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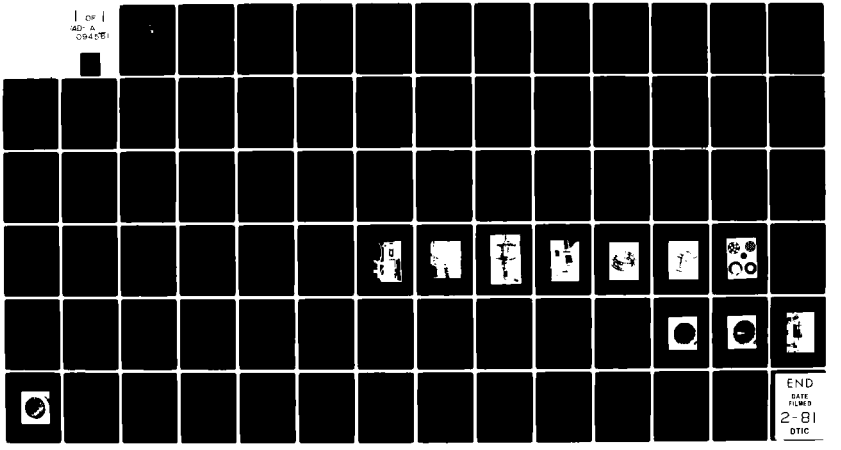

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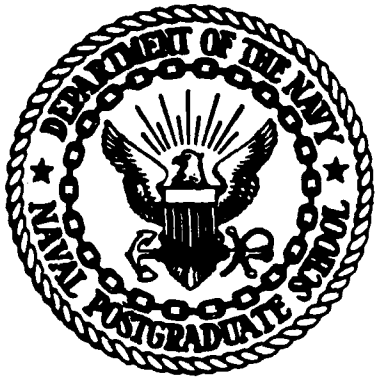

THESIS

The Effect of Canister Geometry on the Effectiveness of Removing Carbon Dioxide with a Constant Mass of Soda Lime

by

Peter Eric Louden

December 1980

Thesis Advisor: P. F. Pucci

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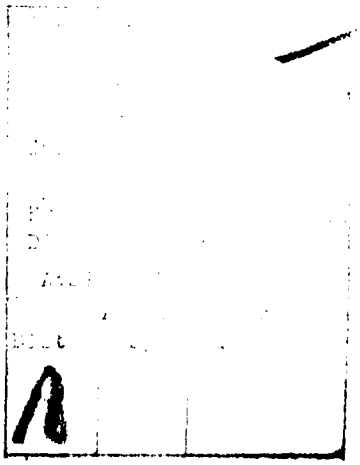

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The Effect of Canister Geometry on the Effectiveness of Removing Carbon Dioxide with a Constant Mass of Soda Lime

by

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ABSTRACT

An investigation was conducted of the effect of canister geometry on the effectiveness of a constant mass of a commercial soda lime, Sodasorb, to absorb carbon dioxide from a mixture of carbon dioxide and air. A comparison of cylindrical canisters with length-to-diameter ratios of 0.15, 0.29, 0.44, 0.80, 1.16, and 2.125 was completed with a constant mass of three pounds of Sodasorb. Annular ring baffles and disk baffles were employed to get a more evenly distributed usage of the Sodasorb with the results compared to the 'straight' through type canisters for the above L/D ratios. A steady flow rate of approximately 2.1 SCFM of saturated air with six percent carbon dioxide at one atmosphere and environment temperature of 70 degrees F was used. It was found that annular ring baffles and disk baffles increased the effectiveness significantly.

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NOMENCLATURE

English Letter Symbols

A_c	Canister cross-sectional area.
D	Inside diameter of the canister.
d_i	Inside diameter of a ring.
d_o	Outside diameter of a disk.
f	Dimensionless Fanning friction factor.
$\sqrt{k}$	Characteristic flow dimension, square root of permeability of the porous media bed.
L	Length of the Sodasorb bed in the canister.
P	Pressure.
Q	Volumetric flow rate.
R	Gas constant.
Re	Reynolds number.
$t_{½}$	Time to reach 0.5 percent carbon dioxide by volume in the effluent gas of the canister. A measure of the absorbent's effectiveness.
V_c	Superficial velocity for the porous media.

GREEK LETTER SYMBOLS

Δ	Difference.
μ	Fluid dynamic viscosity.
ρ	Fluid density.

Subscripts

atm Local atmosphere.

c Canister.

f Flowmeter.

s Standard (temperature and pressure).

Abbreviations

SYM. IDEN. Symbol Identifier for Rings, Disks, and Disks with Holes.

POR Parabaloid of Revolution.

I. INTRODUCTION

The purpose of this investigation is to supplement the collection of data, previously obtained, about the absorption of carbon dioxide from a humidified mixed gas stream for the benefit of the Navy diving community. However, most of the early work done in the field of carbon dioxide absorption was done by persons in the medical profession.

The W. R. Grace Compnay's Sodasorb Manual of Carbon Dioxide Absorption [1][1] states that, "The carbon dioxide absorption technique now universally accepted stems from mine rescue apparatus devised by the German physiologist, Schwann in 1853...Kuhn of Germany revived the idea in 1906, and in 1909 Benedict of England...devised a closed system rebreathing apparatus which employed sodium hydroxide and lime for the absorption of carbon dioxide." R. M. Waters, however, is given the credit for popularizing the technique for surgery starting in 1923. [2]

There are three reasons to utilize a self contained respiratory system for surgery. They are listed below:

a. Cost. The anesthetic agent can not be reused effectively after it has been diluted in the atmosphere;

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[1]Numbers in brackets refer to references listed in the Bibliography.

b. Safety. Most anesthetic agents are flammable and are, therefore, a significant fire and explosion hazard;

c. Safety. The anesthetic agent if released to atmosphere will cause drowsiness among the surgical crew.

A major problem of the self-contained respiratory system is the accumulation of carbon dioxide within the system which, when it reaches 0.5 percent by volume, will cause the onset of the effects hypercapnia, an excess of carbon dioxide in the body tissues, in most patients. [2] This accumulation of carbon dioxide requires the installation of a component that will remove the expired carbon dioxide from the patients recycled breath within the system.

Initially, limewater was employed as the removal agent, but a large amount was required due to the slow reaction rate and low solubility of the calcium hydroxide. Additionally, the pressure drop through the liquid was considered too high to be utilized safely with patients. For diving, one of the early apparatus utilized a canister filled with rope that had been soaked in a caustic potash solution to remove the carbon dioxide from the breathing mixture.

Following this initial work with limewater and caustic potash, several carbon dioxide absorbing chemicals and substances have been tested and used. At present, the principal absorbers are variations of sodalime and barium lime, where sodalime is a mixture of calcium hydroxide and sodium hydroxide, and barium lime is a mixture of the hydroxides of calcium, barium, and sodium.

There is a need within the diving community for divers to breathe 'mixed gasses' such as: air and oxygen, nitrogen and oxygen, helium and oxygen, or other combinations of inert gasses and oxygen, which are very expensive to produce. In diving, the diver is equilibrated to the pressure at his depth and his tidal volume (the volume of air inhaled and exhaled per breath) remains approximately the same at any depth, but each breath will contain a larger percentage of his air supply. Therefore, even though an open type system may be designed for the 'partial pressure of oxygen' type control of his breathing mixture, he would become more time limited with depth. With the closed system, a diver can stay on the job considerably longer than with the open system since only make-up gas is used from his supply tanks. Furthermore, there is a need to have a diver support system which does not allow bubbles to float to the surface for covert type operations. For these and other reasons it was necessary for the Navy diving community to develope and utilize the self-contained recirculating respiratory system where depth and time on the job or covert operations are major concerns.

The size of an entire diver breathing system is limited due to the requirement for portability. Therefore, the determination of characteristics for various absorption canister configurations should assist the Navy in the selection of the appropriate size, geometry, and configuration of the absorption canister so that the canister will meet the size constraints

of the diving improvement programs and still adequately perform the task of carbon dioxide removal.

The Sodasorb for this investigation is of the indicating type utilizing ethyl violet as the exhaustion indicator. Ethyl violet is pH sensitive and remains colorless above a pH of 10.3. Before usage, Sodasorb has a pH essentially of 14, but as the carbon dioxide reacts with the free hydroxyl groups, the pH starts to decrease. When the Sodasorb has turned a deep purple, it has lost its ability to react quickly with carbon dioxide and, therefore, is useless for the purpose intended. Utilizing the patterns of color throughout the Sodasorb bed, one can determine the macroscopic flow paths of the carbon dioxide-air mixture. With this information, various configurations may be utilized in an attempt to divert the flow for more complete utilization of the Sodasorb.

The investigation that Miller [3] conducted varied flow rates (1, 2, and 3 scfm, nominal), length-to-diameter ratios (1.225, 1.6, and 2.125), ambient temperatures (40, 55, and 70 deg F), and carbon dioxide fractions of the inlet gasses (4.0, 6.0, and 8.0 percent by volume). A canister with an inside diameter of four inches was utilized, such that varying the length-to-diameter ratios also varied the mass of Sodasorb utilized. Since varying the mass of Sodasorb also varies the stoichiometric capacity for reaction with the carbon dioxide, it is believed that a constant mass of Sodasorb will produce a more useful correlation of the results. Miller defined

effectiveness as 'the time a given absorption system operates before the exit carbon dioxide reaches one-half percent by volume." Ploss [4] utilized this definition, as did this investigator.

Ploss [4] conducted experiments with two four-inch diameter canisters while varying the characteristics by inserting axial spacers (1 or 2) or annular rings (1, 2, 3, or 4) at regular intervals along the canister. The spacers allowed open spaces of varying length (1/8, 1/4, or 1/2 inch). The annular rings extended from the wall towards the center of the canister one-half inch. The hypothesis that led to these variations in the canister was that channeling occurred during the absorption process. Elam [5] defines channeling as the flow "of expired air along preferential paths of lesser resistance in the absorbent bed..." He, further, states that channeling "decreases the efficiency and reliability of the carbon dioxide absorption." It was postulated that these "preferential paths" occur along the walls of the canister where there is no interlocking of Sodasorb granules. Additionally, he found that the fines of Sodasorb caused channeling by filling voids and blocking flow paths, thus causing flow to occur elsewhere in the canister. Ploss [4] concluded that "channeling does not appear to be a significant factor," since neither the annular rings nor the axial spacers produced a significant improvement in the effectiveness obtained.

It is believed by this investigator that channeling has a considerable affect on the effectiveness of absorption in the lower length-to-diameter ratio cannisters, specifically, and in the higher ratios, probably. Utilizing the indicating type Sodasorb, channeling should be visibly demonstrated in the bed.

Miller [3] passed three nonreacting gasses through the Sodasorb bed and verified that the friction factor relationship developed by Ward [6] is an appropriate model for flow through Sodasorb. Ploss [4] determined pressure drops through Sodasorb using the reacting gas, air with six percent carbon dioxide, and modified the Ward relationship with a new constant that fit the data of the two cannisters that he utilized.

The objectives of this investigation are listed below:

1. Determine the effect of cylindrical canister geometry on the effectiveness of the absorbent bed, specifically, length-to-diameter ratio while holding the mass of Sodasorb constant at three pounds.

2. Determine the effect that annular rings and circular discs, installed as baffles in the canister, have on the effectiveness of the Sodasorb bed by inhibiting the channeling of gasses along the walls of the cannister.

3. Determine the effect of utilizing an 'interlocking cylinder wall' to inhibit channeling.

4. Determine Sodasorb bed absorption characteristics for various canister configurations utilizing the colorations

resulting from the ethyl violet indicator.

5. Compare the pressure drop through the Sodasorb bed with the value predicted utilizing the relationship of Ward, as modified by Ploss, for friction factor.

6. Determine the 'best' configuration for a canister based on the data obtained from the above.

II. SUMMARY OF THEORY

A. CARBON DIOXIDE ABSORPTION PROCESS

Several carbon dioxide absorbing chemicals have been tested and utilized by the anesthesiologists and the Navy, but the alkaline metal and alkaline earth metal hydroxides have been found to be the most practical due to cost, availability, and absorption capacity. They are potassium, sodium, calcium, lithium, and barium with the barium and lithium hydroxides being the most expensive while the sodium and calcium hydroxides are the least costly.

The specific substances utilized by the Navy in recent years have been Baralyme and Sodasorb, where Baralyme is a mixture of barium hydroxide, calcium hydroxide, and potassium hydroxide and Sodasorb is a mixture of calcium hydroxide, sodium hydroxide, and potassium hydroxide. Both substances are registered trademarks and are manufactured by patented processes. Both Baralyme and Sodasorb require a minimum moisture content to effect the carbon dioxide reaction, but the barium hydroxide of Baralyme forms a hydrate which maintains a certain moisture percentage chemically, while none of the chemical compounds of Sodasorb forms a hydrate. Water is added mechanically to both mixtures, but the Baralyme requires less attention during storage to prevent drying out. The presence of this water is very important for effective removal

of carbon dioxide. Adriani [2] states that, for Sodasorb, "Neutralization becomes progressively more effective as the moisture content increases up to approximately 20 percent." The presence of water in Baralyme has a similar affect on its carbon dioxide removal. Since Baralyme is less effective than Sodasorb, the Navy, in 1978, selected Sodasorb as the carbon dioxide absorbing agent that would be utilized in their closed cycle rebreathing systems. As a result of this action, only the Sodasorb will be the subject of this investigation.

The absorption of carbon dioxide by Sodasorb is the neutralization of an acid gas by a base in a thin film of aqueous sodium hydroxide solution on the surface of the Sodasorb particle. The W. R. Grace Company [1] presents the first two reactions occuring in the absorption process as:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \qquad (1)$$

$$2H_2CO_3 + 2Na^+ + 2OH^- + 2K^+ + 2OH^- \rightleftharpoons 2Na^+ + CO_3^= + 2K^+ + CO_3^= + 4H_2O \qquad (2)$$

The carbonic acid of Eq. (2) must dissociate, which is very slow in this case, before the reaction can take place. Alternatively, Danckwerts [7] presented two reactions that could take place at this initial step after the carbon dioxide is in contact with an aqueous solution of sodium hydroxide as:

$$CO_2 + OH^- \rightleftharpoons HCO_3^- \qquad (3)$$

$$CO_2 + H_2O \rightleftharpoons HCO_3^- + H^+ \qquad (4)$$

where Eq. (4) is the same as Eq. (1) plus the dissociation reaction. He, further, points out that Eq. (3) is more than 30 times as fast as the reaction by Eq. (4) at room temperature and that Eq. (3) can be regarded as instantaneous when pH is greater than 10. It is believed by this investigator that Eq. (3) is the dominant reaction for the initial reaction with carbon dioxide, since it, also, does not require the relatively slow dissociation of carbonic acid. This reaction should cease in a relatively short time since the approximate weight percent of the hydroxides of sodium and potassium is only three precent. Any help from the hydroxide of calcium for the direct absorption of carbon dioxide from solution is deemed negligible due to the low solubility of calcium hydroxide. Worsening this situation is that as more carbon dioxide is reacted with hydroxyl ions, the resulting bicarbonate ions undergo a further dissociation represented by the following equation

$$HCO_3^- \longrightarrow H^+ + CO_3^= \qquad (5)$$

which when a hydroxyl gorup contacts the hydrogen ion, there is an instantaneous and irreversible reaction producing water (Eq. 6), thus helping to deplete the supply of hydroxyl ions necessary for sustaining the absorption reaction, but as Refs. [1], [2], and [8] point out, the hydroxides of sodium and potassium are regenerated by a series of reactions involving the calcium hydroxide and the sodium and potassium carbonates

present as follows:

$$H^+ + OH^- \longrightarrow H_2O \qquad (6)$$

$$Ca(OH)_3 + H_2O \rightleftharpoons Ca^{++} + 2OH^- + H_2O \qquad (7)$$

$$Ca^{++} + 2OH^- + CO_3^{=} \longrightarrow CaCO_3 + 2OH^- \qquad (8)$$

Since the calcium hydroxide of Eq. (7) has a low solubility, there are very few calcium ions in the solution, but when the calcium ion reacts with the carbonate ion, the resulting reaction is irreversible since calcium carbonate is insoluble in aqueous solution. This offsets the equilibrium and more calcium ions are released into solution. The reactions represented by Eqs. (7) and (8) are considered to be rate limiting for the entire carbon dioxide absorption process with Sodasorb.

It is believed that Eqs. (3), (5), (6), (7), and (8) are representative of the reactions occurring in the removal process.

B. PRESSURE DROP THROUGH THE SODASORB BED

One of Miller's [3] objectives was to determine the flow resistance through a Sodasorb bed for three non-reacting gasses. He compared his results with various flow resistance relationships and determined that the flow resistance model developed by Ward [6] fit his data well. This relationship is shown in equation form below:

$$f = \frac{1}{Re} + C \qquad (9)$$

where Re is the Reynolds number based on the superficial velocity[2] and the characteristic dimension, which is the square root of the permeability. [3] For the porous media and non-reacting fluids that Ward utilized in his investigation, it was determined empirically that the constant, C, equaled 0.55. Miller's data supported this value of the constant, as well.

Ploss [4] assumed that the original Ward relationship held for reacting gasses, as well, but that the constant would have to be changed. Utilizing the data that he obtained using air with six percent carbon dioxide, Ploss ascertained that the constant should be 1.67.

With friction factor thus determined, the pressure drop is given by the following equation:

$$\Delta P = \frac{f \rho V_c^2}{\sqrt{k}} L \qquad (10)$$

where ρ is the gas density, Vc is the superficial velocity, L is the length of the total Sodasorb bed, and k is the characteristic dimension. See Appendix C for sample calculations utilizing this relationship.

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[2]Superficial velocity is defined as the volume flow rate divided by the cross-sectional area of the canister.

III. EXPERIMENTAL APPARATUS

The test installation utilized was basically the same as that constructed by Miller [3] and modified by Ploss [4]. The installation measures the gas flow through the canisters, the volume percentage of carbon dioxide into and out of the canisters, the temperatures and pressures at the ends of the canisters while controlling the humidity and the temperature of the incoming gas supply. The canister environmental temperature was the room ambient temperature, which was always within two degrees of 70 degrees fahrenheit. The overall system schematic is shown in Fig. 1. The following system description is divided into four subsystems which are gas supply and flow measurement, carbon dioxide measurement, temperature measurement and control, and description of the canister.

A. GAS SUPPLY AND FLOW MEASUREMENT

An Ingersol-Rand three-stage, low-pressure, 40-horsepower air compressor was utilized to charge two air banks to 190 psig. The air was filtered and cooled prior to storage in the air banks. A Fairchild Hiller Model 10 air regulator reduced the air pressure to ten psig. The flow rate of air was then controlled by a 3/8-inch gate valve and filtered through a ten micron filter.

The medical grade carbon dioxide was supplied from high pressure cylinders reduced to ten psig by a Matheson Model 8-320 regulator. The carbon dioxide was piped to a Hoke control valve and then admitted to the main air supply line. The mixture of carbon dioxide and air passed through a half-inch Fischer and Porter Model 10A3500 convertible indicating flowrator meter (shown in Fig. 2), rated at 4.6 standard cubic feet per minute at a standard temperature of 70 degrees F and standard pressure of 14.7 psia. The main gas supply line then contained a thermocouple, pressure tap for measuring line pressure, a branch line consisting of a one-half inch gate bypass valve and a carbon dioxide measuring probe, and a one-half inch gate main gas supply valve. The line pressure was measured using a Meriam type W. 0 - 30 inches, mercury manometer. The gas was then piped to the water bath.

At the water bath, the gas was brought to 100 percent relative humidity by piping it into the first stage copper-cooling coil, first stage humidifier, second stage copper-cooling coil, second-stage humidifier, primary water separator (shown in Fig. 3) and then to the canister.

B. CARBON DIOXIDE MEASUREMENT

The gas passed through the canister, which was horizontal and out of the water bath. Upon exiting the Sodasorb bed, the hot discharge gas entered at the mid-point of a 14-inch vertical plexiglas discharge chamber bolted to the canister. Some

initial condensation occurred in this chamber. Located at the top of the discharge chamber were two ports: one port was for the main discharge of gas, while the other port was for the piping of the gas to the infrared detector for sampling (shown in Fig. 4). The gas exiting through the main discharge port passed through a 1-inch inside-diameter tube to the atmosphere via a one-half inch gate exhaust valve. This exhaust valve was utilized to maintain a positive flow of the effluent gas through the sampling port to a modified Wilkes Miran IA (shown in Fig. 5) variable filter infrared analyzer. The gas exiting the discharge chamber via the sampling port passed through a one-fourth-inch inside-diameter tube to a distribution manifold via a condenser. From the manifold, the sampling gas was dehumidified by passing through a vertical bed of anhydrous indicating Drierite (CaSO4)(See Fig. 5). The incoming gas to the infrared detector was at atmospheric temperature.

The infrared detector was calibrated prior to and upon completion of each run with 0.5% and 6% by volume carbon dioxide premixed with nitrogen. These calibration gasses were available through a distribution manifold with air quick-disconnect fittings. The infrared detector was utilized in an open loop mode with settings delineated in Appendix A.

C. TEMPERATURE MEASUREMENT AND CONTROL

The bath temperature was controlled by cooling and stabilizing the bath temperature with a constant-temperature

circulating water bath constructed at the Naval Postgraduate School. The controller utilized to maintain the desired temperature was a Versa Therm Proportional Electronic Temperature Controller, Model 2156.

Temperatures were monitored with Omega stainless steel sheathed exposed junction copper-constantan thermocouples. The thermocouples outputs were directed through a 24-element switch to a Newport Model 267 digital pyrometer that indicated temperature in degrees Fahrenheit. (shown in Fig. 2) The thermocouples were located at the inlet and exit of the canister to monitor the temperatures of the influent and effluent gasses.

D. DESCRIPTION OF THE CANISTERS

Six canisters were used in this investigation to evaluate Sodasorb's effectiveness. The canisters had varying inside diameters and a corresponding length such that they all held three pounds of Sodasorb. This gave length-to-diameter ratios of 0.15, 0.29, 0.44, 0.80, 1.16, 2.125 that were tested for effectiveness. Two sample canisters are shown in Figs. 6a and 6b. The Sodasorb was contained at the gas inlet and exhaust by fine wire-mesh screens composed of 0.017 inches diameter wire of 18 squares per linear inch. The openings between the wires were .00149 square inches and 48 percent of the screen's total cross-sectional area was void.

All tests with annular ring or disk type baffles were conducted using the above mentioned canisters. The positions and

sizes of these baffles varied and are listed in the notes of Figs. 9-13. The annular ring and the disk baffles were made of 1/16 inch thick teflon sheet and extended from the inside diameter of the canister toward the center, leaving the listed diameter open to flow. Disks were centered and allowed gas to flow between them and the canister wall. There is a deviation to the above for disks listed in Figs. 12 and 13 with an 'H', where these disks completely block the flow of gas except through holes placed in the disks. Figure 7 shows sample disks of each type. All of the dimensional and dimensionless geometric relati ıships are given in Table I.

For the rough wall test, vaseline was rubbed on the wall of the canister and expended Sodasorb was stuck to the vaseline so that the canister wall was interlocking with the main bed of Sodasorb.

The axial pressure difference across the entire Sodasorb bed was monitored using pressure-tap holes with 1/16-inch diameter and connected through a manifold for selecting the desired pressure position. Pressures were indicated on an Ellison two-inch inclined manometer.

IV. PRESENTATION AND DISCUSSION OF RESULTS

A total of 65 test runs were conducted. Of these, seven tests were invalidated due to the Sodasorb retaining screens slipping. Two of the test were completed in an effort to duplicate the results of similar test reported in Refs. [3] and [4]. The remaining 56 test runs and repeat runs were made for new geometric configurations.

Due to the randomness of bed packing and subsequent flow patterns, numerous repeat runs were made which showed scatter among the effectiveness data. Therefore, the data plotted in the Figs. 8-13 are the arithmetic means where repeat runs were made. For a typical set of data, say for L/D of 0.44, run numbers 1, 2, 3, and 4, the arithmetic mean was 21.9 minutes and the deviation of the sample was 4.2 minutes.

All influent volumetric flow rates contained 6.0% by volume carbon dioxide. The standard volumetric flow rate of the gas was determined in accordance with the procedure contained in Appendix B.2 and 2.1 SCFM was the approximate flow rate for all test runs.

Tables II through VII show the experimental data recorded for the tests evaluating Sodasorb's effectiveness with various canister geometric configurations.

Table VIII lists the test data for non-baffled canisters of different length for comparing the actual pressure drop

through the Sodasorb bed versus the pressure drop predicted using Eq. 10.

Sodasorb's effectiveness as a function of length-to-diameter ratio for the baffleless canisters is shown in Figs. 8a and 8b. As can be seen from these figures, the length-to-diameter ratio has a marked effect on the effectiveness of a constant mass of Sodasorb and appears to exhibit a linear relationship of effectiveness as a function of the natural log of the length-to-diameter ratio for the values tested. At the low end of L/D ratios, the superficial velocity of the gasses will have dropped so low that molecular diffusion of the gas becomes overiding and is beyond the scope of this investigation. For the large L/D ratios, there is, of course, a point where this relationship must 'tail off' since there is a practical limit to the diameter of a canister, but this investigator believes that the effectiveness will start to drop prior to reaching the limiting Sodasorb particle size due to the increased superficial velocity of the gasses, again out of the scope of this investigation.

Figures 9 through 13 are comparisons of a given length-to-diameter ratio with each figure showing Sodasorb's effectiveness as a function of ring configuration. As predicted prior to experimentation, annular ring and disk baffles increase the effectiveness of a Sodasorb bed in the removal of carbon dioxide from an air stream and it is significant for almost all length-to-diameter ratios tested. Note that the specific effect of

a type of configuration changes with the length-to-diameter ratio. For example, the trend for the ring-ring configuration is an increasing effectiveness with an increasing length-to-diameter ratio. This is attributed to the inadequate utilization of Sodasorb at the walls for the smaller ratios while the larger ratios allow for a more favorable gas distribution with subsequent higher percentage of the Sodasorb bed used. Also note that the configuration of only an entrance ring baffle produces a significant increase in effectiveness for all cases and while it is the highest for some of the ratios, it is within 6.5% of the highest for all of the ratios. Furthermore, the latter configuration produces the smallest pressure drop with the exception of the non-baffled canisters.

The actual pressure drop for the baffleless canister as well as the predicted values of this pressure drop are plotted as a function of the entire canister length in Fig. 14.

The interlocking wall canister, although more effective than the smooth wall canisters, is deemed too difficult to pack since great care must be taken to ensure that there are no major gaps between the wall and the bed.

Sodasorb bed usage diagrams for length-to-diameter ratios of 1.16, 0.80, and 0.44 are presented in Figs. 15-17. When viewing these figures, it should be borne in mind that the white section at the entrance of the canisters is used Sodasorb, while the white sections at the exit of the canisters is unused Sodasorb. The white section at the beginning remained dark

purple while the test run was in progress, but rapidly paled after securing the humidified carbon dioxide-air mixture. This is thought to be the result of drying out of the Sodasorb in this area.

The following discussion of Figs. 15-17 is this investigator's perception of the flow of gasses through the Sodasorb bed and the consequential absorption patterns that occurred during the test runs. The method of their construction is included in Appendix A, section F. Note that where flow is discussed, it refers only to the flow of gas with carbon dioxide still present. After the carbon dioxide is removed, the flow can go anywhere but cannot be perceived using the color patterns of the Sodasorb bed.

Figure 15a - The flow of gas entered the canister and immediately started channeling along the walls as indicated by the dark purple coloring along the wall. Some of the flow entered the main body of the bed and most, if not all, of this fraction had migrated out to the wall of the canister before it exited the canister. This was evidenced by the dark purple coloring over the entire first half of the bed followed by increasing diameter of white, unused Sodasorb in the shape of a parabaloid of revolution (POR) with apex in the center, radially, and approximately one inch from the exit of the bed.

Figure 15b - The entrance ring caused the gas to enter the center portion of the bed with subsequent usage and flow, some of which went straight through the canister and the other which migrated to the wall leaving half of an ellyptical torus of Sodasorb unused at the exit. This is evidenced by the dark purple coloration to about 3/4 of an inch from the exit with some dark purple coloring at the center of the exit and all along the canister wall.

Figure 15c - The ring at the entrance had the same effect as in Fig. 15b., but the ring at the exit caused too long of a flow path for gas to channel along the wall to any great extent as witnessed by the light purple coloring along the wall. The dark purple coloring indicated the flow tended to move through the canister with a flow path larger than the ring opening but closed back down to a very small path at the exit.

Figure 15d - Again the ring at the entrance had the same effect at the entrance region as the previous two canisters, but the exit disk forced the flow to migrate out to the wall. Although there is a large volume of white unused Sodasorb at the exit, this is the only configuration that led to an almost flat interface between used and unused Sodasorb as indicated by the coloring pattern. This is the type interface desired but its depth from the exit was almost half the bed with effectiveness much less than the previous configuration.

Figure 16a - The flow, usage, and coloration are the same as Fig. 15a with the apex of the POR of unused Sodasorb at the center of the canister, radially, and approximately two inches from the exit of the bed.

Figure 16b - The pattern of usage and flow was similar to Fig. 15b but the center flow did not make it to the exit as in Fig. 15b and fell short of the exit by about 3/4 of an inch.

Figure 16c - Again, a previous pattern, that of Fig. 15c, applies.

Figure 16d - This configuration and the next were a direct result of the pattern of Fig. 16c and caused a similar pattern which was a little less effective than that configuration but useful as the basis for Fig. 16e's configuration.

Figure 16e - This configuration had similar patterns to the previous two figures, but the disk forced the center flow toward the walls. The result was that the small light purple section at the exit of Fig. 16d was enlarged in the configuration fo Fig. 16e, but not darkened. It was thought that a larger section would have been utilized and have gotten darker. This was not the case even through the effectiveness increased by about 16% over the configuration of Fig. 16d.

Figure 16f - In this configuration, an entrance pattern similar to the previous three configurations occurred. The flow pattern continued to within an inch of the exit where

it channeled to a hole in the exit disk.

Figure 17a - The flow, usage, and coloration patterns are the same as Figs. 15a and 16a with apex of the POR of the unused Sodasorb at the radial center and approximately 2.5 inches from the exit of the bed.

Figure 17b - This is similar to Fig. 17a except that the exit ring has caused the apex of the POR of the unused Sodasorb to move about one inch closer to the exit.

Figure 17c - This, too, is similar to Fig. 17a except that the exit ring has caused the diameter of the POR at the exit to be the same as the exit ring. It, also, caused a 3/4 inch thick band of light usage around the POR.

Figures 17d and 17e - These coloration patterns are the same, yet, the effectiveness was considerably different. It seems that the usage of the bed of Sodasorb must have been more in the former configuration than the latter but not enough to cause a discernible variation in coloration.

V. CONCLUSIONS

The following conclusions may be made from the results of this investigation:

1. The length-to-diameter ratio was experimentally determined to have a significant effect on the effectiveness of a constant mass of Sodasorb to remove carbon dioxide from a gas.

2. Channeling occurs along the walls of the 'straight' through canisters and was evidenced by purple rings of used Sodasorb at the effluent end of the canisters(see examples in Figs. 18a, 18b, and 19). Furthermore, channeling ocurred within the bed (see example in Fig. 20) and may be attributed to randomness of the shape of the particles, causing non-symmetric flow paths.

3. The installation of annular ring and disk baffles can be used to control flow paths through the Sodasorb beds to achieve a more even distribution of bed usage. This can result in a significant improvement in Sodasorb effectiveness.

4. Ward's relationship for friction factor as modified by Ploss does not produce a predicted pressure drop that compares well with the actual pressure drop for the shorter canisters, but in the longer canisters it gives a value that may be considered conservative but usable.

6. Based on the results of this investigation, it has

been shown that for length-to-diameter ratios of .8 and less, an annular ring baffle at the entrance of the bed produces the 'best' effectiveness results with the minimum pressure drop. For the length-to-diameter ratio of 1.16, an annular ring baffle at the entrance and the exit will produce the 'best' canister effectiveness.

VI. RECOMMENDATIONS FOR FURTHER STUDY

Based on the findings of this investigation, the following recommendations for study are submitted:

1. An investigation of the relationship which compares unsteady flow with steady flow is necessary to correlate the results of this study to actual breathing systems. A machine which simulates breathing would be the ideal means of achieving this end.

2. In conjunction with recommendation number one, the system should be a closed system such that any residual carbon dioxide in the effluent from the canister remains in the system just as it would in the actual breathing system.

3. Increased pressure may have an effect on the absorption process and, therefore, should be investigated to find out what the relationship is.

4. Since there are a large number of configurations of baffling available, many untested, further testing in this area should be completed.

TABLE I

CANISTER, RING, AND DISK DIMENSIONS

CANISTER			RING			DISK			DISK WITH HOLES			
L in.	D in.	L/D	SYM. IDEN.	d_i in.	d_i/D	SYM. IDEN.	d_o in.	d_o/D	SYM. IDEN.	No. of HOLES	d_i in.	d_i/D
1.375	9.0	0.15	R6	6.0	0.67	D4	4.0	0.44				
			R4	4.0	0.44							
2.1875	7.5	0.29	R4.5	4.5	0.60	D4.5	4.5	0.6				
2.875	6.5	0.44	R3.5	3.5	0.54	D3.5	3.5	0.54				
4.375	5.5	0.80	R2.5	2.5	0.45	D3	3.0	0.55	H1-9	9	1.0	0.18
			R4	4.0	0.73	D4	4.0	0.73				
5.5	4.75	1.16	R2.25	2.25	0.47	D2.25	2.25	0.47	H.5-17	17	0.5	0.11

TABLE II

SODASORB EFFECTIVENESS RESULTS FOR L/D = 2.125

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT (SCFM)	t1/2 (min)
	ENTRANCE	MIDDLE	EXIT	OTHER		
1	-	-	-	-	2.14	34.8
2	-	-	-	-	2.11	36.1
3P	-	-	-	-	2.08	38.5
4P	-	-	-	-	2.10	40.5
5P	-	-	-	-	2.07	37.0

Note: Run numbers with a 'P' are data from Ploss [4]

TABLE III

SODASORB EFFECTIVENESS RESULTS FOR L/D = 1.16

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT	t1/2
	ENTRANCE	MIDDLE	EXIT	OTHER	(SCFM)	(min)
1	-	-	-	-	2.06	35.5
2	-	-	-	-	2.05	27.6
3	-	-	-	-	2.05	24.0
4	-	-	-	-	2.04	23.6
5	-	-	-	-	2.06	23.0
6	-	-	-	-	2.07	25.7
7	R2.25	-	-	-	2.07	39.1
8	R2.25	-	-	-	2.06	39.3
9	R2.25	-	R2.25	-	2.09	42.1
10	R2.25	-	R2.25	-	2.07	40.0
11	R2.25	-	D2.25	-	2.08	37.1
12	R2.25	-	D2.25	-	2.09	32.9
13	R2.25	-	H.5-17	-	2.06	40.3
14	R2.25	-	H.5-17	-	2.07	40.9

Note: 'R' is for annular ring, number is diameter of hole in inches.
'D' is for disk baffle, number is diameter of disk in inches.
'H' is for disk that closes off the exit except for holes, the first number following 'H' is diameter of the holes in inches and the second is the number of holes in the disk.

TABLE IV

SODASORB EFFECTIVENESS RESULTS FOR L/D = 0.80

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT	t1/2
	ENTRANCE	MIDDLE	EXIT	OTHER	(SCFM)	(min)
1	-	-	-	-	2.12	27.8
2	-	-	-	-	2.11	36.6
3	-	-	-	-	2.12	20.0
4	R2.5	-	-	-	2.02	39.6
5	R2.5	-	-	-	2.06	37.5
6	R2.5	-	-	-	2.09	36.0
7	R2.5	-	R2.5	-	2.15	30.4
8	R2.5	-	R2.5	-	2.12	35.0
9	R2.5	-	R2.5	-	2.05	36.0
10	R2.5	-	R2.5	-	2.07	35.3
11	R2.5	-	R4	-	2.10	33.1
12	R2.5	-	D3	-	2.16	33.6
13	R2.5	-	D3	-	2.10	40.2
14	R2.5					
15	R2.5	D3	R2.5	-	2.09	36.6
16	R2.5	R4	D4	-	2.06	38.5
17	R2.5	-	H1-9	-	2.08	39.3
18	-	-	-	ROUGH WALL	2.11	35.9

Note: 'R' is for annular ring, number is diameter of hole in inches.
'D' is for disk baffle, number is diameter of disk in inches.
'H' is for disk that closes off the exit except for holes, the first number following 'H' is diameter of the holes in inches and the second is the number of holes in the disk.

TABLE V

SODASORB EFFECTIVENESS RESULTS FOR L/D = 0.44

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT (SCFM)	t1/2 (min)
	ENTRANCE	MIDDLE	EXIT	OTHER		
1	-	-	-	-	2.11	27.5
2	-	-	-	-	2.10	20.4
3	-	-	-	-	2.11	16.0
4	-	-	-	-	2.10	23.7
5	R3.5	-	-	-	2.07	41.5
6	R3.5	-	-	-	2.11	39.1
7	R3.5	-	R3.5	-	2.09	36.1
8	R3.5	-	R3.5	-	2.10	33.7
9	R3.5	-	D3.5	-	2.10	33.6
10	R3.5	-	D3.5	-	2.10	32.9

Note: 'R' is for annular ring, number is diameter of hole in inches.
'D' is for disk baffles, number is diameter of disk in inches.

TABLE VI

SODASORB EFFECTIVENESS RESULTS FOR L/D = 0.29

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT (SCFM)	t1/2 (min)
	ENTRANCE	MIDDLE	EXIT	OTHER		
1	-	-	-	-	2.05	19.8
2	-	-	-	-	2.11	16.1
3	-	-	-	-	2.10	17.5
4	-	-	-	-	2.10	30.8
5	-	-	-	-	2.13	19.3
6	R4.5	-	-	-	2.05	40.0
7	R4.5	-	R4.5	-	1.80	27.4
8	R4.5	-	D4.5	-	1.98	38.6
9	R4.5	-	D4.5	-	2.05	37.8
10	R4.5	D4.5	R4.5	-	2.07	34.6

Note: 'R' is for annular ring, number is diameter of hole in inches.
'D' is for disk baffle, number is diameter of disk in inches.

TABLE VII

SODASORB EFFECTIVENESS RESULTS FOR L/D = 0.15

Temperature = 70 deg F - CO_2 Input = 6% BY VOL

RUN #	CONFIGURATION				Qs INPUT	t1/2
	ENTRANCE	MIDDLE	EXIT	OTHER	(SCFM)	(min)
1	-	-	-	-	2.13	13.5
2	-	-	-	-	2.09	15.7
3	R6	-	-	-	2.17	21.9
4	R6	-	D4	-	2.06	22.1
5	R4	-	D4	-	2.08	18.3
6	R6	-	R4	-	2.09	14.8

Note: 'R' is for annular ring, number is diameter of hole in inches.
'D' is for disk baffle, number is diameter of disk in inches.

TABLE VIII

Length of Sodasorb Bed (in)	Actual ΔP (in H_2O)	Predicted ΔP (in H_2O)
1.375	0.015	0.008
2.1875	0.02	0.019
	0.025	0.020
4.375	0.09	0.088
5.5	0.15	0.167
	0.14	0.163

Note: Predicted P values were calculated using Eq. 10.

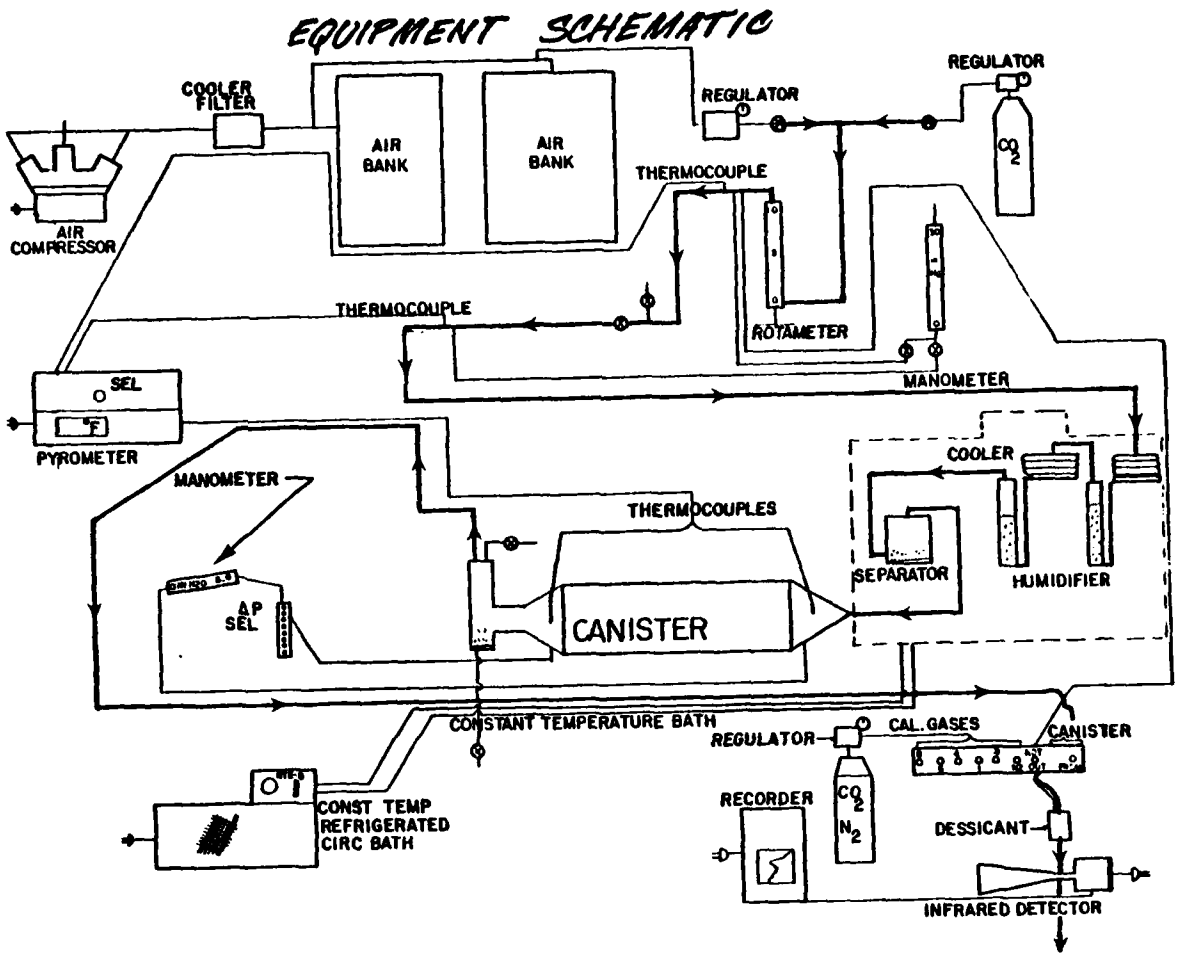


Figure 1. Equipment Schematic.

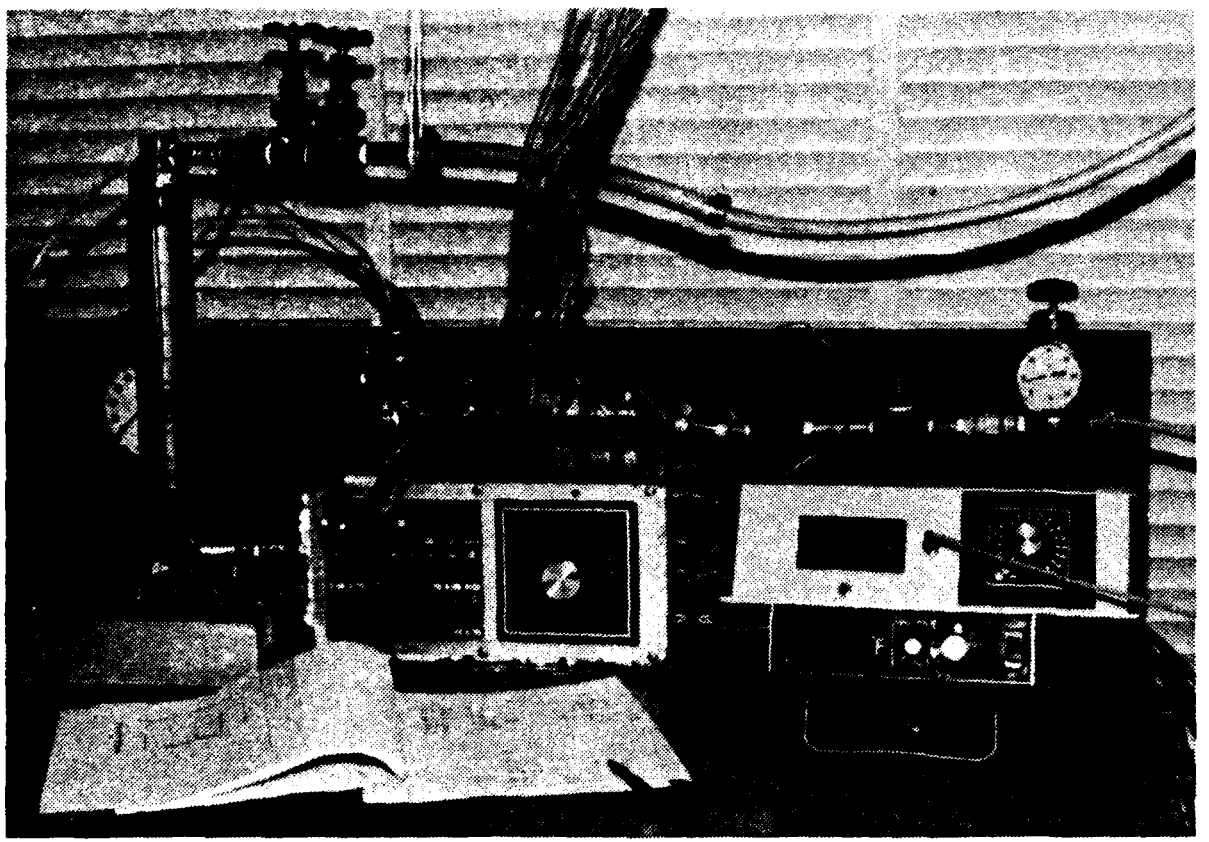


Figure 2. Flowrator, 24 element switch, and digital pyrometer.

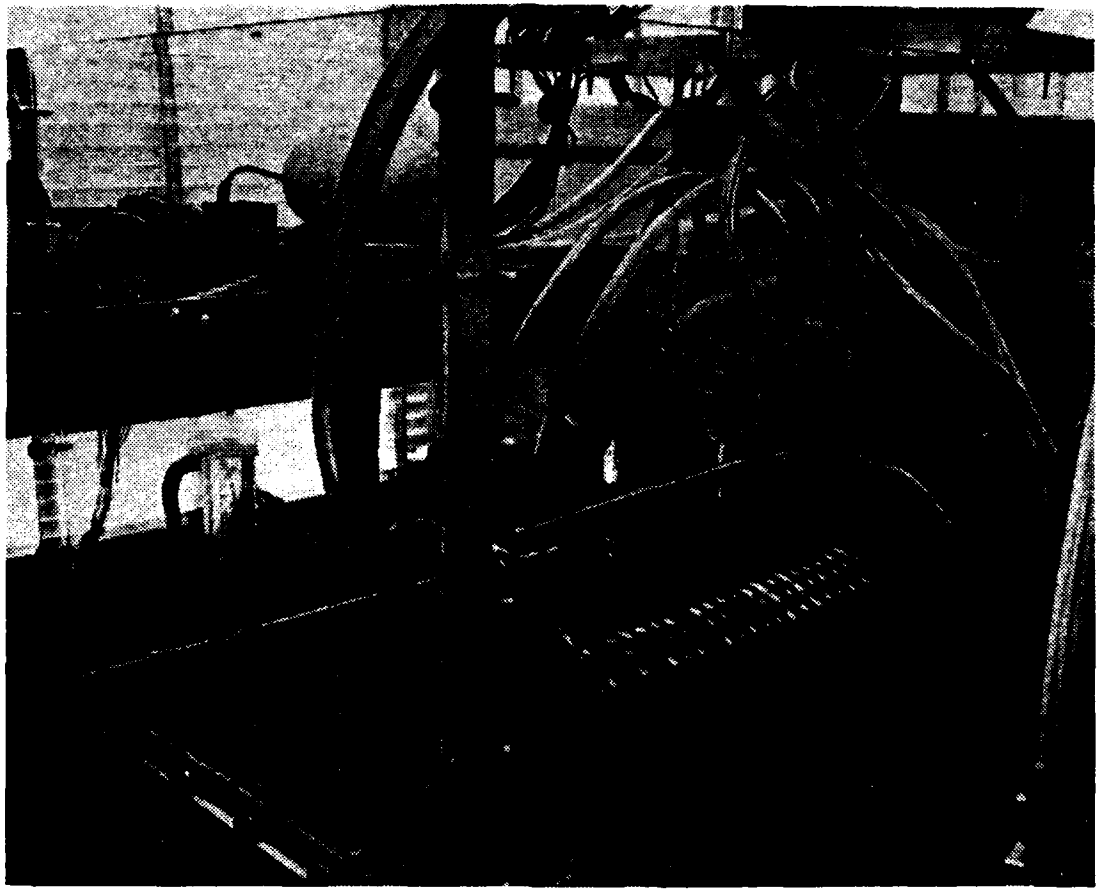


Figure 3. Constant temperature bath with humidifiers and cooling coils.

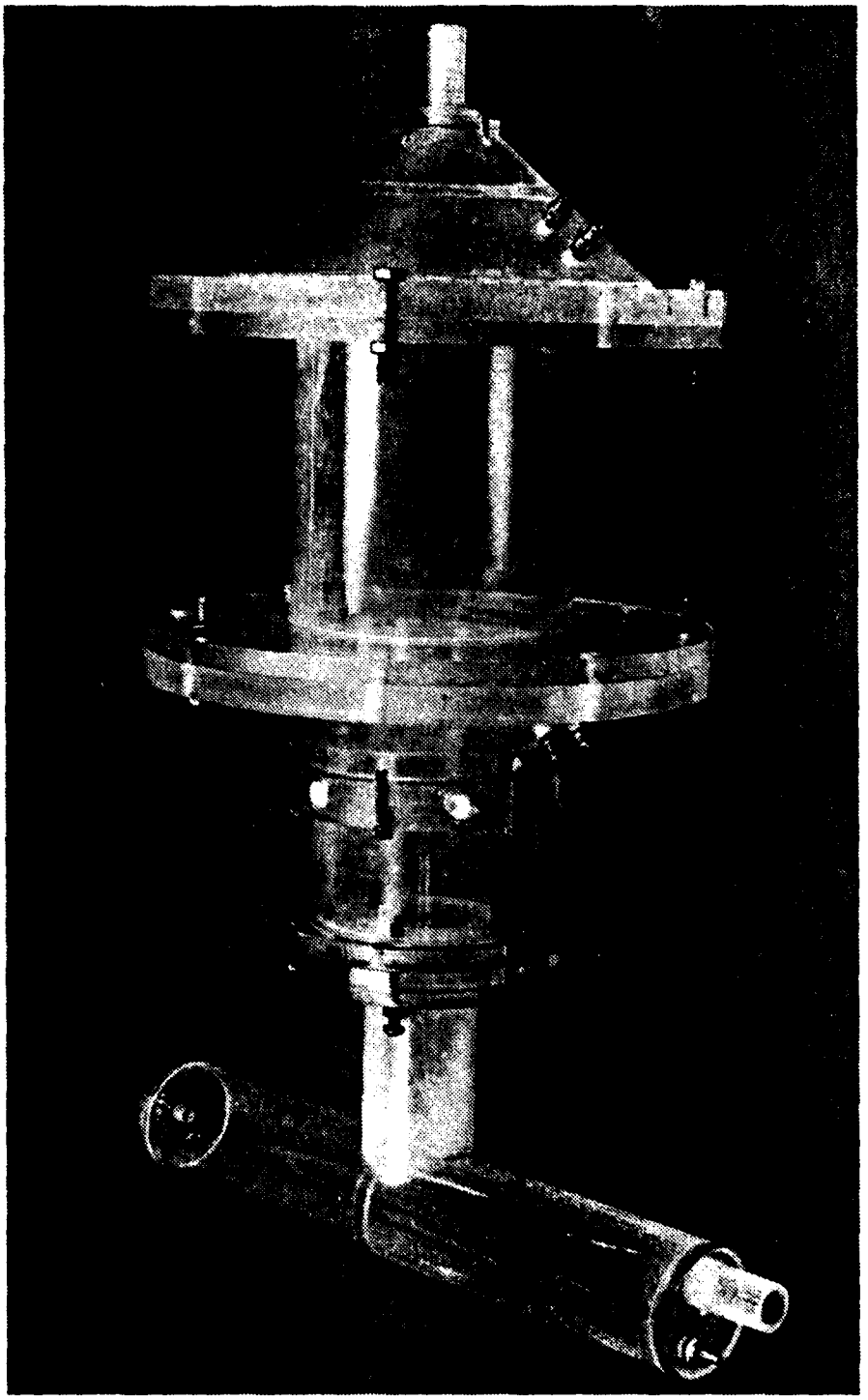


Figure 4. Canister with effluent water separator attached.

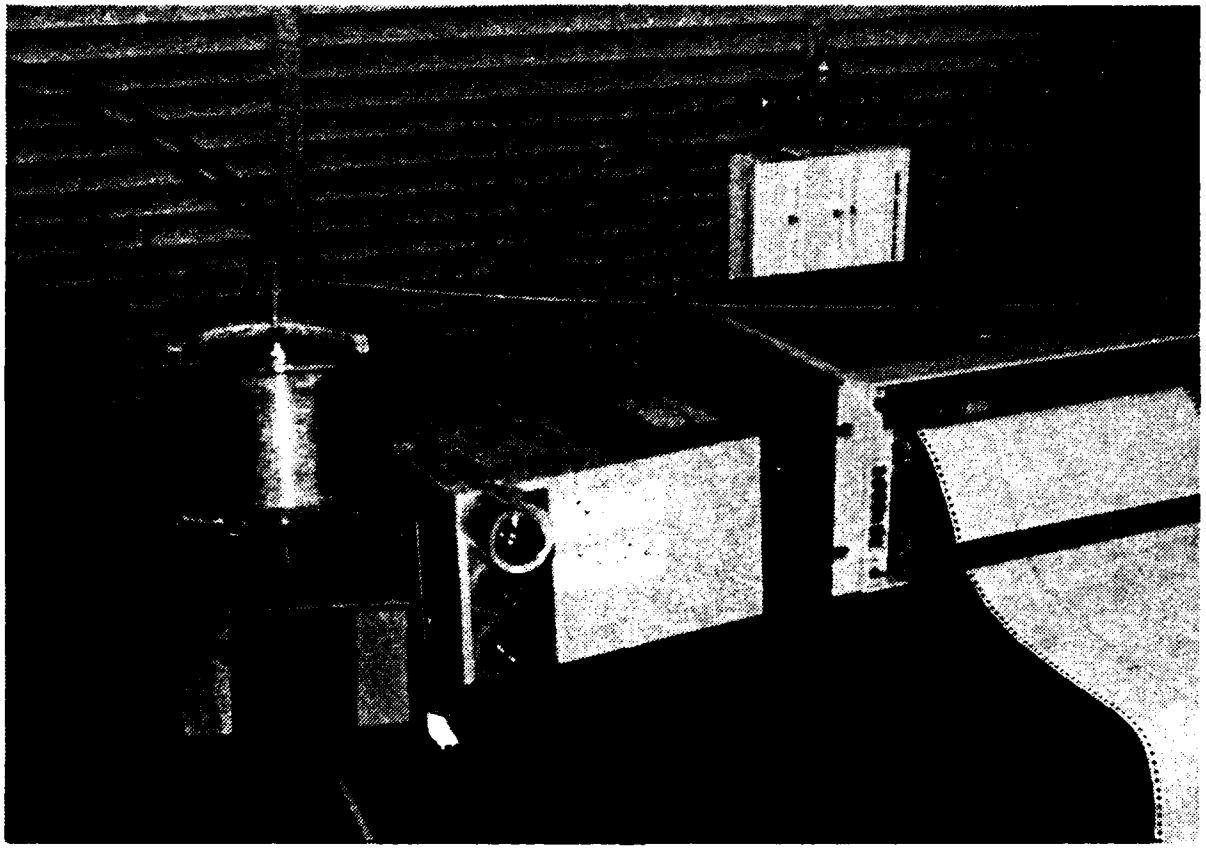


Figure 5. Infrared detector, primary dessicant, and data recorder.

Figure 6a. Canister 'spool piece', L/D = 0.15.

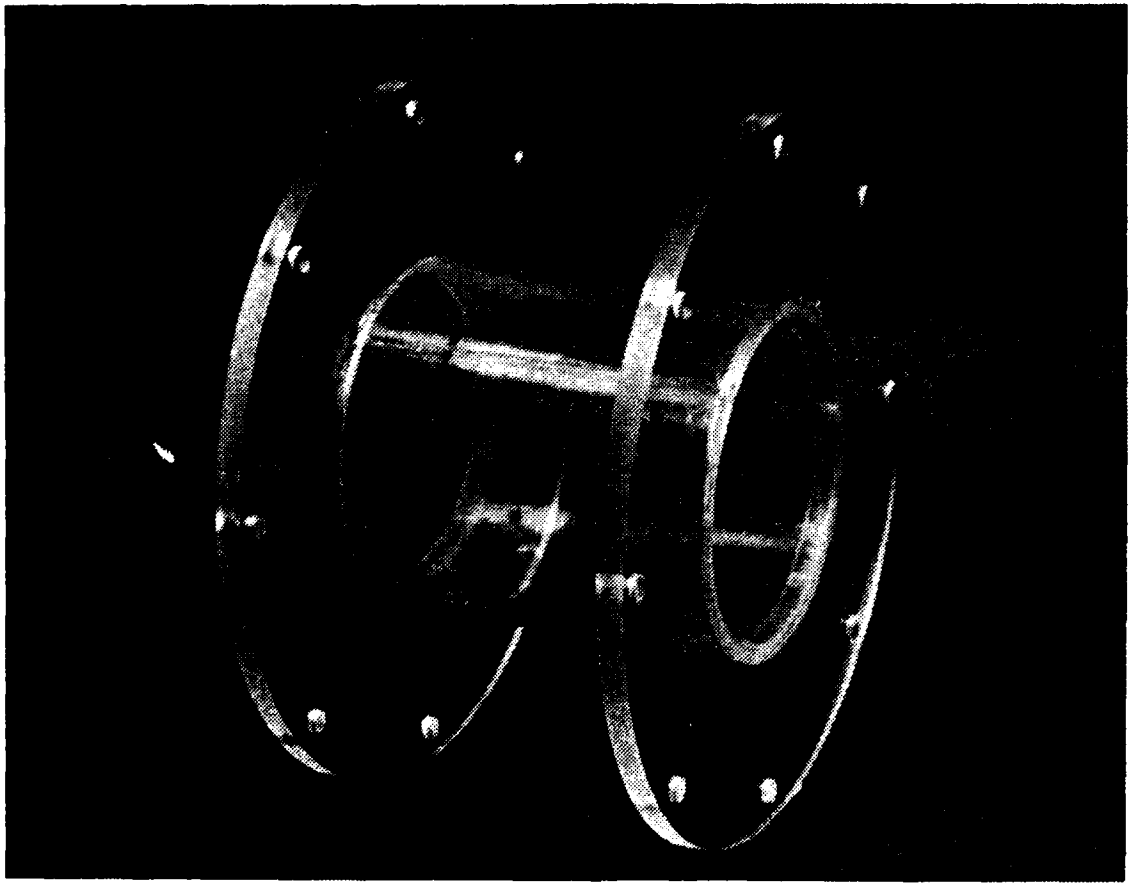


Figure 6b. Canister 'spool piece', L/D = 0.80.

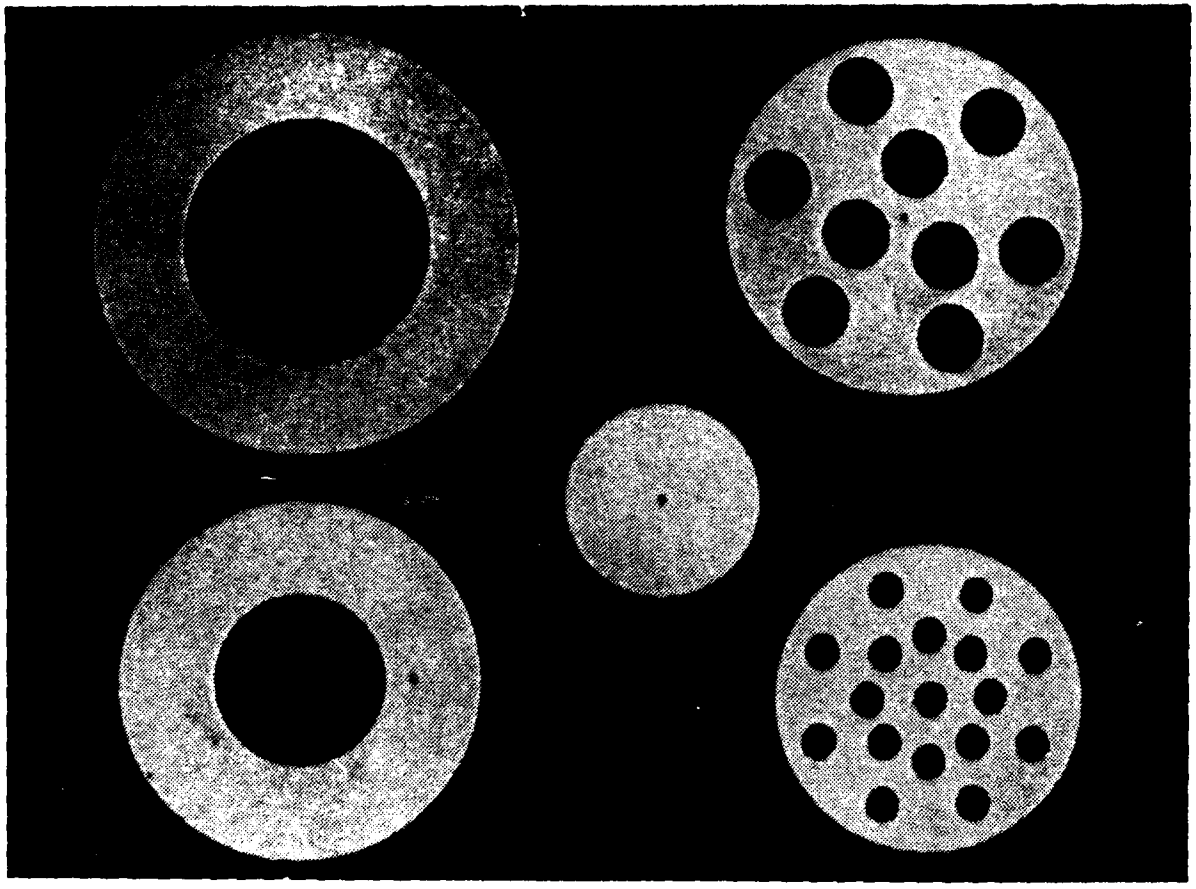


Figure 7. Examples of annular rings and disk baffles.

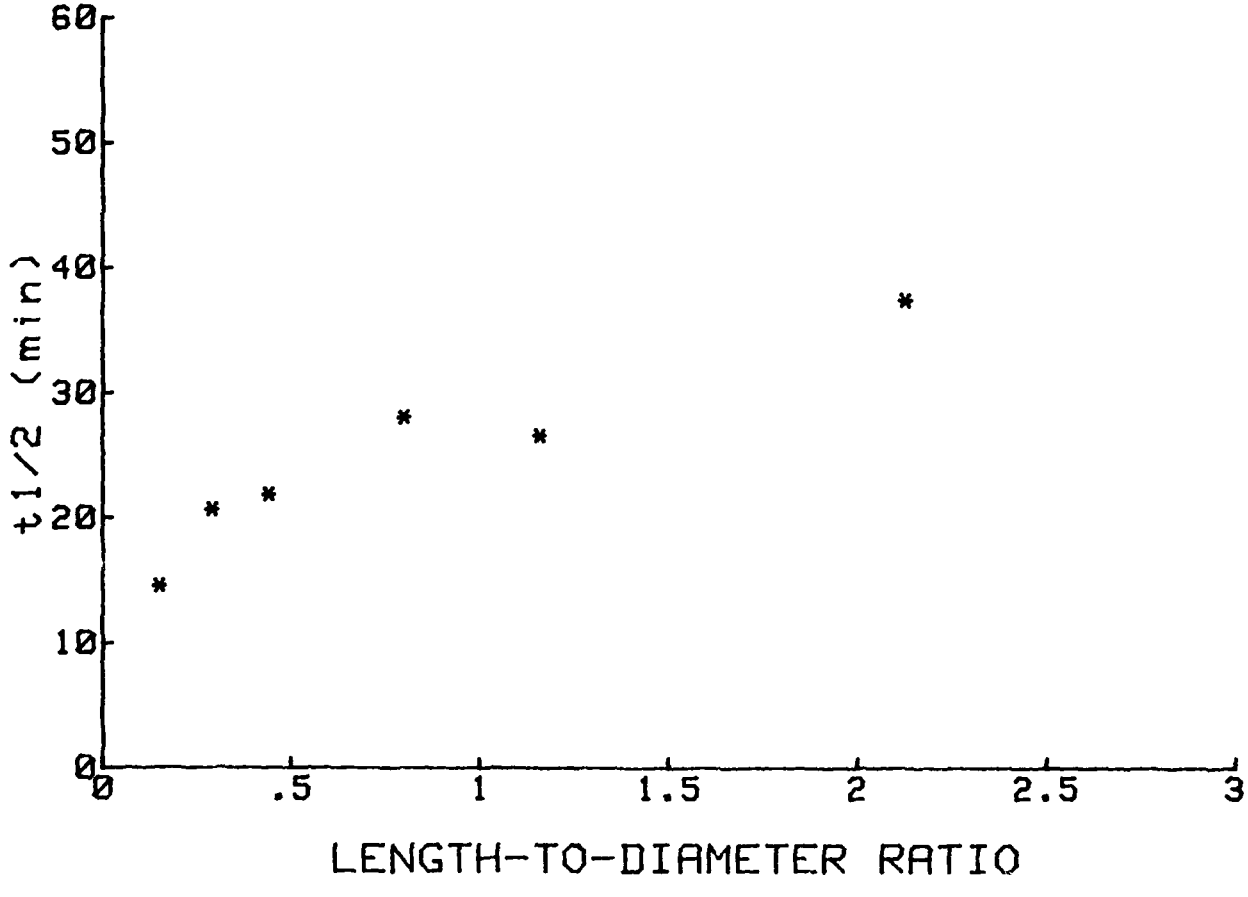


Figure 8a. Effectiveness versus Length-to-Diameter Ratio.

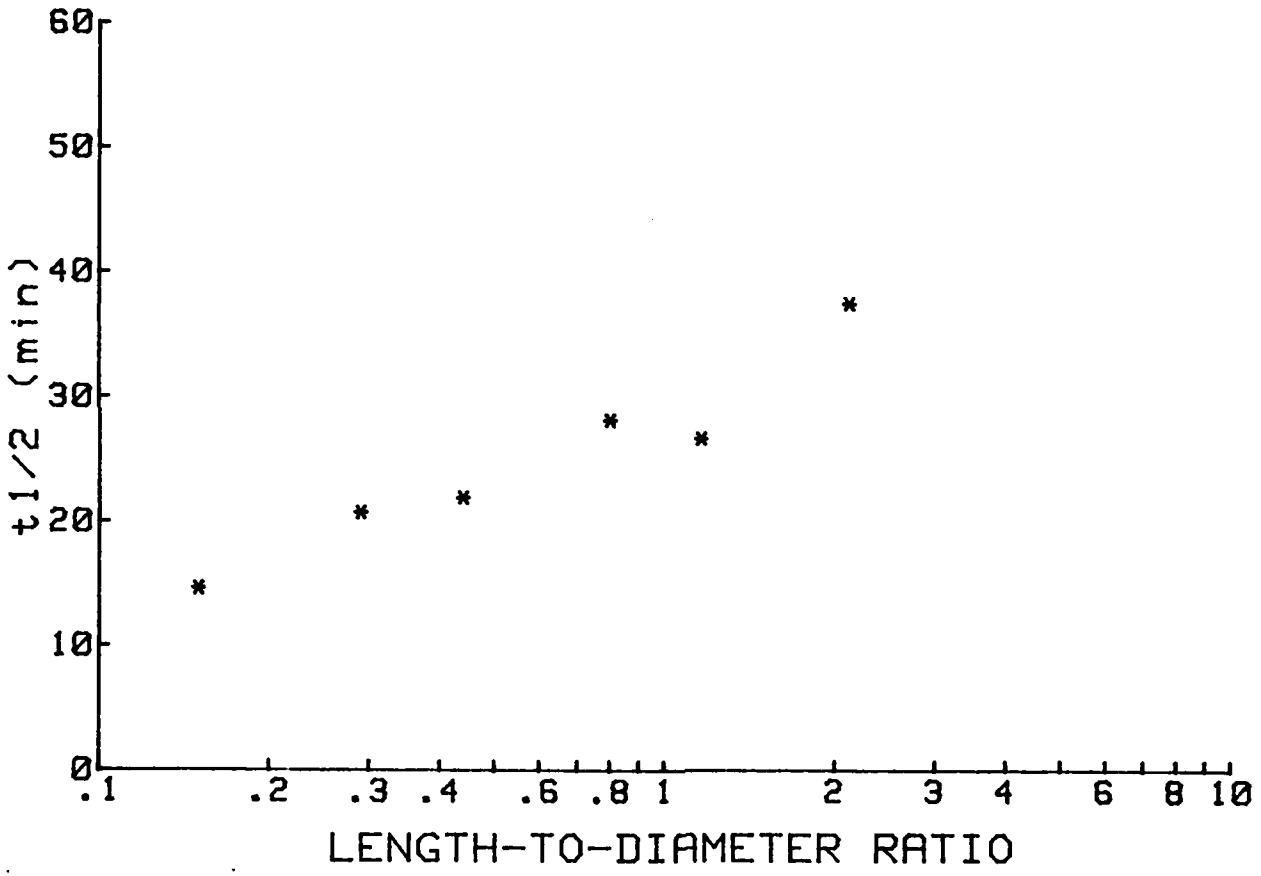
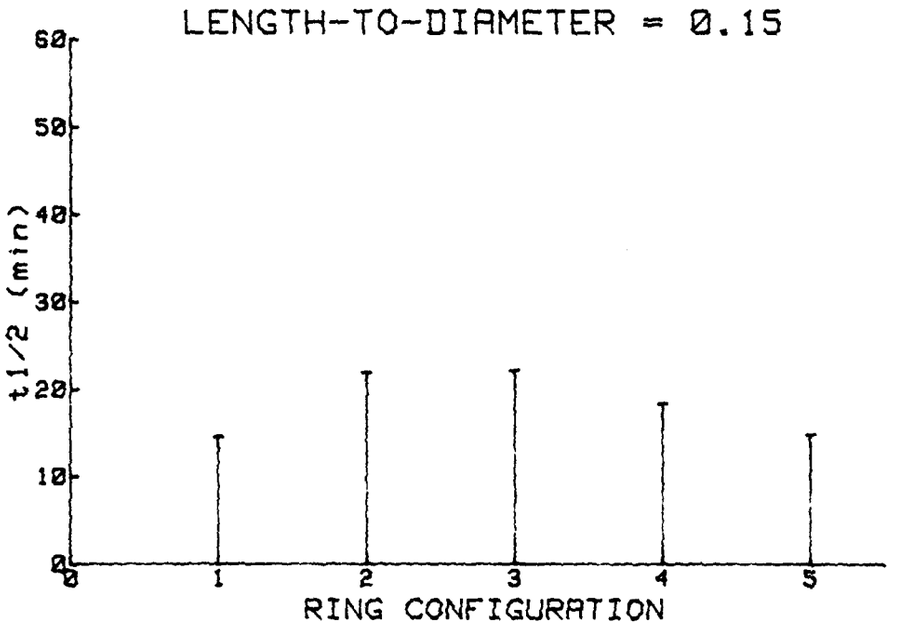


Figure 8b. Effectiveness versus Length-to-Diameter Ratio.



RING CONFIGURATION LEGEND

1 - NO RINGS OR DISKS

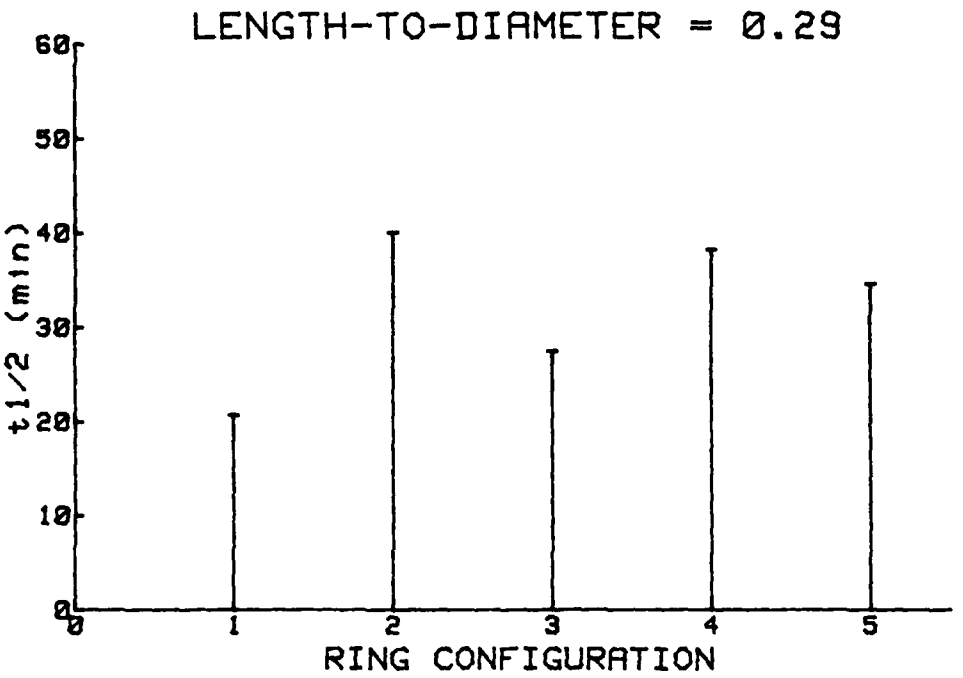
2 - RING (d_i = 6 in) AT ENTRANCE

3 - RING (d_i = 6 in) AT ENTRANCE
DISK (d_o = 4 in) AT EXIT

4 - RING (d_i = 4 in) AT ENTRANCE
DISK (d_o = 4 in) AT EXIT

5 - RING (d_i = 6 in) AT ENTRANCE
RING (d_i = 4 in) AT EXIT

Figure 9. Effectiveness versus Ring Configuration.



RING CONFIGURATION LEGEND

1 - NO RINGS OR DISKS

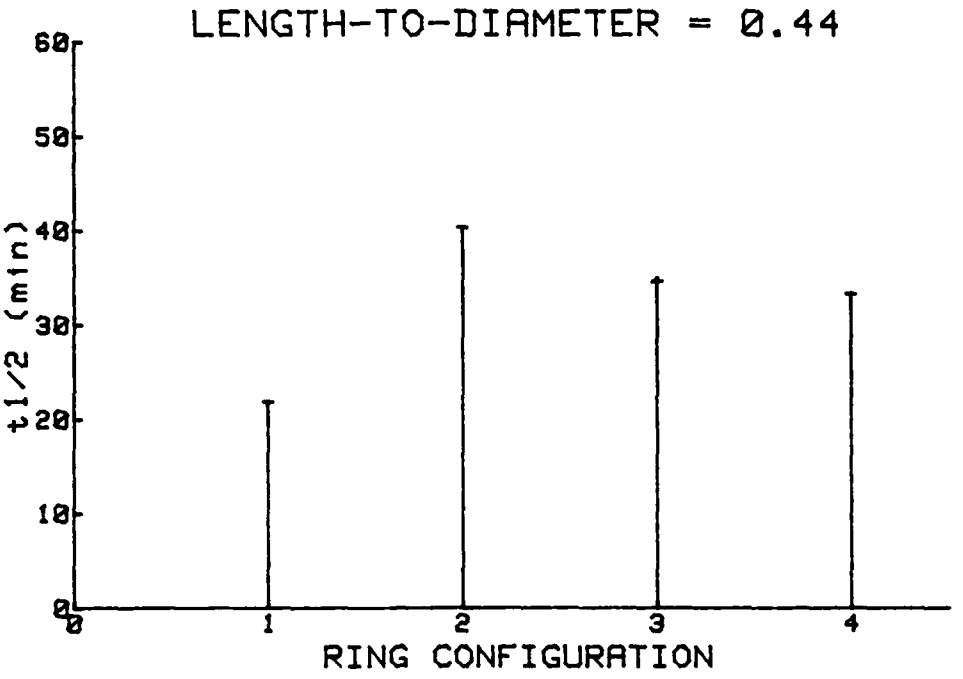
2 - RING (d_i = 4.5 in) AT ENTRANCE

3 - RING (d_i = 4.5 in) AT ENTRANCE
RING (d_i = 4.5 in) AT EXIT

4 - RING (d_i = 4.5 in) AT ENTRANCE
DISK (d_o = 4.5 in) AT EXIT

5 - RING (d_i = 4.5 in) AT ENTRANCE
DISK (d_o = 4.5 in) AT MIDDLE
RING (d_i = 4.5 in) AT EXIT

Figure 10. Effectiveness vs Ring Configuration.



RING CONFIGURATION LEGEND

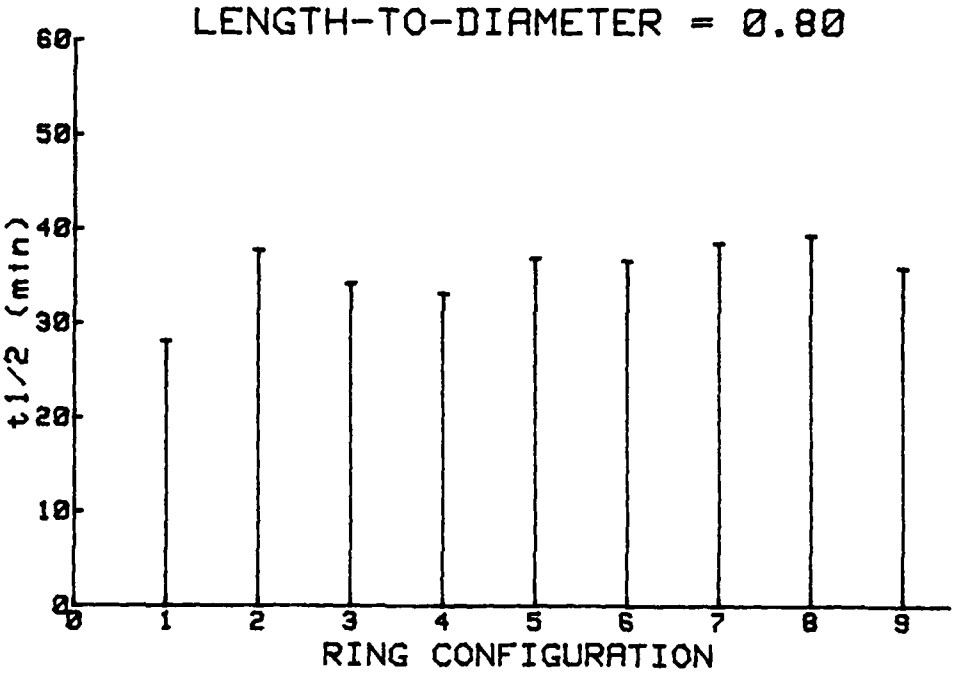
1 - NO RINGS OR DISKS

2 - RING (d_i = 3.5 in) AT ENTRANCE

3 - RING (d_i = 3.5 in) AT ENTRANCE
RING (d_i = 3.5 in) AT EXIT

4 - RING (d_i = 3.5 in) AT ENTRANCE
DISK (d_o = 3.5 in) AT EXIT

Figure 11. Effectiveness vs Ring Configuration.



RING CONFIGURATION LEGEND

1 - NO RINGS OR DISKS

2 - RING (d_i = 2.5 in) AT ENTRANCE

3 - RING (d_i = 2.5 in) AT ENTRANCE
RING (d_i = 2.5 in) AT EXIT

4 - RING (d_i = 2.5 in) AT ENTRANCE
RING (d_i = 4 in) 1 1/4 in. FROM EXIT

5 - RING (d_i = 2.5 in) AT ENTRANCE
DISK (d_o = 3 in) AT EXIT

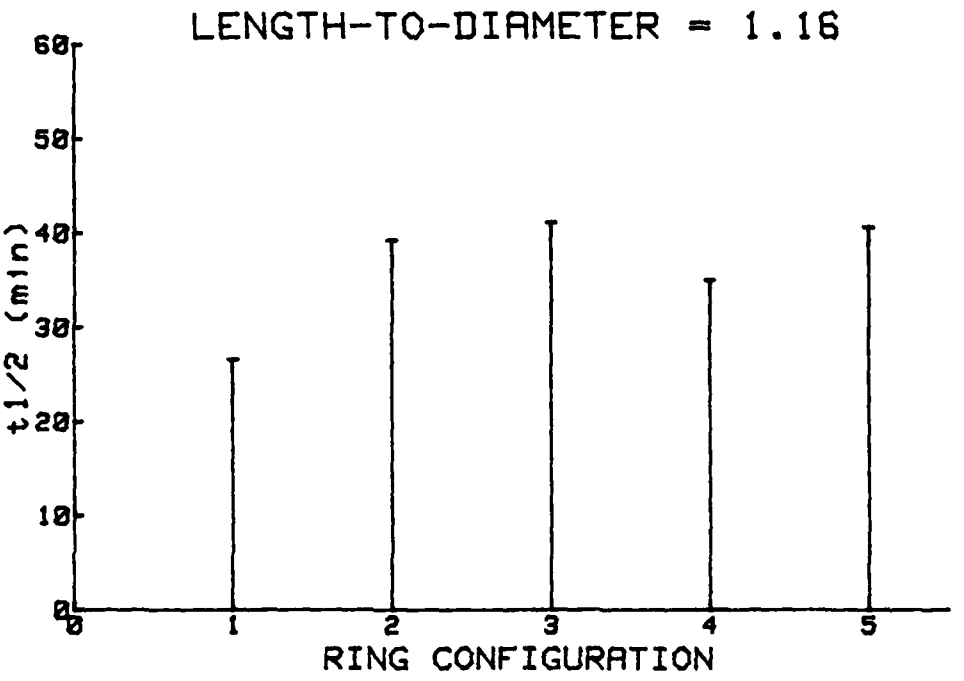
6 - RING (d_i = 2.5 in) AT ENTRANCE
DISK (d_o = 3 in) AT MIDDLE
RING (d_i = 2.5 in) AT EXIT

7 - RING (d_i = 2.5 in) AT ENTRANCE
RING (d_i = 4 in) 1 1/4 in. FROM EXIT
DISK (d_o = 4 in) AT EXIT

8 - RING (d_i = 2.5 in) AT ENTRANCE
DISK WITH 9-1 in. HOLES AT EXIT

9 - ROUGH WALL

Figure 12. Effectiveness vs Ring Configuration.



RING CONFIGURATION LEGEND

1 - NO RINGS OR DISKS

2 - RING (d_i = 2.25 in) AT ENTRANCE

3 - RING (d_i = 2.25 in) AT ENTRANCE
RING (d_i = 2.25 in) AT EXIT

4 - RING (d_i = 2.25 in) AT ENTRANCE
DISK (d_o = 2.25 in) AT EXIT

5 - RING (d_i = 2.25 in) AT ENTRANCE
DISK WITH 17-1/2 in. HOLES AT EXIT

Figure 13. Effectiveness vs Ring Configuration.

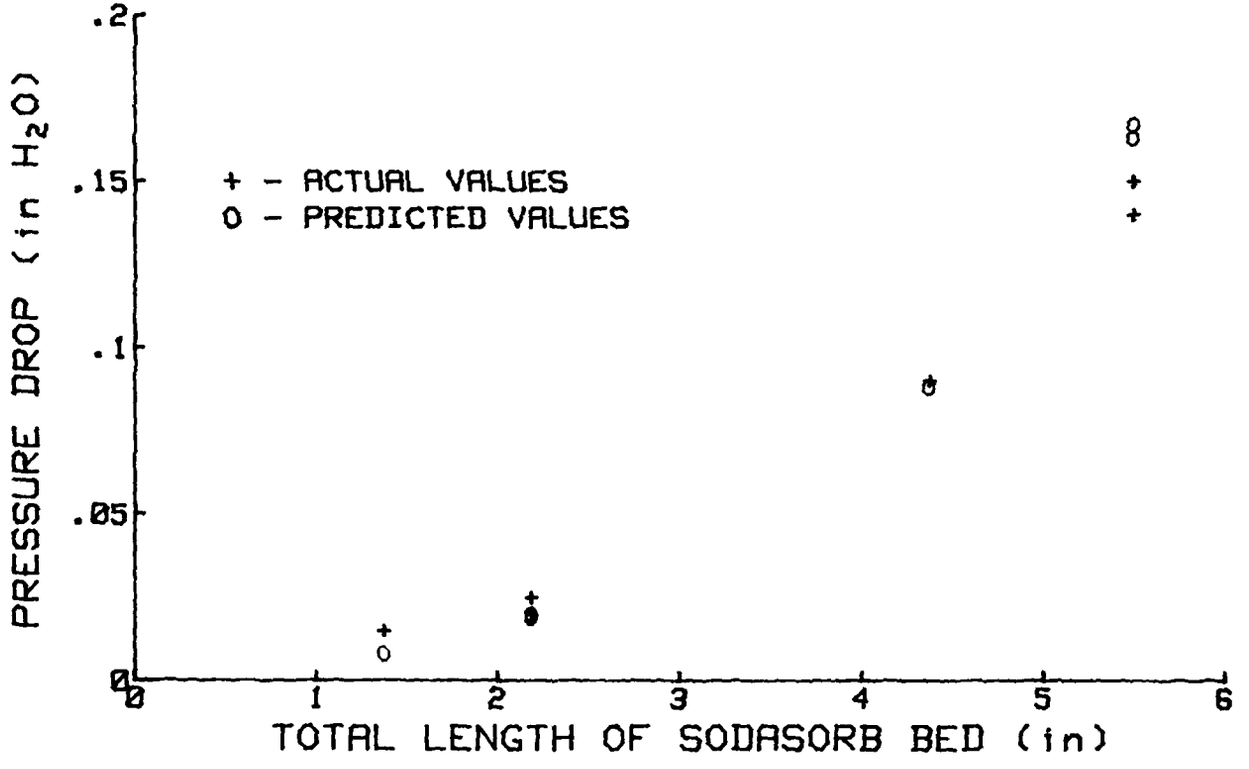


Figure 14. Pressure drop versus total length of Sodasorb bed for entire 'straight' through canister.

The legend for the figures on the next three pages is as follows:

t1/2 : effectiveness (min)

Q : air flow rate (SCFM)

W : white Sodasorb

L : light purple Sodasorb

D : dark purple Sodasorb.

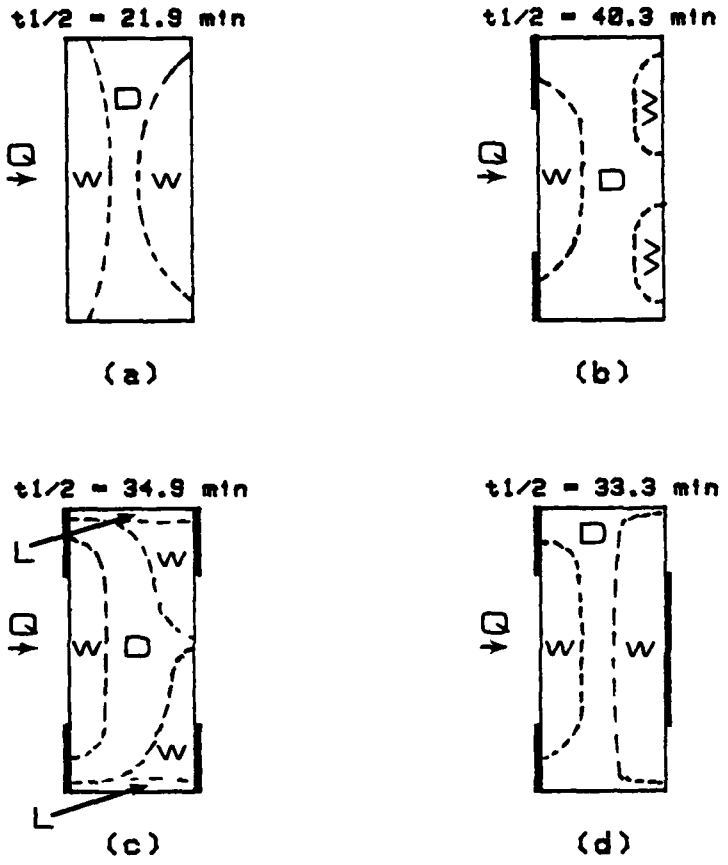


Figure 15. Sodasorb Coloration due to different configurations for L/D of 0.44. (a) 'straight' through canister, (b) R3.5 at entrance, (c) R3.5 at entrance and exit, and (d) R3.5 at entrance and D3.5 at exit.

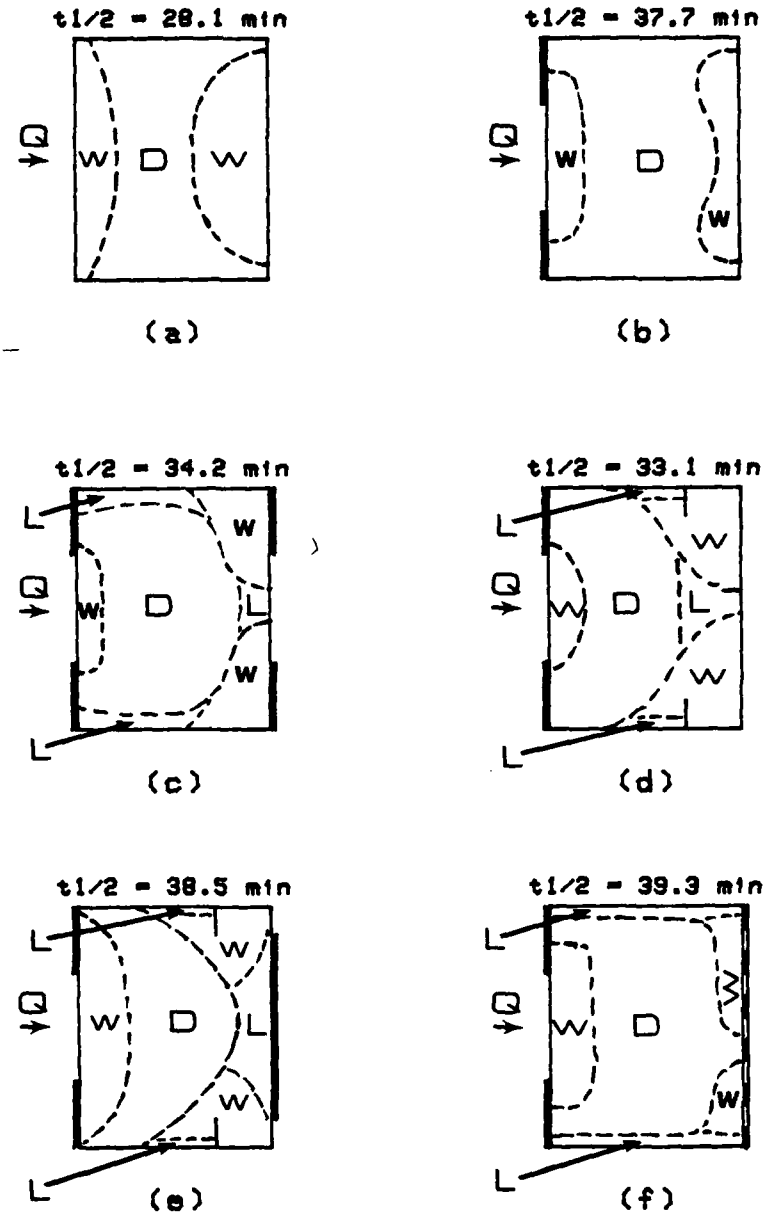


Figure 16. Sodasorb Coloration due to different configurations for L/D of 0.80. (a) 'straight' through canister, (b) R2.5 at entrance, (c) R2.5 at entrance and exit, (d) R2.5 at entrance, and R4 1 1/4 inches from exit, (e) R2.5 at entrance, R4 1 1/4 inches from exit, and D4 at exit, and (f) R2.5 at entrance and H1-9 at exit.

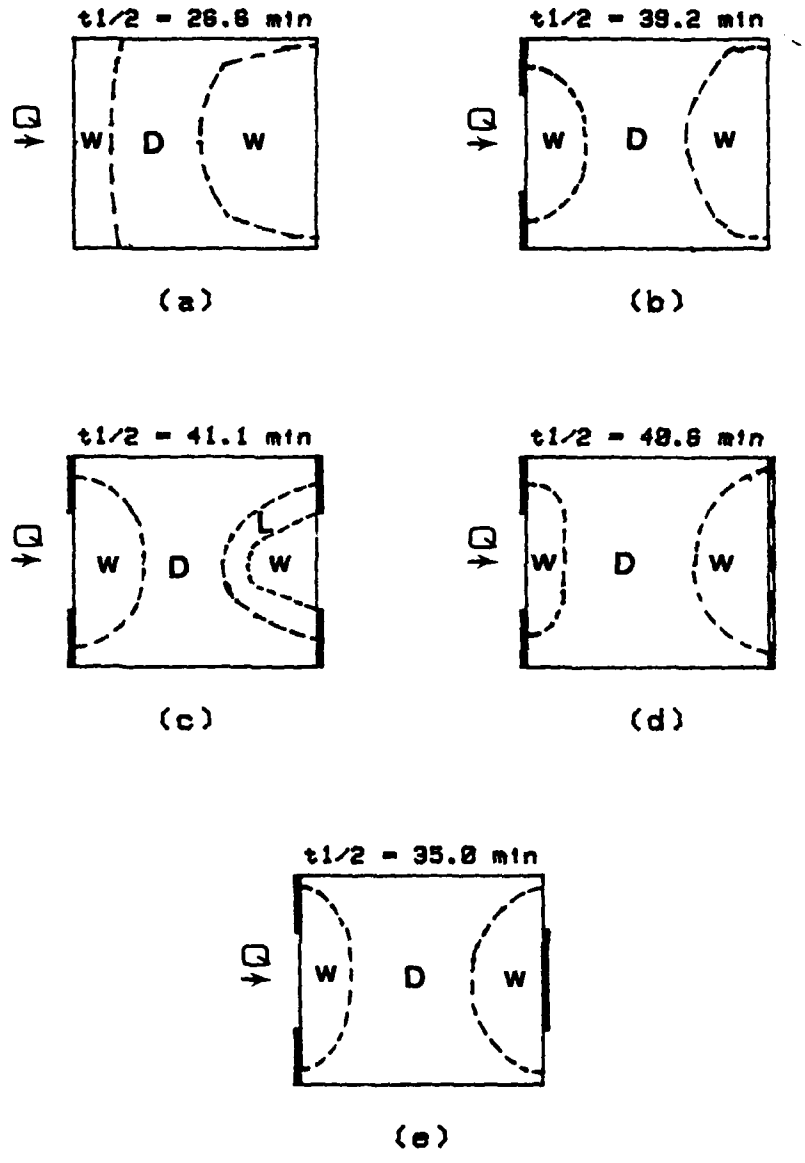


Figure 17. Sodasorb Coloration due to different configurations for L/D of 1.16. (a) 'straight' through canister, (b) R2.25 at entrance, (c) R2.25 at entrance and exit, (d) R2.25 at entrance and H.5-17 at exit, (e) R2.25 at entrance and D2.25 at exit.

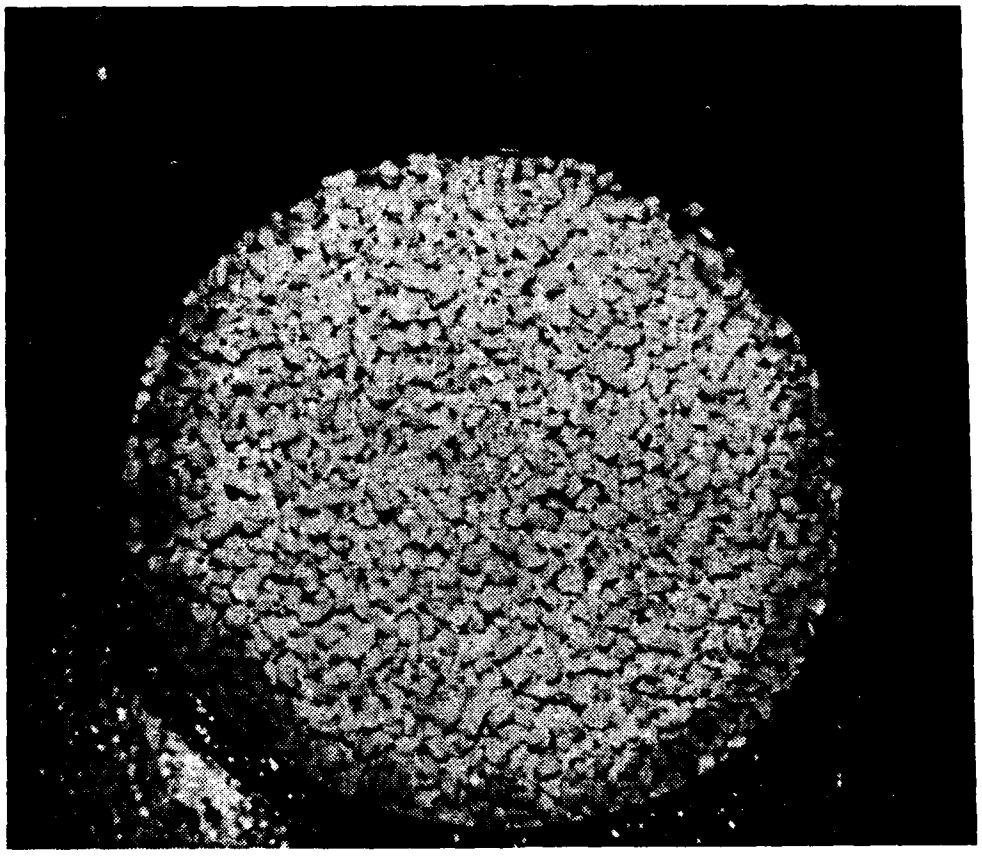


Figure 18a. Example of channeling at exit.

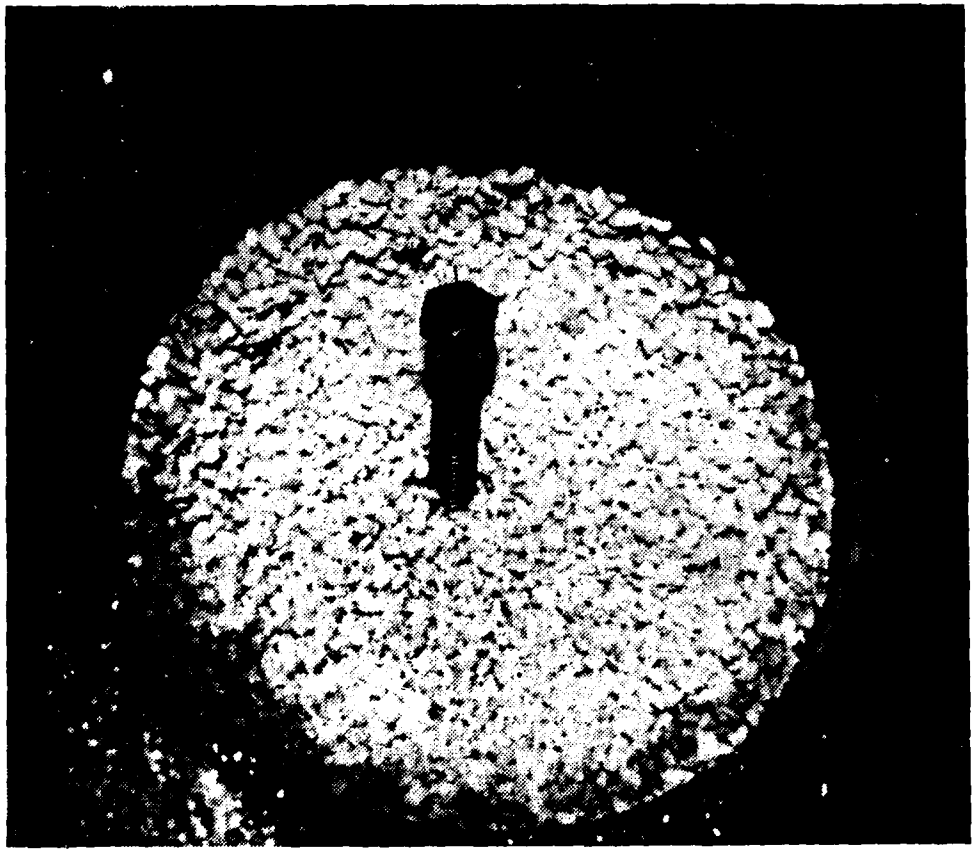


Figure 18b. Example of channeling at 2.75 inches from exit.

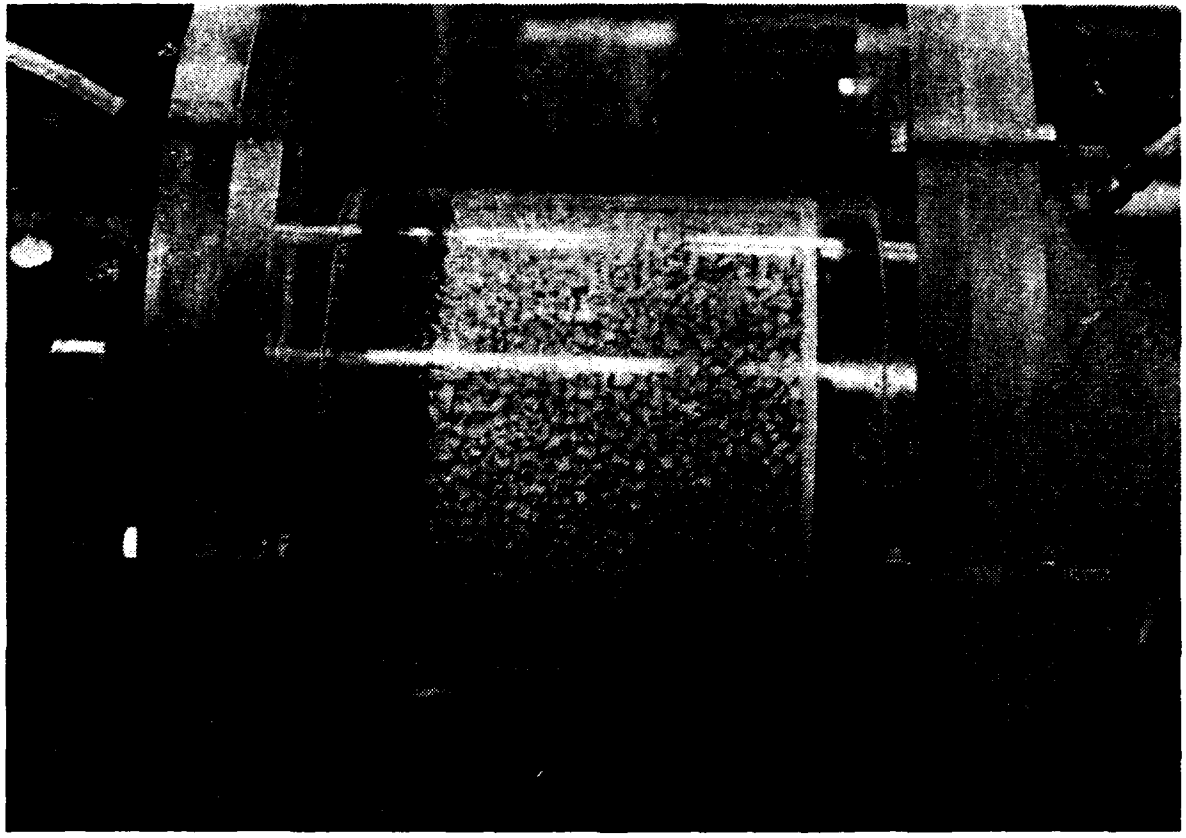


Figure 19. Example of channeling along the wall.

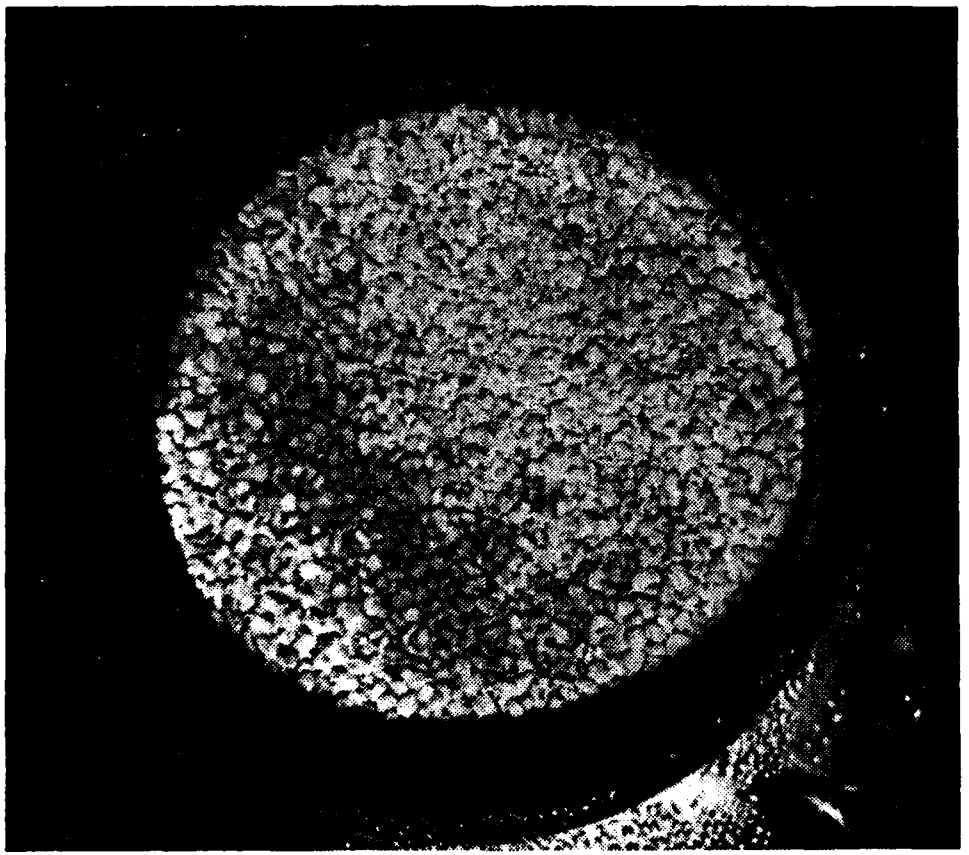


Figure 20. Example of channeling within the bed.

APPENDIX A: EXPERIMENTAL PROCEDURES

A. ALIGNMENT OF THE INFRARED DETECTOR

1. Warm up for 30 minutes.

2. Purge with nitrogen for five minutes.

3. RANGE to CAL, GAIN to 10X, T A FCN switch to 100%T, SLIT to 0, check meter reading of 0.

4. SLIT to 0.5 mm, WAVELENGTH to 3.5 micrometers, TIME CONSTANT to one second.

5. PATHFINDER fully counter-clockwise to stops, then clockwise to 0. Adjust continuous GAIN to a meter reading of 0.6.

6. PATHFINDER fully counter-clockwise to 14.26. PATHFINDER clockwise slowly to a maximum meter reading. (The PATHFINDER was consistently at 40 for a maximum meter reading on all runs.)

7. T A FCN switch to A1, SLIT to 2 mm, WAVELENGTH to 4.25 micrometers.

8. By adjusting the continuous GAIN to read from 0 to 1.0 on the meter, align the recorder to the exact same value as the meter.

9. Adjust continuous GAIN to a meter reading of 0 while nitrogen is being supplied to the infrared detector.

B. TWO HOURS PRIOR TO THE FIRST RUN OF THE DAY

1. Check and replace the Drierite dessicant, if necessary, in the input line to the infrated detector.

2. Verify recorder is aligned with the infrared detector meter reading.

3. Zero all manometers.

4. Fill the water bath and constant-temperature refrigeration unit and provide a large siphon between them to assure equal water levels regardless of the flow setting on the constant-temperature refrigeration unit. Regulate the flow to maximum from the constant-temperature refrigeration unit to the water bath.

5. Drain the water separators (to the infrared detector and in the gas supply line).

6. Blow down the exhaust from the canister hose to remove any moisture.

7. Fill both humidifiers with water to 50% level.

8. Lower the temperature in the bath with ice and stabilize with constant-temperature refrigeration unit, if required.

9. Position thermocouples at the desired positions in the canister. Check for consistent temperature readings. Wipe out inside of the canister with ethyl alcohol and thoroughly blow dry.

C. 45 MINUTES PRIOR TO RUN

1. Shut the supply valve and open the bypass valve at the rotameter exhaust.

2. Fill the canister with fresh Sodasorb. Ensure screens are securely in position to prevent any movement in the Sodasorb. Horizontally inspect the canister to ensure that no movement of Sodasorb takes place with mild shaking of the canister.

D. 30 MINUTES PRIOR TO RUN

1. Check the calibration fo the infrared detector.

2. Ensure the supply hose is not connected to the canister. Establish the desired supply flow rate and valume percentage of carbon dioxide. The carbon dioxide regulator and the air supply regulator should both be at approximately ten psig. Open the valve to the canister and close the by-pass valve. This will produce a pressure in the rotameter which is a little less than what will occur during the run. Recheck the percentage of carbon dioxide with a calibrated gas. Select and record a desired recorder speed. Connect the output from the canister exhaust to the infrared detector.

E. COMMENCEMENT OF RUN

1. When the recorder pen is aligned to a predetermined starting mark, connect the supply hose to the inlet of the canister. RECORD the start time.

2. Ensure flow to the infrared detector.

3. Do NOT allow moisture, dessicant dust or any greater than atmospheric pressure at the infrared detector.

F. COMPLETION OF RUN

1. Purge the infrared detector with nitrogen until the meter reads 0.

2. Check the calibration of the infrared detector at the cutoff carbon dioxide percent. (Do NOT readjust the continuous GAIN from that of the original calibration.)

3. Measure and record the input percentage of carbon dioxide.

4. Determine to the nearest tenth of a minute the time (t1/2) to termination of experiment.

5. Purge the infrared detector with nitrogen.

6. Secure the supply of carbon dioxide to the influent gas, remove the hose from the canister supply connection, and immediately disassemble the canister in the vertical position.

7. Record the coloring of the Sodasorb. Using a vacuum cleaner, selectively remove one-half inch to one inch of Sodasorb and record coloring. Continue until all Sodasorb is removed.

8. Clean and dry all components.

9. Replace drierite in the infrared detector supply line, if necessary.

G. CONSECUTIVE RUNS

1. If consecutive runs are desired, proceed to B.5.

APPENDIX B

1. SAMPLE CALCULATIONS FOR THE PRESSURE DROP ACROSS THE CANISTER.

GIVEN: Test Run # 3-5.5

$Q = 2.11$ SCFM, $D = 5.5$ in, $L = 4.375$ in,

$A_c = 23.76\ in^2$ $T_{avg} = 100\ ^oF = 560\ R$

$P_c \approx P_{atm} = 30.07$ inHg $= 14.77$ psia

From Reynolds and Perkins [9]:

$$R = 53.34\ \frac{ft\text{-}lbf}{lbm\text{-}R}$$

$$\mu = 0.04590\ \frac{lbm}{ft\text{-}hr}$$

Solution:

$$\rho = \frac{P}{RT} = 0.07122\ \frac{lbm}{ft^3}$$

$$V_c = \frac{Q}{A_c} = 12.765\ \frac{ft}{min}$$

From Miller [3]:

$$Re = \frac{\rho V_c}{\mu}\sqrt{k} = 0.39615$$

From Ploss [4]:

$$f = \frac{1}{Re} + 1.67 = 4.1943$$

$$\Delta P = \frac{f\rho V_c^2}{\sqrt{k}}L = 0.088\ \text{in}\ H_2O \qquad \text{(B-1)}$$

2. THE EFFECTIVENESS OF SODASORB IN REMOVING CARBON DIOXIDE FROM AN AIR MIXTURE.

Air containing 6.0 percent by volume carbon dioxide was passed through the porous bed of Sodasorb at approximately 2.1 standard cubic feet per minute. The standard volumetric flow rate was calculated by:

$$Q_s = Q_f \sqrt{\frac{P_f \quad T_s}{P_s \quad T_f}} \qquad \text{(SCFM)} \qquad \text{(B-2)}$$

where:

$T_s = 530$ (R)

$P_s = 14.7$ (psia)

The volume percentage input of carbon dioxide was measured and the time (t1/2) for 0.5 percent carbon dioxide by volume in the exhaust from the canister was experimentally determined.

APPENDIX C: EXPERIMENTAL UNCERTAINTY ANALYSIS

The sources of error in the results presented are due to instrument precision and accuracy, inaccuracies in geometrical measurements, and uncertainty in physical constants.

Instrumentation errors occurred in measuring flow rate, temperature, pressure, volume percentage of carbon dioxide in the gas and time for exhaust gas to reach 0.5% by volume carbon dioxide. The following uncertainties were estimated:

P_{atm}:	negligible			
ΔP_L :	0.10	$\pm$ .005	in H_2O	$\pm$ 5.0%
P_f :	15.0	$\pm$ .05	psia	$\pm$ 0.3%
CO_2 :	6.0	$\pm$ .1	%	$\pm$ 1.7%
CO_2 :	0.5	$\pm$ .01	%	$\pm$ 2.0%
$t_{1/2}$:	30.0	$\pm$ .05	min	$\pm$ 0.8%
T :	530.	$\pm$ 2.	R	$\pm$ 0.4%
Q_f :	2.00	$\pm$ .05	SCFM	$\pm$ 2.5%
L :	4.4	$\pm$ .1	in	$\pm$ 2.3%
D :	5.5	$\pm$ .05	in	$\pm$ 0.9%

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