DESIGN AND DEVELOPMENT OF AN ENGINEERING MODEL PHOTOSYNTHETIC GAS EXCHANGER

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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 (PGE) process is one of the better means of achieving such a closed ecology.

Before a PGE system can be utilized to support man in space, there is much in the way of engineering and biological testing that must still be done. This report describes the design and preliminary testing of an engineering model PGE system capable of supporting one man. The unit was designed for various purposes, such as:

1. To test automatic control of a steady-state PGE system under various modes of operation.

2. To provide algae grown under steady-state conditions for nutritional purposes.

3. To test utilization of treated human waste.

4. With suitable additions to the equipment, to evaluate

physiological variables under closed environmental conditions.

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II

SYSTEM REQUIREMENTS AND DESIGN BASIS

System Requirements

The requirements of the system are as follows:

1. The PGE shall be capable of processing the carbon dioxide output of one man.

2. The system shall incorporate means for the controlled introduction of all necessary fluids and for the continuous withdrawal of excess algal material so as to maintain the desired concentration of algae in suspension. Appropriate fluid circulation devices shall also be included.

3. Equipment for the separation of algal cells from the withdrawn suspension shall be provided.

4. The system shall be adaptable to operate by means of stored carbon dioxide or in conjunction with live subjects. (The unit as designed is operated with stored CO_2 and can easily be adapted to operate with live subjects.)

5. Indicating and recording equipment shall be provided for measuring the inlet and outlet gas composition, suspension density and temperature, and other variables necessary to insure adequate control.

6. The system shall be designed to operate on 110-115-volt, 60-cycle power.

Design Basis

The engineering model PGE system developed under this study was based on the following design parameters:

1.	Algae species	Thermophilic Chlorella (Sorokin-Myers 71105 strain)
2.	Algae concentration, minimum (density)	0.2% vol/vol
3.	Density control	Continuous dilution at 0.1 vol/hr or (alternate) optical photometer
4.	Light source	"Power Groove" fluorescent lamps

5.	Over-all energy conversion efficiency	2.0%
6.	Lighting area (minimum)	6 sq ft/cu ft of culture volume
7.	Culture velocity at lamps (minimum)	0.5 ft/sec
8.	Gas-liquid contact method	Counter-current sparging tower, liquid velocity 0.2 ft/sec
9.	Carbon dioxide measurement	Infrared analyzer
10.	Oxygen measurement	Paramagnetic analyzer
11.	Suspension density measurement	Optical photometer

III

DESCRIPTION OF EQUIPMENT

General Arrangement

The photosynthetic gas exchange system consists of three major components, the light contact chamber, the gas contact tower, and the instrument and control console. An overall view of the system is shown in Figure 1.

The circulation of algae suspension is depicted in Figure 2. Algae culture is circulated within the 18-pass light contacting chamber where a nearly constant temperature profile is maintained. From the light contacting chamber the culture suspension flows into the top of the gassing tower where it mixes with incoming nutrient. The suspension passes over a gas disengaging baffle and falls to the liquid level, which is approximately 12 inches below the top of the gas contact tower. The suspension flows from top to bottom while CO_2 enriched air is admitted through the sparger situated in the base of the tower. The gas bubbles up through the suspension where absorption occurs, then enters the head space where it is exhausted to the atmosphere or, alternately, directed to the gas analyzing apparatus. At the same time the suspension flows from the bottom of the gassing tower into the suction side of the algae circulating pump, and the entire cycle is repeated. The discharge line of the pump contains a drain valve which is actuated by either of two signals: culture density or culture level in the gassing tower. Upon opening of the drain valve, culture is discharged to a centrifuge that extracts the algal material from the suspension.

The concentration of carbon dioxide and oxygen is measured in both incoming and exiting air streams. The gas is kept at a pressure slightly above ambient by a back pressure valve in the system, eliminating the need of using a sampling pump. The analyzers are connected in such a fashion that one of each analyzer is used for detection measurement in both incoming and exhausting gas streams.

Exhaust gas from the gas contacting tower passes through a vapor condenser minimizing water loss in the system.

The light contacting chamber and gassing tower are situated adjacent to one another on the test floor, each being mounted on a special foundation (see Figures 3 and 4). Each foundation is so designed as to achieve the following two purposes:

1. The exact height differential between the levels in each component - this minimizes the amount of pump work necessary to effect proper flow.

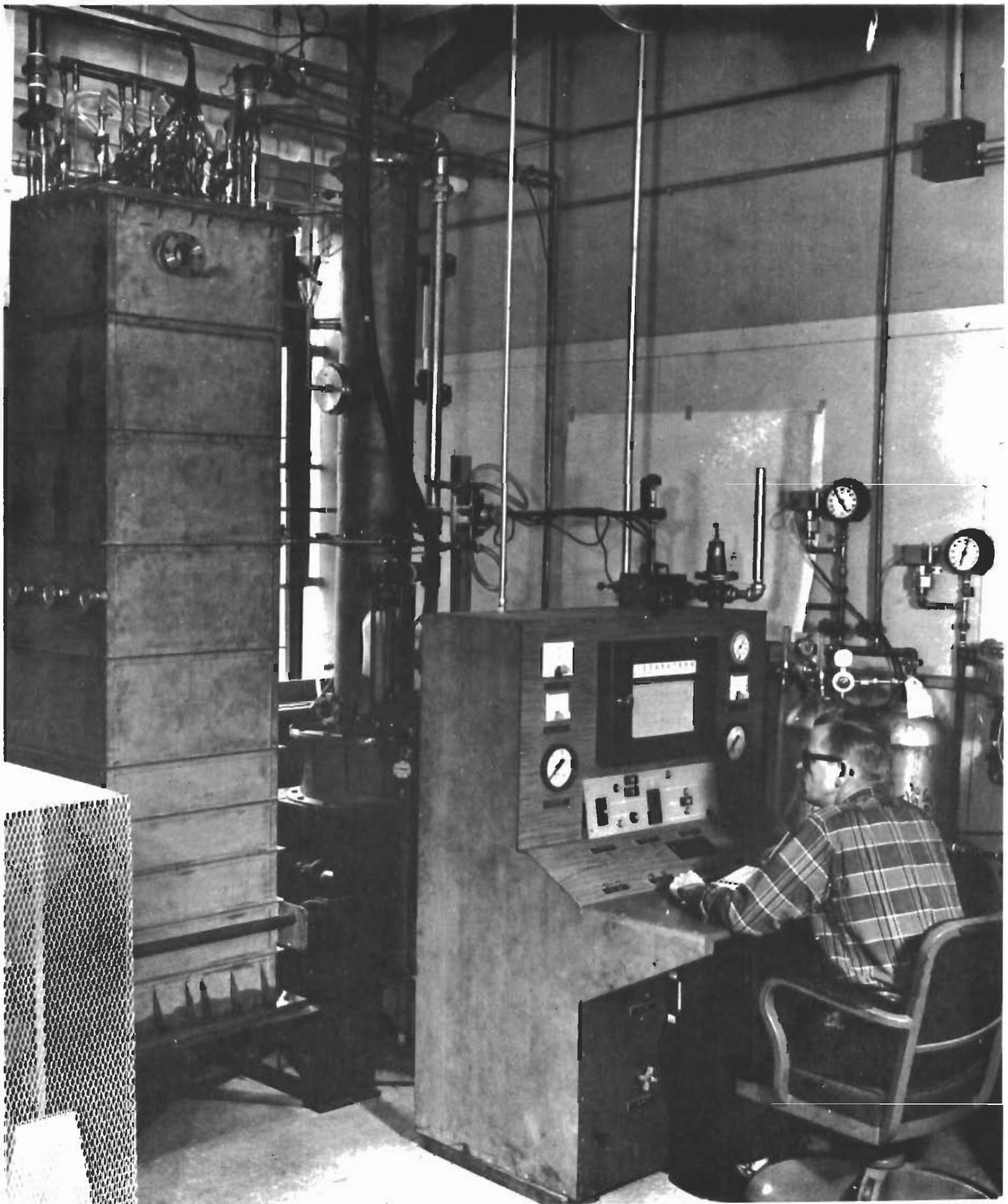


FIGURE I GENERAL VIEW OF PHOTOSYNTHETIC GAS EXCHANGE SYSTEM

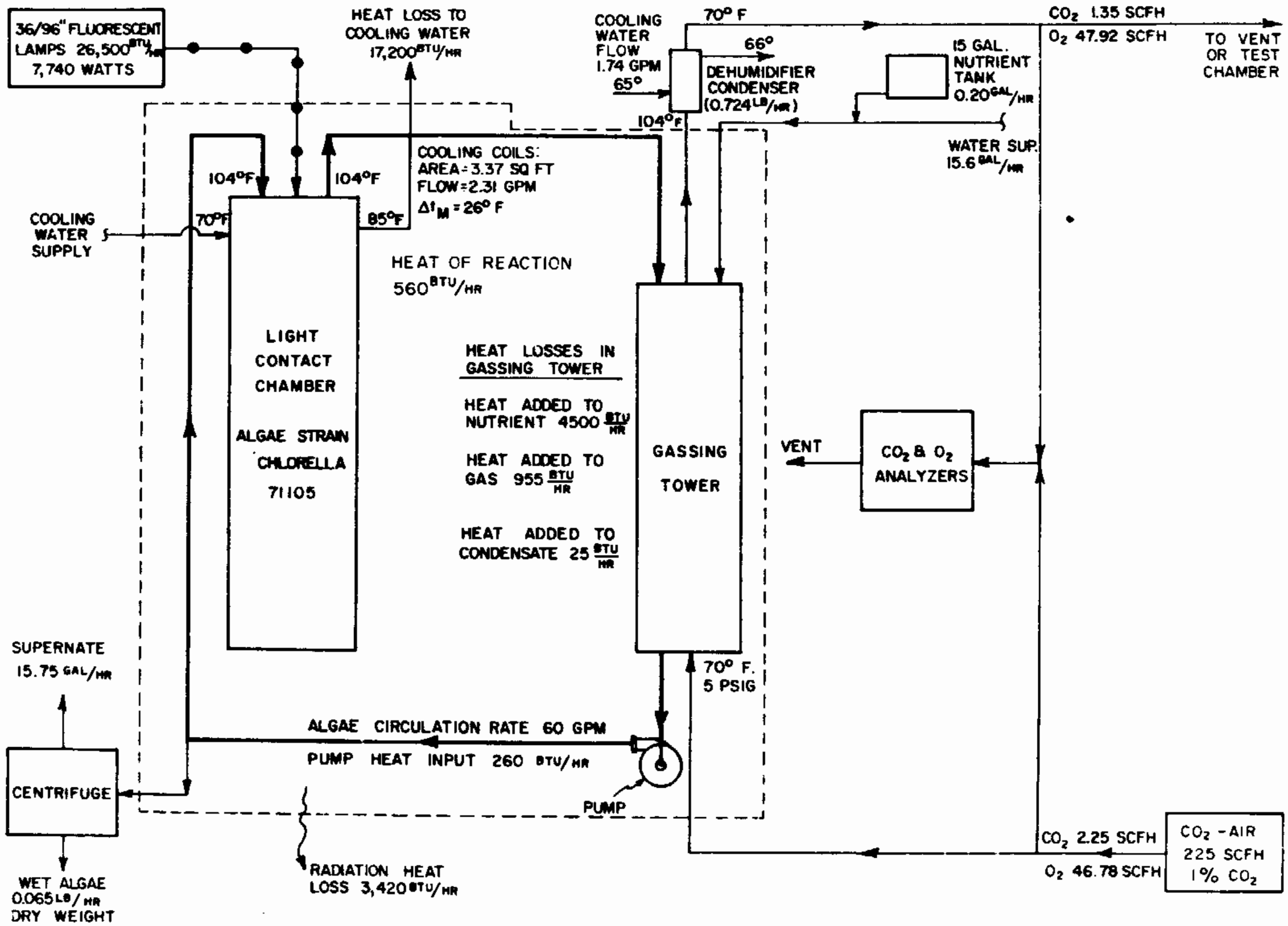


FIGURE 2 PROCESS DIAGRAM-DESIGN BASIS

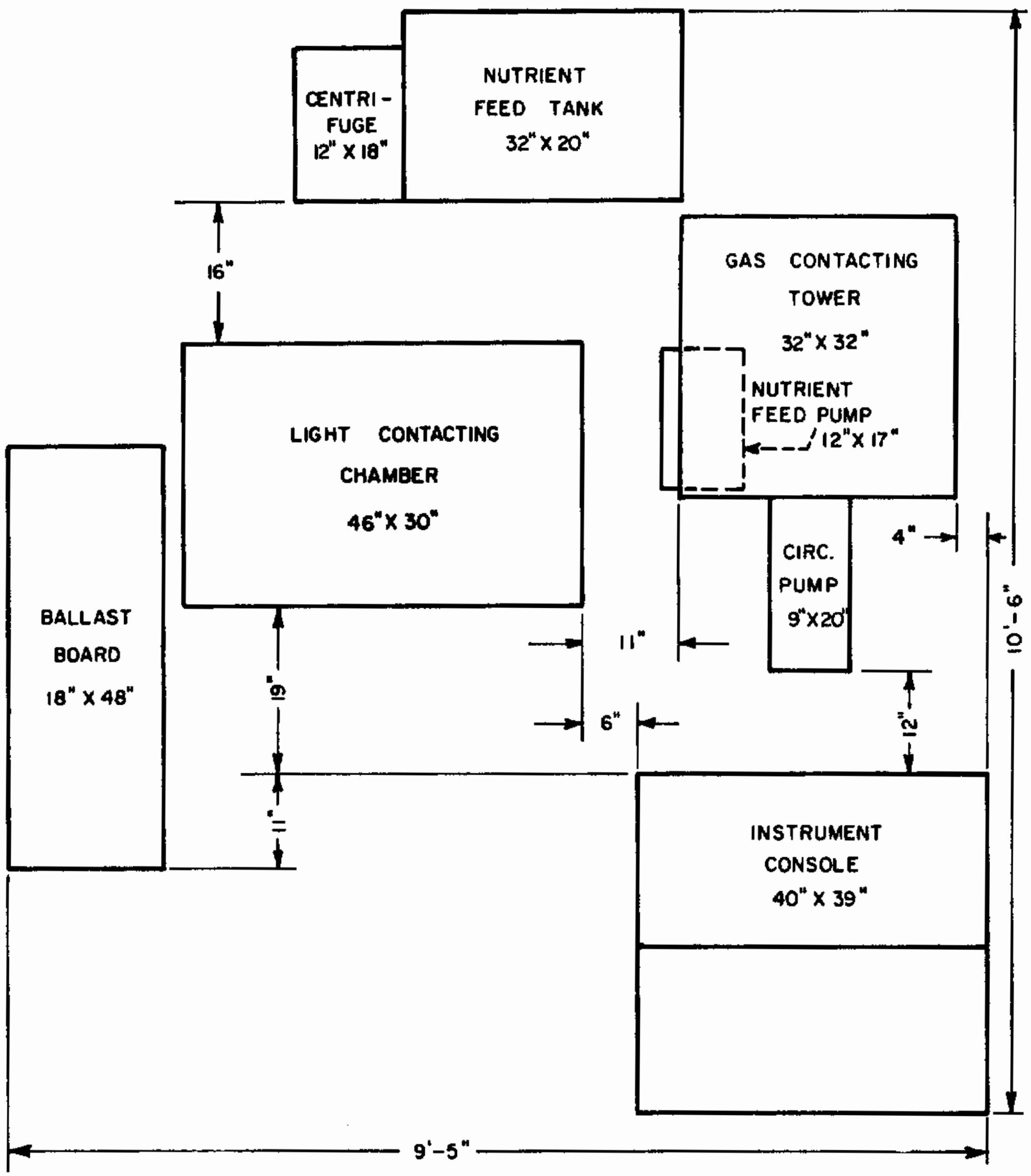


FIGURE 3 MAJOR COMPONENT ARRANGEMENT (PLAN VIEW)

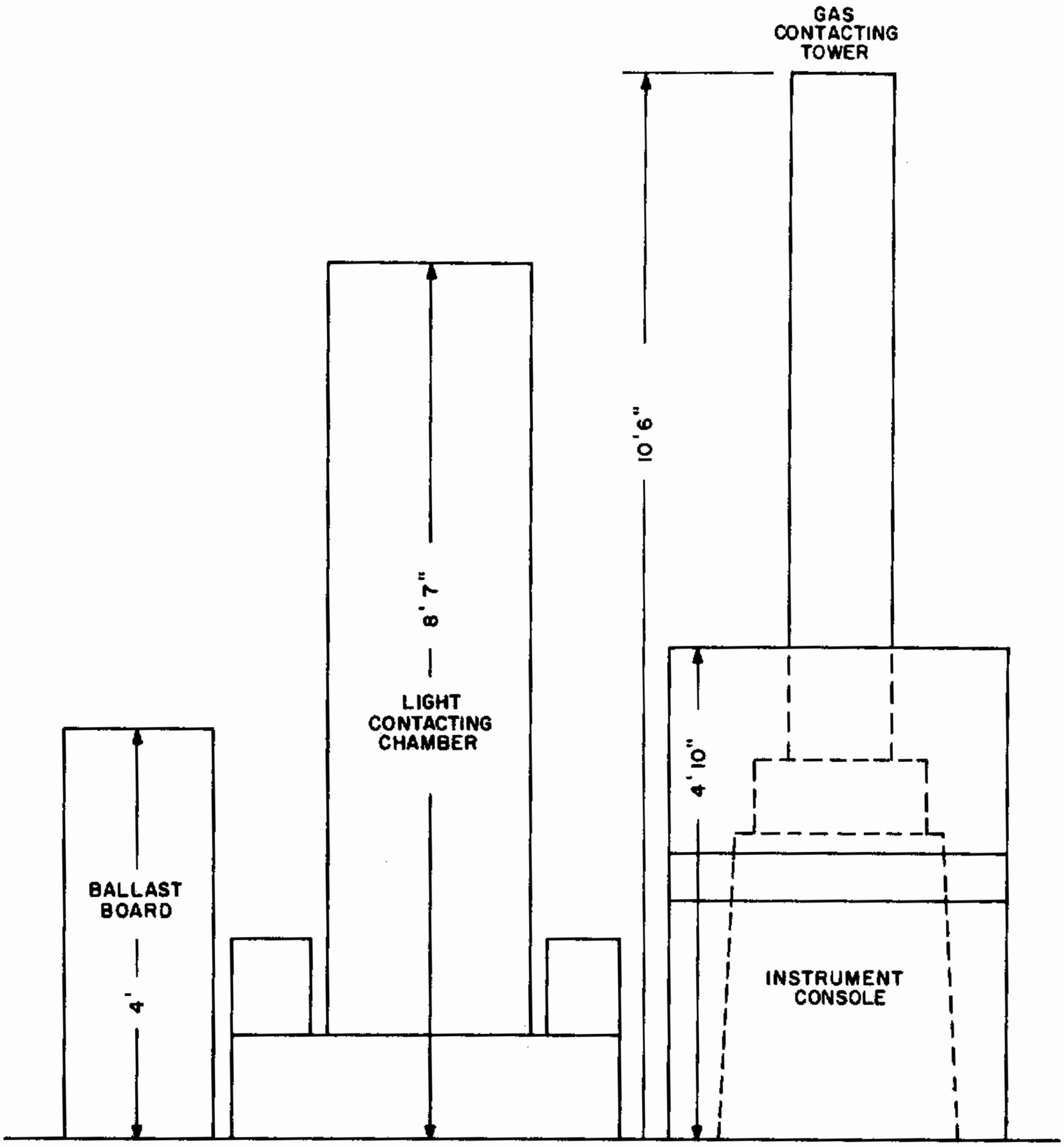


FIGURE 4 MAJOR COMPONENT ARRANGEMENT (ELEVATION)

2. Ease of maintenance - this is especially true in the case of the light contacting chamber foundation, which incorporates a pivoted trunion. This enables the entire unit to be swung into a horizontal attitude, which facilitates servicing operations or disassembly.

The nutrient inlet mentioned previously is supplied with the proper concentration of nutrient salts dissolved in water. Concentrated nutrient is stored in a 15-gallon polyethylene drum and discharged into a water line by a metering pump. Proper dilution is affected by a throttling valve located in the water line.

The concentrated nutrient solution is prepared by diluting the following chemicals with water to 36 liters of solution:

Chemical	Quantity	Grade	Suggested Vendor
$MgSO_4 \cdot 7H_2O$	3600 grams	USP	Dow Chemical
KH_2PO_4	720 grams	Purified	Fisher Scientific Cat. No. P-284
NaCl	1440 grams	USP	International Salt
Urea	1152 grams	Crystals	Allied Chemical - Nitrogen Division
NaFe Sequestrene	11.5 grams	-	Geigy Chemical
Antifoam B	10.5 grams	-	Dow Corning

Collection of Algae

A liquid level controller automatically discharges algae suspension to the sump tank when the level in the gassing column rises above a preset operating level. The algae suspension feeds continuously from the sump tank to a centrifuge where separation of algae and liquid takes place. After 1-1/2 hours of operation, the centrifuge is shut down and the algae paste removed. After cleaning, the centrifuge is put back "on stream."

Gas Compositions

Carbon dioxide (required for growth of the algae) is fed to the gassing column as a gas mixture of CO_2 and air. The CO_2 concentration of this mixture can be varied from 0.5 to 4.0 per cent by volume, as required.

The desired composition is obtained by mixing CO_2 and air in the 1-inch pipe line feeding the gassing column. Both gas supplies are maintained at the same pressures (about 100 psig) and the concentrations of CO_2 and O_2 in this mixture are recorded continuously by a Lira infrared analyzer and a Beckman paramagnetic oxygen analyzer, respectively. The flow rates of each gas are controlled by flow controllers in each supply line.

Major Component Description

Light Contacting Chamber - The light contacting chamber is a rectangular structure 21-1/2 inches by 22-1/4 inches in section and 90 inches high containing a liquid volume of 131 gallons. The body is fabricated from 1/8-inch sheet type 316 stainless steel and 1 inch by 1 inch by 1/8 inch angle - 316 on the interior, 304 on the exterior - while both heads are 3/8-inch plate-type 316 and flanges are 1/2-inch type 316 plate. The interior of the chamber is baffled to provide eighteen vertical passes; each channel brings the culture into direct contact with two 96-inch "Power Groove" fluorescent lamps (see Figures 5 and 6). To remove heat generated by the lamps, passes 4, 10 and 16 are fitted with 1/4-inch trombone cooling tubes with a total surface area of 3.38 sq ft. An external jacketed pipe provides an additional 2.05 sq ft of cooling surface.

The chamber is fitted with a central drain at the bottom and intake and discharge manifolds at the top.

Gas Contacting Tower - The gas contacting tower consists of three main subassemblies - the column, sump and gas sparger, and head. The liquid hold-up volume of the column, not correcting for bubble volume, is 27.6 gallons.

The column is 78 inches long, 10 inches internal diameter (1/8-inch wall thickness) and flanged on both ends. The top flange accepts the head assembly plate, which is fabricated from 1 inch thick acrylic plastic. Gusseted to this and passing through the center line is the 1-1/2 inch IPS algae supply line, which extends about 11 inches below the top of the column. Located at the end of this supply line is a gas disengaging baffle that serves to separate the oxygen-rich air from the culture.

The bottom column flange is piloted to fit the sump and sparger assembly. The sump is 18 inches in diameter and 9 inches high fabricated from 1/4-inch plate type 316 and provided with an outlet at the bottom. The sparger is located concentric with and inside the sump (see Figure 7). The sparger is composed of an acrylic plastic retainer with a built-in pressure equalizing chamber and a 10-3/4 inch diameter porous stainless steel (316) sparger plate of 165-micron pore size. The 1/8-inch thick plate is cross braced for stiffness and has an O-ring seal at its outer edge to prevent large bubble formation from leakage around the plate. The sparger is located 62 inches below the free surface of the liquid in the tower. The entire unit is assembled leak-tight by two O-ring seals, one in the column top flange, the second in the sump flange. The gas contacting column is fitted with a level gage glass and opposed sighting ports for observance of sparging action.

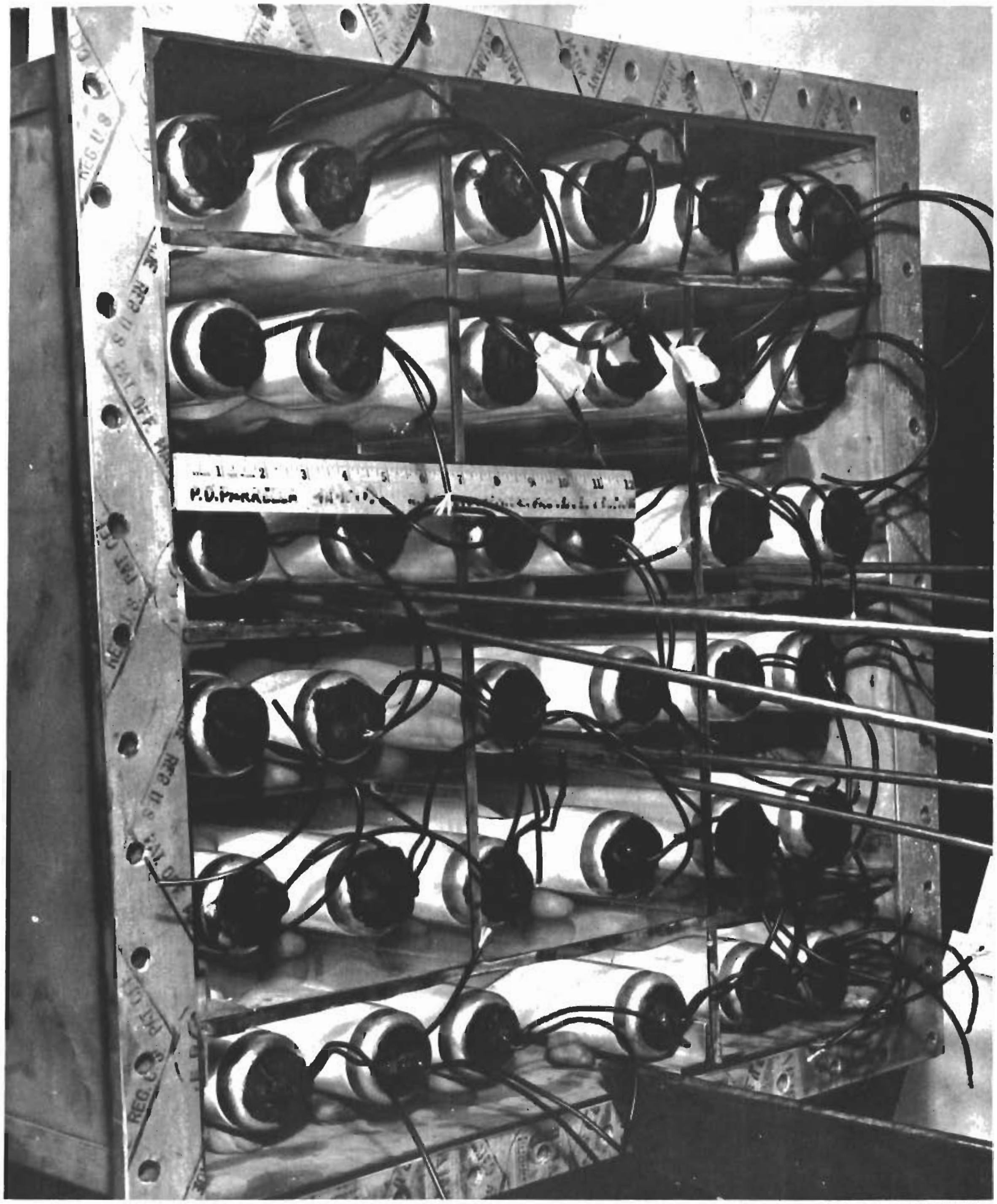


FIGURE 5 LIGHT CONTACTING CHAMBER-LAMP AND BAFFLE ARRANEMENT

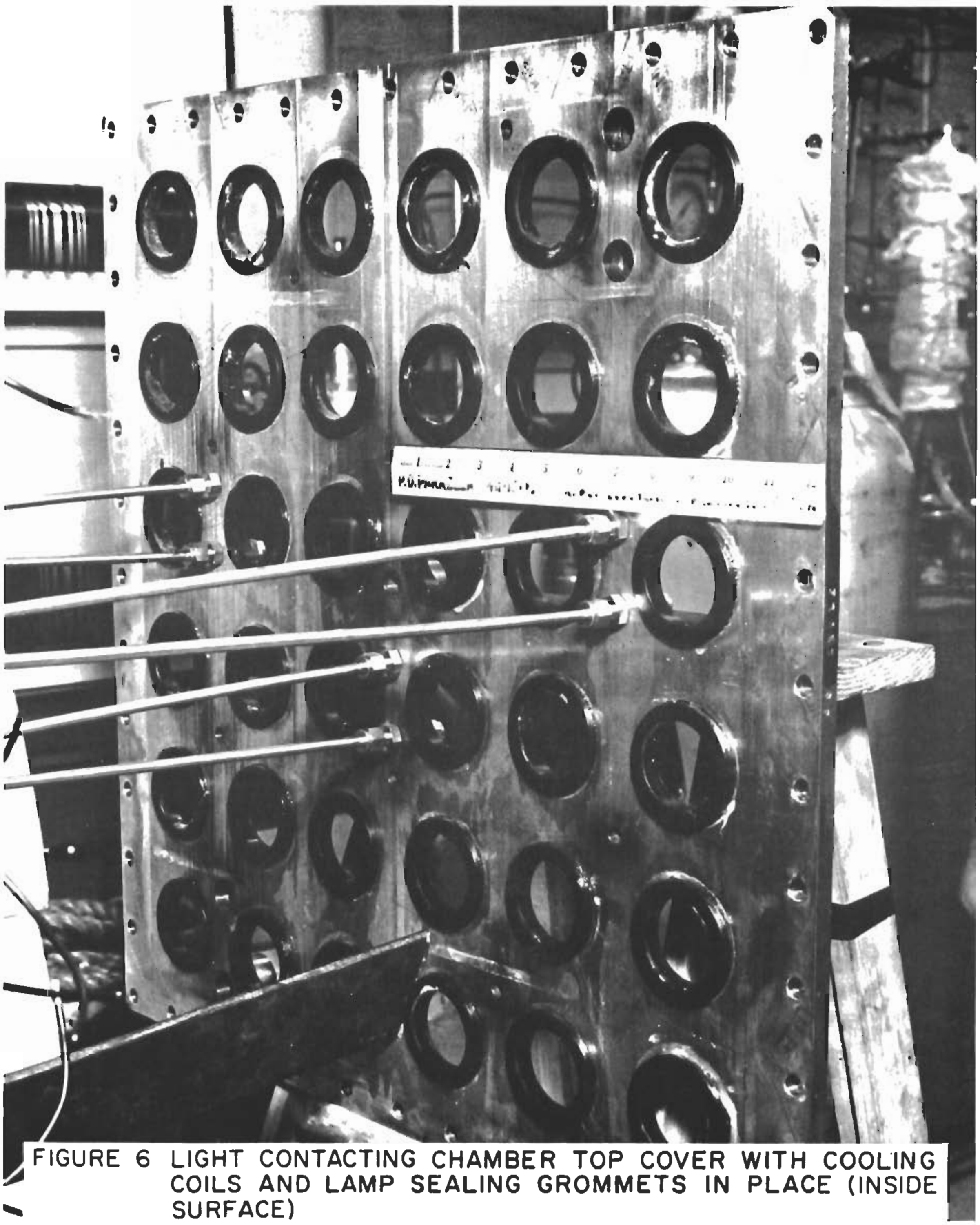


FIGURE 6 LIGHT CONTACTING CHAMBER TOP COVER WITH COOLING COILS AND LAMP SEALING GROMMETS IN PLACE (INSIDE SURFACE)

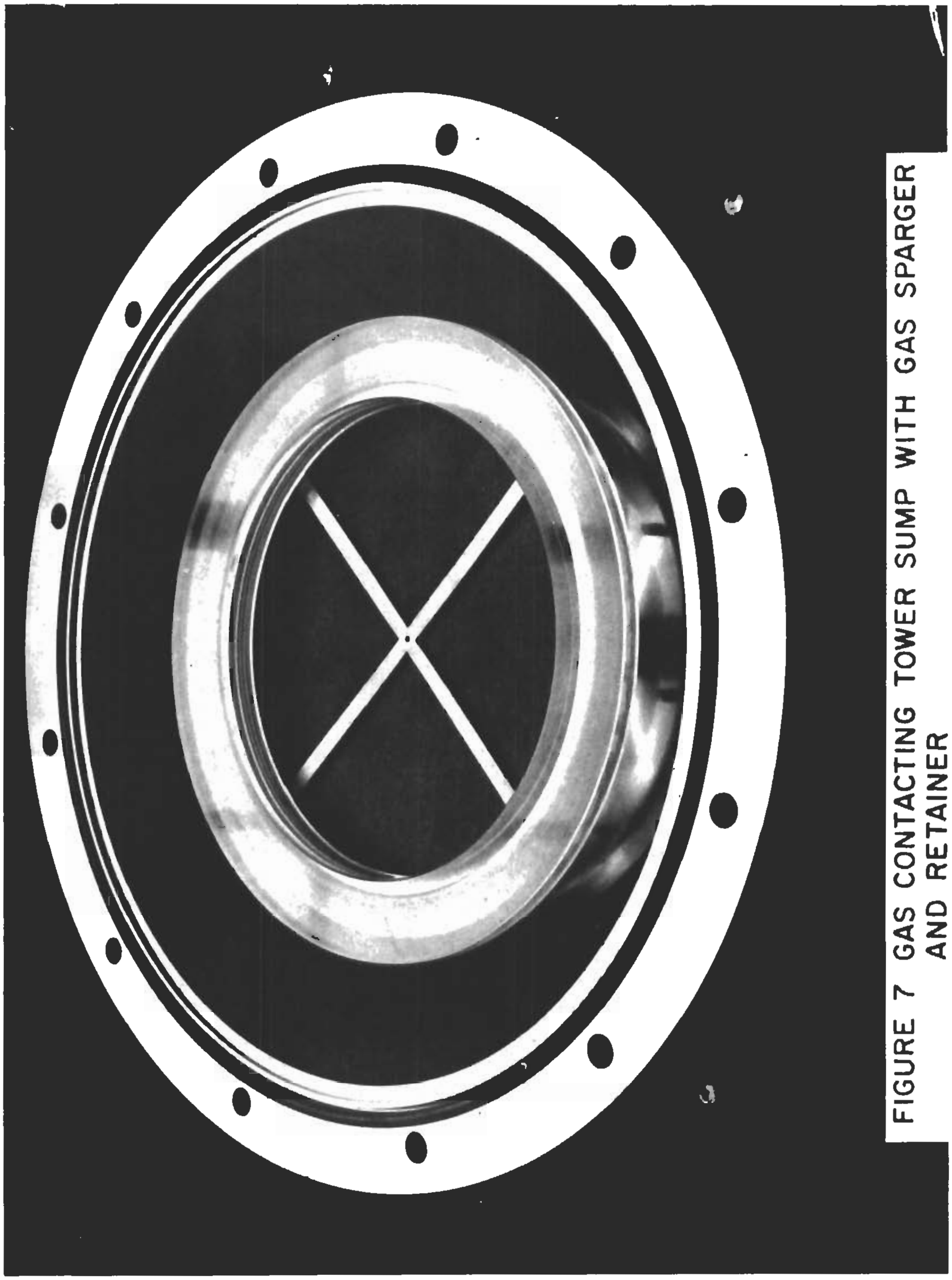


FIGURE 7 GAS CONTACTING TOWER SUMP WITH GAS SPARGER AND RETAINER

Outlet Gas Dehumidifying Condenser - This unit is installed in the gas discharge line of the gas contacting tower. The condenser consists of a 4-inch IPS pipe 28 inches long with tapered ends, 1-1/2 inch IPS at inlet and 1 inch IPS at outlet. The pipe is concentrically jacketed by a 5-inch IPS pipe that is fitted with a 1/2-inch IPS inlet and outlet. Cooling water is circulated through the outer jacket and gas flows within the 4-inch IPS pipe, which gives a cooling surface area of 2.66 sq ft. The entire condenser is mounted on a 22-1/2 degree angle from the horizontal to affect proper condensate drainage. All material is 316 stainless steel.

Nutrient Feed Tank - The 15-gallon feed tank is equipped with an agitator for preparation of concentrated nutrient. The mixer consists of a 316 stainless steel shaft and 3-inch diameter impeller rotated at 1500 rpm by 1/3 hp motor. The tank volume provides a 48 hour span between refills.

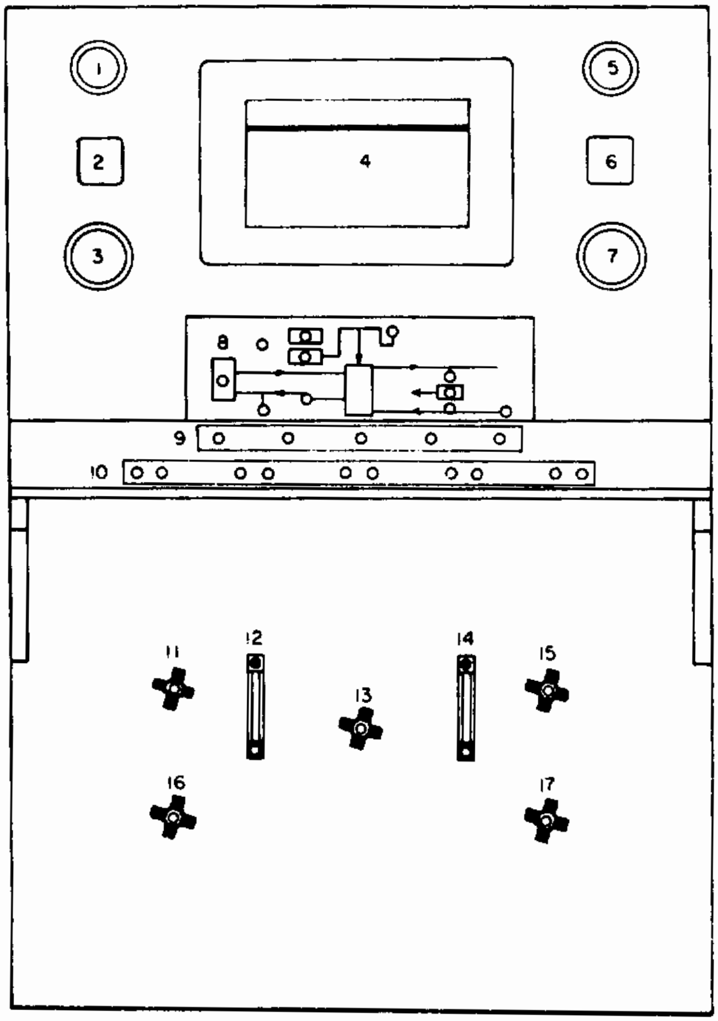
Algae Separation Centrifuge - As algae suspension is harvested from the gas contacting tower it is fed into a continuous-type laboratory centrifuge rated at 24 gallons per hour of algae suspension. The centrifuge is powered by a 1/3 horsepower, 115-volt, a-c motor. All parts in contact with the algae suspension or cells are of 316 stainless steel.

Suspension Circulation Pump - The pump used to circulate the culture through the system is a centrifugal-type capable of delivering 60 gallons per minute at 8.6 psig. Pump power is from a 3/4 horsepower, drip-proof, 1725-rpm, 115-volt, 60-cycle, single-phase,a-c motor. The pump is constructed of 316 stainless steel.

Nutrient Feed Pump - Metering of the concentrated solution of nutrient salts into the metered water supply is achieved by an adjustable stroke piston pump capable of delivering 0.1 to 0.3 gallons per hour of solution. The feed pump is rated to deliver against a 20-ft head of water. The head is of PVC construction with glass ball checks, 316 s/s plunger, and Hasteloy "C" push rod. The pump is driven through a gear reduction unit by a 1/3-horsepower, 115-volt motor of drip-proof construction.

Instrumentation and Control

General - Instrumentation and control are based upon the system concept whereby measurements and orders from and to the process mounted instruments connect to a central console. Both mechanical and electrical instruments are used. A front view of the instrument console is shown in Figure 8.



1. Suspension Density Indicator
2. % CO_2 Indicator
3. Duplex Pressure Gage (Liquid System)
4. Multipoint Recorder*
5. Air Flow Indicator
6. % O_2 Indicator
7. Duplex Pressure Gage (Gas System)
8. Graphic Panel
9. Circuit Toggle Switches
10. Motor Switches (Stop-Start)
11. CO_2 Control Valve
12. CO_2 Flow Meter
13. Air Flow Control Valve
14. Sample Stream Flow Meter
15. Water Flow Control Valve
16. Test Gas Valve (Zero-Gas)
17. Test Gas Valve (Span-Gas)

*CO_2 and O_2 concentrations, suspension density and system temperatures

FIGURE 8 INSTRUMENT CONSOLE

Electrical Power - Overall power is supplied through a manual contactor and thence in three directions:

Constant service bus (ØB)

Control power relay (ØA)

Lamp power relay (ØA, B and C)

The constant service bus (Phase B) is used to supply constant power to the gas analyzer sampling system, the emergency air supply system, the multi-point recorder, and the two gas analyzers. As soon as power is supplied to the board, these devices are allowed to warm up or to operate independently of other controls. The Control Power relay (Phase A) is of the locking type and is operated from the front of the console. It supplies power to the following control circuits:

Agitator

Circulating pump

Centrifuge

Light chamber temperature control system

Gassing chamber level control system

Density control system

Four position mode control switch

The Lamp Power relay (Phases A, B and C) is also controlled from the front of the panel board and allows voltage to be applied to the 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 is below 102°F. Locking relays can be de-energized by their respective stop buttons.

Control Circuits - Energizing of the Control Power relay allows the agitator, circulating pump, and the centrifuge to be started by means of their own locking relays and push buttons. The agitator and circulating pump are provided with indicating lamps mounted in the graphic panel.

The light chamber temperature control system is automatic, wherein an adjustable, bi-metallic finger probe turns the water cooling solenoid valve on and off according to its setting. A check of this temperature control can be obtained from any one of five dial temperature indicators set into the walls of the light chamber. A bi-metallic finger probe in the 13th pass set for 102°F serves as a high temperature lamp cutoff.

The gassing chamber level control system works automatically, but how it is used depends on the Mode Control Selector switch. The same is true of the density measuring system.

Regardless of the settings or combinations of devices used on 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 are automatically sampled by means of a combination of solenoid valves and a programmer switch. Essentially, the incoming gas stream is analyzed for 60 seconds, the outgoing gas line for 100 seconds, and neither line for 20 seconds. The status of this sampling is shown by the three signal lights on the graphic panel. The center signal light denotes the 20-second period when both solenoids are off.

During the 20-second period, the gas analyzers can be standardized by opening the respective valves on the zero or span gas lines. The Analyzer Sampling switch should be off during this standardizing procedure.

Emergency Air Supply - To prevent the sparging plate in the gas contacting tower from becoming clogged due to a failure in the gas supply, an emergency gas supply circuit is provided. A low pressure of supply air de-energizes a solenoid valve which allows an emergency air supply to pass into the gassing chamber. Simultaneously, an audible alarm on the back of the console signifies this emergency operation. As soon as the supply air pressure comes back to normal, this system automatically resets itself. The alarm can be changed to a red panel lamp indication by operating the Acknowledge switch on the console.

Gassing Chamber Level System - The liquid level in the gassing chamber is controlled by a combination of electrodes and a relay circuit. As the level comes up from the bottom of the gas contacting tower, it contacts level probe L3. As the level continues to rise, it reaches L2, causing a relay to lock in through L3. If the level were to fall, this relay would remain locked in until the level fell below L3. If the level were to rise, another relay would lock in. If the level then fell, both relays would remain locked in until the level fell below L3.

As stated above, the action of these relays is utilized by proper selection of the Mode Control switch.

Mode Control - Four positions of the Mode Control Selector switch are furnished:

1. Manual feed to L1 - In this position, the metering pump and watering solenoid valve can be manually operated by their respective toggle switches. However, they cease operating when the level in the gas contacting tower exceeds L1 of the level probe. They are operable again below L3. The metering pump is slave to the watering switch. Pure nutrient cannot be added except by turning the water supply off.

2. Automatic algae density to L1 - In this position, the algae density controller will energize the drain valve, the nutrient feed pump, and the watering solenoid when the algae density exceeds a pre-set value (see section on algae density controller). Again, exceeding the level L1 will de-activate the entry of nutrient and water, down to L3. In this position, the drain loading valve must be set so that the entry rate exceeds drain rate.

3. Manual drain - In this position the drain valve opens.

4. Automatic level-constant feed - In this position, manual control of the water and nutrient feeds will finally cause the drain valve to open above L2 and close below L3. In this position, the drain loading valve must be set so that the drain rate exceeds the entry rate.

Algae Density Controller - The algae density control system consists of a density element, a related density measuring circuit and a density indicating controller.

The density element has a revolving shutter which cleans the windows of an optical path through an algae sample stream by depressing the motor switch. A micro-switch allows the controller to "look" at the algae density; otherwise, it "looks" at a reference air path which returns the controller pointer to zero. The motor switch should be let up when the micro-switch is activated by the rotor cam to ensure that the controller looks at the algae stream path.

Miscellaneous Details - All flow controllers are of the self-actuated differential pressure type whereby each maintain a constant differential pressure across a manually operated needle valve. For example, the gas analyzer flow control valve consists of the flow controller, its related needle valve, and a rotameter. To increase the flow through the series connected rotameter, the operator simply opens the needle valve.

System pressure is maintained constant by means of the back pressure control valve. This device continuously monitors its own supply pressure and regulates it according to the manually set spring adjustment inside its body.

The gas flow measurement is accomplished by a calibrated orifice meter, using a sealed pressure gage as a differential pressure meter.

All temperatures are indicated by dial type thermometers or are recorded by means of iron-constantan thermocouples. Because the recorder is also monitoring the gas analyses and algae density, it is calibrated in millivolts. Ice bath reference junctions are required for accurate temperature recording.

IV

TEST OPERATION

After completion of assembly, calibration of instruments, static testing and routine shakedown, the system was operated on a 24 hour/day, 5 day/week basis to study system capability, gas exchange, algal growth rates, etc. Emphasis was placed on establishing a culture of consistent density (0.1 to 0.2% vol/vol) while operating at continuous dilution.

After the system was thoroughly cleaned the gassing rate was set at 63 SCFH and the system was filled with nutrient solution. The lamps and circulating pump were turned on and the system temperature gradually increased to 98°F, at which time the system was inoculated with 45 liters of 0.1% vol/vol algal suspension. The gassing rate was increased to 120 SCFH and the system was operated as a batch process until the algal density increased to 0.2% vol/vol. Nutrient was then introduced to the gas contacting column at the rate of 15.2 gallons per hour and the system was switched over to continuous dilution operation.

During the test period, algal densities, gas and liquid flow rates and compositions, system temperatures and pressures, etc. were continually recorded. The algal densities were indicated by packed cell volume or optical density measurements on the harvested algal suspension. The automatic photocell device, designed for continuous measurement of algal density, was found to drift continually from its zero point and had to be removed for modifications. The instrument was designed to scan air automatically (as a standard) and also scan the algal suspension. In order to stabilize the reading, the instrument was modified to monitor the algae only, and standardization was changed to a manual operation, thus eliminating the repeated switching of the instrument between the two readings. This modification reduced the drift of the meter.

Typical operating conditions during continuous dilution operation were as follows:

Inlet gas flow rate	120-130 SCFH
Suspension circulation rate	60 gpm
Suspension temperature	100 ± 2°F
Inlet CO_2 concentration	1.0-2.0%
Flow to gas analyzers	1.5-2.0 SCFH
Nutrient flow rate (total)	15.2 gph (0.1 system vol/hr)
Nutrient ratio, concentrate: total	1 part: 80 parts (vol/vol)

The first thirty hours of testing consisted of batch type operation during which the algal density increased from 0.01% to 0.2% vol/vol. A summary of typical data recorded during this period is presented in Table I. The growth curve during this period is shown in Figure 9. As seen from this curve, the lag phase was nine hours. Following this lag period, the algae entered the logarithmic growth phase. Initially the algal concentration was recorded by withdrawing a sample of the suspension and measuring its optical density with an electrophotometer. However, when the algal density had increased to the point where it was necessary to dilute the sample, the packed cell volume of the sample was measured rather than the optical density. At the lower algal densities, the packed cell volumes are difficult to measure accurately. Theoretically the oxygen production rates (and the CO_2 consumption rates) could be determined by (1) measuring the change in composition of the feed gas as it passed through the gas contacting column, or (2) by measuring the algal growth rate and relating this rate to an equivalent gas exchange rate.

The first method is most effective in systems where the differences in composition between inlet and outlet gases are significant as in multi-pass adsorbers.

Since the present system operated as a single pass, open system, the observed changes between inlet and outlet gas were too small to be considered significant and the gas exchange rates had to be calculated from the algal growth rate.

If the log phase of Figure 9 is assumed to be linear (middle portion of the curve), the growth rate can be calculated from the slope of the line. By this method the algal growth rate was found to be 23.8 grams dry algae per hour which is equivalent to an oxygen production rate of 0.93 SCFH and a CO_2 consumption rate of 0.77 SCFH. Doubling times as low as 6.3 hours were obtained during this batch operation.

Table II summarizes typical data for the period during which the system was operating as a continuous culture. The highest growth rate recorded during this period was 28.0 grams dry algae per hour (equivalent to 1.09 SCFH O_2 and 0.90 SCFH CO_2) and the average growth rate over an eight hour period was 18.7 grams dry algae per hour (equivalent to 0.73 SCFH O_2 and 0.61 SCFH CO_2). In addition, the algal density during this eight hour period was constant, within the limits of error of the measurement, indicating culture stability at those operating conditions. For this interval the doubling time was calculated to be 10.2 hours which is in good agreement with the doubling time calculated for the preceding batch operation. The longer doubling time recorded during the continuous operation is to be expected since the average algal density during the continuous operation was higher than the average density during the batch operation.

Due to the limited time available for actual testing, information such as optimum operating levels of CO_2 feed, nutrient dilution rate, and suspension circulation rate could not be determined.

TABLE I

TYPICAL BATCH OPERATION

Time (Hours)	Air Flow (SCFH)	Inlet Gas Pressure (PSIG)	pH	Algal Density (OD)	Circulation Rate (GPM)
0100	127	2.8	5.90	0.090	60
0300	127	2.7	5.85	0.115	60
0500	144	2.3	5.80	0.305	60
0700	143	2.3	5.95	0.445	60
0900	119	1.4	5.80	0.620	60
1100	109	2.7	5.75	0.758	60
1300	115	2.8	5.75	0.850	60
1500	131	2.8	5.75	0.16*	60
1700	125	2.8	5.90	0.18*	60
1900	125	2.8	6.00	0.19*	60

*% vol/vol

TABLE II

TYPICAL CONTINUOUS OPERATION

Time (Hours)	Air Flow (SCFH)	Inlet Gas Pressure (PSIG)	pH	Algal Density (% vol/vol)	Nutrient Flow (GPH)	Circulation Rate (GPM)
2400	115	2.8	5.85	0.13	15.2	60.0
0100	115	2.8	5.85	0.12	15.2	60.0
0200	115	2.8	5.85	0.12	15.2	60.0
0300	115	2.8	5.85	0.11	15.2	60.0
0400	115	2.8	5.85	0.11	15.2	60.0
0500	115	2.8	5.85	0.11	15.2	60.0
0600	115	2.8	5.85	0.13	15.2	60.0
0700	115	2.8	5.85	0.13	15.2	60.0

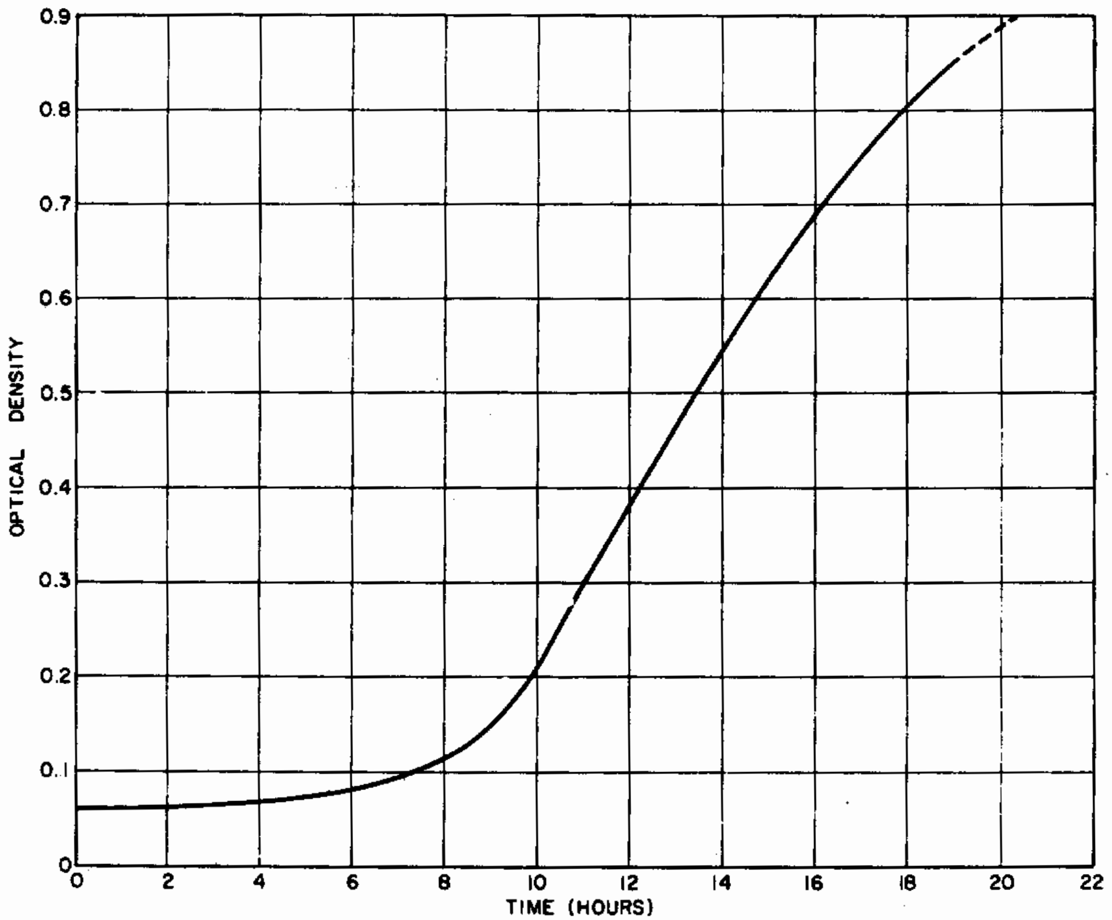


FIGURE 9 GROWTH CURVE-OPTICAL DENSITY VS TIME

Nevertheless, the performance test did demonstrate that this photosynthetic system has the capability of meeting the requirements of one man. Under optimum conditions it is anticipated that this system will exceed the requirements of one man.

V

SUMMARY

A photosynthetic gas exchange system instrumented to provide for continuous recording of oxygen and carbon dioxide analyses, algae density and temperature was designed, fabricated, and tested. The system consisted of three major components: a multi-pass light chamber, a counter-current gas contacting tower, and an instrument console. In addition, a centrifuge was provided for the harvesting of algae. Based on the growth rate of algae, the unit utilized up to 0.90 SCFH of carbon dioxide and produced up to 1.09 SCFH of oxygen.