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SKYLAB ATMOSPHERIC CONTAMINATION CONTROL

By C. D. Ray
Structures and Propulsion Laboratory

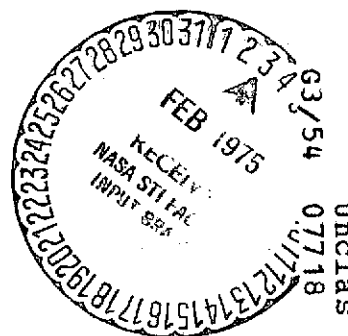
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16. ABSTRACT <p>Descriptions of the Skylab contamination removal systems, preflight analysis and testing, and flight results are presented. Results indicate that the combination of materials selection, the onboard removal devices, and the offgassing tests proved to be an effective means of controlling spacecraft contaminant levels.</p>			
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SKYLAB ATMOSPHERIC CONTAMINATION CONTROL

I. INTRODUCTION

Numerous atmospheric contaminants are offgassed within any spacecraft cabin as a result of material and metabolic generation. Material selection control and testing were utilized during the Skylab program to minimize material offgassing and the subsequent buildup of contaminant levels.

There was no specific hardware in the Skylab environmental control system designed for the sole function of removing contaminants, other than CO₂. However, the charcoal canisters in the molecular sieve unit and waste management systems, the condensing heat exchangers, and the Linde 13X and 5A molecular sieve material had considerable capability to scrub the cabin air of generated contaminants.

Descriptions of the hardware which removed contaminants, the preflight analysis and testing, and the flight results will be presented.

II. CONTAMINATION REMOVAL SYSTEM DESCRIPTION

A schematic of the Skylab air purification system is shown on Figure 1. Under normal operating conditions, one molecular sieve unit, two charcoal canisters, and two condensing heat exchangers were available for contaminant removal. In addition, the charcoal in the waste management compartment (WMC) was available whenever the WMC was occupied and the fan turned on. None of these components were specifically designed for trace contamination control. The mole-sieve units were designed for CO₂ removal, the charcoal canisters for odor control, and the condensing heat exchanger for water removal.

Two mole-sieve units were available for CO₂ control. Under normal mission operating conditions, only one of the two mole-sieve units was required at one time for CO₂ removal. However, cabin atmosphere was also circulated through the condensing heat exchanger and the charcoal canister in the inactive

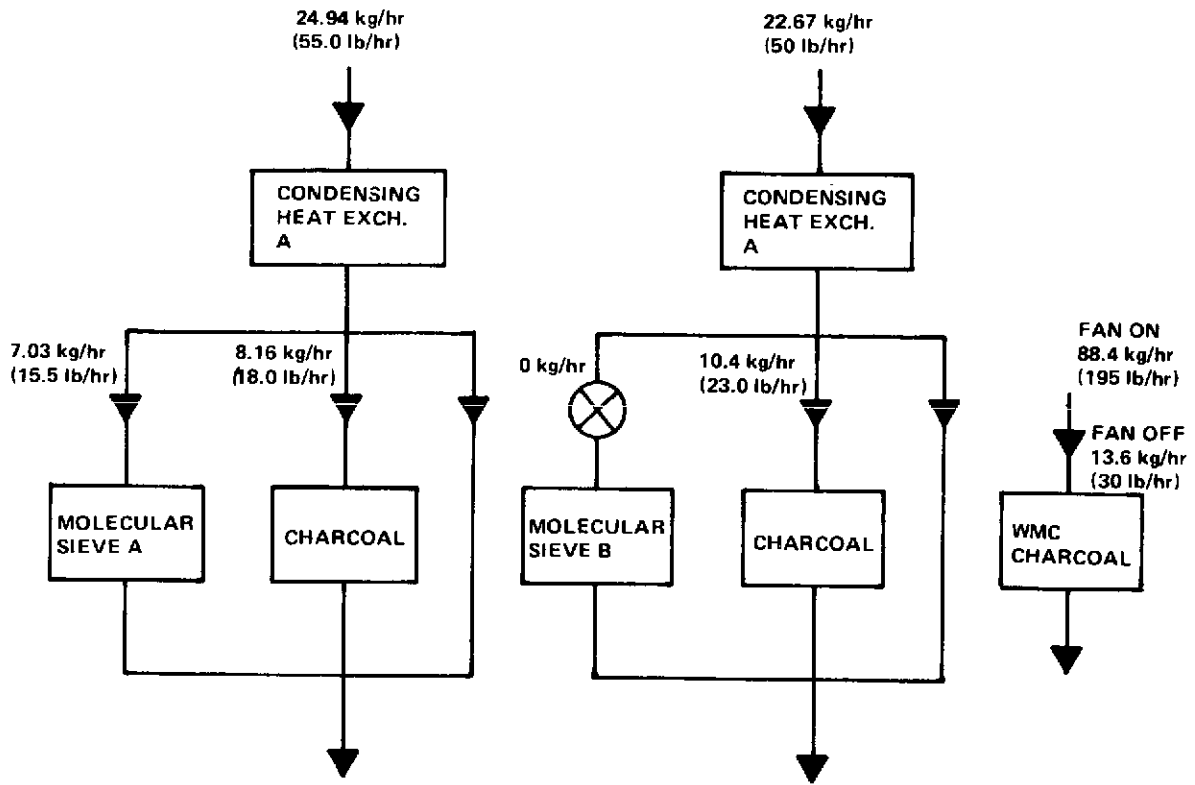


Figure 1. Atmosphere contaminant removal schematic.

mole-sieve, in order to provide additional water vapor and odor removal capability. Each mole-sieve unit consisted of two separate beds (Fig. 2), and each bed contained 4.7 kg (10.35 lbm) of Linde Type 13X Zeolite and 3.17 kg (7.0 lbm) of Type 5A Zeolite. The 13X material was used as a pre-dryer section and the 5A material for CO₂ removal. During normal operation, the mole-sieve unit operated such that a complete cycle took 30 minutes (15 minutes to adsorb and 15 minutes to desorb). While one bed was adsorbing water, CO₂, and trace contaminants, the other bed was being desorbed to space vacuum. At the end of a 15 minute desorb period, the bed was regenerated and ready to again adsorb contaminants.

Excess water vapor as well as trace contaminants were removed from the atmosphere, as it was circulated through the condensing heat exchangers. This was accomplished by condensation within each condensing heat exchanger (Fig. 3), whereby condensate was transported from the fins through wicking devices to the water separator assemblies by diffusion. The water separator plate assemblies served to hold back the atmosphere and allow passage of condensate into the condensate tank.

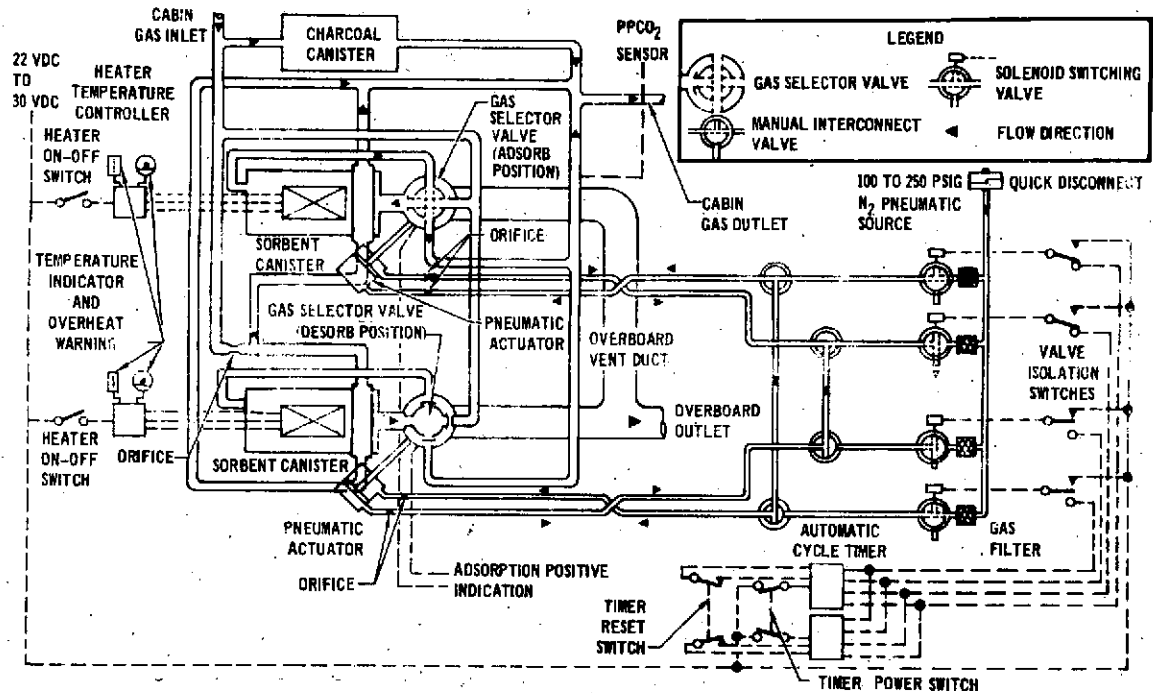


Figure 2. Single molecular sieve system.

Odor and trace contaminant removal was provided by two coconut shell charcoal canisters [4.08 kg (9 lbm) of charcoal in each canister] in the molecular sieve units and by one charcoal canister [4.54 kg (10 lbm)] in the Orbital Workshop (OWS). The charcoal canister in the OWS was part of the waste management ventilation unit, which was mounted through the forward compartment floor in a position over the waste management compartment. This assembly was composed of a fan, a charcoal bed, filters, and a sound suppressor assembly, as shown on Figure 4. Periodic changeout of these charcoal canisters were planned to insure effective odor control.

III. PREFLIGHT ANALYSIS AND TESTING

A. Material Selection and Offgassing Tests

All materials considered for use on Skylab, including stored materials and experiments, were evaluated for flammability and offgassing characteristics [1, 2, 3]. The NASA Headquarters Document [3] was the result of activities carried out during the Skylab program by the Flammability and Toxicity Working Group. This group was charged with the responsibility of developing uniform

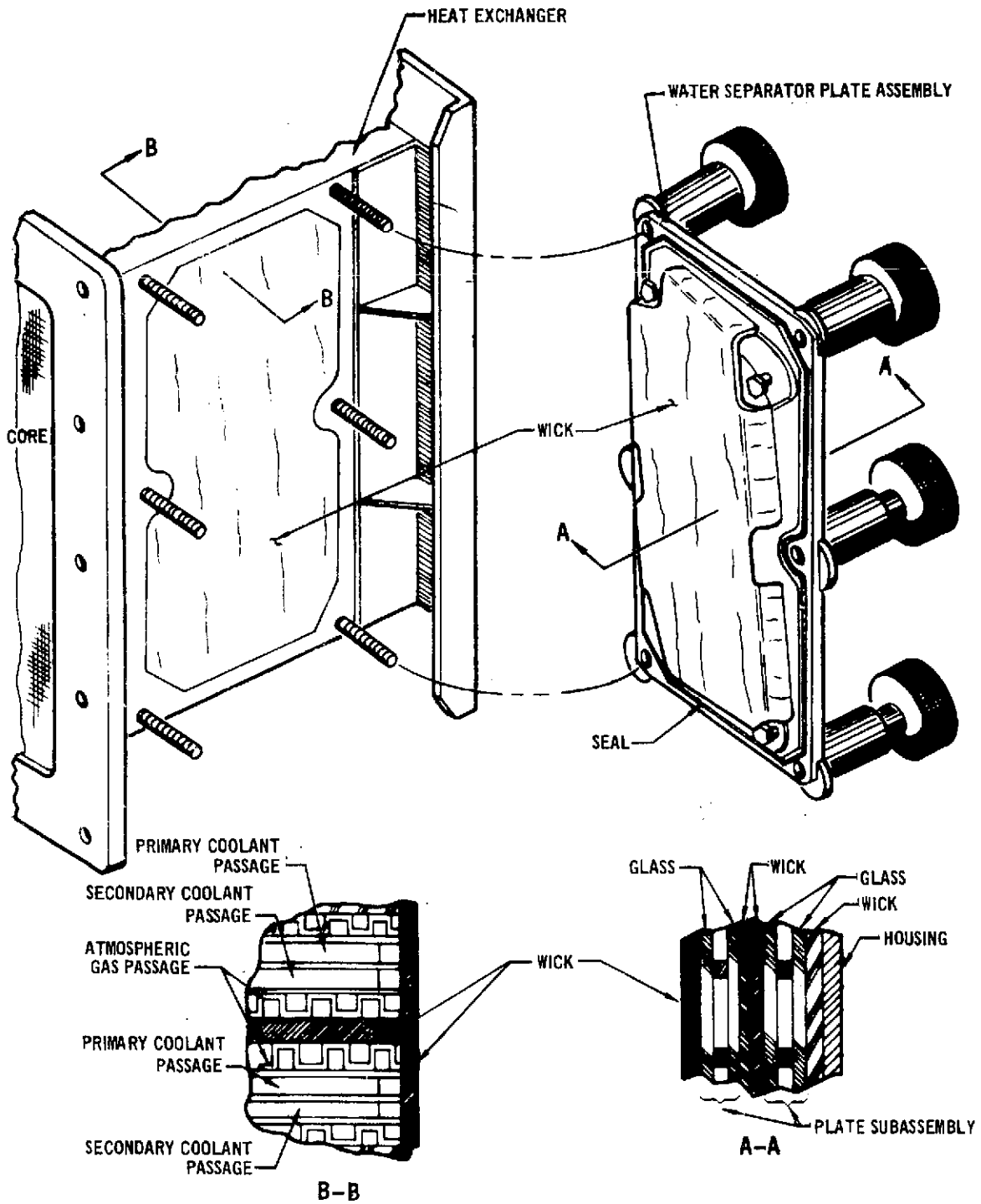


Figure 3. Condensing heat exchanger schematic.

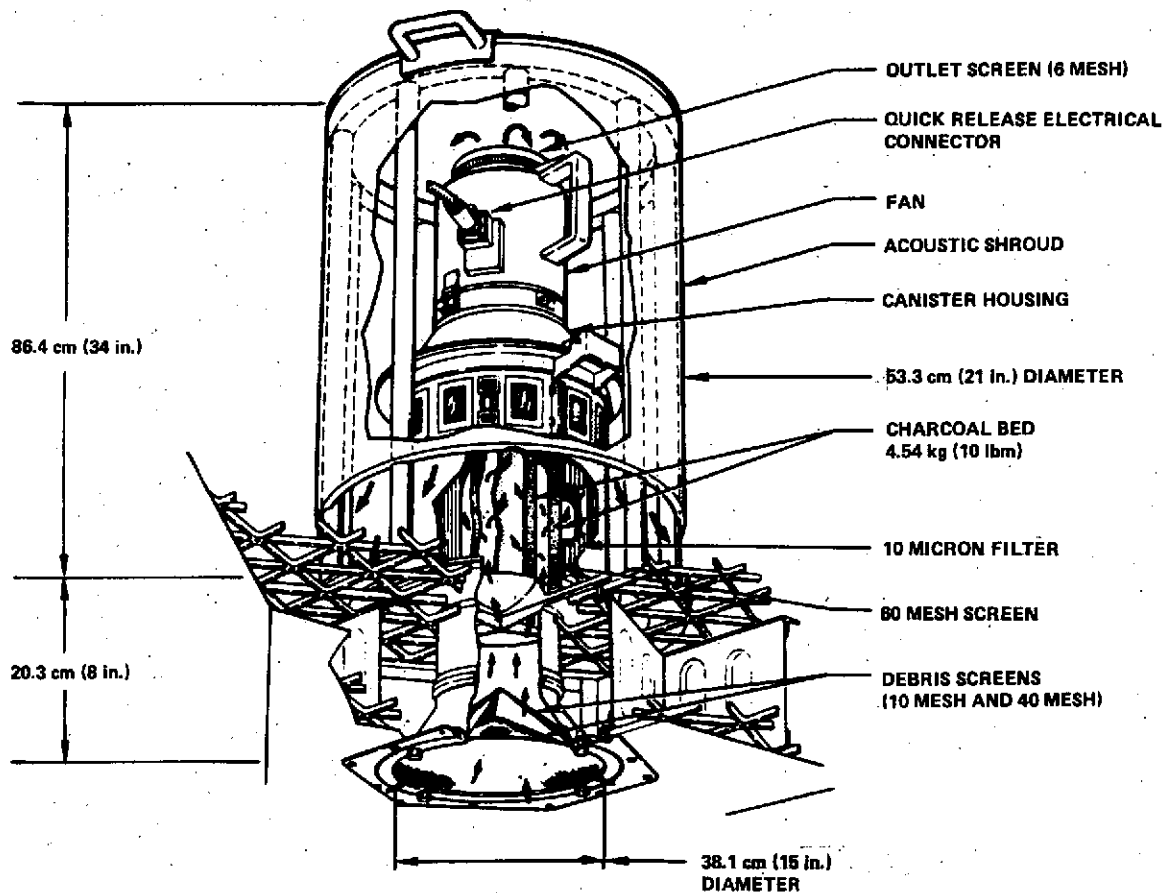


Figure 4. Waste management compartment ventilation unit.

flammability and offgassing specifications. In accordance with these specifications, materials were tested to determine organic offgassing products and carbon monoxide. The maximum allowable level of total organic outgassing in the material tested could not exceed $100 \mu\text{g/g}$ of the sample, and carbon monoxide outgassing could not exceed $25 \mu\text{g/g}$ of the sample. Once materials had passed these tests, they could be considered for use on Skylab.

In addition to individual material tests, atmospheric analyses of the Multiple Docking Adaptor/Airlock Module (MDA/AM) were performed at McDonnell Douglas-Eastern Division and of the Orbital Workshop (OWS) at Kennedy Spacecraft Center (KSC) during pre-flight checkouts. These tests provided confidence that the material selection control was adequate for minimizing contaminant levels.

The 84-hour MDA/AM altitude chamber test simulated flight conditions, except that the cabin area was not manned and some heat generating equipment (Apollo Telescope Mount Control and Display Console) was not in operation. Procedures called for periodic sampling of the cabin atmosphere, using cryogenic traps and grab samples during the test. The Environmental Control System (ECS) was inactive until the 76th hour of the test, but was turned on between the 76th and 84th hours. Results of this test indicated the presence of the compounds shown on Table 1. All of the listed compounds, with the exception of CO, are commonly used solvents or cleaning agents. CO was the only compound that was above acceptable limits. The CO concentration rose at a rate of 0.1 ppm/hr for the first 44 hours and was at a level of 12 ppm just prior to the ECS being activated. At this point, the CO level rose sharply to 23 ppm at the end of the test. Because of the dispersion of simultaneous CO readings during the test, it was concluded that the 23 ppm was unrealistic and a much lower level could be expected inflight.

The OWS offgassing test was conducted at KSC, with no measureable amount of contaminants detected.

TABLE 1. COMPOUNDS DETECTED DURING THE MDA/AM ALTITUDE CHAMBER TEST

Chloroform	Toluene
Freon 113	Ethanol
Methyl Chloroform	Isopropanol
Tetrachloroethylene	Acetone
Trichloroethylene	Methyl Ethyl Ketone (MEK)
Benzene	Carbon Monoxide (CO)

B. Computer Analysis

A knowledge of contaminant generation rates and maximum allowable concentration levels is required to determine the design adequacy of contaminant control systems. Rombach [4] developed a computer program under MSFC contract which predicted the concentration level of 212 contaminants, compared

predicted levels to maximum allowable concentrations, and analyzed the air purification system's capability to remove contaminants. This computer program did not produce conclusive results because: (1) material generation rates were difficult to establish, (2) literature values for maximum allowable concentrations were not consistent, and (3) contaminant control device removal capability for various contaminants had not been evaluated.

The material generation rates for a particular spacecraft depends upon the cabin configuration, materials of construction, and onboard experiments. The only material generation data available during the Skylab program was obtained from an offgassing test of 25 percent of the materials used in the Apollo Command Module (pre-fire configuration). This data provided an estimate of individual contaminant generation rates, but not a very satisfactory one.

Review of the literature indicated very little agreement as to what the maximum allowable concentrations of various contaminants should be. The National Academy of Science [5] established an excellent list of maximum allowable levels late in the Skylab program. Unfortunately, these were available too late to be used in the computer analysis.

Considerable data was available for charcoal removal of contaminants, as shown in Table 2. The data in this table is from Rombach [4] and is a compilation from many sources. Duell and Moberg [6] conducted a study which identified many contaminants adsorbed by charcoal. In addition, Analytical Research Laboratories have conducted analyses of many of the Apollo charcoal canisters which indicated the presence of many contaminants [7,8]. Based on these data, it was possible to establish the removal capability of the Skylab charcoal canisters.

Review of literature indicated that very little work had been done to define contaminant removal capability of condensing heat exchangers and molecular sieve material. A test program was defined and conducted at MSFC, as described in the next section.

C. MSFC Molecular Sieve/Condensing Heat Exchanger Testing

These tests were conducted to determine what contaminants would be adsorbed by the mole-sieve material and whether the adsorbed contaminants would degrade mole-sieve performance.

TABLE 2. CAPACITY OF ACTIVATED COCONUT CHARCOAL
FOR SPECIFIC VAPORS

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
1	Acetaldehyde	0.0
2	Acetic acid	15.0
3	Acetone	6.5
4	Acetonitrile	7.5
5	Acetylene	0.0
6	Acrolein	6.0
7	Allene	0.0
8	Allyl alcohol	0.3
9	Ammonia	0.0
10	Amyl acetate	27.0
11	Act-amyl alcohol	17.0
12	Tert-amyl alcohol	19.0
13	Benzene	10.0
14	Benzyl ether	> 50.0
15	1, 3-Butadiene	0.7
16	n-Butane	1.4
17	Butene-1	1.0
18	Cis-butene-2	1.0
19	Trans-butene-2	1.0
20	2-(2-butoxybutoxy) ethyl acetate	> 50.0
21	2-n-Butoxy ethanol	30.0
22	2-n-Butoxy ethyl acetate	> 50.0
23	Butyl acetate	20.0
24	n-Butyl alcohol	12.0
25	Sec-butyl alcohol	13.0
26	Tert-butyl alcohol	10.5
27	n-Butyl benzene	40.0
28	Tert-butyl benzene	33.0
29	Butyl ethylene	10.0
30	Butyraldehyde	9.0
31	Butyric acid	23.0
32	γ -Butyrolactone	12.5
33	Caprylic acid	> 50.0
34	Carbon disulfide	6.5

TABLE 2. (Continued)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
35	Carbon monoxide	0.0
36	Carbon tetrachloride	15.5
37	Carbonyl fluoride	0.0
38	Carbonyl sulfide	6.0
39	Chlorine	0.0
40	Chlorobenzene	21.0
41	Chloroethyne	0.1
42	Chloroform	10.5
43	Citric acid	> 50.0
44	p-Cresol	42.0
45	Cumene	27.0
46	Cyclohexane	10.0
47	Cyclohexanol	21.0
48	Cyclohexene	10.8
49	Cyclopropane	0.0
50	Cyclopentane	6.3
51	Cyclopentene	6.0
52	Decalin	44.0
53	Diacetone alcohol	29.0
54	Dichloroacetylene	0.0
55	Dichlorobenzene	38.0
56	1, 1-Dichloroethane	29.0
57	Diethyl benzene	40.0
58	Diisobutyl ketone	35.0
59	1, 4-Dimethoxy benzene	> 50.0
60	Dimethylamine	0.8
61	2, 2-Dimethyl butane	19.0
62	2, 3-Dimethyl butane	8.0
63	Dimethyl butene	4.0
64	Dimethyl cyclohexane	21.0
65	Dimethyl cyclopentane	20.0
66	Dimethyl ethyl benzene	40.0
67	Dimethyl furan	14.0
68	Dimethyl naphthalene	> 50.0
69	Dimethyl pentane	13.0
70	Dimethyl propane	2.0

TABLE 2. (Continued)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
71	Dimethyl sulfide	5.0
72	1, 3-Dioxalene	6.5
73	1, 4-Dioxane	14.0
74	Ethane	0.0
75	2-Ethoxyethanol	20.0
76	2-(2-ethoxyethoxy) ethanol	48.0
77	2-(2-ethoxyethoxy) ethyl acetate	> 50.0
78	2-Ethoxyethyl acetate	29.0
79	Ethyl acetate	19.0
80	Ethyl acetylene	1.0
81	Ethyl alcohol	8.0
82	Ethylamine	1.0
83	Ethyl benzene	22.0
84	2-Ethyl butanol	24.0
85	Ethyl butyl ether	14.0
86	Ethyl chloride	2.0
87	Trans-1, me-3, ethyl cyclohexane	24.0
88	Ethylene	0.0
89	Ethylene dichloride	12.0
90	Ethylene glycol	31.0
91	Ethylene oxide	0.9
92	Ethyl ether	5.0
93	Ethyl formate	7.0
94	Ethyl mercaptan	4.0
95	Ethyl nitrite	3.0
96	Formaldehyde	0.0
97	Formic acid	10.5
98	Freon-11	7.5
99	Freon-12	1.0
100	Freon-22	0.0
101	Freon-23	0.0
102	Freon-31	0.5
103	Freon-113	14.0

TABLE 2. (Continued)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
104	Freon-114	7.8
105	Freon-125	0.2
106	2-Furaldehyde	26.0
107	Furan	4.0
108	Furfuryl alcohol	28.0
109	Heptane	15.0
110	n-Heptene	14.0
111	Hexafluorobenzene	6.0
112	Hexamethylcyclotrisiloxane	47.0
113	n-Hexane	11.0
114	Hydrogen	0.0
115	Hydrogen cyanide	1.0
116	Hydrogen fluoride	0.0
117	Hydrogen sulfide	0.0
118	Indene	36.0
119	Indole	> 50.0
120	Isobutane	0.5
121	Isobutyl alcohol	10.0
122	Isobutylene	0.5
123	Isobutyraldehyde	8.0
124	Iso-octane	16.0
125	Iso-pentane	4.7
126	Isoprene	4.0
127	Isopropyl acetate	13.0
128	Isopropyl alcohol	9.0
129	Isopropyl chloride	5.0
130	Isopropyl ether	10.5
131	Isopropyl formate	9.5
132	Lactic acid	18.0
133	Lithium hydroxide	30.0
134	Mesitylene	29.0
135	Mesityl oxide	19.0
136	Methane	0.0
137	2-methoxy ethanol	16.0
138	Methyl acetate	7.5

TABLE 2. (Continued)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
139	Methyl alcohol	6.0
140	Methyl amine	0.3
141	Methyl butene	5.0
142	Methyl n-butyrate	15.0
143	Methyl chloride	0.1
144	Methyl chloroform	14.0
145	Methyl cellosolve acetate	24.0
146	Methyl cyclohexane	15.0
147	Methyl cyclohexanone	29.0
148	Methyl cyclopentane	10.0
149	Methylene chloride	6.0
150	Methyl ethyl benzene	28.0
151	Methyl ethyl ketone	9.5
152	Methyl ethyl thiophene	0.3
153	Methyl formate	4.0
154	Methyl furan	8.5
155	3-Methyl hexane	14.0
156	Methyl isobutyl ketone	18.0
157	Methyl isopropyl ketone	14.0
158	Methyl mercaptan	0.8
159	Methyl methacrylate	15.0
160	Methyl naphthalene	> 50.0
161	2-Methyl pentane	8.5
162	3-Methyl pentane	11.0
163	Methyl n-propyl ketone	14.0
164	Methyl thiophene	17.0
165	Napthalene	> 50.0
166	Nitric oxide	0.0
167	Nitrogen dioxide	0.0
168	Nitrous oxide	0.0
169	Ozone	20.0
170	Octane	20.0
171	n-Pentane	5.3
172	2-Pentene	5.0
173	Perchloroethylene	26.0
174	Phenol	30.0

TABLE 2. (Continued)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
175	2-Phenyl, 2-Propanol	> 50.0
176	Phosgene	3.0
177	Propionaldehyde	5.0
178	Propane	0.1
179	Propionic acid	19.0
180	Propyl acetate	17.0
181	n-Propyl alcohol	11.0
182	n-Propyl benzene	28.0
183	Propyl chloride	6.7
184	Propylene	0.0
185	Propylene aldehyde	13.0
186	Propyl mercaptan	8.8
187	Propyne	0.1
188	Pseudocumene	30.0
189	Skatole	> 50.0
190	Styrene	23.0
191	Sulfur dioxide	0.0
192	Tetrafluorobenzene	6.0
193	Tetrafluoroethylene	0.0
194	Tetrafluoromethane	0.0
195	Tetrahydrofuran	8.0
196	Tetramethylbenzene	45.0
197	Thiophene	11.0
198	Thioxene	23.0
199	Toluene	16.0
200	Toluene diisocyanate	> 50.0
201	Trichloroethylene	15.0
202	Trifluorobenzene	4.0
203	Trimethyl butane	12.0
204	1, 1, 3-Trimethyl cyclohexane	29.0
205	Trimethyl hexadiene	26.0
206	Trimethyl hexane	23.0
207	Trimethyl silanol	6.0
208	Valeric acid	36.0

TABLE 2. (Concluded)

No.	Contaminant	Charcoal Adsorption Capacity (percent of charcoal weight)
209	Vinyl chloride	0.5
210	Vinylidene chloride	6.0
211	Vinyl methyl ether	1.0
212	Xylenes	21.0

It was difficult to determine a list of contaminants and their associated levels that would be present in Skylab, primarily because material generation rates were not available. A list of contaminants that were tested on an individual basis is shown in Table 3. The majority of these contaminants and levels were specified by Johnson Spacecraft Center (JSC), as those noted during analysis of Apollo charcoal canisters. The remainder of the contaminants were selected because of the possibility that they might exist in the Skylab atmosphere. In addition to the individual contaminant testing, a mixed gas test was run with the concentration levels shown in Table 4. The contaminants and their associated levels shown in this table were specified by JSC.

1. Test Setup Description and Test Procedure.¹ The testing consisted of two phases. Phase I testing was accomplished using a special test molecular sieve bed (fabricated by MSFC) and the associated plumbing required to simulate the operation of a flight mole-sieve unit (additional testing was required on a flight type mole-sieve unit). A qualification unit was obtained and used for Phase II testing.

The special test mole-sieve bed (Phase I) is shown as a schematic in Figure 5 and pictorially in Figure 6. The test bed was a stainless steel rectangular container designed to contain approximately the same amount of Linde Type 13X and 5A molecular sieve material as one flight sorbent canister. The test bed was connected to a 258.5 mm Hg (5 psia) source and a 0.001 mm Hg (10^{-3} torr) vacuum chamber. The bed inlet was connected to a mixing chamber that was supplied with the necessary gases required to simulate Skylab flight atmospheric conditions. These gases included a 6.26 kg/hr (13.8 lbm/hr) dry air flow, a CO₂ supply to maintain 5.2 mm Hg, a steam supply to control the bed inlet dewpoint between 7.77°C and 11.65°C (46°F and 53°F), and

1. Information on the test program was taken from a report written by C. F. Hanks [9].

TABLE 3. INDIVIDUAL CONTAMINANT LIST
(MSFC MOLE-SIEVE TEST)

Contaminant	Test Unit	Concentration, ppm
1. Hydrogen	P	900
2. Ammonia	P	60
3. Methyl chloride	P	20
4. Freon 12	P	500
5. Benzene	P, Q	5
6. Freon 113	P	500
7. Xylene	P	50
8. Toluene	P	50
9. Acetone	P	500
10. Isopropyl alcohol	P	100
11. Acetaldehyde	P, Q	50
12. Methyl isobutyl ketone	P, Q	10
13. Dichloromethane	P	25
14. Carbon monoxide	P	75
15. Methyl chloroform	P, Q	90
16. Methyl ethyl ketone	P, Q	100
17. Coolanol 15	Q	50

P denotes special test bed,
Q denotes mole-sieve qual unit

TABLE 4. MIXED GAS TEST CONTAMINANT LIST

Contaminant	Concentration, ppm
1. Freon 113	5.0
2. Benzene	0.3
3. Xylene	0.3
4. Toluene	0.3
5. Acetaldehyde	0.3
6. Acetone	0.5
7. Methyl isobutyl ketone	0.4
8. Isopropyl alcohol	0.8
9. Dichloromethane	0.3
10. Methyl chloroform	0.3
11. Methyl ethyl ketone	0.5
	<u>9.0</u>

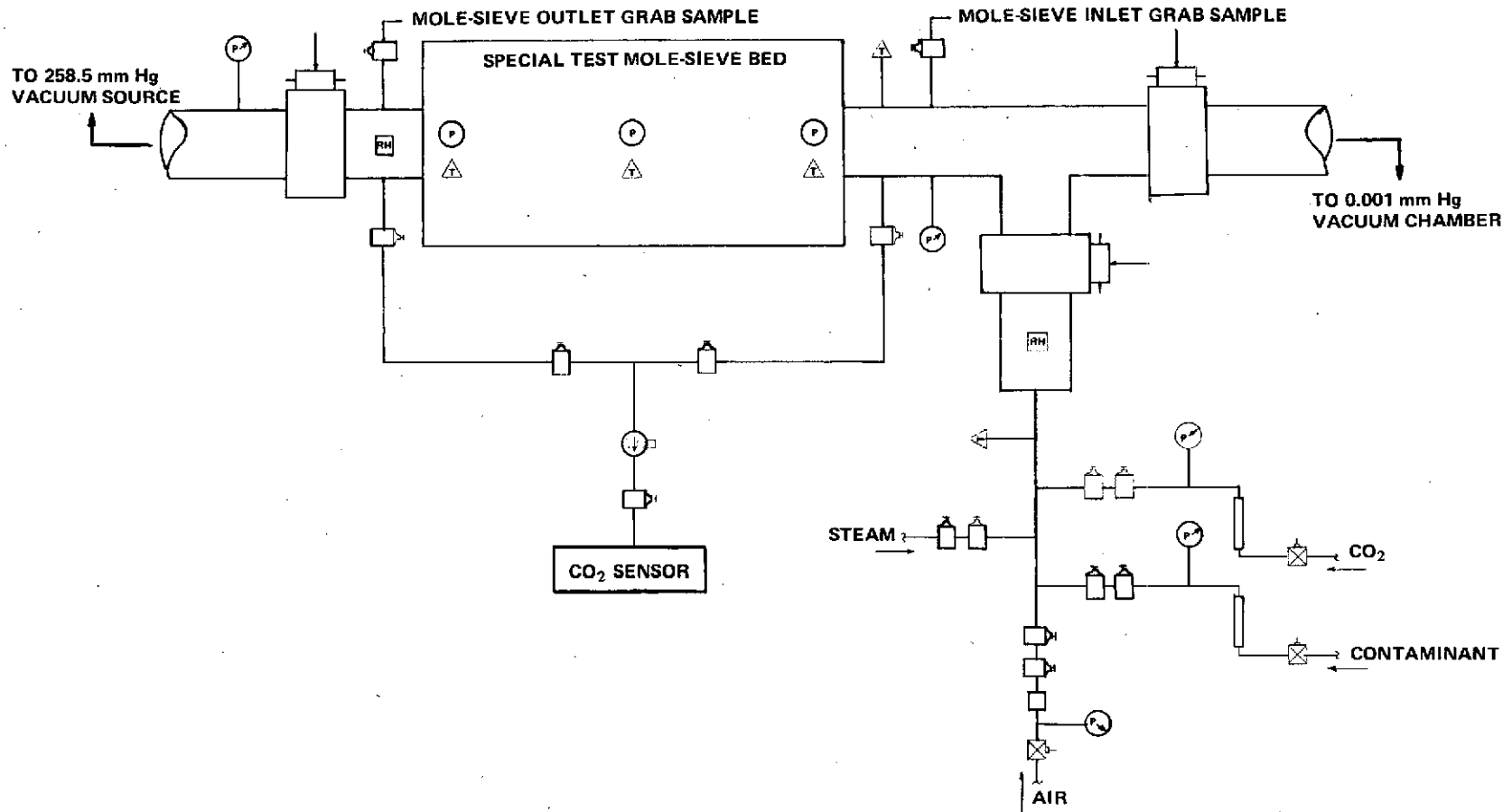


Figure 5. Schematic of special test mole-sieve unit.

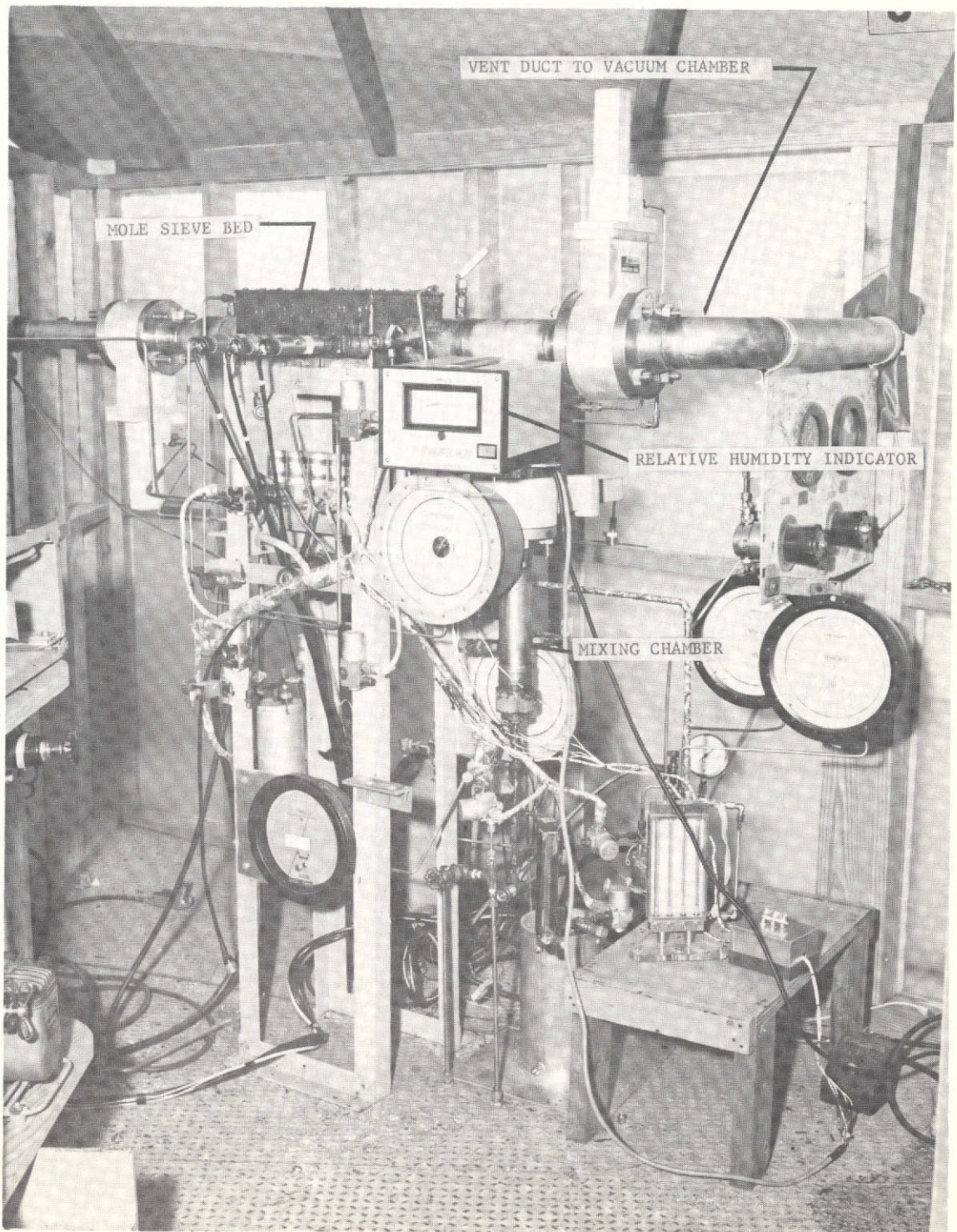


Figure 6. View of special test mole-sieve unit.

a contaminant supply. Those contaminants that are gases at atmospheric conditions were premixed with GN₂ and injected into the air flow. A small amount of heated GN₂ was bubbled through liquid contaminants and, then, injected into the air flow.

The test bed was instrumented, as shown in Figure 5. The bed inlet and outlet CO₂ concentrations were monitored with a Beckman Model 315B Infrared CO₂ Analyzer. The relative humidity was measured with a Phys-Chemical Research Corporation Humeter Relative Humidity Indicator. Molecular sieve bed pressures were measured with Piranni vacuum gages.

A test consisted of a series of 15 minute adsorb and 15 minute desorb cycles. During the adsorb cycle, the bed was exposed to the 258.5 mm Hg source and the desired test conditions at the inlet of the test bed. During the desorb cycle, the bed was isolated from the 258 mm Hg (5 psia) source and gas flows, and exposed to the 0.001 mm Hg vacuum chamber conditions. During each test, a gas sample was taken periodically, both upstream and downstream, of the test bed and analyzed with gas chromatograph techniques. The results gave inlet and outlet concentration levels which could be used to determine the contaminant removal capability of the molecular sieve material. Bed inlet and outlet CO₂ levels were monitored and recorded continuously during a test for a determination of the bed's CO₂ removal capability and degradation, if any.

The qual unit mole-sieve test setup (Phase II) is shown as a schematic in Figure 7 and pictorially in Figure 8. The setup consisted of the qual mole-sieve unit; a 258.5 mm Hg vacuum chamber; a 0.001 mm Hg vacuum chamber; a Gemini condensing heat exchanger (CHX); a commercial (non-flight) compressor; a humidifier; and the associated plumbing, gas supplies, and instrumentation necessary to control and measure test parameters.

The qual unit, the CHX, the compressor, and the humidifier were housed in the 258.5 mm Hg chamber. The chamber atmosphere was conditioned with injection of CO₂, contaminants, and water vapor from the humidifier to simulate Skylab flight condition, as in Phase I testing. The compressor circulated the 258.5 mm Hg chamber atmosphere through the CHX (which controlled the mole-sieve inlet dewpoint) and the contaminants were injected into the 258.5 mm Hg chamber, using the same techniques as were used for Phase I tests. For the mixed gas test, the contaminants were premixed in the liquid state and injected with a hypodermic syringe through a membrane into the 258.5 mm Hg chamber. Mole-Sieve inlet and outlet CO₂ concentrations were monitored, as in Phase I testing.

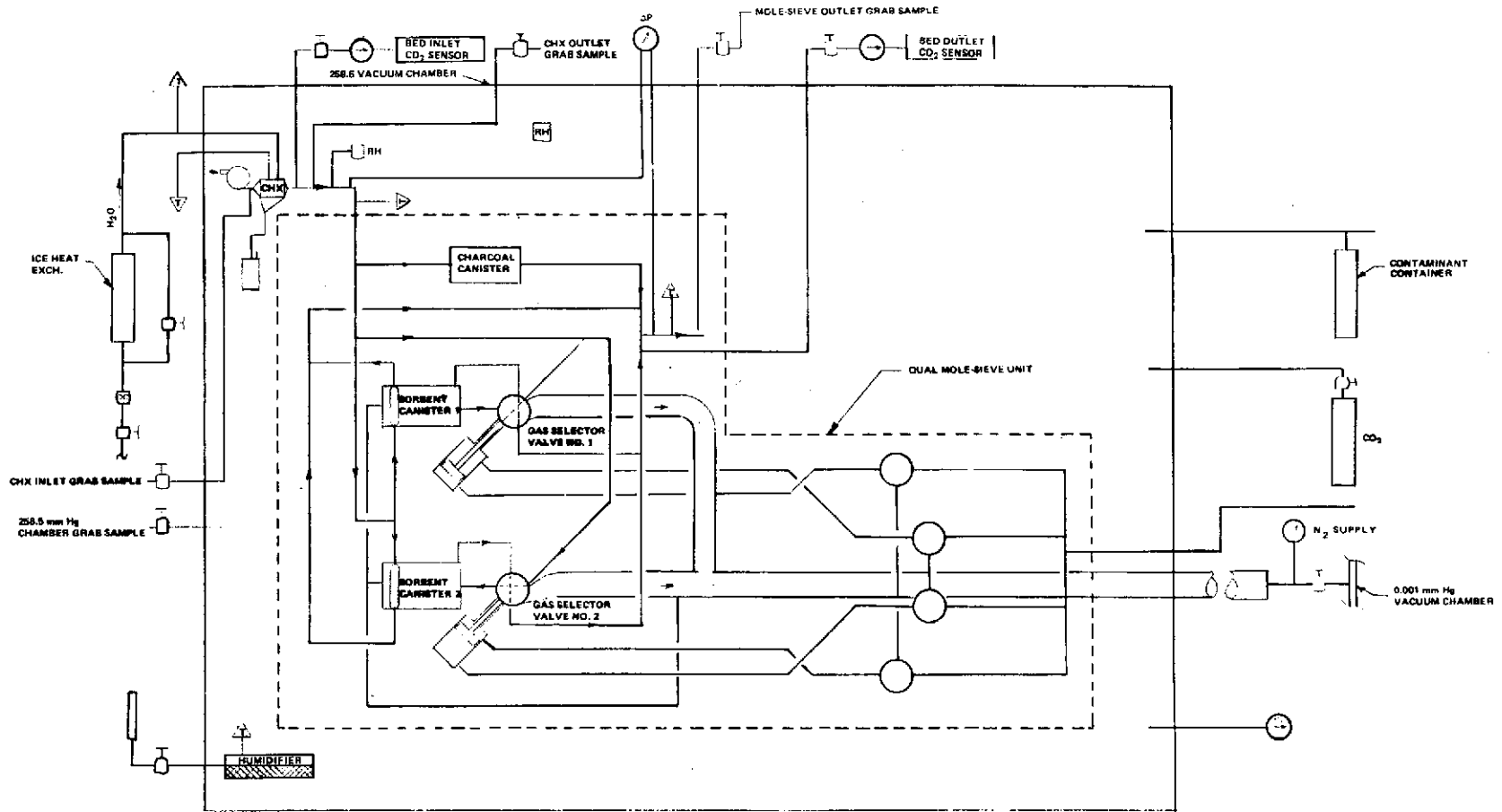


Figure 7. Schematic of qualification unit mole-sieve test instrumentation.



Figure 8. View of qualification unit mole-sieve test facility.

After component checkout of the CHX and mole-sieve units, the beds were baked out so that they would be in a regenerated condition for the test. Actual testing consisted of the following:

- a. Baseline test to establish bed performance
- b. Individual contaminant injection tests
- c. Bed bakeout
- d. Mixed gas test of 48 hour duration.

For all contaminant tests, enough baseline cycles were run to establish equilibrium conditions of chamber humidity and CO₂ levels. After contaminant injection, gas samples were taken periodically at the CHX inlet, CHX outlet, and mole-sieve unit outlet. Inlet and outlet CO₂ levels were monitored continuously.

2. Test Results. Contamination tests indicated that molecular sieve material had 100 percent removal efficiency for all contaminants tested with the exception of hydrogen and carbon monoxide, as shown in Table 5. No removal capability was noted for these two gases. The CHX has some capability for contaminant removal, especially for Coolanol 15.

A data band plot of bed outlet CO₂ levels for all contaminants tested using the special test mole-sieve unit (Phase I) is shown in Figure 9. This data shows the inconsistencies of the special test bed's CO₂ adsorption efficiency. Due to this fact, it was concluded that the CO₂ adsorption and degradation data obtained using this bed was not a sufficient guide from which to form valid conclusions.

There was no performance degradation noted for the tests performed using the qual mole-sieve unit. A typical CO₂ performance curve (for methyl isobutyl ketone injection) is shown in Figure 10. Similar performance curves were obtained for the other individual contamination injection tests. The mixed gas test performance data is shown in Figure 11. A facility power failure caused a break in the 48-hour mixed gas test, as shown in this figure. Gas sample results indicated a chamber contaminant level of 3 ppm, less than the required level of 9 ppm. No performance degradation was noted.

The results of these tests indicated that molecular sieve material has the capability to adsorb almost all contaminants tested without appreciable bed performance degradation.

TABLE 5. CHX AND MOLE-SIEVE REMOVAL EFFICIENCY

Contaminant	Test Inlet Concentration, ppm	Removal Efficiency, percent	
		CHX	Mole-Sieve
1. Hydrogen	900	(1)	0
2. Ammonia	60	(1)	100
3. Methyl chloride	20	(1)	100
4. Freon 12	500	(1)	100
5. Benzene	5	8.7	100
6. Freon 113	500	(1)	100
7. Xylene	50	(1)	100
8. Toluene	50	(1)	100
9. Acetone	500	(1)	100
10. Isopropyl alcohol	100	(1)	100
11. Acetaldehyde	50	2.6	100
12. Methyl isobutyl ketone	10	33	100
13. Dichloromethane	25	(1)	100
14. Carbon monoxide	75	(1)	0
15. Methyl chloroform	90	15.2	100
16. Methyl ethyl ketone	100	1.1	100
17. Coolanol 15	50	89	100

(1) Not tested.

D. Trace Contaminant Measurement Devices

In addition to effective materials control and onboard contaminant removal devices, it was desirable to have a contaminant measurement device to give a real-time indication of contaminant levels. State-of-the-art trace contaminant measurement devices were investigated during the Skylab program but none were attractive from a cost or design standpoint.

The Apollo Program's gas chromatograph was a candidate but was not selected because of the cost required to refurbish it using materials that would pass NASA flammability and offgassing tests. In addition there was some question as to the design adequacy of this gas chromatograph.

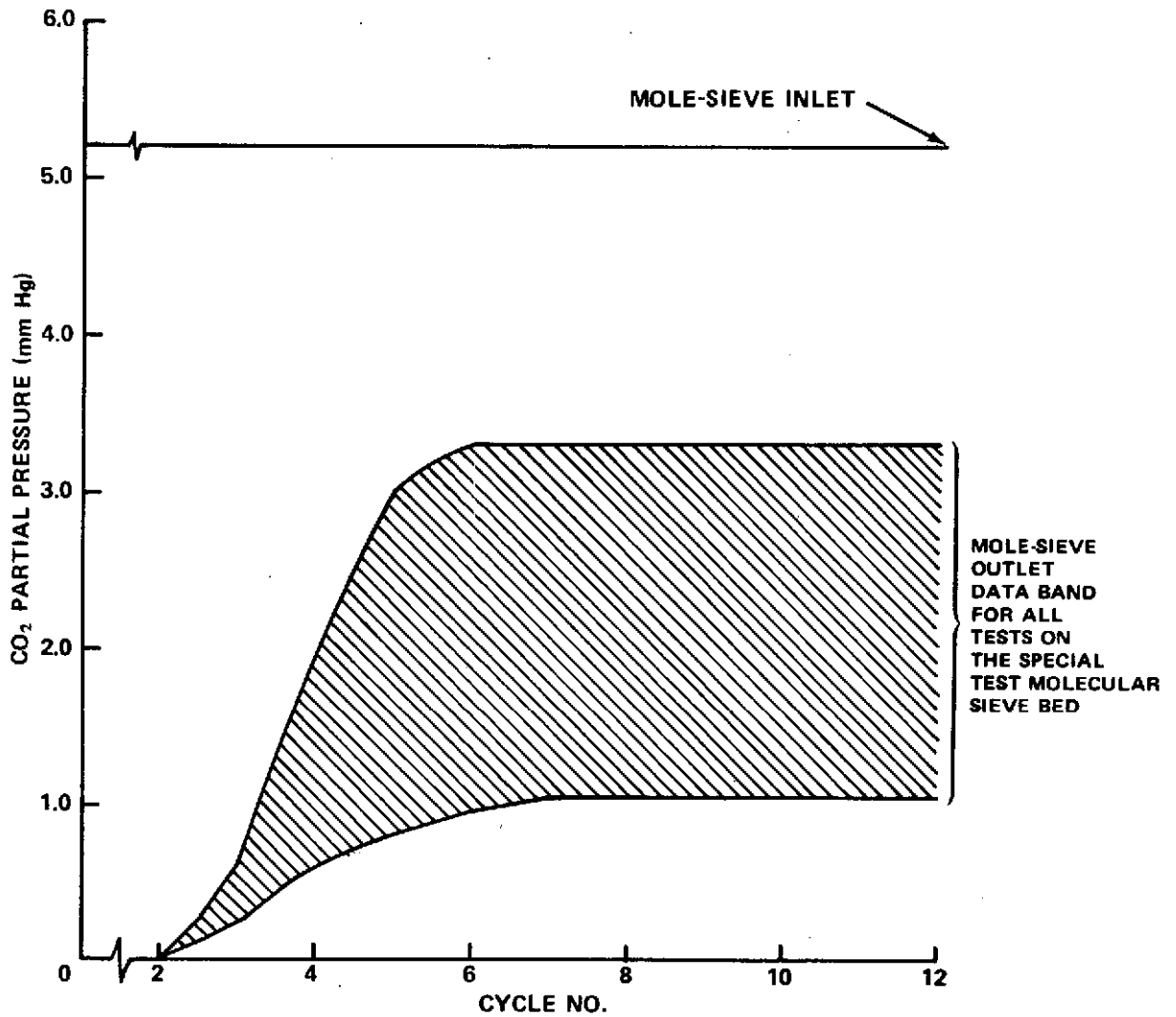


Figure 9. Results of special mole-sieve test.

An inflight contamination gas detector tube system (Draeger tubes) was investigated but was found to be impractical when detailed safety, engineering, and operational aspects of off-the-shelf hardware were taken into consideration. In order to develop a system that would be compatible with Skylab design criteria, it was estimated that 2.2 million dollars would be required. Funding was not available to support a development program of this cost.

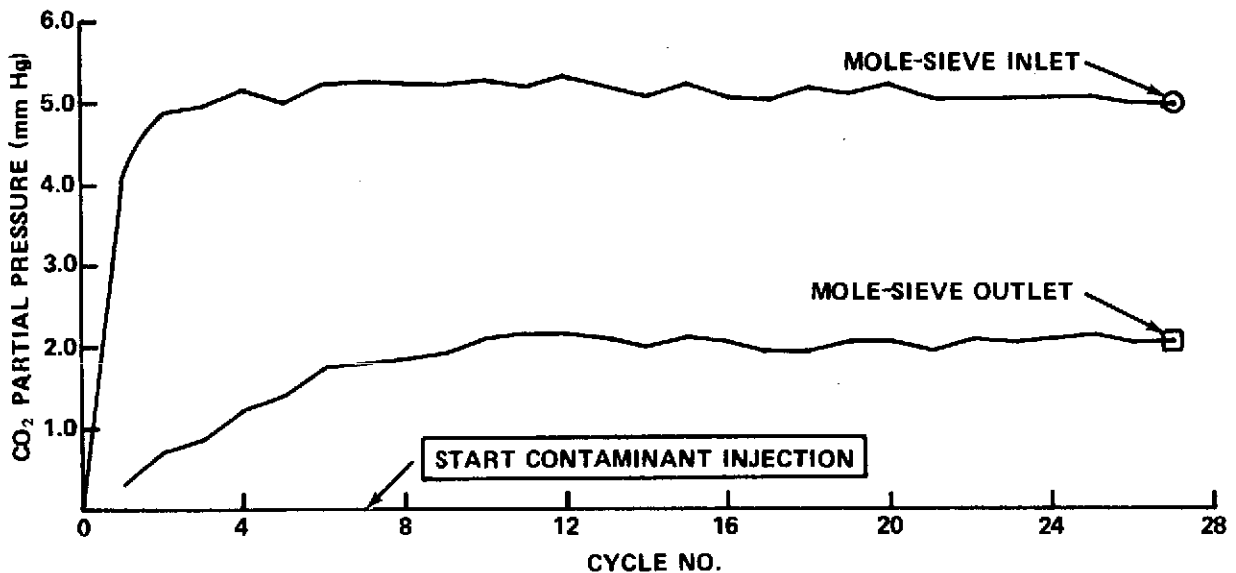


Figure 10. Results of qual unit methyl isobutyl ketone test.

Based on CO levels noted during the MDA/AM offgassing test (Section III. A.), the JSC Director of Life Sciences recommended that commercially available "sniffer" tubes for CO be used during the Skylab mission. These CO sensing instruments were not approved for Skylab.

No contaminant level measuring devices were onboard Skylab at launch and no plans were made for the crew to carry up such devices.

IV. SKYLAB FLIGHT RESULTS

A. Crew Contaminant Readings

Loss of the meteoroid shield during boost caused high OWS temperatures with suspected offgassing of contaminants (CO and toluene diisocyanate) from the OWS polyurethane foam. A vent/repressurization scheme (Fig. 12) was initiated to purge Skylab of the contaminants prior to SL-2 crew entry. The SL-2 crew took toluene diisocyanate (TDI) samples, using Draeger tubes, and CO samples with a Mine Safety Appliance device prior to entry. There was no indication of the presence of TDI and less than 25 ppm of CO. The device used to measure CO levels gave only an approximate value since it was a color changing material and one color represented 0 to 25 ppm. Also, problems had

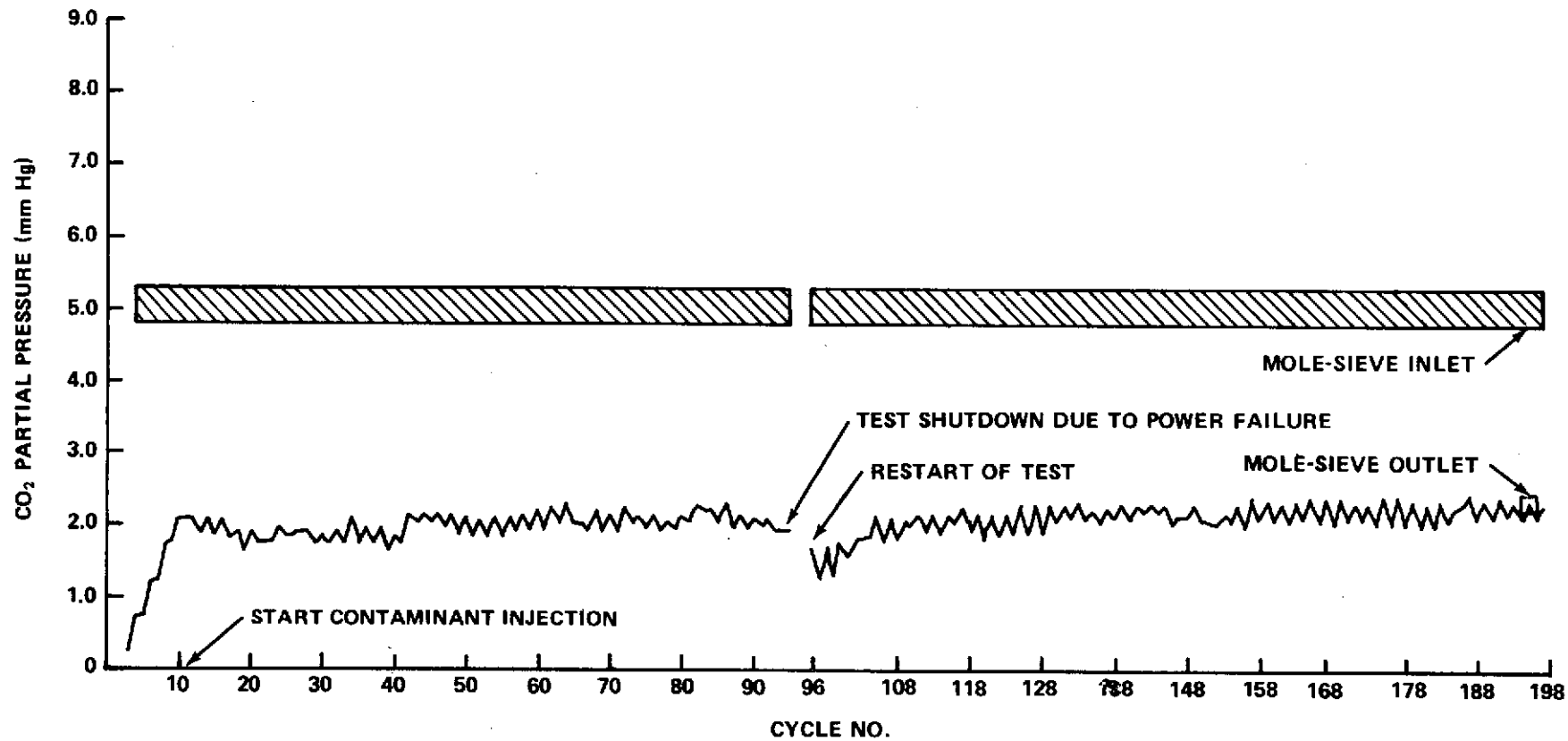


Figure 11. Qual unit mixed gas test results.

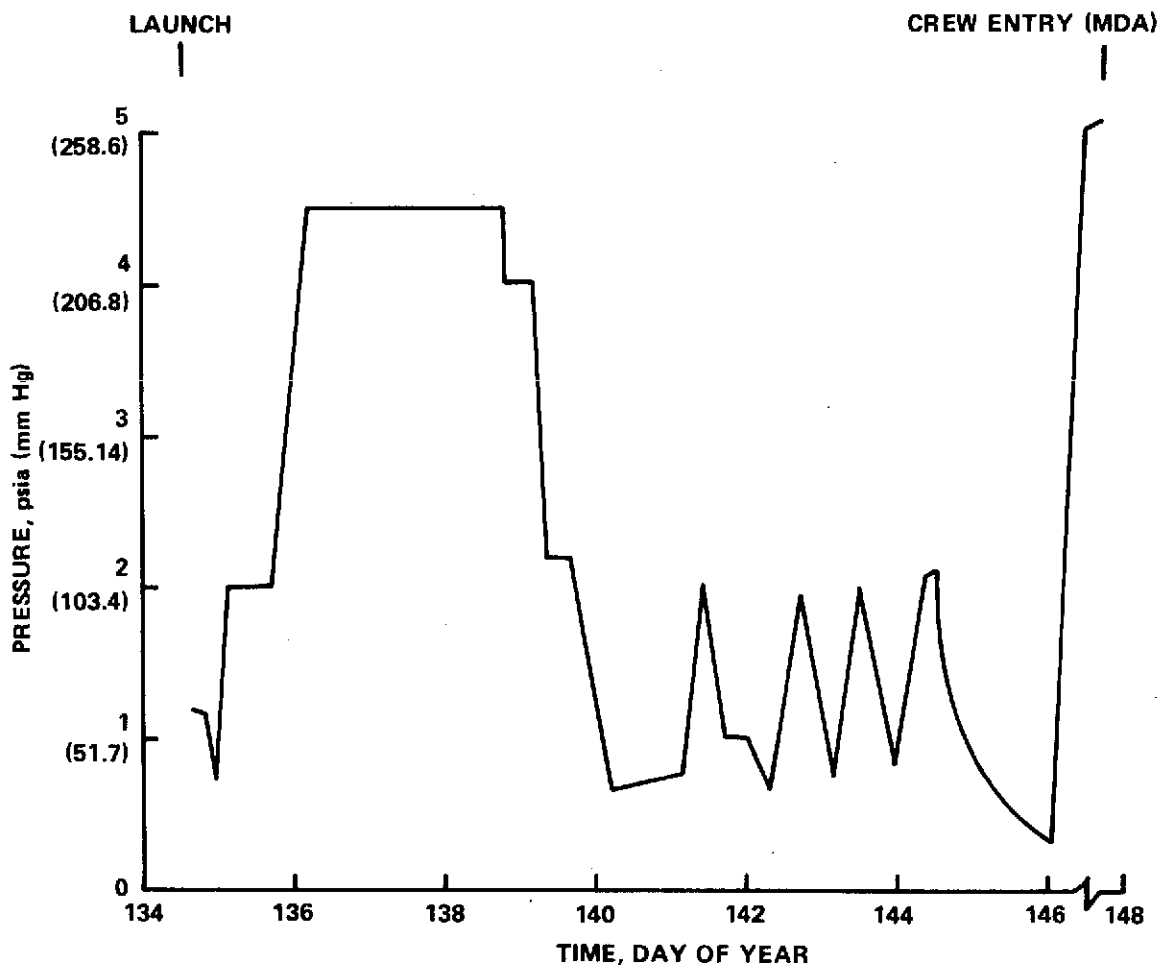


Figure 12. Vent/repressurization history prior to SL-2.

been encountered with the material changing color in the 0 to 25 ppm range while stored. The SL-3 and SL-4 crew took one TDI sample each, with no indication that this contaminant was present. The two crews, on every occasion that they sampled for CO, found that the sensing material had changed to the 0 to 25 ppm color during storage. Therefore the CO level was less than 25 ppm, but no estimate of the absolute value could be made. Indications were that the vent/repressurization scheme was effective in removing offgassed contaminants.

B. Charcoal Canister Performance

The mole-sieve and WMC charcoal canisters performed their design function of removing odors, as well as removing contaminants. Table 6 summarizes the charcoal canister usage and replacements during the missions. The only means available to evaluate the performance of the odor removal system was via crew comments. Comments received during technical debriefings of all three crews indicated that the system performed very well. The following is taken from the SL 1/4 Technical Debriefing, pg. 12-24.

"No problems. The odor removal system in the workshop was outstanding. Odors just did not persist. They were very quickly removed. The waste management compartment odor removal was outstanding. There was no way anyone using the waste management compartment offended or bothered anyone else in the workshop. We were amazed how well the odors were removed and how good the workshop smelled in general. I thought that we were going to have to get used to some very peculiar odors during our mission up there. When we entered the workshop, we were quite pleasantly surprised to find that there was no particular odor that bothered us. It stayed that way the entire time. I wouldn't guarantee that very much longer, because as we mentioned before, we left the workshop in the as-used condition, with little or no cleaning."

An analysis was performed on three mole-sieve charcoal canister samples which were returned by the SL-4 crew, as well as one unexposed sample for control. The control sample was obtained from a backup mole-sieve charcoal canister and the three returned samples from end of mission SL-3, mid-mission SL-3, and mid-mission SL-4, respectively [10]. The samples were vacuum-thermally desorbed and the desorbates were analyzed by gas chromatography-mass spectrometry. Individual component identification was accomplished for the presence or absence of over 240 compounds.

There were more than thirty compounds which were identified in these samples. Four compounds; methyl, ethyl, and isopropyl alcohols and acetone; constituted 81 to 93 percent of the total recovery, exclusive of water. Water recovery constituted approximately 20 percent of the weight of the charcoal desorbed. Traces of Coolanol-15 were also present. The complete results of the chemical analysis is shown in Table 7.

TABLE 6. SKYLAB CHARCOAL CANISTER USAGE

Mission	Replace Mole Sieve Charcoal Canisters (2)	Replace WMC Charcoal Canisters
SL-2	172/10:50	172/08:25
SL-3	247/17:20 267/15:30	247/16:00 267/09:00
SL-4	364/20:50	346/(time not known) 009/(time not known)
	Total Used -10 (2 Installed +8 spares)	Total Used -6 (1 Installed +5 spares)
	Total Launched -10 (2 Installed +8 spares)	Total Launched -6 (1 Installed +5 spares)

Results of this charcoal analysis indicated the presence of Coolanol-15. During SL-3, Coolanol-15 leaks in the AM primary and secondary coolant loops were detected. It was impossible to determine whether these leaks were inside or outside the spacecraft so the possibility existed that amounts of Coolanol were leaking into the cabin area. A conservative analysis (leak rate of 0.15 lb/day of Coolanol) indicated a level of less than 10 ppm of Coolanol in the cluster atmosphere. This analysis assumed Coolanol removal by the WMC and mole-sieve charcoal canisters, condensing heat exchangers, and mole-sieve material. This calculated level could be in the form of Coolanol-15, as well as secondary butyl alcohol and isopropyl alcohol which result when water and Coolanol combine. Results of this charcoal analysis, as well as analysis of returned CO₂ cartridges, indicated that Coolanol was present within Skylab. However, due to the demonstrated ability of onboard equipment to remove Coolanol from the atmosphere, it is unlikely that any significant amount of Coolanol was present in the atmosphere.

C. Molecular Sieve Performance

The molecular sieve system performed very well throughout all of the Skylab missions. This tended to substantiate test results shown in Section III. C. which indicated that adsorbed contaminants would not affect mole-sieve

TABLE 7. ANALYSES OF COMPONENTS VACUUM-THERMALLY
DESORBED FROM SKYLAB CHARCOALS

Blank Charcoal		
Compound	Molecular Weight	$\mu\text{g/g}$
Propane	44.09	0.077
Butane	58.12	0.061
Propylene	42.08	1.2
1-Butene	56.10	0.12
2-Pentene	70.13	0.047
Isoprene	68.11	0.017
2-Hexene	84.16	0.0012
Cyclohexane	84.16	0.24
Toluene	92.13	0.21
Methyl alcohol	32.04	0.28
Ethyl alcohol	46.07	0.068
Isopropyl alcohol	60.09	0.26
Acetone	58.08	0.28
Acetonitrile	41.05	0.049
Total Excluding Water		2.90
Water		1.5×10^4
Charcoal S/N 30-111 End of Mission SL-3		
Freon 12	121.00	0.49
Freon 113	187.39	0.97
Ethane	30.07	0.049
Butane	58.12	0.25
Hexane	86.17	0.40
n-Heptane	100.20	0.067
Ethylene	28.05	0.041
Propylene	42.08	2.4
Methyl acetylene	40.07	0.03
1-Butene	56.10	2.0
2-Pentene	70.13	0.37
Isoprene	68.11	0.13
2-Hexene	84.16	0.86
Methylcyclohexene	96.17	0.035

TABLE 7. (Continued)

Compound	Molecular Weight	$\mu\text{g/g}$
Charcoal S/N 30-111 End of Mission SL-3 (Cont' d)		
Cyclohexane	84.16	0.075
Benzene	78.11	0.072
p-Xylene	106.16	0.15
Furan	68.07	0.075
Methyl alcohol	32.04	7.6
Ethyl alcohol	46.07	7.5
Isopropyl alcohol	60.09	17.0
Isobutyl alcohol	74.12	0.074
Acetone	58.08	18.0
Ethyl acetate	88.10	3.4
Butyl acetate	116.16	0.041
Coolanol 15		<0.2
Total Excluding Water		61.84
Water		2.11×10^5
Charcoal S/N 101-135 Mid Mission SL-3		
Freon 12	121.00	0.30
Freon 113	187.39	3.6
Propane	44.09	1.1
Butane	58.12	1.1
Hexane	86.17	0.24
n-Heptane	100.20	0.089
Propylene	42.08	8.4
Methyl acetylene	40.07	0.05
1-Butene	56.10	5.9
2-Butene (cis)	56.10	2.4
2-Pentene	70.13	0.90
Isoprene	68.11	1.0
2-Hexene	84.16	1.7
Methylcyclohexene	96.17	0.029
Cyclohexane	84.16	0.11
Benzene	78.11	0.0018
Toluene	92.13	0.096

TABLE 7. (Continued)

Compound	Molecular Weight	$\mu\text{g/g}$
Charcoal S/N 101-135 Mid Mission SL-3 (Cont' d)		
p-Xylene	106.16	0.098
Furan	68.07	1.3
Methyl alcohol	32.04	33.0
Ethyl alcohol	46.07	37.0
Isopropyl alcohol	60.09	61.0
Isobutyl alcohol	74.12	0.11
Acetone	58.08	40.0
Ethyl acetate	88.10	5.5
Butyl acetate	116.16	0.12
Coolanol 15		<0.3
Total Excluding Water		205.8
Water		2.07×10^5
Charcoal S/N 00-117 Mid-Mission SL-4		
Freon 12	121.00	0.12
Freon 113	187.39	0.28
Propane	44.09	0.021
Butane	58.12	0.032
Hexane	86.17	0.11
Propylene	42.08	0.15
Methylacetylene	40.07	0.020
1-Butene	56.10	0.12
2-Butene (cis)	56.10	0.033
2-Pentene	70.13	0.61
Isoprene	68.11	0.061
2-Hexene	84.16	0.013
Cyclohexane	84.16	0.030
Benzene	78.11	0.0068
Toluene	92.13	0.018
Furan	68.07	0.058
Methyl alcohol	32.04	7.8
Ethyl alcohol	46.07	2.8

TABLE 7. (Concluded)

Compound	Molecular Weight	$\mu\text{g/g}$
Charcoal S/N 00-117 Mid-Mission SL-4 (Cont'd)		
Isopropyl alcohol	60.09	12.0
Isobutyl alcohol	74.12	0.0065
Acetone	58.08	13.0
Ethyl acetate	88.10	0.20
Acetonitrile	41.05	0.20
Unidentified C ₁₀ -C ₁₃		
Hydrocarbons		0.10
Coolanol 15		<0.04
Total Excluding Water		38.30
Water		1.98×10^5

performance. No hardware failures of any type were experienced on the active mole-sieve and, as a result, the backup was never activated. The active mole-sieve was operated continuously throughout the 84 days of the SL-4 mission without requiring a mid-mission bakeout. The molecular sieve had been qualified, based on bakeouts at 28 day intervals.

Preflight analysis had indicated that the molecular sieve would maintain the CO₂ level at approximately 5.0 mm Hg. Although flight levels were subject to some interpretation due to molecular sieve system CO₂ sensor accuracy (± 1.4 mm Hg), evaluation of all available data indicates they performed near predicted values. Means, other than the molecular sieve sensors, to monitor CO₂ levels were available onboard the Skylab. Unfortunately, one of them — the portable CO₂/dewpoint monitor — had failed earlier due to the high temperatures in the OWS where it had been stowed, and could not be used. The other method involved using the M171 mass spectrometer in the OWS. Prior to and following each M171 performance, a sample of cabin gas was analyzed by the mass spectrometer, and the percent, by volume, of O₂, H₂O, and CO₂ in the cabin gas were read out to the ground by the crew. By knowing the cluster total pressure at the time, it was possible to calculate the partial pressures of O₂, H₂O, and CO₂.

Soon after MDA hatch opening on mission SL-2, it became apparent that the readings from the molecular sieve PCO_2 sensors varied somewhat from each other and from the preflight predictions. Throughout all of the missions, the M171 mass spectrometer data were used to "calibrate" the molecular sieve inlet CO_2 sensors. Eighteen data samples during SL-2, 27 samples during SL-3, and 36 samples during SL-4 were obtained and used. Analysis of all the data resulted in the conclusion that the molecular sieve A inlet sensor (D209) remained within specification limits while the molecular sieve B inlet sensor (D213) was sometimes outside of specification limits.

The calibration data from the M171 mass spectrometer have been used, along with the molecular sieve inlet sensor (D209) readings, to produce CO_2 profiles for the missions and the results are presented in Figures 13, 14, and 15. The correction used on the D209 data averaged approximately 0.9 mm Hg and the correction always increased the quoted level from the level indicated by D209. As a result, the data provided are believed to represent an upper limit on the actual CO_2 levels. As indicated by the data, the CO_2 level during SL-2 was near the preflight prediction of 5.0 mm Hg. The level was slightly higher during SL-3 with the daily average generally being 5.5 mm Hg or lower. The level increased above 5.5 mm Hg after Day Of Year (DOY) 227 and a bakeout was performed on DOY 231, after which the level returned to lower values. The higher CO_2 levels during the bakeout (Fig. 14) were a result of the long bakeout times (Table 8) with only one bed functioning. As reported previously, the CO_2 levels were maintained at desired levels throughout SL-4 without a molecular sieve bakeout. The significantly lower CO_2 levels depicted during EVA days were a result of reduced CO_2 generation rates with only one crewman internal to the vehicle and the smaller volume of atmosphere being conditioned with the hatches closed.

V. CONCLUSIONS AND RECOMMENDATIONS

Skylab flight results have indicated that the combination of materials selection, onboard removal devices, and preflight offgassing tests can be an effective means of controlling spacecraft contaminant levels. As there were insufficient onboard monitoring equipment to establish various contaminant levels, this conclusion was based on the ground demonstrated removal capability of equipment, the results of ground offgassing tests, and the fact that there was no evidence of crew sickness, other than that caused by the adaptation to "zero-g" conditions.

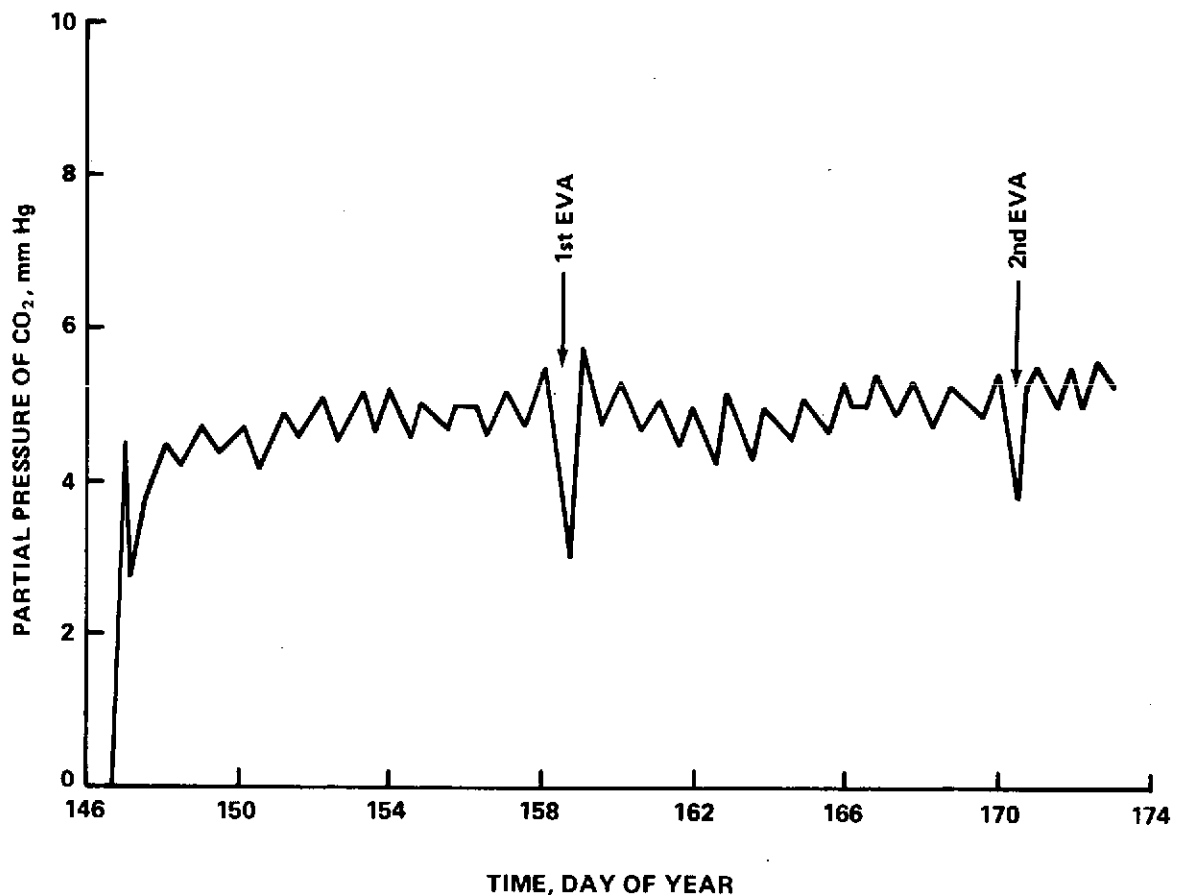


Figure 13. CO₂ partial pressure profile for SL-2.

The following recommendations apply to the establishing of procedure requirements for atmospheric contamination control of future spacecraft:

1. An effective materials screening program should be carried out to eliminate materials with offgassing characteristics above established criteria.
2. An evaluation of contaminant removal capability of existing onboard equipment by analysis and tests. If this evaluation indicates that existing equipment is not adequate in controlling contaminants to acceptable levels, special removal devices such as sorbent beds and catalytic oxidizers should be considered for inclusion in the Environment Control System (ECS) design.
3. Offgassing tests of major components and experiments should be carried out to verify that offgassing results are at an acceptable level.

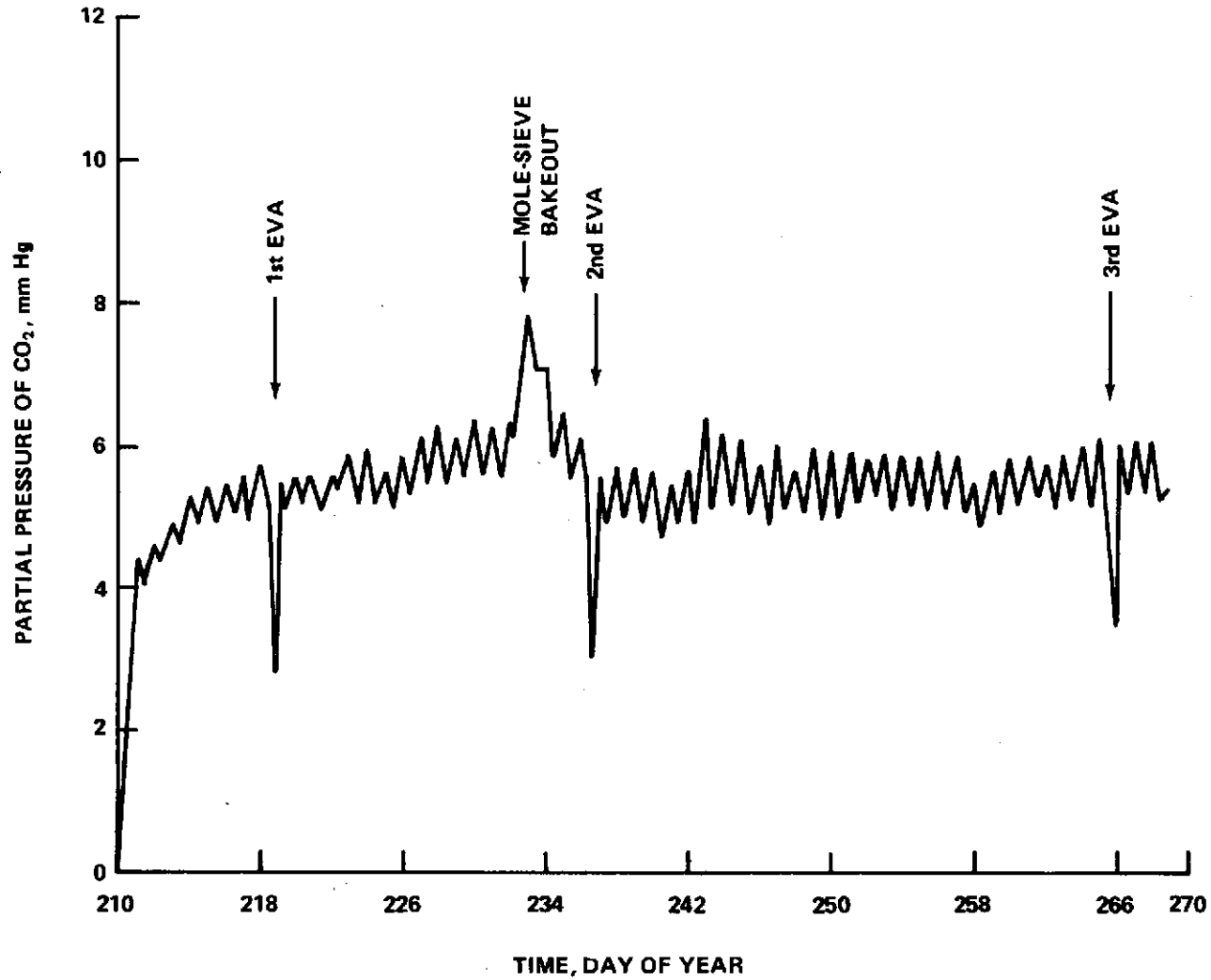


Figure 14. CO₂ partial pressure profile for SL-3.

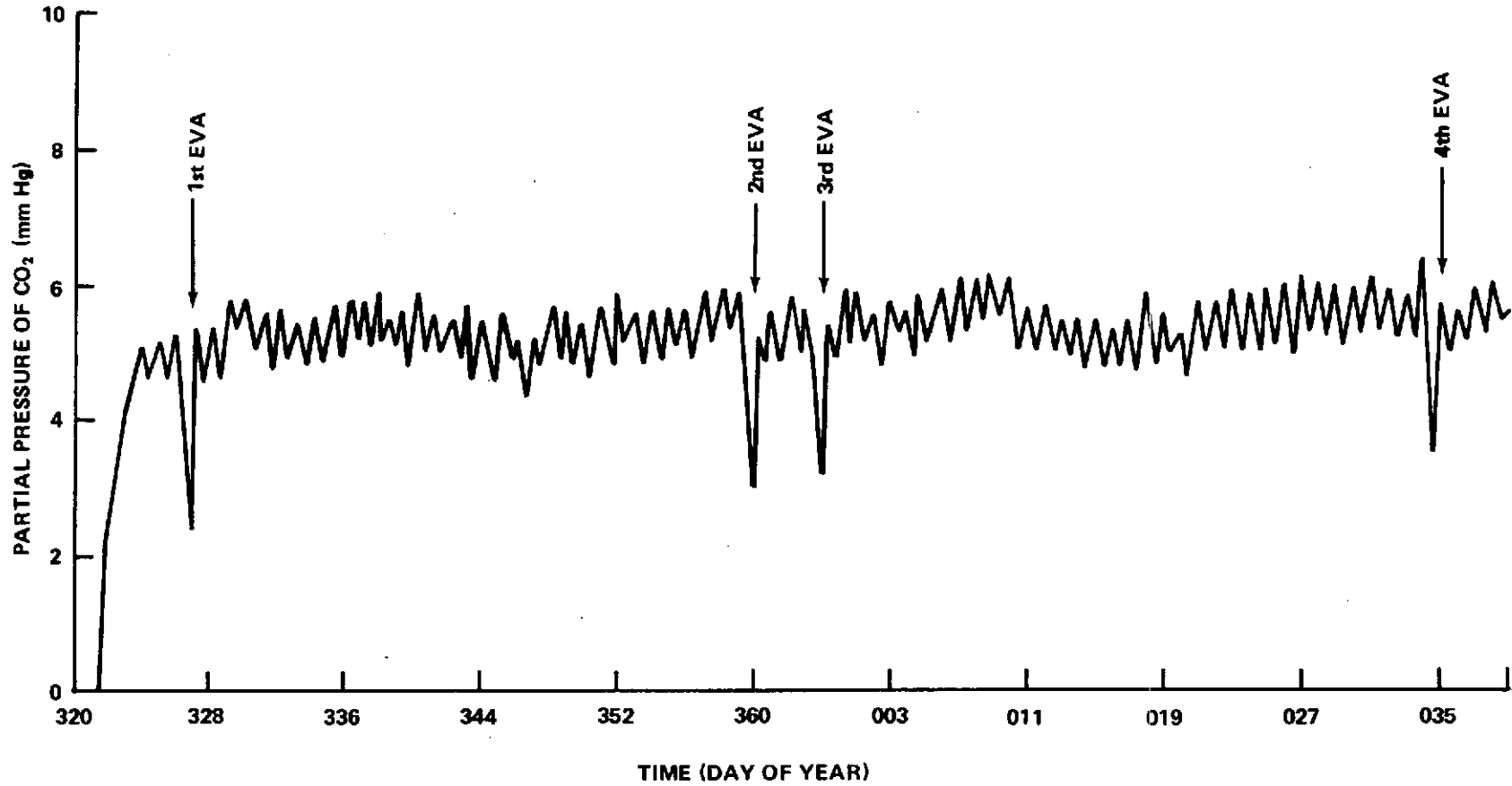


Figure 15. CO₂ partial pressure profile for SL-4.

4. Selective monitoring of contaminants should be carried out. State-of-the-art has not advanced to a point which would allow the economical monitoring of all contaminants of interest, but a select group of prime importance could be monitored at a reasonable cost.

5. A list of contaminants and the maximum allowable levels that should be controlled and monitored needs to be established.

A procedure of this kind would insure adequate control of atmospheric contaminants and would give greater confidence that crew safety would be maintained.

TABLE 8. SKYLAB MOLE-SIEVE BAKEOUT SUMMARY

	Bed 1	Bed 2
SL-2 Initiate Bakeout	146:18:05	147:14:45
Terminate Bakeout	146:23:30	147:19:41
Total Duration (Hours)	5:25	4:56
SL-3 Initiate Bakeout	210:01:30	210:11:50
Terminate Bakeout	210:11:50	210:17:40
Total Duration (Hours)	10:20	5:50
Initiate Bakeout	232:01:10	233:02:04
Terminate Bakeout	232:12:30	233:16:12
Total Duration (Hours)	11:20	14:08
SL-4 Initiate Bakeout	321:15:43	321:21:15
Terminate Bakeout	321:21:15	322:03:15
Total Duration (Hours)	5:32	6:00

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APPROVAL

SKYLAB ATMOSPHERIC CONTAMINATION CONTROL


By C. D. Ray

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

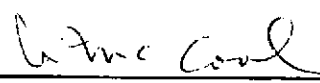
This document has also been reviewed and approved for technical accuracy.



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