AMRL-TR-66-167

SUPEROXIDE CONFIGURATIONS FOR ATMOSPHERE CONTROL SYSTEMS

M. J. McGOFF
J. C. KING

MSA RESEARCH CORPORATION
MINE SAFETY APPLIANCE COMPANY

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FOREWORD

This program was initiated by the Life Support Division, Biomedical Laboratory, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. The effort was conducted by MSA Research Corporation, a Division of Mine Safety Appliances Company, Evans City, Pennsylvania 16033, under Contract No. AF 33(615)-2792, in support of project 6373, "Equipment for Life Support in Aerospace," task 637302, "Respiratory Support Equipment." The effort sponsored by this contract started in April 1965 and was completed in June 1966. Mr. Clemens M. Meyer of the Biotechnology Branch, Life Support Division, Aerospace Medical Research Laboratories, was the contract monitor.

This technical report has been reviewed and is approved.

Wayne H. McCandless
Technical Director
Biomedical Laboratory
Aerospace Medical Research
Laboratory

ABSTRACT

Solid superoxide forms were studied to evolve optimized configuration designs for life support of one man on 2-, 4-, 8-, 24-, and 48-hour space missions. Suitable designs were developed to generate O_2 for these missions, but CO_2 control becomes progressively more difficult as mission time decreases. Optimization for short mission configurations was gained by dynamic flow designs, preheating inlet flow streams, and use of a catalyzing agent. The evolution of available O_2 was as high as 85% for 4-hour mission configurations and as high as 98% for 24-hour missions. The superoxide configurations that have been developed are in plate form as opposed to discs since the former have more efficient O_2 generation and CO_2 absorption characteristics. This was the effect of flow orientation rather than specific shape, per se. The configurations feature rippled superoxide plates, which, when packaged, achieve a 20% increase in bulk density over granules, and a lower pressure drop, thereby minimizing fan power. Heat generated by the superoxide reaction was utilized in the following manner: the inlet flow stream was preheated by refluxing a part of the outlet flow stream with it. This technique increased performance of the inlet portion of the superoxide bed. Mass transfer correlations were developed to describe the mechanics of the reactions. Effects of humidity, reduced pressure, O_2/N_2 balance and densification of solid forms on the mass transfer behavior of the superoxide configurations are described.

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Section I

INTRODUCTION

A potassium superoxide atmosphere control unit was developed at MSAR and has been reported in AMRL-TR-65-44*. This was a 24-hour unit which provided O_2 and absorbed CO_2 for one man. It employed solid disc-shaped superoxide forms which achieved an increase in bulk density, lower pressure drop, and less water sensitivity than traditional granular beds. This departure from the use of conventional granular-type chemicals for atmosphere control gave a new perspective on the application of these chemicals for life support.

The present work was undertaken to further encompass the performance analysis and investigation of various geometrical configurations using high density forms of sodium and potassium superoxide. The product of this work was to yield information on performance studies of configurations which would best fit a designated mission.

Tests were made and optimum configurations were selected for 2-, 4-, 8-, 24-, and 48-hour missions. Solid, non-granular forms were evaluated, granular forms being specified as not to be a part of this effort. Two modules of solid superoxide form were delivered to AMRL for subsequent evaluation.

Mechanics of control were studied. Coefficients for O_2 generation and CO_2 absorption were devised. Mass transfer numbers were calculated from experimental data generated from tests. These relations integrated with performance of the solid superoxide forms help explain configuration behavior.

The data thus generated in this program can be applied in life support design application for superoxide atmosphere control systems.

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*McGoff, M.J., Potassium Superoxide Atmosphere Control Unit, AMRL-TR-65-44 (AD 624 556), Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, September 1965.

Section II

EXPERIMENTAL

The following criteria were followed in the development of superoxide configurations for atmosphere control of manned space chambers.

Type of System	One man chemical oxygen back up emergency life support
Mission Time	2-, 4-, 8-, 24-, and 48-hours
Metabolic Requirements	
O_2 consumption range	22.7 to 45.4 g/hr
CO_2 production range	22.7 to 50 g/hr
H_2O production range	22.7 to 45.4 g/hr
Space Assembly Atmosphere	
Total pressure	380-760 mm Hg
Atmosphere	Pure O_2 to air O_2/N_2 ratio
CO_2 level	3.8 to 7.6 mm Hg
Temperature	24 $\pm$ 6°C
Relative humidity	50%
Others	
Weight, volume and power	Minimum
Dusting	Minimum

Other requirements were to determine influence of humidity on performance, effects of reduced pressure, O_2/N_2 ratio, water uptake and determination of the period of time that elapsed before the O_2 level is sufficient to maintain man's metabolic requirements. This latter requirement pertained to rate measurements and required that monitoring instrumentation be installed in testing each configuration.

Configurations were tested in a sealed 3680 liter (130 cu ft) space chamber or in a sealed 212 liter (7.5 cu ft) chamber. Simulation was done with an MSAR Metabolog (man simulator). A schematic of the 3680 liter chamber and test equipment is shown in figure 1. The 212 liter chamber, not shown, was placed inside the 3680 liter chamber and was looped in stream with the simulator through the cooler and back to the simulator. The simulator uses a fuel, (acetylene) that is catalytically combusted to produce an RQ of 0.8 (RQ - volume CO_2/volume O_2). The catalytic combustion of acetylene does not generate the total water production requirement and water was added as required. Gases from the simulator were enriched with moisture by fuel consumption and water makeup. These warm gases passed through a cooler where the temperature was lowered and some water was removed to maintain humidity. The simulator consumed O_2 at the specified rate of 45 g/hr or 31.7 liters/hr (STP) and produced CO_2 at the constant rate of 50 g/hr or 25.3 liters/hr (STP). All configurations were tested at the upper specified rates, 45.4 g/hr O_2 and 50 g/hr CO_2; no simulation was done at the lower level of 22.7 g/hr O_2 and CO_2.

The space chamber was monitored by instruments to record O_2, CO_2 and humidity. These were MSA O_2 and CO_2 LIRA. Serdex and an Aminco humidity meter were used for moisture measurement. The instruments were calibrated and checked regularly to assure accurate readings. These instruments were manifolded and used to read gas concentrations in the chamber and the canister inlet and outlet streams.

Thermocouples to measure chemical bed temperatures and electrical power leads to operate fans were introduced into the space chamber through hermetically sealed plugs. Power supply for fans was available from a 28-v, dc source or a 100 watt, 115-v ac, 400-cycle inverter.

The space chamber was checked for leaks and sealed tight by a screw-type door closure before beginning the tests. Sampling lines and instrumentation were checked for leak tightness.

Most of the testing was conducted at sea level. Some of the tests were made at a reduced pressure of 1/2 atmosphere. Reduced pressure was accomplished by evacuating the chamber with a Nash vacuum pump.

Testing was confined to solid KO_2 and NaO_2 forms, although granules were used in one of the tests to characterize the properties of the KO_2. All tests were made at forced circulation conditions: no static, passive testing was done.

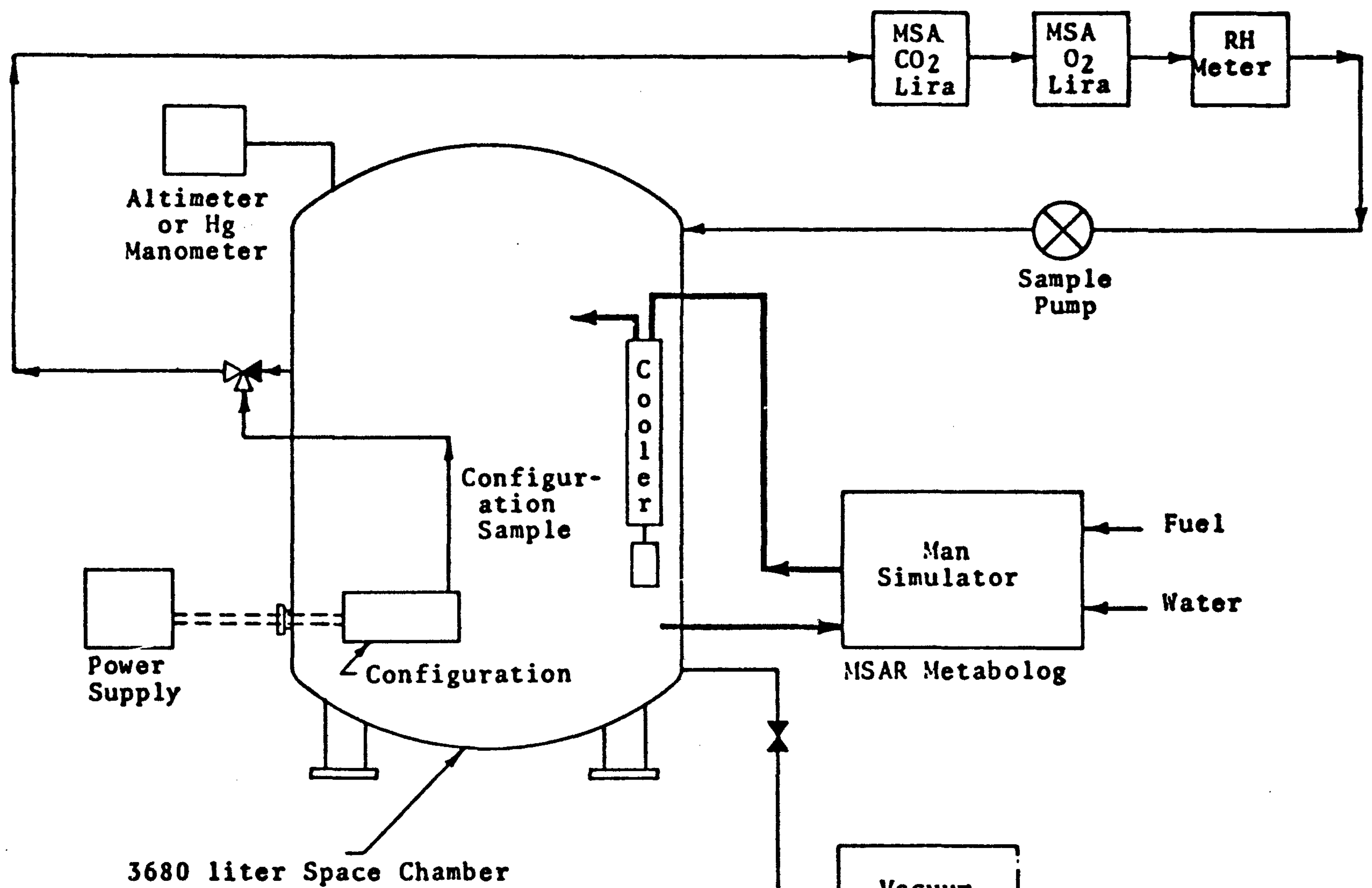

FIG. 1 - FLOW SCHEMATIC FOR CONFIGURATION TESTS

The rates of O_2 generation and CO_2 absorption were calculated by monitoring the chamber conditions to obtain mass balances. The simulator operated at a fixed level and variations in the chamber gas concentrations reflected configuration performance. These chamber gas measurements also gave inlet conditions for the configurations since the fan drew the flow stream directly from the chamber. As mentioned previously, samples of the flow stream passing out of the configuration were analyzed and these further defined performance and moisture removing capacity of the particular designs.

Chemical and physical methods of enhancing performance were studied. Chemical methods included affects of catalyzing agents, peroxide blending with superoxides, blending of sodium and potassium superoxides, addition of CO_2 absorbing chemicals to the superoxide and water spray treatment to precondition the superoxide with a hydroxide surface. An eutectic NaO_2-KO_2 was prepared, but could not be tested in solid shapes since forming qualities were poor. Physical preparations encompassed four disc sizes and four plate designs. Molding of asbestos fibers with the superoxide to increase porosity was evaluated. Effects of flow rate, densification, geometry, and influence of temperature were primary aspects of physical investigations. Consideration was given in all designs to obtain self-supporting characteristics.

A cursory test was made on the strength of superoxide forms as a function of formation pressure. Dusting and material compatibility tests were not made since fabrication of actual atmosphere control systems was not a part of this effort. Dusting and material compatibility of superoxides was reported in AMRL-TR-65-44.

Section III

TESTING

The superoxide configurations were constructed with two basic shapes - plates and discs. Various geometries were assembled to study influences of length and flow velocities. A single configuration consisted of individual styles of plates or discs; hybrid combinations within a single package were not examined.

Superoxide Forms

Four disc sizes and three styles of plates were examined. Molds were fabricated to form fluff-type superoxide into the various shapes.

Figures 2, 3, 4, and 5 show 7 cm, 9.5 cm, 14.5 cm and 38 cm diameter size discs which were examined. The thickness of the discs was approximately 0.48 cm with the exception of the 38 cm disc, which was pressed to a thickness of 2.2 cm. A self-supporting superoxide structure was made by 1/4 in. deep saw cuts. This represented a configuration that had, in effect, cubical superoxide granules supported by a superoxide disc. The surface areas and weights for each disc are given for these designs.

Figures 6, 7, and 8 show plate designs. Figure 6 is a corrugated pattern across the 11.4 cm length. These plates did not have uniform thickness and considerable unreacted superoxide was left within the corrugated pattern.

Figures 7 and 8 show plate configurations having uniform thicknesses. Figure 7 is a rippled style and figure 8 is a diagonal rippled pattern. The latter design afforded lateral movement of the flow stream as well as an axial flow.

Twenty-Four-Hour Configurations

A one-man 24-hour superoxide atmosphere control unit was developed which contained 110 - 9.5 cm (3-3/4 in.) KO_2 discs*. Additional investigation of the performance of disc configurations was pursued in this work to determine if improved performance could be attained by changing diameter and length (L/D ratio). Testing for all 24-hour configurations was made at the specification of 45.4 g/hr O_2 or 31.7 liters/hr (STP), 50 g/hr CO_2 or 25.[illegible] liters/hr (STP) and 45.4 g/hr H_2O. Ideally, a 24-hour mission configuration would generate 760 liters (STP) O_2, absorb 609 liters (STP) CO_2 and remove 1090 g of water.

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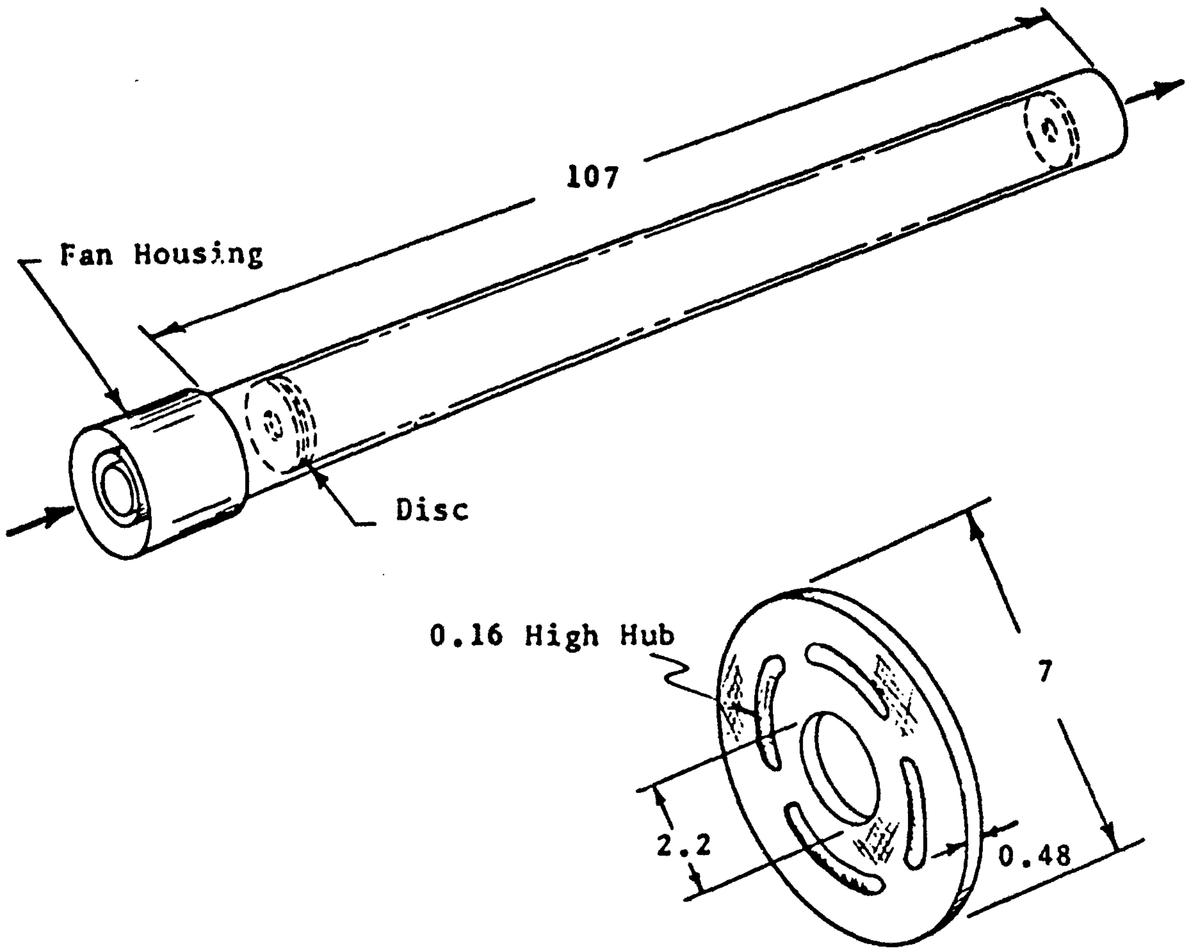
*McGoff, M.J., Potassium Superoxide Atmosphere Control Unit, AMRL-TR-65-44 (AD 624 556), Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, September 1965.

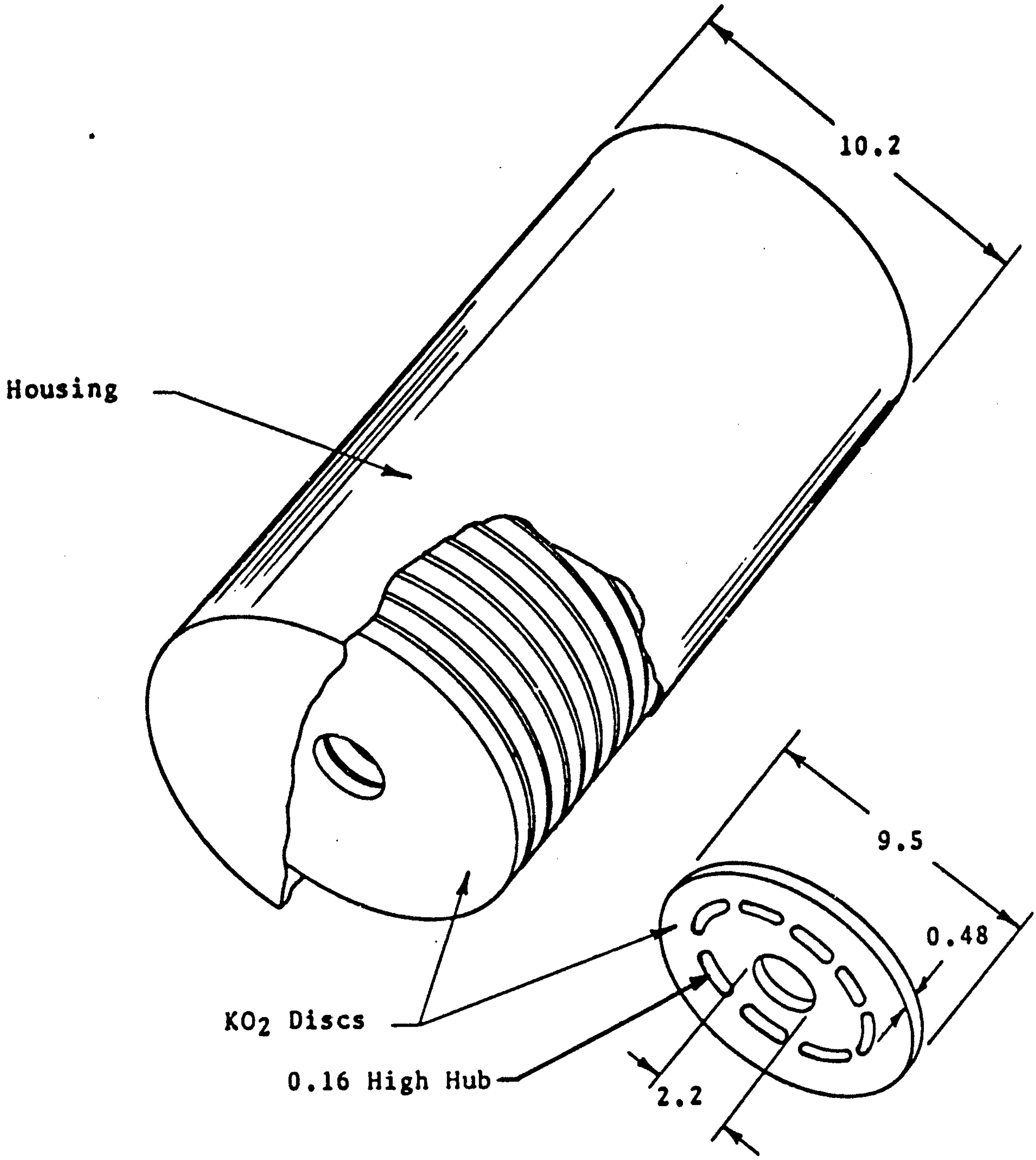


Dimensions in Centimeters

Superoxide Disc

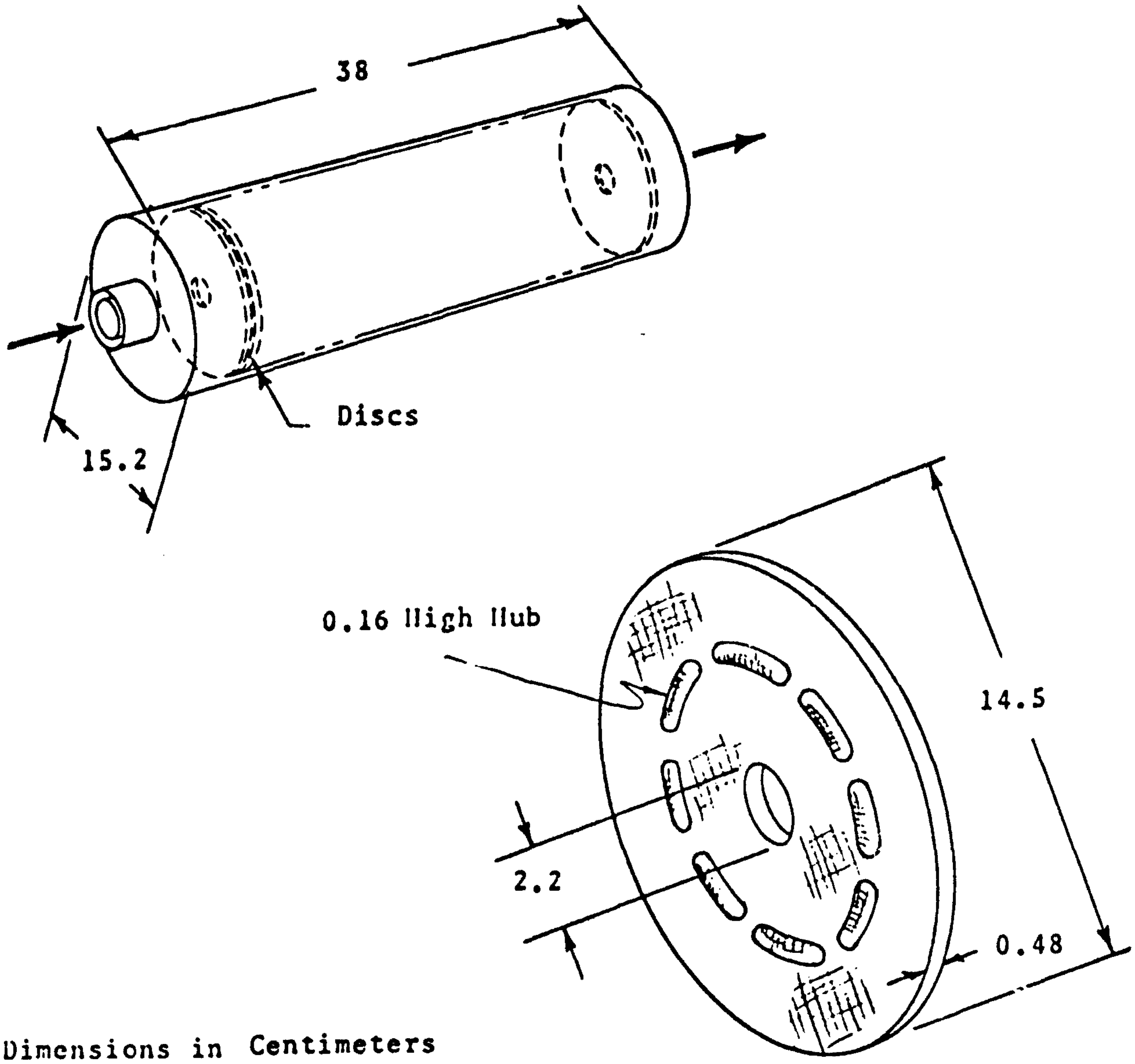
Surface Area - 90 cm^2
Weight (Approx.) - 23 g

FIG. 2 - DISC CONFIGURATION WITH CIRCUMFERENTIAL HUBS



Dimensions in Centimeters

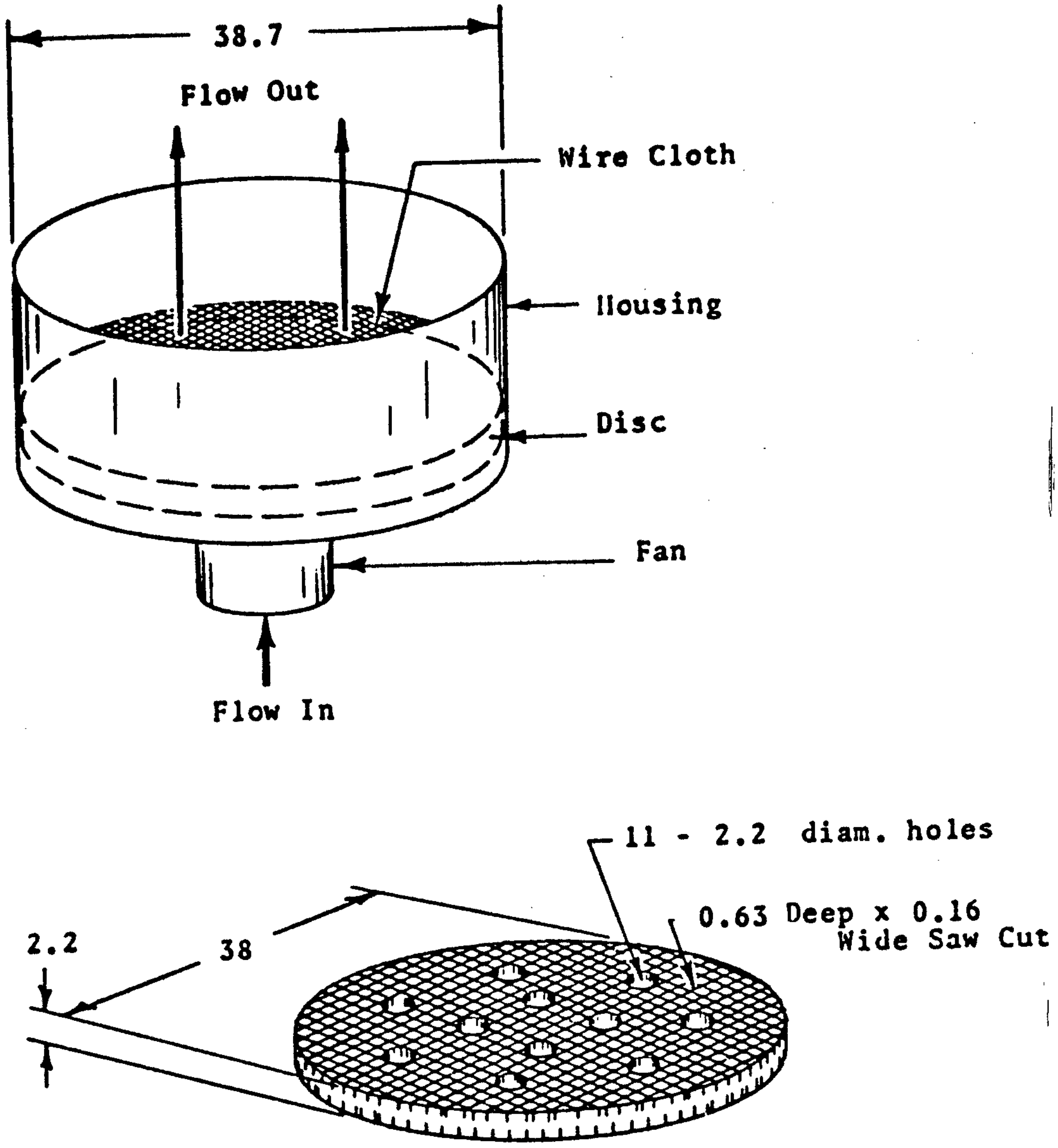
FIG. 3 - DISC CONFIGURATION WITH CIRCUMFERENTIAL HUBS



Superoxide Disc

Surface Area - 352 cm^2
Weight Approx.) - 79 g

FIG. 4 - DISC CONFIGURATION WITH CIRCUMFERENTIAL HUBS



Dimensions in Centimeters

<u>Superoxide Disc</u>

Surface Area - 7300 cm^2
Weight (Approx.) - 3300 g

FIG. 5 - DISC CONFIGURATION WITH WAFFLE PATTERN

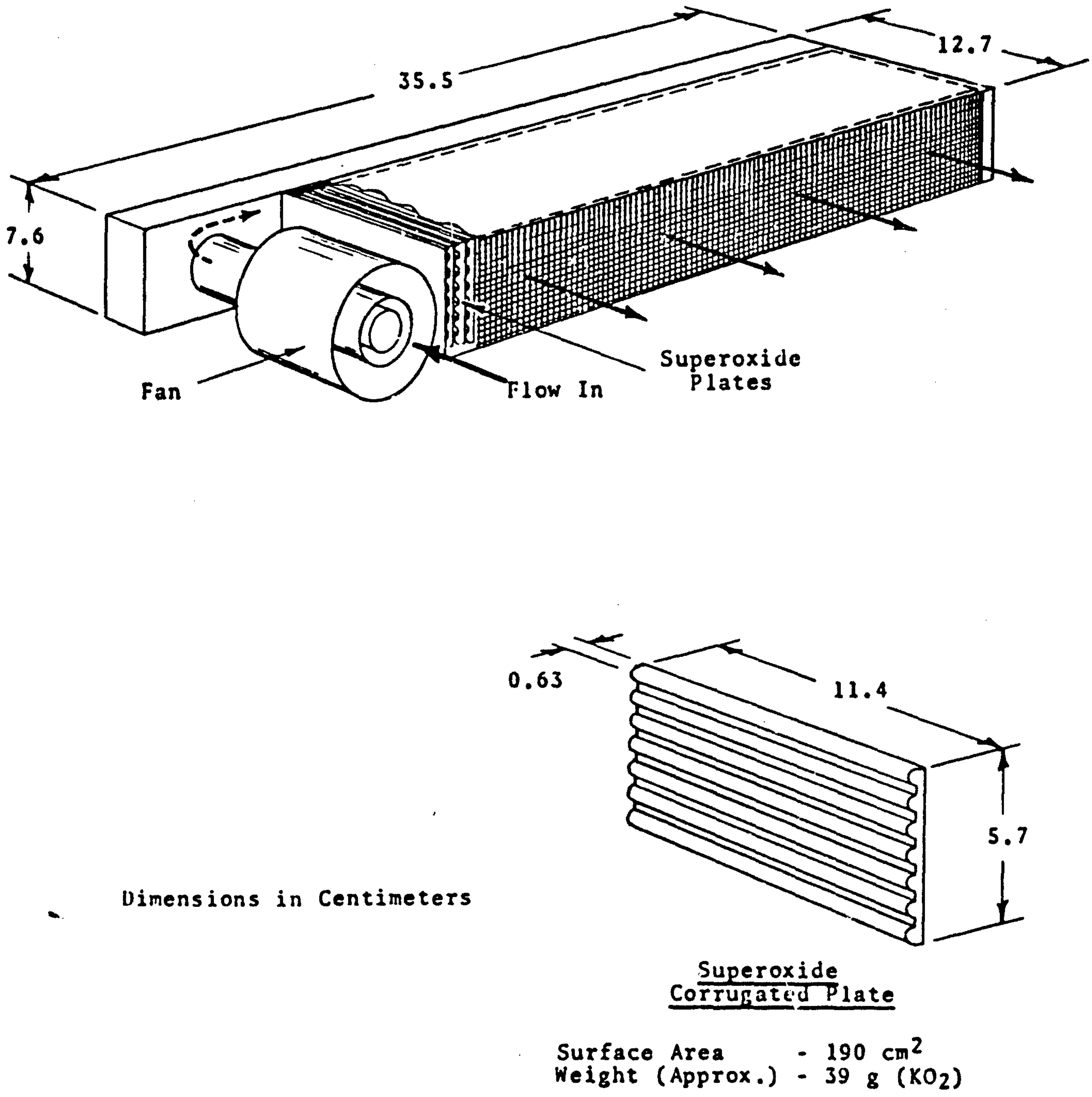


FIG. 6 - CORRUGATED PLATE CONFIGURATIONS

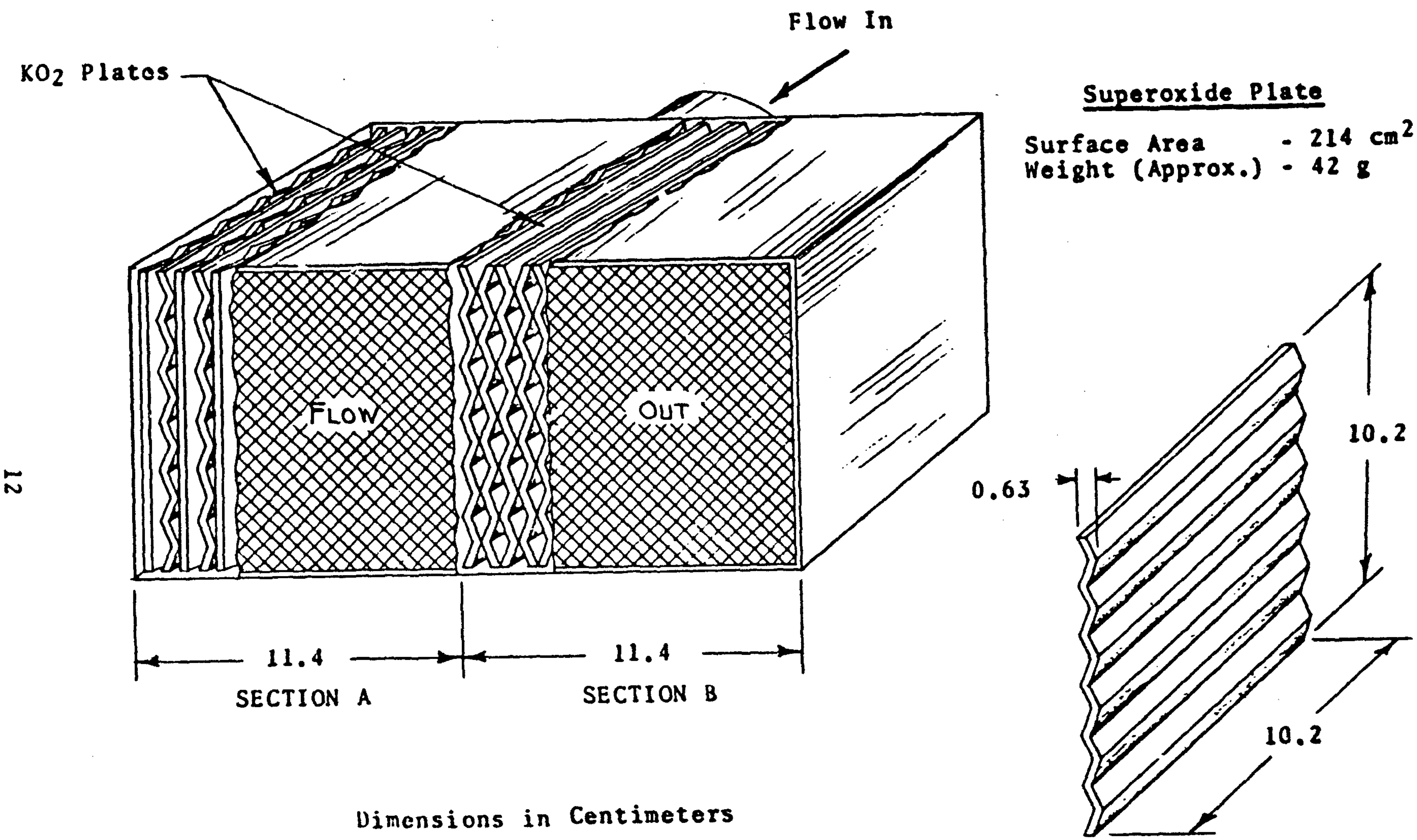


FIG. 7 - RIPPLED PLATE CONFIGURATIONS

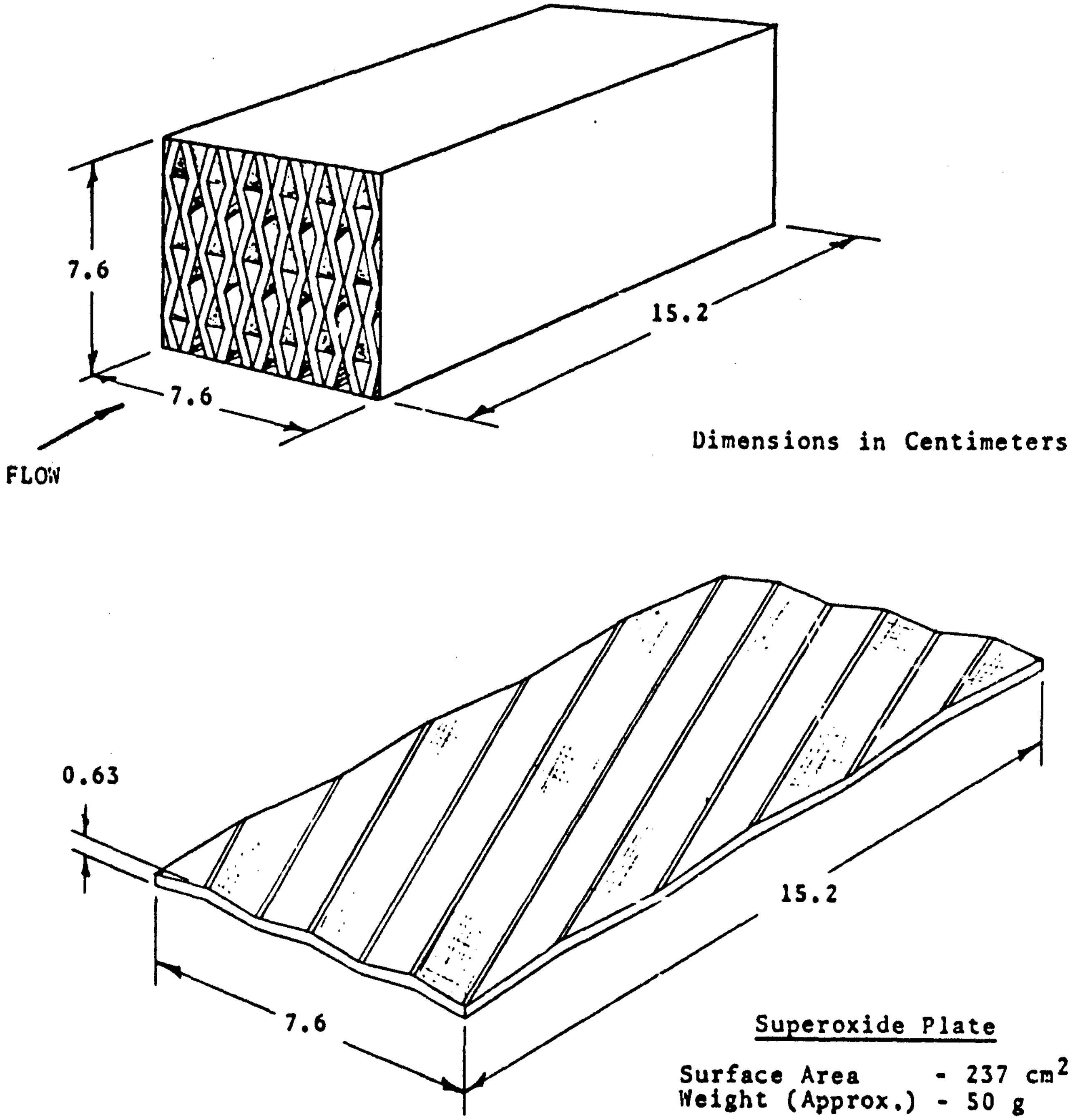


FIG. 8 - DIAGONAL RIPPLED SUPEROXIDE PLATE CONFIGURATION

Tests With Discs

Tests with disc designs featured flow through a central hole in the discs as well as flow around the outside of the discs and between the containment shells.

Increased densification of the superoxide was an objective in this work, but adverse effects were found when discs were formed at higher pressures. This was found in Test 1, a 24-hour configuration having 175 - 7 cm diam. KO_2 discs packaged in tandem to a length of 106.5 cm (see figure 2), giving an L/D ratio of 16.0. The discs had a central 2.2 cm hole for air passage. Volume of the configuration envelope was 4100 cm^3, weight 4100 g, and surface area 15,800 cm^2. An annular flow passage was provided by the 7.62 cm ID containment tube and the outside of the discs. The discs were formed at 296 Kg/cm^2. This test was terminated after 13 hours when O_2 generation and CO_2 absorption were low as evidenced by chamber gas concentrations. The O_2 evolved was 391 liters (STP) and CO_2 absorbed was 207 liters (STP). Flow rate for this test was 272 liters/min.

Improvement was obtained with this configuration when the 7 cm discs were pressed at 113 Kg/cm^2. Test 69 had 180 - 7 cm discs and the configuration generated 750 liters (STP) O_2 and absorbed 415 liters (STP) CO_2 in 24 hours.

Test 6 was made with fifty 14.5 cm diam. KO_2 discs. Bed length was 31.6 cm, the L/D ratio was 2.2. The volume of this configuration, including the 2.2 cm central flow hole was 5330 cm^3 and the weight was 3925 g. The surface area of this configuration was 17,600 cm^2. This configuration evolved 758 liters (STP) O_2 and absorbed 547 liters (STP) O_2. The RQ was 0.72. These discs weighed 3925 g and were pressed at a force of 81 Kg/cm^2. The O_2 efficiency was 81%. The average relative humidity for this test was 48% at 24°C.

The 9.5 cm disc (see figure 3) was the type used in atmosphere control units*. This configuration has an L/D ratio of 7.2. The configuration contained 110 - 9.5 cm discs and occupied a volume of 4920 cm^3, including the 2.2 cm central hole. The weight of these configurations was 3900 g and surface area was 16,700 cm^2. Three tests were made of an average relative humidity of 39% at 24°C, and a decrease in O_2 generated is accompanied by decreasing flow rate.

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*McGoff, M.J., Potassium Superoxide Atmosphere Control Unit, AMRL-TR-65-44 (AD 624 556), Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, September 1965.

Flow Rate Liters/min.	O_2 Generated Liters (STP)	CO_2 Absorbed Liters (STP)	O_2 Efficiency (%)	RQ
178	702	472	77.5	0.67
133*	605	396	67.2	0.65
229	790	484	83.6	0.61

*Terminated After 18 Hours.

The 9.5 cm disc configuration was again investigated in this program. Test 76 was made at a higher relative humidity of 63% at 24°C. A higher humidity as well as lower flow rate as shown above, adversely affected performance of the 9.5 cm.disc configuration. Flow rate decreased from 269 liters/min. to 147 liters/min. and CO_2 absorption was only 364 liters (STP); O_2 generation was 700 liters (STP) and the O_2 efficiency was 76.1%. The RQ for this test was 0.52.

The data for 24-hour disc configuration tests is given in the Appendix. These results of the disc configuration show that decreased flow and increased humidity harmed performance, especially CO_2 absorption properties. This effect was also demonstrated in plate configurations. The higher humidities swelled the superoxide forms, which decreased the flow area, hence decreased flow rate and performance.

Tests With Plates

Plate forms of superoxide can be packaged into various combinations of cross-sectional areas and bed lengths. Rectangular shells were used, with flow passing through channels formed by the plates. The plate surfaces are in direct contact with the flow stream, whereas in disc arrays the surfaces are less actively exposed since the flow stream passes through a central hole and the annulus.

Test 40 was a 24-hour plate configuration having ninety-six 10.2 cm x 10.2 cm rippled KO_2 plates (see figure 7). The configuration had six beds, each containing 16 plates, and bed length was 61 cm long. This configuration had a weight of 3895 g in a chemical envelope of 6300 cm^3: surface area was 20,300 cm^2. Flow rate averaged 204 liters/min. dropping from 271 liters/min. to 137 liters/min. during the test. O_2 generation was 895 liters (STP); 90.2% efficiency, and CO_2 absorption was 551 liters (STP). The RQ was 0.62. The CO_2 concentration was only 0.63% after

24 hours, increasing to 0.87% at 26-1/2 hours when the test was terminated. The average humidity in the test chamber was low, being 32% RH at 24°C. This configuration was the most efficient for O_2 generation and CO_2 absorption in the prescribed 24-hour test.

Test 68 was a 24-hour plate configuration which contained eighty 7.6 cm x 15.2 cm diagonally rippled KO_2 plates (see figure 8). These plates provided a two-plane directional flow path because of the diagonal pattern. The configuration volume was 5900 cm^3, being 7.6 cm x 12.7 cm x 61 cm long. The configuration had a weight of 4095 g and surface area was 19,150 cm^2. The more random flow path provided by the diagonal pattern of the 7.6 cm x 15.2 cm plates was expected to give better performance than the 10.2 cm x 10.2 cm plates at a corresponding flow rate. A lower flow rate was selected for Test 68. Flow rate was 91 liters/min. at the start and 85 liters/min. at the end of the test. The configuration had a lower flow rate than Test 40 and velocity through the configuration also was lower. The test terminated after 24 hours and 845 liters (STP) O_2 was generated and 468 liters (STP) CO_2 absorbed. The O_2 efficiency was 85.6% and RQ was 0.55. The average humidity was 52% RH at 24°C. Final CO_2 concentration was 2.0% after 24 hours in the 3680 liter chamber. This configuration performed more poorly than the Test 40 configuration because of the lower flow rate and higher humidity; the diagonal pattern plate showed no advantage at a low flow. Test 70 showed these effects also.

Test 70 was a configuration identical to Test 40, having ninety-six 10.2 cm x 10.2 cm KO_2 plates. The configuration was heavier, weighing 4130 g. Test conditions differed for this configuration; flow was lower at 150 liters/min. and humidity was higher, averaging 51% RH at 24°C. The O_2 generation was slightly higher than Test 40, being 908 liters (STP) O_2 but CO_2 absorption was lower at 475 liters (STP) CO_2. The O_2 efficiency was 93.1% and RQ was 0.55. The CO_2 concentration in the 3680 liter chamber was 1.89% after the 24-hour test.

As with disc configuration, the 24-hour test with plate type configurations demonstrated that better performance is gained with higher flow rates and lower humidities.

Test 81 was a 24-hour plate configuration. This configuration used 100 - 7.6 cm x 15.2 cm diagonally rippled KO_2 plates. The weight of KO_2 was 4195 g. The chemical envelope was 15.2 cm x 15.2 cm x 30.4 cm long for a total volume of 7050 cm^3. The container for the plates was approximately 15.5 cm square x 35.5 cm long. An inlet and exit manifold (see figure 9) were employed for a U-return of the flow which passed through two KO_2 beds (25 plates per bed) on a top tier and two beds on the bottom

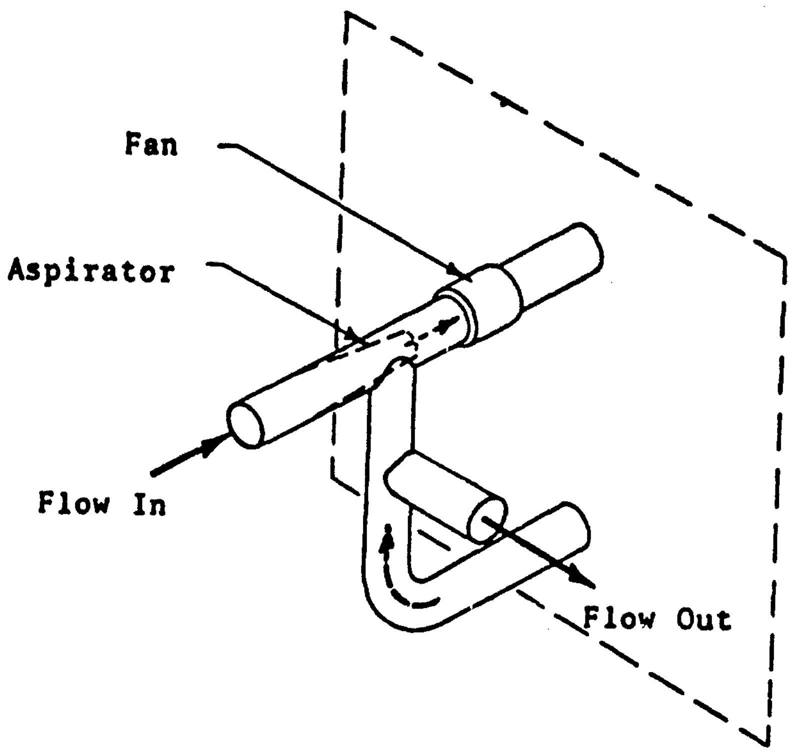


FIG. 9 - REFLUX MANIFOLD

tier thereby providing a flow path 61 cm long. This manifold aspirated flow into the configuration with a fan which internally circulated flow greater than flow into and out of the canister. The net flow into the canister decreased from 241 to 150 liters/min. averaging 195 liters/min. The total internal flow through the configuration was 1100 liters/min. at the start of the test and the reflux flow was approximately 849 liters/min. The reflux stream preheated the inlet stream entering the configuration approximately 17°C initially, decreasing to 11°C near the end of the test. This configuration test was made at an average 50% RH at 24°F. The generated O_2 was 907 liters (STP), averaging 37.9 liters/hr (STP) O_2 and CO_2 absorbed was 491 liters (STP), averaging 20.4 liters/hr (STP) for the 24 hours. Final CO_2 concentration in the chamber was 1.2%. Flow did not decrease as much as in Test 40 but average flow was lower, being 195 liters/min. for Test 81 compared to 204 liters/min. average for Test 40. A larger flow area was provided by the Test 81 configuration compared to Test 40. If an equivalent humidity would have existed, in Test 40, larger flow reduction would probably have occurred and performance would have decreased.

Recirculation of the outlet flow can be utilized to preheat inlet flow streams as was described in Test 81 above. Better inlet bed performance is obtained, and is important for short missions to optimize performance. This approach is discussed more fully in the 8-hour and 4-hour configuration mission design tests.

Eight-Hour Configurations

The theoretical amount of KO_2 and NaO_2 for an 8-hour mission to meet an O_2 supply rate 45.4 g/hr is 1090 g KO_2 and 737 g NaO_2. The lower specified rate is 227 g/hr and the weight of KO_2 and NaO_2 would be one-half the above. The majority of tests for an 8-hour mission design were conducted with plates rather than discs when it was determined that more effective utilization was gained with the plates. At the upper specified rates of 45.4 g/hr O_2, 50 g/hr CO_2 and 45.4 g/hr H_2O, ideal performance for an 8-hour mission would be represented by the generation of 253 liters (STP) O_2 and the absorption of 213 liters (STP) CO_2.

The designs tested produced adequate O_2 but were short in CO_2 absorption. Over-design augmented CO_2 pickup. Tests were designed on the basis of providing near theoretical amounts of superoxide and manipulating conditions to enhance CO_2 absorption properties.

Tests With Discs

Tests 4 and 5 were conducted with 7 cm KO_2 discs of the type used in Test 1. Each configuration had a surface area of

5420 cm^2. Test 4 contained 60 discs pressed at 171 Kg/cm^2 and had a weight of 1736 g. The bed length was 40 cm. The volume of the chemical, including the 2.2 cm central hole, was 1540 cm^3. Test 4 generated 244 liters (STP) O_2 and absorbed 87.5 liters (STP) CO_2 with a flow rate of 257 liters/min. Test 5 contained 60 discs pressed at 295 Kg/cm^2; the same densification as Test 1 discs. The configuration weighed 1350 g, the bed length was 36.8 cm and the volume was 1410 cm^3. This configuration generated 133 liters (STP) O_2 and absorbed 62.5 liters (STP) CO_2. The flow rate for this test was 280 liters/min. O_2 efficiency for Tests 4 and 5 were 59% and 42% respectively and corresponding RQ's were 0.36 and 0.53. Both tests were terminated after 7 hours. The harder pressed discs of Test 5 performed more poorly than Test 4.

Test 36 again investigated 7 cm diam. discs using KO_2 discs pressed at 125 Kg/cm^2 with a weight of 1200 g. The O_2 generation was inadequate for an 8-hour mission, being only 154.5 liters (STP), and CO_2 absorbed was 78.5 liters (STP).

Test 7 was made with a single 38 cm diam., 2.2 cm thick KO_2 disc having eleven 2.2 cm holes for flow passage. The surface area was increased by 0.63 cm deep saw cuts. The disc was pressed at 120 Kg/cm^2. The configuration was intriguing since it represented a granular KO_2 bed self-supported upon a disc of KO_2. The configuration was very heavy for an 8-hour configuration with a weight of 3320 g. Surface area was 7280 cm^2. Flow rates were 269 liters/min. decreasing to 226 liters/min. after 6 hours when the test was terminated. O_2 generation was only 114.5 liters (STP) and CO_2 absorbed was 83 liters (STP). Poor performance is attributed to the large thickness which was needed to give structural integrity to this diameter disc and to the hardening of surfaces by the saw cuts.

Test 31 was an 8-hour configuration comprised of thirty-five 9.5 cm KO_2 discs formed at 127 Kg/cm^2. The configuration was 23 cm long and the volume was 1640 cm^3. The weight was 1175 g and surface area of the discs was 5340 cm^2. Flow rate was 223 liters/min. and decreased to 167 liters/min. after 8 hours. O_2 generated was lower than Test 4 above, being 184 liters (STP), but CO_2 was greater at 105 liters (STP). The O_2 efficiency was 65.5% and RQ was 0.57.

Test 33 was with the same configuration as Test 31 but the last disc was without a hole. This configuration weighed 1180 g and generated 178 liters (STP) O_2 and absorbed 94 liters (STP) CO_2. No appreciable differences in performance were observed and no advantage was gained by this alteration.

Tests With Plates

The plate designs generally exhibited greater O_2 production and CO_2 absorption per gram of superoxide than did disc designs. These were extensively investigated in development of an 8-hour design. Tests 10, 11, 12, 13, and 72 were plate configurations having short 10.2 cm to 11.4 cm long, chemical beds. Theoretically, higher reaction rates should occur at inlet zones as compared to downstream zones since higher gas concentrations of CO_2 and moisture are present at the inlets than at the outlets.

Configurations of Test 10, 11, and 12 were chemical packages 6.4 cm x 25.4 cm x 11.4 cm long and occupied a volume of 1840 cm^3. Test 10 had 40 KO_2 corrugated plates, each measuring 6.4 cm x 11.4 cm x 0.63 cm thick (see figure 6). Test 12 had the same number except the plates were a blend of 55% KO_2 - 45% NaO_2. Test 11 was made with 36 NaO_2 corrugated plates, made thicker than KO_2 plates to obtain structural rigidity. Tests 13 and 72 were made with 10.2 cm x 10.2 cm rippled plates (see figure 7). These configurations were 10.2 cm x 22.9 cm x 10.2 cm long, occupying a volume of 2360 cm^3. Test 13 had 37 KO_2 and Test 72 had 36 KO_2 plates. Flow for Test 13 was 255 liters/min. initially decreasing to 198 liters/min. and Test 72 had a flow rate of 373 liters/min.

Performances of these configurations tested at 255-367 liters/min. flow rate are given below. The comparative performance of short bed configurations shows that Test 11 made with NaO_2 was the most effective configuration with Test 10 next most effective, on the basis of O_2 generated and CO_2 absorbed per pound of chemical. Test 11 was made with NaO_2 plates pressed at 134 Kg/cm^2 and were structurally weak and friable. Flow rate dropped from 277 liters/min. to 71 liters/min. because of enlargement of the plates from reaction and because of plate breakage. Although the Test 11 configuration performed well, on the basis of O_2 generated and CO_2 absorbed per pound, its structural properties made it an unsuitable design.

10.2-11.4 cm Bed Length

Test No.	Superoxide Type	Weight (g)	Surface Area (cm^2)	Volume (cm^3)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Eff. (%)	RQ
10	KO_2	1470	7220	1835	247	153	72.8	0.62
11	NaO_2	1400	6520	1835	371	168	93.8	0.45
12	55% KO_2 - 45% NaO_2	1505	7220	2000	270	136	73.0	0.51
13	KO_2	1640	7700	2360	236	161	60.0	0.68
72	KO_2	1555	7220	2360	252	94	67.0	0.37

Tests 39, 52, 53, 56, 71, 74, and 77 were made with plates having bed lengths of 30.4 cm. These tests investigated two types of plate designs, flow rates, and the effect of preheating.

Tests 39, 71, and 74 were made with 10.2 cm x 10.2 cm rippled pattern KO_2 plates (see figure 7). Test 39 had 25 plates pressed at 115 Kg/cm^2 and arranged in a 5.1 cm x 10.2 cm x 10.2 cm long bed. Tests 71 and 74 were larger configurations, having thirty-nine 10.2 cm x 10.2 cm plates. The plates of Test 71 were pressed at 115 Kg/cm^2, the same as Test 39, and the plates of Test 74 were pressed at 320 Kg/cm^2 to show effects of densification. Tests 71 and 74 were approximately 10.2 cm x 10.2 cm x 30.4 cm long beds. Both Tests 71 and 74 generated more O_2 than Test 39 because of larger amounts of KO_2 but CO_2 absorption in Test 39 was greater than in either Test 71 or 74. Flow rate for these tests was 246 liters/min. decreasing to 170-184 liters/min. at the end. Slightly lower humidity was present in the 3680 liter chamber for Test 39 than for Tests 71 and 74 where the humidity averaged 55% RH at 24°C. CO_2 absorbed by the Test 39 configuration was 99 liters (STP), while approximately 85 liters (STP) was absorbed in Tests 71 and 74. The Test 39 configuration was smaller and had a smaller flow area. This increased gas velocity and mass flow rate which presumably contributed to a slightly better CO_2 absorption even though the configuration had less superoxide. Data on these configurations are shown below.

Tests 52, 53, 56, 57, and 77 were made with 7.6 cm x 15.2 cm diagonally rippled KO_2 plates (see figure 8) with 30.4 cm long bed lengths. These tests investigated the prehating of the inlet flow stream, reduced pressure and mass flow. Tests 52, 53, 56, and 57 configurations had a volume of 3000 cm^3. Twenty-four 7.6 cm x 15.2 cm plates were used. Tests 52 and 53 were duplicate

30.4 cm Bed Length

10.2 cm x 10.2 cm KO_2 Plates

Test No.	Weight (g)	Surface Area (cm^2)	Volume (cm^3)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Eff.	RQ
39	1160	5350	1775	187	99	67.4	0.53
71	1590	8320	2725	225	86	60.0	0.38
74	1660	8320	2725	221	85	56.4	0.39

tests except that the Test 53 configuration had a jacket through which the inlet flow passed and was preheated. Flow for these tests was approximately 170-198 liters/min. The jacket design of Test 53 was not effective and was altered for Tests 56 and 57. Tests 56 and 57 were made with inlet flow temperatures increased approximately 8°C higher than Tests 52 and 53, by jacketing the configuration and using reaction heat to preheat the inlet flow stream. Flow rate for Test 56 was 357 liters/min. and for Test 57 it was 110 liters/min. The O_2 generation and CO_2 absorption characteristics showed no discernable differences. Test 57 demonstrated the largest O_2 production of 212 liters (STP) and Test 52 absorbed the most CO_2, 110 liters (STP). These configurations were inadequate for an 8-hour configuration design since O_2 generation and CO_2 absorption were low.

Test 77 was a larger configuration having forty 7.6 cm x 15.2 cm plates arranged in a 10.2 cm x 7.6 cm x 30.4 cm long bed. The volume was 2370 cm^3. An increase in O_2 generation was seen, 278 liters (STP); however, CO_2 absorption was comparable to Test 52, 53, 56, and 57, being 106 liters (STP). The effect of preheating by jacketing the canister in the above tests was not of large enough magnitude to be considered an advantage. Test 77 was made at a flow of 243 liters/min. decreasing to 108 liters/min. Higher CO_2 absorption and O_2 generation was anticipated with this larger design; however, the decrease in flow lowered CO_2 absorption. The performances of the 30.4 cm long bed configurations made with 7.6 cm x 15.2 cm diagonally rippled plates are given below.

30.4 cm Bed Length

7.6 cm x 15.2 cm KO_2 Plates

Test No.	Weight (g)	Surface Area (cm^2)	Volume (cm^3)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Eff. (%)	RQ
52	1220	5730	1770	193	109	65.0	0.57
53	1225	5730	1770	173	98	58.0	0.57
56	1200	5730	1770	200	91	69.0	0.43
57	1210	5730	1770	212	105	72.5	0.50
77	1720	9470	2365	279	107	68.7	0.38

Three 8-hour plate configuration tests were made with 45.7 cm long beds having thirty-nine 7.6 cm x 15.2 cm diagonally rippled KO_2 plates, packaged to 8.3 cm x 7.6 cm x 45.7 cm dimensions. These were Tests 65, 67, and 73. A heat exchanger used the warm exit flow stream to heat the inlet flow stream. Tests 67 and 73 were conducted at a reduced pressure of 1/2 atmosphere. The results of Test 67 were invalidated because of low CO_2 production by the man simulator. Test 65 was made at one atmosphere pressure and a flow of 167 liters/min. In Test 67, the flow was 133 to 142 liters/min. at one atmosphere. In Test 73 the flow was increased to give a volumetric flow rate of 226 liters/min. at one atmosphere. The results of these tests with 45.7 cm long beds are given below.

45.7 cm Bed Length

7.6 cm x 15.2 cm KO_2 Plates

Test No.	Weight (g)	Surface Area (cm^2)	Volume (cm^3)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Eff. (%)	RQ
65	1580	9220	2870	287	159	75.0	0.55
67*	1590	9220	2870	249	69	64.8	0.27
73*	1575	9220	2870	274	135	74.0	0.49

*Reduced Pressure Tests at 1/2 Atmosphere

Reduced pressure did not affect O_2 generation rates, although lower mass flow rates would decrease both O_2 and CO_2 absorption. At reduced pressure, the concentration of the inert gas film about the superoxide forms is lower, theoretically reducing diffusion resistance through this inert film thereby improving overall kinetics. The results of this test indicate that this inert gas film is not the major controlling resistance and that diffusion into the solid is controlling.

Test 65 had a more effective preheating arrangement with inlet temperatures elevated by 14-17°C. This aided O_2 production and CO_2 absorption of the inlet beds: chemical analysis showed the inlet and outlet beds to be equally effective. In previous designs without a preheated inlet flow stream, the O_2 generated and CO_2 absorbed were always less for the inlet bed. The center bed, however, evolved more O_2 and absorbed more CO_2 than either the inlet and outlet beds.

Four-Hour Configurations

Four-hour configurations tests were made in a 212 liter sealed chamber; a few tests were made in a 3680 liter chamber. The smaller chamber showed gas concentration changes more quickly than the larger chamber and pointed up performance characteristics more quickly. Plates were used entirely since discs did not provide as rapid O_2 generation and CO_2 absorption characteristics.

With shorter mission configurations, it becomes progressively more difficult to meet required performance with lower-surface solid shapes. Chemical methods of optimizing performance were studied. CO_2-absorbing additives and peroxide additives were investigated. A series of 4-hour tests were made with the configuration plates sprayed with water, thus providing a KOH surface (Tests 41, 46, 47, and 48). This approach was unsuitable since the CO_2 absorption per pound of superoxide showed no increase over other four-hour configuration designs. Preheating the inlet flow stream, varying bed lengths and flow rate effects were examined.

Tests With Additives

Five tests were made with 4-hour configurations in which chemical additives were blended with KO_2.

Test 28 had sixteen 10.2 cm x 10.2 cm rippled KO_2 plates arranged in a 10.2 cm x 10.2 cm x 10.2 cm long configuration. Plates in the array were treated with different additives, and analyzed separately after the run. Flow rate was 277 liters/min. Additives were LiOH, Na_2O_2, ascarite (NaOH) and $CuOCl_2$. The performances of these blends are shown in Table I. The plates containing 5% Na_2O_2 were more effective than plates containing 10% and 20% Na_2O_2 and were as effective as the plates containing 1% $CuOCl_2$ in CO_2 absorption. The pure KO_2 plates and 1% $CuOCl_2$ plates generated more O_2.

Test 38 was a 13 plate configuration of 10.2 cm x 10.2 cm rippled NaO_2 plates having the additives used in Test 28. This configuration had a weight of 895 g and a surface area of 2775 cm^2. Flow rate was 305 liters/min. None of the additives showed significant improvement over pure NaO_2. The NaO_2 configuration was less efficient than the KO_2. This resulted from making the NaO_2 plates thicker and pressing them harder at 225 Kg/cm^2 to make them hold together. Compositions and chemical analysis of the various plates are given in Table II.

Test 63 was made with twenty 7.6 cm x 15.2 cm plates (see figure 8), blended with 75% KO_2 and 25% LiOH granules. The volume of the configuration was 580 cm^3 (6.4 cm x 7.6 cm x 15.2 cm long) and weighed 805 g. Surface area was 4770 cm^2. Flow rate was

TABLE I - SUMMARY OF INDIVIDUAL PLATES

Plate Size 10.2 cm x 10.2 cm x 0.63 cm

<u>Run 28 - 4-Hour Test</u>

Plate No.	KO_2 Blend	Weight (g)	Forming Pressure (Kg/cm^2)	O_2 Available liters (STP)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Efficiency (%)	RQ
1-2	KO_2	90.7	130	21.7	12.2	7.2	56.3	0.59
3-4	KO_2 and 10% LiOH	101.1	130	21.5	11.9	7.2	55.3	0.60
5-6	KO_2 and 20% Na_2O_2	111.6	130	24.5	11.8	8.3	49.8	0.71
7-8	KO_2 and 10% Na_2O_2	101.3	130	23.1	14.0	9.8	60.7	0.70
9-10	KO_2 and 5% Na_2O_2	96.4	130	22.4	14.9	10.4	66.6	0.68
11-12	KO_2 and 10% Ascarite	101.8	130	21.5	12.9	8.1	60.1	0.62
13-14	KO_2 and 1% $CuOCl_2$	99.0	130	23.6	16.3	10.4	68.9	0.62
15-16	KO_2	90.3	105	21.3	16.3	11.8	76.4	0.73
		Totals		179.6	110.3	73.2	61.3	0.66

TABLE II - DATA ON INDIVIDUAL COMPOSITIONS

Run 38 - 4-Hour Test

Plate No.	Composition	Weight (g)	Weight Gain (g)	O_2 Available liters (STP)	O_2 Generated liters (STP)	CO_2 Absorbed liters (STP)	O_2 Efficiency (%)	RQ
1-2	NaO_2	136.4	4.5	40.2	20.4	11.3	50.7	0.56
3-4	NaO_2 + 10% LiOH anh.	138.6	4.0	36.5	19.5	11.3	53.5	0.58
5-6	NaO_2 + 20% Na_2O_2	139.5	9.2	40.4	20.6	9.9	51.0	0.48
7-8	NaO_2 + 10% Na_2O_2	137.5	6.3	38.5	16.4	10.5	42.6	0.64
9-10	NaO_2 + 5% Na_2O_2	139.1	5.0	39.9	19.5	11.3	48.9	0.58
11-12	NaO_2 + 10% Ascarite	136.5	4.9	35.9	18.7	11.8	52.0	0.58
13	NaO_2 + 1% $CuOCl_2$	69.2	0	20.1	9.1	3.7	45.1	0.41
		Totals		251.5	124.2	69.8	49.1	0.55

169 liters/min. These plates were pressed with LiOH granules which were crushed into the KO_2 giving a plate with one side being KO_2 and the other LiOH. Anhydrous LiOH powder was blended in Test 28 and Test 38. In a 4-hour test, this configuration liberated 137.5 liters (STP) O_2 and absorbed 75 liters (STP). A high O_2 efficiency of 82.4% was obtained.

Test 66 incorporated the same mixture as Test 63 in a 24-plate design of 10.2 cm x 10.2 cm rippled plates. This configuration was 7.6 cm x 7.6 cm x 30.4 cm long to give a volume of 1770 cm^3. Surface area was 5720 cm^2 and the configuration weighed 982 g. A performance increase was gained with 171 liters (STP) O_2 liberated and 93.2 liters (STP) CO_2 absorbed. The O_2 efficiency was 85%. Flow rate ranged from 175 to 185 liters/min.

Test 79 was a 20 plate KO_2 configuration, like Test 63. The additive was 1% $CuOCl_2$. The configuration weight was 805 g. The test was conducted in a 3680 liter chamber whereas Test 63 was made in a 212 liter chamber. The configuration used a reflux manifold of the same design as discussed for Test 81 to preheat the inlet flow stream. The flow rate was 325 liters/min. The O_2 generation showed an increase over Test 63 at 144 liters (STP) but CO_2 dropped off to 53 liters (STP) compared to 73.5 liters (STP) in Test 63. The O_2 efficiency was 78.3%. Lower CO_2 absorption is attributed to lower CO_2 concentration in the 3680 liter chamber test where CO_2 concentration did not exceed 0.8%, while in Test 63 CO_2 was 4% in the 212 liter chamber.

A limit of 7.6 mm Hg (1% CO_2) partial pressure of CO_2 is specified for the designs. When related to chamber volume size, the tolerance for CO_2 can be relaxed with larger chambers. For smaller chambers volumes, this becomes more critical and can be compensated for by increasing the size of the configurations.

Inlet Flow Stream Preheating

By preheating the inlet flow stream, the inlet bed performance improved to comparable levels observed for downstream beds. Without preheating, inlet bed O_2 efficiencies were 50% compared to 70% for downstream beds. Downstream beds benefited from the preconditioning afforded by upstream bed reactions which can increase the temperature.

Tests 50, 51, and 54 were configurations having twelve 7.6 cm x 15.2 cm KO_2 plates arranged in a 3.8 cm x 7.6 cm x 30.4 cm long bed. The surface area for these configurations were 2870 cm^2. Test 50 had a preheated inlet flow stream provided by a jacket which surrounded the canister. This test was made at an average flow rate of 200 liters/min. This configuration weighed 605 g, generated 111 liters (STP) O_2 and absorbed 82 liters (STP) CO_2.

Tests 51 and 54 did not have a preheated inlet flow stream but flow rates differed for these tests. Flow rate for Test 51 was 300 liters/min. and for Test 54 the flow was 125 liters/min. The larger flow rate for Test 51 contributed to higher O_2 evolution and CO_2 absorption; however, both tests were less effective than Test 50. The respective O_2 generations for Test 51 and 54 were 101 liters (STP) and 89.5 liters (STP) and the CO_2 absorptions were 76.5 liters (STP) and 63.8 liters (STP). A summary of these test configuration inlet and outlet beds is given below.

Test No.		Inlet Bed	Outlet Bed	Combined	Comment
50 -	O_2 liters (STP)	52.8	48.7	111.4	Preheated
	CO_2 liters (STP)	47.5	34.5	82.0	Inlet Flow
	O_2 Eff. (%)	83.8	73.5	79.0	Stream
	RQ	0.76	0.71	0.74	
51 -	O_2 liters (STP)	34.2	66.7	101.0	Inlet Flow
	CO_2 liters (STP)	31.1	45.2	76.3	Stream Not
	O_2 Eff. (%)	52.0	89.6	72.0	Preheated
	RQ	0.91	0.68	0.76	
54 -	O_2 liters (STP)	29.7	59.6	89.4	Inlet Flow
	CO_2 liters (STP)	16.7	46.9	63.6	Stream Not
	O_2 Eff. (%)	47.0	72.0	61.2	Preheated
	RQ	0.56	0.79	0.71	

These configurations did not deliver the desired O_2 supply and required greater CO_2 absorption capacities. Increases were effected by increasing the number of plates.

Test 59 was a 15 plate configuration which was 5 cm x 7.6 cm x 30.4 cm long and weighed 622 g. This configuration weighed the same as the 12 plate configurations since the plates were made thinner and therefore lighter. Flow for this test averaged 113 liters/min. and O_2 production was 113 liters (STP) and CO_2 absorption was 75.8 liters (STP). The flow rate for this test was near that of Test 54 discussed above. Increasing the surface area increased performance.

Test 62 was a nineteen 7.6 cm x 15.2 cm plate configuration in which an air to air heat exchanger was used to raise the inlet flow stream. The exchanger created a high pressure drop, lowering flow to 85 liters/min. Low flow decreased performance and the test was terminated after 3 hours.

Tests 64, 78, and 79 were 20 plate configurations. Test 64 was made in a 212 liter chamber and Tests 77 and 79 in the 3680 liter chamber. These configurations were 6.4 cm x 7.6 cm x 30.4 cm long and the volume of the chemical package was 1475 cm^3. Surface area of the twenty 7.6 cm x 15.2 cm KO_2 plates was 4770 cm^2. Test 64 configuration weighed 840 g and inlet air was preheated by a heat exchanger. The average flow rate was 250 liters/min. Test 78 configuration weighed 822 g and the inlet flow stream was preheated by mixing some of the outlet flow stream with it. Thus, the heat exchange was obtained without jacketing the container or a heat exchanger. The return flow for Test 78 was 1.5 that of the inlet flow. Flow rate from the system into the configuration was 300 liters/min. which decreased to 133 liters/min. Total flow rate initially, through the configuration was about 710 liters/min. with 425 liters/min. being returned. Performance was lower in Test 78 than in Test 64 because of an average lower flow rate and lower CO_2 concentration in the larger chamber. Test 64 showed 140 liters (STP) O_2 and 86 liters (STP) CO_2. Test 78 showed 92.5 liters (STP) O_2 and absorbed 32 liters (STP) CO_2.

Test 79 was the same configuration as Test 78 but the KO_2 plates were seeded with 1% $CuOCl_2$. This configuration showed a net improvement over Test 78. This configuration benefited from the combined effects of preheating, increased flow rate and the addition of a catalyzing agent.

Two-Hour Configurations

All 2-hour configurations tested were made with chemical additives to optimize performance characteristics. The additive most effective was copper oxychloride ($CuOCl_2$). Plates were used in preference to discs to give more dynamic design. A single test (Test 18) was made with KO_2 plates impregnated with 5% by weight asbestos fibers to determine if permeability of the solid KO_2 plate could be increased by the fibrous interstices. More plates were used in two-hour configurations, as the test continued, so that O_2 delivery and CO_2 absorption could be increased. Most of the tests were made in a 212 liter sealed chamber. Several tests were also made in the 3680 liter chamber.

The theoretical amount of KO_2 for a 2-hour configuration is 272 g KO_2 and 182 g NaO_2. The limited surface area presented by solid superoxide design creates a formidable problem.in optimization. Efficiencies of 75% of available O_2 for 2-hour configurations gave close approximations to theoretical requirements; however, CO_2 absorption capacities fall short and design on 2-hour configurations, as with other mission configurations designs, is predicated upon CO_2 requirements.

Test 15 involved study of the initial 2 hour configuration design. The configuration consisted of seven 10.2 cm x 10.2 cm rippled KO_2 plates seeded with 1% $CuOCl_2$, weighing 359 g and having a surface area of 1500 cm^2. The chemical volume was 525 cm^3 (10.2 cm x 10.2 cm x 10.2 cm long bed). O_2 production efficiency was 65%; 56.3 liters (STP) O_2 was evolved and 44.7 liters (STP) CO_2 was absorbed.

Lithium peroxide was added to this configuration in Tests 16 and 17. Less O_2 was evolved and less CO_2 was absorbed. Test 19 contained 1/2% $CuOCl_2$ and this blend performed less effectively than the 1% $CuOCl_2$ used in Test 15. Test 20 also contained 1/2% $CuOCl_2$ along with 2-1/2% $LiCl_2$ as an additional moisture absorber; no improvement was gained. Test 23 had 5% $LiCl_2$ and showed no beneficial effects. Test 21 contained 5% LiOH and had very adverse effects on performance, only 35.7 liters (STP) of O_2 was generated and 15.9 liters (STP) CO_2 was absorbed. Test 22 had manganese oxide as an additive and this proved ineffective. The above configurations weighed approximately 340 g.

Test 24 was made with NaO_2 and this configuration evolved 56.6 liters (STP) O_2 but was less effective than Test 15 since only 35.7 liters (STP) CO_2 was absorbed. This configuration weighed 454 g. This increase in weight resulted because of compounding difficulties with NaO_2. In Test 25, a blend of 75% NaO_2 and 25% Li_2O_2 performed similarly to the Test 24 model. A blend of 80% KO_2 and 20% Li_2O_2 was also ineffective in Test 26. Test 27, made with 5% $KMnO_4$ as a catalyst with eight 10.2 cm x 10.2 cm KO_2 plates, did not show effective O_2 or CO_2 results.

Two-hour test configurations were made with 7.6 cm x 15.2 cm plates. Bed lengths of 15.2 cm and 30.4 cm were investigated. The combination of preheating the inlet flow stream and adding 1% $CuOCl_2$ was investigated. Test 55 had eight 7.6 cm x 15.2 cm KO_2 plates weighing 395 g. This test configuration was unacceptable with only 50.1 liters (STP) O_2 delivered and 20.9 liters (STP) CO_2 absorbed. The harmful effect of increasing flow areas, which decreases mass flow rate, was shown in Test 61, made with ten 7.6 cm x 15.2 cm KO_2 plates. Although more KO_2 plates were used than in Test 55, less O_2 was produced and less CO_2 was absorbed.

Tests 82-85 were made in a 3680 liter chamber. The number of plates was increased to 12 and weight of these configuration was approximately 454 g. These configurations included a reflux manifold to preheat the inlet flow and additives were blended with KO_2 and NaO_2. The configurations of Tests 82-84 were 7.6 cm x 7.6 cm x 15.2 cm long, with volumes of 880 cm^3. Test 82 had 1% $KMnO_4$ as an additive to the KO_2 plates. Test 83 contained 1% $CuOCl_2$ as an additive to NaO_2 plates. The NaO_2 plates had to be pressed harder than KO_2 plates to achieve structural rigidity. Test 84 contained 1% $CuOCl_2$ as a catalytic additive to KO_2 plates. The configurations of Tests 82, 83, and 84 gave off comparable amounts of O_2; Test 84 being the largest at 75.5 liters (STP): CO_2 absorption was the largest in Test 84 also, being 40.8 liters (STP) CO_2. These configurations were tested in a 3680 liter chamber in which the initial CO_2 concentration was increased to 0.5% by addition of CO_2 to the chamber.

Test 85 was a configuration of 12 plates of the same composition as Test 84. The configuration was arranged so that the flow path was across the shorter 7.6 cm width of the plates. O_2 production was slightly less at 71.6 liters (STP), as was CO_2 absorption at 34.8 liters (STP). Flow rates were of equal magnitude but a lower mass flow rate prevailed in the Test 85 configuration. This is explained as the cause of lower efficiency.

Forty-Eight-Hour Configurations

Two 48-hour configuration tests were made in Tests 9 and 75. The theoretical requirement for a 48-hour mission to supply 45.4 g O_2/hr is 6540 g KO_2 and 4540 g NaO_2.

Test 9 was a configuration having 100 - 14.5 cm KO_2 discs having a weight of 7860 g. The volume of the configuration was 10,650 cm^3. Flow rate averaged 300 liters/min. and humidity averaged 40% at 24°C. The discs, having a 2.2 cm central hole, were contained in a 15.2 cm diameter duct which provided a 0.35 cm annular clearance. The configuration evolved 1825 liters (STP) O_2 and absorbed 1274 liters (STP) CO_2. The configuration evolved 97% of the available O_2 and RQ was 0.70. Both O_2 and CO_2 control exceeded specified amounts of 1520 liters (STP) O_2 and 1217 liters (STP) CO_2. This configuration represented a sizeable amount of superoxide and this was shown to over-ride the moisture control of the cooler in the chamber.

Test 75 was a combination of fifty 14.5 cm KO_2 discs and eighty 7.6 cm x 15.2 cm KO_2 plates. The discs were upstream and bed length was 31.8 cm. The plates were in a downstream bed which was 61 cm long. This size disc showed lower initial O_2 generation rates in Test 6, a 24-hour configuration design and in Test 9 discussed above. The design plan was to have the upstream disc bed act as a preconditioning bed reducing the moisture content of the flow stream to the downstream KO_2 plate bed and thereby provide more uniform O_2 generation. The round duct of the KO_2 discs was jointed to the rectangular duct of the KO_2 plates with a 1.25 cm plenum between the two beds. The test was made at a flow rate of 345 liter/min. and average humidity was 44% RH at 24°C. Both O_2 and CO_2 performance were near, but below, specification; O_2 generation was 1438 liters (STP) and CO_2 absorption was 820 liters (STP).

Although the 14.5 cm discs performed well in Test 9, this size disc showed poor performance in this test with only 508 liters (STP) O_2 generated (55% efficiency) and 249 liters (STP) CO_2 absorbed. O_2 efficiency for the plates in this 48-hour test was 99%; 928 liters (STP) O_2 was evolved and 572 liters (STP) CO_2 absorbed. Plates demonstrated superior performance over discs in this configuration test. The 14.5 cm discs performed well in Test 6 (a 24-hour test) and Test 9 discussed above. The flow rate and humidities for these tests were very nearly the same for the three tests. Poor performance of the discs may have been due to low flow rate through the annular area while most of the flow passed through the central hole of the discs. The outer surfaces of the discs would thereby be less exposed to the flow stream which would adversely affect performance. The plate surfaces are always exposed to the flow stream and thereby exhibit superior performance.

Man Tests

Three-man tests were made with solid superoxide forms. In these tests, the subject exhaled into the configuration and inspired through an adjoining breathing bag circuit. O_2, CO_2 and moisture concentrations were monitored. Volume of the rebreather circuit was about 74 liters.

Test 32 was made with ten 9.5 cm KO_2 discs (see figure 3). The weight was 332 g and surface area of the discs was 1520 cm^2. Bed length was 6.4 cm. This test was terminated after 1 hour when CO_2 concentrations reached 3%, making the subject uncomfortable. O_2 efficiency was 33.5%; 26.9 liters (STP) O_2 was evolved.

Test 35 contained twenty 9.5 cm KO_2 discs. This configuration had twice the weight and surface as the Test 32 configuration. This test was terminated after 2 hours when CO_2 concentration reached 2.37%. O_2 efficiency was 44%; 708 liters (STP) O_2 was evolved.

Test 37 contained thirty 9.5 cm KO_2 discs. The weight of this configuration was 1000 g and had a surface area of 4570 cm^2. Bed length was 19 cm. This test was terminated after 2.3 hours at which time CO_2 concentration was 2.16%. O_2 efficiency was 40.8%; 97.4 liters (STP) O_2 was evolved.

Tests With Granules

Test 8 consisted of six - 6-hour tests with 2-4 mesh KO_2 granules made from KO_2 fluff of various densities and O_2 content. Although granules were not to be employed in a mission configuration, the tests were performed to demonstrate starting KO_2 density effects on O_2 generation and CO_2 absorption capability. The tests were made at 255 liters/min. with 1000 g of 2-4 mesh KO_2 granules, packaged in a 15.2 cm diameter canister. Bed length ranged from 7.6 cm to 10.2 cm. The lowest RQ (volume ratio CO_2/O_2) was observed in Test 8F which had granules made from fluff having the lowest apparent density of 0.2 g/cm^3. The highest RQ was 0.72 in Tests 8C and 8E which utilized granules made from KO_2 fluff having densities of 0.46 g/cm^3 and 0.42 g/cm^3 respectively.

Structural Tests

The strength of superoxide forms was measured in a shear test. The superoxide forms were fixed to a table edge and a bucket suspended by a wire, was hung from the superoxide forms. Weights were added to the bucket until the superoxide forms broke. The force to shear the superoxide forms was recorded. The shear strength increased with forming pressure. KO_2 exhibited higher shear values than NaO_2. The tests were made with plates. The shear stress was calculated by dividing the crossectional area perpendicular to the force, into the force required to break the plates. The results are given in Table III. The results of the tests show KO_2 to be approximately twice as strong as NaO_2 at a forming pressure of 320 Kg/cm^2 and five times as strong at 105 Kg/cm^2.

TABLE III - STRENGTH OF SUPEROXIDE FORMS

Plate Composition	Pressure to Form (Kg/cm^2)	Average Shear Stress (Kg/cm^2)	Type of Plate and Size
KO_2	70	2.8	Flat
	105	3.5	6.4 cm x 11.4 cm
	210	5.3	
	320	7.1	
NaO_2	105	0.7	Flat
	320	3.9	6.4 cm x 11.4 cm
KO_2	105	3.2	Rippled
	300	5.3	10.2 cm x 10.2 cm
KO_2 & 25% LiOH	104	2.5	Flat Plate
	320	3.5	6.4 cm x 10.4 cm

The configuration designs tested were self-spacing and self-supporting. To gain strength, the plates may be pressed at higher forming pressure, but as discussed previously, this tends to decrease the O_2 evolution and CO_2 absorption properties. The plates can be made more resistant to breakage by pressing wire mesh with the superoxide. The network of wires through the superoxide plates prevents disintegration of pieces if the plate becomes fractured. This technique was found feasible with the wavy-pattern of the 7.6 cm x 15.2 cm diagonally rippled plates and 10.2 cm x 10.2 cm rippled plates.

Section IV

DESIGN PHASE

The generation of oxygen from superoxide configurations is dependent upon the presence of moisture in the flow stream. For KO_2 this reaction is:

$$KO_2 + H_2O \longrightarrow 2KOH + 3/2\ O_2$$

This reaction must occur to form the hydroxide which is necessary for absorption of CO_2. The reaction of CO_2 may be either:

$$2KOH + CO_2 \longrightarrow K_2CO_3$$

$$\text{or} \quad 2KOH + CO_2 \longrightarrow KHCO_3 + H_2O$$

Thus, the two driving forces in performance of a superoxide configuration are the moisture and carbon dioxide concentrations.

Other factors to consider are the type of superoxide, flow rate and mass flow rate, surface to volume ratio, pressure to shape the forms and temperature.

Design Coefficients

Rate data was collected from the configuration tests. This data was collected for disc and plate type configurations. The rate of O_2 generation and CO_2 absorption in liters/hr (STP) can be calculated by monitoring chamber conditions during tests to obtain a mass balance of constituents. Inlet and outlet streams were monitored for constituent gas concentrations to supplement this data and provide additional information for correlating performance.

The generation of oxygen and absorption of carbon dioxide by superoxides are mass transfer operations. The superoxide configurations can be treated in this manner. Like heat transfer coefficients in heat exchange operations, mass transfer coefficients can be described for exchange of mass. In heat exchange, the overall coefficient is related to amount of heat transferred, q, by the equation:

$$q = U A \Delta T_{LM}$$

Analogously, in mass transfer, the mass transfer coefficients, $K_g a$ can be described for both O_2 production rate and CO_2 absorption rate in grams/hr of gas by the equation:

$$\text{grams/hr} = K_g a \times \text{Volume} \times \Delta P_{LM}$$

Whereas in heat transfer the driving force is the temperature difference, ΔT, in mass transfer this driving force is the partial pressure of reference gases. For O_2 generation with superoxide, this is the vapor pressure of water in the flowing stream. For O_2, the generation coefficient is defined to be:

$$K_g a\ (O_2) = \frac{\text{grams/hr } O_2}{V\ \Delta P_{LM}}$$

where $K_g a$ is the overall transfer coefficient for O_2 production in units of:

$$\frac{\text{grams } O_2}{\text{hr-cm}^3\text{-atmosphere}}$$

and a is the surface to volume ratio of the configuration. In mass transfer operations, this is referred to as the interfacial area per unit of volume of apparatus. Variations in coefficients due to variations in flow rates, type of packing, etc., have been attributed to changes in the value of a as much as to changes in K_g. In the case with superoxide, reaction of the shapes can change this value as the configuration becomes spent and can be expected to be changing continuously. Other units are, V, the volume of the configuration in cubic centimeters and ΔP_{LM}, the driving force for O_2 generation in atmospheres. This latter term is the log mean pressure difference exerted by the vapor pressure of water. This was determined by measurement of inlet and outlet gas streams of the configuration.

Likewise, for CO_2 absorption, an overall coefficient can be described:

$$K_g a\ (CO_2) = \frac{\text{grams/hr } CO_2}{V\ \Delta P_{LM}}$$

For O_2 generation the ΔP_{LM} is:

$$\Delta P_{LM} = \frac{H_2O \text{ concentration in} - H_2O \text{ concentration out}}{\ln \dfrac{H_2O \text{ concentration in}}{H_2O \text{ concentration out}}} = \text{atmosphere}$$

Similarly for CO_2 absorption, the ΔP_{LM} is:

$$\Delta P_{LM} = \frac{CO_2 \text{ concentration in} - CO_2 \text{ concentration out}}{\ln \dfrac{CO_2 \text{ concentration in}}{CO_2 \text{ concentration out}}} = \text{atmosphere}$$

In testing the configurations both moisture and CO_2 concentrations into and out of the configurations were monitored and the ΔP_{LM} for O_2 generation and CO_2 absorption were calculated. Rates of O_2 generation and CO_2 absorption in liters/hr (STP) were calculated by mass balances between the simulator and the chamber. These were then converted to grams/hr. The volume of the configuration performance, were calculated periodically as the tests progressed. An average coefficient was obtained from these calculated values.

Configuration tests were basically of two types: 1) passive-dynamic design with discs having no direct forced flow between them and 2) dynamic designs with plates where the surfaces are directly exposed to forced flow streams. The latter are referred to as dynamic designs and were employed as the design approach for short mission configurations because of their more responsive characteristics.

A fresh surface of superoxide possesses no surface barrier for O_2 generation and O_2 is readily evolved from it. As the reaction proceeds from the surface and into it, a surface crust forms and impedes O_2 generation and CO_2 absorption. Thus, the reciprocal of the overall coefficients (K_ga) above are comprised of gas film resistance (k_g, analogous to a gas film resistance in heat transfer), and a diffusion resistance (k_s) offered by the solid chemical reactants. The relationship of these resistances can be expressed by the equation:

$$1/K_ga = 1/k_g + 1/k_s$$

Utilization of available O_2 in short mission configurations was more difficult since less bulk superoxide was required, and thus there was less surface area for reaction. In the above equation, the gas film resistance, $1/k_g$, can be decreased by increasing flow rate. This increases the individual O_2 generation and CO_2 absorption coefficients thereby enhancing performance with the same surface area.

Increasing inlet temperatures also increased performance since chemical reaction rates are favored by temperature increases. A chemical additive such as $CuOCl_2$ was effective in increasing reaction rates. These three techniques were used to gain performance increases which are more important in short mission designs. Longer mission configurations have more superoxide and hence more area and chemical additives for quick release of oxygen are not necessary. Higher moisture concentrations in the flow stream also increase O_2 generation.

Results and Correlations

Oxygen generation coefficients and CO_2 absorption coefficients for plate configurations used in Tests 40, 65, 68, 70, and 81 are shown in Figures 10 and 11. In Figure 10, the O_2 generating coefficient K_ga is plotted versus percent O_2 depletion, and Figure 11 is a plot of the CO_2 absorption coefficient versus O_2 depletion. Both plots show drop in coefficients with time. This is due to 1) decrease in active chemical surface-to-volume ratio with time and 2) a steady increase in diffusion resistances. The latter is a result of the reaction products which build up and impede gas diffusion into and out of the solid superoxide forms. This crust may have become more impervious at higher humidities effecting a decrease in coefficients. Examination of the forms exposed to higher humidities appeared to have a more glazed surface than those exposed to lower humidity conditions. Figures 12 and 13 are corresponding plots for disc configurations. These configurations are inherently less dynamic since areas between adjacent discs have less turbulent flow patterns. These disc configurations showed lower coefficients initially, but fell off less rapidly in comparison to plate configurations. The plate configuration for Test 40 displayed the most dynamic CO_2 control of all configurations tested. CO_2 was absorbed at the production rate of the simulator and detectable ($>$ 0%) CO_2 concentrations in the chamber were not observed until 60% of the O_2 was depleted. Lower flow rate and higher humidity detracted from performance. Tests 68 and 70 were made at flow rates of 100 liters/min. and 150 liters/min. respectively and Test 40 at 255 liters/min. Specific humidities were higher in Test 68 and 70, averaging 0.0098 g H_2O/g air (corresponds to 53% RH at 24°C) compared to 0.0070 g H_2O/g air ($\sim$ 38% RH at 24°C) for Test 40. Test 81 was a 24-hour plate configuration with a reflux manifold to preheat the inlet flow stream. The flow rate into the configuration averaged 195 liters/min. which gave a velocity of 82 cm/sec.

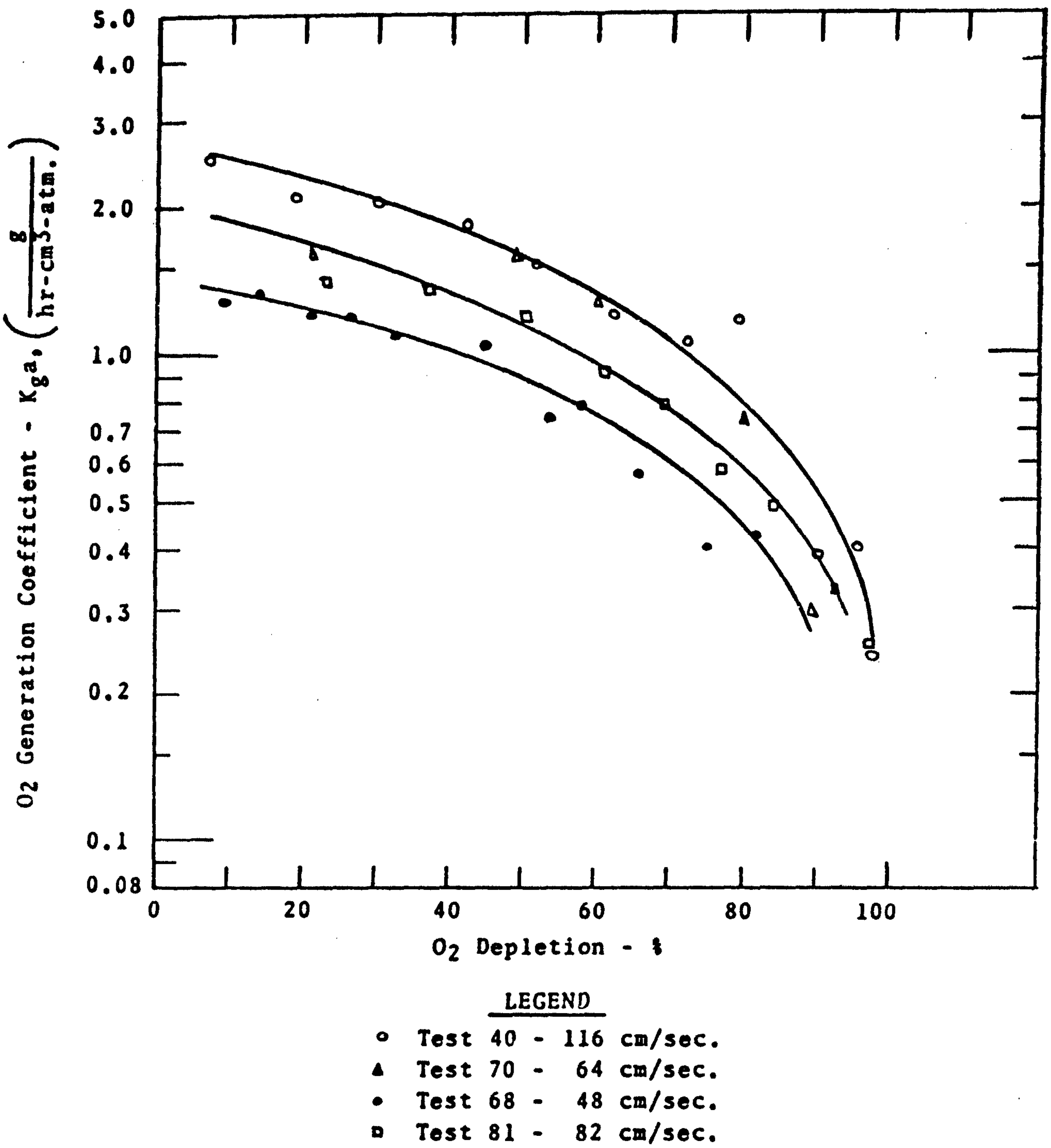


FIG. 10 - O_2 GENERATION COEFFICIENTS WITH KO_2 PLATES

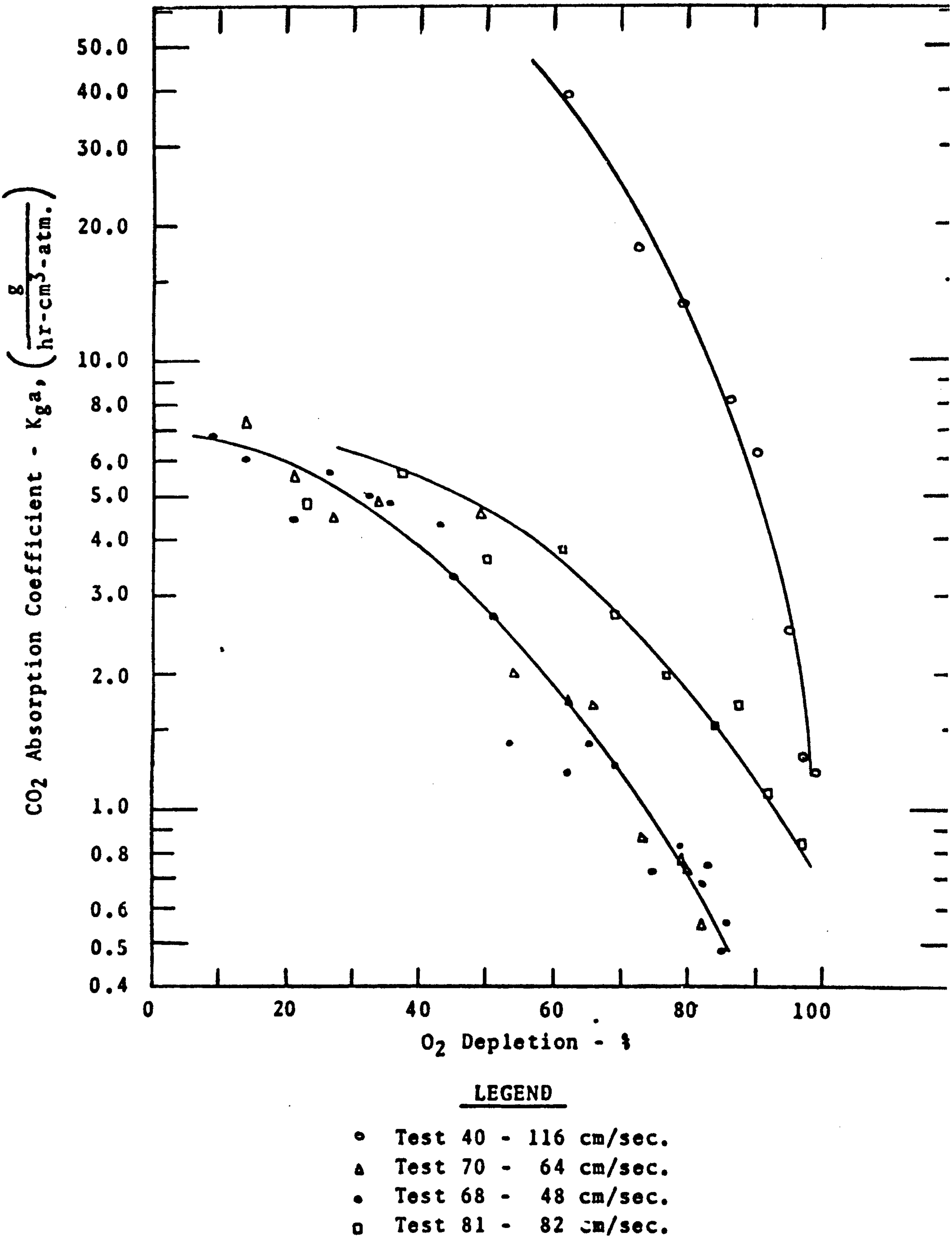
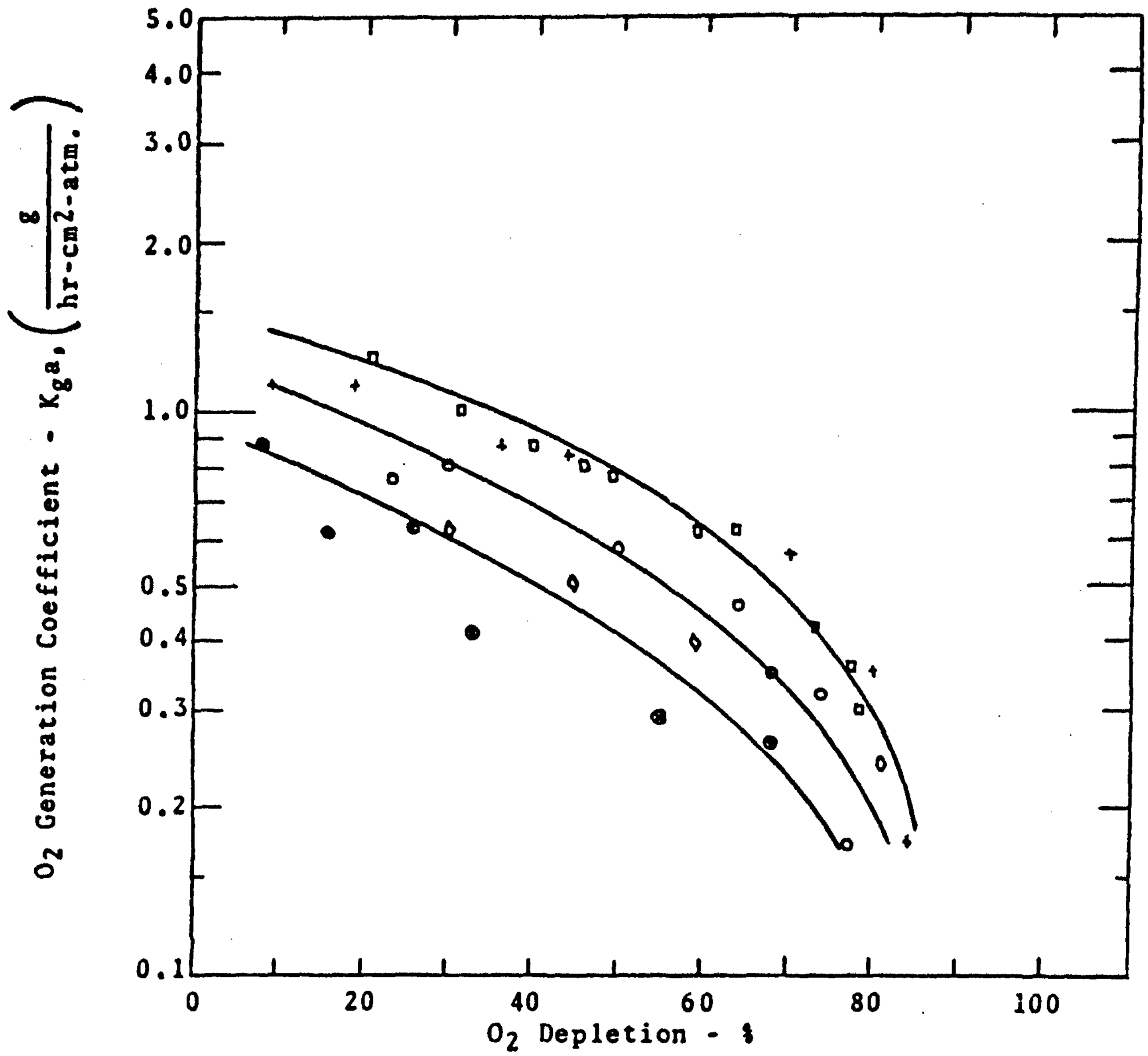


FIG. 11 - CO_2 ABSORPTION COEFFICIENTS FOR KO_2 PLATES



LEGEND

- ◊ 14.5 cm discs x 32 cm long - 35 cm/sec.
- ● 9.5 cm discs x 69 cm long - 35 cm/sec.
- ○ 9.5 cm discs x 69 cm long - 50 cm/sec.
- + 9.5 cm discs x 69 cm long - 64 cm/sec.
- □ 7.0 cm discs x 107 cm long - 59 cm/sec.

FIG. 12 - O_2 GENERATION COEFFICIENTS FOR DISCS

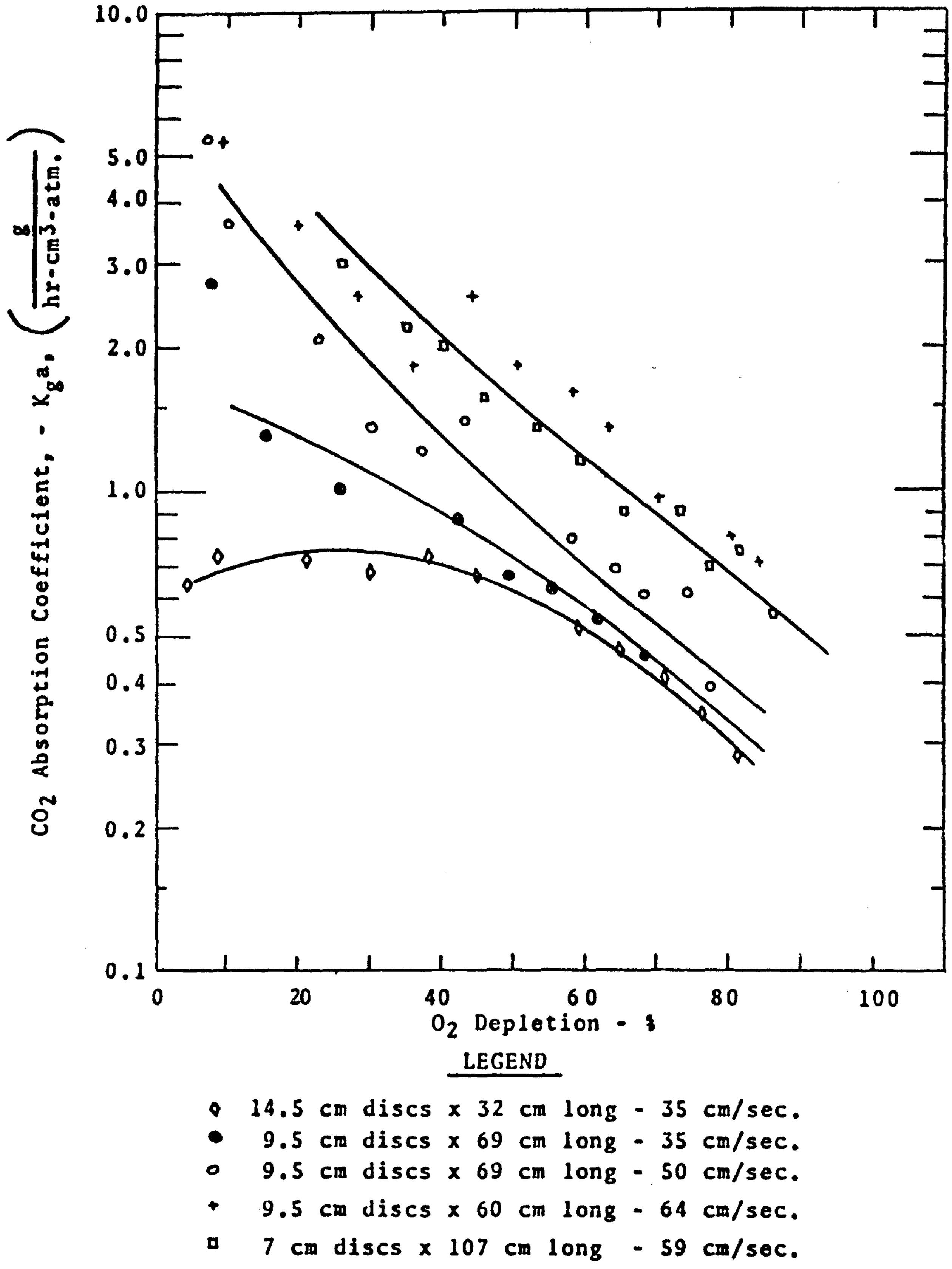


FIG. 13 - CO_2 ABSORPTION COEFFICIENTS FOR DISCS

through the plates. The effect of increasing velocity is demonstrated in Figures 10 and 11.

The relationship of the overall resistance (reciprocal of overall coefficients) for O_2 generation is shown in Figure 14 for Test 40, 65, 68, 70, and 81. This relationship is represented as a straight line plot of the form:

$$Y = a + b\ (X)$$

and is analogous to the equation relating the overall coefficients with individual coefficients as a function of O_2 depletion:

$$1/K_g = 1/k_g + 1/k_s\ (X)$$

Thus, the intercept (at X = 0, no O_2 depletion) represents the gas film resistance, and the slope the resistance of the solid chemical reactants. The gas film resistance for Test 40 is lowest (higher coefficient, k_g) for the three tests and Test 40 had the highest flow rate. The relationship can be seen to be a function of velocities through the configuration. Test 40 (velocity was 116 cm/sec.) had the lowest overall resistance with increasing resistance as velocity decreased. The velocity in Test 70 was 64 cm/sec. and in Test 68 it was 48 cm/sec. The absorption coefficients for the plate configurations of Tests 40, 65, 68, 70, and 81 are shown in Figure 15. Disc configuration behaved in this manner; increasing flow rate lowered resistance and increased coefficients. The disc configurations exhibited higher resistance values than plate configurations at corresponding flow rates.

Figures 14 and 15 for plate configuration also illustrate performance of Test 65, which was an 8-hour configuration. This configuration was smaller than the 24-hour configurations of Test 40, 68, and 70 and had a preheated flow stream which increased the inlet temperature by 8-12°C. The combined effect of preheating and a high mass flow through the configuration increased performance by lowering the surface resistance, as represented by lower slope lines. The initial resistances, or generation and absorption coefficients, are higher since less bulk superoxide was present. The lower slope for Test 65 demonstrated performance gained by higher inlet temperature and flow. This was again illustrated in Test 81, a 24-hour configuration which had the inlet stream preheated by using a reflux manifold.

The plots of Figures 14 and 15 are shown as straight lines. Above 80% O_2 depletion, data became scattered, suggesting

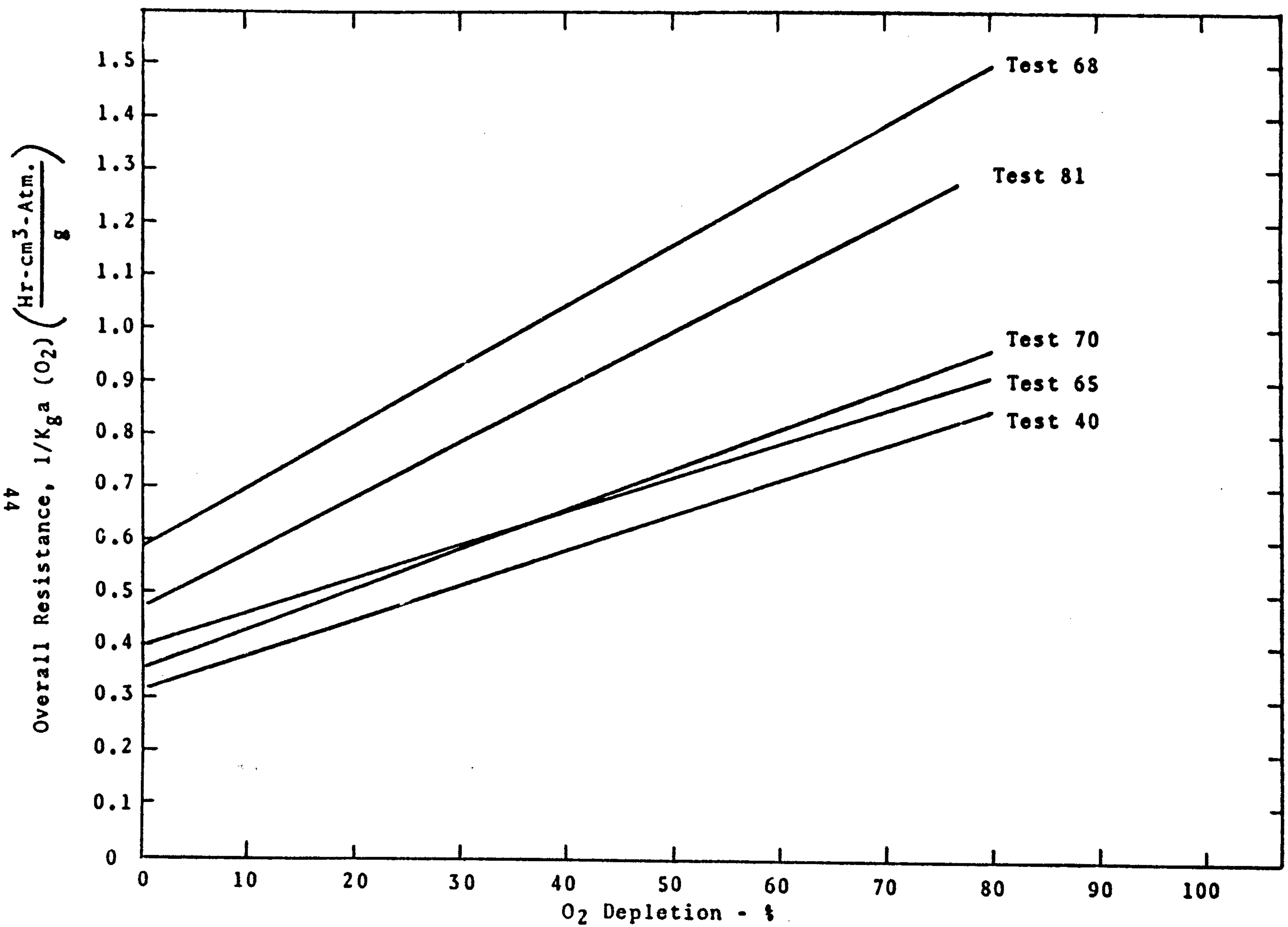


FIG. 14 - O_2 GENERATION RESISTANCES IN KO_2 PLATES

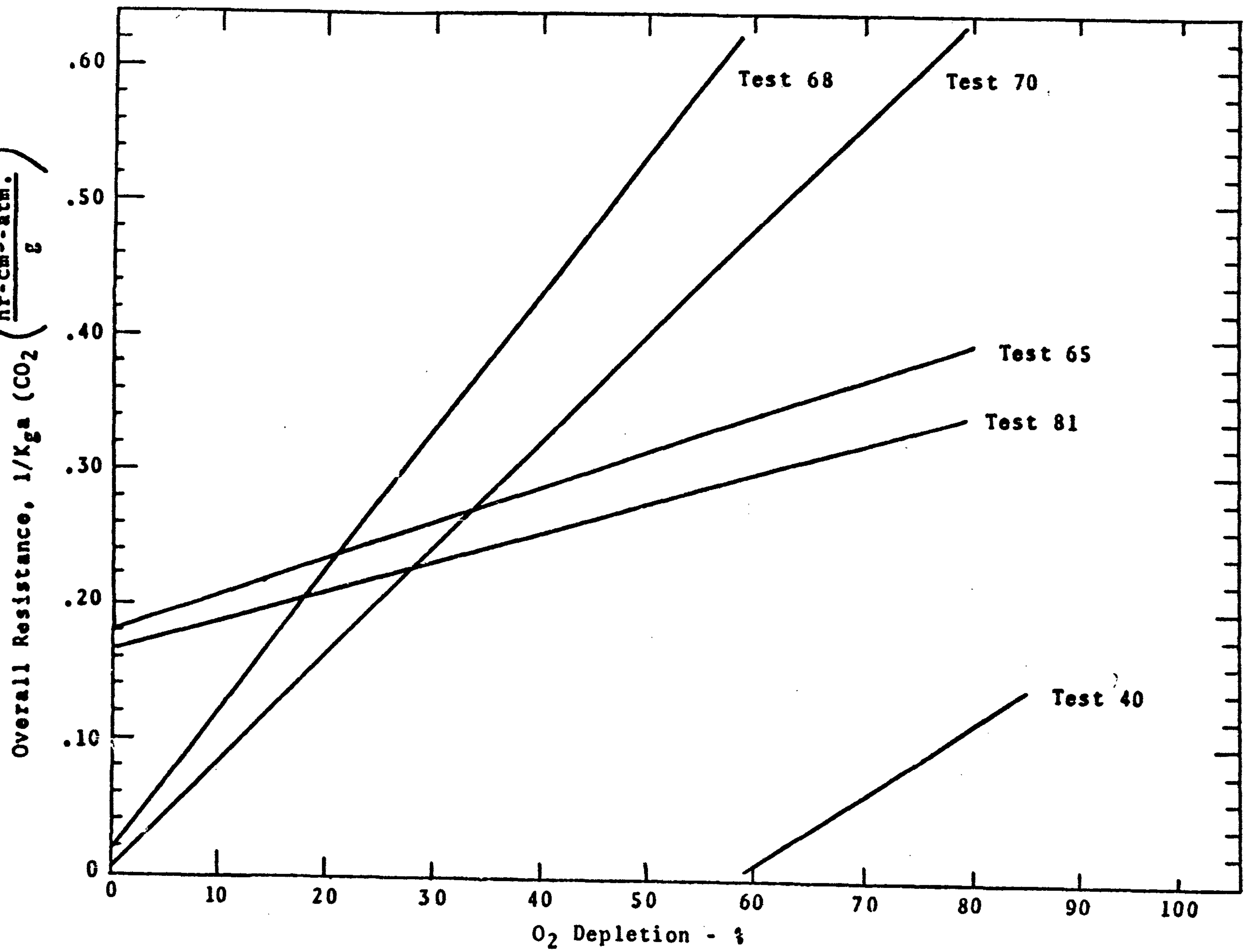


FIG. 15 - CO_2 ABSORPTION RESISTANCE IN KO_2 PLATE CONFIGURATIONS

that the overall reaction rates are not truly linear and are of higher order.

Individual coefficients are shown to change very rapidly. The use of HTU, height of a transfer unit with dimensions of centimeters, is employed in mass transfer because it is more nearly constant. The HTU when plotted against mass flow, designated by G and with units of g/hr-cm^2, gives a general correlation of the mass transfer operations. The HTU for O_2 generation and CO_2 absorption were calcualted from the relation:

$$HTU = \frac{G}{K_g a \ (1-y)_f} \quad \text{where}$$

G is the mass flow rate of gas through the configuration per unit crossectional area for flow. $K_g a$ is the average transfer coefficient for O_2 generation or CO_2 absorption observed during the test. The units for $K_g a$ in this application are:

$$\frac{\text{g (gas being transferred)}}{\text{hr-cm}^3 \text{ (chemical volume) - atmosphere}}$$

The term $(1-y)_f$ is the pressure in atmospheres of a layer of insoluble gas through which the soluble gases (H_2O in the case of O_2 generation and CO_2 for the case of CO_2 absorption) must pass. The value of y in the term $(1-y)_f$ represents the partial pressure in atmospheres of the diffusing gas. This value is low in relation to the total pressure $(1-y)_f$ and is essentially the ambient pressure.

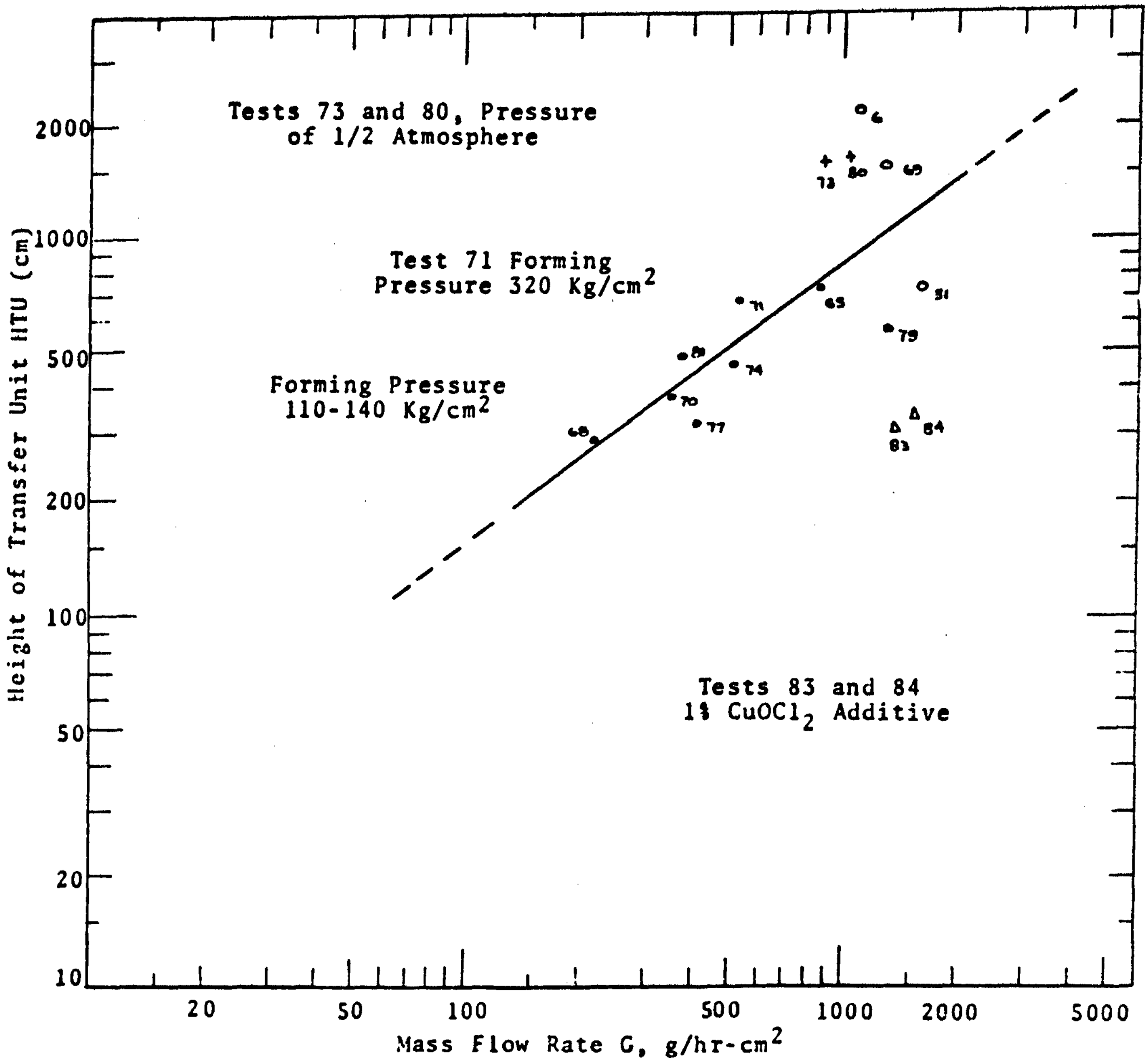
For configuration tests made at atmospheric pressure; (P = 1 atm.) the HTU for O_2 becomes:

$$HTU_{O_2} = \frac{G}{K_g a \ (O_2)}$$

and for CO_2:

$$HTU_{CO_2} = \frac{G}{K_g a \ (CO_2)}$$

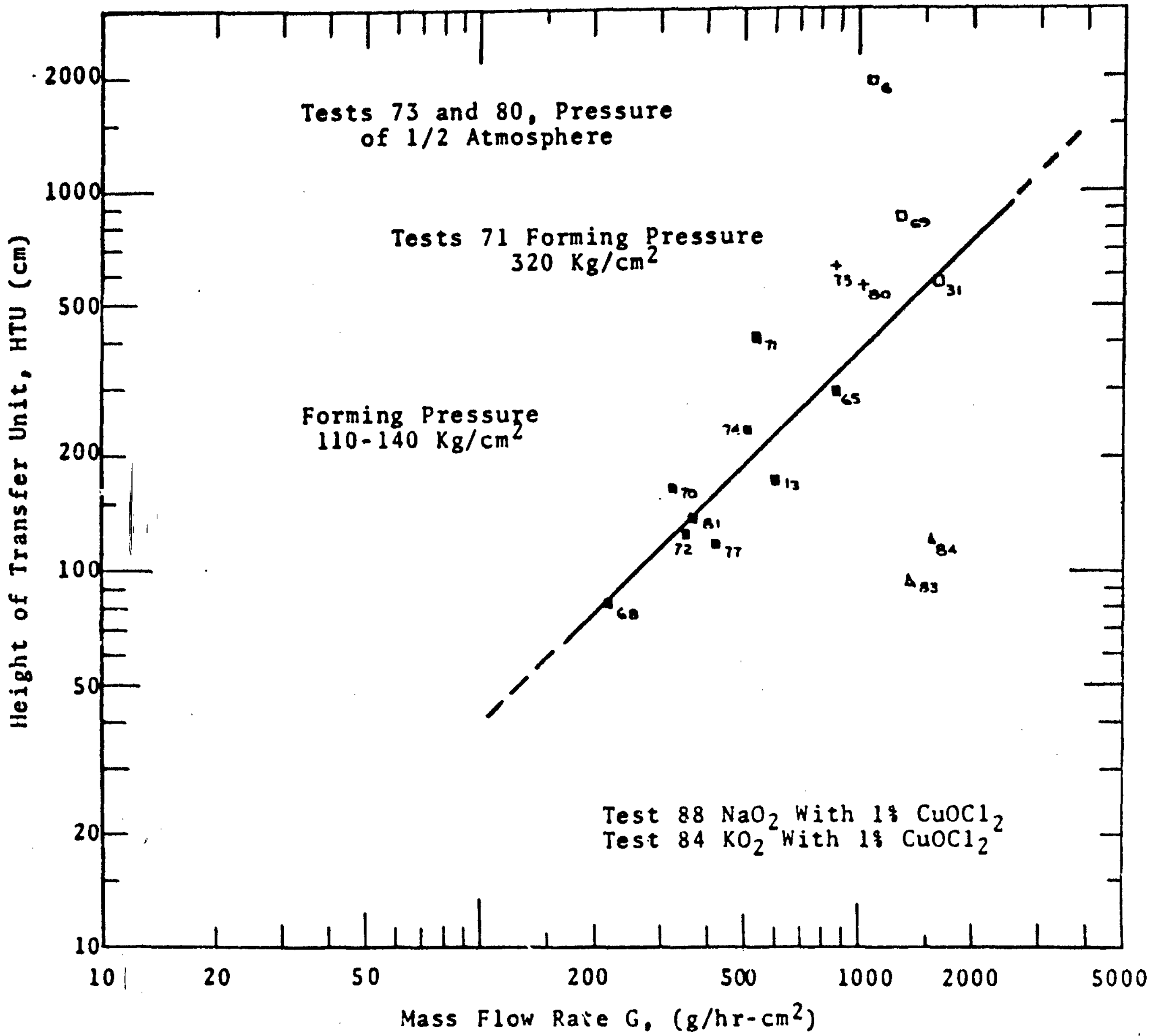
Values of HTU for O_2 plate configuration tests are shown in Figure 16 and for CO_2 in Figure 17. These are shown as straight



LEGEND

- ● Plates (Number designates test)
- O Discs
- \+ Plates at 1/2 Atmosphere
- Δ Plates with 1% $CuOCl_2$

FIG. 16 - HTU FOR O_2 GENERATION WITH KO_2 CONFIGURATIONS



LEGEND

- ■ Plates (Number designates test)
- □ Discs
- + Plates at 1/2 Atmosphere
- △ Plates with 1% $CuOCl_2$

FIG. 17 - HTU FOR CO_2 ABSORPTION WITH KO_2 CONFIGURATIONS

line plots for the short range of data obtained from the configuration tests.

This treatment when applied to disc configuration yielded scattering of data points and the performance of disc configurations is less definitive than for plates. Mass flow rates were calculated using the flow area through the disc configuration as was done in plate configuration. However, the non-dynamic flow pattern of disc configuration contributed to less predictable performance and scattered results.

For an absorption bed of differential thickness, dz, the mass balance and mass transfer relations can be expressed as:

$$G\,dy = K_g a\,(y-y^*)\,dz \tag{1}$$

rearranging gives

$$\frac{dy}{(y-y^*)} = \frac{K_g a}{G}\,dz \tag{2}$$

defining HTU as given previously to be

$$HTU = \frac{G}{K_g a}$$

results in

$$\frac{dy}{y-y^*} = \frac{dz}{HTU} \tag{3}$$

HTU will be nearly constant for a given column and equation (3) can be integrated:

$$\int_{y_2}^{y_1} \frac{dy}{y-y^*} = \frac{Z}{HTU} \tag{4}$$

and a quantity of NTU can be defined as:

$$NTU = \frac{dy}{y-y^*} \tag{5}$$

hence we have

$$NTU = \frac{Z}{HTU} \tag{6}$$

For the case where the equilibrium gas concentration y^* is small compared to the gas concentration y, the NTU becomes

$$NTU = \int_{y_2}^{y_1} \frac{dy}{y} = \ln \frac{y_1}{y_2} \tag{7}$$

This occurs for any non-reversible reaction. Thus the relation

$$\ln \frac{y_1}{y_2} = \frac{Z}{HTU} \tag{8}$$

Where y_1 is inlet concentration of the gas being absorbed and y_2 is the outlet gas concentration. The relation of the plots of Figures 16 and 17 provide a basis for calculating configuration performance.

Applications of the Equations

The plots of Figures 16 and 17 were generated from 8-hour and 24-hour test data on plates pressed at 110-140 Kg/cm^2. As discussed previously, the higher forming pressure decreased performance, that is, displaced the line plot of HTU vs G upward.

A single configuration design may not match both the O_2 production or CO_2 absorption desired. This was demonstrated in the tests where O_2 production was adequate but CO_2 absorption lagged.

The equations and correlation plots presented previously can be used to predict configuration performance. Complete utilization of available O_2 cannot be achieved especially for short mission configurations and must be considered in the design. Test data for 8-hour plate-type configurations have shown an O_2 efficiency of 70% with KO_2 and for 24-hour configurations the O_2 effeciency is approximately 90%. A second point to consider is that CO_2 absorption is a more limiting factor on design than is O_2 generation. Therefore, calculations illustrate configuration based on CO_2 absorption capability. This assumes that the inlet flow stream has moisture which is necessary to generate O_2 and produce hydroxide for CO_2 absorption. Most of the configuration tests were made at humidities of 50% RH at 24°C and lower.

To illustrate the use of the correlation plots and equation we decided to design an 8-hour configuration which will provide:

> 45.4 g O_2/hr, 50 g CO_2/hr using 7.6 cm x 15.2 cm diagonally rippled plates (see figure 8) and 70% utilization of available O_2.
>
> For the reaction of superoxide,
>
> $$KO_2 + H_2O \longrightarrow 2KOH + 3/2\ O_2$$
>
> the amount of KO_2 can be calculated.
>
> $$KO_2 = \frac{144}{48}\ 45.4\ g\ O_2/hr \times 8\ hr =$$
>
> $$1090\ g\ KO_2$$
>
> For a 70% utilization the amount of KO_2 required becomes:
>
> $$1090/0.7 = 1560\ g\ KO_2$$

For plates weighing 44 g each, approximately 36 plates are required. Arbitrarily, arrange the plates as 2 beds in series, each bed having 18 plates. Each bed being 15.2 cm long to give a total bed length of 30.4 cm.

(a) Select a flow rate and calculate bed length required to generate 45.4 g/hr O_2.

A trial calculation is made for 400 liters/min. STP flow rate.

Chamber humidity is 50% RH at 24°C (1.46% H_2O)

$$400 \text{ liters/min. (STP)} = 24{,}000 \text{ liters/hr (STP)} =$$

$$31{,}200 \text{ g/hr flow (air)}$$

Calculate outlet moisture concentration y_2, to generate:

45.4 g/hr O_2

Amount of H_2O required is:

$$18/48\ (45.4) = 17.1 \text{ g/hr } H_2O \text{ or } 31{,}200$$

$$(0.0146 - y_2) = 17.1$$

$$y_2 = \frac{439}{31{,}200} = .0141 \text{ or } 1.41\% \text{ outlet}$$

moisture concentration

$$\text{Number Transfer Units, NTU} = \int_{y_2}^{y_1} \frac{dy}{y} =$$

$$\ln y \Big]_{y_2}^{y_1}$$

$$\text{NTU} = \ln \frac{1.46}{1.41} = \ln 1.035 = 0.0344$$

Flow area for 18 plate wide configuration (1.61 cm^2 per plate)

$$A = 18 \times 1.61 = 29 \text{ cm}^2$$

Mass flow rate, G = g/hr cm^2

$G = 31,200/29 = 1070$ g/hr cm^2

HTU for O_2 from Figure 16

HTU = 900 cm for G = 1075 g/hr-cm^2

Bed Length Z = NTU x HTU = 0.034 x 90 = 30.7 cm

This checks with 30.4 cm length above and at a flow of 400 liters/min. the average O_2 generation should be approximately 45.4 g/hr.

(b) For this configuration and flow rate, what bed length is required to remove 50 g/hr if the inlet CO_2 concentrations is 1% (y_1 = 1%).

50 g/hr CO_2

Calculate outlet concentration at

$$31,200\ (0.001 - y_2) = 50$$

$$y_2 = \frac{260}{31,000} = 0.0084 \quad (0.84\%\ CO_2)$$

$$\text{Number of transfer units, NTU} = \Big[\ln y\Big]_{y_2}^{y_1} =$$

$$\ln \frac{0.010}{0.0084} = 0.1735$$

HTU for CO_2 from Figure 17

HTU = 390 for G = 1070 g/hr cm^2

Bed length required, Z for CO_2 removal

Z = NTU x HTU = 0.1735 x 390 = 67.7 cm long bed is needed.

This shows that a single configuration may not satisfy O_2 generation and CO_2 absorption requirements depending upon the limits set. If the inlet CO_2 concentration, y_1 is permitted to be 2.0%, the bed length can be matched. The higher CO_2 concentration provides a greater driving force for absorption and shortens the bed.

Let y_1 = 2.0% CO_2 inlet concentration

Calculate outlet concentration, y_2 at 15 SCFM flowrate

$$31{,}000\ (0.02 - y_2) = 50$$

$$y_2 = \frac{620 - 50}{31{,}000} = \frac{.570}{31{,}000} = 0.0184$$

$$\text{Number of Transfer Units, NTU,} = \Big[\ln y\Big]_{y_2}^{y_1} =$$

$$\ln \frac{0.020}{0.0184} = 0.0805$$

HTU for CO_2 is 390 from above

Bed length required, Z, for CO_2 removal

$$Z = \text{NTU} \times \text{HTU} = 0.0805 \times 390 = 31.4\ \text{cm}$$

The above calculations illustrate the use of the equations and plots and show the effects of gas concentrations upon performance of a selected configuration. The calculations for this configuration show that at a flow of 400 liters/min. (STP) the average O_2 generation will be 45.4 g/hr and CO_2 absorption rate will be 50 g/hr at an inlet CO_2 concentration of 2.0%. One might also have selected a 36 plate wide array rather than the 18 plate arrangement. Calculations for this configuration at 400 liters/min. (STP) would show a decrease in O_2 generation rate and CO_2 absorption rate because of a decrease in mass flow rate. Conversely a narrower and a longer configuration might be selected. An increase in O_2 generation rate and CO_2 absorption would be obtained because of the increase in mass flow rate, however, the pressure drop would increase because of the longer bed length.

Configuration Recommendations

The investigation of the superoxide configurations has yielded data from which designs are suggested for 2-, 4-, 8-, 24-, and 48-hour missions. Plate configurations are recommended over disc configurations, and the diagonal plate design provides less chance of flow obstruction from breakage. In the disc design a fragment could obstruct the center hole and adversely affect performance. With this type of plate design, the flow can still pass through the many channels provided by the diagonal pattern. The use of KO_2 is recommended for these designs since NaO_2 did not possess equivalent structural integrity. For 2- and 4-hour mission designs, seeding of the KO_2 with 1% $CuOCl_2$ promotes more effective performance for these short life missions. No advantage is gained in longer life missions since the additional time promotes better utilization of the superoxide.

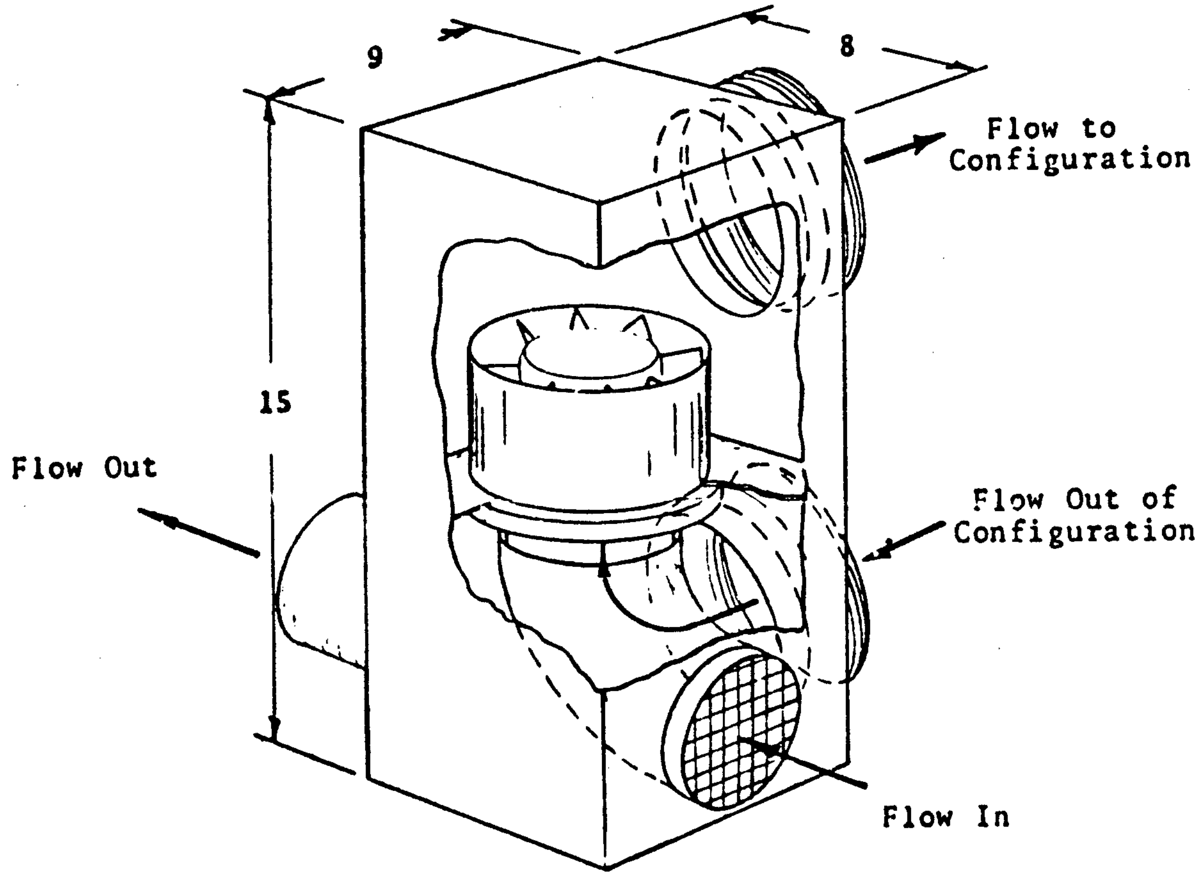
A reflux manifold is suggested to partially recirculate exhaust gases. Gasesflowing into the configuration are preheated, promoting better utilization of the inlet superoxide bed. Figure 18 represents a reflux manifold design.

Figure 19 shows a design for 2-hour and 4-hour configurations. The inlet and outlet parts mate to the reflux manifold shown in Figure 18. The 2-hour and 4-hour designs use 7.6 cm x 15.2 cm diagonally rippled KO_2 plates seeded with 1% $CuOCl_2$ to give accelerated performance and more efficient utilization of the superoxide in the short mission time.

Specifications for the five mission configurations are tabulated for comparison.

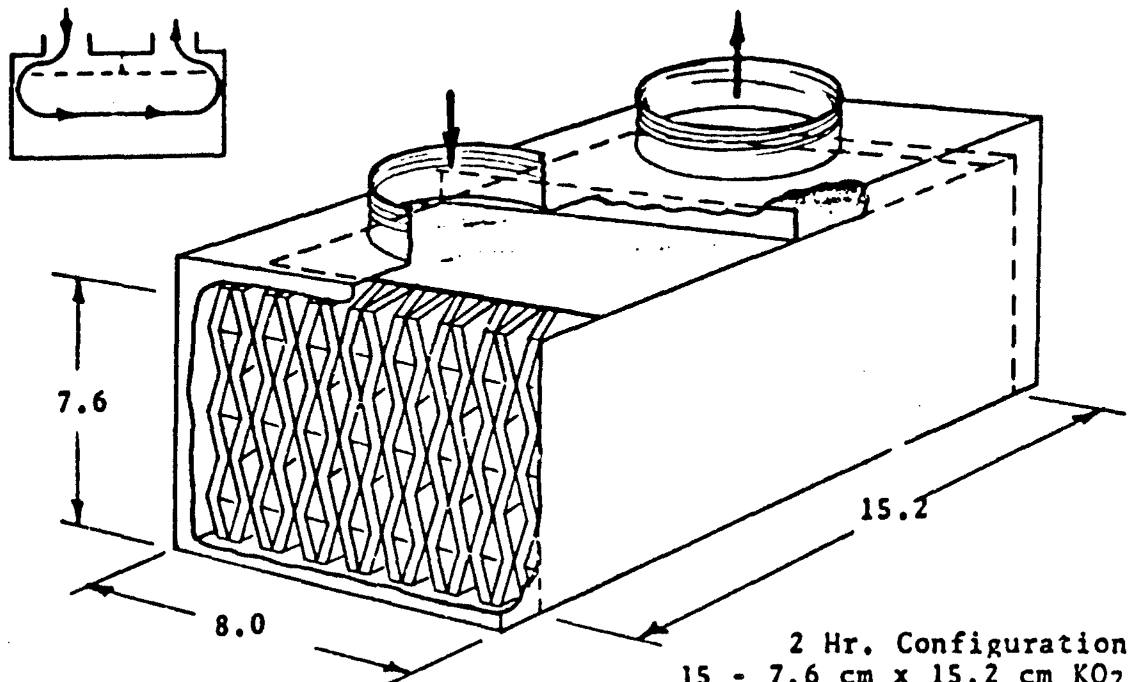
Mission Configuration (hr)	No. Plate	Weight (g)	Volume of Plate Envelop (cm^3)	Inlet Flow Rate (liters/ min.)	Total* Internal Flow Rate (liters/ min.)	Pressure Drop (cm H_2O)	Power (watts)
2	15	660	923	425	1150	1.8	27
4	24	1060	1400	280	850	3.6	24
8	40	1760	2300	425	1150	2.5	27
24	100	4000	5400	225	850	2.3	24
48	200	8000	10,800	85	280	0.8	21

* Total flow less inlet flow gives reflux flow.

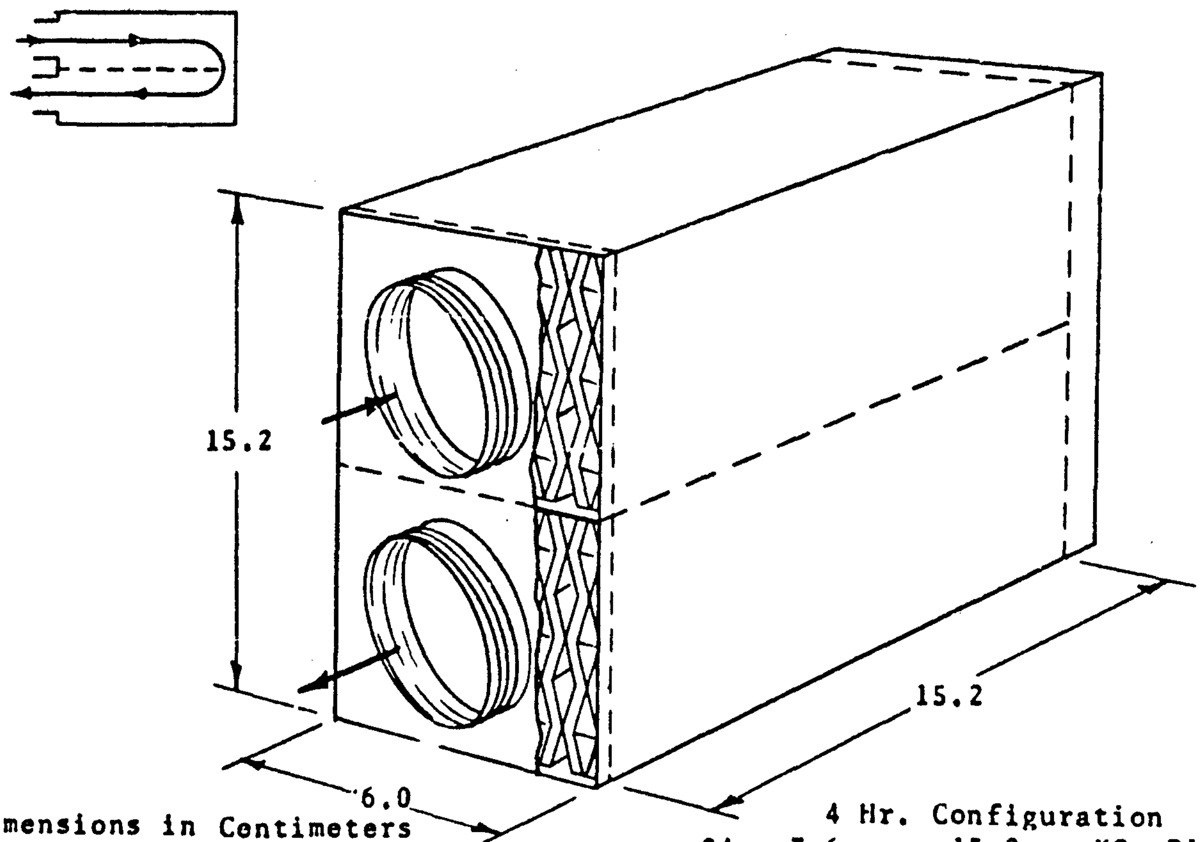


Dimensions in Centimeters

FIG. 18 - REFLUX MANIFOLD



2 Hr. Configuration
15 - 7.6 cm x 15.2 cm KO_2 Plates
with 1% $CuOCl_2$



Dimensions in Centimeters

4 Hr. Configuration
24 - 7.6 cm x 15.2 cm KO_2 Plates
With 1% $CuOCl_2$

FIG. 19 - TWO-HOUR AND FOUR-HOUR CONFIGURATION DESIGNS

Figure 20 represents the 8-hour and 24-hour mission configuration. The 48-hour mission configuration, not shown, would be two 24-hour mission configurations in series.

Configuration Samples

Two laboratory samples of the KO_2 configurations shown in Figures 2-4, 6-8 were submitted to AMRL. Samples of NaO_2, 50% NaO_2 - 50% KO_2, KO_2 with 1% $CuOCl_2$ and KO_2 with 25% LiOH were also furnished. These were pressed to the 7.6 cm x 15.2 cm diagonally rippled plate configuration pattern. Three modules containing six 7.6 cm x 15.2 cm plates were also supplied to illustrate packaging formation. One module contained KO_2 plates, another KO_2 plates with 1% $CuOCl_2$ and a third KO_2 plates having internal wire mesh. A six plate module of 10.2 cm x 10.2 cm rippled KO_2 plates was a fourth module delivered for evaluation. These six plate modules were encased in No. 2 mesh wire cloth.

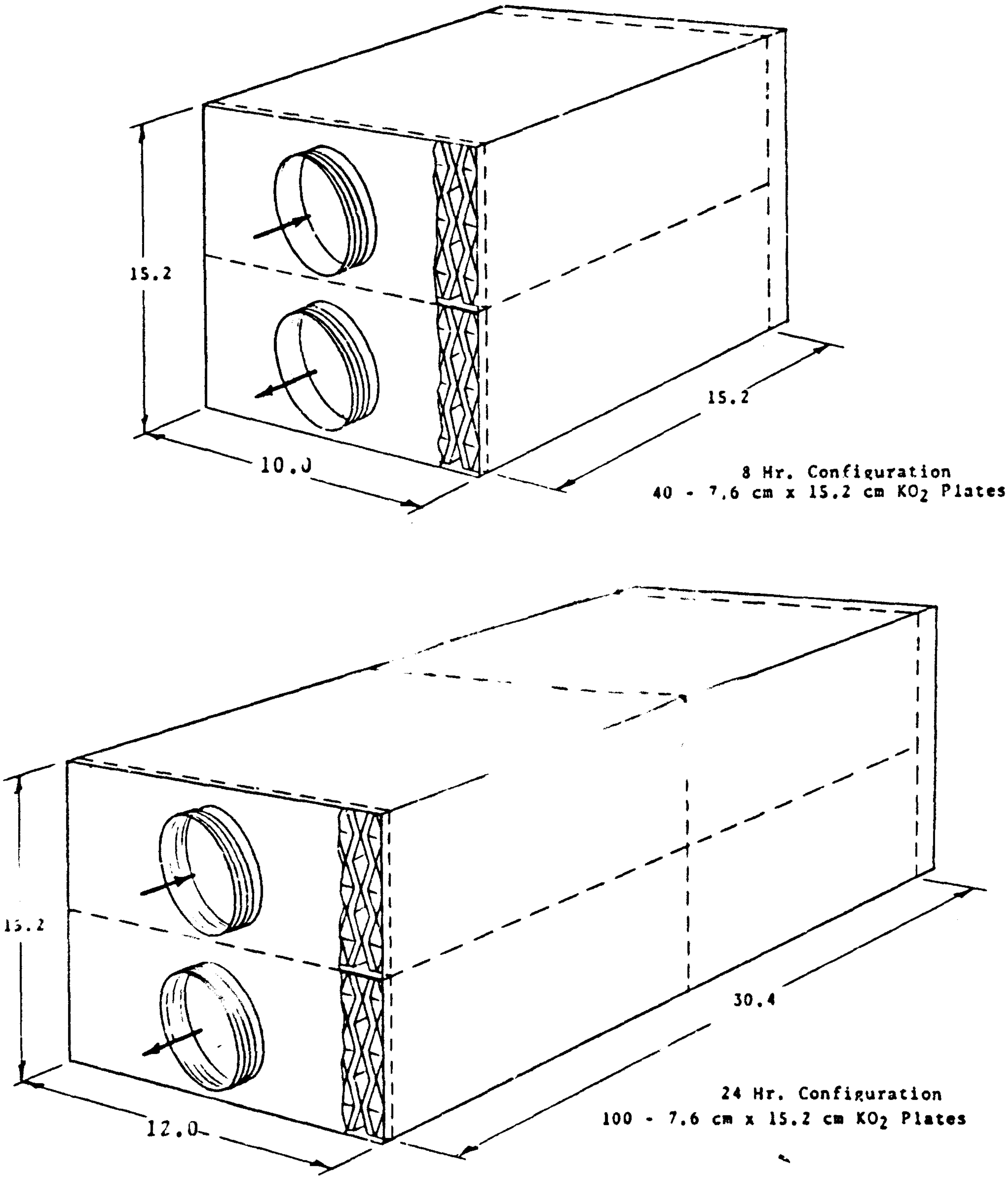


FIG. 20 - EIGHT-HOUR AND TWENTY-FOUR-HOUR CONFIGURATION DESIGNS

Section V

CONCLUSIONS AND RECOMMENDATIONS

Solid superoxide configurations have been further defined for application to life support systems. Analysis of 2-, 4-, 8-, 24-, and 48-hour mission configuration tests has supplemented the engineering design parameters.

Plate designs are more efficient than disc designs tested because of the more dynamic flow arrangements. The more dynamic flow patterns of plate type configurations lead to more definitive performance than do disc configuration designs.

The theory of the O_2 generation and CO_2 absorption by a superoxide configuration was advanced in this work. The rate limiting factors for O_2 generation and CO_2 absorption consisted of a gas film resistance and a diffusion resistance into the solid superoxide. The gas film resistance was shown to be decreased by increasing flow or velocity through the configuration. The diffusion resistance of the solid was shown to be decreased, especially for CO_2 absorption by increasing temperatures. These factors were integrated into performance correlations.

Correlation of results was obtained by application of mass tranfer equations. For O_2 generation, the superoxide was considered on its moisture absorption properties. Both O_2 generation and CO_2 absorption correlations were represented as a height of a transfer unit versus mass flow rate to effect the desired mass exchange. The correlation equations provide a method of calculating configuration performance and assist the analysis of the effects of ambient pressure and O_2/N_2 balance.

Chemical methods to accelerate reactions and improve performance were studied. The addition of $CuOCl_2$ proved to be beneficial in short 2-hour and 4-hour mission configurations but offered no advantage in longer mission configuration designs. Additions of lithium and sodium hydroxides and peroxides to the superoxide to give more CO_2 absorption capability were of no apparent value.

No design advantages are offered by NaO_2 over KO_2 in solid superoxide configurations. The NaO_2, even when pressed harder than the KO_2, does not have equivalent structural strength and the performance is not as good because of decreased porosity.

Densification had more adverse effects on performance than benefits to be gained in volume savings. In one case a disc configuration volume of 4120 cm^3 had a density of 0.88 g/cm^3 when the discs were pressed at 120 Kg/cm^2: when pressed at 320 Kg/cm^2 the density was 1.01 g/cm^3. In the latter case O_2 generation decreased 45% and the CO_2 absorption decreased 40%. Both disc and plate-type configurations showed poorer performance with increased densification.

High humidity decreased performance in the absorption of CO_2 more than generation of O_2. Swelling of the superoxide forms occurred to a greater degree at the higher humidities than at lower humidities. This swelling constricted the flow area and decreased the flow rate.

Reduced pressure and combination of O_2/N_2 balance had no serious effects on configuration performance. If mass flow rate is maintained at a lower pressure comparable performance will be obtained. Theoretically, at the same partial pressure of CO_2, absorption at a lower total pressure should be somewhat greater than that at a higher pressure since the inert gas is less concentrated. In the few pressure reduced tests made, O_2 generation was comparable to that at ambient pressure and there was a slight decrease in CO_2 absorption. There is evidence that mass flow was somewhat lower than measured.

Recommendations

For short mission configurations, optimization approaching theoretical amounts of superoxides becomes increasingly difficult to attain. Chemical additives of the catalytic type offer some improvement, but the primary factor is to increase surface area. Since solid forms have a limiting surface-to-volume ratio and must retain some thickness for structural rigidity, the use of granules is indicated to increase surface exposure. Deviation from solid configurations and study of granular forms to obtain adequate CO_2 control for short mission designs is recommended. Granular forms were examined in a test to characterize KO_2 made from different fluff starting materials; however, no further granular tests were made since the work was to investigate only solid forms. Designs encompassing granular forms of superoxide and granular type of driers and CO_2 absorbers in combination would be of interest.

Scale up of configuration designs to service more than one man is recommended for further study. Testing designs for several men would extend the correlation plots presented in this report.

More work at reduced pressure would extend the information of superoxide for application to back-pack service or in transfer modules. More extensive testing should be performed to fully determine effects of rarified atmospheres and inert gases other than nitrogen.

High humidity causes swelling of the superoxide configurations, and decreases flow. This effect is minimized by using solid shapes, rather than granules. Whether the high humidity or decrease flow harms configuration performance was not fully ascertained. Tests made at constant flow rate would determine if crusting of the superoxide surfaces is the major impediment.

APPENDIX

CONFIGURATION TEST DATA

CONFIGURATION TEST DATA

Simulation: 1.12 SCFH O_2; 0.896 SCFH CO_2; 0.1 lb m/hr H_2O

Test Chamber: Pressure - 1 Atm.
Atmosphere - Air

Test No.	1	2	3	4	5	6	7
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	238	238	238	238	238	238	238
- Specific Gravity	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Run Time (hr)	13	12	12	7	7	24	6
Chemical Configuration	Disc	Plate	Plate	Disc	Disc	Disc	Disc
Dimensions (cm)	7 x 0.63	6.3 x 11.4 x 0.63	6.3 x 11.4 x 0.63	7 x 0.63	7 x 0.63	14.5 x 0.63	38 x 2.2
Pressure to Form (Kg/sq cm)	1430	650-750	650-750	830	1430	390	580
Number of Shapes Used	175	60	60	60	60	50	1
Total Chemical Weight (g)	4103	2344	2458	1336	1348	3926	3320
Total Surface Area (sq cm)	15,800	11,450	11,150	5420	5420	17,600	7300
Chemical Bed Length (cm)	106.7	11.4	76.2	40.1	36.8	32.5	2.3
Housing - Free Flow Area (sq cm)	46.3	242.0	36.2	46.3	46.3	183	1200
Flow Area, Total* (sq cm)	12.2	54.7	27.9	12.2	12.2	19.7	83.3
Residence Time (sec.)	0.3	0.1	0.1	0.1	0.1	0.1	0.04
Final O_2 Concentration (%)	16.5	18.0	17.2	18.3	16.0	16.0	17.0
Final CO_2 Concentration (%)	4.4	3.3	2.2	3.6	3.4	2.6	2.6
Chamber Volume (liters)	3680	3680	3680	3680	3680	3680	3680
Flow Rate (liters/min.)							
Start	27.0	26.2	29.2	25.6	28.3	27.6	26.8
End	24.8	20.3	15.5	25.6	27.3	23.9	22.5
Chemical Analysis							
O_2 Evolved, liters (STP)	392.0	396.0	398.5	243.0	132.6	75.8	114.0
CO_2 Absorbed, liters (STP)	206.5	209.5	196.5	87.5	70.8	54.8	83.0
O_2 Efficiency (%)	40.0	71.0	68.0	59.0	41.5	81.0	15.1
RQ	0.5	0.5	0.5	0.4	0.5	0.7	0.7
Ave. O_2 Pro. Rate, liters/hr (STP)	30.2	30.2	33.1	34.9	19.0	31.7	19.0
Ave. CO_2 Abs. Rate, liters/hr (STP)	15.8	17.5	16.4	12.4	10.1	22.8	13.6

*Crossectional Area of Canister Perpendicular to Flow.

Test No.	8A	8B	8C	8D	8E	8F
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	232	234	227	239	231	238
- Specific Gravity	0.5	0.42	0.45	0.32	0.42	0.20
Run Time (hr)	6	6	6	6	6	6
Chemical Configuration	Granules	Granules	Granules	Granules	Granules	Granules
Dimensions (cm)	2-4 Mesh	2-4 Mesh	2-4 Mesh	2-4 Mesh	2-4 Mesh	2-4 Mesh
Pressure to Form (Kg/sq cm)	580	580	580	580	580	580
Number of Shapes Used	---	---	---	---	---	---
Total Chemical Weight (g)	1000	1000	1000	1000	1000	1000
Total Surface Area (sq cm)	---	---	---	---	---	---
Chemical Bed Length (cm)	9.2	7.9	9.2	10.2	9.9	9.2
Housing - Free Flow Area (sq cm)	183	183	183	183	183	183
Flow Area, Total (sq cm)	---	---	---	---	---	---
Residence Time (sec.)	0.38	0.34	0.31	0.39	0.39	0.35
Final O_2 Concentration (%)	18.0	16.9	17.0	17.3	18.0	17.0
Final CO_2 Concentration (%)	2.19	2.61	2.23	2.49	1.83	2.01
Chamber Volume (liters)	3680	3680	3680	3680	3680	3680
Flow Rate (liters/min.)						
Start	255	263	266	269	263	260
End	216	204	198	170	105	184
Chemical Analysis						
O_2 Evolved, liters (STP)	152.4	136.3	143.0	135.3	154.8	162.4
CO_2 Absorbed, liters (STP)	92.8	83.8	103.3	88.0	111.2	94.8
O_2 Efficiency (%)	65.8	58.5	63.0	56.6	66.9	68.2
RQ	0.63	0.61	0.72	0.65	0.72	0.59
Ave. O_2 Pro. Rate, liters/hr (STP)	25.5	22.7	23.9	22.6	25.8	27.0
Ave. CO_2 Abs. Rate, liters/hr (STP)	16.0	14.0	17.2	14.6	18.8	15.8

Test No.	9	10	11	12	13	14
Chemical	KO_2	KO_2	NaO_2	KO_2-NaO_2	KO_2	NaO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	239	282	246	239	224
- Specific Gravity	0.32	0.33	---	---	0.33	---
Run Time (hr)	49	8	8	8	8	5.5
Chemical Configuration	Disc	Plate	Plate	Plate	Plate	Plate
Dimensions (cm)	14.5 x 0.63	6.3 x 11.4 x 0.63	6.3 x 11.4 x 0.63	6.3 x 11.4 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	390	650-750	650-750	650-750	650	650
Number of Shapes Used	100	40	36	40	37	19
Total Chemical Weight (g)	7860	1417	1401	1501	1638	976
Total Surface Area (sq cm)						
Chemical Bed Length (cm)	66	11.4	11.4	11.4	10.2	10.2
Housing - Free Flow Area (sq cm)	183	161.5	161.5	161.5	232	142
Flow Area, Total (sq cm)	19.7	35.5	35.5	35.5	65.2	24.2
Residence Time (sec.)	0.28	0.09	[illegible]	0.09	0.17	0.08
Final O_2 Concentration (%)	19.0	17.0	19.8	19.0	20.0	29.0
Final CO_2 Concentration (%)	2.16	2.13	1.62	1.41	1.23	3.09
Chamber Volume (liters)	3680	3680	3680	3680	3680	3680
Flow Rate (liters/min.)						
Start	275	255	277	277	257	180
End		161	71	91	[illegible]	---
Chemical Analysis						
O_2 Evolved, liters (STP)	1827.0	248.0	371.0	270.0	246.0	199.0
CO_2 Absorbed, liters (STP)	1263.0	152.7	167.5	136.0	159.6	104.3
O_2 Efficiency (%)	97.2	72.8	93.8	73.0	60.0	91.0
RQ	0.7	0.62	0.45	0.51	0.68	0.53
Ave. O_2 Pro. Rate, liters/hr (STP)	37.3	30.8	46.4	33.7	29.4	36.2
Ave. CO_2 Abs. Rate, liters/hr (STP)	26.0	19.1	20.8	16.9	20.0	18.9

Test No.	15	16	17	18	19	20
Chemical	KO_2 and 1% $CuOCl_2$	KO_2 and 3.5% Li_2O_2	KO_2, 1% $CuOCl_2$ and 10% Li_2O_2	KO_2 and asbestos fibers	KO_2 and 1/2% $CuOCl_2$	KO_2, 1/2% $CuOCl_2$ and 2.5% LiCl
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	239	239	239	239	239
- Specific Gravity	0.33	0.33	0.33	0.33	0.33	0.33
Run Time (hr)	2	2	2	2	2	2
Chemical Configuration	Plate	Plate	Plate	Plate	Plate	Plate
Dimensions (cm)	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	650	650	650	650	650	650
Number of Shapes Used	7	7	7	8	8	8
Total Chemical Weight (g)	359	327	267	358	363	326
Total Surface Area (sq cm)	1500	1500	1500	1710	1710	1710
Chemical Bed Length (cm)	10.2	10.2	10.2	10.2	10.2	10.2
Housing - Free Flow Area (sq cm)	90.5	90.5	80.5	80.5	80.5	80.5
Flow Area, Total (sq cm)	17.0	17.0	16.8	19.4	19.4	19.4
Residence Time (sec.)	0.04	0.06	0.04	0.05	0.05	0.04
Final O_2 Concentration (%)	17.0	11.5	14.0	15.0	18.0	16.0
Final CO_2 Concentration (%)	2.82	4.8	2.67	2.04	2.07	2.52
Chamber Volume (liters)	212	212	212	212	212	212
Flow Rate (liters/min.)						
Start	274	187	255	221	224	283
End	204	167	255	221	309	331
Chemical Analysis						
O_2 Evolved, liters (STP)	55.2	53.5	47.6	46.7	51.3	50.7
CO_2 Absorbed, liters (STP)	35.9	33.7	33.4	35.1	30.0	34.5
O_2 Efficiency (%)	65.0	68.5	75.0	54.8	59.2	65.0
RQ	0.65	0.63	0.7	0.75	0.59	0.68
Ave. O_2 Pro. Rate, liters/hr (STP)	27.3	26.5	23.8	23.4	25.7	25.4
Ave. CO_2 Abs. Rate, liters/hr (STP)	18.0	16.9	16.7	17.6	15.0	17.3

Test No.	21	22	23	24	25	26
Chemical	KO_2 and 5% LiOH	KO_2 and 5% MnO_2	KO_2 and 5% LiCl	NaO_2	NaO_2 and 20% Li_2O_2	KO_2, 1% $CuOCl_2$ and 19% Li_2O_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	239	239	--	--	239
- Specific Gravity	0.33	0.33	0.33	--	--	0.33
Run Time (hr)	2	2	2	2	2	2
Chemical Configuration	Plate	Plate	Plate	Plate	Plate	Plate
Dimensions (cm)	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	650	650	650	1090	1090	650
Number of Shapes Used	8	8	8	8	8	8
Total Chemical Weight (g)	331	345	342	473	397	431
Total Surface Area (sq cm)	1710	1710	1710	1710	1710	1710
Chemical Bed Length (cm)	10.2	10.2	10.2	10.2	10.2	10.2
Housing - Free Flow Area (sq cm)	80.5	80.5	80.5	80.5	80.5	80.5
Flow Area, Total (sq cm)	19.4	19.4	19.4	19.4	19.4	19.4
Residence Time (sec.)	0.05	0.05	0.05	0.05	0.05	0.04
Final O_2 Concentration (%)	13.0	17.0	16.5	14.8	15.2	17.5
Final CO_2 Concentration (%)	5.9	1.97	2.47	3.39	2.97	3.49
Chamber Volume (liters)	212	212	212	212	212	212
Flow Rate (liters/min.)						
Start	261	233	224	233	255	269
End	258	224	247	82	193	218
Chemical Analysis						
O_2 Evolved, liters (STP)	35.6	54.1	37.3	57.1	54.6	48.4
CO_2 Absorbed, liters (STP)	15.8	32.6	17.5	35.4	33.4	29.3
O_2 Efficiency (%)	44.7	68.6	48.2	43.4	51.2	60.6
RQ	0.47	0.6	0.47	0.62	0.61	0.6
Ave. O_2 Pro. Rate, liters (STP)	17.8	27.1	18.7	28.6	27.3	24.2
Ave. CO_2 Abs. Rate, liters (STP)	8.0	16.3	8.9	17.7	16.7	14.7

Test No.	27	28	29	30	31	32*
Chemical	KO_2 and 5% $KMnO_4$	KO_2 Blends	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	239	239	239	239	239
- Specific Gravity	0.33	0.33	0.33	0.33	0.33	0.33
Run Time (hr)	2	4	4	[illegible]	8	1
Chemical Configuration	Plate	Plate	Plate	Plate	Disc	Disc
Dimensions (cm)	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	9.5 x 0.63	9.5 x 0.63
Pressure to Form (Kg/sq cm)	610	610	510, 1020 and 1540	41[illegible]	610	610
Number of Shapes Used	8	16	16	16	35	10
Total Chemical Weight (g)	317	792	752	748	1173.6	334.6
Total Surface Area (sq cm)	1730	3440	3440	3440	5350	1525
Chemical Bed Length (cm)	10.2	10.2	10.2	10.2	22.9	6.4
Housing - Free Flow Area (sq cm)	51.7	103.4	103.4	51.7	80.6	80.6
Flow Area, Total (sq cm)	19.4	38.8	38.8	19.4	13.4	13.4
Residence Time (sec.)	0.04	0.09	---	0.09	0.2	---
Final O_2 Concentration (%)	16	14	18.6	18	19.5	19
Final CO_2 Concentration (%)	5.3	3.8	2.67	5.88	1.67	3.03
Chamber Volume (liters)	212	212	212	212	3680	73.5
Flow Rate (liters/min.)						
Start	410	278	326	258	225	---
End	311	291	379	162	166	---
Chemical Analysis						
O_2 Evolved, liters (STP)	41.0	110.0	100.0	119.0	184.0	26.9
CO_2 Absorbed, liters (STP)	22.4	72.5	58.5	72.5	105.0	14.2
O_2 Efficiency (%)	57.0	61.5	55.8	66.4	65.5	33.5
RQ	0.52	0.66	0.58	0.61	0.57	0.53
Ave. O_2 Pro. Rate, liters/hr (STP)	20.7	27.5	25.2	29.7	22.9	26.9
Ave. CO_2 Abs. Rate, liters/hr (STP)	10.8	18.[illegible]	14.7	18.2	13.0	14.2

*Man Test

Test No.	33	34*	35**	36	37	38
Chemical	KO_2	KO_2, Na_2O_2 NaO_2	KO_2	KO_2	KO_2	NaO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	239	239	239	239	
- Specific Gravity	0.33	0.33	0.33	0.33	0.33	
Run Time (hr)	8	2.5	2	8	2.3	4
Chemical Configuration	Disc	Disc	Disc	Disc	Discs	Rippled Plates
Dimensions (cm)	9.5 x 0.63	10.2 x 10.2 x 0.63	9.5 x 0.63	7 x 0.63	9.5 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	610	610	610	610	610	1090
Number of Shapes Used	35	14	20	54	30	13
Total Chemical Weight (g)	1178.5	767.3	667.3	1199.6	1000.8	896.8
Total Surface Area (sq cm)	5360	3010	3050	4880	4520	2780
Chemical Bed Length (cm)	22.9	10.2	12.7	35.6	19.1	10.2
Housing - Free Flow Area (sq cm)	80.6	103.5	80.6	45.2	80.8	103.3
Flow Area, Total (sq cm)	9.7	34.0	13.3	12.2	13.3	31.6
Residence Time (sec.)	0.2	0.04	---	0.23	---	0.07
Final O_2 Concentration (%)	19	24	22	18.5	22	11.5
Final CO_2 Concentration (%)	2.16	1.7	2.37	2.67	2.16	5.8
Chamber Volume (liters)	3680	212	73.5	3680	73.5	212
Flow Rate (liters/min.)						
Start	245	484	---	305	---	317
End	243	458	---	283	---	263
Chemical Analysis						
O_2 Evolved, liters (STP)	178	83.6	70.8	1545	125	125
CO_2 Absorbed, liters (STP)	94.2	49.8	34.5	81.2	48.7	71.2
O_2 Efficiency (%)	63.1	47.4	44.4	53.8	40.8	49.8
RQ	0.53	0.59	0.49	0.51	0.46	0.55
Ave. O_2 Pro. Rate, liters/hr (STP)	22.1	15.3	35.4	19.3	42.4	31.4
Ave. CO_2 Abs. Rate, liters/hr (STP)	11.9	9.1	17.3	9.9	20.4	17.3

* After 2.5 hr, CO_2 Concentration exceeded 6% (Recorder off scale) Simulator turned off. Configuration tested additional 3 hr. Total test period 5.5 hr.

** Man Test. Fan used, flow at 250 liters/min.

Test No.	39	40	41	42	43	44
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	239	232	232	232	232	232
- Specific Gravity	0.33	0.33	0.33	0.33	0.33	0.33
Run Time (hr)	8	26.5	4	4	4	4
Chemical Configuration	Plates	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	25	95	16	18	18	18
Total Chemical Weight (g)	1159.4	3895.2	702.4	744.7	765.6	749.4
Total Surface Area (sq cm)	5360	20,350	3440	3870	3870	3870
Chemical Bed Length (cm)	30.5	61.0	20.3	30.5	30.5	33.0
Housing - Free Flow Area (sq cm)	51.7	103.3	51.7	38.8	38.8	38.8
Flow Area, Total (sq cm)	19.4	38.8	19.4	14.5	14.5	7.7
Residence Time (sec.)	0.16	0.55	0.09	0.1	0.29	0.3
Final O_2 Concentration (%)	20	24	12, 21	20	22.5	24
Final CO_2 Concentration (%)	1.95	0.87	2.49, 0.15	2.75	1.5	1.6
Chamber Volume (liters)	3680	3680	212	212	212	212
Flow Rate (liters/min.)						
Start	247	273	283	272	91	86
End	188	136	252	297	128	93
Chemical Analysis						
O_2 Evolved, liters (STP)	186.3	92.6	250.5	116.7	115.4	
CO_2 Absorbed, liters (STP)		570	75	79.7	78.5	82.6
O_2 Efficiency (%)	67.4	98.2	62.7	67.8	65.0	73.2
RQ	0.53	0.62	0.68	0.66	0.66	0.65
Ave. O_2 Pro. Rate, liters/hr (STP)	23.3	33.6	25.5	29.1	28.8	31.7
Ave. CO_2 Abs. Rate, liters/hr (STP)	12.5	20.7	17.3	19.3	19.0	20.7

Test No.	45	46	47	48	49	50
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	204	232	232	174	232	232
- Specific Gravity	0.33	0.33	0.33	0.33	0.33	0.33
Run Time (hr)	4	4	4	4	4	4
Chemical Configuration	plates	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	21	21	21	18	18	12
Total Chemical Weight (g)	853.6	884.9	901.0	788.8	766.3	607.0
Total Surface Area (sq cm)	4520	4520	4520	3870	3870	2870
Chemical Bed Length (cm)	30.5	30.5	30.5	38.1	38.1	15.2
Housing - Free Flow Area (sq cm)	51.7	45.2	45.2	38.8	38.8	58.2
Flow Area, Total (sq cm)	19.4	19.4	19.4	19.4	19.4	14.2
Residence Time (sec.)	0.4	0.4	0.4	0.2	0.1	0.12
Final O_2 Concentration (%)	20	28	30	18	25	18
Final CO_2 Concentration (%)	2.2	1.6	1.6	3.1	1.9	2.3
Chamber Volume (liters)	212	212	212	212	212	212
Flow Rate (liters/min.)						
Start	117.0	119.0	109.6	189.6	247.0	221.0
End	104.5	93.4	79.0	204.5	272.0	181.2
Chemical Analysis						
O_2 Evolved, liters (STP)	111.0	137.4	139.0	86.8	114.5	111.1
CO_2 Absorbed, liters (STP)	78.3	83.8	94.0	83.2	74.7	82.1
O_2 Efficiency % - total	64.0	67.0	67.0	63.0	64.0	79.0
% - inlet bed	54.0	55.0	61.0	64.0	76.0	84.0
% - middle bed	66.0	69.0	68.0	72.0	64.0	--
% - outlet bed	72.0	77.0	71.0	54.0	53.0	74.0
RQ - total	0.7	0.61	0.62	0.96	0.65	0.74
- inlet total	0.61	0.5	0.56	0.92	0.69	0.76
- middle bed	0.71	0.64	0.64	0.9	0.67	
- outlet bed	0.77	0.67	0.64	1.1	0.59	0.72
Ave. O_2 Pro. Rate, liters/hr (STP)	27.7	34.2	34.8	21.8	28.6	27.7
Ave. CO_2 Abs. Rate, liters/hr (STP)	19.5	20.9	23.5	20.9	18.7	20.4

Test No.	51	52	53	54	55	56
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	232	242	242	242	242	242
- Specific Gravity	0.33	0.38	0.38	0.38		
Run Time (hr)	4	8	8	4	1 1/2	8
Chemical Configuration	Plates	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	12	24	24	12	8	24
Total Chemical Weight (g)	607.8	1222.6	1229.6	605.5	394	1198
Total Surface Area (sq cm)	2870	5730	5730	2870	1910	5730
Chemical Bed Length (cm)	15.2	30.5	30.5	15.2	15.2	30.4
Housing - Free Flow Area (sq cm)	58.2	58.2	58.2	58.2	38.7	58.1
Flow Area, Total (sq cm)	14.2	14.2	14.2	14.2	14.5	4.8
Residence Time (sec.)	0.1	0.3	0.3	0.15	0.34	---
Final O_2 Concentration (%)	15	20	18	12	20.8	19
Final CO_2 Concentration (%)	2.5	1.7	2.9	6	1.5	0.96
Chamber Volume (liters)	212	3680	3680	212	212	3680
Flow Rate (liters/min)						
Start	272	176	180	179	227	356
End	320	204	198	74	148	334
Chemical Analysis						
O_2 Evolved, liters (STP)	101	193	173	89.4	50.1	199.5
CO_2 Absorbed, liters (STP)	76.4	109.3	97.6	63.7	20.9	85.2
O_2 Efficiency % - Total	72	65	58	61	52.3	69.0
% - inlet bed	52	48	52	47	---	63.5
% - middle bed	---	78	59	---	---	---
% - outlet bed	90	88	69	72	---	74
RQ - Total	0.76	0.57	0.59	0.71	0.42	0.43
- inlet bed	0.9	0.43	0.51	0.58	---	0.32
- middle bed	---	0.61	0.6	---	---	---
- outlet bed	0.68	0.66	0.66	0.79	---	0.52
Ave. O_2 Pro. Rate, liters/hr (STP)	25.2	24.1	21.5	22.4	---	24.9
Ave. CO_2 Abs. Rate, liters/hr (STP)	19.3	13.6	12.2	15.9	---	11.3

Test No.	57	58*	59	60	61	62
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	242	242	242	242	242	242
- Specific Gravity	--	--	0.38	0.38	0.38	0.3
Run Time (hr)	6 3/4	2 5/6	4	3	2	4
Chemical Configuration	Plates	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	24	16	15	12	10	19
Total Chemical Weight (g)	1210	782	623	488	423	774
Total Surface Area (sq cm)	5730	3820	3580	2870	2390	4540
Chemical Bed Length (cm)	30.4	60.8	15.2	30.4	30.4	30.4
Housing - Free Flow Area (sq cm)	58.1	38.7	72.7	43.6	32.3	29.1
Flow Area, Total (sq cm)	14.5	4.8	25.8	25.8	19.4	14.5
Residence Time, (sec.)	0.34	---	0.18	0.26	0.16	0.3
Final O_2 Concentration (%)	20.8	19.0	18.0	18.0	14.3	20.0
Final CO_2 Concentration (%)	1.5	0.96	3.84	4.5	>6.0	1.23
Chamber Volume (liters)	3680	73	212	212	212	212
Flow Rate (liters/min.)						
Start	111	---	105	181	164	104
End	91.4	---	125	189	170	85
Chemical Analysis						
O_2 Evolved, liters (STP)	212	91	113.3	76.5	35.1	104.8
CO_2 Absorbed, liters (STP)	105	51.4	75.8	46.4	17	43.2
O_2 Efficiency (%)	72.5	48.2	75	65	34.6	56
RQ	0.5	0.56	0.67	0.61	0.49	0.41
Ave. O_2 Pro. Rate, liters/hr (STP)	31.4	32.3	28.3	25.5	17.6	26.4
Ave. CO_2 Abs. Rate, liters/hr (STP)	15.6	18.1	19	22.9	8.5	10.8

* Man Test with Breathing Bag.

Test No.	63	64	65	66	67*	68
Chemical	KO_2 and 25% LiOH	KO_2	KO_2	KO_2, 25% LiOH and 1/2% $CuOCl_2$	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	242	242	242	242	242	242
- Specific Gravity	0.38	0.38	0.38	0.38	0.38	0.38
Run Time (hr)	4	4	8	4	8	24
Dimensions (cm)	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	20	20	39	24	39	81
Total Chemical Weight (g)	815	823	1581	978	1588	4096
Total Surface Area (sq cm)	4780	4780		5730	9230	19,170
Chemical Bed Length (cm)	30.4	30.4	42.7	30.4	42.7	61.0
Housing - Free Flow Area (sq cm)	29.1	29.1	58.1	58.1	58.1	96.9
Flow Area, Total (sq cm)	14.5	14.5	19.4	19.4	22.6	32.3
Residence Time (sec.)	0.15	0.12	0.38	0.32	0.2	1.29
Final O_2 Concentration (%)	16.8	19.3	21.2	25.8	---	22.5
Final CO_2 Concentration (%)	2.25	4.59	0.93	1.32	---	2.01
Chamber Volume (liters)	212	212	3680	212	3680	3680
Flow Rate (liters/min.)						
Start	167	198	167	175	133	91
End	206	300	---	184	142	85
Chemical Analysis						
O_2 Evolved, liters (STP)	137.6	139.8	287.5	171.1	254.6	848
CO_2 Absorbed, liters (STP)	73.7	86.1	158.6	93.2	67.8	468
O_2 Efficiency (%)	82.4	70.2	75.0	85.4	64.8	85.6
RQ	0.54	0.63	0.55	0.54	0.27	0.55
Ave. O_2 Pro. Rate, liters/hr (STP)	34.5	34.8	35.9	35.7	31.1	35.4
Ave. CO_2 Abs. Rate, liters/hr (STP)	18.4	21.5	19.8	23.2	8.5	19.6

* Test conducted at reduced pressure 1/2 atm. (~380 mm Hg).

Test No.	69	70	71	72	73*	74
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	242	242	236	236	236	236
- Specific Gravity	0.33	0.3	0.29	0.29	0.29	0.29
Run Time (hr)	24	24	8	8	8	8
Chemical Configuration	Discs	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	7 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	10.2 x 10.2 x 0.63	7.6 x 15.2 x 0.63	10.2 x 10.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	180	96	39	36	39	39
Total Chemical Weight (g)	3646	4132	1290	1552	1575	1662
Total Surface Area (sq cm)	2520	3185	1706	1194	1443	1290
Chemical Bed Length (cm)	106.7	61	30.5	10.2	45.7	30.5
Housing - Free Flow Area (sq cm)	45.8	103	103	232	58.1	103
Flow Area, Total (sq cm)	12.2	38.7	31.5	87.2	21.0	31.5
Residence Time (sec.)	0.31	1	0.23	0.14	0.23	0.23
Final O_2 Concentration (%)	21	25.7	22	21.8	24	22
Final CO_2 Concentration (%)	1.86	1.89	2.13	2.19	1.08	1.07
Chamber Volume (liters)	3680	3680	3680	3680	3680	3680
Flow Rate (liters/min.)						
Start	249	150	246	377	170	246
End	113	150	187	377	218	170
Chemical Analysis						
O_2 Evolved, liters (STP)	751.3	908.3	225.2	242.6	274.3	221.1
CO_2 Absorbed, liters (STP)	409.9	495.6	86.6	93.9	134.5	85.2
O_2 Efficiency (%)	86.2	93.1	60.0	66.4	74.0	56.4
RQ	0.55	0.55	0.38	0.39	0.49	0.39
Ave. O_2 Pro. Rate, liters/hr (STP)	31.4	37.9	28.3	30.3	34.2	27.8
Ave. CO_2 Abs. Rate, liters/hr (STP)	17.0	20.7	10.8	11.6	17.0	10.8

* Reduced pressure test at 1/2 atm. (380 mm Hg).

Test No.	75	76	77*	78*	79*	80**
Chemical	KO_2	KO_2	KO_2	KO_2	KO_2 and 1/2% $CuOCl_2$	KO_2
KO_2 Fluff - Avail. O_2, cc/g (STP)	236	236	236	236	236	236
- Specific Gravity	0.29	0.29	0.29	0.29	0.29	0.29
Run Time (hr)	48	24	8	4	4	8
Chemical Configuration	Discs and Plates	Discs	Plates	Plates	Plates	Plates
Dimensions (cm)	14.5 x 0.63 and 7.6 x 15.2 x 0.63	9.5 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	545	545	545	545
Number of Shapes Used	130	110	40	20	20	40
Total Chemical Weight (g)	7866	3904	1720	824	804	1616
Total Surface Area (sq cm)	6250	2590	1468	740	740	1483
Chemical Bed Length (cm)	91.5	68.6	30.5	30.5	30.5	30.5
Housing - Free Flow Area (sq cm)	182.5 and 97.0	78.2	87.2	43.9	43.9	97.0
Flow Area, Total (sq cm)	19.7 and 38.7	94.4	32.3	16.1	16.1	32.3
Residence Time (sec.)	0.64	0.14	0.1	0.1	0.09	0.15
Final O_2 Concentration (%)	24.3	23.6	22.6	22.6	22.1	52
Final CO_2 Concentration (%)	2.1	2.88	1.38	0.96	0.75	1.44
Chamber Volume (liters)	3680	3680	3680	3680	3680	3680
Flow Rate (liters/min.)						
Start	283	269	243	297	329	388
End	408	147	108	133	218	470
Chemical Analysis						
O_2 Evolved, liters (STP)	1440	700	278	92.6	148.7	237.4
CO_2 Absorbed, liters (STP)	821.8	363.5	104.4	32.1	53.0	117.1
O_2 Efficiency (%)	77.6	76.1	68.7	47.7	78.3	62.2
RQ	0.57	0.52	0.38	0.55	0.36	0.45
Ave. O_2 Pro. Rate, liters/hr (STP)	30	29.2	34.8	23.2	37.4	29.7
Ave. CO_2 Abs. Rate, liters/hr (STP)	17.3	15.3	13.3	7.7	13.3	14.7

* Reflux test to preheat inlet flow stream.

** Reduced pressure test at 1/2 atm. (~380 mm Hg) and 50% O_2/50% N_2 ratio.

Test No.	81*	82*	83*	84*	85*
Chemical	KO_2	KO_2 with 1% $KMnO_4$	NaO_2 with 1% $CuOCl_2$	KO_2 with 1% $CuOCl_2$	KO_2 with 1% $CuOCl_2$
KO_2 Fluff - Avail. O_2, cc/g (STP)	236	236	280	236	236
- Specific Gravity	0.31	0.31		0.31	0.31
Run Time (hr)	24	2	2	2	2
Chemical Configuration	Plates	Plates	Plates	Plates	Plates
Dimensions (cm)	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63	7.6 x 15.2 x 0.63
Pressure to Form (Kg/sq cm)	545	545	750	510	545
Number of Shapes Used	100	12	12	12	12
Total Chemical Weight (gm)	4195	495	481	474	474
Total Surface Area (sq cm)	23,700	2840	2840	2840	2840
Chemical Bed Length (cm)	61	15.2	15.2	15.2	7.6
Housing - Free Flow Area (sq cm)	116.3	48.4	48.4	48.4	96.8
Flow Area, Total (sq cm)	40.3	19.4	19.4	19.4	38.8
Residence Time (sec.)	0.75	0.1	0.05	0.05	0.05
Final O_2 Concentration (%)	28.0	23.1	23.1	21.9	21.1
Final CO_2 Concentration (%)	1.2	1.05	0.87	0.87	0.99
Chamber Volume (liters)	3680	3680	3680	3680	3680
Flow Rate (liters/min.)					
Start	241	306	332	425	346
End	150	88	396	346	351
Chemical Analysis					
O_2 Evolved, liters (STP)	907	72.5	72.3	75.6	71.6
CO_2 Absorbed, liters (STP)	490.5	29.7	32.3	40.8	34.8
O_2 Efficiency (%)	91.7	61.2	54.2	68.4	64.6
RQ	0.54	0.41	0.45	0.54	0.49
Ave. O_2 Pro. Rate, liters/hr (STP)	37.7	36.2	36.2	37.9	35.7
Ave. CO_2 Abs. Rate, liters/hr (STP)	20.4	15.0	16.2	20.4	17.6

* Reflux test to preheat inlet flow stream.

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13. ABSTRACT Solid superoxide forms were studied to evolve optimized configuration designs for life support of one man on 2-, 4-, 8-, 24-, and 48-hour space missions. Suitable designs were developed to generate O_2 for these missions, but CO_2 control becomes progressively more difficult as mission time decreases. Optimization for short mission configurations were gained by dynamic flow designs, preheating inlet flow streams, and use of a catalyzing agent. The evolution of available O_2 was as high as 85% for 4-hour mission configurations and as high as 98% for 24-hour missions. The superoxide configurations that have been developed are in plate form as opposed to discs since the former have more efficient O_2 generation and CO_2 absorption characteristics. This was the effect of flow orientation rather than specific shape, per se. The configurations feature rippled superoxide plates, which, when packaged, achieve a 20% increase in bulk density over granules, and a lower pressure drop, thereby minimizing fan power. Heat generated by the superoxide reaction was utilized in the following manner: the inlet flow stream was preheated by refluxing a part of the outlet stream with it. This technique increased performance of the inlet portion of the superoxide bed. Mass transfer correlations were developed to describe the mechanics of the reactions. Effects of humidity, reduced pressure, O_2/N_2 balance and densification of solid forms on the mass transfer behavior of the superoxide configurations are described.

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	ROLE	WT	ROLE	WT	ROLE	WT
Carbon Dioxide Removal Oxygen production Water Vapor removal potassium superoxide Sodium superoxide Atmosphere control						

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