FOREWORD

This report was prepared by General Dynamics Corporation, Electric Boat Division, Groton, Connecticut. The study, design, fabrication, and testing on which this report is based were carried out under Contract AF33(616)-8008 initiated by the Applied Ecology Section, Sustenance Branch, Life Support Systems Laboratory, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division. 2/Lt D. H. Jensen, Applied Ecology Section, served as contract monitor. The responsibility for this work was transferred to Biospecialties Section, Physiology Branch, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories. This work was performed in support of Project No. 7164, "Space Biology Support," and Task No. 716403, "Environmental Biology." 1/Lt J. E. Vanderveen, Biospecialties Section, served as contract monitor.

The authors, Harold Wallman (Project Engineer for the contractor), John Dodson, Victor Speziali, and Allen Rabe are engineers in the Chemical Engineering Section, and Russell Nickerson and Rodney Cordeiro are engineers in the Instrument Section, all of Electric Boat Division. The report has been assigned Electric Boat Division Document No. U413-62-108.

ABSTRACT

This study was conducted to design, fabricate, and test a liquid-gas contactor and liquid-gas separator system capable of operation as a photosynthetic gas exchanger. The system is designed to handle the oxygen requirements of one man and to be capable of operation under weightless conditions. The gas exchange system consists of four major components: (1) a multi-pass light chamber, (2) an agitated liquid-gas contactor, (3) a centrifugal liquid-gas separator, and (4) an instrument console. We have demonstrated that this system has the capability of supporting one man under normal gravity and should be capable of operation under weightless conditions.

PUBLICATIONS REVIEW

This technical documentary report has been reviewed and approved.

Jos M Quashnock

Jos. M. Quashnock
Colonel, USAF, MC
Chief, Biomedical Laboratory

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I

INTRODUCTION

As the man-in-space program progresses and longer missions are planned, it becomes more imperative that a closed-cycle system be developed which will substantially reduce the need for carrying stored supplies. The photosynthetic gas exchange process is one of the better means of achieving such a closed ecology. This process involves mass transfer between liquid algal suspension and a gas, and therefore, some means of assuring sufficient contact between the two phases must be provided. Since weightless conditions will exist in the first phase of space exploration, the normal rules of behavior of liquids and gases will not apply. A system must be designed which is capable of providing mass transfer of CO_2 into the algal suspension and mass transfer of O_2 out of suspension. The entire system must have the capability of operation under weightless conditions.

The objectives of this program are:

1. Perform a design study of possible methods of liquid-gas contact under weightless conditions including a recommendation of the optimum method.

2. Design and fabricate a contactor unit based on the design study.

3. Test the contactor unit as part of a photosynthetic system.

II

SYSTEM REQUIREMENTS AND DESIGN BASIS

System Requirements

The requirements of the system are as follows:

1. The system shall be capable of separating 0.1 pound of oxygen per hour (i.e., a capacity equivalent to approximately the req. of one man).

2. Operation in a weightless environment (hypothetical) or under normal gravity conditions shall be possible.

3. Design of the contactor shall preclude clogging with algae or foreign material and shall not introduce contaminants or other damaging factors into the algal suspension.

4. The unit shall be designed as a single pass system supplied with a CO_2-air mixture.

Design Basis

The photosynthetic gas exchanger developed under this study was based on the following design parameters:

1.	Species of alga	Thermophilic Chlorella pyrenoidos (Sorokin-Myers 71105 strain)
2.	Concentration of algal cells, minimum (packed cell volume)	0.2% vol/vol
3.	Suspension density control	Continuous dilution at 0.1 vol/hr
4.	Light source	Power Groove fluorescent lamps
5.	Over-all energy conversion	2% efficiency
6.	Lighting area (minimum)	6 sq ft/cu ft of suspension volume
7.	Suspension velocity at lamps (minimum)	0.5 ft/sec
8.	CO_2 measurement	Infrared analyzer

9.	O_2 measurement	Paramagnetic analyzer
10.	Suspension density measurement	Optical photometer

III

DESIGN COMPARISON OF DIRECT CONTACT SYSTEM WITH MEMBRANE SYSTEM

For operation under weightless conditions there are two basic schemes that should be considered to effect the required mass transfer of gas:

1. A membrane system in which the gas phase and liquid phase are separated by a gas permeable film.
2. A direct contact system in which the gas and liquid phases are intimately mixed, and are then separated in a centrifugal device.

Effect of Carbon Dioxide Concentration

When enough light and enough nutrient are available to allow for a high level of algal activity, the absorption of CO_2 by the algae will take place rapidly once the gas is in solution. The large surface area of the algae in suspension and the biological action of the algae aid in increasing the rate of this step in the mass transfer process. Therefore, the transfer of CO_2 from the liquid phase into algal cells will not be a rate controlling step, and the CO_2 concentration in the liquid phase will remain at a relatively low level. Insofar as CO_2 nutrient is concerned, the rate controlling step is the transport of CO_2 from the gas to the liquid (culture) phase. For this reason, in both direct and indirect contact systems, the size of the contactor is a function of the partial pressure of CO_2 in the incoming air stream. Increasing the CO_2 concentration in the gas stream will increase the effectiveness of the contactor unit, thus permitting a decrease in contactor size for a given amount of CO_2 to be transferred. There is apparently an upper limit of carbon dioxide partial pressure beyond which algal growth is inhibited, however.

At one atmosphere pressure this limit corresponds roughly to a CO_2 concentration of 10% in the feed stream for the direct contactor. At this concentration and one atmosphere pressure, the CO_2 concentration in the liquid phase can be found by the Henry's Law equation:

$$p = Hx \qquad (1)$$

where p = partial pressure of solute in gas phase, atm

H = proportionality constant

x = mole fraction of solute in liquid phase

The equilibrium CO_2 concentration in pure water, for a CO_2 concentration in the gas phase of 10 mol % may be calculated as follows:

Sample Calculation

$p = 0.1$ atm

$H = 2.28 \times 10^3$ at 39°C (Ref 1)

$x = 0.1/2.28 \times 10^3 = 4.39 \times 10^{-5}$ mols CO_2/total mols

$\cong 4.39(10^{-5})$ mols CO_2/mol H_2O $(44/18)$ (10^3) =

0.107 grams CO_2/liter of solution

For the indirect contact (membrane) system the exact limit is uncertain but probably is somewhat above 15% (at one atmosphere) on the gas side of the membrane. Since the carbon dioxide concentration in the cabin air will be on the order of 0.5 to 1%, a considerable saving in contactor size can be effected by pre-concentrating the CO_2 to the optimum level for algal growth before the gas stream is fed into the contactor.

A molecular sieve unit is one convenient method of raising the CO_2 concentration. With such a unit, the percentage of carbon dioxide in the feed stream to the contactor can be adjusted as desired. This should lead to a decrease in the weight, volume, and power of the contactor unit, and incur a relatively small penalty in these factors due to the concentrator. The overall system would then be smaller and lighter. The molecular sieve unit has therefore been included in the design discussion of both the direct and indirect systems.

Preliminary Considerations - Indirect Versus Direct Contact Systems

The possibilities for design of the liquid-gas contactor unit have been limited to two promising alternatives. One is an indirect contact system using a membrane which keeps the liquid and gas phases separate while permitting mass transfer of gas molecules. The other is a direct contact system between the liquid and gas phases. In either case, the gas contactor will be separate from the light chamber. A molecular sieve bed will be used to pre-concentrate the CO_2 in the entering gas stream. The auxiliary units (apart from the contactor unit itself) will be practically the same for both systems. These auxiliary units include:

a. Two molecular sieve concentrators for the CO_2 (one regenerates while the other is on stream).

b. Silica gel drying units to remove H_2O preceding the CO_2 concentrators.

c. A surge vessel to assure the proper mixing of air and CO_2.

d. A cyclone separator* to remove gas from liquid under zero gravity.

e. Pumps, heat exchangers, piping, valves, and controls required for the above.

The light contact vessel constitutes the most essential part of the photosynthetic gas exchange system. The liquid-gas contactor may be considered to be the principal auxiliary component to the light contact vessel. The design of the light contact vessel will have very little effect on the choice of a contactor.

Since the other auxiliary items, such as the algae separator and nutrient feed pump, are similar, a comparison of the contactor units should indicate which of the two overall systems - direct contact or membrane - is the more desirable. The following sections analyze the alternatives in detail.

Membrane System

In the membrane contactor the gas and liquid are circulated on opposite sides of a membrane which is permeable to gases but not to liquids. The membrane material having the highest permeability, combined with good strength for relatively thin films, is silicone rubber. Most recent information obtained from previous Electric Boat Division tests and from silicone rubber manufacturers was used in calculating the size of the membrane unit.

The size of a membrane exchanger depends to a great degree upon the permeability of the membrane.

Permeability is defined as:

$$P = \frac{Wd}{Ap} \tag{2}$$

where P = permeability, standard cubic feet-mil/hr-ft^2-psi

W = gas flow rate, SCF/hr

d = membrane thickness, mils

A = membrane area, ft^2

p = partial pressure of gas, psi

---

*The cyclone separator may be unnecessary in the membrane system if the O_2 bubbles permeate the membrane and diffuse back into the gas stream. However, it is unlikely that complete, effective operation can be achieved by this means. See discussion on page 10.

Data obtained from the manufacturer indicated the permeability for silicone rubber membranes to be 0.075 SCF-mil/hr-ft^2-psi. Experimental data obtained at Electric Boat Division substantiates this permeability value. The minimum thickness in which these films are currently made is 5 mils.

With permeability known and thickness selected, the flow rate in SCF per hour per square foot can be calculated as a function of CO_2 partial pressure. Since the CO_2 produced by one man is estimated at 0.9 cubic feet per hour,* the total area of membrane surface needed can be calculated.

The carbon dioxide concentration on the gas side is not constant throughout the membrane unit. As the gas stream flows along the membrane surface, the carbon dioxide is depleted due to transfer across the membrane and the CO_2 partial pressure (and consequently the driving force) is therefore gradually decreased. It was decided to assume a one-pass operation in which CO_2 entered at some high concentration and left the unit at a concentration of 1%.

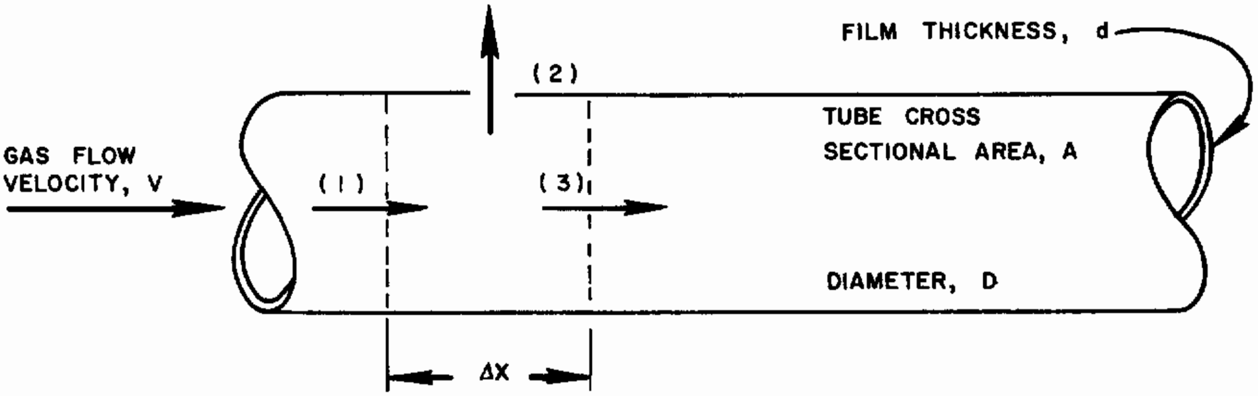


FIGURE I CYLINDRICAL MEMBRANE SEGMENT

---

*This estimate is based on the metabolic rate under normal conditions. It is not yet known whether this rate will change significantly in the weightless situation and under the special conditions of stress, diet control, etc., imposed on the space traveler. However, the above estimate can serve as a basis for calculation.

(1) Gas entering the membrane tube of length ΔX

(2) Gas permeating the film and entering the liquid

(3) Gas leaving the membrane tube over length ΔX

The following terms are now defined:

C_{CO_2} = concentration of CO_2, mols/ft^3
V = gas flow velocity, ft/hr
D = diameter of tube, ft
A = cross sectional area of tube, ft^2
d = thickness of film, mils
p = permeability, here defined in units of mol/hr-ft^2-(mol/ft^3)/mil
π = 3.14

The following is the calculation for unit length of membrane (see Figure 1):

(1) $= C_{CO_2} AV\big|_X$ (mols/hr)

(2) $= \dfrac{C_{CO2}\ P\ \pi\ D\Delta X}{d}$ (mol/hr-ft^2) ft^2

(3) $= C_{CO_2} AV\big|_{X+\Delta X}$ (mols/hr)

Increasing the exit concentration of CO_2 from the membrane unit above 1% would decrease the size of this unit, as the average driving force would then be higher. However, the flow rate of material through the membrane would have to be increased in order to accomplish the same amount of CO_2 removal. Increasing the exit concentration would also place a greater burden on the molecular sieve concentrator unit, the size of which would consequently have to be increased.

The behavior of a gas flowing through a given section of membrane tube can be described with the aid of Figure 1.

Setting the first term equal to the latter two terms, and taking the indicated limit as ΔX approaches zero, there is obtained:

$$\frac{AV}{D}\frac{dC_{CO2}}{C_{CO_2}} = \frac{P\pi}{d}\,dx \qquad (3)$$

The differential equation may now be expressed in integrable form and integrated:

$$\ell n \frac{C_2}{C_1} = \frac{\pi PD}{AVd} (X_2 - X_1) \qquad (4)$$

Sample Calculation: In a typical case, assume that the inlet CO_2 concentration to the membrane unit is 15% whereas the exit CO_2 is 1%. It is desired to find the required membrane exchanger area. (With the diameter of the membrane tube selected at 1 inch, and the length of tube X, determined by calculation, the required area may be easily calculated.)

$P = 1.10$ mol-mil/hr-ft^2-mol/ft^3(=0.075 SCF-mil/hr-ft^2-psi)

$D = 1$ inch = 0.083 ft

$AV = 6$ ft^3/hr (total gas flow rate)

$d = 5$ mils

$$\frac{\pi PD}{AVd} = 0.0096/\text{ft}$$

$$\ln (C_2/C_1) = \ell n\ 15 = 2.708$$

$$\Delta X = 2.708/0.0096 = 282 \text{ ft}$$

$$\text{Total area} = 2\pi r\ X = 73.8 \text{ ft}^2$$

In order to estimate the volume of the membrane unit, an estimate in terms of volume per unit surface area is required.

It has been assumed that 10 ft^2 of membrane surface area can be contained in a volume of 1 ft^3* (Ref 2). Using the above method of calculation, the membrane area was determined as a function of initial CO_2 concentration while holding the final concentration at 1%. This area was then converted to a volume, and the volume was plotted against per cent CO_2 (at 1 atmosphere) for comparison with the direct contact system (See Figure 2).

The photosynthetic reaction generates approximately one mole of oxygen for every mole of carbon dioxide consumed. Since oxygen is not appreciably soluble in water, the oxygen formed will rapidly leave the solution and form bubbles on the liquid side of the membrane. These bubbles will contain nearly 100% O_2, as carbon dioxide is absorbed

---

*This ratio did not appear directly in the article but was calculated from the information given there.

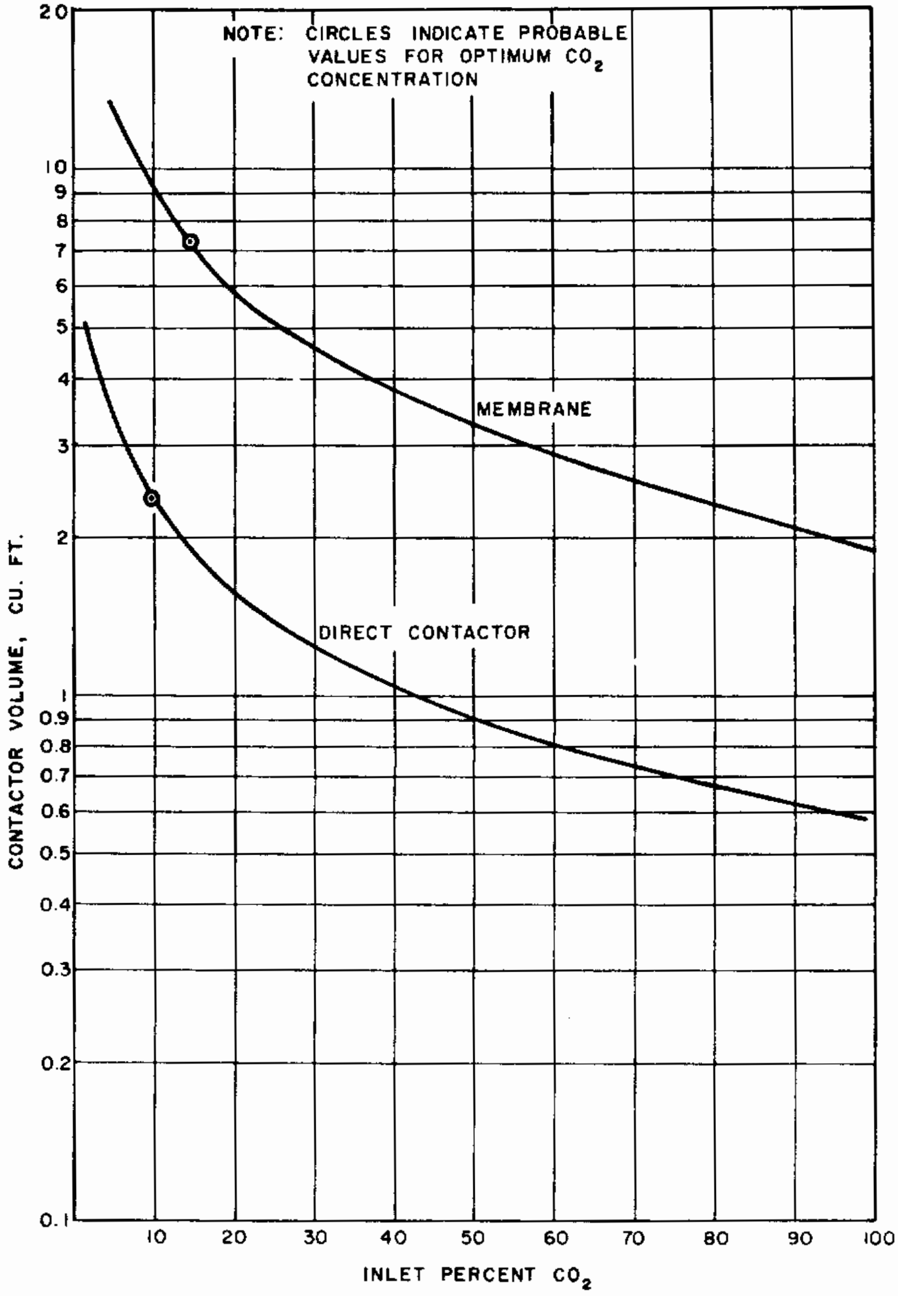


FIGURE 2 VOLUME OF CONTACTOR vs PERCENT CO_2 FOR DIRECT CONTACT AND MEMBRANE SYSTEMS FOR 1% CO_2 EXIT CONCENTRATION

very rapidly by the algae. (Some nitrogen may be present due to diffusion across the membrane from the air stream, but the very slight solubility of nitrogen in water would inhibit mass transfer of appreciable quantities to the liquid side of the membrane.)

The membranes under discussion are more permeable to carbon dioxide than they are to oxygen by a factor of about 5. Therefore, the membrane area needed to transfer 100% O_2 is roughly the same as that required to transfer 20% CO_2. The oxygen bubbles formed will be randomly dispersed through the liquid phase, consequently only limited contact between the bubbles and the membrane will be achieved. Depending upon gas cohesion forces and gas-membrane adhesion forces, oxygen gas held by adhesion at the membrane will permeate through it and will return to the breathing atmosphere. If the oxygen bubbles migrate to the membrane, this would reduce the efficiency of the membrane for transfer of CO_2 into the liquid phase.** With all of the liquid-side membrane surface covered with gas bubbles, the CO_2 molecules would have to diffuse across a stagnant gas film after crossing the membrane. The membrane area, and therefore the volume, would have to be greatly increased to assure the proper rate of transport.

One solution considered for this problem was the design of two concentric membranes with the outer area being about five times as large as the inner area. Hopefully, the CO_2 would pass into the culture through the inner membrane and oxygen would leave by way of the outer membrane. It is probable, however, that such unidirectional flow may only be achieved at the expense of obtaining impractically high steady state operating pressures in the CO_2 feed stream, and perhaps also in the liquid culture vessel, since O_2 is produced throughout the system, not just in the contactor.

To summarize, it would be difficult to insure that all the oxygen bubbles migrate to and adhere to the membrane. If, in fact, this is the case, it is still necessary to increase the membrane area to insure that the oxygen would diffuse out of the liquid phase as CO_2 is transported into the liquid. Consequently, to insure efficient gas transfer, a cyclone separator unit must be included in the design of a membrane system.

Direct Contact System

If a direct contact system is to be used, there are two possible methods of approach. One is to sparge or bubble the gas through a liquid, and the other is to spray liquid droplets through a gas. The choice would depend on the system mass transport characteristics. To transport a CO_2 molecule from one phase to another, it must cross a stagnant gas film and a stagnant liquid film. Resistance to mass transport is considered to be concentrated in these two areas (resistance precisely at the interface is generally assumed negligible). The diffusion

---

** Due to counterdiffusion.

coefficient, film thickness, degree of turbulence in the bulk gas or liquid phase, and affinity (solubility) of the solute gas in the liquid phase all affect the rate of mass transfer.

In general, gaseous diffusion coefficients are larger than liquid diffusion coefficients by a factor of about 10^4. For a system without membranes the film thickness is directly dependent on the degree of mixing to which the bulk gas or liquid phases are subjected. When the gaseous component is readily soluble in the liquid, as, e.g., NH_3 in water, liquid film resistance is generally negligible and the mass transfer process is said to be gas film controlled. In this case it is advantageous to reduce the thickness of the stagnant gas film by increasing gas phase turbulence. This can best be accomplished with a continuous gas phase, viz., a spray contacting system.

In the case of CO_2 and water, however, the carbon dioxide will diffuse through the stagnant gas film much more rapidly than through the stagnant liquid film. A spray contactor would therefore not be feasible as there is no way of creating turbulence within the liquid drops. On the other hand, agitation and turbulence would minimize the liquid film thickness in a gas-sparged exchanger (continuous liquid phase). The gas-sparged exchanger is therefore the preferred method of direct contact for this application. A turbine or other mechanical mixer could be used to create the maximum possible surface area and turbulence. As in the case of the membrane exchanger, the size of the contactor will depend on the rate of mass transfer of CO_2 from the gas phase to the liquid phase. This rate will depend on the CO_2 concentration in the gas being sparged to the contactor.

The problem of mass transfer in an operation in which gas is bubbled through a tank of liquid is rarely discussed in the chemical engineering literature. However, the literature does treat the case of contacting gas and liquid phases over an inert packing, viz., ceramic rings, etc. In order to establish an order of magnitude size range of the direct contact unit, preliminary calculations were made using two extreme assumptions. First, using mass transfer coefficients available for the case of gas-liquid contact in a packed tower, the size of the contactor was estimated at less than one cubic foot.* Second, assuming that molecular diffusion was the only driving force for mass transfer (no mixing, no currents) the unit size was estimated to be greater than ten cubic feet.* The contactor size will lie somewhere between these two extremes.

The basis for the calculation of contactor size needed for the direct contact unit was an experimental study made at Electric Boat Division. In this study a gas stream was bubbled into a water-filled column. Two different gas compositions were used, one contained 5% CO_2 in air and the other contained 100% CO_2; the gas was bubbled through a sparger with four holes, each 1/16 inch in diameter.

---

*For a CO_2 concentration in air of 1%

In the experiment the quantity of CO_2 absorbed was measured and plotted as a function of time. The slope of the curve (i.e., the rate of CO_2 absorption decreased rapidly as the CO_2 level in the water approached saturation. A later test using the algae nutrient medium instead of water showed no significant change in the CO_2 absorption rate.

In a photosynthetic system the carbon dioxide concentration in the water would be maintained at a lower concentration by the algae. Therefore, it is reasonable to assume that the initial absorption rate will apply for sizing the liquid-gas contactor.

The initial absorption rate in this system varies according to the formula:

$$R = kp^n \tag{5}$$

where R = rate, ppm/minute

k = constant

p = partial pressure of gas, mm Hg

n = constant, slope of curve

A logarithmic plot of absorption rate against CO_2 concentration must therefore be a straight line. Using the two known concentrations (100% and 5%), this plot was made, and the intermediate concentrations were obtained from the curve.

As in the case of the membrane unit, a single pass was assumed, with air entering the system at a given initial CO_2 concentration and leaving at a concentration of 1%. Again the pressure driving force is logarithmic and a log mean value for concentration driving force is valid in sizing the unit.

The size of a contactor unit was estimated for various percentages of carbon dioxide in the entering gas stream. A curve was then plotted on the same axis as the curve for the membrane unit in order to compare the two contactors. In order to put the comparison on a fair basis, a factor of 10% was added to the direct contactor size to account for the volume of gas bubbles (estimated at 3%) and internal tank auxiliaries.

Sample Calculation:

Initial CO_2 concentration = 10%

Log mean CO_2 concentration = (10-1)/ln 10 = 3.90%

Absorption rate (from log plot) = 13.5 ppm/minute (by weight) = 0.0135 gram/liter-min

CO_2 produced = 0.83 gram/min (1-man requirement)

Volume needed = (0.83 gram/min) (1/0.0135 gram/liter-min) (0.0351 ft^3/liter) = 2.16 ft^3

2.16 + 0.22 = 2.38 cubic feet (total volume)

The above calculations were based on comparison with a simple sparger unit operating under normal gravity. The proposed system under zero gravity will, of course, behave differently than the normal-gravity case. (Sparging in a unit with no agitation would be unsatisfactory as a bubble emerging from a tube would generally continue to grow at the orifice rather than disengage. This would eventually lead to comparatively large irregular masses of liquid and gas. Since transfer rates depend directly on the total surface area between phases, some way must be found to break up the entering gas stream into smaller bubbles. This could be done by a suitable agitating device.)

In the laboratory experiment, the bubbles were formed by sparging gas through openings 1/16 inch in diameter. Under normal conditions the diameter of a gas bubble approximates the diameter of the opening from which it comes. The diameter of the bubbles formed in the experiment can then be assumed to average approximately 1/16 inch. Therefore, if the gas bubbles created by the action of the mixer in an actual contactor are about 1/16 inch in diameter, the calculated size will be accurate. It is reasonable to assume that an average bubble size of this diameter or smaller can readily be produced.

Contactor Selection

Figure (2) shows contactor size as a function of CO_2 concentration in the inlet gas. It can be seen that, for any given CO_2 percentage, the membrane unit requires at least three times the volume of the direct contactor. The membrane unit would require use of 77% CO_2 to occupy the same volume as a direct contactor using 10% CO_2. It is unlikely that such a high percentage of CO_2 could be used. Therefore, the direct contact system would be chosen over the membrane system on the basis of volume (or weight) of the contactor.

The direct contactor requires a power supply to operate the mixer, while the membrane unit has a somewhat different requirement. The membrane unit entails the pumping of fluid through long, narrow channels, containing many constrictions and bends. The power required to overcome the resulting pressure drop may be sizable and analytically can be shown to be of the same order of magnitude as the power needed to operate the mixer in the direct contactor. The size and weight advantage of the direct contactor will therefore remain essentially unchanged by power considerations.

On the basis of reliability and ease of design, the direct contact system once again would be chosen over the membrane unit. The thin membranes would be fragile and might be subject to rupture or tearing under the high acceleration forces. The oxygen bubbles formed on the liquid side of the membrane, as mentioned previously, pose a difficult problem.

The following table summarizes the comparison of the direct contact and membrane systems:

Design Parameters	Comparison of Alternate Systems
Reliability	Membrane less reliable due to possibility of rupture and O_2 bubble formation.
Weight and Volume	Direct contactor smaller by factor of 3.
Power Consumption	Approximately equal.
Ease of Operation	No apparent advantage to either unit.
Cleaning and Maintenance	Membrane more subject to clogging with algae due to numerous narrow openings.
Contamination of Algae	No apparent advantage to either unit.
Leakage	Rotating shaft seal on mixer might be problem in direct contactor.

The above table shows that the direct contactor has a clear advantage over the membrane unit. A direct contact liquid-gas contactor was therefore selected. The engineering model described in the next section is based on this concept.

IV

DESCRIPTION OF EQUIPMENT

GENERAL ARRANGEMENT

The photosynthetic gas exchange system is designed to function under conditions of weightlessness or normal gravity and consists of four major components, the light chamber, the gas contactor, the centrifugal liquid-gas separator, and the instrument and control console. An overall view of the system is shown in Figure 3.

Figure 4 is a flow diagram showing the relationship of the components within the system. The suspension leaves the circulating pump where a small portion is bled to a drain; the major part of the stream is mixed with nutrient solution at the circulating pump exit line. The suspension flows through the light chamber into the gas contactor. The contactor is provided with a gas and suspension nozzle which thoroughly mixes the algal suspension with CO_2 enriched air metered from the gas mixing circuit. The mixture is sparged into the contactor where a turbine mixer continuously breaks up and disperses the bubbles into the suspension. From the gas contactor the mixture enters the centrifugal liquid-gas separator. Here the suspension and gas mixture are subjected to a helical flow path and consequent centrifugal force which effects separation of gas from suspension. Up to this point in the loop the fluids are under positive pressure due to the outlet head of the circulating pump. The residual pressure at the outlet of the gas separator serves to drive the fluid out of the separator and back to the circulating pump where the process is repeated. The oxygen-rich air under the same pressure is fed to the exhaust gas analyzers and vented to the atmosphere.

Comprising more or less separate subsystems are the nutrient feed circuit and the gas feed circuit. The nutrient supply loop consists of a storage drum where nutrient salts are dissolved in water and the mixture stirred to prevent precipitation of the salts. This concentrated nutrient is fed to a metering pump where a metered supply of fresh water is drawn from a constant head supply tank. The nutrient is diluted to the proper concentration as it is metered into the outlet line of the culture circulating pump. The nutrient supply tanks have not been designed for operation under weightless conditions since, in the ultimate system, nutrient would be recycled and thus these feed tanks would not be required.

The CO_2 gas circuit has been designed to permit the accurate metering of gases under weightless conditions. The system consists of a separate air supply line and a CO_2 metering system which, 5 times each minute, successively charges and discharges a small chamber of known pressure and volume (265 cc). Thus, a predetermined amount of CO_2 gas is fed into the mixing chamber where it is combined with air and subsequently discharged into the gas contactor.

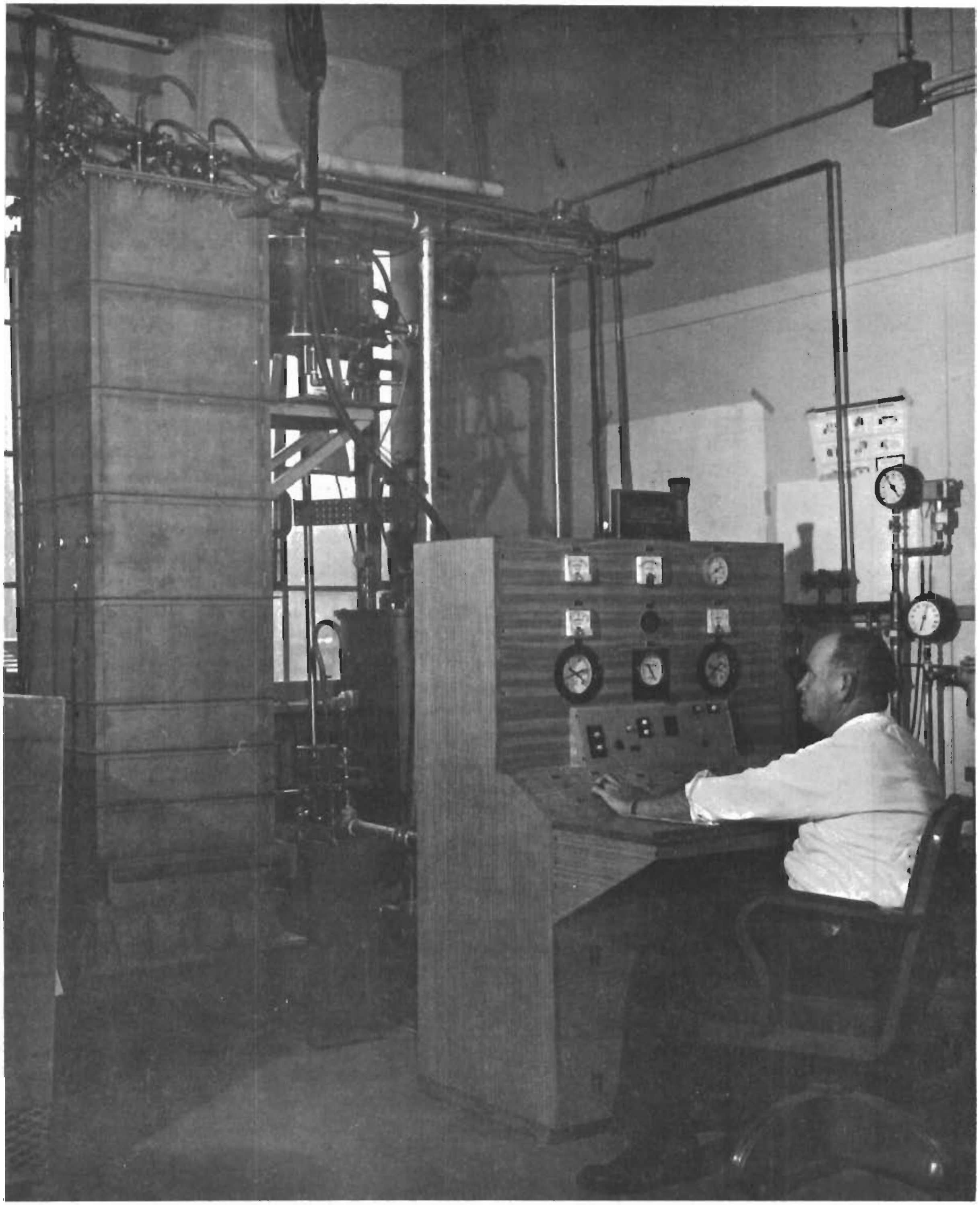


FIGURE 3 OVERALL VIEW OF PHOTOSYNTHETIC GAS EXCHANGER SYSTEM

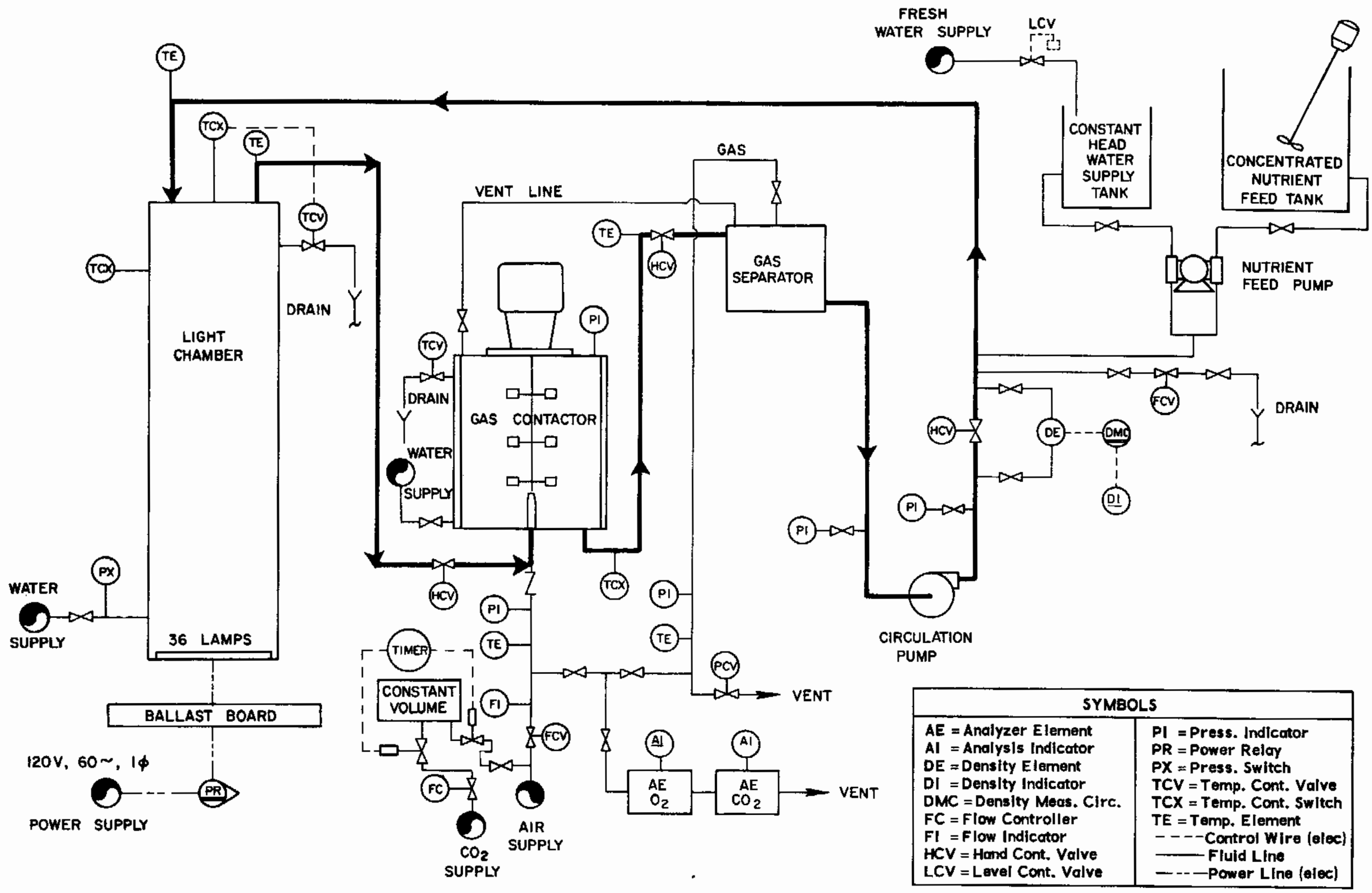


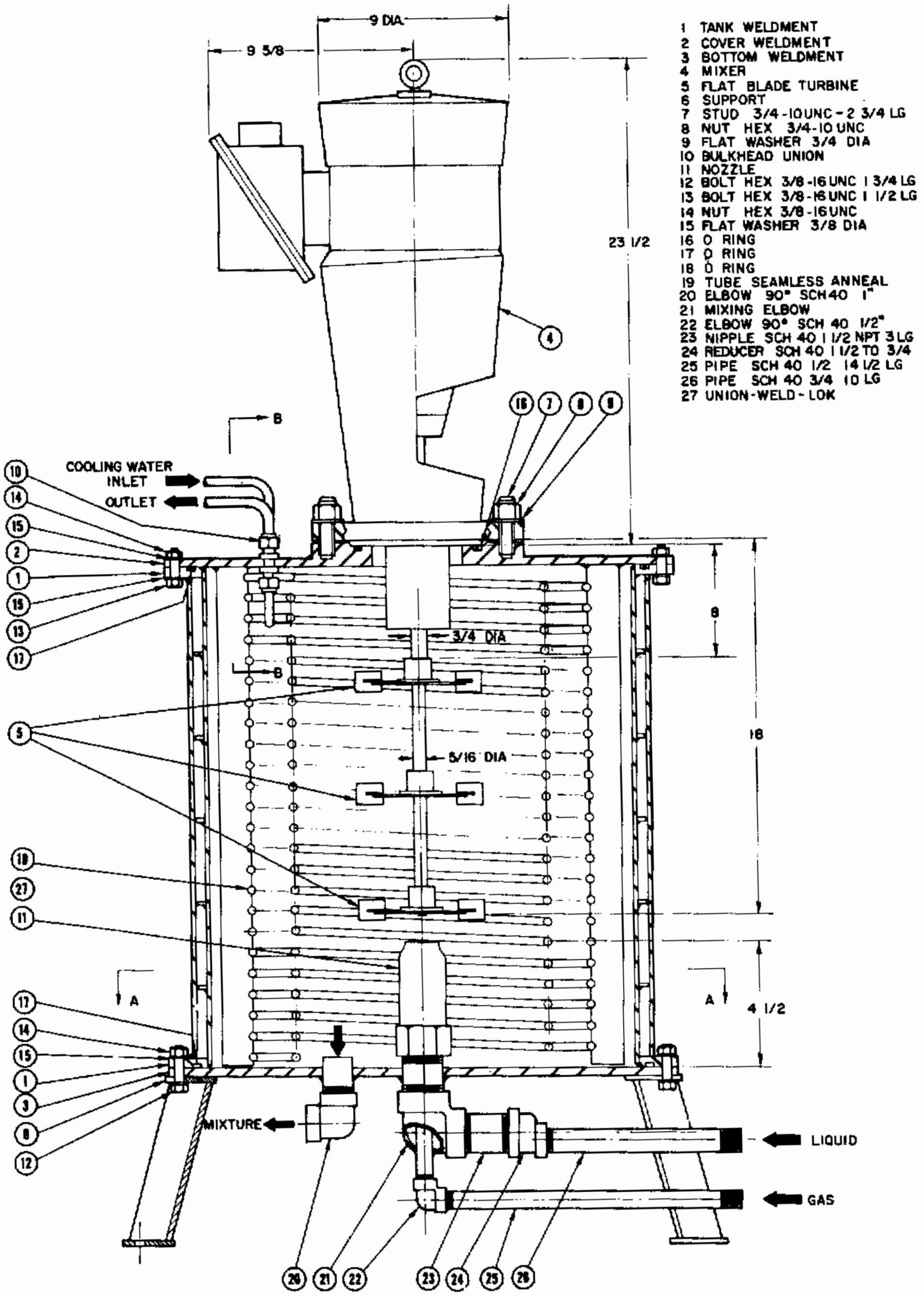
FIGURE 4 ENGINEERING FLOW DIAGRAM

MAJOR COMPONENT DESCRIPTION

Light Chamber - The light chamber is a rectangular structure 21-1/2 inches by 22-1/4 inches in cross section and 90 inches high containing a liquid volume of 131 gallons. The body is fabricated from type 316 stainless steel. The interior of the chamber contains a series of transparent plastic baffles arranged to give 18 vertical passes; each channel brings the culture into direct contact with two 96-inch Power Groove fluorescent lamps. Heat generated by the lamps is removed by trombone cooling coils fitted in passes 4, 10 and 16. Each coil is fabricated from 3/8-inch type 316 stainless steel tubing providing a total surface area of 8.8 sq. ft. The light chamber is fitted with a central drain and each baffle is notched at its bottom to provide flow between chambers when draining. Additionally, the chamber is fitted with a concave observation window allowing the operator a visual check of culture density and lamp surface condition.

Gas Contactor - The gas contactor is a cylindrical vessel 20 inches in diameter and 24 inches high with a liquid capacity of approximately 30 gallons. A turbine type mixer is fitted at the top of the contactor by means of a flange with an O-ring seal. The mixer shaft extends into the contactor through a stuffing box. The mixer is powered by 1/4 hp, 115/230 volt, 60-cycle motor which drives the shaft at 1725 rpm. Within the contactor itself are 6 vertical baffles arranged radially. The 1-1/2-inch by 1/4-inch thick baffles prevent the formation of a vortex due to the turbine rotation and cause vigorous turbulence and break-up of bubbles thus giving good gas absorption by the liquid. Girdling the contactor is an annular cooling water jacket segmentally baffled to provide crossflow; the jacket provides 10.5 sq ft of surface area. Located within the gas contactor between the turbine and the agitator baffles is a helical cooling water coil fabricated from 3/8-inch diameter tubing which provides an additional 14.3 sq ft of surface area. All material of this unit in contact with the culture is type 316 stainless steel except the stuffing box and turbine shaft - these are made of type 304 stainless. The gas contactor is vented at its top into the gas separator inlet. A pressure gage is mounted on the contactor to monitor internal pressure. A cutaway view of the contactor is shown in Figure 5.

Centrifugal Liquid-Gas Separator - In the absence of the effects of a gravitational force, means must be provided for the separation of the gases dispersed in the culture. This is accomplished by the centrifugal gas separator. The separator is constructed of clear acrylic plastic and is cylindrical in shape. The inlet stream enters tangentially thus imparting a curved flow path to the fluid resulting in unequal forces being exerted on the gas and the liquid suspension. As a result, mechanical separation is affected, the gas being drawn off via a tap located at the center and the suspension discharged tangentially where it enters the suction side of the circulating pump. The separator is fitted with an "impeller" supported by two outboard bearings spaced 3 inches apart and located on the same side of the shaft. The impeller is driven by the velocity of the incoming fluid and rotates at



1	TANK WELDMENT
2	COVER WELDMENT
3	BOTTOM WELDMENT
4	MIXER
5	FLAT BLADE TURBINE
6	SUPPORT
7	STUD 3/4-10UNC-2 3/4 LG
8	NUT HEX 3/4-10 UNC
9	FLAT WASHER 3/4 DIA
10	BULKHEAD UNION
11	NOZZLE
12	BOLT HEX 3/8-16UNC 1 3/4 LG
13	BOLT HEX 3/8-16UNC 1 1/2 LG
14	NUT HEX 3/8-16UNC
15	FLAT WASHER 3/8 DIA
16	O RING
17	O RING
18	O RING
19	TUBE SEAMLESS ANNEAL
20	ELBOW 90° SCH40 1"
21	MIXING ELBOW
22	ELBOW 90° SCH 40 1/2"
23	NIPPLE SCH 40 1 1/2 NPT 3 LG
24	REDUCER SCH 40 1 1/2 TO 3/4
25	PIPE SCH 40 1/2 14 1/2 LG
26	PIPE SCH 40 3/4 10 LG
27	UNION-WELD-LOK

FIGURE 5 LIQUID GAS CONTACTOR
(Sectional view)

approximately 100 rpm. This enables the body of fluid within the separator to be accelerated to speed without liquid flooding the gas circuit. The inlet pipe is flared into a fan shape at the entrance for better distribution of fluid across the blade; the number of blades was selected on the basis of having each successive blade turning into the fluid stream before the blade immediately ahead leaves the stream. A seal is provided at the shaft to eliminate leakage into the bearing housing. The bearings, end plates, shaft and impeller blades are constructed of stainless steel. The upper and lower end plates are sealed by O-rings. Details of the separator are shown in Figure 6a and Figure 6b.

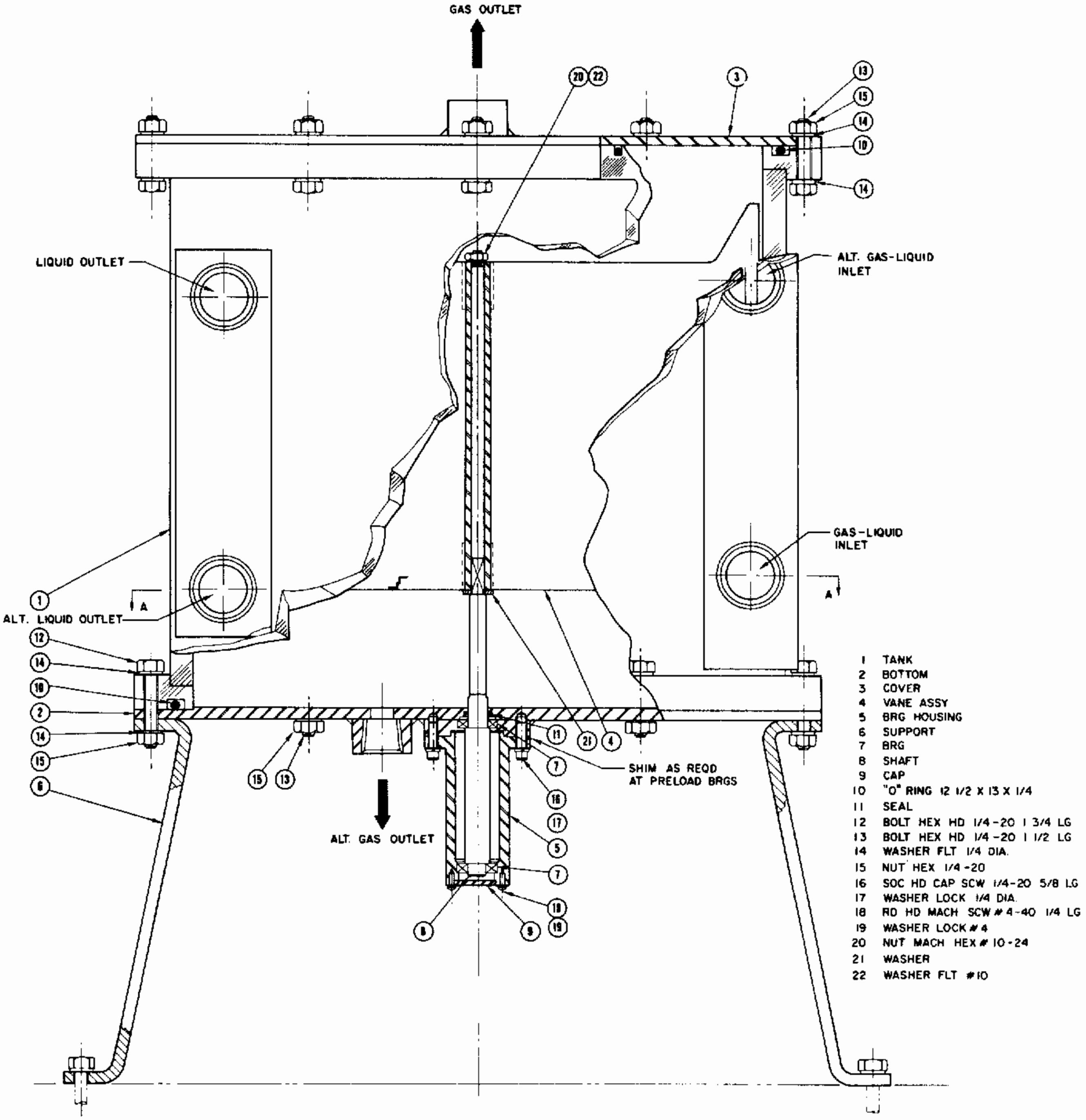
Suspension Circulation Pump - The centrifugal suspension circulating pump is constructed of type 316 stainless steel and rated at 60 gpm with an output head of 48 ft. It is driven at 1750 rpm by a splash-proof 2 hp, 115/230 volt, 60 cycle motor. A throttle valve is located in the pump discharge line in order to balance liquid suspension and gas flows to the gas separator.

Nutrient Feed Pump - Metering of the concentrated solution of nutrient salts into the metered water supply is accomplished by a duplex type pump. The pump has individually adjustable strokes which can be varied from 0 to 100%. Maximum flows are 29 gph on the water side and 985 cc/hr on the concentrated nutrient side. The pumping action is staggered so that as the water is being drawn into the cylinder on one side the nutrient solution is being discharged from the other cylinder. Mixing of the two streams takes place downstream from the pump at a mixing tee in the line. Materials on the water side of the pump are cast iron, stainless steel and plastic; materials on the nutrient side are plastic, stainless steel, glass, and ceramic.

The pump is driven by a 1/3 hp, 115 volt, 60 cycle motor rotating at 1725 rpm. The output shaft of the motor passes through a reducer which gives an 18:1 speed reduction.

Nutrient Feed Tank - The polyethylene nutrient feed tank has a liquid capacity of 15 gallons. It is fitted with a bottom discharge and has a 316 s/s propeller mixer.

Fresh Water Storage Tank - This is a 5-gallon seamless molded polyethylene drum with a float level valve for controlling the water flow into the drum. This tank was incorporated into the system for two reasons: first, direct water line pressure on the suction side of the nutrient pump holds both sets of check valves open and flooding occurs; second, the float level valve provides a more or less constant head on the suction side of the nutrient pump ensuring more accurate metering of water.



1	TANK
2	BOTTOM
3	COVER
4	VANE ASSY
5	BRG HOUSING
6	SUPPORT
7	BRG
8	SHAFT
9	CAP
10	"O" RING 12 1/2 X 13 X 1/4
11	SEAL
12	BOLT HEX HD 1/4-20 1 3/4 LG
13	BOLT HEX HD 1/4-20 1 1/2 LG
14	WASHER FLT 1/4 DIA.
15	NUT HEX 1/4-20
16	SOC HD CAP SCW 1/4-20 5/8 LG
17	WASHER LOCK 1/4 DIA.
18	RD HD MACH SCW # 4-40 1/4 LG
19	WASHER LOCK # 4
20	NUT MACH HEX # 10-24
21	WASHER
22	WASHER FLT # 10

FIGURE 6a LIQUID GAS SEPARATOR
(Sectional View)

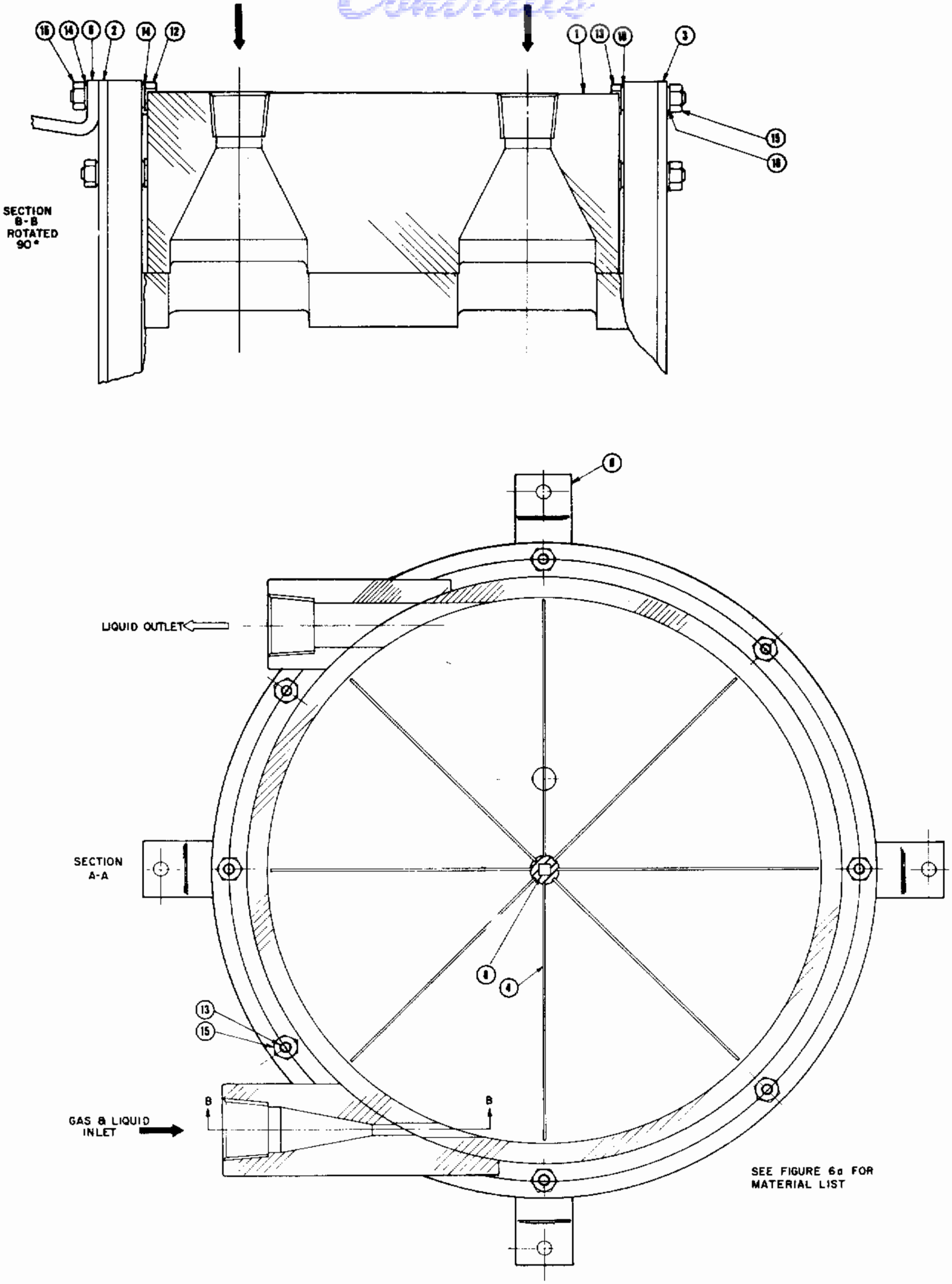


FIGURE 6b LIQUID GAS SEPARATOR
(Plan and detail)

INSTRUMENTATION AND CONTROL

General - Instrumentation and control are based upon the system concept whereby measurements and orders from and to the process mounted instruments are connected to a central console. Both mechanical and electrical instruments are used. A front view of the instrument console is shown in Figure 7. The locations of some of the control points are shown in Figure 3.

Electrical Power - Overall power is supplied through a manual three-phase contactor with neutral.

Constant service buss	(ØB & N)
Control power relay	(ØA & N)
Lamp power relay	(ØA-ØB-ØC & N)

The constant service buss (phase B & N) is used to supply constant power to the oxygen analyzer, the carbon-dioxide analyzer and the nutrient agitator. These devices are allowed to warm up or to operate independently of other controls. The control power relay (phase A & N) is of the locking type and is operated from the front of the console. It supplies power to the following control circuits:

Light chamber temperature control system

Density measuring system

Circulating pump

Carbon-dioxide control circuit

Gas contactor temperature control system

Manual or automatic drain control system

Metering pump

Indicator lamp for phase A & N

The lamp power relay (phases A & N, B & N and C & N) is also controlled from the front of the console and allows voltage to be applied to 36 fluorescent lamps in the light contacting chamber. This relay can be locked in only when there is both sufficient water pressure for cooling purposes and the temperature in the 13th pass of the light chamber is below 102° F. Locking relays can be de-energized by their respective stop buttons. In order to leave six fluorescent lamps on at all times, a triple-pole, double-throw (3PDT) switch has been placed in the rear of the console. In the down position the six lamps operate normally, that is with the rest of the lamps. With the switch in the up position, the six lamps remain on as long as the manual three phase contactor is

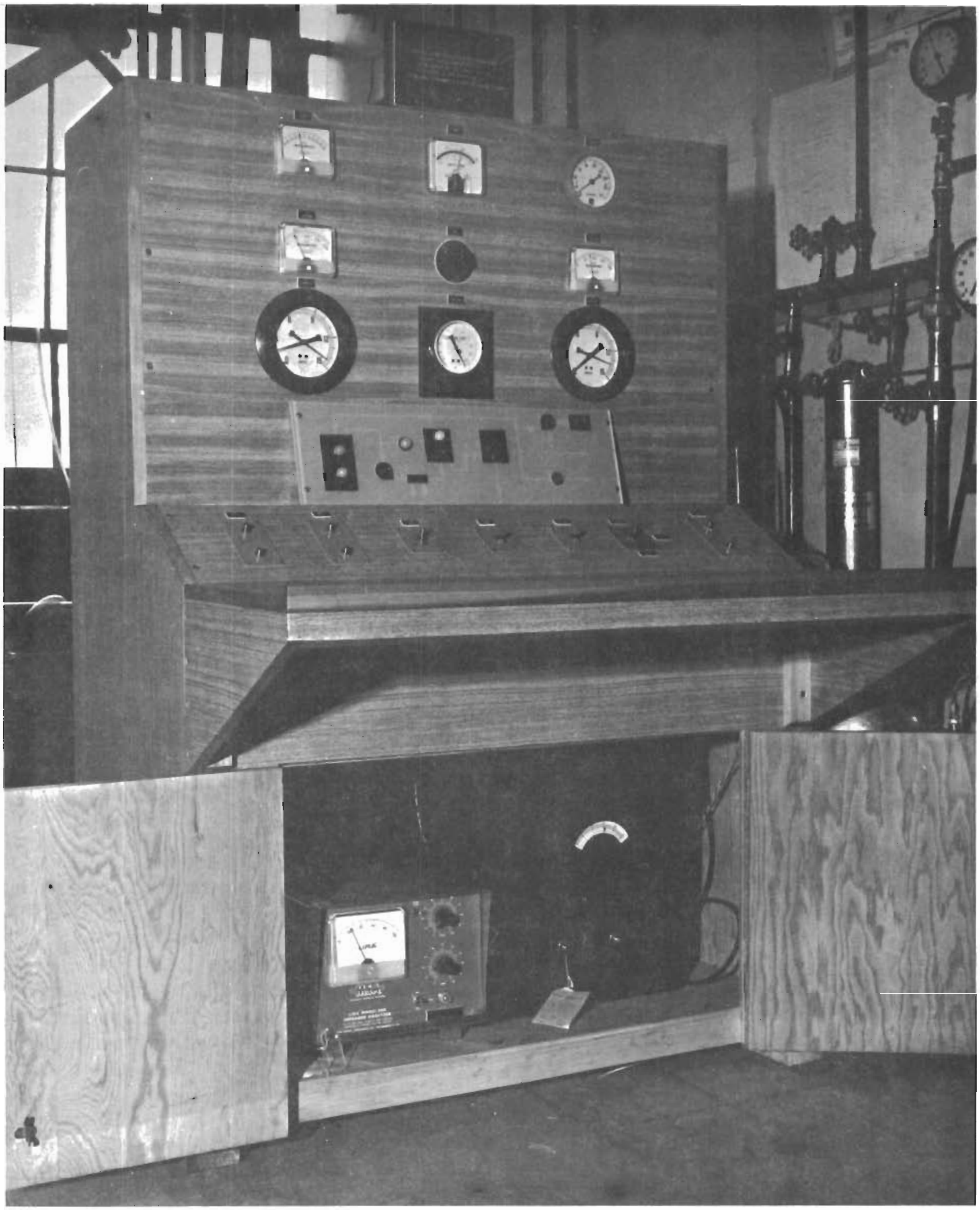


FIGURE 7 INSTRUMENT CONSOLE- FRONT VIEW

on. This allows start-up with a reduced number of lamps. It should be noted here that there is a center position on the switch which leaves the six lamps out of the circuit.

Control Circuits - Energizing of the control power relay allows the density measuring system to be energized by its switch on the rear of the console; the circulating pump to be started by means of its own locking relay and push buttons; and the gas contactor agitator and the metering pump to be operated by their switches. The control power relay, the circulating pump, the gas contactor, the metering pump, and the lamp power relays are provided with indicating lamps mounted in the graphic panel on the front of the console.

The light chamber temperature control system is automatic, wherein an adjustable, bi-metallic finger probe operates the water cooling solenoid valve as indicated by a light in the graphic panel. A check of this temperature control can be obtained from a dial temperature indicator set into the wall of the light chamber or from the temperature indicator on the front of the console. The latter indicator measures the temperature at any one of five thermocouples by means of a selector switch.

The gas contactor temperature control system is the same as the light chamber control system. A check of this temperature control can be obtained from the temperature indicator on the front of the console. Of the five thermocouples, the one closest to the temperature control system should be used for checking purposes.

The system drain solenoid valve can be operated from the front of the console by means of a triple-pole double-throw switch and is indicated by a light in the graphic panel. The 3PDT switch in one position allows manual drain and in the other position will allow automatic drain with the addition of an inventory control system. There is a center position, "off" for this switch.

Regardless of the settings or combinations of devices actuated from the control panel circuit, the control power relay stop button will de-energize these circuits when pressed.

Gas Analyses - The incoming and outgoing gas streams can be manually sampled by a manifold on the rear of the console. Both the oxygen analyzer and the carbon-dioxide analyzer are located in the bottom of the console. There is an indicating meter for each of the analyzers on the front of the console. The manifold also provides for standard gases for the analyzers.

Algal Density System - The algal density system consists of a density element, a power supply, and a density indicator on the front of the console.

The density element has a wiping plunger which can be operated manually to clean the windows of an optical path through a sample stream. The power supply furnishes voltage to a lamp and a four arm bridge. One arm of the bridge contains a photo-cell which receives light from the lamp through the sample algae stream. The unbalance in the bridge is indicated by the meter on the front of the console, which indicates the change in algal density. The flow of algal suspension through the density element can be adjusted.

V

TEST OPERATION

After completion of assembly, calibration of instruments, static testing, cleaning, and routine shake-down, the system was operated on a 24 hour/day, 5 day per week basis to study system capability, gas liquid contacting, gas liquid separation, and algal growth rates. The unit was operated for two series of tests, the first with gas-liquid mixture entering the separator through the bottom inlet and the second with the mixture entering through the top inlet. High speed close-up photographs were taken before inoculation in both test series to show the behavior of the separator (see Section VI). In the first series of tests several minor mechanical and electrical malfunctions occurred; these malfunctions were serious enough to interfere with proper algal growth and the data obtained were inconclusive. After making necessary repairs, satisfactory operation was obtained. The second test series is described in the following paragraphs.

General Start-up and Operating Procedure

The system was filled with nutrient solution, and the lamps, circulating pump, and gas system were turned on. The gas-liquid system was then dynamically balanced at a liquid flow of 60 gpm and a gas flow of 150 SCFH. The temperature of the circulating liquid was gradually increased to 98°F and the system inoculated with 25 liters of 0.1% packed cell volume algal suspension. The gassing rate was increased to 185 SCFH, and the system was operated as a batch process until the algal density reached 0.27% packed cell volume. Nutrient was then introduced at the rate of 62.5 liters/hr (16.6 gals/hr) and the system operated on a continuous dilution basis.

During the test period, algal densities, liquid flow rates, gas flow rates and compositions, and system temperatures and pressures were read from the indicators once an hour and recorded. The algal densities were obtained by reading the optical density of a sample in an electrophotometer and converting to algal density as per cent packed cell volume.

Theoretically the oxygen production rates (and the carbon dioxide consumption rates) could be determined by (1) measuring the change in composition of the feed gas as it passed through the system or (2) by measuring the algal growth rate and relating this rate to an equivalent gas exchange rate. The first method is more direct and is preferred providing the differences in composition between inlet and outlet gases are significant.

Batch Operation

If the log phase of the growth curve during batch operation is assumed to be linear, the growth rate can be calculated from the slope of the line (see Figure 8). Calculated data for the batch operation is listed in Table I. The algal growth rate for this period was 25.8 gms dry algae per hour which is equivalent to an oxygen production rate of 1.01 SCFH and a CO_2 consumption rate of 0.83 SCFH.

Continuous Operation

Typical operating conditions during the continuous dilution phase were as follows:

Inlet Gas Flow Rate	185-190 SCFH
Suspension Circulation Rate	60 gpm
Suspension Temperature	100 ± 2°F
Inlet CO_2 Concentration	1.38 - 1.50%
Outlet CO_2 Concentration	0.52 - 0.55%
Inlet Oxygen Concentration	20.6 - 20.8%
Outlet Oxygen Concentration	21.1 - 21.5%
Inlet Gas Pressure	13-14 PSIG
Pressure in Gas Contactor	8-10 PSIG
Nutrient Feed Rate	16.6 gals/hr
Nutrient Ratio: $\frac{\text{Concentrate}}{\text{Total}}$	$\frac{\text{1 part vol}}{\text{80 parts vol}}$
System Dilution Rate	0.1 vol/hr

Table II summarizes typical calculated data for the period when the system was operated as a continuous culture. The average growth rate over this period was 29 gms dry algae per hour (equivalent to 1.18 SCFH of oxygen and a CO_2 consumption of 0.98 SCFH). The doubling time was calculated as 10.2 hours, at an average density of 0.20% packed cell volume. The average oxygen production by calculation from the change in gas composition was 1.15 SCFH with a CO_2 consumption of 1.62 SCFH (see Section VI).

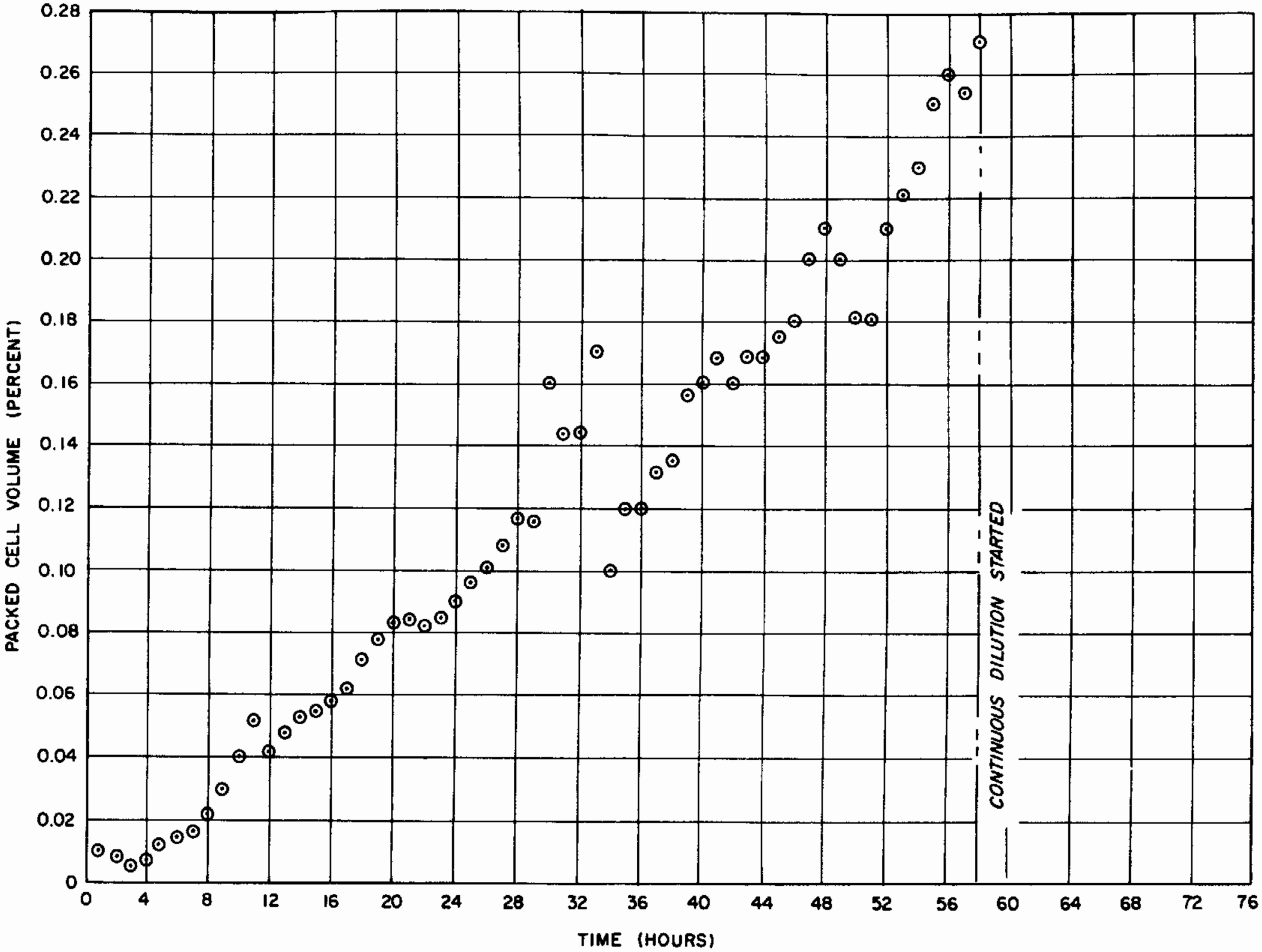


FIGURE 8 PACKED CELL VOLUME VERSUS TIME BATCH OPERATION

TABLE I

BATCH OPERATION DATA AND CALCULATIONS

TIME	Inlet Gas Press. (PSIG)	Gas Flow (SCFH)	CO_2 in (%)	CO_2 out (%)	ΔCO_2 (SCFH)	O_2 in (%)	O_2 out (%)	ΔO_2 (SCFH)	Algal Density (PCV %)
2300	15.0	149	1.15	0.55	0.89	20.70	20.90	0.30	0.180
2400	15.0	170	0.90	0.40	0.85	20.75	20.95	0.34	0.210
0100	14.0	168	1.15	0.55	1.03	20.75	21.30	0.34	0.220
0200	14.8	192	1.15	0.38	1.32	20.70	21.25	1.06	0.230
0300	14.8	192	1.15	0.40	1.43	20.65	21.25	1.15	0.250
0400	14.8	192	1.25	0.42	1.57	20.65	21.25	1.15	0.260
0500	14.8	192	1.26	0.50	1.45	20.75	21.25	0.96	0.255
0600	14.0	188	1.26	0.42	1.58	20.75	21.20	0.84	0.270

TABLE II

TYPICAL CONTINUOUS OPERATION DATA AND CALCULATIONS

TIME	Inlet Gas Press. (PSIG)	Gas Flow (SCFH)	CO_2 in (%)	CO_2 out (%)	ΔCO_2 (SCFH)	O_2 in (%)	O_2 out (%)	ΔO_2 (SCFH)	Algal Density (PCV %)	Dilution Rate (g/h)
0700	13.5	187	1.38	0.53	1.57	20.75	21.20	0.84	0.225	16.6
0800	13.5	187	1.40	0.52	1.65	20.65	21.10	0.84	0.200	16.6
0900	13.5	187	1.38	0.53	1.59	20.60	21.25	1.12	0.185	16.6
1000	13.5	187	1.50	0.55	1.78	20.65	21.30	1.23	0.187	16.6
1100	13.5	187	1.48	0.53	1.78	20.65	21.35	1.31	0.175	16.6
1200	13.5	187	1.35	0.53	1.53	20.80	21.50	1.31	0.160	16.6
1300	13.5	187	1.35	0.53	1.53	20.80	21.45	1.23	0.170	16.6
AVERAGE	13.5	187	1.41	0.53	1.62	20.70	21.31	1.15	0.196	16.6

VI

DISCUSSION

Since this unit was primarily designed as a liquid-gas contactor and liquid-gas separator system capable of operation under weightless conditions, the observation of the gas separator and gas contactor operated under normal gravity conditions is of prime importance.

Gas Separation

Figure 9a and Figure 9b are close-ups of the gas-liquid entrance and liquid exit with bottom entrance of the mixed stream. A small quantity of gas was entrained in the exiting liquid stream with gas separation being about 95-96% complete. Figure 9c and Figure 9d show the behavior of the gas separator under top entrance conditions. There were very few entrained gas bubbles in the liquid exit line with a gas separation of approximately 98-99%. It is true that under the latter condition advantage was taken of the force of gravity, but under gravity independent conditions the concave vortex in the center of the vessel would be a hollow cylinder of water. With a top entering stream the water is successively moved downwards making two to three circuits of the circumference before leaving and should give comparable separation under weightless conditions. In any case separation of 95-99% of the gas is more than adequate since a small quantity of gas circulating through the rest of the system would not interfere with its operation.

Gas Liquid Contacting

The agitation in the liquid gas contactor was sufficient to give a widely dispersed gas-liquid suspension. No noticeable gas separation or pockets of gas were apparent at operating flow ratios. Bubble dispersion was excellent as can be seen in the mixed stream in Figures 9a and 9c. Under weightless conditions this dispersion would be uniform and no separation would occur until the high velocity stream entered the centrifugal separator.

Liquid Inventory

Under continuous operating conditions the liquid inventory was satisfactorily managed by adjusting the needle valve in the algae withdrawal line to give a discharge rate equal to the nutrient feed rate. Under normal gravity test conditions, the level in the liquid-gas separator was quite sensitive to liquid inventory change for any balanced set of conditions.

Algal Growth and Gas Exchange

The oxygen production calculated from algal growth during the continuous phase checked very closely with the average oxygen production

LIQUID-GAS SEPARATOR

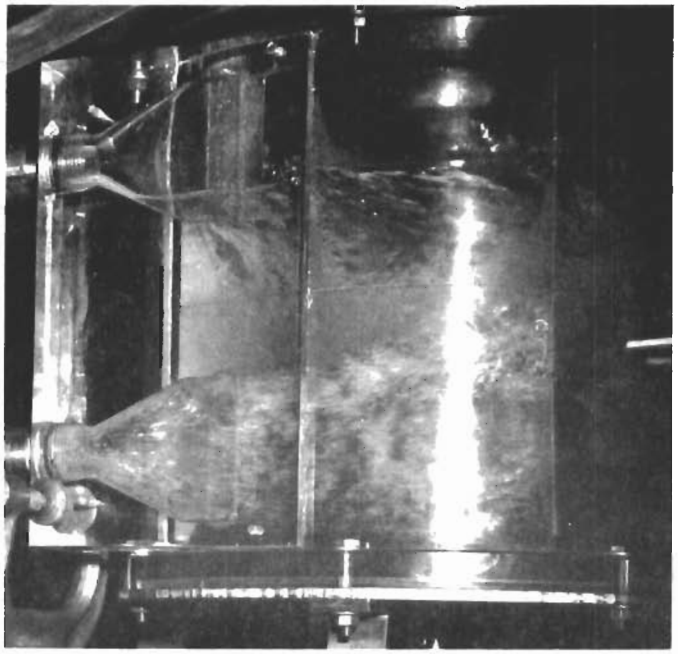


FIGURE 9a

BOTTOM ENTRANCE - ENTRANCE SIDE

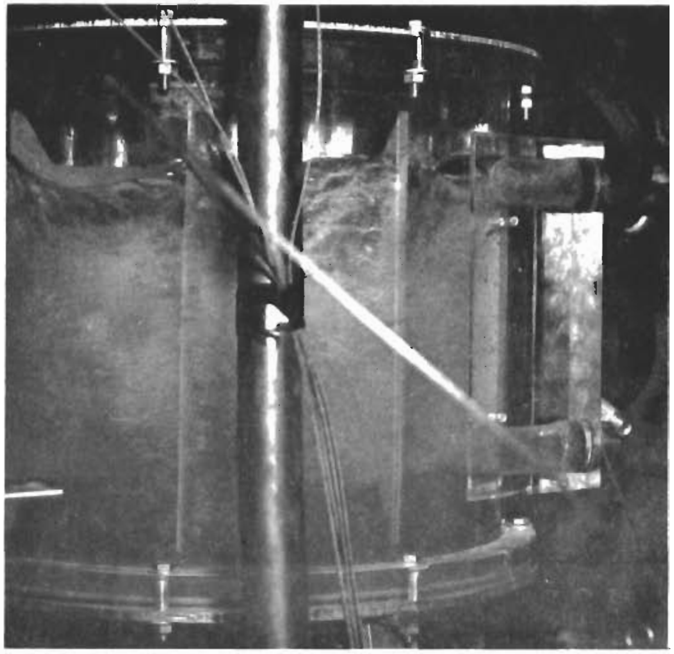


FIGURE 9b

BOTTOM ENTRANCE - EXIT SIDE

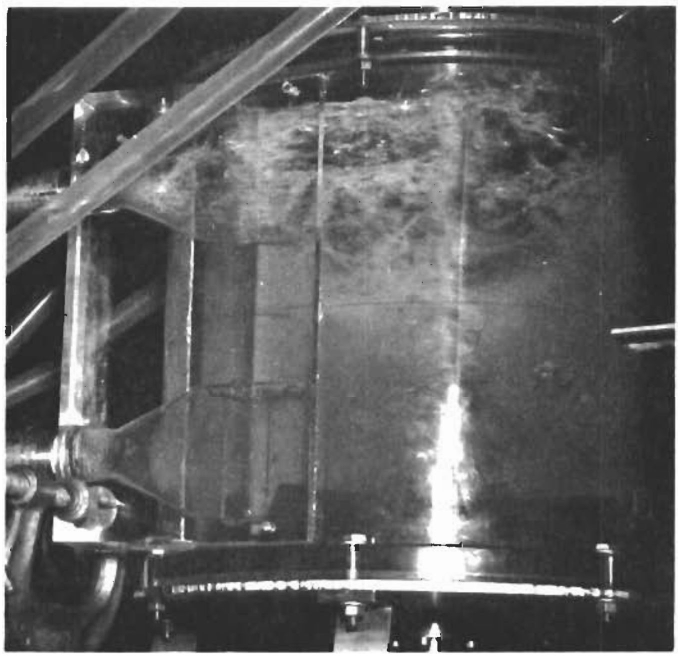


FIGURE 9c

TOP ENTRANCE - ENTRANCE SIDE

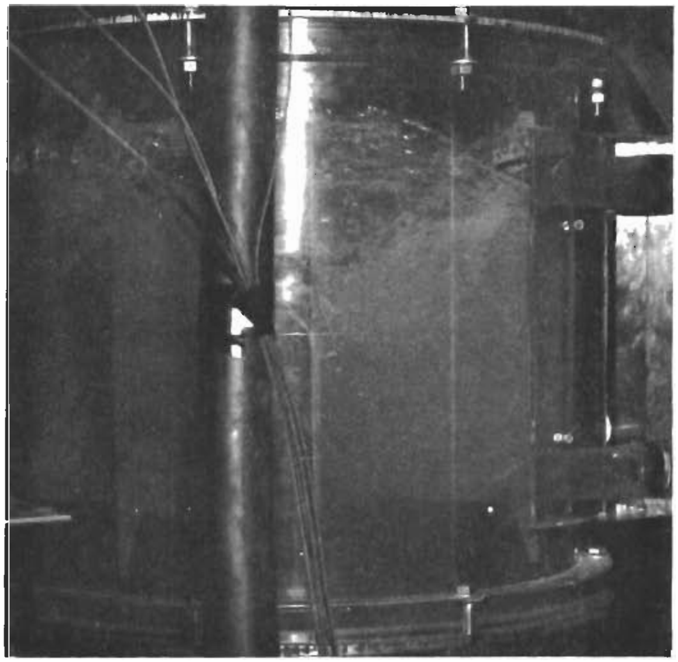


FIGURE 9d

TOP ENTRANCE - EXIT SIDE

computed from analyses of the gas streams entering and leaving the apparatus (see Section V).

The carbon dioxide consumption rate based on changes in gas stream composition is considerably more than the theoretical equivalent amount calculated from algal growth. This discrepancy can be explained by the fact that the inlet composition, because of the method used for introducing CO_2, was subject to surges, and the readings had to be averaged. The outlet composition was very steady, as expected, since the incoming gas was thoroughly mixed in going through the system.

Due to the limited time available for actual testing, information such as optimum operating levels of CO_2, nutrient dilution rate, and suspension circulation rates could not be determined. Nevertheless, the performance test did demonstrate that this photosynthetic gas exchange system possesses the capability of meeting the requirements of one man under normal gravity and under weightless conditions. Under optimum conditions it is anticipated that this unit will exceed the requirements of one man.

VII

SUMMARY

A liquid-gas contactor and liquid-gas separator system capable of operation as a photosynthetic gas exchanger under weightless conditions was designed, fabricated, and tested. The system consists of four major units: a multi-pass light chamber, an agitated liquid-gas contactor, a centrifugal gas-liquid separator, and an instrument console. Based on the growth rate of algae, the unit produced up to 1.15 SCFH (0.102 lb/hr) of oxygen under normal gravity and should give satisfactory performance under weightless conditions.

REFERENCES

1. Perry, J. H., Chemical Engineers' Handbook, 3rd Ed., Mc-Graw-Hill Book Co., New York, 1950, p. 674
2. Cohan, H. J., Chem. Eng. Progress, 57, No. 2, p. 75, February 1961