changeover time would represent a performance effficiency loss. The system design criteria establishes a 10 second target for changeover, including pressure equalization. With a minimum cycle time anticipated of 10 minutes, 10 seconds represents a maximum of 1.7% performance loss per cycle. This value is a maximum, being reduced by longer cycles.

The HS-C schematic, showing all features to be packaged, is given in Figure 19. Figure 20 incorporates pressure, flow, and cycle time criteria for the conditions considered.

Cycle timing for 10 man nominal loading was established during analytical design of the canister, ECS-730024-L-019 (Ninth Progress Report). The other conditions examined include 10 man max, four man nominal, and four man max loadings. Timing for these off design conditions was achieved by conservatively assuming bed saturation in 10 minutes for CO_2 and 30 minutes for H_2O from module test data. The required performance (mass sorbate/mass HS-C, hour) was then ratioed to the demonstrated performance at these duty cycles to obtain the duty cycle prediction. All conditions so calculated were CO_2 limited. The exact timing will be determined during test.

Timer range selection was established to provide maximum flexibility. Water performance from the module tests exceeded that demonstrated on previous contracts. Therefore, performance at reduced air temperature and dew point levels is unsubstantiated by module testing due to limited scope of the tests. The timer range selected provides five times the maximum cycle prediction and is assumed adequate.

HS-C Flight System

The results of the canister and breadboard system sizing efforts were used to update the projected HS-C flight system sizing. The revised data is presented in Table 8 and defines the projected flight system weights and penalties. However, deletion of the fail operational-fail safe requirement greatly affect the conclusions of this study and render the data in Table 8 as invalid. An update of the HS-C flight concept per current Shuttle groundrules was presented in the PDR handout booket entitled "Preliminary Design Review of a Regenerable CO_2 and Humidity Control System (Extended Shuttle Application); December 18, 1975; NASA Contract NAS 9-13624."

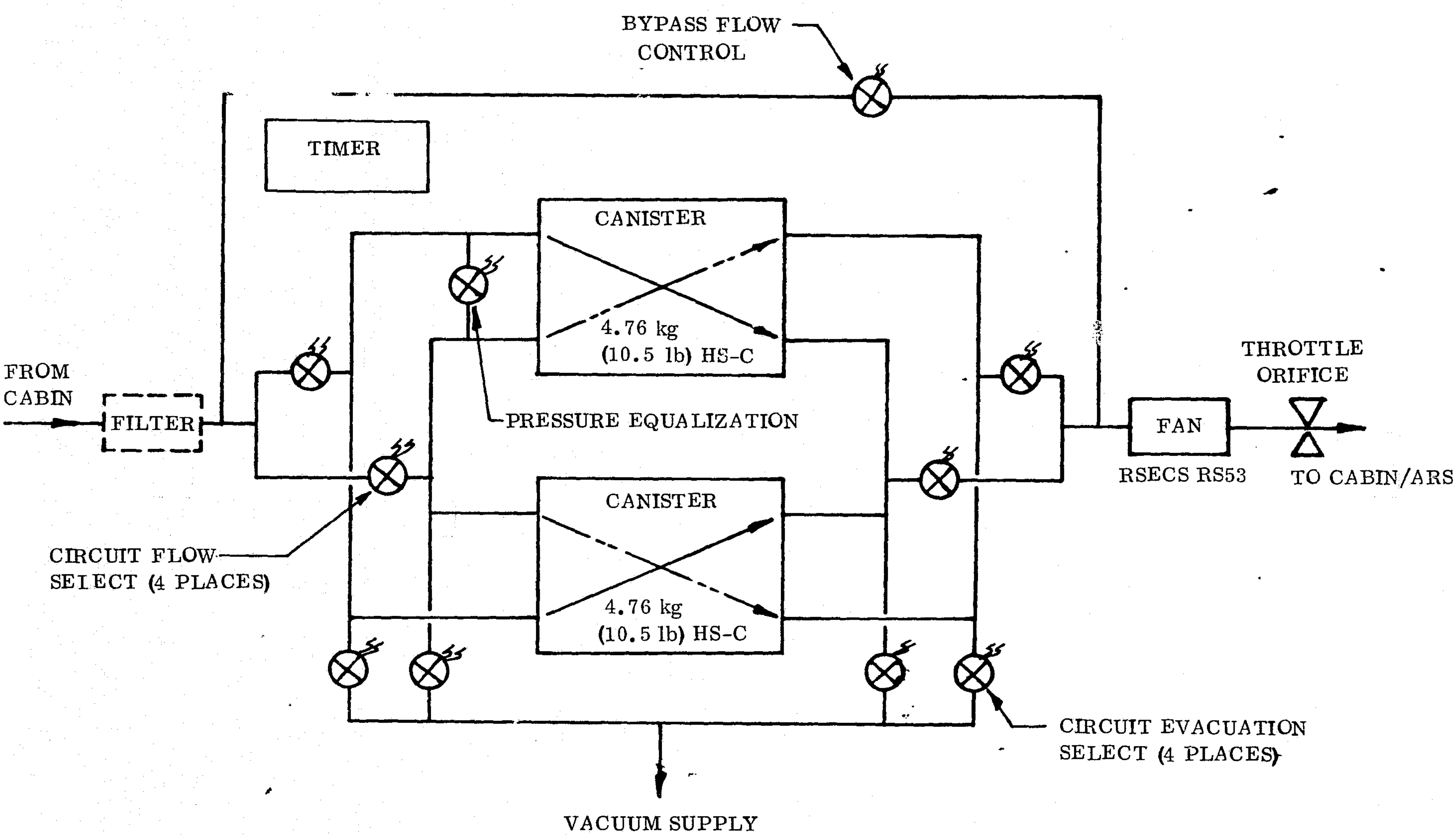


FIGURE 19 BREADBOARD SYSTEM SCHEMATIC

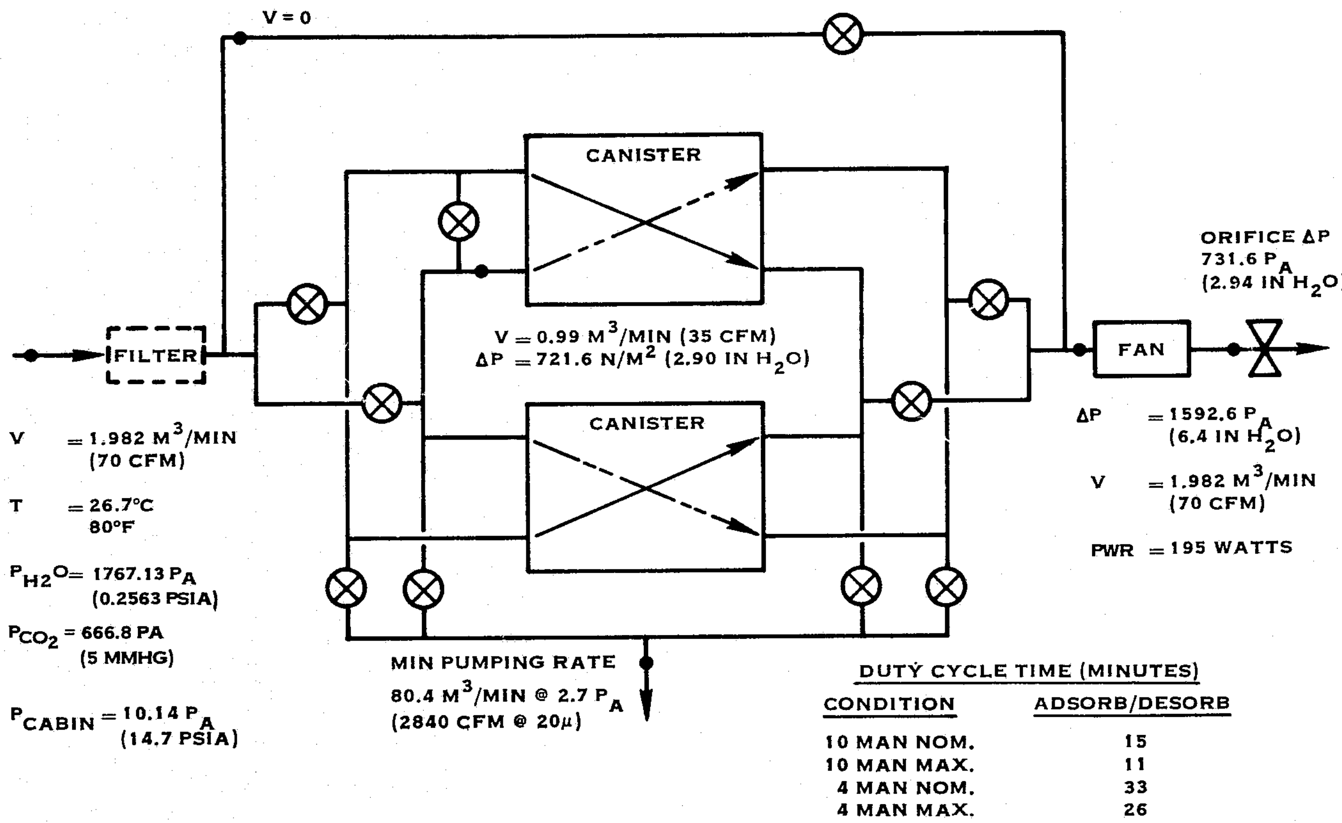


FIGURE 20 BREADBOARD SYSTEM FLOW CHART

TABLE 8 SYSTEM DEFINITION

Parameter	Design	
Control Function	CO_2	
Cycle Time (Minutes)		
10 Man	15	
4 Man	52	
Weights, Expendable		
kg/hr (lb/hr)		
Power	0.069	(0.153)
Ullage 10 Man	0.304	(0.669)
4 Man	0.088	(0.193)
Weights, Fixed		
kg (lb)		
HS-C/Bed	4.76	(10.5)
Total HS-C	28.60	(63.0)
Total System	105.40	(232.30)
Weight, Total*	140	(309)
kg (lb)		

Reference ECS-730024-L-006, Table VI (Third Progress Report).

* Per mission, assuming seven day mission at 26.7°C (80°F) cabin air, 16.1°C (61°F) dew point, and 38 hr at 10 man nominal loading and 131 hr at 4 man max loading.

RSECS Integration

A review of RSECS integration recommendations showed the removal of the LiOH canisters and plumbing the HS-C system into the RSECS ARS flow at that point. However, airstream purification and odor control, accomplished in the LiOH canisters by using charcoal in the bed, is lost by that method.

Accordingly, the HS-C system integration was redefined to be plumbed to the RSECS inlet upstream of the ARS fans. This logic provides multiple advantages. The HS-C system fans are pumping to ambient pressure (pressure drop makeup only), making the unit's performance in the RSECS the same as when operated as a separate assembly. With the LiOH canisters reinstalled, charcoal beds can be substituted for the LiOH cartridge, retaining the purification feature. Series redundant LiOH, through cartridge replacement, becomes an inherent "fail safe" feature of the RSECS/HS-C system. Finally, use of the parallel LiOH canisters provides backup design for HS-C for the departure (prelaunch and ascent burn) and return (reentry, cruise, and post landing) mission phases. A schematic block diagram of this change is given as Figure 21 of this report.

The information is important for consideration of integration of a subsequent flight prototype HS-C system but must be tempered by the fact that RSECS integration with the breadboard system was deleted as a program requirement.

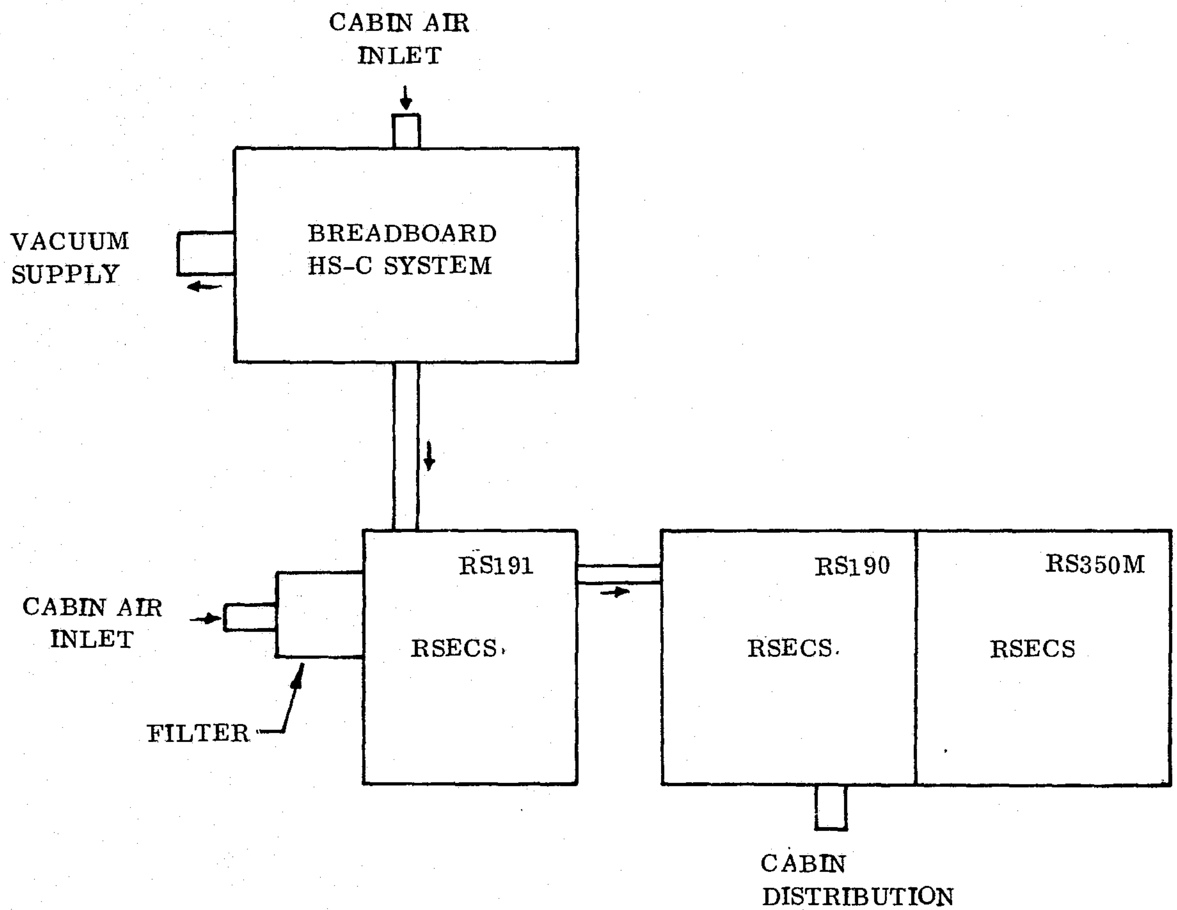


FIGURE 21 - HS-C/RSECS INTEGRATION

Reference SVSK 85312, SH 2

BREADBOARD SYSTEM DESIGN

The Breadboard System Design Task is defined in the Statement of Work by section 3.2.2 and WBS 2.0. The objective of this task was to formulate a design for the breadboard system that would accurately represent the flight system operation. Cabin volume, bed heat, process gas heat, and mass transfer were primary characteristics to be simulated to permit breadboard evaluation of the performance, control, and functional aspects of the system.

The approach to this task was to utilize the results of the breadboard systems analysis task (WBS 1.0) and the engineering data developed under Contracts NAS 9-11971 and NAS 9-12957 to design a system capable of meeting Shuttle requirements.

The design task is divided into three major areas; requirements, canister design, and system design. Each of these areas will be discussed in the following subsections.

Requirements

The breadboard system was designed to two sets of primary requirements.

The first set was a Requirements Specification document that identified Shuttle operational, metabolic, and physical requirements. This document was prepared by Hamilton Standard and approved by the NASA as part of the analysis task (WBS 1.0). This document has been included as Appendix C of this report. It should be noted that the requirements for fail operational-fail safe redundancy and RSECS integration were deleted after completion of the design task. The breadboard system design was not revised to reflect the modifications but reflects the requirements of the specification as presented in Appendix C. No revisions were made to the breadboard design because the changes in Shuttle philospphy affect only the flight design and did not affect the purpose or projected output of the breadboard system and testing.

The other major set of design requirements were generated as a result of the breadboard analysis task (WBS 1.0). These requirements include canister sizing, flow and pressure drop characteristics, plus the other requirements as presented previously in Tables 7 and 8.

Together, these two sets of requirements served as the base of the design effort and are directly reflected in the resulting breadboard system.

HS-C Canister Design

The HS-C canister was designed to a flight configuration as defined by the Hamilton Standard drawing number SVSK 87382 which is shown in a reduced form in Figure 22.

The canister concept selected is a single stack of twelve, 5.08 cm (2 inch) high and two, 2.54 cm (1 inch) high, aluminum "Duocel" foam blocks. Every other layer, or block, is headered together, providing an adsorb and desorb bed. The foam blocks are a parallelogram, having an air flow width of 7.62 cm (3 inches) as prescribed and a length of approximately 70 cm (24 inches).

Two heights of foam were used to maintain the axis of symmetry for heat transfer at the ends. One of the 2.54 cm (1 inch) high beds is headered to six of the 5.08 cm (2 inch) high beds. These thin layers are analagous to the subscale model and are located at each end of the stack.

The layers are separated by .3 mm (.012 inch) thick parting sheets. These parting sheets are supported by the extension of separate foam sections into the header area, thereby supporting the parting sheets over their entire area. This portion of the aluminum foam will not be filled with HS-C.

Retention of the HS-C material is by means of 50 mesh aluminum screen. The screen is supported on both sides by the aluminum foam, with HS-C material trapped on the inside. This design precludes buckling of the screen with resulting looseness found in test units.

Loading of the HS-C is accomplished by means of threaded plugs at the ends of the aluminum foam blocks. The plugs, or fill ports, are kept as large as practicable to facilitate loading. Plugs are located at each end to allow reloading of the canister, if required.

Provisions are incorporated into the plugs for a moderate preload of the HS-C. These foam springs allow for settling and thermal variations in the HS-C volume.

The header manifold is a round cross-section extending from the furthest bed layer to a standard 6.35 cm (2.5 inch) Marman flange. There are four such connections on each canister providing inlet, outlet, and double end desorption.

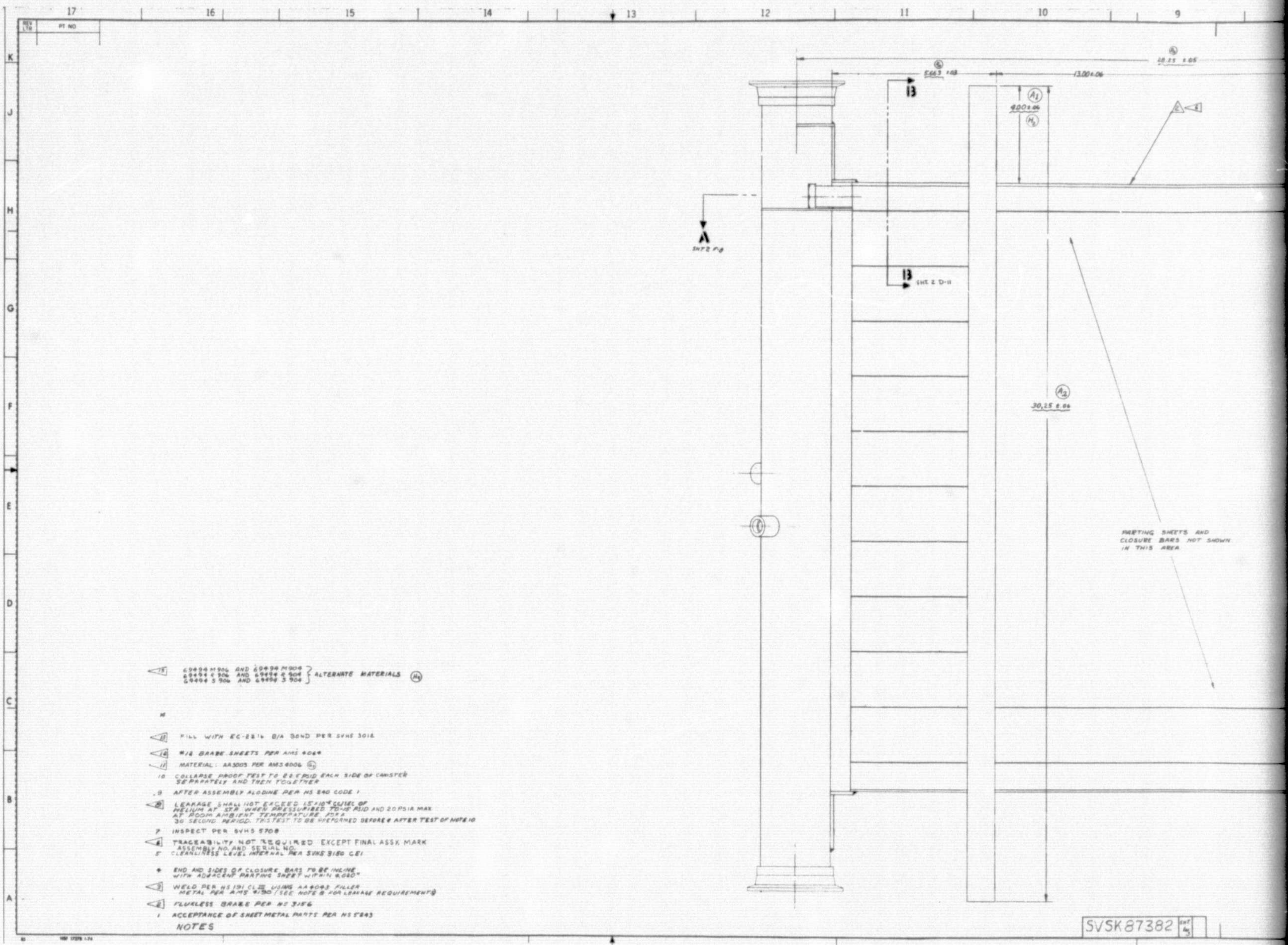
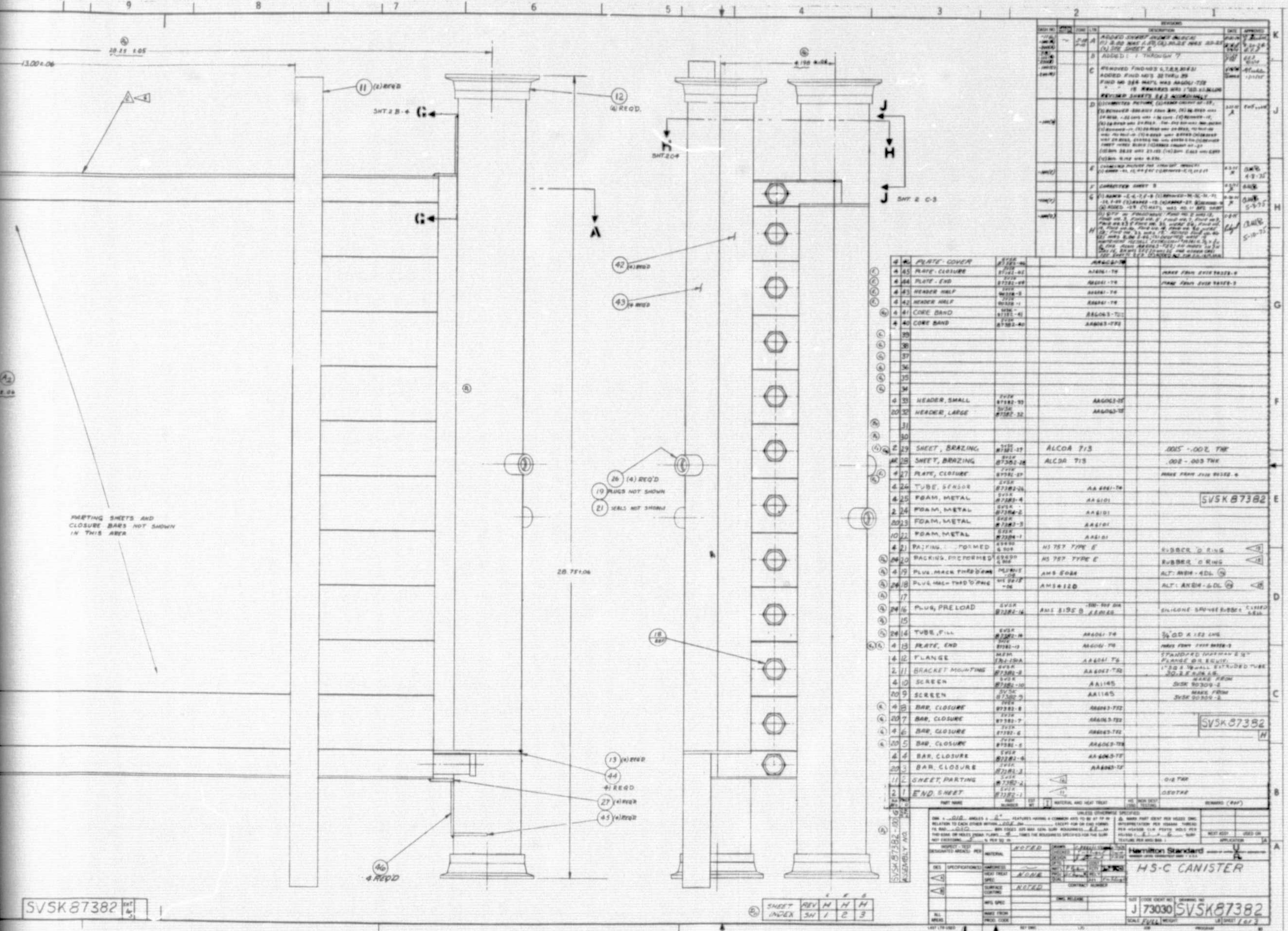


FIGURE 22 HS-C CANISTER DRAWING



CANISTER DRAWING (SHEET 1)

FOLDOUT FRAME 2

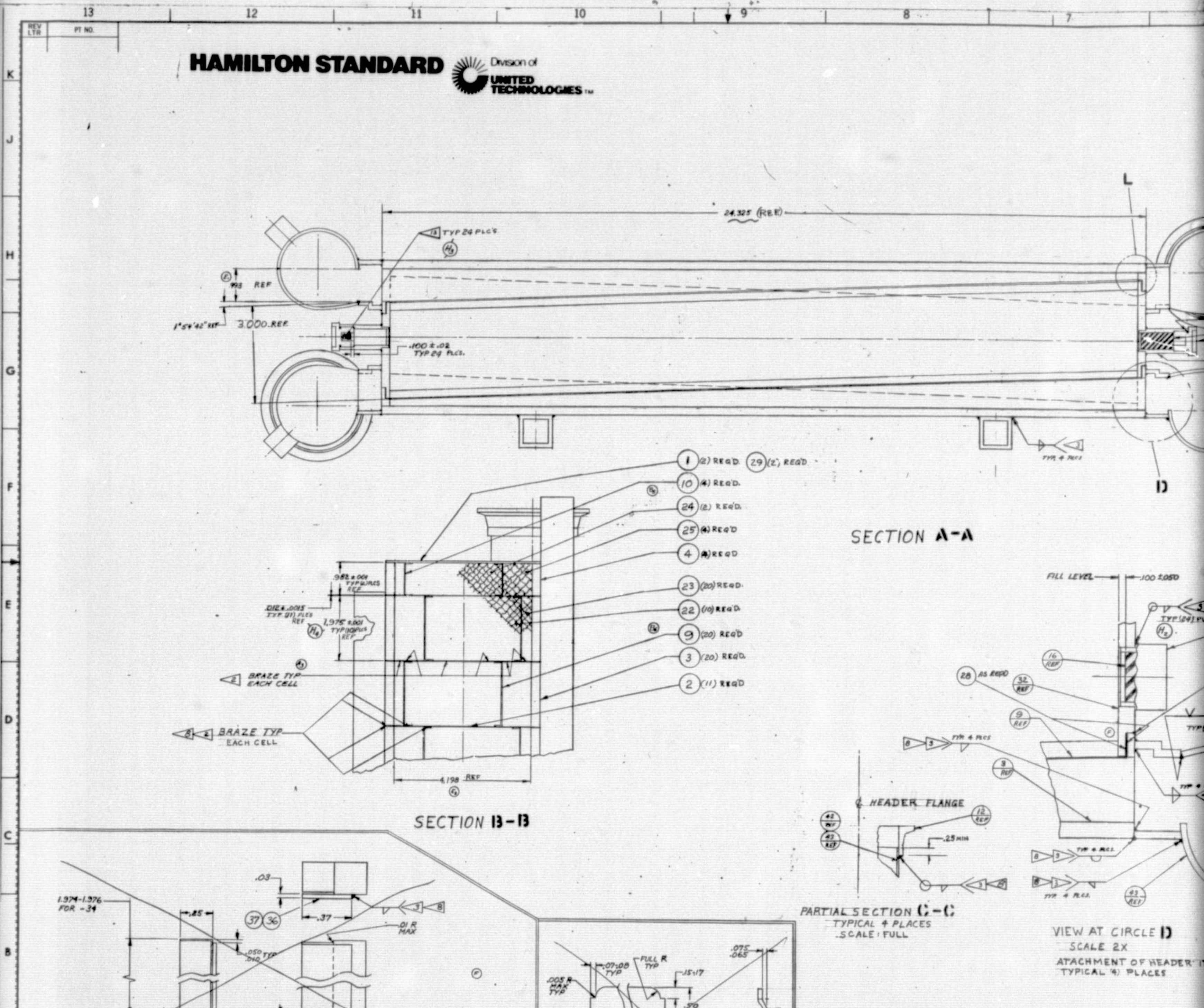
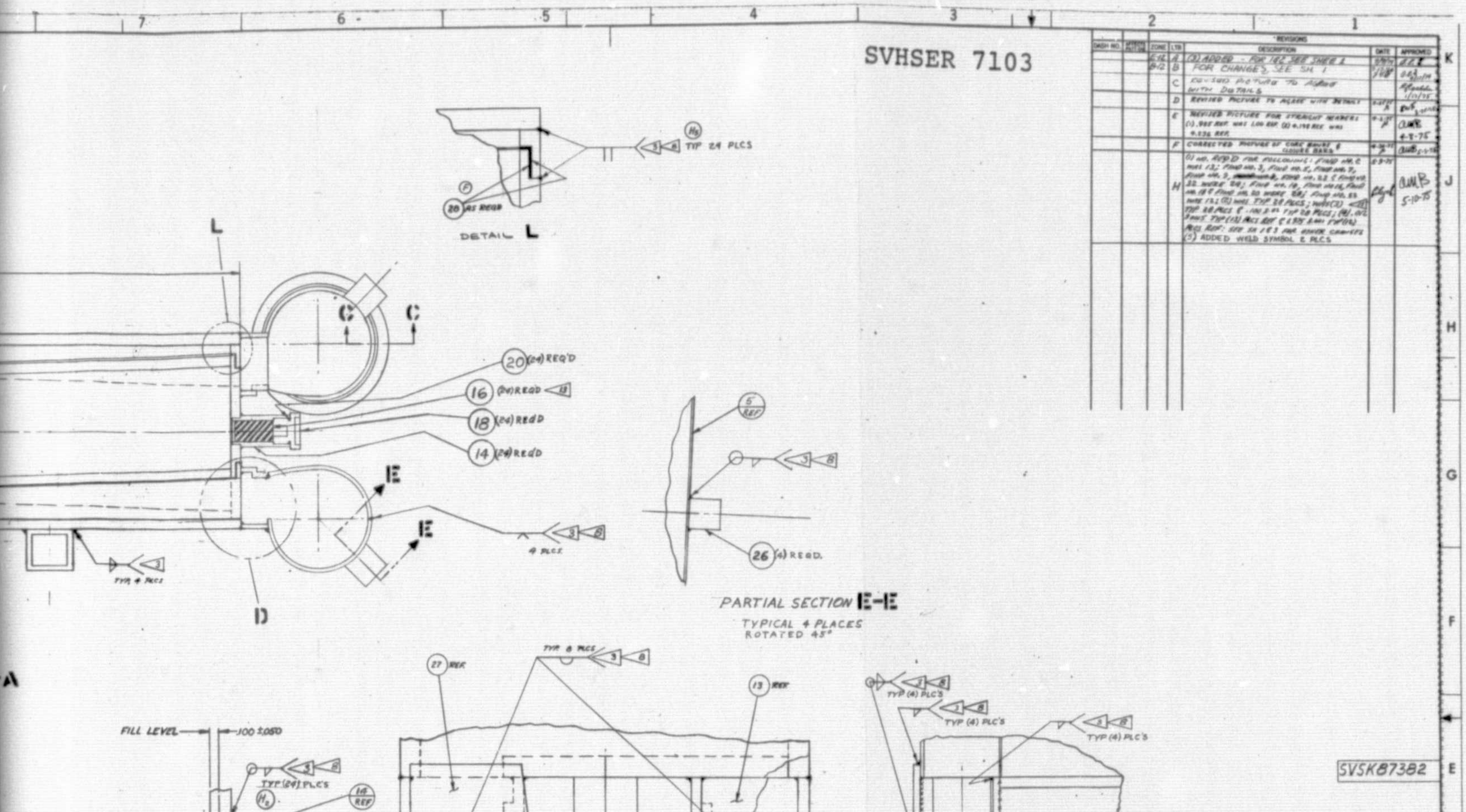


FIGURE 22 HS-C CANISTER DRAWING

(SHEET 2)



HS-C CANISTER DRAWING

(SHEET 2)

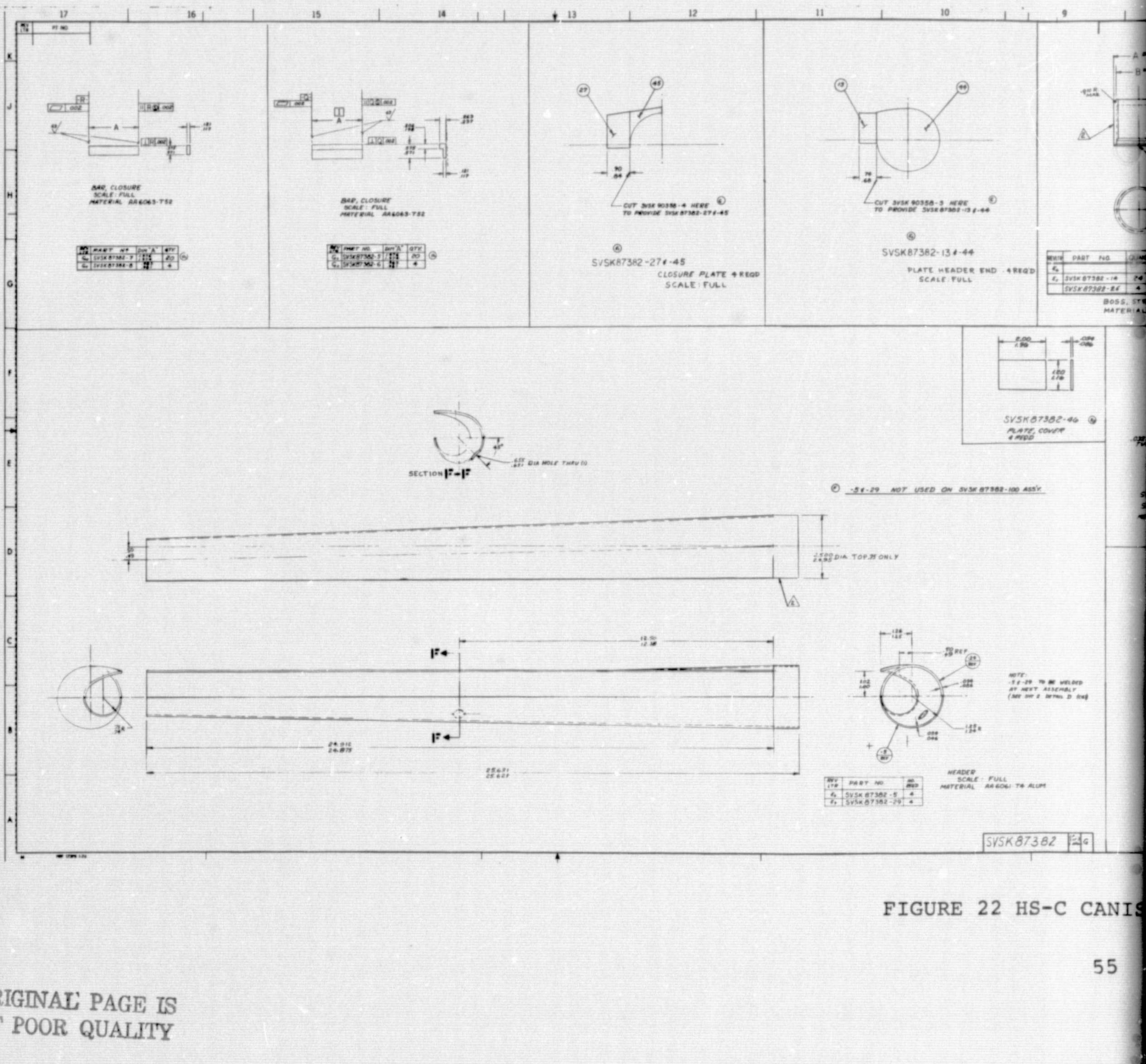


FIGURE 22 HS-C CANIS

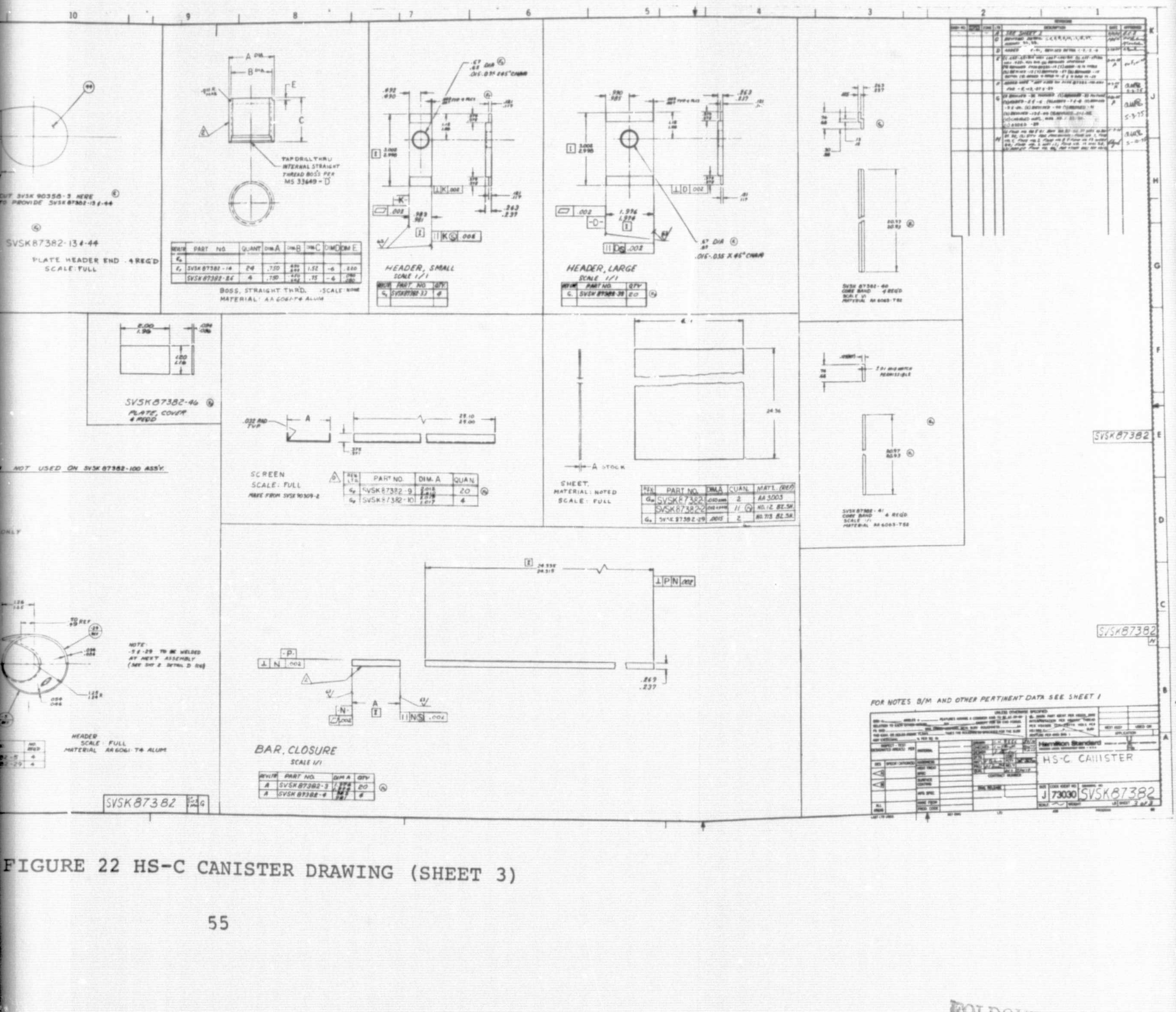


FIGURE 22 HS-C CANISTER DRAWING (SHEET 3)

FOLDOUT FRAME 2

The overall canister size is 73 cm (28.75 in) x 69.1 cm (27.2 in) x 17.1 cm (6.74 in) wide. The design weight of the canister is 18.65 kg (41.1 lb) versus an analytical assumption of 19.05 kg (42 lb). The designed pressure drop at a flow of 0.99 m^3/min (35 cfm) is 89.6 N/m^2 (0.36 in H_2O) against a target of 124.6 N/m^2 (0.5 in H_2O). The design ullage is 2.39 times the bed volume versus a target of 2.50.

This summary shows that all analytical design criteria were met. Further weight reductions could be made by incorporation of non-standard material sections at higher cost and longer fabrication lead time. Calculations in support of this design may be found in Appendix D of this report.

System Design

The complete breadboard system was designed to RSECS integration packaging constraints. The resultant package is defined by the Hamilton Standard drawing number SVSK 85461 which is shown in a reduced form as Figure 23.

The component layout and plumbing arrangement is compliant with the system schematic of Figure 2. A list of major components is presented in Table 9. As can be seen from this list, most components are commercially available. These components were carefully selected to simulate the functional requirements of the system.

The breadboard system is shown almost completed in Figure 24. These photographs showed the packaging arrangement prior to adding the HS-C canisters. When the program was modified to delete one canister and RSECS integration, the top canister was replaced by the controller package. The controller was originally designed to be remotely located outside the RSECS test facility. With RSECS testing no longer a requirement, the controller was mounted directly to the breadboard system. The final package arrangement can be seen in the test setup photograph of Figures 6 and 32.

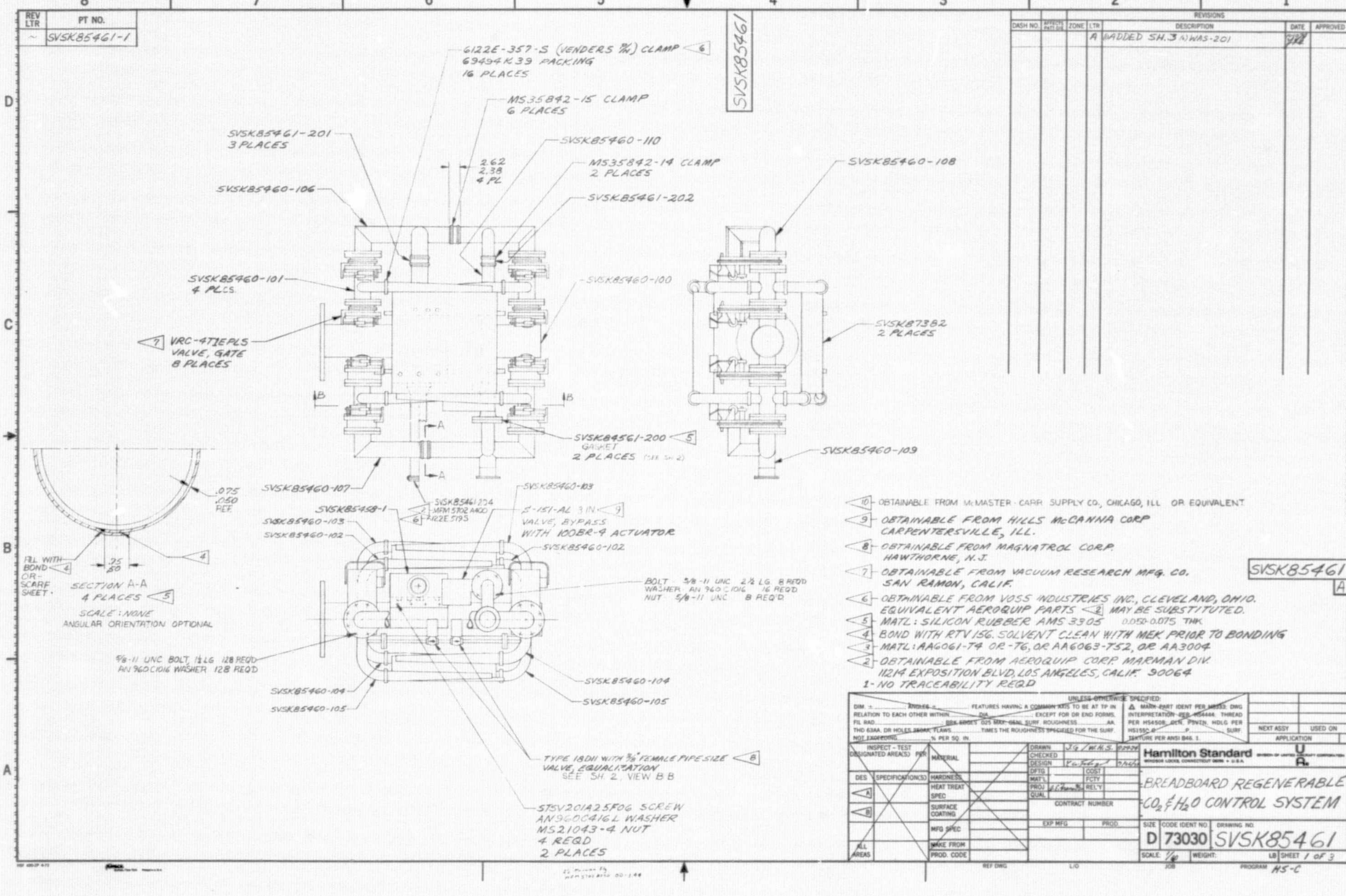


FIGURE 23 BREADBOARD SYSTEM (SHEET 1)

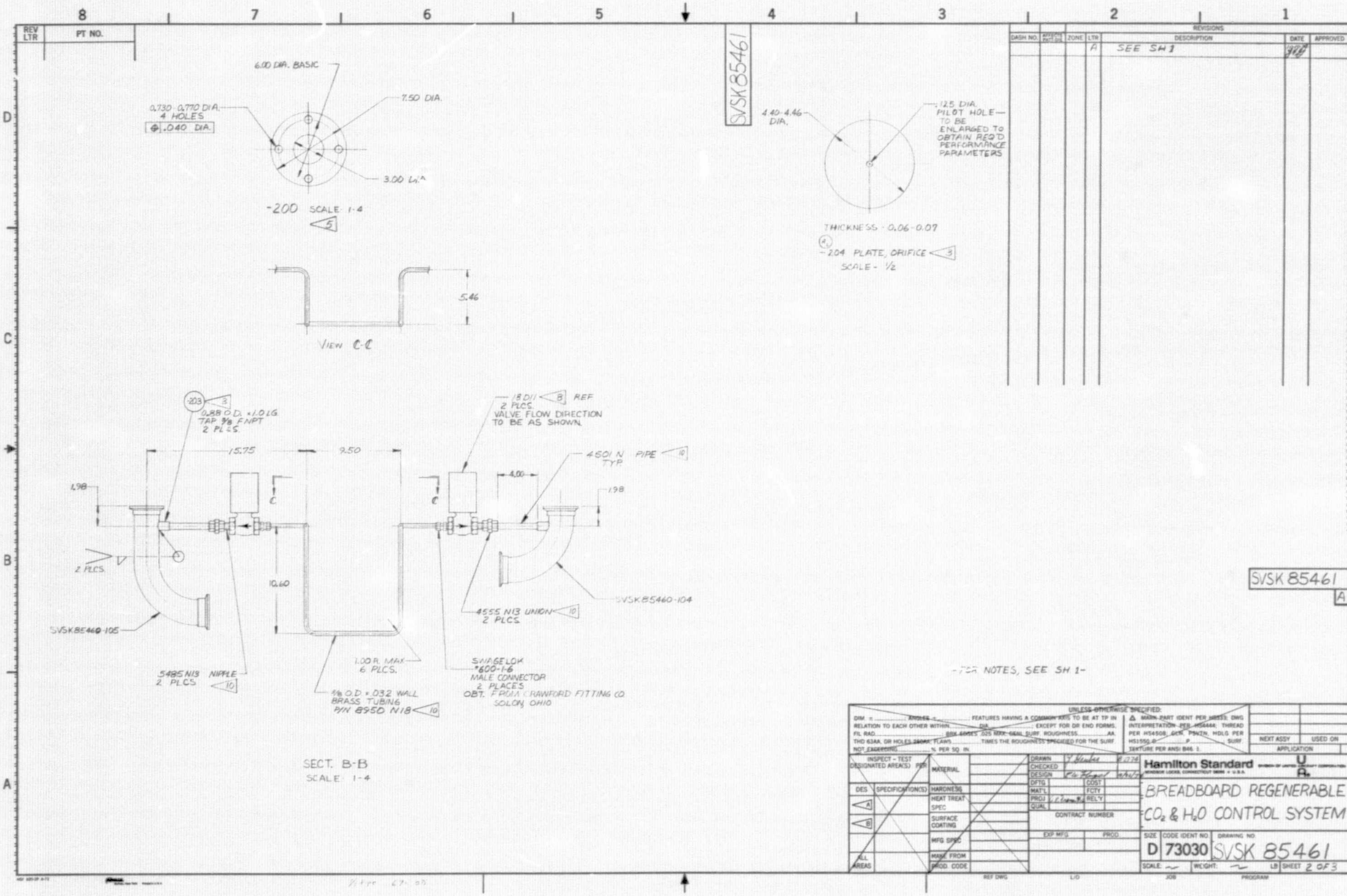


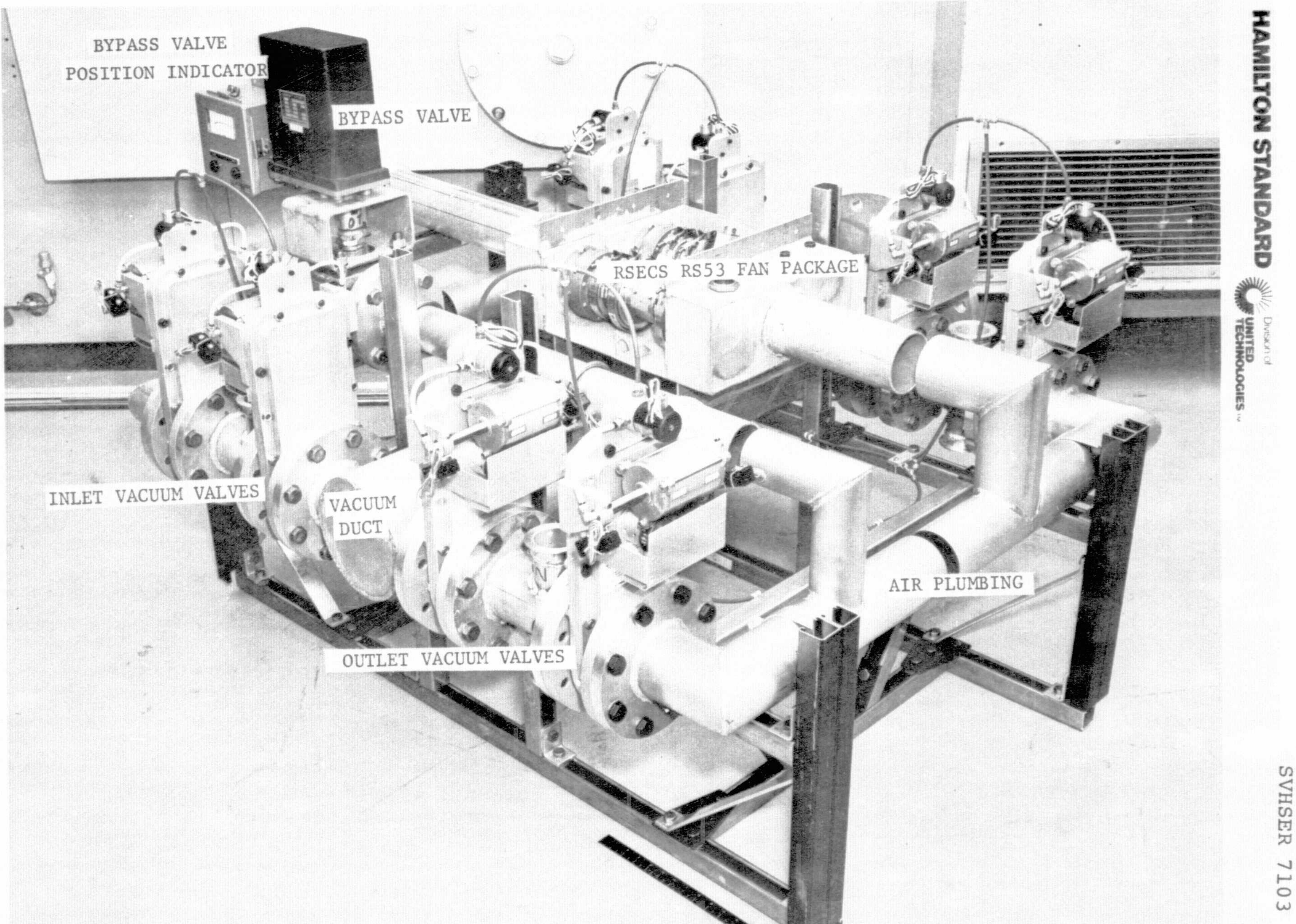
FIGURE 23 BREADBOARD SYSTEM (SHEET 2)

TABLE 9

MAJOR COMPONENTS LIST

Breadboard Regenerable CO_2 and H_2O Control System (HS-C)

Component	Quantity	Identification
Canister, HS-C	2	SVSK 87382
Valve, Select	8	VRC-4TIEPLSS (SVSK 87416) 4 in Gate Valve
Valve, Press. Equal.	2	Magnatrol 18D11, 3/8
Fan, Air Circ.	2	SVSK 85330 (RSECS RS53)
Filter Inlet	1	SVSK 87427
Valve, Air Bypass	1	Hill-McCann 3"-150 lb Series S151/100 BR4 Actuator
Timer Cycle Control	1	Agastat Programmer Model 2918AF17A



SS 11774-4

FIGURE 24 BREADBOARD SYSTEM ASSEMBLY

HS-C MATERIAL FABRICATION

The HS-C material fabrication task is identified as WBS 3.0. The objective of this task is to manufacture sufficient HS-C material for breadboard system testing. Task WBS 1.0 identified the breadboard system testing. Task WBS 1.0 identified the breadboard system's material requirements to be approximately 27 kg (60 lb).

The approach to this task was to utilize the basic HS-C formula developed by Hamilton Standard and demonstrated on Contracts NAS 9-11971 and NAS 9-12957. New equipment was fabricated to greatly expand the production capability (lot size) of the HS-C material. Those variables that have shown an effect on material performance were carefully controlled. These important variables included substrate size and washing preparation; the coating quantity and the temperature and pressure of the coating operation.

The first step in this task was to evaluate a modified procedure on a small size sample. The modified procedure reduced the total fabrication time by approximately 50%. This procedure was used to manufacture a 100 ml sample on the existing equipment. This sample was evaluated for CO_2 and H_2O adsorption capacity in a comparison test with a known sample of HS-C fabricated under the previous contract. This evaluation established the material prepared with the modified procedure to be identical to that prepared with the original procedure. The modified procedure was, therefore, adopted as the baseline procedure. This sample was also used as the master against which all the newly manufactured HS-C would be evaluated.

The large-scale fabrication equipment was then set up. This hardware was designed to produce a 0.02 m^3 (20 liter) lot of HS-C material in a batch type process. Upon completion of the set up, a quarter size batch was fabricated. A sample of this batch was comparison tested for adsorption capacity against the master sample. This evaluation showed that the new setup produced HS-C identical to that produced by the previous equipment and by the previous procedure.

With the setup proven, three batches of material were fabricated. A sample of each batch was successfully tested against the master. In all cases, the adsorption performance of the new batches were equal to or slightly better than the master.

The total quantity of HS-C produced was .065 m^3 (65 liters) or a total of 25 kg (55 lb). This material was produced in three full batches plus the original quarter size batch.

This task demonstrated the ability to produce high quality HS-C material in large enough quantities to fulfill economically the potential need of the material on Shuttle. In addition, the material from the various batches was shown to be repeatable in performance adsorption capacity. Together, these two parameters of quantity and quality proved the reproducibility of the HS-C material.

The only other conclusion of this task involves the coating equipment. Should large quantities of material be needed in the future, it is recommended that a commercially available, internally vaned, vacuum mixer be procured for the coating operation. The present mixer is a smooth walled glass flask which was not only difficult to rotate from the outside, but also did not produce the desired mixing action on the inside. The procurement of a commercial unit would greatly improve the overall fabrication technique.

BREADBOARD SYSTEM FABRICATION

The Breadboard System Fabrication Task was WBS 4.0 and identified in the Statement of Work by Section 3.2.3. The purpose of this task was to procure, manufacture, and assemble the breadboard system and all its components. This task was relatively straightforward with the exception of the breadboard canister since all other components were commercially available. The system was assembled to the requirements of the packaging drawing, SVSK 85461, with no problems or unique techniques.

The fabrication of the breadboard canister, however, presented considerable technical challenge. The fabrication process was divided into four stages: the fabrication of Duocell foam, the fabrication of two manufacturing feasibility modules, the redesign and fabrication of a third module, and finally, the fabrication of the breadboard canister itself. As such, this section is subdivided into each of these subsections.

Duocell Foamed Aluminum

The advantages of using the foamed aluminum material, known as Duocell, for the canister application are numerous as has been previously mentioned. The fabrication of the Duocell foam in the quantities and tolerances of this application presented an independent development challenge. The Duocell vendor, Energy Research and Generation, Inc. (ERG), ran into initial problems holding the required braze tolerances of the foam for the full .61 m (24 inches) length of each detail. Scrappage rates approached 50% for all four details being ordered. This scrappage also resulted in schedule slips that affected overall program schedules. The Duocell was actually foamed to rough dimensions at ERG and sent to a separate machining house for grinding to final dimensions.

In the five month period of Duocell procurement, ERG and their grinding vendor developed improved techniques for obtaining acceptable pieces. By the end of this period, the scrappage rate was reduced to the 10% range.

The result of this effort is that the Duocell foamed aluminum can be fabricated to tolerances suitable for heat exchanger/chemical bed brazement. The tolerances being held were ± 0.0025 cm (± 0.001 in) on height, $\pm$ 0.005 cm ($\pm .002$ in) on width, and ± 0.05 cm ($\pm .02$ in) on length. These tolerances can now be successfully achieved with low scrappage rates.

First Two Modules

Prior to fabricating the full size breadboard canister per SVSK 87382, it was decided to use 1/4 size modules to prove out the manufacturing techniques and overall braze quality of the unique canister materials and design. These modules represented the first attempts to braze a Duocell stack up with integral retention screens. The integrity and quality of the braze joints between the Duocell and parting sheets and the sandwiching of screen material between the Duocell and parting sheets were of particular importance. The use of modules were used to allow destructive analysis and micro-examination of all detail areas of the core as they would be encountered in the actual breadboard canister.

Two modules were fabricated during the period of October through December of 1974. These modules were both fabricated to the "B" revision of the SVSK 87382 drawing. The main characteristics of this configuration, in addition to the duocell foam, were "C" section closure bars and expanded aluminum screening. Both modules proved out the feasibility of brazing the Duocell foam and the aluminum screen sandwich. The conclusions of both modules is summarized as follows:

- The aluminum foam retains dimensional stability (does not collapse) at the temperatures and loadings necessary for brazing.

- There is adequate contact between the foam and parting sheets, and a good quality braze is achieved.

- The parting sheets remained flat with no signs of perforation.

- There was no plugging of the screen by braze material.

- There were gaps between the HS-C retention screen and the end closure bars. These gaps are partially a result of closure bar movement during stack up and partially due to the method used for screen application. The gaps were large enough to leak HS-C.

- On both modules the closure bars bowed slightly. This resulted in a gap and no braze at the outside edge. At the inside edge, where contact was good, an adequate braze was achieved. Only 50% of the closure bar length was leak tight due to this bowing.

- The expanded aluminum screening was susceptible to work hardening and ripping during forming and was judged not acceptable for canister use.

The last three items were considered serious problems, potentially jeopardizing the success of the full size canister. As a result, a redesign effort was undertaken to prove out potential solutions on a third module.

Third Module

The decision was made to fabricate a third manufacturing development module. This module was a seven-stack, fourteen (14) inch high unit which incorporated:

- Solid closure bars (0.64 cm (.25 in) thick)
- Three different end configurations
- Three different screen types

The solid closure bars eliminate the potential for bowing that was experienced with the inherently weak "C" section closure bars.

The three different end configurations allowed a comparative evaluation of potential solutions to the HS-C retention problem encountered in the first two modules at the screen interface with the end closure bars.

The three different screen types allowed a comparative evaluation of the best screen configuration with respect to handling, fabrication techniques, and brazing effectiveness.

In forming the three screen types, the following observations and comparisons were noted:

Expanded Metal: This material was easily folded and cut. All pieces had to be flattened and were still warped along their length. Consequently, one side had to be stretched to straighten the screen. The folded screen could not support its own weight without buckling and had to be delicately handled.

Photo-Etched: The photo-etched screening was easy to cut and fold. It was flat and straight as received. It was more sturdy than the expanded metal screen, being able to support its own weight. It was judged the best in overall workability and handling.

Photo-Etched With Borders: This material was the most difficult to work with. This screen was configured so that all folds would occur in a solid area rather than the weaker holed area. However, the close proximity of the holed section to the fold line resulted in a distortion of the inherently weak holed/solid interface. A Sheet metal brake is definitely needed to bend this screening, whereas the other configurations can be bent by hand. Cutting the box corner on the bottom two layers was the most difficult with this material.

The module details were assembled and stacked for brazing as shown in the photograph of Figure 25. The braze fixture is also shown fully assembled. The fixture has two leaf springs that preload each of the four vertical sides of core, thus holding all details in proper position during the braze cycle. Side and end preloads were not used on the previous modules. It was assumed that by providing an end preload, constant contact would be maintained between the screen and the end closure bar. The top plate of the fixture is shown with spring loads at each post. This spring load is used to check out the stack up tolerances and was replaced by a fixed load during the braze cycle. A weighted load of 87 kg (191 lb) was applied to the top plate and provided a uniform load of 11.6 kPa (1.68 psi) during brazing.

The module was then brazed, leak checked, and repair welded. In addition, core band and fill port welding techniques were verified. The unit was then tested for HS-C retention capability and filling techniques. Finally, the unit was cut up for a detailed analysis of braze quality, screen integrity, and overall module quality. The conclusions were as follows:

- The extended and trapped screen concept did not leak HS-C material.

- The extended and trapped screen concept leaked HS-C at only one corner due to a wrinkled parting sheet caused by the adjoining layer.

- The box corner concept and the slip joint concept both leaked HS-C material primarily due to wrinkled parting sheets.

- The extended and trapped screen concept was chosen for the breadboard canister. This concept was evaluated successfully in eleven of twleve places in the module.

- Base metal solution of the screen in contact with the heavily clad end sheets was experienced, causing the screen to melt and leak HS-C pellets. Evidence of a similar situation was noticed in the second module.

- Thin braze foil (0.0038 cm (.0015 inch thick)) will be used to braze solid aluminum end sheets, thus avoiding the excess cladding (0.013 cm (0.005 inch thick)) of No. 11 end sheets.

- The photo-etched screen without solid borders was easy to work with, held its shape during and after forming, and brazed well. It has been selected for use on the breadboard canister.

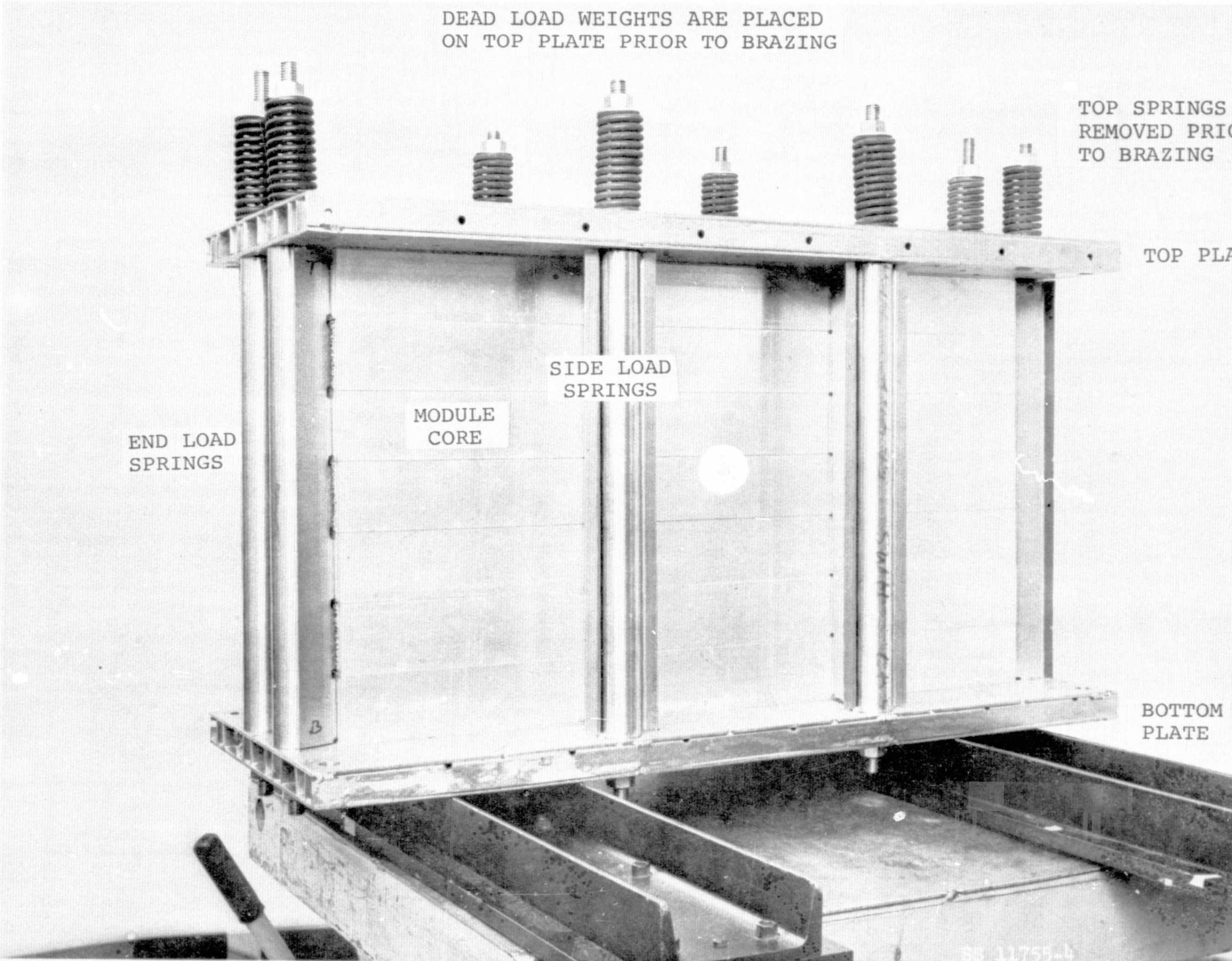


FIGURE 25 THIRD MODULE PRIOR TO BRAZING

- The solid closure bars held their shape and brazed exceptionally well. Repair weld techniques had to be simulated since no leakage was encountered in the large faces of the module.

- The application of an end load during brazing was detrimental to the stability of the parting sheets. The parting sheets wrinkled and caused HS-C leakage. This problem was not encountered on the first two modules when no end load was present. Therefore, the breadboard canister will be brazed with no end load. The folded and trapped screens will hold the end closure bars in place during the brazing operation.

Breadboard Canister

The breadboard canister drawing, SVSK 87382, which had been used to fabricate the first two modules, was changed to reflect the successful conclusions of the third module. The major changes included:

- The closure bars were changed from a "C" shape to 0.64 cm (.25 inch) solid bars. The bars can be machined to a "C" shape after brazing to remove excess weight.

- The screening material was changed to a photo-etched screen. In this process an extremely fine diamond grid pattern is photo masked on 0.015 cm (.006 inch) thick AA6951 aluminum sheets. The holes are then chemically etched. The finished screen and hole pattern is defined by SVSK 90309.

- The end sheets were changed from No. 11 braze sheet to AA3003 aluminum sheet with a 0.0038 cm (.0015 inch) thick sheet of Alcoa 713 braze foil.

- The screen interface with the end closure bar was changed to the extended and trapped concept. The screen actually protrudes out the end of the stack up. The screen is then folded into a recessed area and trapped under an adjoining and overlapping closure bar that is tack welded in place as the last prebraze operation.

The breadboard canister was assembled, stacked, and brazed during May of 1975. The stacked core is shown prior to brazing in Figures 26 and 27.

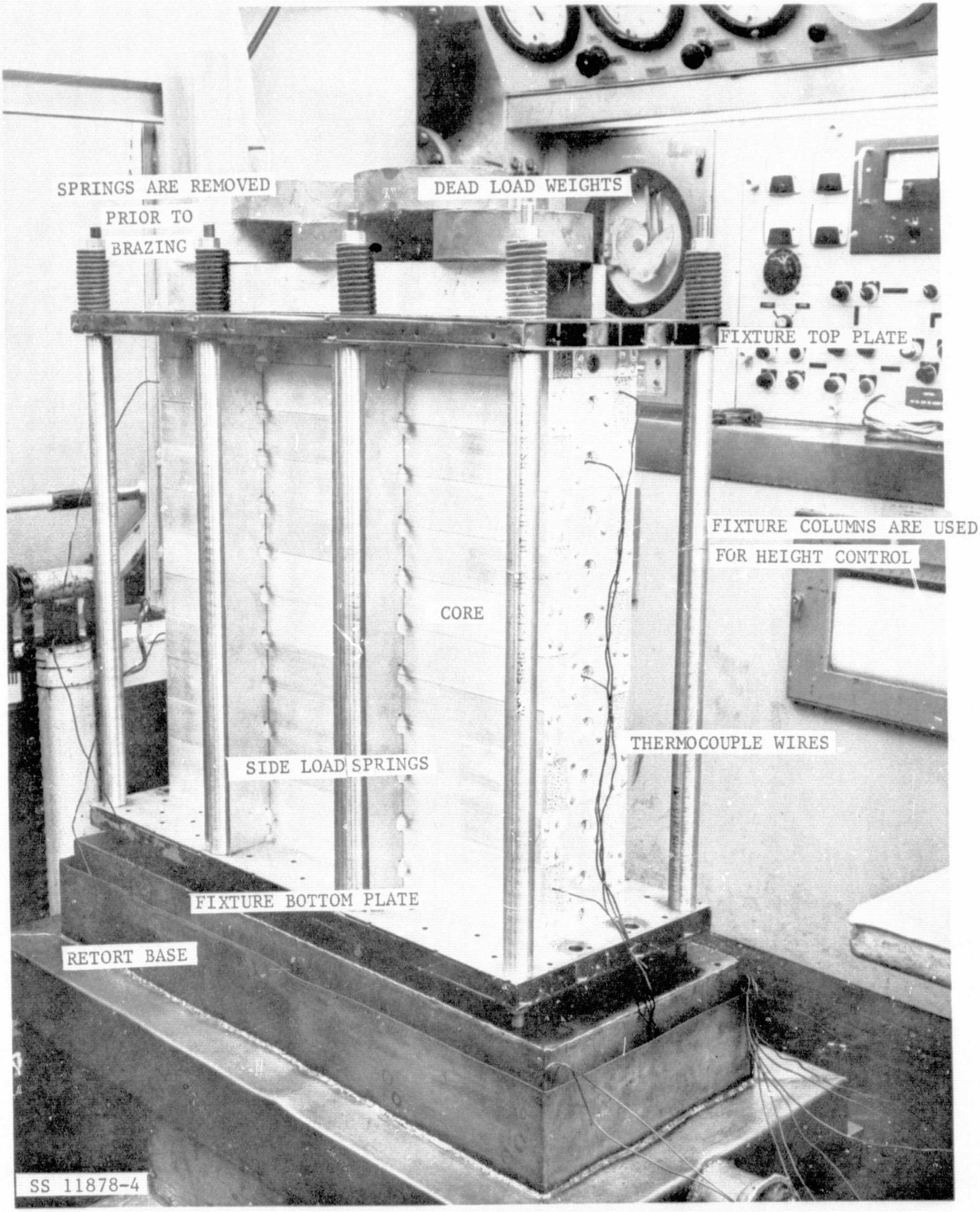


FIGURE 26 THE BREADBOARD CANISTER CORE PRIOR TO BRAZING

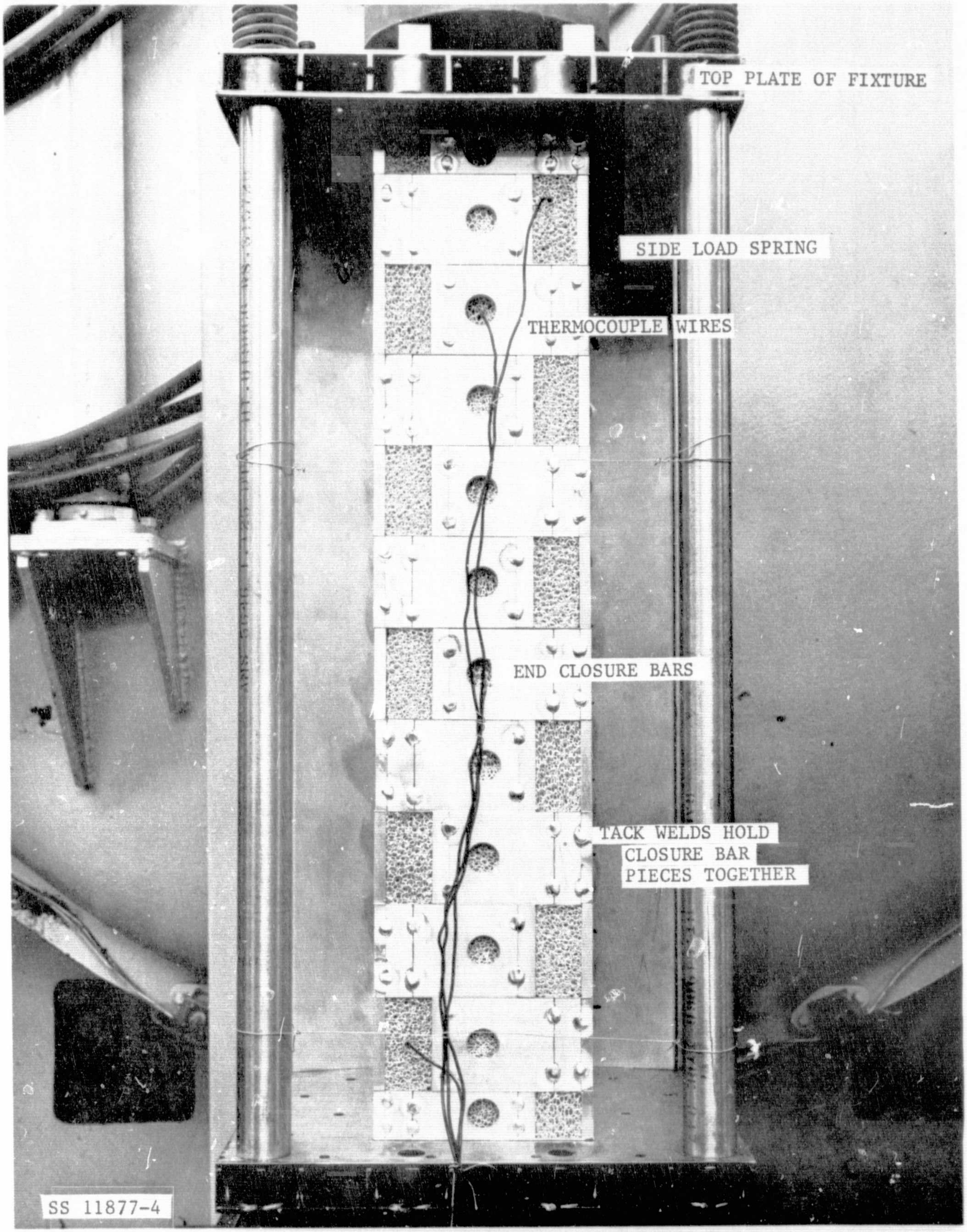


FIGURE 27 THERMOCOUPLE INSTRUMENTING OF THE CORE FOR BRAZING

Figure 26 shows the core sitting on the retort base. The top plate of the brazing fixture has been loaded with 66 kg (146 lb) of weights and provided a uniform load of 8.83 kPa (1.28 psi) during brazing. The spring loads on the top plate were removed before brazing so that only the weight load was acting on the core during the braze cycle. Side spring loads can be seen in this photograph and retained the side growth of the core during brazing.

Figure 27 shows a close-up of the end of the core. Four thermocouple wires were used on each end to monitor the top, middle, and bottom core temperatures during the braze cycle. Tack welds were used to retain the small closure bar pieces. The extended and folded screens are trapped under each of these small closure bars.

The core was brazed satisfactorily and held its shape well during the cycle. Preliminary welding operations, including the assembly of core bands, were accomplished. The leak check fixture was fabricated and assembled. Numerous leak check and weld repair operations were then undertaken. All external leaks were repaired to acceptable levels. However, the weld repair of internal leaks posed a serious problem due to channeling and the difficulty in tracing leaks to their source. A weld repair was attempted on all major leaks three separate times with only moderate success.

It was then decided to attempt an epoxy fix of these leaks. In this operation, Scotchcast (3M Resin 9 (XR-5240)) epoxy was introduced at the visible exit of known leaks. A vacuum was applied to adjacent layers of the core to draw the epoxy into the leak path. After the first repair operation, all corner leaks at flow openings were successfully sealed. This left approximately eight additional leaks which were mapped and located by use of a water tank.

The remaining core leaks were repaired with the Scotchcast epoxy. Two major leaks were discovered under repair welds on the large side of the canister. In these two instances, the welds were machined away, and Scotchweld epoxy (EC2216 B/A) was used to seal the leaks. Normally, these leak areas would be rewelded after machining. However, the heat of welding would adversely affect the already repaired epoxy areas. For this reason, all further weld operations had to be carefully weighed with respect to type, length, and location of each weld.

At this point, the core successfully passed leakage tests with leakage rates of less than 11.4 g/hr (0.025 lb/hr) of STP air. The completed core is shown in the photographs of Figures 28 and 29. These photographs show both ends and both sides of the core.

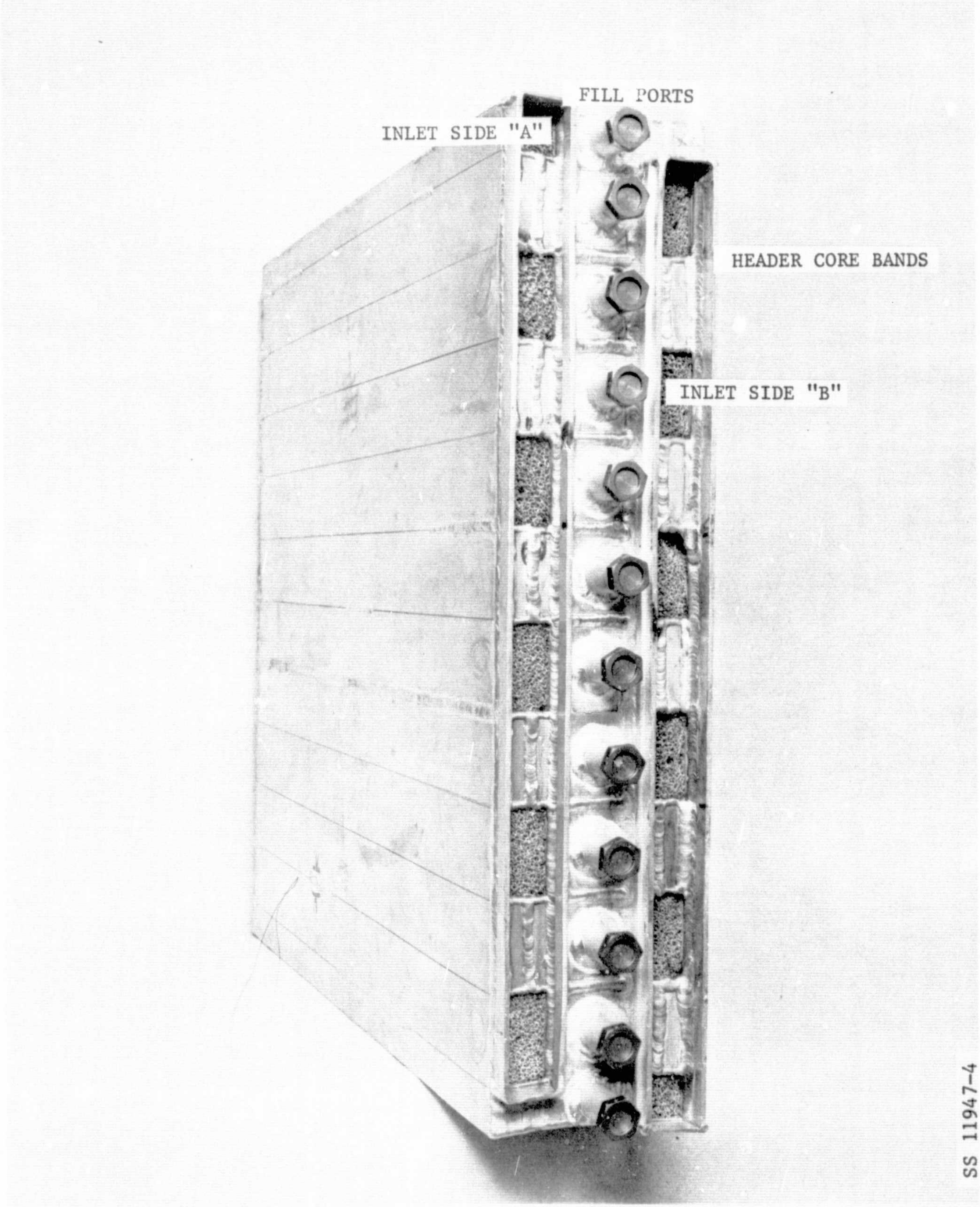


FIGURE 28 COMPLETED CANISTER CORE (SHOWING INLET END AND ONE SIDE)

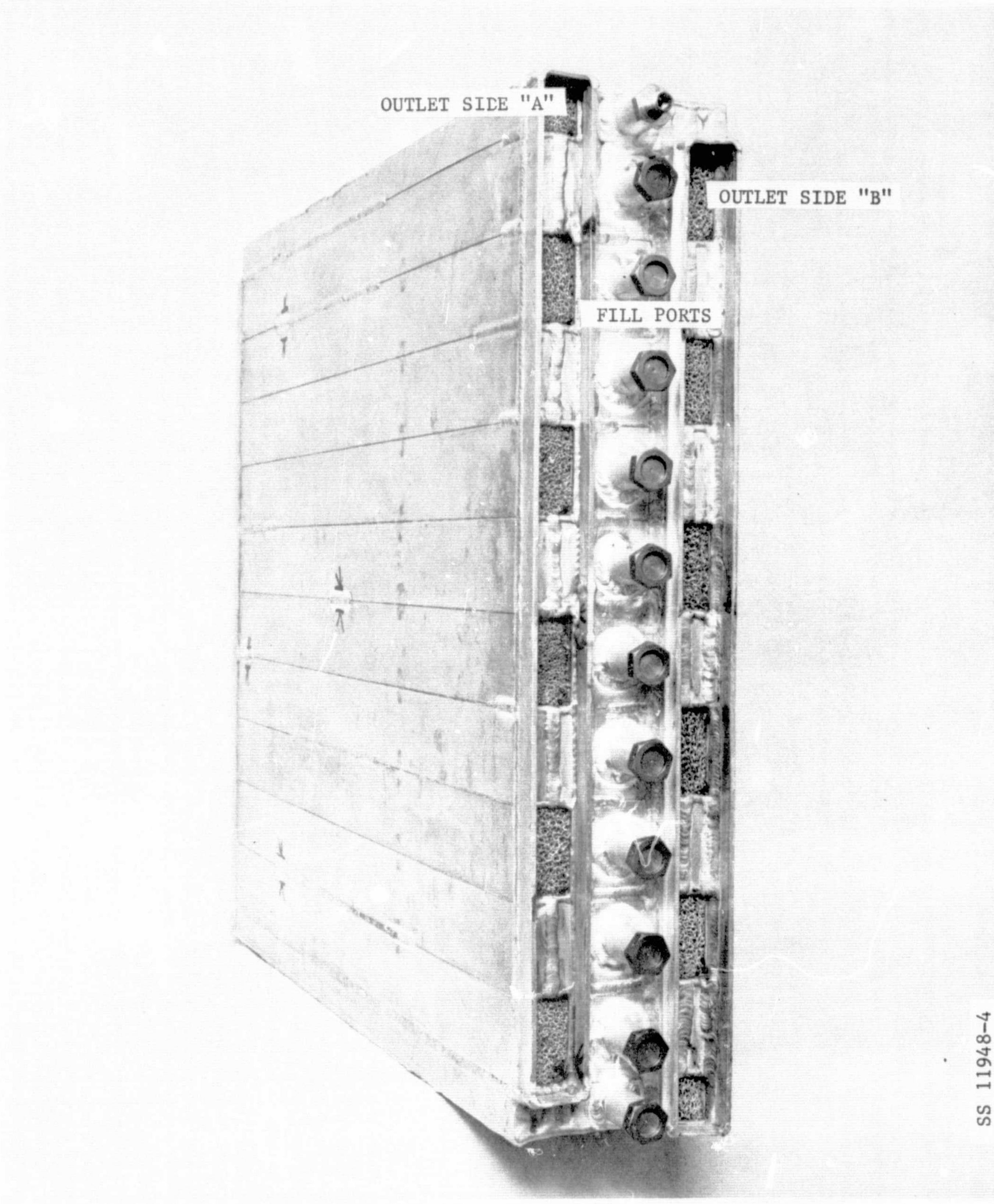


FIGURE 29 COMPLETED CANISTER CORE (SHOWING OUTLET END AND OTHER SIDE)

The installation of headers on the core was then carefully reviewed with regard to potentially damaging the repaired epoxied areas with the heat of welding. As a result, the decision was made to epoxy the headers to the core with the use of backup strips at all joints for added strength. This task was then completed, and the canister was pressure checked and leak checked. A leakage of 2.14×10^{-6} kg/s (0.017 lb/hr) was measured on both sides of the canister. This rate is well below the 6.81×10^{-6} kg/s (0.054 lb/hr) allowance system leakage target.

The breadboard canister was then filled with HS-C chemical. The chemical in each layer was weighed as it was loaded into the canister. The canister was filled in two steps; first, the odd layers were charged through funnels and vibrated until settling of the chemical had stopped; and second, the even layers were charged in the same procedure. All layers were then fitted with glass fill tubes. These tubes were filled with chemical, and the canister was rocked and rotated in all planes while being vibrated. The vibration load was applied to different points on the canister, and settling in all tubes was noted. This process was repeated after setting overnight with no additional settling being noted. An additional 0.5 pounds of chemical was loaded into the canister as a result of this process, bringing the HS-C chemical weight to 9.31 kg (20.5 lb). The target weight of the HS-C was 9.53 kg (21.0 lb).

The completed breadboard canister is shown in Figure 5. The headers and structural backup strips can be seen in the photographs. The small boss protruding out the side of each header is an instrumentation pressure port to be used during testing of the canister.

The breadboard canister was then installed into the breadboard system of Figure 6 to complete the Breadboard System Fabrication Task.

FACILITIES MODIFICATION

The facilities modification task is defined as WBS 5.0. The objective of this task was to improve the vacuum capacity of the existing vacuum system, Rig 52, to be adequate for breadboard system testing.

This task was accomplished in a straightforward manner. The inlet lines and valves to the rig cold traps were enlarged to 300 mm (12.0 in). This change increased the pumping capacity of the rig for CO_2 and H_2O since both are collected in the already adequately sized cold traps.

The vacuum rig was then run to check out proper sequential operation and a leak-tight installation of the revised hardware. This effort completed the facilities modification task.

TEST SETUP

The objective of this task (WBS 6.0) was to provide a test setup adequate to test per the Master Test Plan.

It was determined that the most accurate test approach would require a Shuttle simulated cabin volume. By feeding crew metabolic rates of CO_2 and water vapor into the control volume, the transient response levels of these gases could be measured. When CO_2 partial pressure and dew point remained constant independent of time, it could be concluded that an equilibrium condition existed where HS-C removal rate equalled the crew metabolic production rate.

The use of a control volume simulating the Shuttle cabin size offers two primary advantages; allows an accurate establishment of equalibrium performance conditions, and it allows analysis of transient performance when changing crew sizes or even within each adsorption/desorption cycle.

Shuttle Simulated Cabin Volume

A Shuttle simulated cabin volume was constructed for use by both the HS-C program and the Shuttle ARS program. The test volume proved unacceptable for HS-C testing because of excessive permeation of CO_2 and H_2O through the walls of the enclosure. It was decided to use a separate leak tight, pressure chamber for HS-C testing since an existing facility was available near the test setup.

The antichambers of the 10 x 10 man rated test chamber were chosen for use because of their proximity to 28.3 m^3 (1,000 ft^3). The breadboard system was plumbed in series with Rig 88 and the 10 x 10 antichambers. The 10 x 10 antichambers are shown in Figure 30. The volume of the completed test setup was 29.3 m^3 (1,035 ft^3).

Permeation and leakage tests were conducted on the completed setup with favorable results. Permeation of both CO_2 and humidity into or out of the control volume was virtually non-existent during two 24 hour test periods. No degradation of CO_2 or humidity levels could be measured at either condition 1 or 2 of the Plan of Test, paragraph 4.2.1.3.

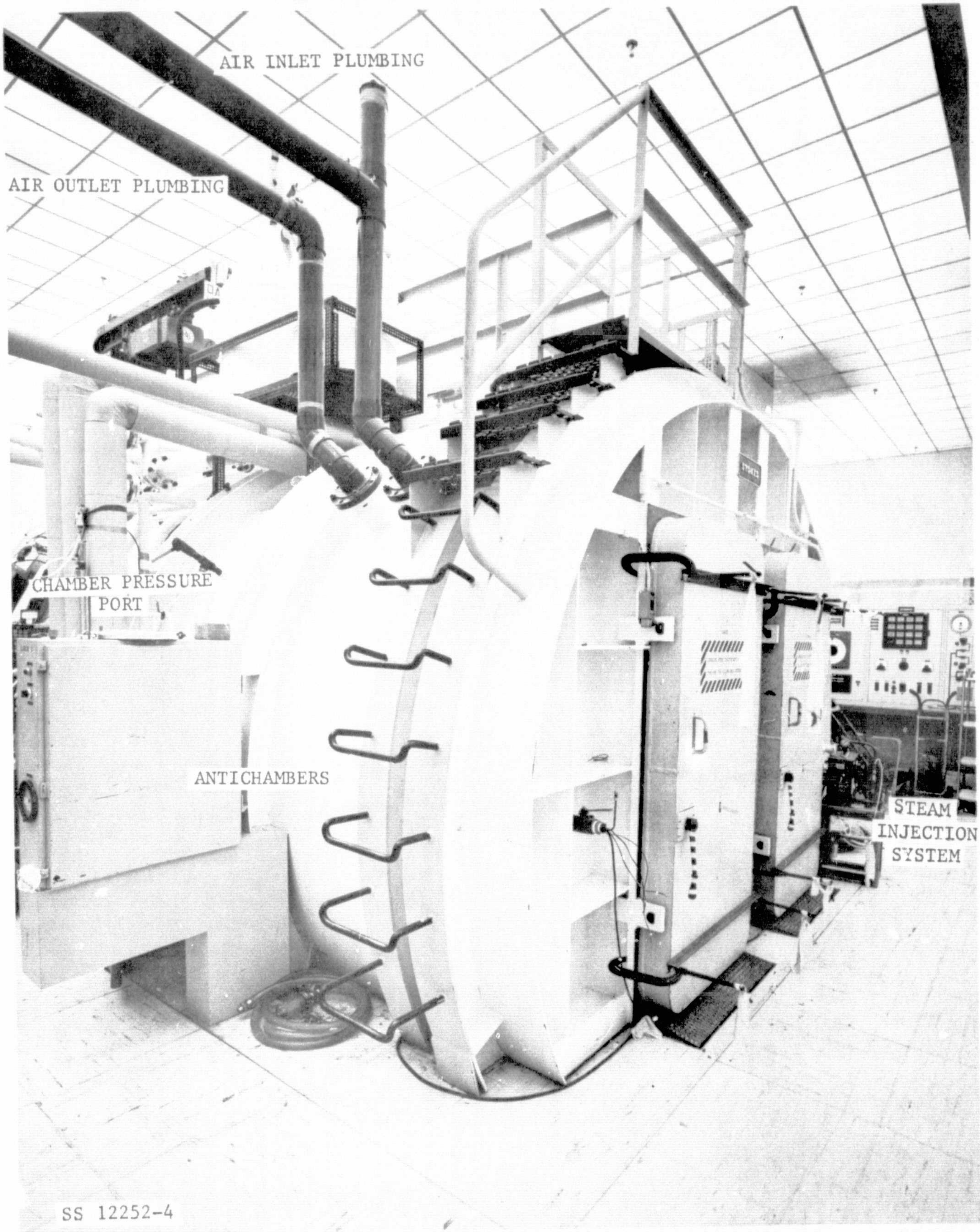


FIGURE 30 10x10 ANTICHAMBERS (USED AS SIMULATED SHUTTLE CABIN)

The pressure holding capability of the revised setup was vastly improved compared to the original setup. The control volume was pressurized to 1.24 kPa (5.0 inches of water) positive pressure. It took 14.2 hours for the pressure to decay to .249 kPa (1.0 inches of water). This calculates to a leakage rate of 1.06 x 10^{-5} kg/s-kPa (0.021 lb/hr-in H_2O). The leakage rate was then corroborated at eight (8) different pressure levels from +2.36 kPa (9.5 in H_2O) to -2.36kPa (-9.5 in H_2O) to see if the pressure change in a 30 minute period would equal that predicted by the leakage rate. The data corroborated the predicted leakage within the accuracy of the instrumentation for both positive and negative chamber pressures.

After the setup and leak testing were completed, a test was conducted to calibrate the actual volume of the entire setup. The HS-C canister was isolated, but all other plumbing was opened to the test chamber, including Rig 88.

In this test .783 kg (1.725 lb) of air was added to the chamber raising the pressure from +.249 kPa (+1.0 in. H_2O) to +2.47 kPa (9.93 in. H_2O). The pressure rise occurred at constant temperature, 24.7°C (76.5°F), over a 22 minute period. It was calculated from the previously given leakage value of 1.06 x 10^{-5} kg/s-kPa (0.021 lb/hr-in H_2O) that the leakage out of the volume over 22 minutes (1320 s) at an average pressure of 1.37 kPa (5.5 in H_2O) would be:

$$\text{leakage} = 1.06 \times 10^{-5} \text{ kg/s-kPa} \times 1320 \text{ s} \times 1.37 \text{ kPa} = .0192 \text{ kg } (0.424 \text{ lb})$$

Therefore, knowing that .0192 kg (.0424 lb) out of the original 0.783 kg (1.725 lb) of air had leaked out of the test volume by the end of the test, the actual volume could be calculated by the formula:

$$\text{Volume} = \frac{\text{Delta Mass} \times R \times T}{\text{Delta P}}$$

$$\text{Volume} = \frac{(1.725-.0424)(53.22)(536.5)}{8.93\ (14.7/407)(144)} = 1{,}035 \text{ ft}^3 = 29.3 \text{ m}^3$$

As a result of these tests, the chamber setup was judged acceptable for performance testing. The volume was within 3.5% of the design goal, and the permeation rate of gas into or out of the test volume was so small they could not be measured in 24 hours. In addition, the setup was relatively leak tight, dropping only 1.0 kPa (4.0 in H_2O) in 14 hours.

Test Setup Description

The completed and integrated test setup is shown schematically in Figure 31.

Air from the simulated Shuttle volume (10 x 10 antichambers of Figure 30) is ducted to Rig 88 where it is first sampled for CO_2 partial pressure and dew point. The air then passes through a blower which provides the total head for the entire plumbing loop. The air then passes through a series of heat exchangers and electric reheaters which provide the temperature conditioning of the air. The air then passes through a venturi and valve arrangement which measures and controls flow rate.

The air is then plumbed to the breadboard HS-C system where it passes through the adsorbing bed and is returned to the simulated Shuttle volume. The breadboard system is shown in the test setup photographs of Figures 6, 32, and 33. Figure 33 shows the CO_2 and dewpoint monitoring equipment in the foreground.

The metabolic CO_2 feed gas is introduced into the airstream in the return duct between the breadboard system and the simulated Shuttle volume. The CO_2 flow is regulated by a needle valve and flow rater. The feed rate is accurately measured by time averaging the decreasing weight of the high pressure CO_2 storage bottle.

The metabolic water feed system injects steam directly into the simulated Shuttle volume. The feed rate is controlled by a calibrated micro-metering valve mounted on the outlet of the constant water volume steam generator. Water flow to the steam generator is measured by time averaging the weight of a separate water storage tank. The storage tank is not plumbed to a water supply but is batch filled with triple distilled water.

The inside of the simulated Shuttle volume is arranged to guarantee adequate mixing of air. Return air from the breadboard system, rich in CO_2, exhausts at one side of the chamber near the steam injection flow. A fan is used to mix the steam and return air with the chamber air. The air intake to the breadboard system is located at the opposite side of the chamber so that it draws the mixed air. It is the CO_2 and humidity levels of this intake air that are used as the primary measurements of HS-C performance.

Rig 52 provides the vacuum supply for HS-C desorption. Rig 52 includes two parallel LN_2 cold traps which freeze CO_2 and water. In addition, the rig has three separate stages of vacuum pumps and blowers capable of 1.4 m^3/s (3,000 cfm) flow at 6.7 Pa (50 microns) inlet vacuum.

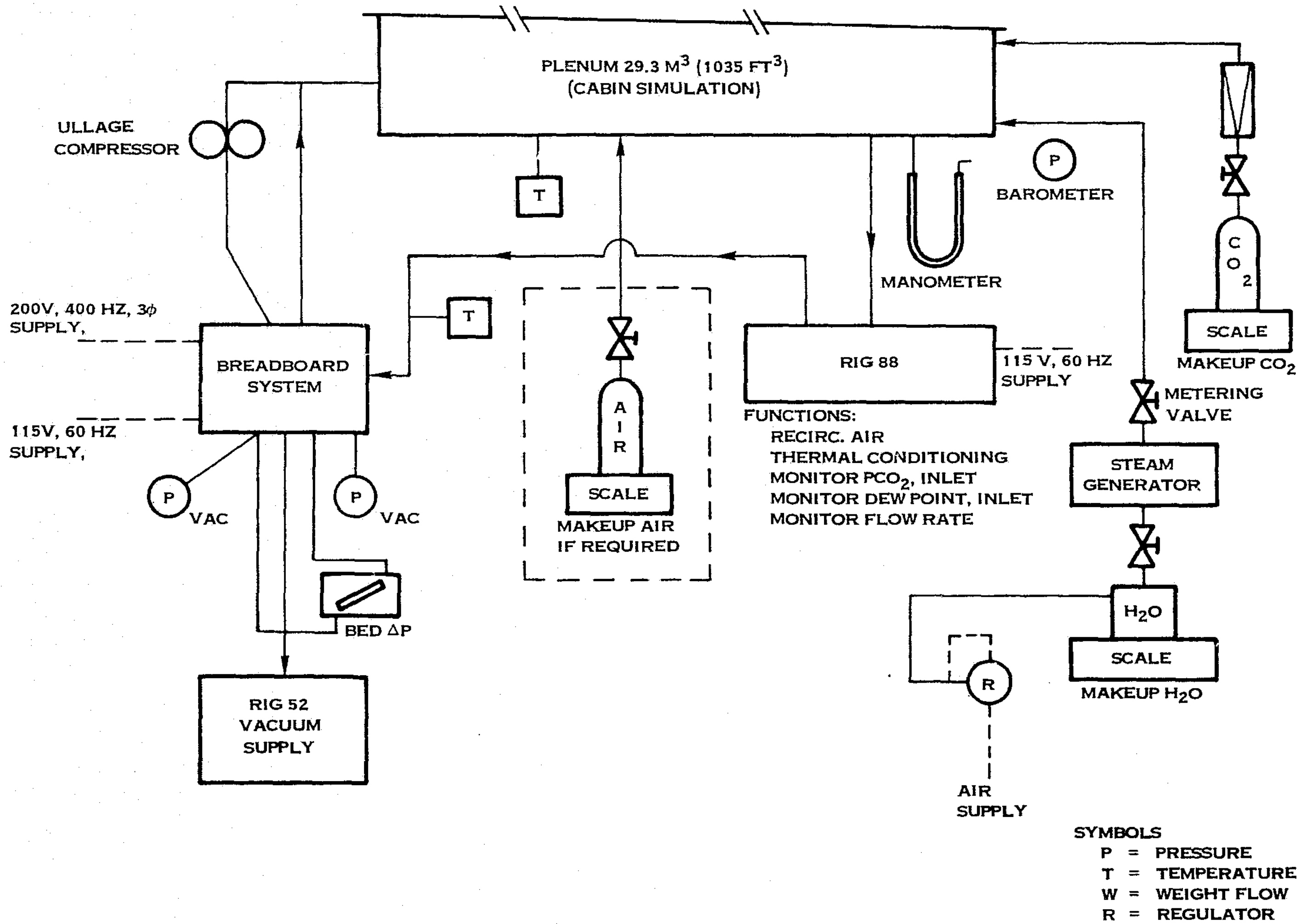


FIGURE 31 BREADBOARD SYSTEM TEST SETUP

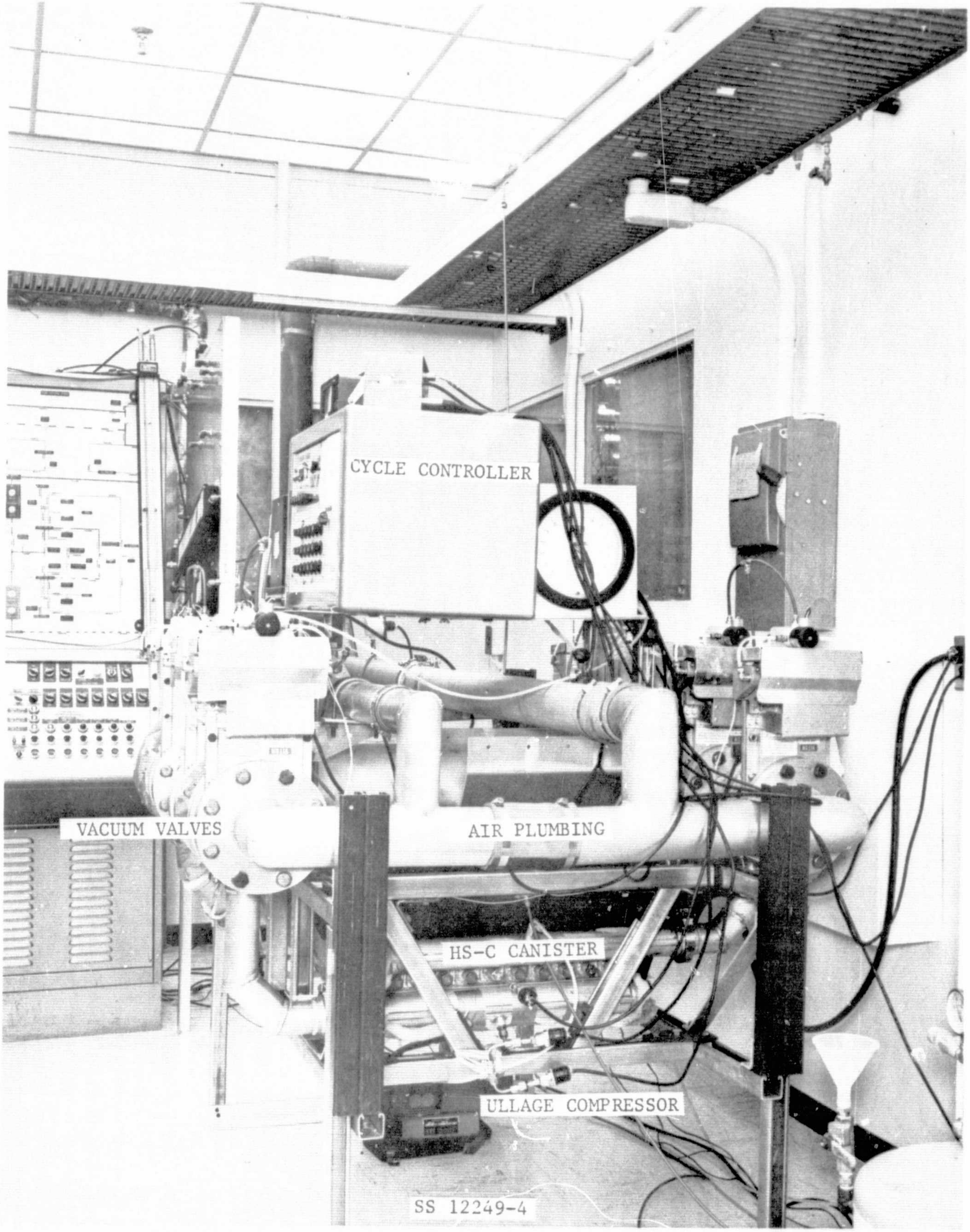


FIGURE 32 BREADBOARD SYSTEM TEST SET UP

HAMILTON STANDARD Division of UNITED TECHNOLOGIES

FIGURE 33 BREADBOARD SYSTEM TEST SET UP SHOWING DATA COLLECTION EQUIPMENT

Instrumentation

The parameters to be measured during testing were defined in the test setup schematic of Figure 31. The specific instruments used in each location are defined in Table 10.

All instrumentation was calibrated prior to testing by the Instrumentation and Metrology Department. All calibrations were maintained up-to-date throughout the test period. In addition, the Infra-Red CO_2 Analyzers (Liras) and Hygrometers (Dew Pointers) were calibrated each day of testing.

TABLE 10

DATA REQUIREMENTS AND INSTRUMENTATION LIST

Parameter	Units	Accuracy	Instrument	Range and Units	Notes
Rig 88 and HS-C Flow	cfm	± 10%	Venturi/Manometer	0 to 30 in H_2O	Indigenous to Rig 88
Rig 88 Outlet Temperature	°F	± 2°	Thermocouple	20 to 150°F	
Makeup CO_2 Flow	lb/hr	± 2% Full Scale	Flowrater	0 to 1.2 lbm/hr	
Makeup H_2O Flow	lb/hr	± 5%	Metering Valve	0 to 3.3 lbm/hr	
HS-C Inlet Temperature	°F	± 2°	Thermocouple	20 to 150°F	
HS-C System Cycle Time	minutes	± 1% Cycle	Stop Clock	0 to 60	
HS-C System Vacuum		± 5% Non-Linear Scale	Hastings Gage and Pickup or Equivalent	0 to Atmos	
HS-C Bed Press. Delta	in H_2O	± 0.05	U-Tube Manometer	0 to 20 inches	
Plenum Temperature	°F	± 2°	Thermocouple	20 to 150°F	
Plenum Dew Point	°F	± 2°	Hygrometer	-40 to 120°F	Indigenous to Rig 88
Plenum PCO_2	mmHg	± 2% Full Scale	Infra-Red Analyzer	0 to 100% (100% = TBD mmHg)	Indigenous to Rig 88
Plenum/Ambient Press. Delta	in H_2O	± 0.2	U-Tube Manometer	0 to 30 inches	Indigenous to Rig 88
Weight Makeup Air	lbm	± 0.02	Scale	0 to 300 lb	
Weight Makeup CO_2	lbm	± 0.02	Scale	0 to 300 lb	
Weight Makeup H_2O	lbm	± 0.02	Scale	0 to 300 lb	
Ambient Pressure	in. Hg	± 0.05	Barometer		
Ambient Temperature	°F	± 2°	Thermometer	20 to 400°F	

BREADBOARD SYSTEM TEST

The objective of this task (WBS 7.0) was to demonstrate the ability of the breadboard system to provide design compliance and to insure that all operating parameters are understood. This task is defined in the Statement of Work by Section 3.2.4.

Testing of the breadboard system was performed in accordance with the approved Plan of Test. Deviations from the Plan of Test were made with the prior approval of the NASA Technical Monitor and are specifically identified in the appropriate sections of this report.

During the test phase the breadboard system proved its ability to perform all phases of a Shuttle mission. The system handled both four and seven man crews using the optimum ullage-save compressor approach to system operation. The system also maintained performance for a 10 man crew using a pressure equalization approach for greater than the required two day mission. In addition, a vacuum desorption test phase optimized the overall vacuum plumbing requirements by showing that desorption can be raised as high as 1,000 microns with only a marginal effect on system performance.

The Plan of Test was divided into six major test areas as follows:

- Leakage and Instrument Calibration
- Performance Calibration
- Parametric Testing
- Mission Testing
- Ullage-Save Compressor Testing
- Vacuum Desorption Testing

Each of these areas served as an important element in the overall test plan and is presented in detail in the following subsections.

Leakage and Instrument Calibration

The objective of this test series is to verify that all elements of system leakage are understood and accounted for during testing and that all instruments are calibrated within acceptable accuracies.

This test series involved five specific test areas as follows:

- Vacuum System Leakage
- Air System Leakage
- CO_2 and H_2O Permeation
- Canister Flow/Pressure Drop Calibration
- Instrument Calibration

Vacuum System Leakage

The purpose of this test was to insure that the leakage of the vacuum portion of the breadboard system, including the canister, was sufficiently below the vacuum pumping rate to allow desorption of the HS-C beds.

The vacuum test was originally conducted per the Plan of Test, section 4.2.1.1. The requirement of this test was to pump a fully adsorbed bed to below 26.7 Pa (200 microns) in 15 minutes. At the time, a vacuum pressure of 26.7 Pa (200 microns) was considered necessary to desorb the HS-C material adequately. Since that time, considerable information concerning vacuum desorption has been learned which would greatly alleviate this requirement. This information is discussed in detail in a following section entitled "Vacuum Desorption Testing." However, the breadboard system and Rig 52 vacuum facility could not meet the requirement of 26.7 Pa (200 microns) in 15 minutes. Bed "A" took 31.5 minutes to reach 200 microns, and Bed "B" took 24.5 minutes to reach 200 microns.

At that time, a decision was made to deviate from the Plan of Test and independently evaluate each section of the vacuum system for absolute leakage. It was known that Rig 52, the vacuum pumping facility, was leak tight and capable of pulling a vacuum pressure of less than 1.33 Pa (10 microns) up to the breadboard system vacuum valves. As such, a detailed leakage check was conducted on the breadboard system itself. A pressure decay test was conducted on each bed separately and then together. The tests were run with each isolated volume being pumped down to a 93.1 kPa (13.5 psi) negative pressure. The leakage is calculated from the ideal gas formula:

$$\text{Leakage} = \frac{\text{Delta M}}{\text{time}} = \frac{V}{RT}\,\frac{\text{Delta P}}{\text{time}}$$

The resultant leakage is factored according to the full pressure differential experienced in actual testing.

The breadboard system was evaluated before performance testing on September 25, 1975 and again after performance and mission testing on March 3, 1976. The results of the leakage tests are shown in Table 11.

Table 11
Breadboard System Vacuum Leakage

	Before Testing	After Testing
Test Date	9-25-75	3-3-76
Leakage Units	cm^3/s (lb/hr)	cm^3/s (lb/hr)
Bed A	3.31 (.032)	3.21 (.031)
Bed B	5.38 (.052)	6.11 (.059)
Bed A and B	7.66 (.074)	6.73 (.065)

It can be seen from this table that the leakage was virtually unchanged throughout the test period. After the initial test, Bed "B" represented the maximum leakage but was within the original design target of 5.58 cm^3/s (.054/lb/hr). In addition, the Bed "B" leakage represented only 3% of the pumping capacity of Rig 52. The vacuum leakage was, therefore, considered acceptable, and the requirement of section 4.2.1.1.4 of the Plan of Test (26.7 Pa (200 microns) in 15 minutes) was waived.

The post test leakage check verified the structural and functional ability of the valves and canister to withstand the approximately 2,300 pressure cycles that occurred during the life of the test program.

Air System Leakage

The purpose of this test was to establish the leakage rate of the overall air circuit which included the breadboard system air circuit, Rig 88, the Shuttle simulated cabin volume chamber, and all interconnecting plumbing. This test was essential to establish the use of makeup air to the system as a true measure of ullage loss during the mission test phase.

If the system could be shown to be totally leak tight, then all makeup air (required to maintain a constant system pressure) would be a true measure of ullage loss after accounting for already measured vacuum leakage. Conversely, if the air system leakage is such that the system cannot hold pressure, then ullage measurements become unfeasible. In addition, adjustments may be required in both CO_2 and H_2O feed rates to account for losses due to excessive leakage.

An extensive leak test was conducted during the test setup phase of the program and is discussed in detail in that section of this report. The conclusion of that test was that the entire air circuit had a leakage rate of 0.0383 g/hr-Pa (0.021 lb/hr-in H_2O).

The leakage rate is proportional to the differential pressure between the system and ambient. Since it had been decided to maintain a positive pressure of between .25 and 1.24 kPa (1.0 and 5.0 in H_2O) in the system during testing, the average leakage would be 29 g/hr (0.063 lb/hr) of air. This leak rate was sufficiently low to have virtually no effect (0.02%) on CO_2 and H_2O feed rates and mass balances. However, this leak rate is high compared to ullage rates. With ullage rates ranging between 17 and 66 g/hr (0.037 and 0.146 lb/hr), leakage alone would make up between 44 and 100% of the ullage loss. As such, no attempt was made to measure ullage loss with makeup air per section 4.2.1.2 of the Plan of Test since the makeup air would only account for a small fraction of the total ullage loss.

At the onset of mission testing a system pressure decay check indicated increased system air or vacuum leakage. At the worst case with 10 man conditions, the leak was measured at 409 g/hr (0.9 lb/hr) which was 14 times greater than that previously measured. At the time, this leakage was suspected to be into the vacuum rig since the air circuit had been previously tested and found to be leak tight. However, a subsequent test of the HS-C canister and valves indicated that only 0.06 lb/hr was leaking into the vacuum system.

A leakage test of the air circuit was then conducted with the vacuum system off. The results confirmed that the remaining leakage was from the air plumbing circuit between Rig 88 and the breadboard system. The rate at which the closed test volume lost pressure with time is plotted in Figure 34. The pressure profile experienced during mission testing is superimposed on the same curve for reference and confirms the leakage to be from the air circuit. A thorough check out of the plumbing system discovered leaks at two plumbing joints. These were repaired prior to the vacuum desorption testing.

It was concluded that the leakage experienced during the mission testing did not affect the operational performance of the breadboard system. The critical leakage from a performance standpoint is that lost into the vacuum system as it can affect desorption characteristics. Fortunately, vacuum leakage was very small at 27 g/hr (.06 lb/hr) maximum. The remaining leakage (93%) was from the air circuit and did not affect HS-C performance. It only affected the CO_2 and H_2O mass balances between feed rates and removal rates. This imbalance is corrected by increasing the feed rates an average of 1% or reducing the performance rates by 1% as follows:

HS-C Performance = CO_2 and H_2O Removal Rates = .99 CO_2 and H_2O Feed Rates

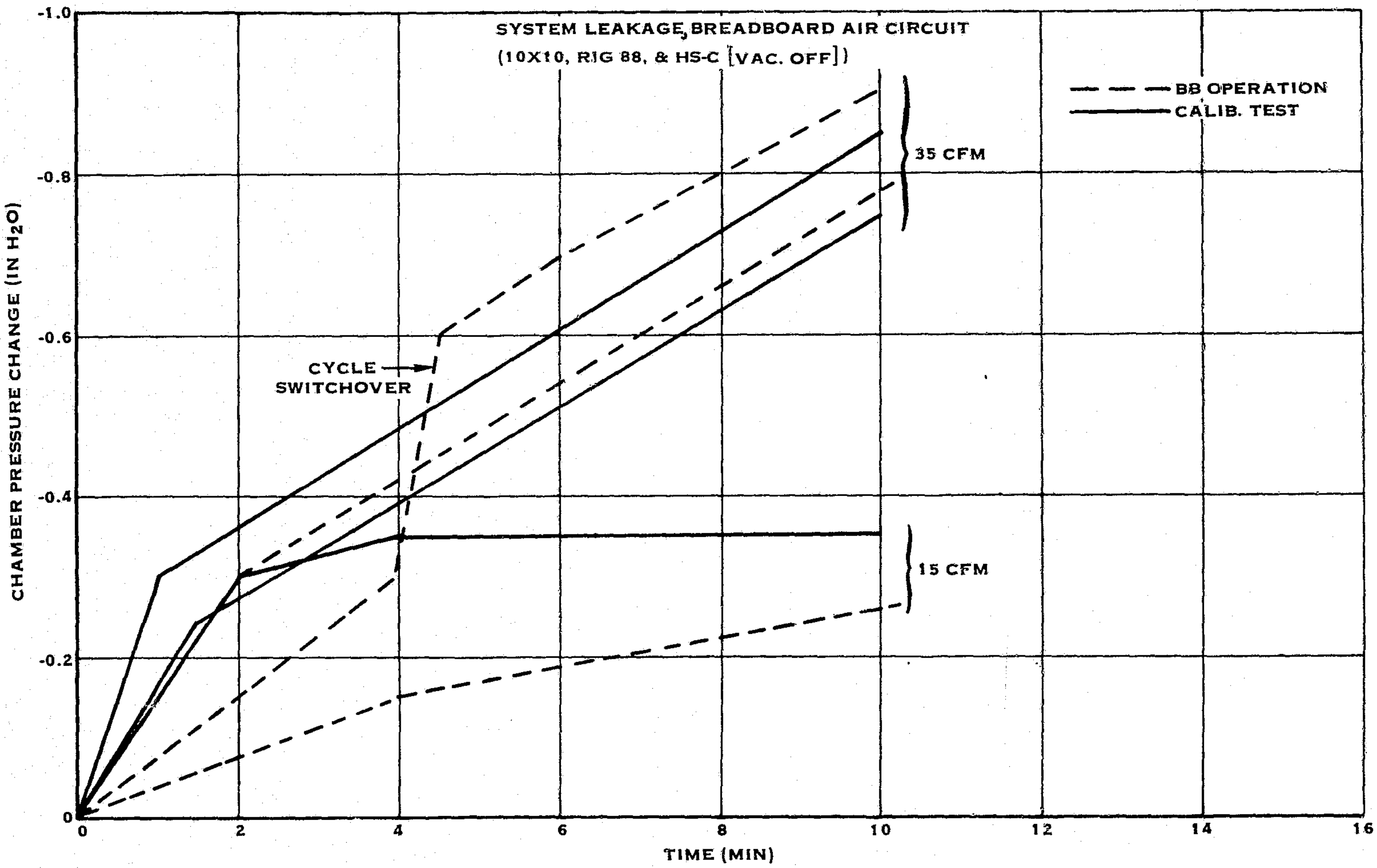


FIGURE 34. TEST SETUP SYSTEM LEAKAGE

Although the air system leakage did increase during the test program, it had only a 1% effect on HS-C performance and was, therefore, not considered to have detrimentally affected any of the test results.

CO_2 and H_2O Permeation

The purpose of this test was to calibrate the rate of CO_2 and H_2O partial pressure change within the air circuit due to permeation. Permeation was a concern with the original test setup and eventually dictated the abandonment of that facility as previously discussed. After changing to the 10 x 10 steel chamber as a simulated cabin volume, permeation was nonexistent and ceased being a test variable.

The permeation test called for setting predetermined levels of CO_2 and dew point in the air circuit and monitoring these levels for a minimum of 16 hours. Two separate tests were run with a CO_2 level of 1.0 kPa (7.5 mm Hg) and a dew point of 15.6°C (60°F). In both tests there was no perceivable change in either CO_2 level or dew point after a 24 hour period. In addition, as performance testing proceeded, the morning start-up levels of CO_2 and dew point were periodically monitored and found to be the same as the shutdown levels of the previous afternoon.

The only perceivable drop in partial pressures was noted after a 26 day down period extending from December 11, 1975 to January 6, 1976. During this period the CO_2 level dropped from 0.53 kPa (4.0 mm Hg) to 0.35 kPa (2.6 mm Hg) for an average drop of 0.0072 kPa/day (0.05 mm Hg/day). The dew point dropped from 15.0°C (59°F) to 12.8°C (55°F) for an average drop of 0.085°C/day (0.15°F/day). The ambient dew point is traditionally in the (30°F) range during this time of year, thus resulting in a maximum driving potential for H_2O to migrate out of the air circuit.

The imperviousness of the completed test setup to CO_2 and H_2O migration was verified in both the daily checks and the extended calibration period. The permeation values measured during the extended period were so low they verified why degradation could not be measured during the 24 hour tests.

The conclusions of the permeation tests were that:

- Permeation is virtually nonexistent.
- Adjustments due to permeation was not required during testing.
- Corrections or adjustments of test data were not required due to permeation effects.

Canister Flow/Pressure Drop Calibration

The original purpose of this test was to calibrate the breadboard system's bypass flow control valve by mapping the bed airflow as a function of bed pressure drop. With the revised test setup, Rig 88 is used to regulate and control airflow, thus negating the use of the bypass valve for flow control. The Plan of Test was revised accordingly, but the flow/delta P mapping was retained as reference information for future design work.

During the test the airflow was increased in approximately 10 increments from 0 to 0.0212 m^3/s (0 to 45 cfm). The airflow was then decreased in the same increments to measure any hysteresis in the instrumentation. A slight hysteresis effect was encountered, and the data was averaged to produce the curves of Figure 35. The data points marked "Misc." are a compilation of daily data points collected over the full test program. These points indicate the repetitive nature of the bed flow characteristics and also that channelling and rearranging of HS-C material did not occur during the test period.

It is also noted that Bed "A" and "B" have different flow characteristics. No conclusive explanation can be given for this difference. Other parametric differences were encountered between beds, but the overall performance of the beds was essentially equal.

Instrument Calibration

The purpose of this calibration was to verify test measurements by demonstrating calibration before and after data collection.

All instrumentation was calibrated prior to testing by the Instrumentation and Metrology Department. All instruments were recalibrated as required by accepted standards during the test period. By the end of testing, all instruments were still within accepted time limits for their calibration. In addition, the CO_2 analyzers, dew pointers, and vacuum pressure instruments received special attention because of the critical nature of their readings. The Infra-Red CO_2 Analyzers (Liras) were calibrated each morning and before any detailed data collection period. The hygrometer (dew pointer) was balanced (null check) each morning and before any detailed data collection period. The vacuum pressure transducers and gage were checked against the calibration master at the conclusion of vacuum desorption testing to measure any drift that may have been introduced during the test period.

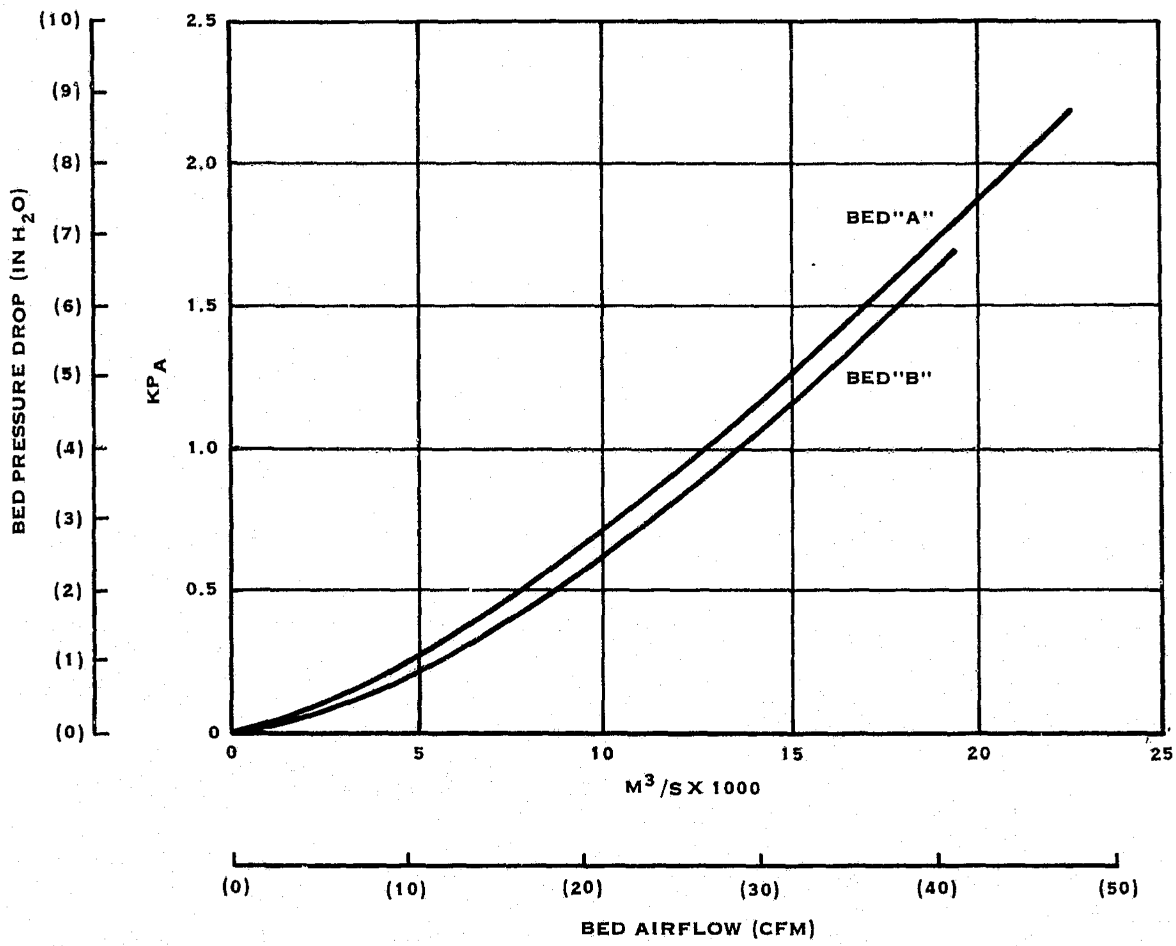


FIGURE 35 BREADBOARD CANISTER FLOW CHARACTERISTICS

Performance Calibration Testing

The purpose of this test is to define the timing and bypass flow required to maintain performance for use in subsequent mission tests. It was the intent of this test phase to run only long enough to establish equalibrium performance at each condition. The subsequent mission tests would be used to verify the long term effect at each condition.

The mission tests are intended to prove out the assumptions and conclusions of both the analysis (WBS 1.0) and design (WBS 2.0) phase of the program. Mission I is intended to prove the feasibility of using timing control to accommodate varying crew sizes and metabolic loadings. Mission II is intended to prove the feasibility of using flow control to handle varying metabolic loadings.

The environmental conditions to be used during testing were the same as those used as design points during the analysis and design phase. These are crew sizes of four and ten men and cabin temperature extremes of 18.3°C (65°F) and 26.7°C (80°F). The combinations of these variables produce four baseline test conditions which are also identified by "Environment Number." The points and nomenclature are as follows:

Test Condition (Environment No.)	Crew Size (Men)	Cabin Temperature °C (°F)
1	10	26.7 (80)
2	4	26.7 (80)
3	10	18.3 (65)
4	4	18.3 (65)

This phase of the test program was used to calibrate and optimize the cycle times and airflow rates necessary to meet each of the environments. The results of performance calibration testing are presented in Table 12. This table identifies the parameters to be used and the performance to be expected during mission testing. The impact of this data on the feasibility of each control scheme is discussed in the following subsections.

Timing Control

Timing control operates with a fixed airflow rate and varies cycle time to accommodate varying metabolic loadings. An airflow rate of 1.0 m^3/min (35 cfm) was established as the minimum required for the 10 man crew and was, therefore, used for all other timing control testing.

Calibration at the Environment 1 and Environment 2 conditions, 26.7°C (80°F) cabin temperature, was accomplished relatively easily because of the close proximity to the small scale test conditions. Testing at the Environment 3 and Environment 4 conditions, 18.3°C (65°F) cabin temperature, however, required testing over many days to achieve equilibrium at each condition. Testing at these latter conditions corroborated earlier parametric testing during Contract NAS 9-11971 in which a 5% reduction in CO_2 performance was recorded at the lower temperature, and an additional 5% reduction was recorded because of reduced humidity through the bed. The most significant results of this phase of testing occurred during Environment 4 where timing control could not meet all specification requirements. When adjusted to maintain an acceptable CO_2 level, the system removed too much water, and the cabin dew point fell below the 35°F limit. When adjusted to maintain an acceptable humidity level, the system CO_2 level rose above the 5.0 mm Hg nominal limit as shown in Table 1. Testing at this same condition with the flow control scheme, however, proved to be quite satisfactory; maintaining a 50°F dew point and a very low CO_2 level of 2.5 mm Hg.

Flow Control

Flow control operates the opposite of timing control. Flow control uses a fixed cycle time and varies the airflow through the HS-C canister to accommodate varying metabolic loadings. The performance with flow control is exceptional as indicated in Table 12. The 10 man cases are identical with the timing control, but the four man cases provide exceptionally low PCO_2 equilibrium points. The CO_2 performance of crew between four and ten men would be proportional to those experienced for the four and ten man loading.

Despite the obvious improvement in CO_2 performance offered by the flow control scheme, there are other parameters affecting the final choice of HS-C control. A thorough evaluation of these indicates that a combination of flow control and timing control actually produce the overall optimum system. This combination of control approaches was tested and is presented in the following section entitled "Parametric Testing."

Detailed Testing

This subsection presents the detailed tests that were run during the performance calibration phase of the test program. All pertinent test data is tabulated and presented in Table 13. As can be seen from this table, 19 test days and 134 test hours were needed to establish equilibrium conditions for the different environments and control schemes.

TABLE 12

TEST RESULTS

PERFORMANCE CALIBRATION TESTING

Environment POT No.	Crew Size Men	Cabin Temp. °C (°F)	Air Flow m^3/min (cfm)	Cycle Time Min Ads/Min Des	Dew Point °C (°F)	PCO_2 kPa (mmHg)
Timing Control						
1	10	26.7 (80)	1.0 (35)	14.8/14.8	14.4 (58)	.64 (4.8)
2	4	26.7 (80)	1.0 (35)	62/62	12.2 (54)	.64 (4.8)
3	10	18.3 (65)	1.0 (35)	10/10	2.8 (37)	.612 (4.6)
4	4	18.3 (65)	1.0 (35)	40/40	−0.6 (31)	.625 (4.7)
4	4	18.3 (65)	1.0 (35)	60/60	2.8 (37)	.800 (6.0)
Flow Control						
1	10	26.7 (80)	1.0 (35)	14.8/14.8	14.4 (58)	.64 (4.8)
2	4	26.7 (80)	0.43 (15)	14.8/14.8	15.9 (60.5)	.27 (2.0)
3	10	18.3 (65)	1.0 (35)	10/10	2.8 (37)	.61 (4.6)
4	4	18.3 (65)	0.43 (15)	14.8/14.8	10.0 (50)	.35 (2.6)

AMILTON STANDARD UNITED TECHNOLOGIES

TABLE 13

DATA SUMMARY
PERFORMANCE CALIBRATION TESTING
(S.I. UNITS)

TEST #	TEST DATE	CYCLE TIME (MIN)	PCO_2 INITIAL (KPA)	PCO_2 FINAL (KPA)	PH O_2 INITIAL (KPA)	PH O_2 FINAL (KPA)	AIR IN TEMP (°C)	ENVIR TEMP (°C)	FLOW (CFM)	TEST TIME (HRS)	SWITCH TIME (MIN)	EXP H_2O REM KG/HR	EXP CO_2 REM KG/HR	A MAX ADS T (°C)*	B MAX ADS T (°C)	A MIN DES T (°C)*	B MIN DES T (°C)	STABIL-ITY	HEADER VAC	
1	10-2	14.7	0.627	0.640	1.626	1.666	26.11	19.4	0.991	6.0	0.25	0.515	0.195	27 2	27.2	15 0	15.3	SI	340	
2	10-6&7	62.5	0.627	0.627	1 760	1.560	22.8	18.3		5.0	0 25			28.9	25.6	10.6	10 0	SI		
3	10-13	14.58	0.660	0.267	1.533	1.800	22.8	18.3	0.416	5.5	0.25	0.272	0.952	21 4	22.2	16 4	14 4	RD		
4	10-9&10	14	0.740	0.893	1.026	0.840	18.3	18.3	0.991	8.9	0.25	0.249	0.200	18 9	20.0	12.2	11 1	RI		
5	10-13	12	0.733	0.866	0.813	0.813	17.2	17.2	0.991	5 5	0.25	0.263	0.200	19 4	14.4	12 2	13 9	RI		
6	10-14	12	0.644	0.746	0.866	0.866	23.9	18.3	0.991	4.0	0.25	0.281	0.200	23 3	22.8	16.7	17 2	RI		
7	10-14	12	0.713	0.736	1.106	1.106	18.3	18.3	0.708	2.0	0.25	0.251	0.203	20 8	20.6	13.9	14.7	RI		
8	10-15	14.42	0.607	0.293	1 253	1.333	19.4	18.9	0.425	6.25	0.25	0 209	0.104	19 ?	19.4	18.0	13.9	RD		
9	10-28	11.75	0.746	0.667	0.986	0.813	18.9	18.9	0.991	2 0	0.25	0.281	0.213	20.0	21.1	13.3	14.4	SI	170/10	
10	10-28	9.75	0.667	0.707	0.813	0.720	18.9	18.9	0.991	3.5	0.25	0.272	0.204	20.0	20.3	14.4	14.4	SI	300/10	
11	10-30	9.75	0.613	0.573	0.773	0.720	18.3	18.3	0.991	4.0	0.25	0.263	0.200	18.9	20.0	13.3	14.4	SD	315/10	
12	10-31	10 4	0.627	0.440	1.373	1.373	25.6	18.3	0.991	5.0	0.25	0.494	0.204	25.6	24.4	16 7	17.8	SD		ACTIVE HEATING
13	11-5	60	0.653	0.600	1.067	0.746	18.6	18.3	0.991	5.0	0.25			19.4	19.4	8.9	12.2	RD		
14	11-5	60	0.640	0.773	0.813	0.720	18.3	18.3	0.991	11.0	0.25							RI		
15	11-7	40	0.587	0.607	0.667	0.593	18.3	18.3	0.991	10.0	0.25							SI		

* TEMP = EXP READING -2°F TO CORRECT FOR CALIBRATION

TABLE 13B

DATA SUMMARY
PERFORMANCE CALIBRATION TESTING
(U.S. UNITS)

TEST #	TEST DATE	CYCLE TIME (MIN)	PCO_2 INITIAL (MMHG)	PCO_2 FINAL (MMHG)	PH O_2 INITIAL (MMHG)	PH O_2 FINAL (MMHG)	AIR IN TEMP (°F)	ENVIR TEMP (°F)	FLOW (CFM)	TEST TIME (HRS)	SWITCH TIME (MIN)	EXP H_2O REM LB/HR	EXP CO_2 REM LB/HR	A MAX ADS T (°F)*	B MAX ADS T (°F)	A MIN DES T (°F)*	B MIN DES T (°F)	STABIL ITY	HEADER VAC	
1	10-2	14.7	4.7	4.8	12.2	12.3	79	67	35	6.0	0.25	1.135	0.43	81	81	59	59.5	SI	340	
2	10-6&7	62.5	4.7	4.7	13.2	11.7	73	65		5.0	0.25			84	78	51	50	SI		
3	10-8	14.58	4.95	2.0	11.5	13.5	73	65	14.7	5.5	0.25	0.6	0.21	70.5	72	61.5	58	RD		
4	10-9&10	14	5.55	6.7	7.7	6.3	65	65	35	8.9	0.25	0.55	0.44	66	68	54	52	RI		
5	10-13	12	5.5	6.5	6.1	6.1	63	63	35	5.5	0.25	0.58	0.44	67.0	58	54	57	RI		
6	10-14	12	4.83	5.6	6.5	6.5	75	65	35	4.0	0.25	0.62	0.44	74.0	73.0	62	63	RI		
7	10-14	12	5.35	5.52	8.3	8.3	65	65	25	2.0	0.25	0.62	0.448	69.5	69.0	57	58.5	RI		
8	10-15	14.42	4.55	2.2	9.4	10.0	67	66	15	6.25	0.25	0.46	0.23	66.5	67.0	59	37.0	RD		
9	10-28	11.75	5.6	5.9	7.4	6.1	66	66	35	2.0	0.25	0.62	0.47	68.0	70.0	56	58.0	SI	370/10	
10	10-28	9.75	5.0	5.3	6.1	5.4	66	66	35	3.5	0.25	0.6	0.45	68.0	68.5	58	58.0	SI	300/10	
11	10-30	9.75	4.6	4.3	5.8	5.4	65	65	35	4.0	0.25	0.58	0.44	66.0	68.0	56	58.0	SD	315/10	ACTIVE HEATING
12	10-31	10.4	4.7	3.3	10.3	10.3	78	65	35	5.0	0.25	1.09	0.45	78	76	62	64.0	SD		
13	11-5	60	4.9	4.2	8.0	5.6	65.5	65	35	5.0	0.25			67	67	48	54	RD		
14	11-6	60	4.8	5.8	6.1	5.4	65	65	35	11.0	0.25							RI		
15	11-7	40	4.4	4.55	5.0	4.45	65	65	35	10.0	0.25							SI		

* TEMP = EXP READING −2°F TO CORRECT FOR CALIBRATION

Parametric Testing

The parametric testing phase of the test program was added in lieu of Mission I to support the active design phase of the Flight Prototype System (WBS 10.0). In conducting the flight prototype design phase, a comprehensive Vehicle Integration Study had identified theoretically optimum airflow rate and cycle time combinations by extropolating breadboard data.

The design requirements for the new flight prototype system had a third major design point that directly affected the application of breadboard data to the new design. A seven man crew size was added for long term mission (30 days) optimization while the 10 man crew was reduced to a two day maximum mission. The 10 man breadboard data was directly applicable to the new flight prototype design. However, the four man parameters now wanted to be optimized around seven man airflows and cycle times rather than the previous 10 man parameters. In addition, no data existed for the projected seven man design point.

The need for test data to back up this new design was viewed as overwhelming by both Hamilton Standard and NASA. On November 11, 1975 it was decided to proceed with the proposed parametric test plan rather than the scheduled Mission I test.

This parametric test phase proved invaluable in establishing the operating parameters of the flight prototype system, providing parametric data for the system design optimization and providing conclusive backup verification of the proposed design at the Preliminary Design Review Meeting held at NASA/JSC on December 18, 1975.

Parametric Test Results

A summary of the results of the parametric test phases are shown in Table 14. Testing centered around seven man metabolic loadings, four man operation at seven man airflow rates and cycle times, and finally, attempting to force 10 man operation at seven man conditions.

Test numbers 5 and 6, the seven man cases, were run first to establish the seven man cycle time and flow rate. Test numbers 1 and 2 were then run and successfully demonstrated that timing control could maintain acceptable PCO_2 and humidity levels at the seven (7) man flow rate of 25 cfm. Test numbers 3 and 4 were then run to establish the flow control equilibrium PCO_2 and humidity levels at the seven (7) man cycle time and four (4) man flow rate. Finally, test numbers 7 and 8 were conducted to establish the minimum airflow requirement for 10 man loadings.

HAMILTON STANDARD
Division of UNITED TECHNOLOGIES

TABLE 14

PARAMETRIC TESTING RESULTS

Test No.	Crew Size Men	Cabin Temp. °C (°F)	Air Flow m^3/min (cfm)	Cycle Time Min Ads/Min Des	Dew Point °C (°F)	PCO_2 kPa (mmHg)
1	4	26.7 (80)	.71 (25)	40/40	10.9 (51.5)	.60 (4.5)
2	4	18.3 (65)	.71 (25)	40/40	3.3 (38)	.64 (4.8)
3	4	26.7 (80)	.43 (15)	20/20	15.6 (60)	.33 (2.5)
4	4	18.3 (65)	.43 (15)	20/20	8.9 (48)	.39 (2.9)
5	7	26.7 (80)	.71 (25)	20/20	13.9 (57)	.60 (4.5)
6	7	18.3 (65)	.71 (25)	20/20	2.2 (36)	.72 (5.4)
7	10	26.7 (80)	.85 (30)	10/10	16.7 (62)	.59 (4.4)
8	10	26.7 (80)	.85 (30)	10/10	16.7 (62)	.60 (4.5)

In order to minimize power penalties and simplify the fan design, it was desired to show the system could offer acceptable 10 man performance at seven (7) man airflow of 25 cfm. Unfortunately, 30 cfm was needed to offer the minimum acceptable performance. The only difference between test numbers 7 and 8 is the vacuum desorption pressure. Test number 7 was run at canister header vacuums of 190 microns while test number 8 was run at a higher pressure of 340 microns. No degradation in performance was noted at the higher pressure.

Detailed Testing

This subsection presents the detailed tests that were run during the parametric test phase of the breadboard test program. All pertinent test data is tabulated and presented in Table 15. Twelve test days and 65 test hours were required to obtain the desired equilibrium data for the eight design points.

Mission I

Mission I testing was originally intended to prove out the long term effect of the timing control approach to HS-C operation. The test was to provide continuous operation for the equivalent of a Shuttle mission. However, during the performance calibration test phase which was run as a preliminary test to predict expected mission performance, it was discovered that four man timing control performance could not meet the required specification limits at the 18.3°C (65°F) cabin conditions. The breadboard system actually removed too much water, and the dew point fell below the 1.7°C (35°F) lower limit.

The feasibility of running the Mission I test with its out-of-spec performance was weighed against the more urgent need to obtain parametric test data to support the then active Flight Prototype Design task (WBS 10.0). It was decided to substitute the parametric testing instead of Mission I since Mission I would not add substantive information to the program. In addition, the major objectives of the Mission I test would be proven in the Mission II test; namely, the ability of the breadboard system to operate continuously and provide acceptable performance for extended periods.

TABLE 15A

DATA SUMMARY
PARAMETRIC TESTING
(S. I. UNITS)

TEST #	TEST DATE	CYCLE TIME (MIN)	PCO_2 INITIAL (KPA)	PCO_2 FINAL (KPA)	PH_2O INITIAL (KPA)	PH_2O FINAL (KPA)	AIR IN TEMP (°C)	ENVIR TEMP (°C)	FLOW M^3 MIN	TEST TIME (HRS)	SWITCH TIME (MIN)	EXP H_2O REM KG/HR	EXP CO_2 REM KG/HR	A MAX ADS T (°C)*	B MAX ADS T (°C)	A MIN DES T (°C)*	B MIN DES T (°C)	STABIL-ITY	HEADER VAC	
16	11-12	20	0.627	0.746	0.880	0.720	18.3	18.9	0.991	6.0	0.25	0.127	0.181		21.1		14.7	RI		FLOW RATE
17	11-13	20	0.684	0.593	1.373	1.600	26.7	21.1	0.711	6.0	0.25	0.363	0.143	25.6	25.6	14.4	16.1	RD		
18	11-17	10	0.573	0.567	1.693	1.593	27.2	25	0.[illegible]07	6.0	0.25	0.513	0.204	28.9	27.8	17.2	19.4	ST	195/10	
19	11-19	10		0.600		1.893	27.2	23.3	0.850	7.0	0.25	0.517	0.195	27.2	27.2	16.7	19.2		220/10A 220/10B	
20	12-2	40	0.613	0.640	0.746	0.773	18.3	21.7	0.708	4.0	0.25	0.172	0.095	21.7	21.7	14.2	14.2	SI	65/40	
21	12-4	49	N/A	0.600	N/A	1.293	25.0	23.3	0.708	2.8	0.25	0.142	0.209	25.0	26.7	15.6	14.4	SD	70/40	
22	12-5	20	0.740	0.527	1.733	1.640	25.0	22.8	0.425	5.0	0.25	0.231	0.095	25.8	25.0	16.7	15.6	RD	115/20	
23	12-6	20	0.546	0.413	1.760	1.146	17.8	19.4	0.430	5.0	0.25	0.150	0.095	21.7	21.7	14.4	13.9	RD	88/20	
24	12-9	20.5	0.400	0.333	N/A	1.666	26.7	25.6	0.425	6.0	0.25	0.254	0.095	27.8	27.8	18.9	19.9	RD	100/20	
25	12-10,11	10	0.467	0.527	1.440	1.706	26.7	25.6	0.986	6.5	0.25	0.567	0.204	28.9	28.3	17.2	18.3	SI	310/10	
26	12-11	10	0.527	0.527	1.706	1.706	25.7	26.1	0.705	5.0	0.25	0.517	0.200	28.9	28.3	17.8	18.3	ST	310/10	

* TEMP = EXP READING −2°F TO CORRECT FOR CALIBRATION

TABLE 15B

DATA SUMMARY
PARAMETRIC TESTING
(U.S. UNITS)

TEST #	TEST DATE	CYCLE TIME (MIN)	PCO_2 INITIAL (MMHG)	PCO_2 FINAL (MMHG)	PH_2O INITIAL (MMHG)	PH_2O FINAL (MMHG)	AIR IN TEMP (°F)	ENVIR TEMP (°F)	FLOW (CFM)	TEST TIME (HRS)	SWITCH TIME (MIN)	EXP H_2O REM LB/HR	EXP CO_2 REM LB/HR	A MAX ADS T (°F)*	B MAX ADS T (°F)	A MIN DES T (°F)*	B MIN DES T (°F)	STABILITY	HEADER VAC	
16	11-12	20	4.7	5.6	6.6	5.4	65	66	35IRR	6.0	0.25	0.28	0.4		70		58.5	RI		FLOW RATE
17	11-13	20	5.13	4.45	10.3	12.0	80	70	25.1	6.0	0.25	0.80	0.315	78	78	58	61	RD		
18	11-17	10	4.3	4.25	12.7	14.2	81	77	28.5	6.0	0.25	1.13	0.45	84	82	64	67	ST	195/10	
19	11-19	10		4.5		14.2	81	74.	30	7.0	0.25	1.14	0.43	81	81	[illegible]	66.5		220/10A 220/10B	
20	12-2	40	4.6	4.8	5.6	5.8	65	71	25	4 0	0.25	0.38	0.21	71	71	[illegible]	57.5	SI	65/40	
21	12-4	49	N/A	4.5	N/A	9 7	77	74	25	2.8	0.25	0.312	0.46	77	80	60.0	58.0	SD	70/40	
22	12-5	20	5.55	3.95	13.0	12.3	77	73	15	5.0	0.25	0.51	0.21	77	77	62.0	60.0	RD	115/20	
23	12-6	20	4.1	3.1	13.2	8.6	64	67	15.2	5.0	0.25	0.33	0.21	71	[illegible]	58.0	57.0	RD	88/20	
24	12-9	20.5	3.0	2.5	N/A	12.5	80	78	15	6.0	0.25	0.56	0.21	82	82	66.0	66.0	RD	100/20	
25	12-10,11	10	3.5	3.95	10.8	12.8	80	78	34.8	6.5	0.25	1.25	0.45	84	83	63.0	65.0	SI	310/10	
26	12-11	10	3.95	3.95	12.8	12.8	80	79	34.9	5 0	0.25	1.14	0.44	84	83	63.0	65.0	ST	310/10	

* TEMP = EXP READING −2°F TO CORRECT FOR CALIBRATION

Mission II Testing

The purpose of this test was to demonstrate bypass flow control of CO_2 and humidity levels during a simulation of a Shuttle mission. The mission test first requires 10 hours of continuous operation at Environment No. 1 followed by a minimum of 20 continuous hours at Environment No. 2. Together, these 26.7°C (80°F) conditions were to log a minimum of 60 hours. The test setup was then reset to 18.3°C (65°F) conditions for an additional 60 hours of testing, including a minimum of 10 continuous hours at Environment No. 3 and a minimum of 20 continuous hours at Environment No. 4.

The Mission II test phase proved out the long term performance that was predicted during the previous performance calibration test phase. The test totaled 126 hours with a continuous operating period of 95 hours. During the test period, the HS-C humidity performance was compatible with the Shuttle ARS (Atmosphere Revitalization Subsystem) performance. The HS-C CO_2 performance, however, was considerably better than the existing Shuttle ARS at all environmental conditions. Both systems remove CO_2 at the metabolic production rate, but the HS-C system maintains lower cabin PCO_2 levels than the Shuttle baseline system.

The detailed presentation of the Mission II test is divided into two subsections. The first is the high temperature, 26.7°C (80°F), cases of Environments Numbers 1 and 2. The second subsection presents the low cabin temperature, 18.3°C (65°F), environments identified as No. 3 and No. 4.

High Cabin Temperature Mission

The high cabin temperature, 26.7°C (80°F), portion of Mission II was accomplished primarily during the week of January 7 through 9, 1976. The test data and performance profiles are presented in Figure 36 and also numerically tabulated in Table 16. The ensuing discussion will reference the curves of Figure 36. Table 16 provides the background data for each curve and also provides actual metabolic feed rates.

Figure 36 presents the test data in the following order, starting from the top and progressing downward.

Environment Number: This is the environmental condition as specified in the Plan of Test and described in a previous subsection.

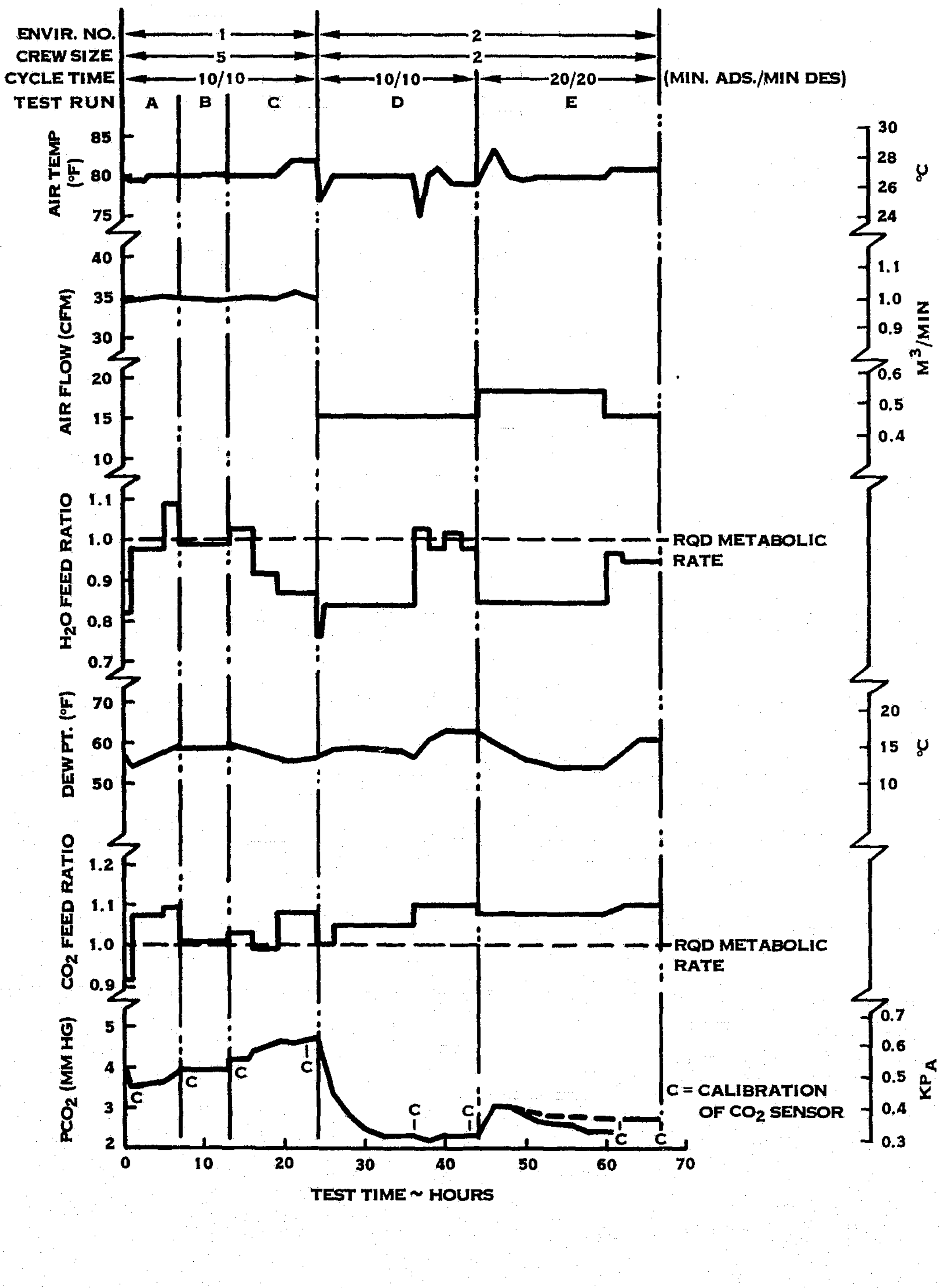


FIGURE 36 MISSION II: HIGH TEMPERATURE PROFILES

TABLE 16A

DATA SUMMARY
MISSION II, HIGH TEMPERATURE
(S.I. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST IDENT	TIME INTO RUN (HR)	TEMP (°C)	FLOW (M^3/MIN)	CYCLE TIME (MIN/MIN)	P CO_2 (KPA)	CO_2 FEED (KG/HR)	CO_2 FEED / CO_2 REQ	DEW PT (°C)	H_2O FEED (KG/HR)	H_2O FEED / H_2O REQ'D.
1	0	A	O	26.7	0.977	10/10	0.533	0.181	0.91	13.9	0.426	0.82
	1	A	1	26.4	0.982	10/10	0.467	0.181	0.91	12.5	0.426	0.82
	5	A	5	26.7	0.991	10/10	0.480	0.213	1.07	15.0	0.510	0.98
	7	A	7	26.7	0.991	10/10	0.520	0.218	1.09	15.3	0.567	1.09
1	7	B	0	26.7	0.991	10/10	0.520	0.218	1.09	15.3	0.567	1.09
	13	B	6	26.1	0.982	10/10	0.527	0.202	1.01	15.0	0.517	.99
1	13	C	0	26.7	0.991	10/10	0.560	0.204	1.03	15.6	0.540	1.03
	15.5	C	2.5	26.7	0.991	10/10	0.560	0.204	1.03	14.7	0.540	1.03
	16.0	C	3	26.7	0.991	10/10	0.587	0.204	0.96	14.7	0.540	1.03
	19.0	C	6	26.7	0.991	10/10	0.613	0.191	1.09	13.3	0.481	0.92
	21.0	C	8	27.7	0.991	10/10	0.613	0.218	1.09	13.1	0.454	0.87
	24	C	11	27.7	0.991	10/10	0.677	0.218	1.04/1.0	13.3	0.454	0.87
2	24	D	0	25.5	0.436	10/10	0.627	0.095	1.0	13.3	0.213	0.76
	26	D	2	26.7	0.436	10/10	0.453	0.095	1.05	14.4	0.236	0.54
	28	D	4	26.7	0.436	10/10	0.373	0.100	1.05	14.7	0.236	0.54
	30	D	6	26.7	0.436	10/10	0.320	0.100	1.05	14.7	0.236	0.84
	32	D	8	26.7	0.436	10/10	0.307	0.100	1.05	14.4	0.236	0.84
	34	D	10	26.7	0.436	10/10	0.307	0.100	1.05	14.4	0.236	0.84
	36	D	12	26.7	0.436	10/10	0.307	0.100	1.05	13.3	0.236	0.84
	38	D	14	26.7	0.436	10/10	0.293	0.104	1.10	16.1	0.290	1.03
	40	D	16	26.7	0.436	10/10	0.307	0.104	1.10	17.2	0.277	0.98
	42	D	18	26.1	0.436	10/10	0.307	0.104	1.10	17.2	0.286	1.02
	44	D	20	26.1	0.436	10/10	0.307	0.104	1.10	17.2	0.277	0.98
2	44	E	0	26.1	0.524	20/20	0.347	0.103	1.08	17.2	0.240	0.85
	46	E	2	28.3	0.524	20/20	0.400	0.103	1.08	16.1	0.240	0.85
	48	E	4	26.7	0.524	20/20	0.400	0.103	1.08	14.7	0.240	0.85
	50	E	6	26.4	0.524	20/20	0.373	0.103	1.08	13.3	0.240	0.85

TABLE 16A (CONTINUED)

DATA SUMMARY
MISSION II, HIGH TEMPERATURE
(S.I. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST INDENT	TIME INTO RUN (HR)	TEMP (°C)	FLOW M^3/MIN	CYCLE TIME (MIN/MIN)	P CO_2 (KPA)	CO_2 FEED (KG/HR)	CO_2 FEED / CO_2 REQ'D	DEW PT. (°C)	H_2O FEED (KG/HR)	H_2O FEED / H_2O REQ'D.
2	52	E	8	26.7	0.524	20/20	0.353	0.103	1.08	12.8	0.240	0.85
	54	E	10	26.7	0.524	20/20	0.347	0.103	1.08	12.2	0.240	0.85
	56	E	12	26.7	0.524	20/20	0.340	0.103	1.08	12.2	0.240	0.85
	58	E	14	26.7	0.524	20/20	0.320	0.103	1.08	12.2	0.240	0.85
	60	E	16	26.7	0.524	20/20	0.320	0.103	1.08	12.2	0.240	0.85
	61	E	17	27.2	0.439	20/20	0.320	0.104	1.09	13.3	0.272	0.97
	62	E	18	27.1	0.439	20/20	0.360	0.104	1.10	13.8	0.268	0.95
	64	E	20	27.1	0.439	20/20	0.360	0.104	1.10	15.8	0.268	0.95
	66.5	E	22.5	26.9	0.439	20/20	0.360	0.104	1.10	15.8	0.268	0.95

TABLE 16B

DATA SUMMARY
MISSION II, HIGH TEMPERATURE
(U.S. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST IDENT	TIME INTO RUN (HR)	TEMP (°F)	FLOW (CFM)	CYCLE TIME (MIN/MIN)	P CO_2 (MM HG)	CO_2 FEED (LB/HR)	CO_2 FEED / CO_2 REQ	DEW PT. (°F)	H_2O FEED (LB/HR)	H_2O FEED / H_2O REQ
1	0	A	0	80	34.5	10/10	4.0	0.40	0.91	57	0.94	0.82
	1	A	1	79.5	34.7	10/10	3.5	0.40	0.91	54.5	0.94	0.82
	5	A	5	80	35	10/10	3.6	0.47	1.07	59	1.125	0.98
	7	A	7	80	35	10/10	3.9	0.48	1.09	59.5	1.25	1.09
1	7	B	0	79	34.7	10/10	3.95	0.446	1.01	59	1.14	0.99
	13	B	6	79	34.7	10/10	3.95	0.446	1.01	59	1.14	0.99
1	13	C	0	0	35	10/10	4.2	0.45	1.03	60	1.19	1.03
	15.5	C	2.5	80	35	10/10	4.2	0.45	1.03	58.5	1.19	1.03
	16.0	C	3	80	35	10/10	4.4	0.45	1.03	58.5	1.19	1.03
	19.0	C	6	80	35	10/10	4.6	0.42	0.96	56.0	1.06	0.92
	21.0	C	8	82	35.0	10/10	4.6	0.48	1.09	55.5	1.00	0.87
	24	C	11	82	35.0	10/10	4.7	0.48	1.09	56.0	1.00	0.87
2	24	D	0	78	15.4	10/10	4.7	0.21	1.0	56.0	0.47	0.76
	26	D	2	80	15.4	10/10	3.4	0.21	1.0	58.0	0.52	0.84
	28	D	4	80	15.4	10/10	2.8	0.22	1.05	58.5	0.52	0.84
	30	D	6	80	15.4	10/10	2.4	0.22	1.05	58.5	0.52	0.84
	32	D	8	80	15.4	10/10	2.3	0.22	1.05	58	0.52	0.84
	34	D	10	80	15.4	10/10	2.3	0.22	1.05	58	0.52	0.84
	36	D	12	80	15.4	10/10	2.3	0.22	1.05	56	0.52	0.84
	38	D	14	80	15.4	10/10	2.2	0.23	1.10	61	0.64	1.03
	40	D	16	80	15.4	10/10	2.3	0.23	1.10	63	0.61	0.98
	42	D	18	79	15.4	10/10	2.3	0.23	1.10	63	0.63	1.02
	44	D	20	79	15.4	10/10	2.3	0.23	1.1	63	0.61	0.98

TABLE 16B (CONTINUED)

DATA SUMMARY
MISSION II, HIGH TEMPERATURE
(U.S. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST IDENT	TIME INTO RUN (HR)	TEMP (°F)	FLOW (CFM)	CYCLE TIME (MIN/MIN)	PCO_2 MM #G (MM HG)	CO_2 FEED (LB/HR)	CO_2 FEED / CO_2 REQ	DEW PT. (°F)	H_2O FEED (LB/HR)	H_2O FEED / H_2O REQ
2	44	E	0	79	18.5	20/20	2.6	0.226	1.08	63	0.53	0.85
	46	E	2	83	18.5	20/20	3.0	0.226	1.08	61	0.53	0.85
	48	E	4	80	18.5	20/20	3.0	0.226	1.08	58.5	0.53	0.85
	50	E	6	79.5	18.5	20/20	2.8	0.226	1.08	56	0.53	0.85
	52	E	8	80	18.5	20/20	2.65	0.226	1.08	55	0.53	0.85
	54	E	10	80	18.5	20/20	2.6	0.226	1.08	54	0.53	0.85
	56	E	12	80	18.5	20/20	2.55	0.226	1.08	54	0.53	0.85
	58	E	14	80	18.5	20/20	2.4	0.226	1.08	54	0.53	0.85
	60	E	16	80	18.5	20/20	2.4	0.226	1.08	54	0.53	0.85
	61	E	17	81	15.5	20/20	2.4	0.229	1.09	56	0.60	0.97
	62	E	18	80.8	15.5	20/20	2.7	0.23	1.10	57	0.59	0.95
	64	E	20	80.7	15.5	20/20	2.7	0.23	1.10	60.5	0.59	0.95
	66.5	E	22.5	80.5	15.5	20/20	2.7	0.23	1.10	60.5	0.59	0.95

Crew Size: The actual design point metabolic feed rate condition; either five or two men. It should be remembered that the breadboard system is half size, and the 10 man loading was actually only to a five man rate.

Cycle Time: The time each bed is on the adsorption cycle compared to the time each bed is on the desorption cycle. Fifteen seconds is required out of each cycle for the switch over of adsorption/desorption beds.

Test Run: This is an identification code letter assigned to each separate test run and is used to code all data sheets and strip charts from either raw or refined data.

Air Temperature: This was the actual temperature of the airflow entering the breadboard HS-C canister.

Airflow: This is actual airflow rate passing through the HS-C canister.

H_2O Feed: This is a normalized ratio of the actual water feed rate divided by the desired metabolic feed rate of the given crew size. A value of 1.0 is a perfect feed rate, while 1.1 represents a feed rate 10% too high, and 0.9 represents only 90% of the required feed rate.

Dew Point: This is a measure of humidity control performance and represents the actual dew point of the simulated Shuttle cabin volume.

CO_2 Feed: This is a normalized ratio of the actual CO_2 feed rate divided by the desired metabolic feed rate of the given crew size. The resultant value converts directly to percentage of required feed as described above in the H_2O feed definition.

PCO_2: This is a measure of the actual PCO_2 level in the simulated Shuttle cabin volume and represents the CO_2 control performance parameter.

As can be seen from Figure 36, the first two attempts at initiating Mission II testing were foreshortened at the seven and six hour point respectively. This testing occurred on December 10 and 11, 1975 and had to be terminated because of repetitive failures of Rig 52, the desorption vacuum source. A detailed investigation identified waterlogged vacuum pumps as the cause of rig shutdown. A thorough dry out procedure followed by the changing of the pump oil in all three blower sections cured this rig problem. It was also concluded that a full 24 hour purging of the rig cold traps is required for continued operation. The around-the-clock nature of the mission test was compatible with the rig purge cycle, whereas the previous performance calibration and parametric test phase only tested and purged the unused cold trap for eight hours a day, thus generating the waterlogging problem.

Mission testing commenced again on January 7, 1976 with successful results. Test Run "C" ran for 11 hours at Environment No. 1. The air temperature and flow were maintained within required limits. The water feed rate, however, averaged only 93% of the required value resulting in an equilibrium dew point of 13.3°C (56°F). This equilibrium dew point correlates perfectly with the parametric humidity control mapping presented earlier in Figure 8. From this mapping the dew point would scale up to a value of 14.4°C (58°F) had the feed rate ratio been 1.0.

Before continuing it should be mentioned that the water feed rate control was disappointing throughout the test program. Steam was generated at constant pressure and fed through a calibrated micrometering valve into the simulated cabin volume. Despite the fact that triple distilled water was fed to the steam generator, a noticeable amount of contamination was discovered daily in the generator residue. It was suspected that this contamination was being generated within the steam boiler and partially clogging the outlet micrometering valve. The valve was observed to have a decreasing drift in feed rate at any setting. Opening the valve fully and closing back to the original setting increased the flow rate. It was assumed this action tended to clean the valve seat/ needle arrangement.

The inability to hold tight water feed rate control is not considered to have negated the significance or performance of the mission tests in any way. The ability of HS-C to remove water is well understood as defined in performance mapping curves of Figure 8. The mission tests only further corroborated the validity of that performance and, conversely, that corroboration allows the performance mapping of Figure 8 to predict full feed rate performance of all mission test runs.

The CO_2 feed rate control was more stable as indicated by Figure 36. During Test Run "C", the CO_2 feed averaged 4% high. The CO_2 level in the simulated cabin was 0.56 kPa (4.2 mm Hg) at start of testing and generally followed the feed rate curve up to an end condition of 0.63 kPa (4.7 mm Hg) at the end of the 11 hour test run. The CO_2 leveled off when the CO_2 feed ratio neared to 1.0 value but would rise when the feed ratio was higher. This is especially true during the last four hours of testing when the feed rate was 9% high, and the PCO_2 level drifted from a stable value of 0.61 kPa (4.6 mm Hg) to a final value of 0.63 kPa (4.7 mm Hg).

At the completion of the Environment No. 1 test requirement, the CO_2 and H_2O feed rates were adjusted to the Environment No. 2 levels. The airflow was lowered to the 0.007 m^3/s (15 cfm) level to accommodate the smaller crew size as defined by the previous performance calibration testing. The two other parameters, air temperature and cycle time, remained the same.

With the test setup adjusted to the two man crew size, the transient effect on the two performance parameters, dew point and PCO_2 level, was plotted. The dew point drifted to 14.4°C (58°F) where it remained stable all night with a feed rate 16% low (feed ratio = .84). In the morning the water feed rate was adjusted to the proper level and maintained for the last eight hours of testing. Consequently, the dew point drifted up and stabilized at 16.4°C (61.5°F) for the last five hours of the test. This is actually 0.3°C (0.5°F) too high and shows that the humidity control function sets the airflow rate requirement of this environmental condition. This is verified by the PCO_2 performance curve which dropped down to an equilibrium level of only 0.31 kPa (2.3 mm Hg). The CO_2 feed rate averaged 7% high for the 20 hour duration of this test while the CO_2 level maintained the equilibrium condition for the last 12 hours of testing.

At the completion of the required 20 hours of continuous operation, a second Environment No. 2 condition was initiated and identified as Test Run "E". The only difference between test Runs "D" and "E" was the bed switch over cycle time.

Test Run "D" used a cycle time compatible with the original breadboard program philosophy of running the four man tests as a variation of the 10 man design points; and, hence, the 10 man dictated 10/10 cycle time.

Test Run "E" was initiated at the direction of NASA to bring the test program more in line with the projected modes as concluded in the then, just completed, Shuttle Vehicle Integration Study. This study identified four man operating conditions as a variation of the more optimum seven man design points. The parametric test phase identified a 20/20 cycle time as baseline for the seven man crew.

It was anticipated that the increasing of cycle time from 10 minutes to 20 minutes would adversely affect both CO_2 and humidity performance. With a dew point already over the high limit, it was decided to increase the airflow rate to 0.0087 m^3/s (18.5 cfm) for at least the night portion of the test. Unforuntately, the recurring water feed control problem compounded this adjustment. The overnight water feed rate was only 85% of what it had been the previous day at the same setting. As a result, the dew point dropped to the 12.2°C (54°F) level by morning. The airflow was then cut back to its original 0.007 m^3/s (15 cfm) level, and the water feed was increased. The dew point then made a dramatic change upwards and stabilized at 15.8°C (60.5°F). This resultant dew point, being so close to that of Test Run "D", corroborated another observation reflected in the humidity performance mapping of Figure 8. There is no perceivable performance differences in humidity removal for cycle times of less than 30 minutes (30/30 cycle time).

The CO_2 performance during Test Run "E" was expected. The equilibrium CO_2 level was slightly higher than Test Run "D" at 0.36 kPa (2.7 mm Hg). The dashed curve of PCO_2 is an assumed projection due to step change in PCO_2 readings as a result of calibrating the CO_2 Liras with 4.5 hours remaining in the test run. The overall CO_2 performance during the two man flow control environments were considered excellent especially when compared to the baseline Shuttle LiOH system that maintains a nominal 0.67 kPa (5.0 mm Hg) PCO_2 level.

Low Cabin Temperature Mission

The low cabin temperature, 18.3°C (65°F), portion of Mission II was accomplished the week of January 12 through 15, 1976. The test parameters and performance profiles are summarized in Figure 37. The backup data for the curves of Figure 37 is presented in Table 17 which also includes the actual metabolic feed rates. Figure 37 presents the test data in the same order and units as Figure 36 in the High Cabin Temperature Mission subsection. For a detailed description of each parameter, please refer to that subsection.

The low temperature portion of Mission II was started per the Plan of Test at Environment No. 3. Unfortunately, repetitive failures of the breadboard system's electronic controller caused a premature ending of the first two runs, Test Run "F" and "G". After rewiring the controller to bypass the failed timing circuit, the mission test continued without further trouble.

Test Run "H" commenced 95 hours of continuous mission testing. Test Run "H" ran 17.5 hours at Environment No. 3 which requires five man metabolic feed rates. The air temperature into the breadboard system was controlled within 1.1°C (2°F) of 18.3°C (65°F). The airflow rate was controlled almost exactly at 1.0 m^3/min (35 cfm) for the test duration.

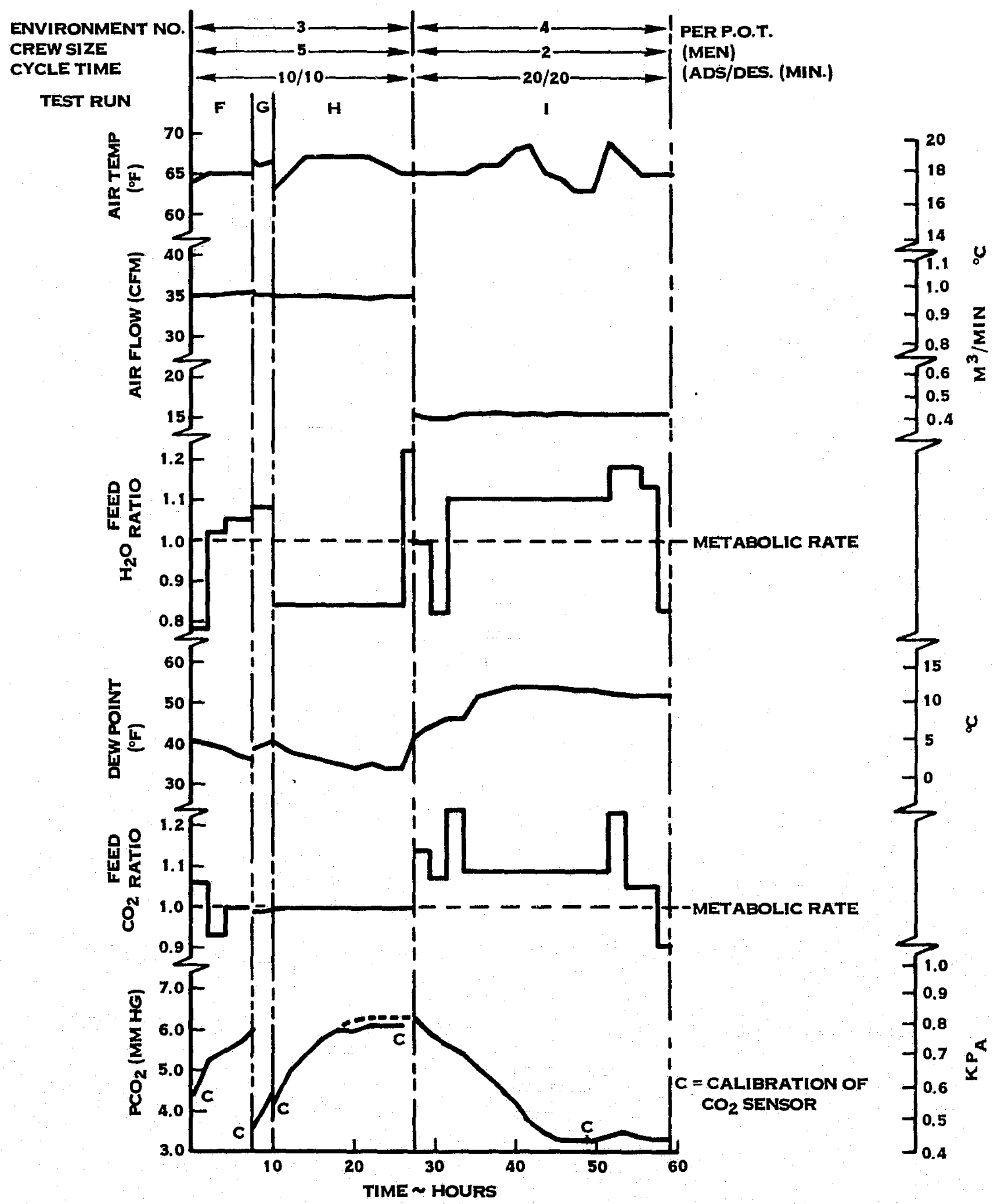


FIGURE 37 MISSION II: LOW TEMPERATURE PROFILES

TABLE 17A

DATA SUMMARY
MISSION II, LOW TEMPERATURE
(S.I. UNITS)

ENV NO	TIME INTO MISSION (HR)	TEST IDENT	TIME INTO RUN (HR)	TEMP (°C)	FLOW (M3/MIN)	CYCLE TIME (MIN/MIN)	PCO (KPA)	CO_2 FEED (KG/HR)	CO_2 FEED / CO_2 REQ'D	DEW PT (°C)	H_2O FEED (KG/HR)	H_2 FEED / H_2 REQ'D
3	0	F	0	17.8	0.994	10/10	0.587	0.211	1.06	5.0	0.195	0.78
	2	F	2	18.3	0.994	10/10	0.693	0.211	1.06	4.4	0.195	0.78
	4	F	4	18.3	1.000	10/10	0.720	0.186	0.93	3.9	0.254	1.02
	6	F	6	18.3	1.003	10/10	0.760	0.200	1.00	2.8	0.262	1.05
	7.5	F	7.5	18.3	1.006	10/10	0.800	0.195	0.98	2.2	0.262	1.05
3	7.5	G	0	19.2	0.997	10/10	0.480	0.193	0.96	3.9	0.269	1.08
	8.5	G	1	18.9	0.991	10/10	0.533	0.193	0.96	5.0	0.269	1.08
	10	G	2.5	19.2	0.991	10/10	0.600	0.195	0.98	4.4	0.249	1.00
3	10	H	0	17.2	0.991	10/10	0.560	0.195	0.98	4.4	0.209	0.84
	12	H	2	18.3	0.991	10/10	0.667	0.196	0.98	3.3	0.209	0.84
	14	H	4	19.4	0.991	10/10	0.720	0.196	0.98	2.8	0.209	0.84
	16	H	6	19.4	0.991	10/10	0.772	0.196	0.98	2.2	0.209	0.84
	18	H	8	19.4	0.991	10/10	0.800	0.196	0.98	1.7	0.209	0.84
	20	H	10	19.4	0.986	10/10	0.800	0.196	0.98	1.1	0.209	0.84
	22	H	12	19.4	0.986	10/10	0.813	0.196	0.98	1.7	0.209	0.84
	24	H	14	18.9	0.991	10/10	0.813	0.196	0.98	1.1	0.209	0.84
	26	H	16	18.3	0.991	10/10	0.813	0.195	0.99	1.1	0.209	0.84
	27.5	H	17.5	18.3	0.991	10/10	0.840	0.195	0.98	5.0	0.304	1.22
4	27.5	I	0	18.3	0.439	20/20	0.840	0.195	1.14	5.0	0.172	0.98
	29.5	I	2	18.3	0.425	20/20	0.786	0.109	1.14	6.7	0.172	0.98
	31.5	I	4	18.3	0.425	20/20	0.746	0.102	1.07	7.8	0.145	0.82
	33.5	I	6	18.3	0.439	20/20	0.720	0.118	1.24	7.8	0.195	1.10
	35.5	I	8	18.9	0.439	20/20	0.667	0.104	1.09	11.1	0.195	1.10
	37.5	I	10	18.9	0.445	20/20	0.027	0.104	1.09	11.7	0.195	1.10
	39.5	I	12	20.0	0.439	20/20	0.573	0.104	1.09	12.2	0.195	1.10
	41.5	I	14	20.3	0.445	20/20	0.507	0.104	1.09	12.2	0.195	1.10
	43.5	I	16	18.3	0.439	20/20	0.467	0.104	1.09	12.2	0.195	1.10
	45.5	I	18	18.1	0.445	20/20	0.440	0.104	1.09	11.9	0.195	1.10
	47.5	I	20	17.2	0.439	20/20	0.440	0.104	1.09	11.7	0.195	1.10
	49.5	I	22	17.2	0.439	20/20	0.440	0.104	1.09	11.7	0.195	1.10

TABLE 17A (CONTINUED)

DATA SUMMARY
MISSION II, LOW TEMPERATURE
(S.I. UNITS)

ENV NO	TIME INTO MISSION (HR)	TEST IDENT	TIME INTO RUN (HR)	TEMP (°C)	FLOW (M3/MIN)	CYCLE TIME (MIN/MIN)	PCO (KPA)	CO_2 FEED (KG/HR)	CO_2 FEED / CO_2 REQ'D	DEW PT (°C)	H_2O FEED (KG/HR)	H_2 FEED / H_2 REQ'D
4	51.5	I	24	20.6	0.439	20/20	0.453	0.104	1.09	11.4	0.195	1.10
	53.5	I	26	19.4	0.439	20/20	0.467	0.118	1.23	11.1	0.209	1.18
	55.5	I	28	18.3	0.439	20/20	0.447	0.100	1.05	11.1	0.209	1.18
	57.5	I	30	18.3	0.439	20/20	0.440	0.100	1.05	11.1	0.200	1.13
	59.0	I	31.5	18.3	0.439	20/20	0.440	0.056	0.91	11.1	0.147	0.83

TABLE 17B

DATA SUMMARY
MISSION II, LOW TEMPERATURE
(U. S. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST RUN	TIME INTO RUN (HR)	TEMP (°F)	FLOW (CFM)	CYCLE TIME (MIN/MIN)	PCO_2 (MM HG)	CO_2 FEED (LB/HR)	CO_2 FEED / CO_2 REQ	DEW PT. (°F)	H_2O FEED (LB/HR)	H_2O FEED / H_2O REQ
3	0	F	0	64	35.1	10/10	4.4	0.465	1.06	41	0.43	0.78
	2	F	2	65	35.1	10/10	5.2	0.465	1.06	40	0.43	0.78
	4	F	4	65	35.3	10/10	5.4	0.41	0.932	39	0.56	1.02
	6	F	6	65	35.4	10/10	5.7	0.44	1.0	37	0.578	1.05
	7.5	F	7.5	65	35.5	10/10	6.0	0.43	0.98	36	0.578	1.05
3	7.5	G	0	66.5	35.2	10/10	3.6	0.425	0.96	39	0.594	1.08
	8.5	G	1	66.0	35	10/10	4.0	0.425	0.96	41	0.594	1.08
	10.	G	2.5	66.5	35	10/10	4.5	0.43	0.98	40	0.550	1.0
3	10	H	0	63	35	10/10	4.2	0.43	0.98	40	0.46	0.84
	12	H	2	65	35	10/10	5.0	0.433	0.985	38	0.46	0.84
	14	H	4	67	35	10/10	5.4	0.433	0.985	37	0.46	0.84
	16	H	6	67	35	10/10	5.8	0.433	0.985	36	0.46	0.84
	18	H	8	67	35	10/10	6.0	0.433	0.985	35	0.46	0.84
	20	H	10	67	34.8	10/10	6.0	0.433	0.985	34	0.46	0.84
	22	H	12	67	34.8	10/10	6.1	0.433	0.985	35	0.46	0.84
	24	H	14	66	35	10/10	6.1	0.433	0.985	34	0.46	0.84
	26	H	16	65	35	10/10	6.1	0.43	0.985	34	0.46	0.84
	27.5	H	17.5	65	35	10/10	6.3	0.43	0.98	41	0.67	1.22
4	27.5	I	0	65	15.5	20/20	6.3	0.24	1.14	41	0.38	0.98
	29.5	I	2	65	15.0	20/20	5.9	0.24	1.14	44	0.38	0.98
	31.5	I	4	65	15	20/20	5.6	0.225	1.07	46	0.32	0.82
	33.5	I	6	65	15.5	20/20	5.4	0.26	1.24	46	0.43	1.10
	35.5	I	8	66	15.5	20/20	5.0	0.229	1.09	52	0.43	1.10
	37.5	I	10	66	15.7	20/20	4.7	0.229	1.09	53	0.43	1.10
	39.5	I	12	68	15.5	20/20	4.3	0.229	1.09	54	0.43	1.10
	41.5	I	14	68.5	15.7	20/20	3.8	0.229	1.09	54	0.43	1.10
	43.5	I	16	65	15.5	20/20	3.5	0.229	1.09	54	0.43	1.10
	45.5	I	18	64.5	15.7	20/20	3.3	0.229	1.09	53.5	0.43	1.10
	47.5	I	20	63	15.5	20/20	3.3	0.229	1.09	53	0.43	1.10
	49.5	I	22	63	15.5	20/20	3.3	0.229	1.09	53	0.43	1.10

TABLE 17B (CONTINUED)

DATA SUMMARY
MISSION II, LOW TEMPERATURE
(U. S. UNITS)

ENV. NO.	TIME INTO MISSION (HR)	TEST RUN	TIME INTO RUN (HR)	TEMP (°F)	FLOW (CFM)	CYCLE TIME (MIN/MIN)	PCO_2 (MM HG)	CO_2 FEED (LB/HR)	CO_2 FEED / CO_2 REQ	DEW PT. (°F)	H_2O FEED (LB/HR)	H_2O FEED / H_2O REQ
4	51.5	I	24	69	15.5	20/20	3.4	0.229	1.09	52.5	0.43	1.10
	53.5	I	26	67	15.5	20/20	3.5	0.26	1.23	52	0.46	1.18
	55.5	I	28	65	15.5	20/20	3.35	0.22	1.05	52	0.46	1.18
	57.5	I	30	65	15.5	20/20	3.3	0.22	1.05	52	0.44	1.13
	59.0	I	31.5	65	15.5	20/20	3.3	0.19	.905	52	0.323	.828

The metabolic feed rate during Test Run "H" averaged 13% low with a feed ratio of only 0.875. This low feed rate is reflected in the dew point curve. The dew point dropped to an equilibrium value of 1.1°C (34°F). During the last 1.5 hours of the test run, the steam injection rate was increased to bring the dew point up to the level predicted by the performance calibration testing. This was also done to establish a realistic starting point for the test run to follow.

Test Run "I" concluded the low temperature portion of Mission II. Test Run "I" ran 31.5 hours at Environment No. 4 conditions. The air temperature rose considerably during the overnight portion of the run due to changing ambient temperatures in the test area. The actual temperature conditioning rig is separated from the breadboard system and requires manual compensation for changing ambient conditions. Efforts to adjust the temperature resulted in the dip and second peak on the themperature curve.

The airflow rate was closely controlled in the 0.42 m^3/min (15.5 cfm) range.

The water feed ratio averaged 5% high for the test duration. The dew point climbed as a result of the lower airflow rate and equalized at 11.1°C (52°F). A correlation between the water feed ratio and dew point curves can be seen. The early dip in feed ratio results in the leveling off of the dew point. The immediate increase in feed ratio is followed by an increase in the dew point.

The same correlation can be seen in the CO_2 feed ratio and PCO_2 level. Although the feed ratio average a relatively constant 8% high value, two distinct peaks can be seen. The first peak tends to flatten the descending PCO_2 curve. The second peak results in an increase in already stabilized PCO_2 level. Dropping the feed ratio back to the required value re-establishes the equilibrium PCO_2 value of 0.44 kPa (3.3 mm Hg).

The overall effect in transcending from five man crews to two man crews was the same for both the high and low temperature missions. The dew point increases as the PCO_2 level decreases. The dew point increases because the low airflow rate does not allow enough water to enter the HS-C bed. The bed has a much higher capacity for water than it can actually see. Conversely, the CO_2 capacity of the HS-C bed is well satisfied under the same operating conditions. The bed becomes fully loaded with CO_2 only at the end of each cycle and is, therefore, operating at maximum efficiency.

The 20 minute cycle time tests of Test Run "E" and "I" accurately define the operating characteristics and performance of the projected flight system operation. The dew point control on the high temperature case dictates the airflow rate, and the resulting CO_2 performance becomes exceptional when compared to the existing Shuttle LiOH approach. (PCO_2 levels of less than 0.44 kPa (3.3 mm Hg) for HS-C compared to 0.67 kPa (5.0 mm Hg) for LiOH.)

Ullage-Save Compressor Testing

Studies have established great system advantages if an ullage-save compressor is used to retrieve the ullage gas normally lost overboard during the switch over cycle. This test phase evaluated the effect and impact of the ullage-save compressor operation on the performance of the breadboard system.

The feasibility of using the ullage-save compressor was proven in a partial mission test of 45.5 continuous hours; called Mission III in the Plan of Test. This test was conducted as a continuation of Mission II accumulating a total of 95 continuous test hours.

The first environmental condition of Mission III was the continuation of Environment No. 4 that concluded Mission II. This continuation allows the direct comparison in HS-C performance parameters. The only adjustment in the test setup was made to the electrical controller to include the compressor cycle. The compressor adds 1.7 minutes to the switch over cycle. Each bed went through a 17.0 minute adsorb cycle, two minute switch over cycle, 17 minute desorb cycle, two minute switch over cycle, and then back to adsorption to repeat the full 19/19 cycle.

The test and performance parameters are presented in Figure 38 with Table 18 providing the backup data. The curves in Figure 38 are presented in the same format and units as was presented for Mission II.

The first test, Test Run "I", was the continuation of Environment No. 4, two men at 18.3°C (65°F). The first three parameters, air temperature, airflow, and H_2O feed ratio, were maintained identical to the previous test.

The effect of the ullage compressor can be seen in the performance parameter of dew point. The dew point rose immediately from the previously established equilibrium level of 11.1°C (52°F) to 12.8°C (55°F). This dew point leveled and maintained a range of 12.2°C (54°F) and 12.8°C (55°F) throughout the 21.5 hour run.

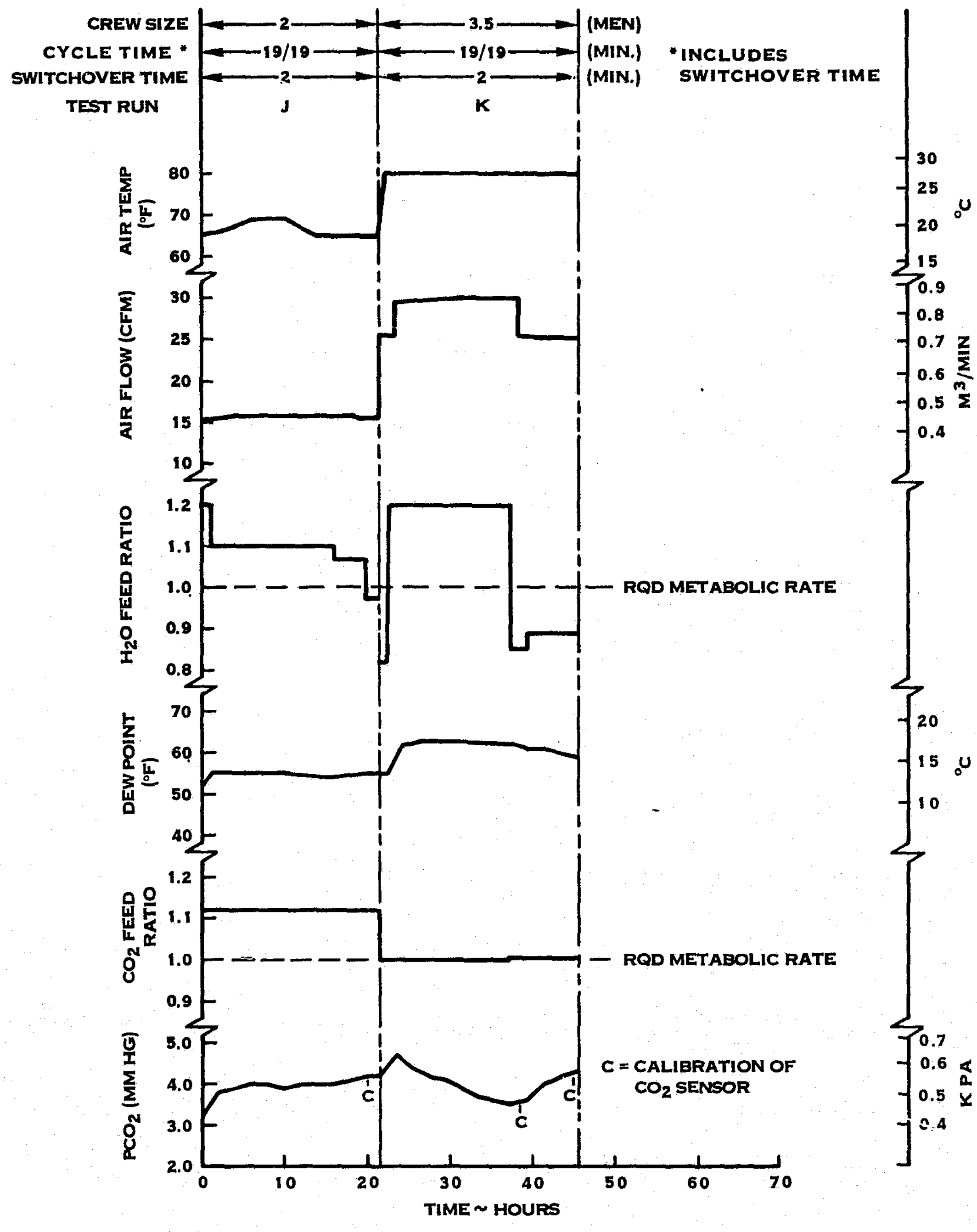


FIGURE 38 ULLAGE-SAVE COMPRESSOR TESTING

TABLE 18A

DATA SUMMARY
ULLAGE-SAVE COMPRESSOR MISSION
(S.I. UNITS)

TIME INTO MISSION (HR)	TEST RUN	TIME INTO RUN (HR)	TEMP (°C)	FLOW (M^3/MIN)	CYCLE TIME (MIN/MIN)	P CO_2 (KPA)	CO_2 FEED (KG/HR)	CO_2 FEED / CO_2 REQ.	DEW PT. (°C)	H_2O FEED (KG/HR)	H_2O FEED / H_2O REQ.
0	J	0	18.3	0.433	19/19	0.440	0.107	1.12	11.1	0.213	1.20
2.0	J	2.0	18.9	0.439	19/19	0.507	0.107	1.12	12.8	0.195	1.10
4.0	J	4.0	19.7	0.446	19/19	0.520	0.107	1.12	12.8	0.195	1.10
6.0	J	6.0	20.6	0.446	19/19	0.533	0.107	1.12	12.8	0.195	1.10
8.0	J	8.0	20.8	0.446	19/19	0.533	0.107	1.12	12.8	0.195	1.10
10.0	J	10.0	20.6	0.446	19/19	0.520	0.107	1.12	12.8	0.195	1.10
12.0	J	12.0	19.2	0.446	19/19	0.533	0.107	1.12	12.5	0.195	1.10
14.0	J	14.0	18.3	0.446	19/19	0.533	0.107	1.12	12.2	0.195	1.10
16.0	J	16.0	18.3	0.446	19/19	0.533	0.107	1.12	12.2	0.195	1.10
18.0	J	18.0	18.3	0.446	19/19	0.547	0.107	1.12	12.5	0.189	1.07
20.0	J	20.0	18.2	0.439	19/19	0.560	0.107	1.12	12.8	0.189	1.07
21.5	J	21.5	18.3	0.439	19/19	0.567	0.107	1.12	12.8	0.173	0.97
21.5	K	0	18.3	0.716	19/19	0.567	0.139	0.99	12.8	0.300	0.82
23.5	K	2.0	26.7	0.722	19/19	0.627	0.139	0.99	16.7	0.440	1.20
25.5	K	4.0	26.7	0.835	19/19	0.587	0.139	0.99	17.2	0.440	1.20
27.5	K	6.0	26.7	0.835	19/19	0.560	0.139	0.99	17.2	0.440	1.20
29.5	K	8.0	26.7	0.541	19/19	0.547	0.139	0.99	17.2	0.440	1.20
31.5	K	10.0	26.7	0.850	19/19	0.520	0.139	0.99	17.1	0.440	1.20
33.5	K	12.0	26.7	0.850	19/19	0.493	0.139	0.99	17.1	0.440	1.20
35.5	K	14.0	26.7	0.850	19/19	0.480	0.139	0.99	16.8	0.440	1.20
37.5	K	16.0	26.7	0.850	19/19	0.467	0.139	0.99	16.7	0.440	1.20
39.5	K	18.0	26.7	0.716	19/19	0.480	0.141	1.01	17.8	0.313	0.85
41.5	K	20.0	26.7	0.708	19/19	0.533	0.141	1.01	17.8	0.327	0.89
43.5	K	22.0	26.7	0.708	19/19	0.560	0.143	1.02	15.6	0.327	0.89
45.5	K	24.0	26.7	0.708	19/19	0.573	0.143	1.02	15.3	0.327	0.89

TABLE 18B

DATA SUMMARY
ULLAGE-SAVE COMPRESSOR MISSION
(U.S. UNITS)

TIME INTO MISSION (HR)	TEST RUN	TIME INTO RUN (HR)	TEMP (°F)	FLOW (CFM)	CYCLE TIME (MIN/MIN)	PCO_2 (MMHG)	CO_2 FEED (LB/HR)	CO_2 FEED / CO_2 REQ	DEW PT. (°F)	H_2O FEED (LB/HR)	H_2O FEED / H_2O REQ
0	J	0	65	15.3	19/19	3.3	0.236	1.12	52	0.47	1.20
2	J	2	65	15.5	19/19	3.8	0.236	1.12	55	0.43	1.10
4	J	4	67.5	15.75	19/19	3.9	0.236	1.12	55	0.43	1.10
6	J	6	69	15.75	19/19	4.0	0.236	1.12	55	0.43	1.10
8	J	8	69.5	15.75	19/19	4.0	0.236	1.12	55	0.43	1.10
10	J	10	69	15.75	19/19	3.9	0.236	1.12	55	0.43	1.10
12	J	12	66.5	15.75	19/19	4.0	0.236	1.12	54.5	0.43	1.10
14	J	14	65	15.75	19/19	4.0	0.236	1.12	54	0.43	1.10
16	J	16	65	15.75	19/19	4.0	0.236	1.12	54	0.43	1.10
18	J	18	65	15.75	19/19	4.1	0.236	1.12	54.5	0.417	1.07
20	J	20	65	15.5	19/19	4.2	0.236	1.12	55	0.417	1.07
21.5	J	21.5	65	15.5	19/19	4.25	0.236	1.12	55	0.38	0.974
21.5	K	0	65	25.3	19/19	4.25	0.306	0.994	55	0.66	0.82
23.5	K	2	80	25.5	19/19	4.7	0.306	0.994	62	0.97	1.20
25.5	K	4	80	29.5	19/19	4.4	0.306	0.994	63	0.97	1.20
27.5	K	6	80	29.5	19/19	4.2	0.306	0.994	63	0.97	1.20
29.5	K	8	80	29.7	19/19	4.1	0.306	0.994	63	0.97	1.20
31.5	K	10	80	30	19/19	3.9	0.306	0.994	62.7	0.97	1.20
33.5	K	12	80	30	19/19	3.7	0.306	0.994	62.5	0.97	1.20
35.5	K	14	80	30	19/19	3.6	0.306	0.994	62.3	0.97	1.20
37.5	K	16	80	30	19/19	3.5	0.306	0.994	62	0.97	1.20
39.5	K	18	80	25.3	19/19	3.6	0.31	1.01	61	0.69	0.85
41.5	K	20	80	25	19/19	4.0	0.31	1.01	61	0.72	0.89
43.5	K	22	80	25	19/19	4.2	0.315	1.02	60	0.72	0.89
45.5	K	24	80	25	19/19	4.3	0.315	1.02	59.5	0.72	0.89

The effect on CO_2 performance is less conclusive. The equilibrium pressure rose from 0.44 kPa (3.3 mm Hg) to 0.53 kPa (4.0 mm Hg). From parametric test data obtained during Contract NAS 9-11971, this increase represents a 5% degradation in CO_2 cyclic capacity. However, the CO_2 feed rate was 4% higher than the preceding test and would automatically represent a higher equilibrium CO_2 level. It was concluded that an insignificant degradation in CO_2 performance might be introduced with the ullage-save compressor operation. This conclusion was further reinforced with Test Run "K".

Test Run "J" verified performance minimum metabolic rates, while Test Run "K" would verify the maximum metabolic rates of 3.5 men at 26.7°C (80°F). The transition into Test Run "K" was accomplished with no interruption in the operation of the breadboard system. It took approximately two hours to stabilize all test parameters of the new environment.

The temperature equalized at 26.7°C (80°F) in 0.5 hours, but the HS-C bed required three hours to reach a stabilized condition at the higher temperature. This lag in bed temperature is partially responsible for the sharp increase in PCO_2 level at the beginning of the run.

The airflow was initially set at 0.71 m^3/min (25 cfm). After two hours the airflow was increased to 0.84 m^3/min (30 cfm) because the dew point was rising above the maximum allowable limit. Unknown at this point in the test was that the water feed rate was actually 20% too high. The test was run overnight at this condition, and the high water feed was not discovered until the next morning.

At this time, adjustments were made to the water feed, and the airflow was also dropped back to its original 0.71 m^3/min (25 cfm) value. The test ran for the final eight hours at this condition.

The dew point, which had equalized at 16.7°C (62°F) for the overnight portion of the run, continued to drop slowly through the day. At the completion of the test, it was at 15.3°C (59.5°F), but the feed rate was 11% low. The equilibrium dew point for a stabilized feed rate is extrapolated to be 16.1°C (61°F) from the performance chart of Figure 8.

The CO_2 feed rate was held perfectly throughout this test period. The PCO_2 level in the simulated cabin volume followed the predicted effect of other parameters. It rose quickly in the first two hours because of the increased feed rate from two men to 3.5 men and also because the time lag in heating up the HS-C beds.

The subsequent decline in CO_2 level follows, exactly, the increase in airflow rate. The CO_2 level rises again when the airflow is decreased at the 38.5 hour. The CO_2 was equalizing at the 0.59 kPa (4.4 mm Hg) level at the conclusion of testing. This final value compares well with the parametric test results of the same environment which had an equilibrium value of .60 kPa (4.5 mm Hg).

The conclusion of Test Run "K" are the same as Test Run "J" and serve as the overall conclusions of the operational impact of the ullage-save compressor on HS-C performance. There is no measurable impact on CO_2 performance. However, an increase of 1.7°C (3°F) to 2.2°C (4°F) in dew point equilibrium will be encountered. This is because the HS-C is still efficiently removing water vapor at the end of the adsorption cycle, but it is removing only a small percentage of the CO_2. As such, the 10% loss in adsorption time affects the water performance to a much greater degree than CO_2 performance.

During the performance calibration test phase, ullage compressor operation was attempted with a five man, 26.7°C (80°F) environment. The normal cycle time for this condition is so short that the two minutes required to switch the beds with the compressor results in a significant loss of available adsorption/desorption time. Equilibrium operating performance could not be achieved at this condition even after reducing the overall cycle time by 50%. As such, full size, 10 man, operation with the ullage-save compressor is considered unfeasible. This conclusion has no impact on the advantages of HS-C for Shuttle since the 10 man mission is for only two days maximum. The ullage compressor offers system advantages for longer missions of between four and seven men. For these crews the ullage compressor has been proven to be feasible by this test phase.

Vacuum Desorption Testing

The Shuttle vehicle vacuum duct has been recognized as a critical item, potentially affecting the incorporation of HS-C on the Orbiter. Following a modification to install a vacuum regulating valve, the breadboard system was tested to understand better the desorption phenomina by establishing HS-C performance as a function of desorption pressure.

The primary objective of this task is to minimize the desorption vacuum duct size. A direct scale-up of the breadboard system test setup would require a 30.5 cm (12 inch) duct size. However, one test, conducted during the parametric test phase, indicated the duct size could be reduced to 15.2 cm (6 inch) with no degradation in performance. Therefore, the objective of this test series was to find out at which desorption pressure level degradation would be encountered. A vacuum duct analysis of the proposed Shuttle installation has established a relationship between vacuum duct size and desorption pressure.

Table 19 shows the relationship of canister header vacuum levels and vehicle vacuum duct size. This data was presented earlier in graph form in Figure 10. The data is based on the worst case desorption rate of 10 men in a 26.7°C (80°F) cabin with a total desorption rate of 1.44 kg/hr (3.18 lb/hr). The table shows what the header vacuum would be for each duct size if 1.44 kg/hr (3.18 lb/hr) of CO_2 and water vapor were passing through the duct into a 5.3 Pa (40 micron) vacuum source.

Table 19
Vehicle Vacuum Duct Sizing

Vehicle Duct Diameter cm (inches OD)	Canister Header Pressure Pa (microns)
30.5 (12.0)	26.7 (200) (1)
15.2 (6.0)	42.7 (320) (2)
12.7 (5.0)	56.0 (420)
10.2 (4.0)	89.3 (670)
8.9 (3.5)	123.3 (925) (3)
7.6 (3.0)	183.3 (1375)
5.1 (2.0)	634.5 (4760)

(1) Condition at which most breadboard testing was conducted.

(2) Parametric testing was conducted at this vacuum level with no degradation in performance.

(3) Analysis indicated the possibility of going as high as 1000 microns before degradation is encountered.

Vacuum Test Results

Vacuum desorption testing was completed on the breadboard system with positive results. It was concluded from this testing that the vehicle vacuum duct can be reduced to a 88 mm (3.5 inch) outside diameter duct. This size duct will allow worst case desorption pressures in the 133 Pa (1,000 micron) range.

No degradation was encountered in either CO_2 or H_2O performance up to the 133 Pa (1,000 micron) level as shown earlier in Figure 9. At 133 Pa (1,000 microns), a marginal 2% CO_2 degradation was recorded. Water performance was not affected at the 133 Pa (1,000 micron) level.

A marked 10% to 12% degradation was encountered in both CO_2 and H_2O performance at the 2,000 micron level. This degradation was repeated in a separate test run after normal performance had been reestablished at optimum vacuum conditions.

An unusual trend effect was measured during the test series. A day to day improvement in CO_2 performance was encountered. This effect is shown in Figure 39. The first and fifth day of testing had identical conditions, but a 19% improvement in CO_2 removal performance was measured. Likewise, the second and sixth days were identical tests with a 23% improvement being measured. The test series ran for 110 continuous hours, whereas the longest previous test at similar conditions ran only 18 hours.

CO_2 Trend Performance

The CO_2 performance data is plotted against header vacuum pressures in Figure 40. Here, the data of Figure 39 can be seen as it was originally accumulated. Each data point is identical by its numerical day of testing. The CO_2 plot made it difficult to draw any firm conclusions until the performance versus test day was plotted in Figure 39. Figure 40 definitely shows that a 10% degradation was encountered in going from the best vacuum (38 Pa (250 microns)) to the worst vacuum (266 Pa (2,000 microns)). What should be remembered is the absolute performance desired at this condition. The metabolic production rate is 0.20 kg/hr (0.44 lb/hr). The only test point that did not meet this requirement was taken on the second day at the worst vacuum. When this data point was repeated on the last day, the performance was 16% greater than required.

The most significant part of the CO_2 trend phenomina is the extremely high performance level at the end of the test period. Testing on the first day was of an acceptable level and consistent with previous testing. This can be seen in Figure 41 by superimposing other 10 man data points onto the graph of Figure 40. Only one previous data point shows superior performance, but it had to be scaled up to the 0.23 kg/hr (.505 lb/hr) level because the test conditions were different. It removed the nominal 10 man production rate at a very low equilibrium PCO_2 level, 0.44 kPa (3.3 mm Hg). A parametric curve from the NAS 9-11971 program

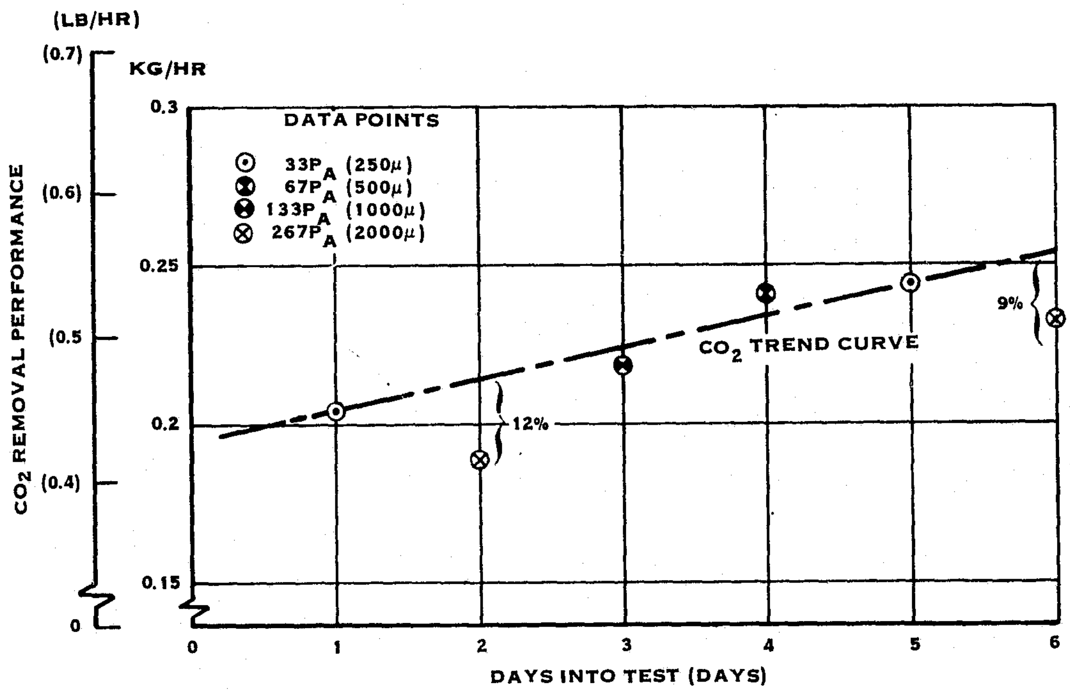


FIGURE 39 CO_2 TREND DATA

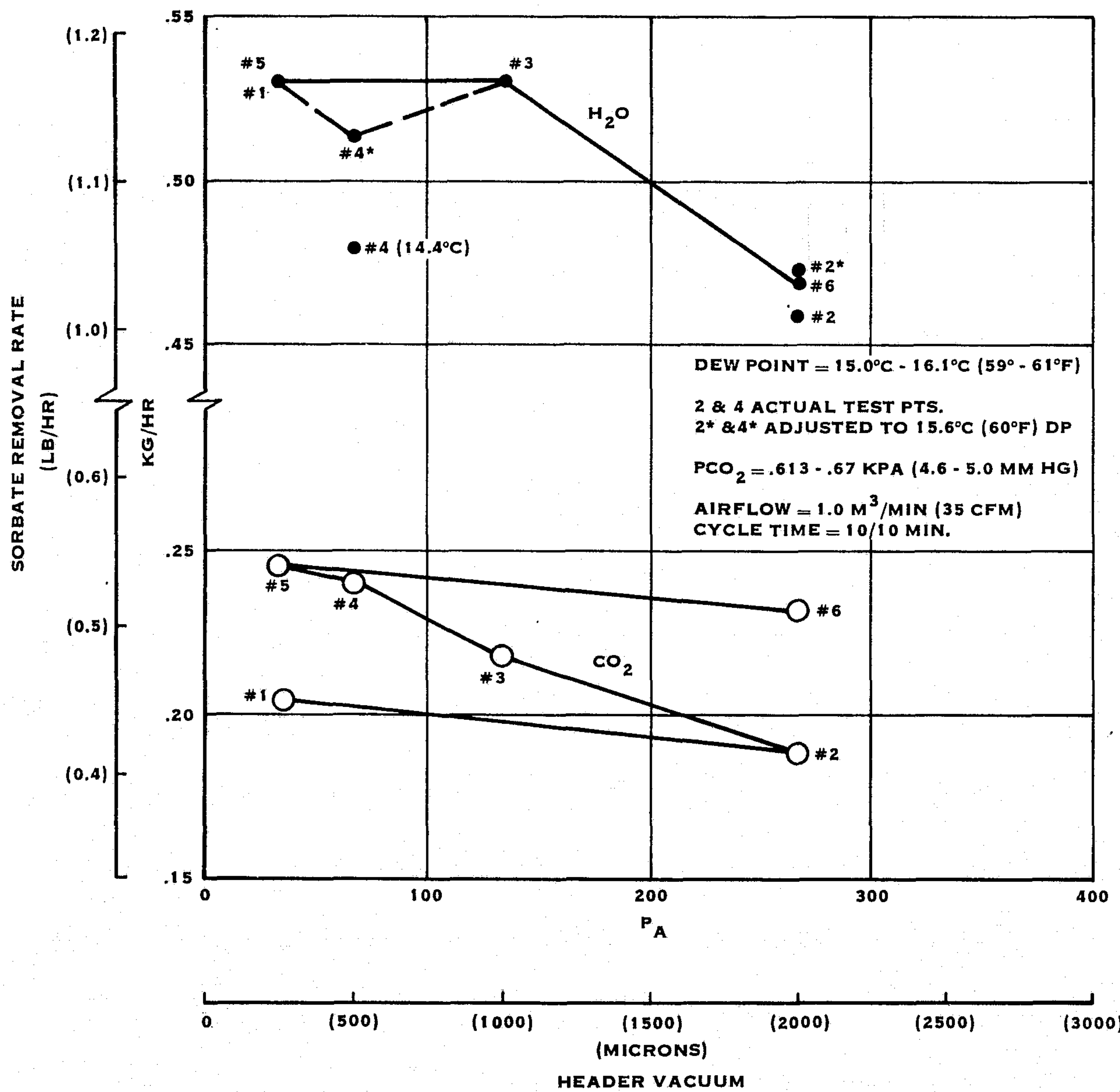


FIGURE 40 THE EFFECT OF DESORPTION PRESSURE ON HS-C PERFORMANCE

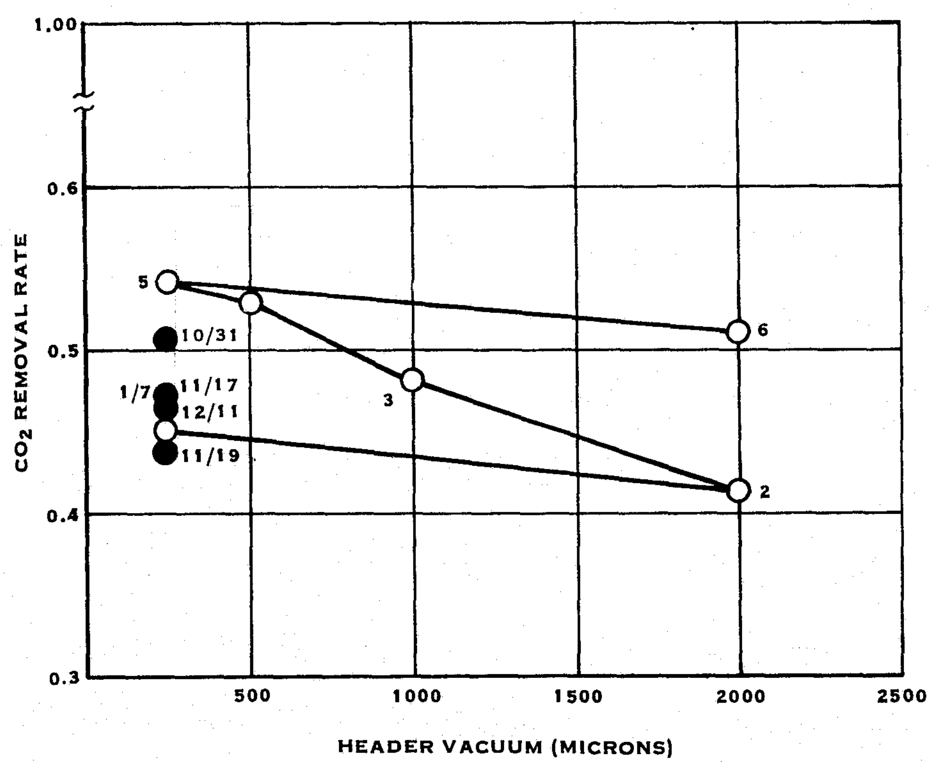


FIGURE 41 COMPARISON OF BREADBOARD DATA TO VACUUM DATA ON CO_2 REMOVAL

was used to scale up the removal rate assuming the equilibrium PCO_2 level was 0.67 kPa (5 mm Hg). Performance on the last three days of the vacuum testing exceeded even this previous best and was independent of the vacuum desorption level.

This trend phenomina suggests the potential for improved performance if the bed is properly prepared for operation. The key to the improved performance lies either in the breaking in or conditioning period of the first few days of testing or perhaps in the dormant state that existed prior to testing. This phenomina is well worth further investigation in the future in an effort to optimize fully the HS-C operating conditions.

Water Removal Performance

The water removal performance did not display a trend effect as shown in Figure 40 . The performance on the last two days of testing corroborated the performance of the first two days at identical conditions. The water removal rate was shown to be dependent on vacuum levels only. The performance was constant for desorption pressures of up to 133 Pa (1,000 microns) but fell off 13% when the desorption pressure rose to 266 Pa (2,000 microns). The data points for the second and fourth day of testing have been corrected because the dew point conditions during testing were low. The test point of the fourth day is the only one that does not fit the curve. This is partially due to the low dew point condition of test. The CO_2 performance for this same test was exceptionally high, and the water discrepancy is, therefore, not considered significant.

Vacuum Pressure Profiles

The actual pressure profiles of the different tests are shown in Figures 42 and 43. Figure 42 shows the absolute pressure measured at the plumbing interface to the canister as a function of time. The corresponding bed pressures are shown in Figure 43.

Comparing the two sets of curves produce the following observations:

- The bed operated over a narrower pressure band than was applied to the headers.

- There was no change in bed pressure for any header pressure below 66 Pa (500 microns).

- The bed pressures on the last two days of testing (#5 and #6) were slightly lower than the identical tests of the first two days (#1 and #2).

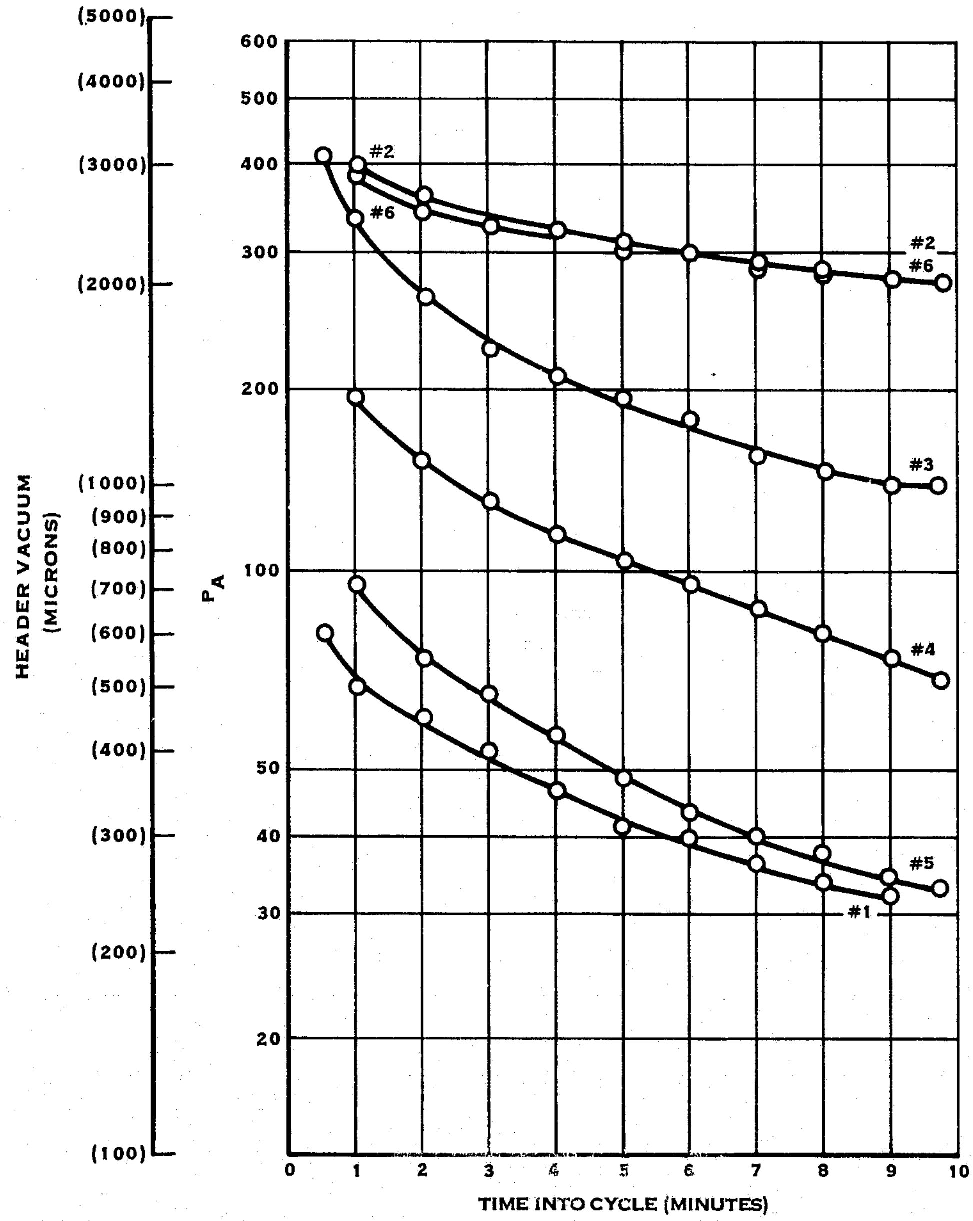


FIGURE 42A HEADER PRESSURE PROFILES (S.I. UNITS)

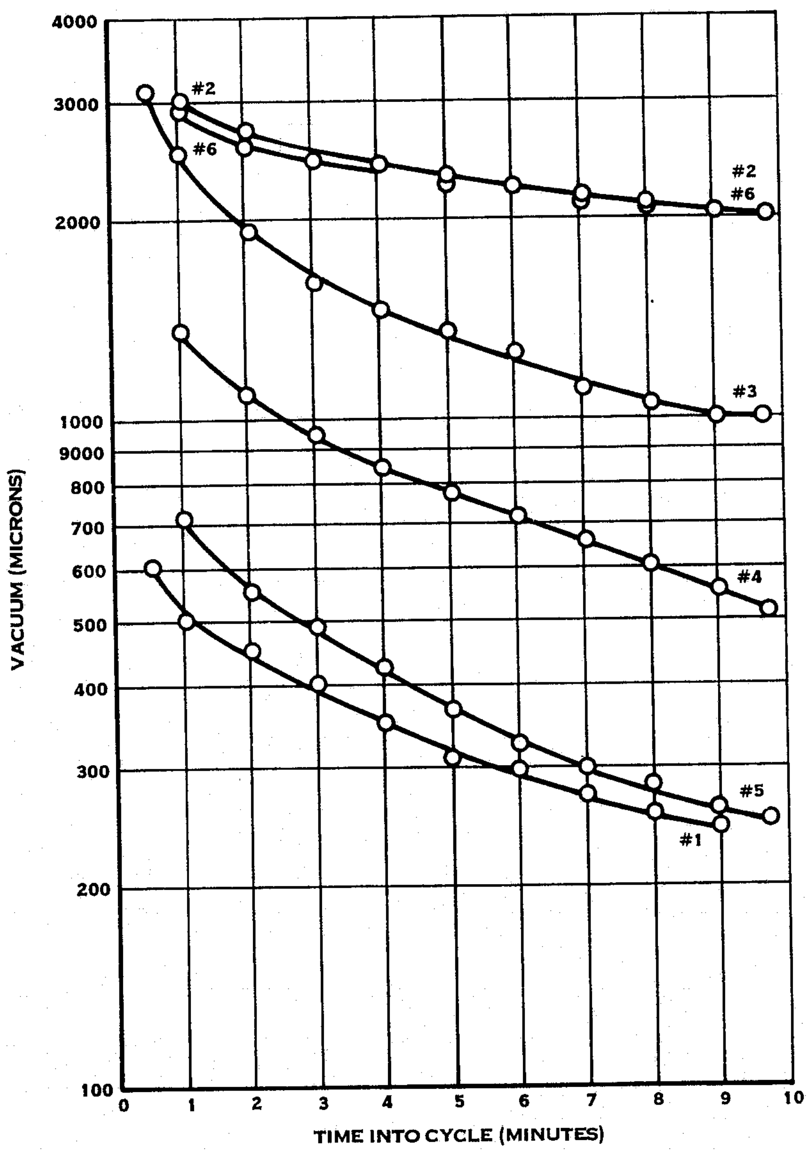


FIGURE 42B HEADER PRESSURE PROFILES (U.S. UNITS)

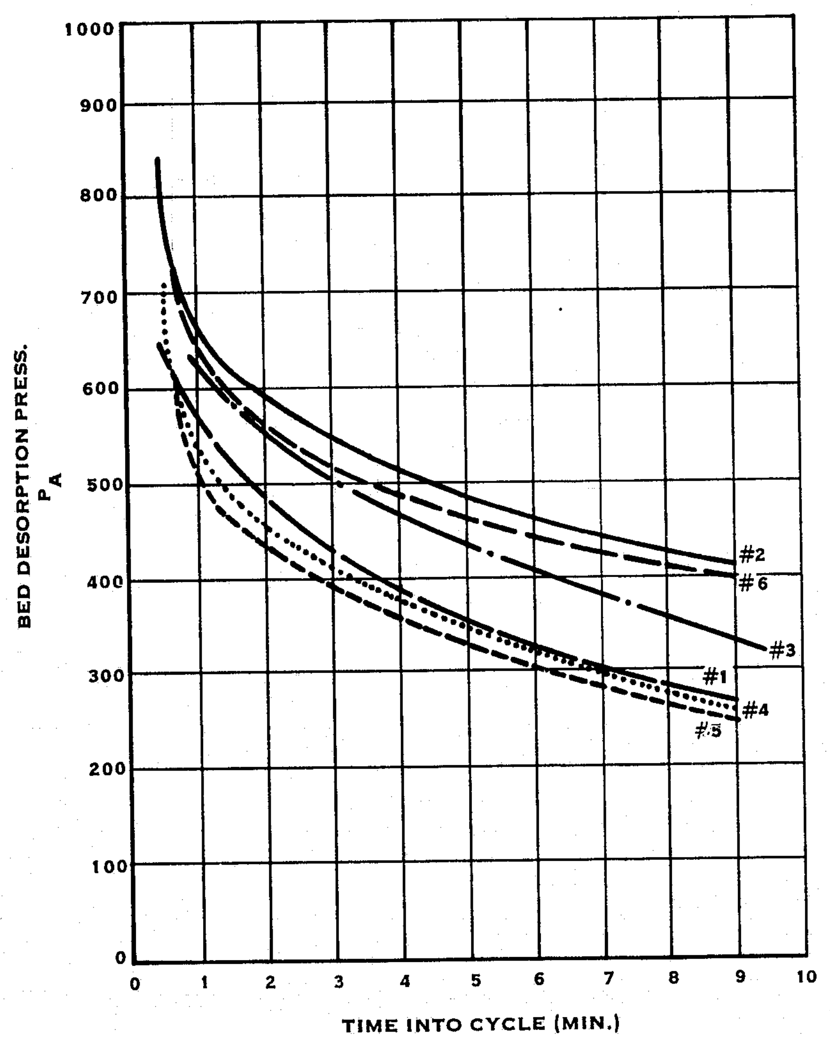


FIGURE 43A BED PRESSURE PROFILES (S.I. UNITS)

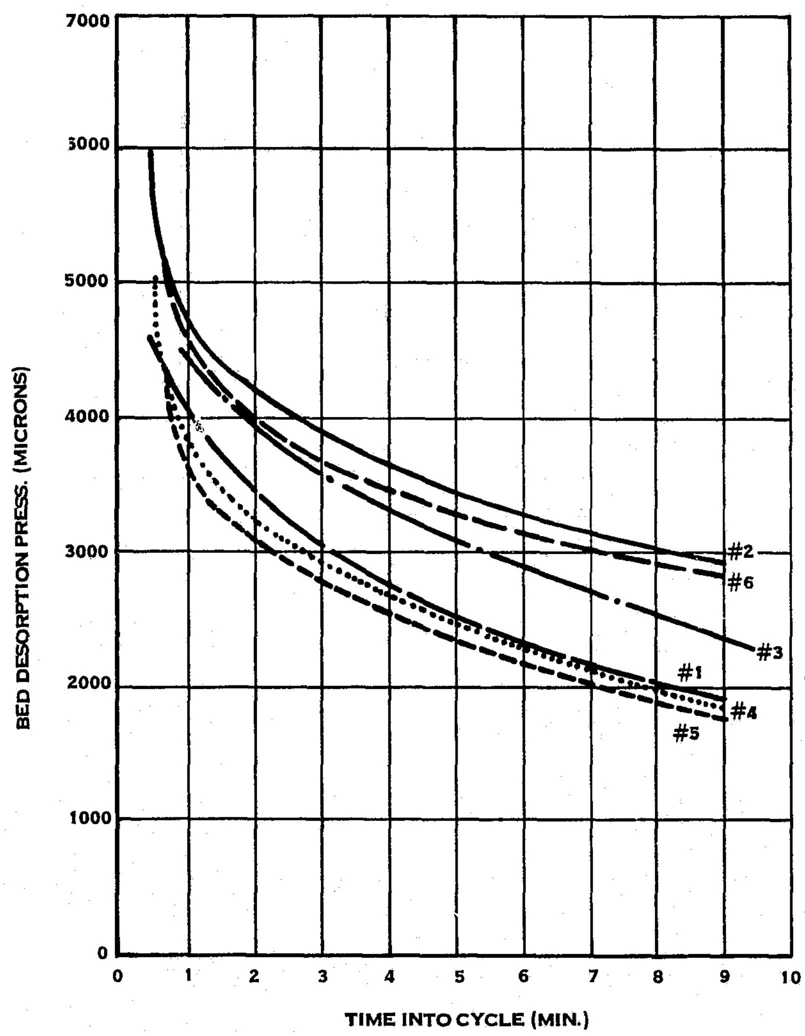


FIGURE 43B BED PRESSURE PROFILES (U.S. UNITS)

These observations produce the following conclusions:

- The greatest physical restriction of the desorbed gases is flowing out of the tightly packed HS-C bed.

- The vacuum plumbing should never be designed to provide less than a 66 Pa (500 micron) pressure.

- The improved CO_2 performance of the last three days of testing is not dependent on desorption pressure since the bed pressure on test #6 was 50% higher than test #1, but the performance was 13% better.

APPENDIX A

TEST DATA SUMMARY

SORBATE MASS SUPPLY CALCULATIONS

SORBATE MASS SUPPLY CALCULATIONS

The following calculation defines the mass of sorbate, CO_2 or H_2O, supplied to the module under standardized conditions on the basis of mass of sorbate per hour per unit mass of HS-C. These calcualtions are used to convert removal efficiency data to quantitative removal performance.

$$\text{supply} = \frac{R_{air}}{R_{gas}} \left(\frac{P_{gas}}{P_{ambient} - P_{gas}} \right) \times \dot{\omega}' \times \rho$$

where $R^{(2)}$ = gas constant $\frac{J}{kg\ ^\circ K}$ $\left(\frac{ft\text{-}lbf}{lbm\ ^\circ Rankine} \right)$

P = gas pressure N/m^2 (psia or mmHg)

$\dot{\omega}$ = volumetric air flow per unit mass HS-C $\frac{m^3/min}{kg\ HS\text{-}C}$ $\left(\frac{cfm}{lb\ HS\text{-}C} \right)$

ρ = density of air @[air stream temperature, 26.7°C (80°F)] kg/m^3 (lb/ft^3)

$\dot{\omega}$ supp = sorbate supply $\frac{\text{mass gas/hr}}{\text{unit mass HS-C}}$

NOTE: Calculations are made in English units and subsequently converted to S.I. units.

<u>Water</u> P_{H_2O} @ 61°F dew point = 0.2655 psia [1]

$$\dot{\omega}\ \text{supp}\ H_2O = \frac{53.34}{85.76} \left(\frac{0.2655}{14.7 - 0.2655} \right) \times \dot{\omega}\ \frac{ft^3/min}{lb\ HS\text{-}C} \times 60\ \frac{min}{hr} \times 0.0735 \frac{lbm}{ft^3}$$

$$= \dot{\omega} \times (.050453)\ \frac{lbm}{hr}\ \frac{H_2O}{lb\ HS\text{-}C}$$

(1) Thermodynamic Properties of Steam, Keenan and Keys
(2) Thermodynamics, Van Wylen

Carbon Dioxide @ spec inlet = 0.667 kN/m^2 (5 mmHg)

$$\text{supp } CO_2 = \frac{53.34}{35.10}\left(\frac{5 \text{ mmHg} \times .019 \frac{\text{psia}}{\text{mm}}}{14.7 - 5 \times .019}\right) \times \dot{\omega}\ \frac{ft^3/min}{lb\ HS\text{-}C} \times 60\ \frac{min}{hr} \times 0.0735\ \frac{lb}{ft^3}$$

$$= \dot{\omega} \times 0.04360\ \frac{lb\ CO_2/hr}{lb\ HS\text{-}C}$$

SORBATE SUPPLY AT MODULE FLOW RATES*

$\dot{\omega}$		$\dot{\omega}\ CO_2$	$\dot{\omega}\ H_2O$
$\frac{m^3/min}{kg\ HS\text{-}C}$	$\left(\frac{cfm\ air}{lbm\ HS\text{-}C}\right)$	$\frac{kg\ CO_2/hr}{kg\ HS\text{-}C}$ $\left(\frac{lbm\ CO_2/hr}{lbm\ HS\text{-}C}\right)$	$\frac{kg\ H_2O/hr}{kg\ HS\text{-}C}$ $\left(\frac{lbm\ H_2O/hr}{lbm\ HS\text{-}C}\right)$
.143	(2.3)	0.10028	0.11604
.206	(3.3)	0.14388	0.16649
.258	(4.15)	0.1809	0.20938

SI Conversions

$$\frac{\frac{ft^3}{min}}{lbm\ HS\text{-}C} \times \frac{.0283\ m^3/ft^3}{.4535\ kg/lbm} = \frac{m^3/min}{kg\ HS\text{-}C}$$

$$\frac{lbm\ gas/hr}{lbm\ HS\text{-}C} = \frac{unit\ mass\ gas/hr}{unit\ mass\ HS\text{-}C}$$

*This data converts removal efficiencies per Table 5 to absolute removal performance by the formula:

CO_2 Removal Performance = CO_2 x CO_2

H_2O Removal Performance = H_2O x H_2O

APPENDIX B

ANALYTICAL DESIGN CALCULATIONS

1. Reference procedures defined in ECS-730024-L-006 (Third Progress Report).

2. Data from module testing, reference ECS-730024-L-018 (Eighth Progress Report).

3. Design criteria:

   a. Design basis, CO_2 data points at 15/15 cycle on 5/15/74 and 20/20 cycle on 5/16/74.

   b. Degradation allowance 10% of required HS-C bed weight.

4. From the data, presented in the eighth progress report, the HS-C is CO_2 design limited. The slope of the CO_2 data curve implies that below a 15/15 duty cycle the performance varies more with airflow than duty cycle. Therefore, the design curve displaced to the final data points indicates a 10 man design bed weight of 8.62 kg (19.0 lb) at a flow rate of 0.042 m^3/min/kg HS-C (3.3 cfm/lb HS-C) and a 15-minute duty cycle.

5. Applying the degradation factor the bed weight is:

$$8.66 \text{ kg} \times 1.1 = 9.53 \text{ kg (20.9 lb)}$$

use 21 lb HS-C

6. The CO_2 removal requirement is:

$$\frac{2.11 \text{ lb } CO_2\text{/man day}}{24 \text{ hr/day}} \times 10 \text{ men} = 0.879 \text{ lb } CO_2\text{/hr}$$

$$= 0.399 \text{ kg } CO_2\text{/hr}$$

7. The calculated bed weight @ 0.042 $\frac{m^3/min}{kg\ HS\text{-}C}$ (3.3 cfm/lb HS-C) is:

Performance @ 3.3 cfm/lb HS-C = 0.046 lb CO_2/lb HS-C hr

$$\text{HS-C required} = \frac{0.879}{0.046} = 19.1\ \text{lb HS-C} < 21\ \text{lb HS-C}$$
$$= 8.66\ \text{kg HS-C}$$

At degraded condition:

$$\text{HS-C required} = \frac{0.879}{(0.046 \times 0.9)} = 21.23\ \text{lb} = 21\ \text{lb m HS-C}$$
$$= 9.53\ \text{kg HS-C}$$

8. Canister weight:

Weight canister = 1.72 (21x0.453) + 2.49

= 18.85 kg

= 41.61 lb

9. Valve weight:

Total flow = 21 lb HS-C x 3.3 cfm/lb HS-C

= 69.3 cfm ≈ 70 cfm

1.98 m^3/min

Flow per canister = 35 cfm

Line size = 2.5 in (ECS-730024-L-006, figure 22)

Valve weight = 3.23 lb (ECS-730024-1-006, figure 21)

= 1.465 kg

10. Pressure drop:

Δ P bed = 2.88 in H_2O (SVHSER 6185, figure 22)

Use 3.4 in H_2O, growth allowance

Δ P header = 0.5 in H_2O

Δ P total = 3.9 in H_2O

= 970.5 N/m^2

11. Power:

$$\text{Power} = \frac{(70 \text{ cfm})\ (3.9 \text{ in } H_2O)}{3.5} = 78 \text{ watts}$$

$$\text{Fixed power penalty} = \left(73.1\ \frac{\text{lb}}{\text{kw}}\right)\left(\frac{78 \text{ watts}}{1000}\right) = 5.70 \text{ lb}$$

$$= 2.59 \text{ kg}$$

$$\text{Expendable power penalty} = \left(1.956\ \frac{\text{lb}}{\text{kw-hr}}\right) \times \left(\frac{78 \text{ watts}}{1000}\right)$$

$$= 0.1526 \text{ lb/hr}$$

$$= 0.069 \text{ kg/hr}$$

12. Water performance

10 man condition:

$$\text{Performance required} = \frac{2.3 \text{ lb/hr}}{19.1 \text{ lb HS-C}} \text{ @ 10 man comdition}$$

$$= 0.120 \text{ lb } H_2O/\text{lb HS-C hr}$$

$$\text{Performance demonstrated} = \begin{array}{l} 0.149 \\ \underline{\times\ 0.9} \text{ degradation allow} \end{array}$$

$$= 0.134 \quad 0.120$$

4 man condition:

$$\text{Performance required} = \frac{1.24}{19.1} = 0.065 \text{ lb } H_2O/\text{lb HS-C hr}$$

Assume bed saturated in 30 minutes:

$$\text{Performance @ 30 minutes} = 0.113 \text{ lb } H_2O/\text{lb HS-C}$$

$$\text{Multiple of 30 minutes} = \frac{0.113}{0.065} = 1.74$$

$$1.74 \times 30 \text{ minutes} = 52.20 \text{ minute cycle}$$

13. Ullage:

$$\text{Ullage volume} = 2.5 \times \text{HS-C vol/cycle}$$

$$= 2.5 \times \left(0.0328\ ft^3/lb\ \text{HS-C}\right)(21\ lb\ \text{HS-C})$$

$$= 1.722\ ft^3/cycle$$

10 man operation:

$$\text{Ullage volume} = \frac{(1.722\ ft^3/cycle \times 60\ min/hr}{15\ min/cycle} = 6.9\ ft^3/hr$$

$$\text{Weight air dumped/hr} = \frac{\left(7.5\ \frac{lb}{in^2}\right)\left(144\ \frac{in^2}{ft^2}\right)\left(6.9\ \frac{ft^3}{hr}\right)}{\left(53.34\ \frac{ft\text{-}lb}{lb\text{-}^oR}\right)\left(540^oR\right)} = 0.2587\ lb\ air/hr$$

$$\text{Weight } O_2 \text{ dumped} = (0.2587)\left(\frac{53.34}{48.28}\right)(0.2) = 0.0572\ lb\ O_2/hr$$

$$\text{Weight } O_2 + \text{tankage} = (1.2)\ (0.0572) = 0.0686\ lb/hr$$

$$\text{Weight } N_2 \text{ dumped} = (0.2587)\left(\frac{53.34}{55.15}\right)(0.8) = 0.2002\ lb\ N_2/hr$$

$$\text{Weight } N_2 + \text{tankage} = (3)\ (0.2002) = 0.6006\ lb/hr$$

$$\text{Ten man ullage} = (0.0686) + (0.6006) = 0.669\ lb/hr$$

$$= 0.304\ kg/hr$$

4 man operation:

$$CO_2 \text{ load} = \frac{2.51\ lb\ CO_2/man\ day}{24\ hr/day} \times 4 \text{ men} = 0.418\ lb\ CO_2/hr$$

$$= 0.19\ kg\ CO_2/hr$$

$$\text{Performance required} = \frac{0.418}{19.1} = 0.022\ lb\ CO_2/lb\ \text{HS-C}\ hr$$

Reference ECS-730024-L-006, figure 7.

$$\frac{0.418}{19.1} \times 100 = 2.19\% \rightarrow 150 \text{ minutes}$$

$$= 2.5 \text{ hrs}$$

$\therefore$ Use H_2O limit, section 12.

$$\text{Four man ullage} = 0.6691 \times \frac{15}{52} = 0.193 \text{ lb/hr}$$

$$= 0.088 \text{ kg/hr}$$

14. Expendable weights per mission:

Mission definition: Reference ECS-730024-L-006, Table B1.

10 man loading	37.95 hr
4 man loading	131.0 hr
	169 hr ≈ 7 days

Assume cabin temperature = 80°F

Dew point = 61°F

CO_2 pressure = 5 mm Hg

Expendable summary

	10 man	4 man
Power (lb/hr)	0.1526	0.1526
Ullage (lb/hr)	0.6691	0.193
	0.8217	0.3456
	x 38 hr	x 131 hr
Expendable Mission Weight (lb)	31.22 lbs	45.27 lbs

Total mission expendable (lb) = 76.49 ≈ 76.5 lb

≈ 34.7 kg

15. Summary of weight:

Fixed weights

HS-C	10.5 lb/bed x 6 beds	=	63.0
Canister	41.6 lb/can x 3 cans	=	124.8
Valves	3.23 lb/valve x 12 valves	=	38.8
Power	5.70 lb	=	5.7
Total fixed		=	232.3 lb
		=	105.4 kg

Expendable weight	=	76.5 lb
	=	34.7 kg

Total weight for mission defined:

140 kg (308.9 lb)

APPENDIX C

REGENERABLE CO_2 AND HUMIDITY CONTROL SYSTEM REQUIREMENTS SPECIFICATION (REVISION A)

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION

SVHSER 7103

REGENERABLE CO_2 AND HUMIDITY CONTROL SYSTEM

REQUIREMENTS SPECIFICATION

REVISION A

11/20/73

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

Prepared by: A. E. Francis

A. E. Francis
Program Engineer

Approved by: F. H. Greenwood

F. H. Greenwood
Program Manager

INTRODUCTION

The Regenerable CO_2 and Humidity Control System, Contract NAS 9-13624, must remove metabolic moisture and CO_2 from air environment simulating that in the Space Shuttle. The system must also interface with the RSECS system, Contract NAS 9-13307.

Definition of requirements and conditions originate from this contract, NAS 9-13624, and from the RSECS design guide, SSP Document A220 Revision D, Amendment #1. In addition, Shuttle power penalties are included.

Analytical Design Requirements

- The system analysis shall be sized for a four-man system at maximum metabolic rates and for a ten-man system at nominal metabolic rates.
- The analytical system design shall be fail-operational, fail-safe.
- When integrated with the RSECS system, there shall be no condensation in the RSECS sensible heat exchanger.
- The following power penalties shall be considered:

Power Penalty

	AC		DC	
Fixed Weight-kg/kw (lb/kw)	33.2	(73.1)	25.7	(56.6)
Expendible Weight-kg/kw-hr (lb/kw-hr)	0.887	(1.956)	0.687	(1.514)

A | • The Shuttle cabin environment is defined by Table I.

• Crew metabolic rates are defined by Table II.

• The adsorbent bed thickness shall be limited to four inches, minimizing data extrapolation.

• The adsorbent to air and adsorbent to adsorbent configurations shall be evaluated.

• Fail safe mission duration is 4 days with 4 man condition.

A | • Radiator penalty for condensing loads shall not be considered.

Hardware Design Requirements

• The fabricated core shall be representative of a flight unit.

• The breadboard system shall be self-contained with a valved interface connection for RSECS.

• The humidity control valve shall be electrically operated/ manually actuated.

• The breadboard system shall be capable of continuous cycling operation but need not contain flight system redundancies (fail-operational, fail-safe).

TABLE I

SHUTTLE CABIN ENVIRONMENT

Parameter	Range	
Cabin Temperature - °C (°F)	18.3-26.7	(65-80)
Cabin Dew Point - °C (°F)	1.7-16.1	(35-61)
CO_2 Partial Pressure-kN/m^2 (mmHg)	0.67-1.01	(5.0-7.6)
Fail Safe	1.33	(10)
Emergency, 2 hr. max.	2.00	(15)
Cabin Volume - m^3 (ft^3)	56.6	(2000)
Cabin Air Pressure-kN/m^2 (psia)	101.4	(14.7)

Ref: NAS 9-13624, SOW paragraph 3.3
SSP Doc. A220, Rev. D, Ammend. #1

TABLE II

CREW METABOLIC RATES

Cabin Temperature °C (°F)	Heat Output kJ/Man-Day (BTU/Man-Day)			
	Nominal		Maximum	
	Latent	Sensible	Latent	Sensible
18.3 (65)	2962 (2805)	8371 (7928)	5174 (4900)	8341 (7900)
21.1 (70)	3838 (3635)	7495 (7098)	6040 (5720)	7476 (7080)
23.9 (75)	4986 (4722)	6347 (6011)	7155 (6776)	6361 (6024)
26.7 (80)	6198 (5870)	5135 (4863)	8350 (7908)	5165 (4892)

CO_2 PRODUCTION

kg/Man-Day (lb/Man-Day)	
Nominal	Maximum
.96 (2.11)	1.14 (2.51)

APPENDIX D

MECHANICAL DESIGN CALCULATIONS, CANISTER

Note: Calculations are predominately in English Units with significant results converted to SI units.

I. Requirements for HS-C Canister

A. 4.763 Kg (10.5 lbs) minimum HS-C per bed per canister.

B. 2 beds in parallel, each (alternately) desorb and adsorb.

C. 19.052 Kg (42 lbs) total HS-C between two canisters.

D. 7.62 cm (3 in) nominal flow depth of bed.

E. 5.08 cm (2 in.) max. bed height except end beds on 2.54 cm (1 in) max. using a 4% Duocel with 10 ppi or equivalent heat transfer core.

F. 33.04 l/sec (70 cfm) total system air flow.

G. ΔP is 3.4 inches of H_2O max. at 35 cfm through each bed.

H. System ullage volume must be less than 2.5 times the bed void volume.

I. Leakage shall not exceed 1.5×10^{-5} cc/sec of helium at STP when pressurized to 15 psid at room ambient temperatures for a 30 second period.

J. Proof test to 22.5 psi.

II. Information

A. Density of HS-C per SVHSER-6040 page 58-59 is .384 gm/cc (.01387 lb/in^3) and .378 gm/cc (.01366 lb/in^3); from the test module (SVKS 88488) the density of HS-C in 4% Duocel is .329 gm/cc (.0119 lb/in^3). The test module density is being used. It is the smallest sample and thus may be the most inaccurate one but it is the only one which includes the effect of Duocel on the packing density.

III. Results

A. The overall dimensions of the test bed canister are 73.025 cm (28.75 in) high x 69.085 cm (27.199 in) long x 17.109 cm (6.736 in) thick.

B. The canister is made up of 12-5.08 cm (2 in) beds and two 2.54 cm (1in) end beds.

C. The weight of each test bed canister is 18.647 Kg (41.117 lbs) plus 9.524 Kg (21 lbs) HS-C = 28.171 Kg (62.117 lbs).

D. The weight of an all aluminum flight canister (thinner end sheets, closure bars, header tubes, an optimized mounting configuration and without test ports) is 15.62 Kg (34.45 lbs).

A. Comments

The following tests were requested by Design in order to assure a good end product:

1. Braze sample module with .012" parting sheet and screen to determine leak proof seal of screen to parting sheet after crushing into Duocel bed.

2. Test of fill capability through fill tubes and Duocel.

3. Crush test of HS-C in a tube to determine packing and load carrying ability before fracturing the beads.

B. Design Leakage

1. Project office requires a leakage note on the layout drawing of "Leakage shall not exceed 1.5×10^{-5} cc/sec. of helium at STP when pressurized to 15 psid at room ambient temperature, for a 30 second period." This is taken from SVHS 2405 spec., paragraph 3.5.2.2, coolant side.

   Design believes 5 scc/hr at 15 psia to vacuum is sufficient for the system.

2. From SVHS 3720-166 spec, paragraph 3.3.1.19 Leakage, for the molecular sieve canister, "Leakage from ambient of 15 psia to evacuated canister shall not exceed 5 scc/hr". This is 5×10^{-4} % of volume. There would be no performance effect on a test system at 100 times that value. The Shuttle total vehicle leakage allowable is about 10 lbs/day, or 157,343 scc/hr., therefore 100 times 5 scc/hr for the system would be ok.

3. When the Duocel material is ordered, we should request a sample of 4% density, 10 ppi material with 50 ppi facing .05 deep to determine whether the separate screen can be eliminated.

IV Design Approach

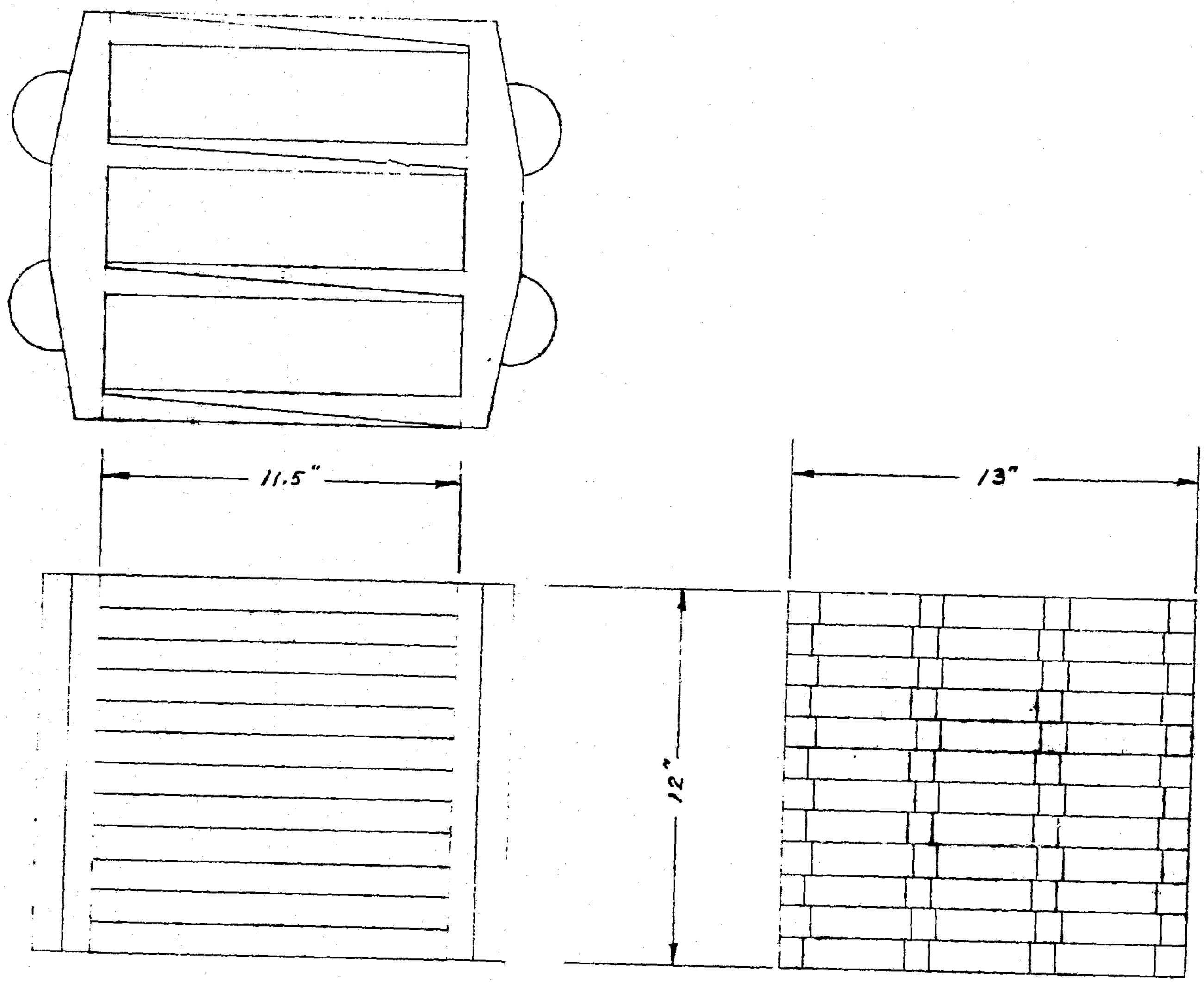
A. Concept Evaluation

Three basic configuration concepts were evaluated.

"A" a three stacked unit (figure 1)
"C" a single stacked unit (figure 2)
"E" a radial flow unit (figure 3)

The "C" configuration provides the least ullage, lowest cost, and smallest overall package arrangement.

5-31-74



TOTAL VOL. LESS HEADERS = 1794 IN^3

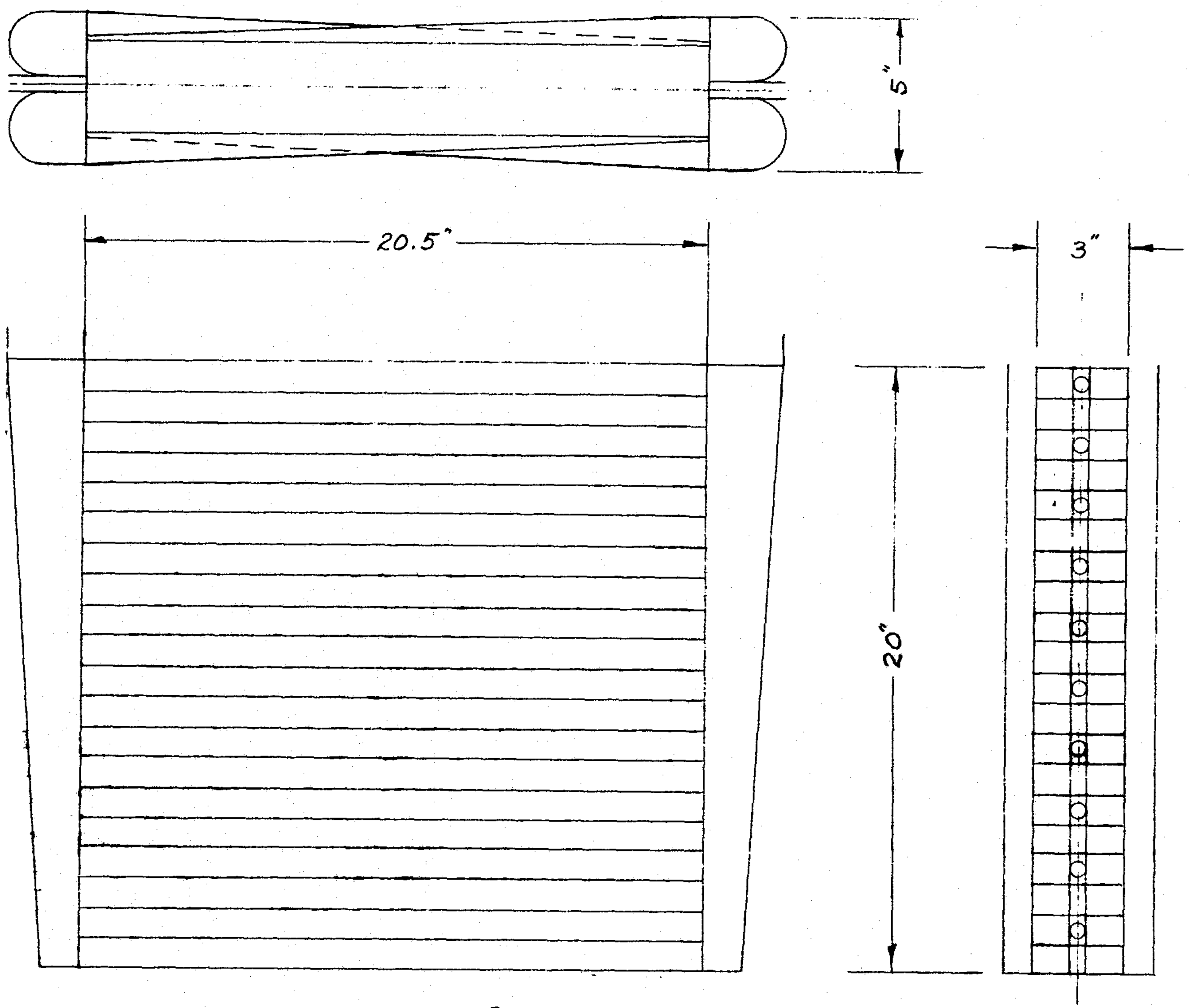
1/5 SIZE

CONFIG. A

Figure 1

6-3-74

HAMILTON STANDARD
Division of UNITED TECHNOLOGIES



TOTAL VOL. LESS HEADERS = 2050 IN^3

CONFIG. C

1/5 SIZE

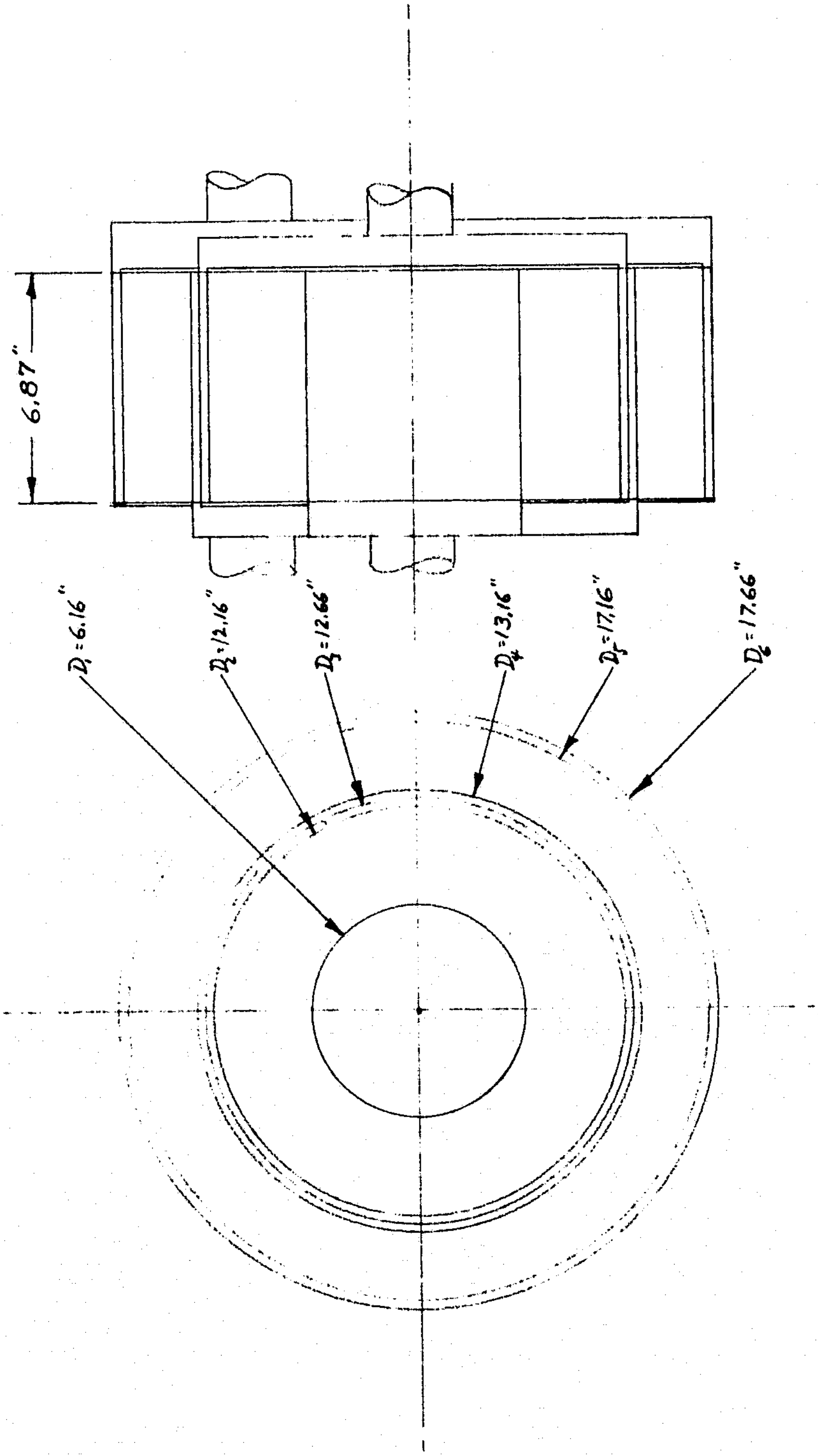
Figure 2

SVHSER 7103

HAMILTON STANDARD Division of UNITED TECHNOLOGIES

6-7-74

1/5 SIZE



CONFIG. "E"

Figure 3

The "E" configuration is the lightest arrangement but is not as efficient as the "C" configuration. The "E" configuration would be extremely difficult and expensive to manufacture.

Because of these factors, the single stacked unit (configuration "C") was decided as the best.

Variations in Duocel density were investigated. The 4% density Duocel, with a crush strength of about 300 psi, was requested by Manufacturing as the best for the brazing operation.

B. Sizing of the HS-C Canister:

For a 50% size canister with 10.5 lbs HS-C per bed; total HS-C per canister = 10.5 x 2 = 21 lbs HS-C. With the density of HS-C = .0119 lb/in^3;

21/.0119	=	1764.7 in^3
4% Duocel	=	70.6 in^3
Total bed vol.		1835.3 in^3

For a bed depth of 3 in, bed area = 1835.3/3 = 611.77 in.^{2}
26" high x 23.5" long x 3" deep is the minimum size of the bed volume and is closer to a square so it is near minimum weight. These dimensions do not consider hardware limitations and tolerances for a normal shuttle mission of 7 days x 100 mission, 7 x 100 = 700 days.
For a 10 min. cycle time, 24 x 6 = 144 cycles per day - 144 x 700 = 100,800 cycles: use 1 x 10^6 cycles for all cyclic analyses.

Parting sheet thickness:
For a 10^6 fatigue cycle life, F_{ty} - 2,000 psi (incl. S.F.) allowing a .2" x .2" pore in the Duocel at the parting sheet.

from HS hx Design Manual section 3.5.4.3

$$T\ (\text{bending}) = \sqrt{\frac{KG\,a2}{S_b}} = \sqrt{\frac{.3(15)\ .2^2}{2,000}} = \underline{.0095\ \text{in.}}$$

$$T\ (\text{tension}) = \frac{Gh}{2\ F} = \frac{15 \times 2}{2 \times 200} = \underline{.00075\ \text{in.}}$$

use .012" no. 12 parting sheets

Proof test. $T = \sqrt{\frac{.3(35).2^2}{8000}} =$ .0072 in. (F_{ty} = 8000 psi)

In the header area outside the bed, the thickness required for the parting sheet is $t = \sqrt{\frac{.5(15).4^2}{2000}} = .025''$ Therefore a weight saving occurs by using .012 parting sheets and filling the pass volume with 4% Durocel.

End sheets are .050" No. 11 stock for handling considerations of the complete heat exchanger and to provide additional stiffness for mounting arrangements. A flight unit would probably use .032 thick end sheets.

C. Configuration Comments

Closure bars may be made from Whitehead Metal M828 extrusion (6063-T52) channel sections 2" x .5" x .125" thick and Whitehead Metal M160 extrusions (6063 -T52) channel sections 1" x .5" x .125" thick. These extrusions have a maximum dimension tolerance of ± .025" and ± .018" respectively. Therefore the extrusion will be machined on the outside to a ± .001" tolerance. The back side of the channel will be machined off to leave an .050" thick wall based on manufacturing preload requirements during brazing; (inside of outstanding legs will not be machined on the test bed unit from a cost consideration. Therefore, their approximate .125" thickness presents a weight saving potential for flight hardware of approximately 4 lb/hx).

A decision was made to include a separate screen to contain the HS-C in the bed rather than to rely on a 50 ppi skin on the Duocel which ERG claim they can make; however, there are no samples of this available and has never been seen by anyone at HSD. To obtain a seal at the edges of the screen it is bent over the edges of the Duocel bed material and crushed into the Duocel during the brazing operation. Sealing the screens at the ends of the beds will require the addition of ALCOA 713 brazing foil between the screen and the closure bars.

A test module should be made to determine if there is enough braze material on a .012" clad sheet to seal the screen and Duocel and to see if the screen will crush into the Duocel during the brazing operation.

D. Filling Comments

Filling the beds with HS-C: The beds will be filled with HS-C through tubes in the end closure bars. The 2" beds have .8125" I.D. tubes while the 1" end beds have .390" I.D. tubes. For the prototype canister, fill tubes will be in both ends of each bed to provide flexibility in developing a fill procedure. If it is found that the beds can be completely filled from one end, the elimination of one set of fill tubes and plugs would save approximately 1 lb in final flight hardware.

a. Pre-load Requirements

Design assumes that the HS-C can withstand 10 psi w/o crushing.
10.5 lbs. HS-C per canister of 13 beds.
10.5/13 = .8077 lb HS-C per bed for a 20 g vibration load, 20 x .8077 =
16.154 lbs. area of bed end = 2" x 3" = 6 in^2
16.154/6 = 2.69 psi
.8125" I.D. tube = .518 in^2
2.69 psi x .518 in^2 = 1.39 lbs.
AMS 3195 B silicone rubber sponge, closed cell plug has density of .02 lb/in^3, compression strength of 10 psi. for 30% of thickness per AMS 3195 B
.10" deflection of 1" thickness = 3.3 psi x .518 = 1.71 lbs.

b. Thermal expansion effects on volume and preload device:
Coefficient of expansion of HS-C approx. 5×10^{-6} in/in/°F
Coefficient of expansion of A^l = 1.3×10^{-5} in/in/°F
Volume of bed:
2 x 3 x 23.934 = 143.604 in^3 less 4% A^l (5.74) = 137.864 in^3 HS-C
HS-C ΔT - 100°F (storage)

$$(1 + 5 \times 10^{-4})^3 = 1 + 15 \times 10^{-4} + 75 \times 15^{-8} + 125 \times 10^{12}$$

$$15 \times 10^{-4} \times 137.864 = .2068 \text{ in}^3 \ \Delta \text{ vol.}$$

A^l ΔT = 100°F

$$(1 + 1.3 \times 10^{-3})^3 = 1 + 3.9 \times 10^{-3} + 5.07 \times 10^{-6} = 2.197 \times 10^{-9}$$

$$3.9 \times 10^{-3} \times 143.604 = .560 \text{ in}^3 \ \Delta \text{ vol.}$$

Total ΔV = .560 - .2068 = .353 in^3

Preload device must be capable of absorbing this ΔV w/o a large change (keep preload below 5 psi).

Linear expansion
ΔT = 100°F
HS-C $5 \times 10^{-4} \times 23.934 = 1.197 \times 10^{-2}$
A^l $1.3 \times 10^{-3} \times 23.934 = \underline{3.111 \times 10^{-2}}$
1.914×10^{-2} Δ length

Load to deflect HS-C 1.914×10^{-2} in. over 23.934" length
.5 mm sphere= .019685 in = 23.934/.019685 = 1215.85 spheres
Each sphere must deflect $1.914 \times 10^{-2}/1215.85 = 1.574 \times 10^{-5}$

$$P = \frac{y^2 E}{1.55^2 \sqrt{\frac{D_1 + D_2}{D_1 \times D_2}}} = \frac{(1.574 \times 10^{-5})^2 \times 4 \times 10^{-5}}{2.4025 \times 10} = 4.125 \times 10^{-6} \text{ lbs.}$$

$$\left(\frac{1}{d}\right)\left(\frac{1}{.866d}\right) = \frac{1}{.019685} \times \frac{1}{.01705} = 2979 \text{ sphere/in}^2$$

$$4.125 \times 10^{-6} \times 2979 = 1.23 \times 10^{-2} \text{ psi}$$

E. Ullage

bed $23.934 \times 1.975 \times 3 \times 12 = 1701.71 \text{ in}^3$

$+ \ 23.934 \times 982 \times 3 \times 2 = 141.02 \text{ in}^3$

1842.73 in^3

less 4% Duocel $- \ 73.71$

$1769.02 \text{ in}^3/1728 = 1.0237 \text{ ft}^3$ HS-C

$1.0237 \times 1728 \times .0119 = 21.05$ lb HS-C

From third program report $.0328 \times 21.05 = .6904 \text{ ft}^3$ void vol.

Header Vol.

$24.27 \times .6 \times 1.975 \times 24 = 690.24 \text{ in}^3$

$+ \ 24.27 \times .6 \times .982 \times 4 = 57.20 \text{ in}^3$

747.44 in^3

Less 4 % Duocel $= 29.90$

$717.54 \text{ in}^3/1928 = .4152 \text{ ft}^3$

Header

$2.5^2 \ \pi/4 = 4.9087$

$+ \ 1.5^2 \ \pi/4 = 1.7671$

$6.6758/2 - 3.3379 \times 26.276 \times 4 = 350.83 \text{ in}^3$

$350.83/1728 = .20303 \text{ ft}^3$

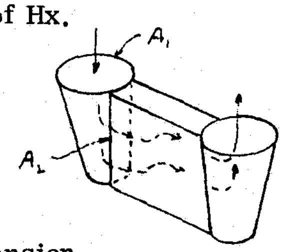
Canister Volume	=	1.309 ft^3 (to Marmon flange or header)
System Ducting	=	$.3438 \text{ ft}^3$
Total Dump Vol.	=	1.6528 ft^3

$1.6528/.6904 = 2.39$ times bed void volume

2.5 times bed void volume is allowed

F. Flow/ΔP Review

ΔP of Hx.



Flow = 35 fpm

$A_1 = .03409 \text{ ft}^2 \quad V_1 = 1026.69$ fpm

$A_2 = .08911 \text{ ft}^2, \quad V_2 = 392.77$ fpm

Expansion

$$\Delta P = q_{1}\left(1 - \frac{A_1}{A_2}\right)^2$$

$$= .3433\left(1 - \frac{.03409}{.08911}\right)^2$$

$$= .3433\,(.6174)^2$$

$$= .1309 \text{ psf}$$

S.A.E. Report 23 Para. 5.3

$$q = \frac{.0756 \times 17.1^2}{2 \times 32.2} = .3433$$

F. (Continued)

Contraction

$\Delta P = q_c \lambda$ $A_1 / A_2 = .3826$ S.A.E. Report 23 Para. 5.2

$\lambda = K_c \times C_c$ $C_c = 1, K_c = .16$

$= .3433 \times .16$

$= .0549$ psf

90^o Turn

$\Delta P = q\, K$ $K = 1.5$ S.A.E. Report 23 Para. 10

$= .3433 \times 1.5$

$= .515 \times 2 = 1.03$ psf

Elbow

$\Delta P = q \lambda$ $\lambda = K \times E \times C = .15 \times 1 \times 1 = .15$

$= .3433 \times .15 = .0515 \times 2 = .103$ psf

Expansion

$$\Delta P = .3433 \left(1 - \frac{.03409}{.08726}\right)^2$$

$= .127 \times 2 = .254$

Contraction

$\Delta P = .3433 \times .15$

$= .051 \times 2 = .102$

Total system $\Delta P = 1.861/5.204 = .358$ in H_2O. The requirements are not to exeed .5 in H_2O. The bed ΔP, including screen, is 3.4 in. H_2O based on the large scale test canister of SVHSER-6040.

Weight (Test Bed)

Parting sheets (.012 x 16% = .014)

.014 x 5.081 x 24.699 x 13 x .1 = 2.284   2.284

End Sheet (.050 8% = .054)

.054 x 5.081 x 24.699 x 2 x .1 = 1.355   1.355

Closure bars

.050 x 1.975 + .125 x .375 x 2 = .1925

.1925 x 27.496 x 24 x .1 = 12.703   12.703

.050 x .982 x .125 x .375 x 2 = .14283

.14285 x 27.496 x 4 x .1 = 1.571   1.571

Headers

$2.5\pi + 1.5\pi = 12.566/2 - 6.283$

$$\left.\begin{array}{l} 6.283 \times 26.276 \times .050 \times .1 \times 2 = 1.651 \\ 6.283 \times 26.276 \times .090 \times .1 \times 2 = 2.972 \end{array}\right\} = 4.623 \qquad 4.623$$

$1.5^2\ \pi/4 \times .050 \times .1 \times 4 = .035$ .035

HAMILTON STANDARD Division of UNITED TECHNOLOGIES

F. (Continued)

Header Angles		
.06 x .5 + .06 x .371 = .0522		
.0522 x 1.724 x .1 x 48 = .432		.432
.522 x .731 x .1 x 4 = .015		.015
.06 x .4225 + .06 x .3625 = .0471		
.0471 x 1.975 x .1 x 24 = .223		.223
Flanges		.359
Closure Plate		
1.192 x .05 x .1 x 4 = .024		.024
Plugs, fill & P tap		
.59 x 1.35 x .p x 24 = 1.912		1.912
.319 x .74 x .1 x 4 = .094		.094
.293 x .61 x .1 x 4 = .071	} .095	
.0825 x .74 x .1 x 4 = .024		.095
Caps		
MS9015-10 = .0414 x 24 = .9936		.994
9015-4 = .0329 x 4 = .1312		.131
Rubber Plugs		
$.8025^2\ \pi/4 \times 1 \times .02 \times 24 = .243$		.243
$.3825^2\ \pi/4 \times 1 \times .02 \times 4 = .009$		.009
Duocel beds		
3 x 1.978 x 23.934 x .04 x .1 x 12 = 6.817		6.817
3 x .982 x 23.934 x .04 x .1 x 2 = .564		.564
Duocel pass		
.6 x 1.978 x 24.278 x .04 x .1 x 24 = 2.766		2.766
.6 x .982 x 24.278 x .04 x .1 x 4 = .229		.229
Screen		
2.478 x 24.434 x 24 ÷ 144 x .09704 = .979		.979
1.482 x 24.434 x 4 ÷ 144 x .09704 = .098		.098
Mounts		
29.25 x .0438 x 2 = 2.562		2.562
	Canister weight	41.117
	+21 lb HS-C	21.000
		62.117 lbs

(63 lbs. total allowable unit)

F. (Continued)

Flight canister weight estimate

End sheets (.032 x 1.08 = .035)

.035 x 5.081 x 24.699 x .1 x 2 = .878   1.355 - .878 = Δwt =   .477

Closure bars

.050 x 1.975 + .050 x .375 x 2 = .12625

.13625 x 27.496 x 24 x .1 = 8.991   12.703 - 8.991 = Δ =   3.712

.050 x .982 + .050 x .375 x 2 = .0866

.0866 x 27.496 x 4 x .1 = .952   1.571 - .952 = Δ =   .619

Headers

$2.5\pi + 1.5\pi = 7.854 + 4.712 = 12.566/2 = 6.283$

6.283 x 26.276 x .040 x .1 x 4 = 2.641

.040 x 2.5 x 1 x .1 x 12 = .12 + 2.641 = 2.761   4.623-2.761 = Δ 1.862

6.670

Test Canister =	41.117
- Δ wt.	- 6.670
Flight canister wt. =	34.447
HS-C =	21.000
Filled canister =	55.447