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DEVELOPMENT OF A SOLID POLYMER ELECTROLYTE ELECTROLYSIS CELL MODULE AND ANCILLARY COMPONENTS FOR A BREADBOARD WATER ELECTROLYSIS SYSTEM

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ABSTRACT

A laboratory development program was undertaken to evaluate the use of the solid polymer electrolyte (SPE) technology in a water electrolysis system (WES) along with ancillary components to generate oxygen and hydrogen for a manned space station application. Standard commercial components were utilized wherever possible. This report presents the results of investigations, surveys, tests, conclusions and recommendations for future development efforts.

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SUMMARY

The purpose of the work described in this report was to investigate and describe the use of a solid polymer electrolyte (SPE) for water electrolysis in a life support system appropriate for a manned space station. The NASA contract required the development of an electrolysis module rated at a one-man capacity of 2.5 lb O_2/day, the investigation of system accessory requirements, a preliminary system design study for a 12-man oxygen generation system, and finally the assembly of a small breadboard system. Reports of the 12-man system study and of the cell/module design were submitted to NASA. One of three four-cell modules was tested at temperature and after about 1700 hours the test was discontinued due to gasket degradation. NASA operated one of the four-cell modules at ambient temperature and 100 ASF for over a period of one year and reported excellent performance. A seven-cell electrolysis module completed more than 11,000 hours of operation without failure or disassembly. A complete one-man rated laboratory breadboard system was fabricated and tested to evaluate system and component performance. System prototype components (including a 13-cell electrolysis module) were designed and fabricated for an oxygen system design point of 10 lb/day (four-man rate). Checkout testing was accomplished on these components to complete the contract.

SECTION 1. INTRODUCTION

The need for a reliable, long-lived, and efficient water electrolysis unit for closed-cycle life-support systems has prompted a number of development programs encompassing both acid and alkaline technologies. Early acid systems using liquid sulfuric or phosphoric acid electrolytes suffered a significant performance penalty, as compared with alkaline systems, in that they required considerably more power to generate a given amount of oxygen. Both acid and alkaline systems with liquid electrolyte have also encountered problems with leakage, materials compatibility, performance stability, and life.

In March 1970, NASA Langley Research Center Contract NAS 1-9750 was awarded to General Electric Company, Direct Energy Conversion Programs, Lynn, Massachusetts, to investigate the use of the solid polymer electrolyte (SPE) technology in a water electrolysis system to generate oxygen and hydrogen for manned space station applications. The program was completed in August 1972, resulting in demonstrated performance/life characteristics of the SPE electrolysis technology and the fabrication of the major components of a four-man rated breadboard oxygen generation system.

SECTION 2. WATER ELECTROLYSIS SYSTEM (WES) DESCRIPTION

The WES components developed and fabricated under Contract NAS 1-9750 were designed to be capable of continuous oxygen generation equivalent to a nominal four-man rate basis (10 lb O_2/day), with a maximum nominal capacity equivalent to a six-man rate. Wherever possible and as directed by the contract, standard commercial materials and components were selected to provide functional demonstration compliance at minimal cost and delivery schedule. It should be noted therefore, that these breadboard components would require modification and redesign in order to provide flight-worthiness to withstand "hard" environment launch vibration, shock and acceleration along with weight and volume reductions, mounting configuration. producibility and maintainability considerations.

2.1 Specification

A "guideline" specification for design capability of the breadboard WES is outlined in Table I.

2.2 Configuration

Figure 1 is a fluid schematic of an SPE water electrolysis system showing the basic arrangement of the breadboard components. It should be realized that additional control components and instrumentation would be necessary for automatic control, performance monitoring, fault isolation, shutdown and safety considerations.

Primary fluid and electrical interfaces to the WES are:

28 VDC to Control Panel
28 VDC to Inverter
115 VAC, 60 Hz to Control Panel
80 psia nitrogen as necessary for scavenging hydrogen overboard (in and out)
Water Coolant (in and out)
Make-up (feed water) (in)
Hydrogen (out)
Oxygen (out)

As shown in Figure 1, feed water is supplied to the WES at a make-up water rate of approximately 11.3 lb/day and 10 psig for an oxygen generation rate of 10 lb/day. The water enters the WES through a check valve which prevents reverse flow when the system is shutdown at normal working pressures. The feed water is mixed with recycled module cooling water upstream of the particulate filter to the water pump. This process water is circulated throughout the WES by a gear-type pump with quantity regulation maintained by the water flow valve and needle bypass valve. The pump design includes an internal relief valve which becomes functional if an internal dead-ended condition arises within the pump. Pressurization of the feed water to 10 psig reduces the pump pressure rise and subsequent journal bearing load and also prevents the relief valve from continuously relieving. Excess pump capacity is delivered through the needle bypass valve. An orifice could be used in place of the needle valve for a flight designed system. The water pump is powered through a DC to 3-phase AC inverter with a 28 VDC input. Downstream of the pump, the water flows through a deionizer resin bed which reduces the ionic contamination level to acceptable WES purity limits of $\geq$ 400,000 ohm-cm.

The water then passes through a regenerative heat exchanger prior to mixing in a temperature regulating valve which controls the supply temperature to the electrolysis module at approximately +100°F. This temperature control maintains electrolysis module performance essentially independent of coolant and environmental temperature variations. The process water is delivered to the cathode (hydrogen generating) side of the 13-cell electrolysis module. Since the electrolysis occurs at the anode, water required for this reaction diffuses through the solid polymer electrolyte at a rate just equal to that required for oxygen generation. The generated oxygen will be saturated at the cell temperature and pressure (approximately +120°F and 62 psia), but will contain no liquid water. The free liquid water required for cell cooling will remain on the cathode side and will exit with the hydrogen as a two-phase mixture. This heated mixture passes through the regenerative heat exchanger to transfer its heat to the incoming colder process water. The two-phase mixture (hydrogen and module cooling water) leaving the regenerative heat exchanger is then cooled to approximately room temperature in the primary heat exchanger which transfers heat to the interface coolant fluid. Waste heat from the power conditioner is removed by the attached heat sink through which the interface coolant is also circulated. A biological resin bed filter is installed immediately upstream of the two-phase separator to remove micro-organisms (i.e., bacteria, molds, fungi, yeast) and particulate matter by three possible mechanisms, namely:

Electrostatic attraction to the resin beads.

Particulate matter depth filtration through the resin bed column.

Retardation or actual destroying of bacteria and mold growth by any localized acidified water within the resin bed column.

The two-phase mixture, therefore, has been pre-cleaned prior to entry into the two-phase separator. The life of the hydrophilic tubes with a pore size of 2 to 3.5 microns within the separator is therefore increased since pore clogging is minimized.

The H_2/H_2O phase separator provides a passive means of separating liquid from a gas in a zero gravity environment using both hydrophilic and hydrophobic separation elements. Primary separation is accomplished by removing water slugs from the two-phase mixture (hydrogen and water) with five hydrophilic porous glass tubes connected in a series fluid flow path. The hydrophilic elements permit the water to pass through the tube wall under a controlled differential pressure to the housing side of the assembly. Gas leaving the last tube, which is normally free of entrained water, passes through three parallel hydrophobic membranes located in the separator cover. The hydrophobic membranes, by their ability to pass only gas, serve as a trap to prevent water carry-over to the hydrogen outlet stream in the event of porous tube failure and/or differential water regulator failure. The pressure differential across the hydrophilic elements is controlled by a differential back-pressure regulator which is referenced to the inlet side of the hydrophobic membranes. The water leaving the differential back-pressure regulator (module cooling water) is mixed with the feed water and returned to suction side of the pump through the particulate filter.

The electrolysis module is supplied by a power conditioner which maintains a constant current corresponding to a pre-selected oxygen generation rate. This electronic unit is capable of 75 amps maximum input to the module which is an oxygen generation rate of approximately 15.3 lb/day.

The WES would normally be operated through a single switch at a fixed oxygen generation rate output.

The final components developed and fabricated in this program are:

1) 13-Cell Electrolysis Module
2) 75 amp Power Conditioner
3) Control Panel
4) Prototype Two-Phase Separator
5) Deionizer Resin Bed
6) Biological Filter Resin Bed
7) Regenerative Heat Exchanger
8) Water Temperature Control Valve
9) Process Water Pump
10) DC/AC Inverter
11) Water Flow Valve
12) Absolute Oxygen Back-Pressure Regulator
13) Absolute Hydrogen Back-Pressure Regulator
14) Differential Back-Pressure Regulator

Weights and volumes of these components are shown in Table II.

The final breadboard components were not operated as an integrated four-man rated system in this contract effort. A one-man rated breadboard system was tested, utilizing a four-cell and a seven-cell electrolysis module, 25 amp power conditioner and a three-tube breadboard phase separator. All other system components were laboratory-type components.

SECTION 3. WES COMPONENT DEVELOPMENT

Breadboard components developed and/or evaluated in this program are the major elements of an oxygen generation system for space station life support or other applications requiring oxygen and hydrogen. These components, when fully designed and modified for flightworthiness and maintainability, could comprise a reliable and efficient life support water electrolysis system (WES) similar to that shown by Figure 1 for the production of oxygen and hydrogen by electrochemical dissociation of water within a solid polymer electrolyte (SPE) module. The following sections describe the major components of this type of WES configuration.

3.1 Electrolysis Module

The solid polymer electrolyte (SPE) electrolysis module is the heart of the system. With water and DC power supplied to the module, oxygen and hydrogen will be generated. Figure 2 is a typical cell schematic. Figure 3 shows the components of laboratory and prototype size electrolysis cells.

The electrolyte used in the SPE electrolysis cell is a solid plastic sheet about 10 mils thick having a cation exchange function with perfluorinated sulfonic acid groups. This ion exchange membrane when saturated with water is the only electrolyte utilized. There are no free acids or alkaline liquids in the system. Ionic conductivity is provided by the mobility of the hydronium ions passing to and from sulfonic acid groups (SO_3^-) from the anode site to the cathode site. The sulfonic acid groups are fixed and do not move, thus the concentration of the acid remains constant within the SPE. In this application, process water is fed to the cathode catalyst electrode to provide the water for electrolysis and waste heat removal. Stoichiometric water for the reaction diffuses through the permeable SPE from the cathode to the anode. Process water could be fed to the anode but liquid water would have to be continuously separated from both H_2 and O_2 gas streams.

<u>3.1.1 History and typical performance characteristics</u>. - Table III presents the history of SPE water electrolysis operation on this contract, excluding any time accumulated during the special high-pressure electrolysis evaluation.

Figure 4 shows the performance of the initial small SPE laboratory cells (No. 7, 10, 11 and 13) with life and at several current densities.

Figures 5 and 6 are chronological performance plots of a full-size single-cell assembly and seven-cell module under various conditions of pressure, temperature, process water feed site, current density, etc.

Table III indicates that the unit which was operated for the longest time was the seven-cell module. All units completed their objectives successfully except the breadboard systems test four-cell module (S/N 1D) which failed due to rubber gasket relaxation during continued high temperature operation. This failure is covered in detail in section 3.1.2.

Except for the number of cells, the four-cell module and the seven-cell module were identical. The seven-cell module "A" is shown in Figure 7. The single-cell module was the first larger size unit and except for size, was similar in configuration to the four- and seven-cell modules.

As shown in Figure 7, the module design consists of a sandwich of SPE membrane and electrode assemblies sealed by rubber gaskets to ambient and stacked together by tie-bolts between aluminum end plates. Belleville washers on each tie-bolt pre-load the rubber in compression to compensate for life-gasket relaxation. Table IV shows the typical tie-bolt torque variation, or conversely rubber gasket relaxation, recorded during the life of the seven-cell module. Figure 8 shows the tie-bolt position location. This unit's more than 11,000 hours of operation were accumulated at relatively low temperature (below 100°F), whereas the four-cell module (S/N 1D) which failed, was operated at a maximum temperature of 190°F.

The structural integrity of the solid polymer electrolyte is demonstrated by the following table of cross-membrane leakage data recorded on the seven-cell Module "A" at two points in time. Nitrogen was delivered to the H_2 cathode side under pressure and with the O_2 anode side at approximately ambient pressure:

Date	Cumulative Gas Generation Time, hr	H_2 Side Pressure, psig	Leakage, cc/hr Measured	Leakage, cc/hr Allowable (max.)
9/1/71	8,463	40.0	41.5	10 cc/hr-cell or
4/27/72	11,062	50.0	57.5	70 cc/hr total

Tabulated below are single-cell impedance checks taken on the seven-cell module at two points in time which illustrate the stability of the SPE with life:

		Impedance, ohm						
		Cells						
Date	Life, hrs	1	2	3	4	5	6	7
8/16/71	8,313	.0024	.0024	.0025	.0025	.0021	.0022	.0023
4/27/72	11,062	.0025	.0028	.0027	.0029	.0022	.0025	.0025

The purity levels of the generated gases from the electrolysis module were checked for compliance against Table I requirements. Typical samples extracted through a "DRIERITE" crystal chamber from the seven-cell Module "A" are as follows:

Oxygen Sample

Constituent	* 500 Hour Life Point 8/12/70, ppm by Vol. Unless Designated Otherwise	** 10628 Hour Life Point 12/2/71, ppm by Vol. Unless Designated Otherwise	*** Limits, ppm by Vol. Unless Designated Otherwise
O_2	(99.724%)	(≥99.764%)	(99.7% min.)
N_2	2,370	1,253	
CO_2	310	1,032	
Argon		<25	
H_2	80	<50	1,000 max.

Hydrogen Sample

Constituent			
H_2		(99.734%)	(99.3% min.)
N_2		2,028	
CO_2		191	
Argon		<25	
O_2		30	2,000 max.
HD (heavy hydrogen)		391	

* Sample removed during the separate 8313 hour 7-cell module S/N "A" testing (see Table III).

** Sample removed during the 2775 hour breadboard system testing with 7-cell module S/N "A" (see Table III).

*** Extracted from Table I.

It is most probable that the N_2 and argon constituents are leakages into the electrolysis system from the air and show up in the sampling equipment during the gas sample extraction. The CO_2 constituent may arise from a combination of:

- air leakage into the electrolysis system,

- the soluble gas in the process make-up water which comes out of solution and permeates the SPE membrane from the cathode hydrogen side to the oxygen anode side,

- minute degradation of the SPE membrane as a byproduct.

A water constituent (2110 ppm) although found in the sample after drying is deleted from the O_2 table since it is not considered an impurity.

The H_2 constituent in the O_2 sample is most probably the result of unreacted hydrogen at the oxygen electrode which probably permeated through the module electrolysis SPE membrane (i.e., from the cathode (hydrogen) side to the (oxygen) anode side).

The O_2 content in the H_2 sample is most probably the result of unreacted oxygen at the hydrogen electrode which originally permeated through the module electrolysis SPE membrane (i.e., from the oxygen anode side to the cathode hydrogen side).

The presence of HD, "heavy" hydrogen gas (the hydrogen isotope deuterium) is expected when water is electrolyzed, since ordinary water contains approximately one deuterium atom for every 6999 hydrogen atoms. The higher than normal concentration of deuterium evident in the cathode water is probably "normal" in this system.

Figures 9 - 11 show the results obtained during the high-pressure electrolysis evaluation phase of the program. For this investigation, a small SPE single-cell assembly (7.2 $in.^2$ cell area) was gasketed in a fixture and tested up to 180°F temperature and 1500 psig pressure. Higher test pressures could not be experienced due to test fixture leakage limitations. Figures 9 and 10 demonstrate the effect on performance of the SPE with pressure and temperature utilizing a 20 mil thick SPE which was selected to reduce the gas permeability effects on cell operation. This increased thickness reduces cell performance as illustrated by Figure 11 which compares 10 and 20 mil thick SPE's at various operating temperatures at constant current density (100 ASF). Due to the increased thickness of the membrane, the performance of the cell at greater than 100 ASF current density was unstable in the cathode feed mode. Operation of the unit in the anode feed mode showed stable operation over the complete test range of 0 to 300 ASF.

<u>3.1.2 One-man rated breadboard systems testing</u>. – This contract required that systems testing be accomplished on a laboratory breadboard basis to demonstrate compatibility and endurance capability of a four-cell SPE electrolysis module and a two-phase breadboard model separator which are the two major or critical items of the WES. A four-cell module (S/N 1D) was designed and fabricated along with the breadboard separator. These items along with a regenerative heat exchanger manufactured by Parker-Hannifin Co., Model No. 3101-6, 4-8-6X316SST, were installed into a laboratory breadboard facility as shown in Figures 12 - 14. Testing was initiated on

April 13, 1971, and continued with minimal attendance and monitoring for 1682 hours. Typical performance is shown by the chronological voltage plot of Figure 15. Polarization data at 22, 26 and 526 hours are shown in Figure 16. Table V lists module data taken at 1147 hours cumulative gas generation time.

On 6/21/71, after 1682 hours of operation, the test was terminated due to a failure of the four-cell module caused by rubber gasket relaxation with subsequent overboard leakage and internal mixing of gases (O_2 and H_2) in the module manifold. The system had operated trouble-free until this point in the continuous life test. Performance of all cells had been normal and all other system components had performed at design levels. It was noted, however, that the hydrogen and oxygen outputs had decreased by 3.56% from approximately the 900-life hour point. This was within instrumentation error, and was not considered sufficient change to shutdown the test at that time.

An immediate investigation of the failure was undertaken to establish the cause and necessary corrective action. Details of the investigation are as follows.

Module failure analysis. — At 0902 hours on 6/21/71, a routine check of the system was made, indicating operation to be normal. At that time a set of performance, pressure and temperature readings was taken. The water tank was refilled due to electrolysis consumption, system operation was resumed and determined to be normal for approximately two hours. The system was then left unattended to continue the life test. At 1400 hours (6/21/72), an abnormally high pressure differential was noted across the phase separator. This had resulted in some gas breakthrough to the water side. Attempts to reduce the differential were unsuccessful, and it was found that pressure stabilization was not possible. Test conditions were immediately recorded and are listed below along with the previous readings:

	Voltage, VDC				Pressures, psig		Temperature, °F		
Time	Cell 1	Cell 2	Cell 3	Cell 4	H_2	O_2	Avg Stack	H_2O Out Stack	H_2O In Stack
0902	1.615	1.624	1.614	1.620	38	48	183	186	168.5
1413	1.606	1.614	1.603	1.610	Unstable		190	194	182.5

Stack gas pressures were subsequently checked and found to be equalized, indicating either internal or external stack leakage. The unit was then shutdown for further investigation.

A module cross-membrane check was made by circulating water through the H_2 side at approximately 38 psig while observing the O_2 outlet for water accumulation. In a short interval, water flow was evident at the oxygen discharge port, which established that an internal leakage failure had occurred. Further verification of this leakage was made by supplying nitrogen to the dead-ended H_2 side and observing flow from the oxygen outlet. Nitrogen pressure of 40 psig supplied to the H_2 and O_2 sides of the module with the module submerged in distilled water demonstrated that overboard (external) leakage was occurring in the region of the "O_2 out manifold", "H_2 out manifold" and "H_2O-in to O_2 side manifold".

Upon removal of the module from the test stand, it was found that the torque levels of the stack tie-rods had decreased by 10 to 15 lb-in. This resulted in torque values of 0 to 3 lb-in. on the external manifold tie-rods (originally 10 lb-in.) and 10 to 12 lb-in. on other perimeter tie-rods (originally 25 lb-in.). In addition, the distance between end plates had decreased by 0.010 in. from initial assembly. The module was retorqued to its original value, resulting in a further decrease in the distance between end plates of 0.020 in. Retorquing eliminated the external leakage; however, internal leakage was still apparent.

Module teardown observations. — The module was then disassembled and the following observations made.

1) Gasket thickness was 0.023 in. at the manifold and 0.025 in. around the perimeter vs. an original thickness of 0.026 to 0.027 in.

2) Cells visually appeared unchanged from their original state, except in the border areas where they had adhered to the gasket and torn slightly during disassembly.

3) Leak checks of the individual cells showed cells 1 and 3 to have leakage areas at 5 psi, whereas cells 2 and 4 evidenced no leakage. Cell 1 showed leakage at the water-in port and cell 3 showed leakage near the hydrogen-out port.

4) Cells 1 and 3 were stripped of catalyst in aqua regia for microscopic examination. Visual and microscopic inspection showed many small pinholes in cell 3 about 1 in. in from the hydrogen-out port. These were apparently caused by excessive heat in the hydrogen compartment. Cell 1 had one hole at the water-in port at the very edge of the active area. This may have been a result of removing the adhered gasket which was strongly bonded to the cell in that area.

5) Also observed but apparently unrelated to the failure were slight evidences of membrane delamination under the screen protector ring on the hydrogen side of the cell and outside of the active area.

6) Wrinkling of the membrane was also noticeable in the gasket areas opposite the water and gas tubes.

7) Loose cell voltage test lead between cell 2 and 3.

8) Reddish-brown corrosion residue deposits at all end plate ports but heavy at stagnant "H_2O-in to O_2 side port".

9) Whitish discoloration of the gasket on three of the four manifold lobes (absent from the stagnant lobe) and only on the side facing the membrane.

Failure analysis conclusions. – As this was the first module of this design to be disassembled (a 7-cell/8313 hr at 80 - 100°F module, a 4-cell/6072 hr at 80 - 170°F module and a single-cell/9344 hr at 80°F module have been operated without failure), it is difficult to determine the significance of all of the above observations. The remaining units were subsequently checked. The four-cell module showed only a 5 lb-in. decrease in torque. It is obvious that the sustained operation at 180°F on the breadboard module caused a relaxation of the silicone rubber gasket material beyond the ability of the Belleville washers to compensate particularly in the manifold lobe area. This would permit hydrogen and oxygen to leak externally, and also permit the higher pressure oxygen to leak into the hydrogen side manifold and then into the hydrogen compartments. The oxygen entering the cell would cause burning in the manner observed on cell 3, ultimately resulting in the holes observed in the membrane.

The delamination of the membrane under the screen protector ring was due to the inability of water to reach the catalyst under the ring. Thus, as catalyst was present, gases could be evolved but water could not readily replenish itself. This resulted in drying and the observed delamination. This condition has been shown to be readily corrected by removal of the catalyst under the protector ring.

The membrane wrinkling under the water and gas manifold tubes is no doubt caused by non-uniform pressure distribution in this area. This is due to the fact that the two or three tubes (depending on which manifold) are molded into the gasket, and the rubber between and on either side relaxes while the tubes do not; thus, tending to wrinkle the membrane in that area. This is readily corrected by replacing the inlet tubes with multi-layered screen sandwiched between two flat metal sheets.

The loose cell voltage lead accounts for occasional erratic cell voltage readout (cells 2 and 3) experienced during the test.

The reddish-brown corrosion residue was analyzed and found to be iron. Presumably the iron accumulation was released by the deterioration of the 316 SST heat exchanger which is adjacent and upstream of the module. This amount of iron did not contribute to any noticeable cell performance degradation during the 1682 hours of operation. Cell electrode contamination was not enough to cause detectable performance change.

Failure analysis corrective actions. — The following corrective actions were initiated.

1) Modify the Belleville washer design to allow for a larger degree of gasket relaxation.

2) Investigate alternate gasket materials which exhibit less relaxation at 170 - 190°F.

3) Review applications for the implications of operating at a lower temperature where successful long-term operation has been demonstrated until the above actions are shown to be positive corrections of the problem.

4) Remove catalyst under the screen protector ring to prevent delamination of the membrane.

5) Replace the inlet tube configuration with a multilayer screen concept to prevent membrane wrinkling.

6) Continue evaluation of present SE-4404 silicone compound material for application as a gasket material for SPE designs.

3.1.3 Four-man electrolysis module design. — Failure analysis corrective actions 1), 4) and 5) above were introduced into a redesigned module per Figure 17 (GE dwg. 1076527-910P1) to provide gas generation of a four-man rate (10 lb O_2/day). Table VI lists the significant design data. Figure 18 shows the assembled unit.

Details of the improvements included in this 13-cell module design are as follows.

1) Unfilled silicone rubber compound SE-4404 offers the lowest compression to date of those elastomers meeting current requirements of module redesign. Compression set of the SE-4404 compound will be additionally lowered by using a "Varox" curing agent and a longer high-temperature (480°F for 24 hours) post-oven cure, resulting in a one-half reduction in the compression set value.

2) The 13-cell module is designed for a proof pressure of 126 psig (2 times maximum operating pressure) and a burst pressure of 252 psig (4 times maximum operating pressure). High strength bolts of 17-4 PH stainless steel and nuts of A286 steel alloy have been utilized for the tie rods. The module end plate thickness has also been increased to accommodate the higher design pressure.

3) The terminal plates have been increased from .020 to .060 inch thick to design for the higher current rating of the module, in addition to increasing thickness of the electrical input tab.

4) Three fluid fittings provided on the module are modified bulkhead fitting with an elongated head. The latter conforms to the shape of the elongated manifold port and provides a self-keying arrangement for torquing during assembly.

5) A circular, ring-type gasket with equal spacing of bolts centered within the gasket has been incorporated in place of the previous lobed design. Also, the fluid ports have been elongated such that they are also centered within the gasket ring. This modification eliminates the lobes for fluid porting which had prevented uniform compression of the gasket seal.

6) The five layers of expanded screens (.022 in. thick) which make up the oxygen and hydrogen cell cavities have been continued through slots in the gasket which communicate with the elongated ports forming the fluid manifolds. The water inlet slot to the hydrogen cavity is .25 in. wide, whereas the hydrogen and oxygen outlet slots are .38 in. wide. This screen-filled porting arrangement provides the support for compression and sealing of the gasket around the manifolds and acts as a fluid restrictor for water flow distribution to the cells. This configuration replaces the flattened two and three-tube cell porting arrangements which caused wrinkling of the SPE membrane in that region.

7) Because a cathode water feed mode has been adopted, the water feed manifold and porting to the oxygen cavity has been eliminated. Also, the oxygen outlet manifold is located close to the water inlet port. The oxygen effluent is therefore cooled to approximately water inlet temperature which reduces the dewpoint of oxygen supplied by the module.

8) The 6.5 in. inside diameter of the SPE membrane protector ring is made coincident with the active diameter of both electrodes. This prevents electrolysis from occurring under this ring which eliminates delamination of the SPE membrane in this region. The screen protector ring has been extended to span and form a cover for the screen ports to the cell and also form an eyelet surrounding the manifold port. The eyelet protects the rubber gasket material from immediate contact with the acid type SPE membrane in the gaseous wet region at the fluid port.

9) The number of Belleville spring washers has been increased to nine pairs to compensate for rubber gasket relaxation or compression set equal to 100% of initial gasket compression, whereas the former design allowed for less than 20% rubber relaxation. In addition, approximately equal spacing of the tie rods will apply spring loading more uniformly to the entire gasket area.

3.2 Power Conditioner

The final 75 amp power conditioner (Figure 19) was constructed as an independent module with a base plate mounting. Open construction and water cooling are the primary physical characteristics. The power components are mounted on the lower portion of the main frame with the component board mounted across the top of the unit. The unit is interconnected to the electrolysis module by two No. 4 power leads and to the control panel through two No. 4 power leads and a control cable.

The power conditioner circuitry is shown schematically in Figure 20 (SK 67A490-767). It is basically a step-down, time-ratio-control current regulator. In addition to its current control capability it has an over-current shutdown and an indicator light to show when it is operating in a voltage-limited condition.

The power circuit is a conventional transistor controlled switch using two parallel transformer coupled transistors. Transformer drive is obtained with a two transistor Darlington drive configuration operating directly from TTL logic gates (SN 7400N). Pulse width control of the fixed repetition rate modulator is obtained by dynamically varying the time constants of the monostable pulse generator SN 74122N over the range of from < 5 microseconds to the maximum width of one half of the 330 microsecond period. The two modulating circuits acting alternately as controlled by flip flop SN 7474, will then provide a continuous drive to the power transistors and a resulting continuous conduction characteristic of voltage limited operation.

The control amplifier (741) is basically an integrating amplifier responding to the error signal difference between the shunt signal and the reference set by the current control of the control panel.

The fixed pulse repetition rate is provided by a unijunction pulse generator which is amplified with a transistor and a logic gate.

The unit is normally controlled by biasing the reference circuit to where it calls for less than zero current. This enables the unit to start-up and shutdown very smoothly at any current setting.

A second power conditioner (rated at 25 amps) was initially built for driving the seven-cell module "A" at this lower current level and has experienced 6322 hours of trouble-free operation. It employes the same basic type of control as the 75 amp conditioner. Present developments in control logic microcircuitry however have enabled the control circuitry for the 75 amp conditioner to be somewhat simplified.

3.3 Breadboard Control Panel

The control panel for the power conditioner is shown in Figure 21. It is basically a standard rack-mounted 19 inch panel containing two meters to measure module voltage and module current along with "ON/OFF" pushbuttons, "SHUTDOWN/RESET" pushbuttons, "CURRENT ADJUST" potentiometer, "VOLTAGE LIMIT OPERATION" indicator and an overload circuit breaker.

The control panel circuitry is shown in Figure 22 (SK 67A490-766). In addition to the basic control components above, the control panel assembly contains the under-voltage circuit which will shutdown the power conditioner when the input voltage is too low for normal operation.

3.4 Two-Phase Separator

In the water electrolysis system (WES), process water for dissociation and heat rejection is continuously circulated to the cathode (hydrogen) evolution side of the SPE module. A mixture (hydrogen/water) exits therefore from the module. In space applications the conservation of water is a prerequisite for life support during extended missions. Consequently, the separation and reuse of water becomes functionally important to the WES. Equally important for space life support criteria is the use of the hydrogen product, when separated from the mixture, to produce more water (e.g., by the reduction of CO_2 in a catalytic reactor). The conversion of the hydrogen, however, was not a requirement of this contract.

In a zero g space environment, two approaches can be employed for the separation of fluids in a two-phase mixture; either passively by hydrophilic and/or hydrophobic materials or dynamically by centrifugal force. The passive approach was investigated for this contract.

Literature surveys were made on materials which under controlled differential pressure will pass water but not gas (hydrophilic) and conversely will pass gas but not water (hydrophobic). This search along with the results from tests made by the GE/DECP laboratory throughout the program are listed in Tables VII and VIII. From initial tables of material data, porous glass tubes and porous polypropylene, respectively, were selected as the hydrophilic and hydrophobic materials. Bench testing of samples was initiated to demonstrate their functional capability on bubble point, flow permeability and filtration life. The encouraging results prompted the design of a laboratory breadboard model separator employing both elements and capable of visual observation (transparent Lexan plastic housing). Figure 23 (1076527-845P1) provides the details of this design. In this configuration, the mixture of H_2/H_2O enters the first of three series-arranged porous tubes. The mixture traverses a helical path against the inner surface of the tubes which causes the water content to centrifugally scrub the inner tube wall at approximately gas velocity. With a controlled differential pressure below the bubble point across the tube wall thickness and water-primed tube pores, the water passes through the tube while the gas continues towards the helical exit. This model included a single porous polypropylene hydrophobic subassembly. The model, after fabrication, was installed in the breadboard systems test facility (Figures 12 - 14) and thereupon accumulated 4458 hours of operation separating hydrogen and water within the limitations of tube bubble points which were in series (inlet to outlet) 6.0, >11.0 and 7.0 psid and at a one-man rate (equivalent oxygen generation). Figure 24 shows a comparison of dry hydrogen and two-phase mixture vs. pressure drop of the two-phase separator breadboard model (Figure 23).

In the fall of 1971, direction was given to develop a four-man rate (equivalent oxygen generation) prototype model separator employing the same nominal size hydrophilic porous tubes (1 3/4 in. OD x 9 in. lg) and hydrophobic porous polypropylene material. The major objective was to design a smaller package by improving the internal functional configuration. Component bench tests were conducted to explore a "close-gap" hydrophobic subassembly configuration (Figure 25) in an attempt to increase the gas permeability beyond that of the breadboard model configuration. Figure 26 presents the results of the evaluation. Comparing the permeability on dry hydrogen shown in Figure 26 with Figure 24, an improvement factor of 1.93 results.

$$\frac{165 \dfrac{\text{cc}}{\text{min.-psi-in.}^2}}{85.5 \dfrac{\text{cc}}{\text{min.-psi-in.}^2}} = 1.93$$

The "close-gap" design approach was therefore adopted for the prototype model with three parallel membrane assemblies to provide the flow area for four-man rate capability. In this same period, water permeability evaluation was also performed on full size 1 3/4 in. OD x 9 in. lg porous tubes. The average results of four tubes separately evaluated was a water permeability of 0.3 cc/min.-psi-in.^{2}. However, actual component test results of the prototype model, Figures 27 (1076527-968P1) and 28, which contains five tubes in series, resulted in an average water permeability of 0.195 cc/min.-psi-in.^{2} under pressure conditions simulating WES operation. The difference between the 0.3 and 0.195 permeabilities is most probably due to gas blockage of pores. This is demonstrated by Figures 29 and 30 in comparing "pressurized" with "unpressurized" data and also the effective area used for the permeability calculation.

3.5 Deionizer Resin Bed

For prolonged water electrolysis system operation using a solid polymer electrolyte module to generate oxygen and hydrogen, it is necessary to supply the module with ionically-clean process water for the electrochemical dissociation reaction. This is to prevent the exchange of dissolved water ions with the hydrogen ion of the SPE membranes, which would result in higher cell resistance and subsequent increased voltage at constant current. More input power would be required by the module to generate the same oxygen and hydrogen rate. Consequently, in all WES operation, a deionizer was used to produce an acceptable ionic water level.

The deionizer configuration is a mixed monobed in volume proportions of cation and anion resins to chemically exchange with any water ions, resulting in increased water quality. Resins are supplied by Illinois Water Treatment Co., Rockford, Ill., per their specification Anion Exchange Resin IWT-A-204G and Cation Exchange Resin ILLCO-C-211. Tables IX and X are summaries of these specifications.

The breadboard model design as shown in Figures 31 (GE dwg. 1076527-957P1) and 32 is capable of removing ionic dissolved solid species up to 100 ppm for 180 days at a make-up water rate equivalent to a nominal six-man off-design condition of 75 amps electrolysis module input current.

Water flow vs. pressure drop testing was completed on the assembled unit with results as shown in Figure 33.

3.6 Biological Filter Resin Bed

During bench life tests of scaled-down size hydrophilic porous tubes for development of the two-phase separator, clogging of the tube pores was occasionally experienced. These sample tubes were installed in the simple electrolysis test setups of the single-cell module and four-cell module "B" with tube pressure drop vs. time being monitored. Pore contamination by bacteria, mold, etc. was verified by extensive water sample analysis. These test setups, although adequate for SPE module evaluation, provided an environment for growth of microorganisms; namely temperature, open reservoirs, plastic nutrients, etc. Consequently, the setups were uncontrolled test vehicles for the porous tubes, whose pores of 2 to 3.5 microns became excellent filters for the setup.

In an effort to increase tube life by reducing microorganism clogging, a biological filter resin bed was installed in the test setup upstream of the tube. This was proven to be successful in accelerated test setups. It is hypothesized that the biological resin bed performs this filtering function most probably by three mechanisms:

1) Electrostatic attraction of microorganisms to the resin beads.

2) Particulate matter depth filtration through the lengthy resin bed column.

3) Retardation or actual destruction of bacteria and mold growth by the localized acidified water within the resin bed column.

The biological filter configuration is a mixed monobed in volume proportions of cation and anion resins. Resins used are supplied by the Illinois Water Treatment Co., Rockford, Ill., per their specifications Anion Exchange Resin IWT-A-704A and Cation Exchange Resin IWT-C-381. Tables XI and XII are summaries of these specifications.

A breadboard model design of a biological filter resin bed would be employed in the WES immediately upstream of the separator. The unit is shown in Figures 34 (GE dwg. 1076527-958P1) and 35.

This bed performs a dual function in that it will also ionically clean the circulation water of the WES.

3.7 Regenerative Heat Exchanger

The water electrolysis system schematic (Figure 1) includes regenerative and primary heat exchangers. The heat exchanger design is a tube within a tube shaped into a coil.

The regenerative heat exchanger transfers heat picked-up by the hydrogen/water mixture within the module to the relatively cool process water entering the temperature regulating valve. Consequently, the module heat loss from the circulating water is reduced and the module temperature is elevated and a steady temperature is maintained resulting in less variation in module performance (voltage at constant current as a function of temperature).

A commercial heat exchanger (Model No. 3101-6 4-8-6x316 SST) was purchased from the Parker-Hannifin Co., Cleveland, Ohio, to provide the regenerative function during the breadboard systems testing. Figure 36 shows this heat exchanger which was thermally insulated with a polyether urethane foam.

The primary heat exchanger function is to transfer the remaining heat picked-up by the two-phase hydrogen/water mixture to the interface coolant fluid available to the WES. Thus, the H_2/H_2O mixture entering the two-phase separator will be at or near cabin temperature. Water-masking of the hydrophobic subassemblies due to condensation of the saturated hydrogen is less likely in the close-gap, multiple porous polypropylene assemblies.

Laboratory coolers were improvised for the function of a primary heat exchanger.

It is expected that for flight hardware, the primary and regenerative heat exchangers would be designed and fabricated into a single assembly with considerable weight and volume savings.

A heat transfer study was made of a typical water electrolysis system as shown in the schematic of Figure 37. A mathematical model for the system using primary and regenerative heat exchangers was programmed on the GE Mark II Time Sharing Computer System. Summaries of computer case studies and test facility coolant criteria are given in Tables XIII and XIV, respectively. The Appendix includes the results of six case studies.

3.8 Water Temperature Regulating Valve

The water temperature regulating valve controls the process water temperature entering the electrolysis module. This valve mixes the water heated by the regenerative heat exchanger with a portion of the process water which bypasses the regenerative heat exchanger to maintain essentially constant temperature leaving the valve. The functional advantage of such a valve in the system is twofold: a wide range in coolant temperature is permissible while maintaining a constant electrolysis module temperature; and a rapid rise in mean temperature of the electrolysis module is provided for during start-up.

Table XV presents the GE/DECP valve procurement specification. The Standard-Thomson Corp., Waltham, Mass., fabricated a valve (Model No. 8A767-Rev. 002) for breadboard WES operation. Figure 38 is a drawing of a typical valve. The actual valve purchased is as shown in Figure 39. Valve function is performed by an internal spool or actuator which contains a hermetically sealed eutectic wax. Expansion and contraction of the wax due to temperature variations results in valve displacement and subsequent proportioned mixing of "hot" and "cold" entering water.

3.9 Process Water Pump

Table XVI presents the process water pump procurement specification.

The pump (Model No. 02-70-316-731) which is similar to an "off-the-shelf" item used as a galley pump in the Boeing 707 aircraft, was purchased from the Micropump Corp., Concord, Calif. Figure 40 presents an abstract of data from the vendor's pump data bulletin. Figure 41 shows the water pump, along with the water flow valve.

Figure 42 presents component test results. The performance characteristics demonstrate that this magnetically-coupled gear pump has considerably more flow capacity than required for four- or six-man WES operation. Consequently, as shown by the WES fluid schematic (Figure 1), a bypass valve is required to deliver excess flow from the pump discharge to suction inlet. This technique was decided upon for this particular pump after having experienced an internal relief valve spring failure. During earlier component testing, excess flow would return to the suction side through an internal pump relief valve. It is hypothesized that cyclic stressing of the spring occurring with many starts and stops of the pump caused material fatigue with subsequent spring rupture. With a bypass around the pump, the relief valve operates only in a redundant safety mode. According to the vendor, reduced capacity pumps could be supplied after a design modification to the gears.

Also, during earlier component testing, magnetic uncoupling of the motor driver magnet from the pump driven magnet was experienced. Pump teardown revealed rub and wear marks on the driven "canned" magnet, with corresponding marks on the surrounding seal cup. It was hypothesized that during pump operation when the driven "canned" magnet rotor is revolving at approximately 12, 000 rpm, a pressure difference existed across the magnet to cause magnet shift on the rotor shaft resulting in facial contact with the seal cup and subsequent uncoupling. Corrective action was to drill two

.055 in. diameter holes 180° apart in the hub of the magnet to permit pressure equalization. No uncoupling failures of the pump have been experienced since introducing this change.

3.10 DC/AC 3-Phase Inverter

The three-phase pump inverter is shown in Figure 43. The front panel contains an on/off control with an indicator light and the input and output power jacks.

The internal circuitry is shown in Figure 44 (GE dwg. SK 67A490-765). All of the circuitry except for the step-up transformers is contained on a single circuit board. The power circuit is a standard three-phase bridge configuration which drives the primaries of the output step-up transformers.

The bridge transistors are driven through a single-stage of direct-coupled transistors. These are driven in the desired sequence by the control logic consisting of a repetition rate generator and the necessary encoding and decoding logic to generate the required output waveform.

Overall pump performance is shown in Figure 42.

3.11 Water Flow Valve

The water temperature rise through the electrolysis module is sensitive to water flow rate and the pressure rise of the pump is a function of water supply pressure and component pressure losses. It is necessary to maintain a constant process water flow rate in order to limit the temperature at the outlet of the electrolysis module to 150°F at the maximum off-design oxygen generation rate of approximately a six-man rate ($\sim$ 15 lb/day). A flow valve is used to maintain a constant process water flow rate through the pump.

The flow valve consists of a variable orifice (externally adjustable) through which all the pump output flows in series with a pressure regulator. Flow is adjustable from 0 to 44 lb/hr.

Figure 42 presents the component performance characteristics of the water flow valve, along with the process water pump and the DC/AC inverter.

Figure 45 shows the basic valve. Figure 41 includes the actual valve procured from the Micropump Corp., Concord, Calif., in accordance with the GE specification of Table XVII.

3.12 Absolute Hydrogen Back-Pressure Regulator

As shown in the WES schematic (Figure 1), a "hydrogen-side" regulator is employed to establish a pressure level on the discharge side of the two-phase separator and for system operation in conjunction with the process water pump pressure rise.

Table XVIII presents the GE specification to which the manufacturer, AUSCO, Inc., Port Washington, N. Y., designed and fabricated a regulator. The delivered regulator (Figure 46) was manufactured in accordance with the vendor drawing of Figure 47.

The regulator is a soft-seated valve with biasing compression spring capable of external adjustment and a sealed evacuated bellows to control the upstream pressure (back-pressure).

Towards the latter portion of the program, the regulator was installed in the test facility and breadboard system tests performed using seven-cell Module "A" and the nominal 25 amp power conditioner. Steady state operation (101 ASF current density), starts and stops were performed during which time the regulator performed very satisfactorily.

3.13 Absolute Oxygen Back-Pressure Regulator

An absolute oxygen back-pressure regulator was designed and fabricated by AUSCO, Inc., in accordance with the GE specification of Table XIX and Figure 47. Figure 46 shows the actual regulator procured. The regulator is identical to the hydrogen type described in section 4.12 except for control point setting and performed equally as well as the hydrogen regulator.

This regulator establishes a nominal 20 psi O_2 side greater than H_2 side differential in the electrolysis module, without inter-reference of the two sides.

3.14 Differential Back-Pressure Regulator

The WES (Figure 1) includes a differential regulator to control the water outlet pressure on the discharge side of the two-phase separator below a reference pressure of the system. This pressure regulation controls the pressure difference across the hydrophilic tubes of the two-phase separator. AUSCO, Inc., designed and fabricated a differential regulator to perform this function in accordance with GE specification (Table XX) and their drawing (Figure 48). The regulator is similar to the O_2 and H_2 absolute types except the inboard side of the bellows is not evacuated but referenced as explained above. Figure 46 shows the actual regulator as purchased. The system test results on this regulator were very satisfactory. However, conclusion of the program precluded extensive testing of this regulator.

SECTION 4. CONCLUSIONS

1) The solid polymer electrolyte (SPE) electrolysis module demonstrated a capability for long life and invariant performance. Endurance testing under this program included the following*:

. Four single laboratory cells:	9606, 9134, 8971 and 8265 hours, respectively.
. Single-cell module:	9344 hours.
. Four-cell module:	6072 hours (including 3151 cycles of 60 minutes "on"/40 minutes "off" power).
. Seven-cell module:	11,088 hours.
. Four-cell module breadboard system test:	1682 hours.

2) The present temperature limitation of breadboard electrolysis module operation is about +150°F. However, this limitation is expected to be raised ($\geq$ +180°F) in the near future as improvements are realized in the temperature tolerance of resilient gasket materials and the module mechanical design.

3) The SPE cell is capable of high-pressure application although testing was limited to 1500 psig due to fixture leaks. It is anticipated that 3000 psig is feasible with fixture improvements.

4) Long life operation (six months) at higher temperature is expected with resilient material changes in the cell assembly of the electrolysis module.

5) Operational limits of the passive two-phase separator designed in the program is largely determined by two factors:

a) Differential pressure across the hydrophilic tubes must be regulated below the bubble point.

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* NASA Langley Research Center tests of a four-cell module over a period of one year verified performance characteristics obtained in this laboratory at ambient temperature and 100 ASF.

b) Flooding of the hydrophobic membrane has not been fully evaluated. Transients occurring during stop/starts are felt to be potential cause of such flooding.

6) The "cathode-feed" method of process water supply has the advantage of requiring only one separator, but at the expense of slightly higher voltage at constant current density.

7) The "anode-feed" method of process water supply has the advantage of lower voltage at constant current density, but at the expense of requiring two separators.

SECTION 5. RECOMMENDATIONS

The successful development of water electrolysis system components under this contract reached a point which warrants more extensive verification and off-design testing to demonstrate system compatibility. This follow-on work should include the development of a full "membrane-type" hydrophilic/hydrophobic separator and an advanced technology module for higher current density and temperature operation which promises significant weight and volume savings for space application.

It is therefore recommended that the following new program by considered:

1) Assemble into a laboratory system and test the breadboard components developed under Contract NAS 1-9750 and including the procurement of a primary heat exchanger, check valves, particulate filter and associated test equipment and instrumentation. This system would be used to explore continuous and cyclic (starts and stops) operation up to and beyond the four-man rate design point, and also define component limitations during system operation up to an off-design point of a six-man rate (approximately 75 amps current demand).

2) Redesign, refurbish as necessary and package the components along with controls, electronics and instrumentation into a frame with acceptance test WES operation at GE/DECP. This system would then be delivered to NASA or a designated test contractor for extensive testing.

3) Develop materials suitable for use at higher temperatures, which would allow an electrolysis module to operate at higher current density. This advanced module along with ancillary components procured as necessary for higher temperature operation (e.g., temperature regulating valve, temperature sensors, etc.) would be designed to replace the respective components in the breadboard system test above. After development and testing at GE/DECP, these items would be delivered to NASA or a designated test contractor for further WES operation and evaluation.

4) Develop and fabricate a breadboard full "membrane-type" separator and/or a dynamic centrifugal separator. After acceptance testing at GE/DECP, the separator would be delivered to NASA or a designated test contractor for WES operation.

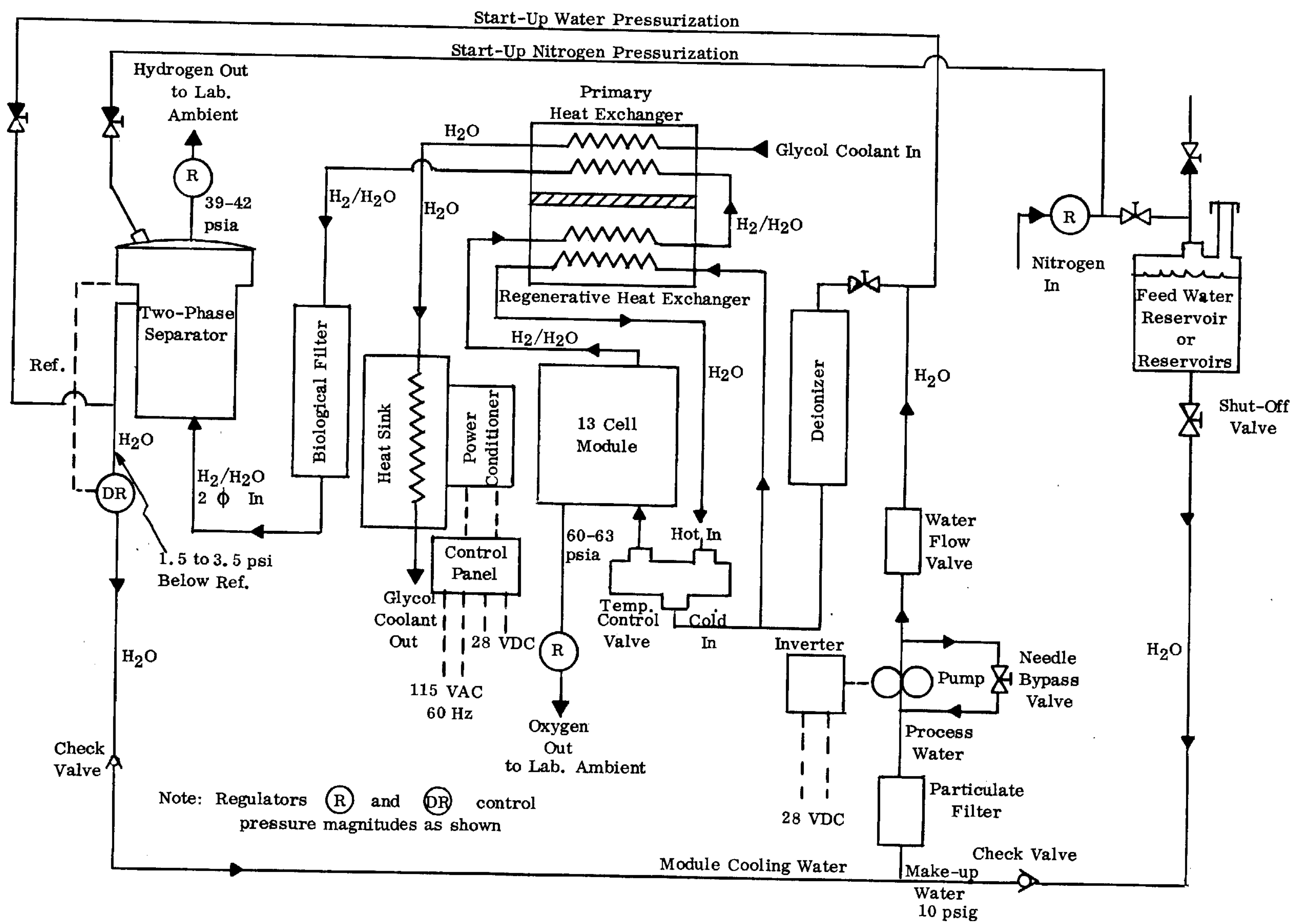


Figure 1. - "4-Man" Breadboard Water Electrolysis System Fluid Schematic

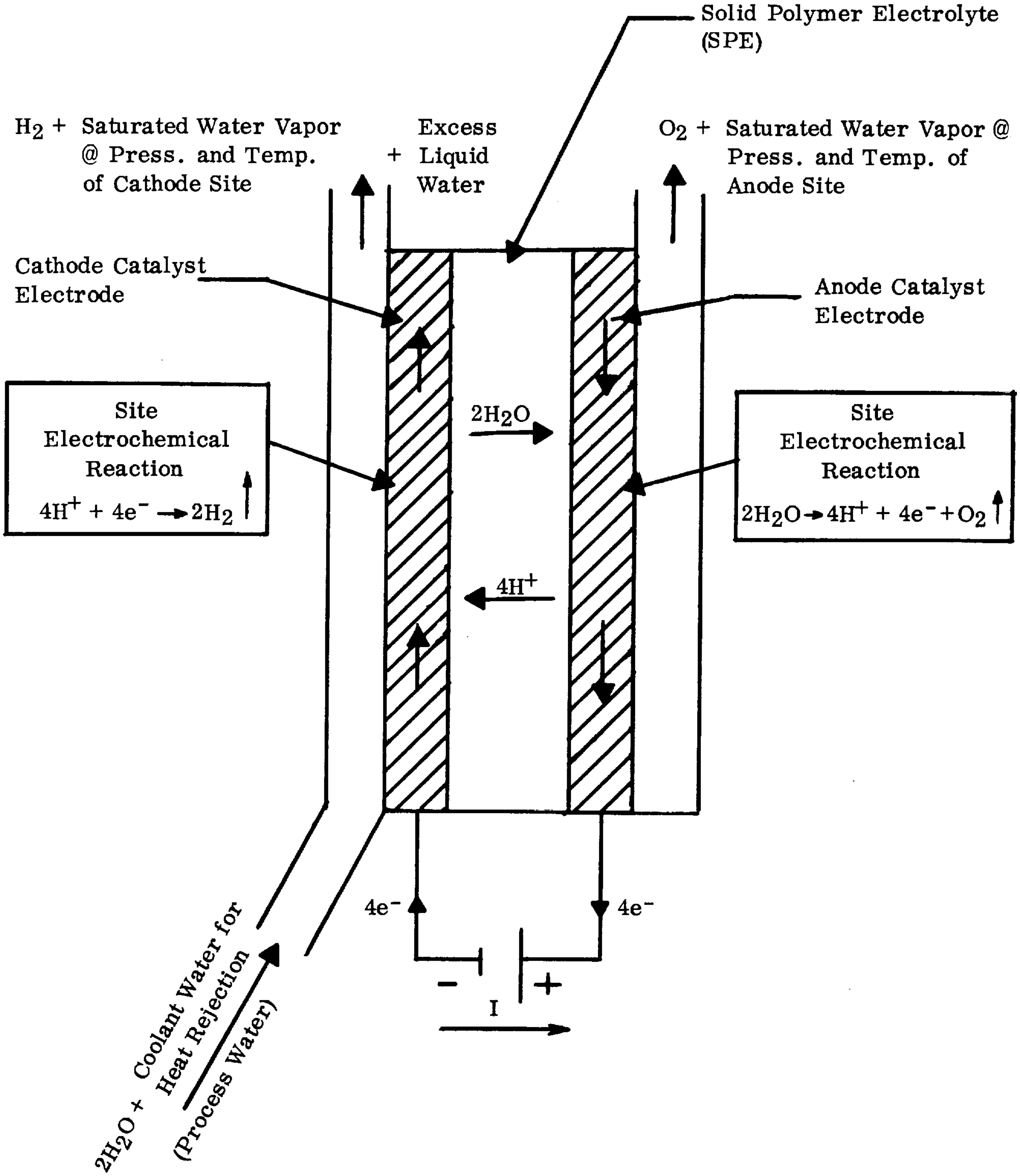
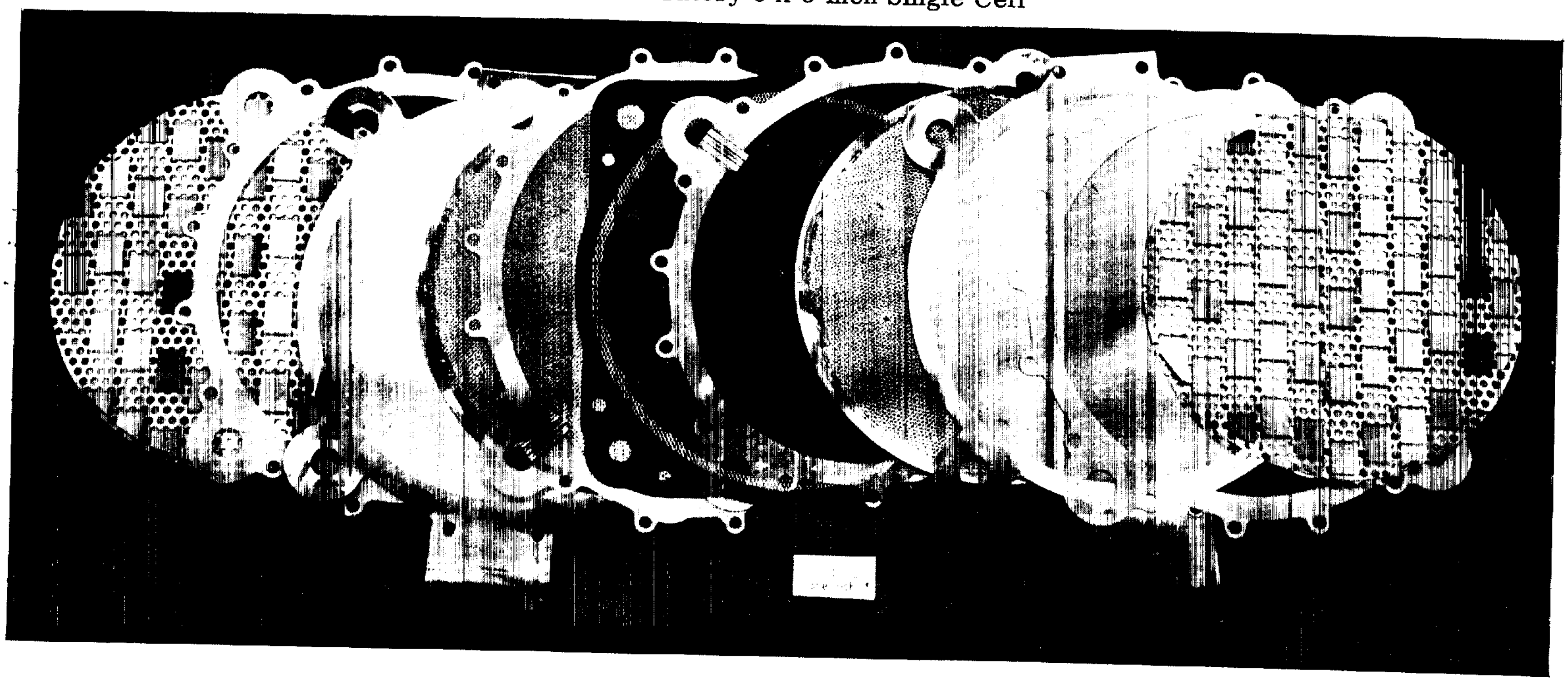


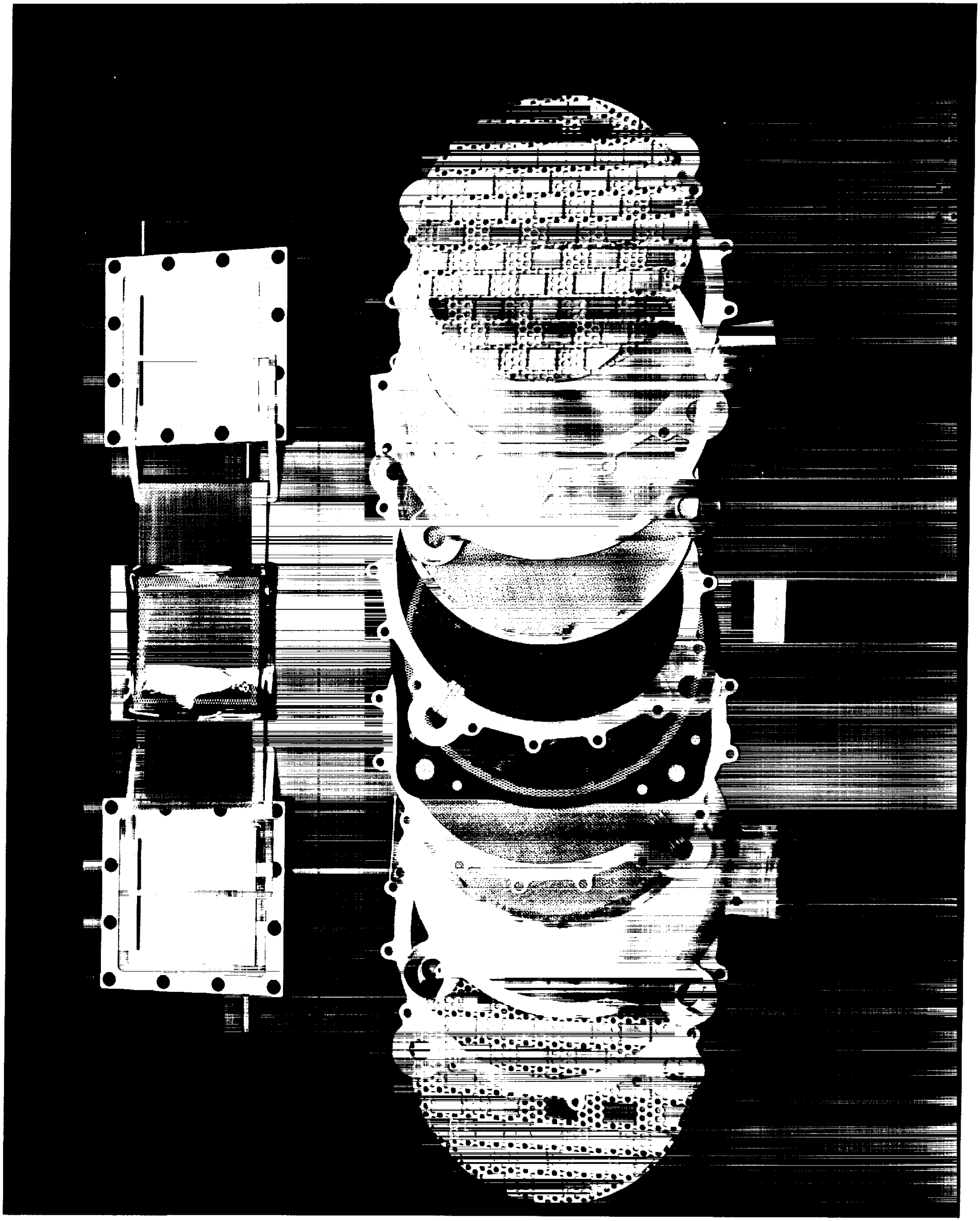
Figure 2. - SPE Electrolysis Cell Schematic

Laboratory 3 x 3 inch Single Cell



Full-Size Prototype Single Cell

Figure 3



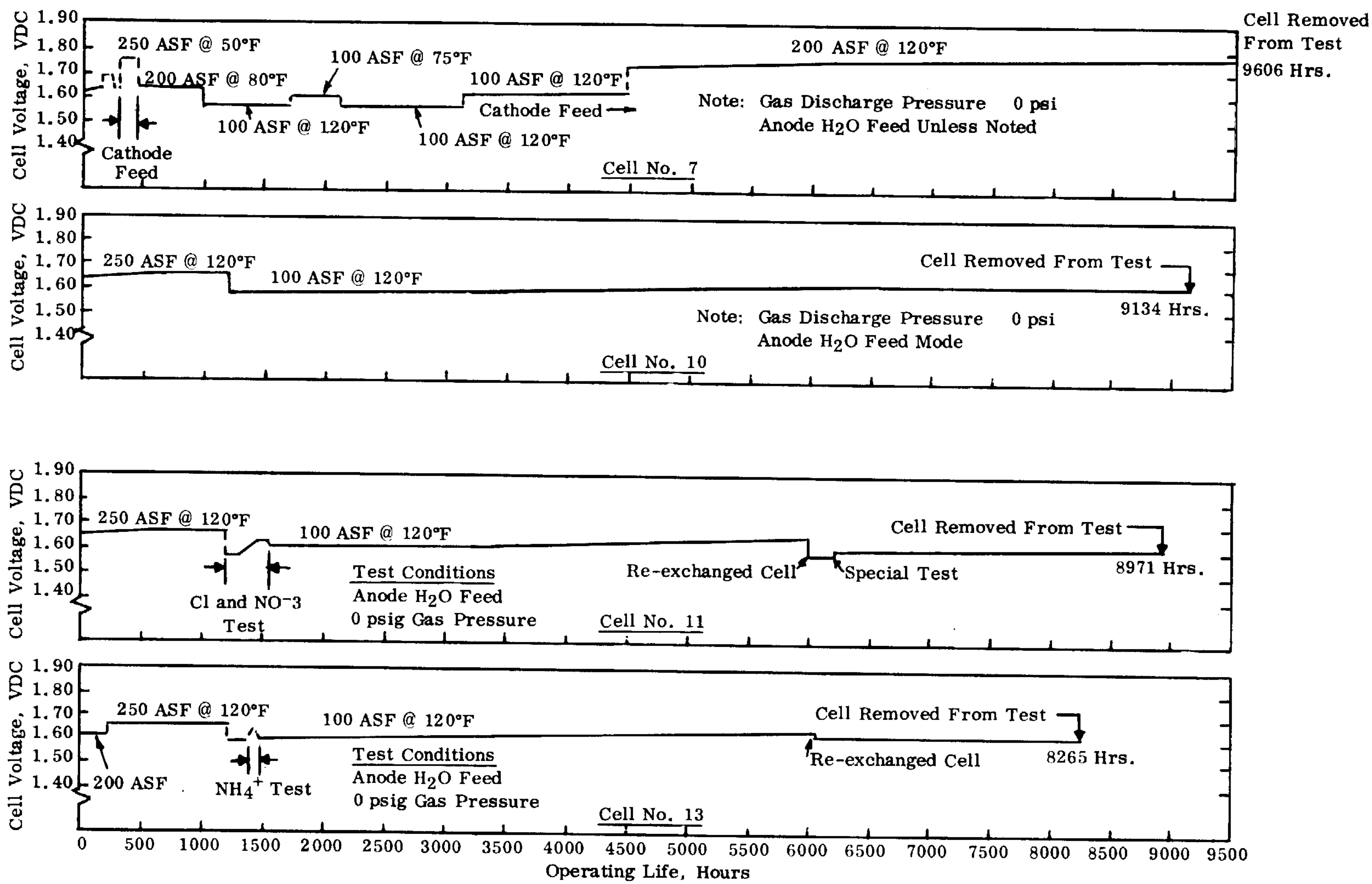


Figure 4. - Laboratory Single-Cell Life Test Performance

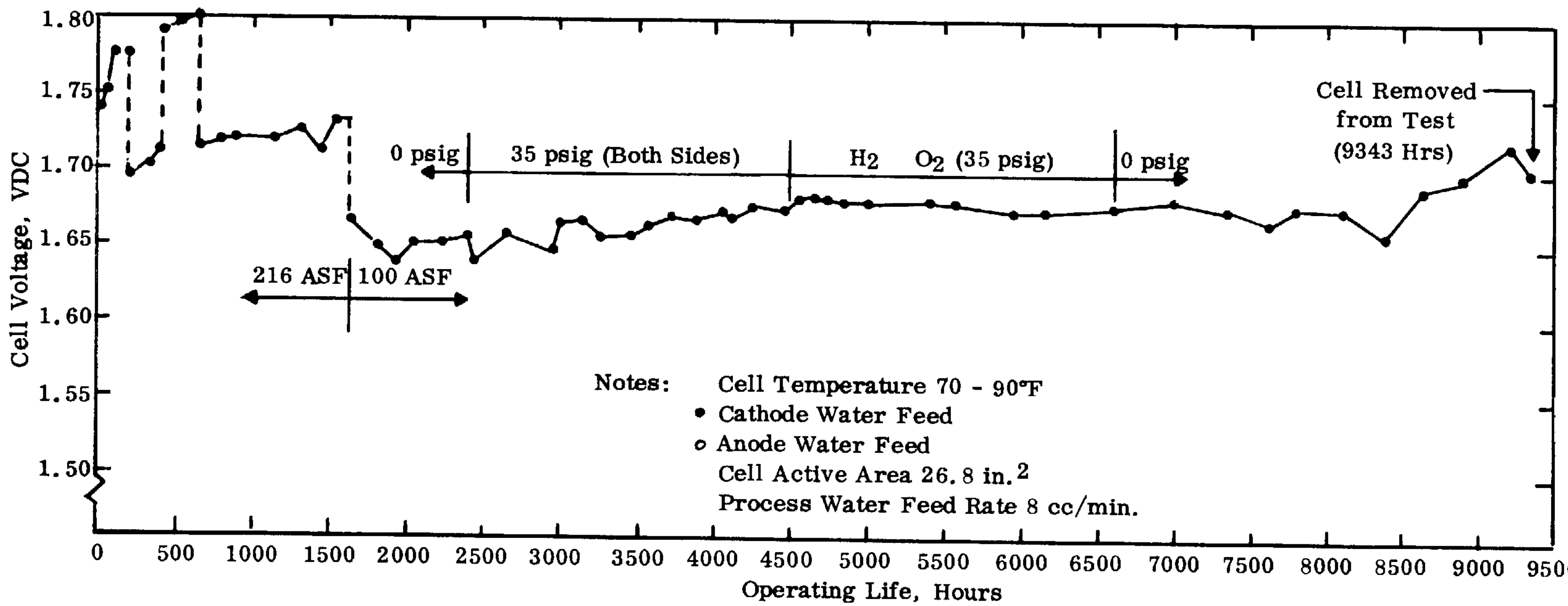


Figure 5. - Single-Cell Module Performance/Life Testing

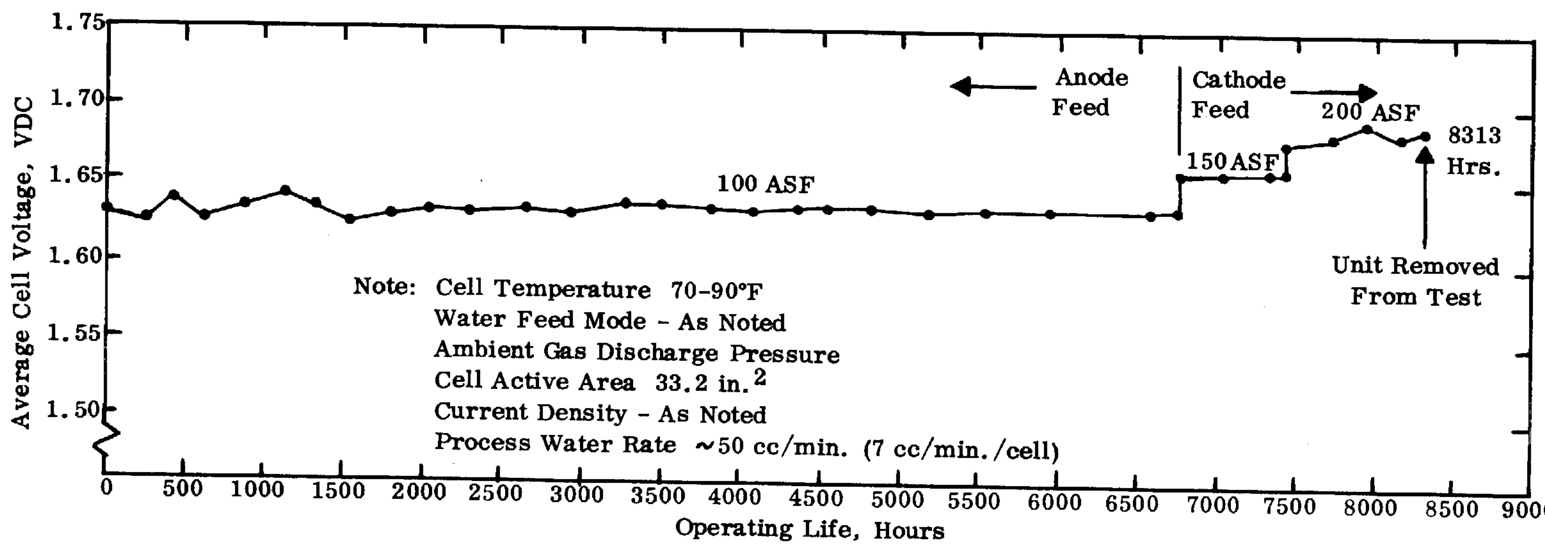


Figure 6. - Seven Cell Module "A" Life Testing

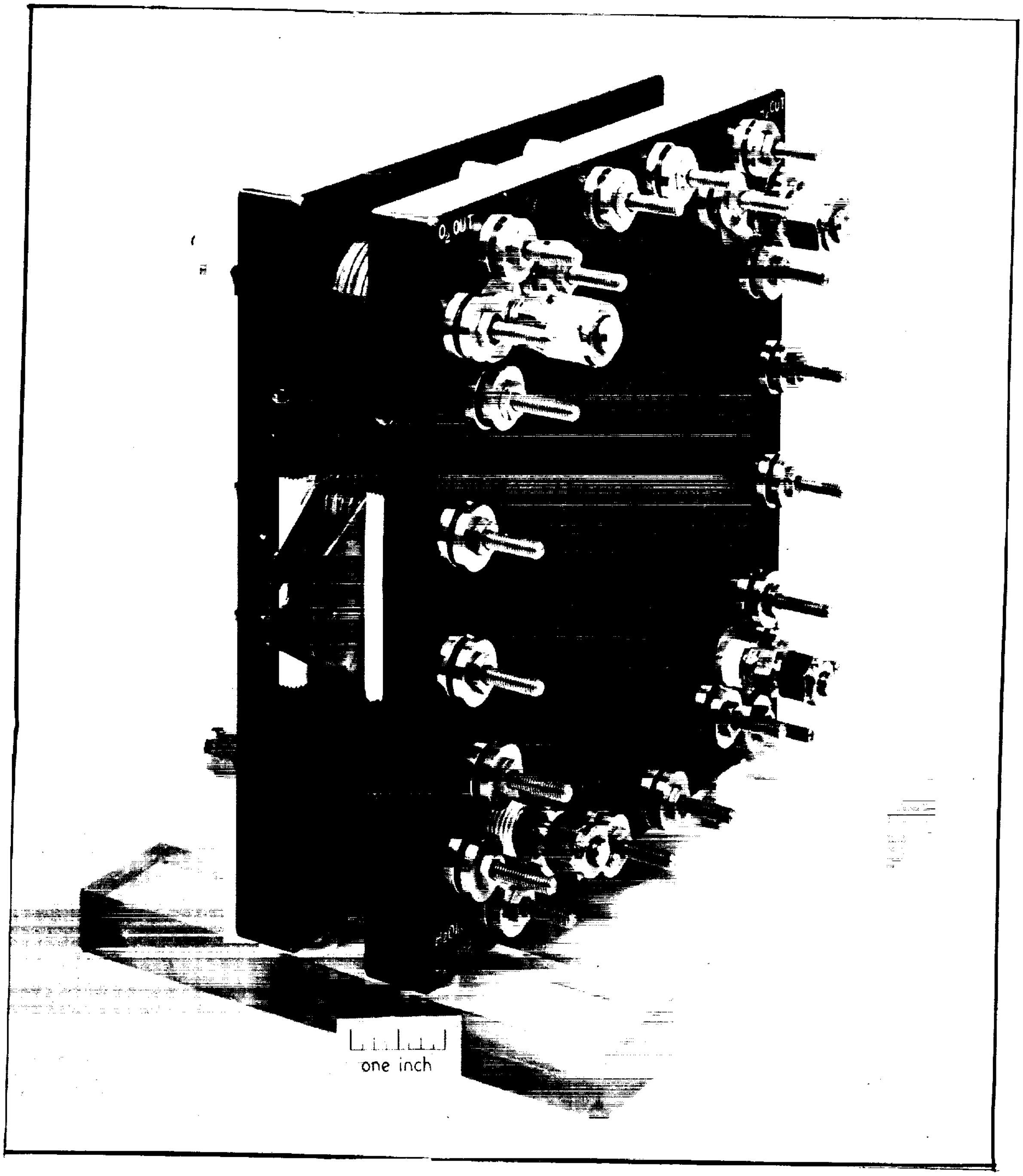
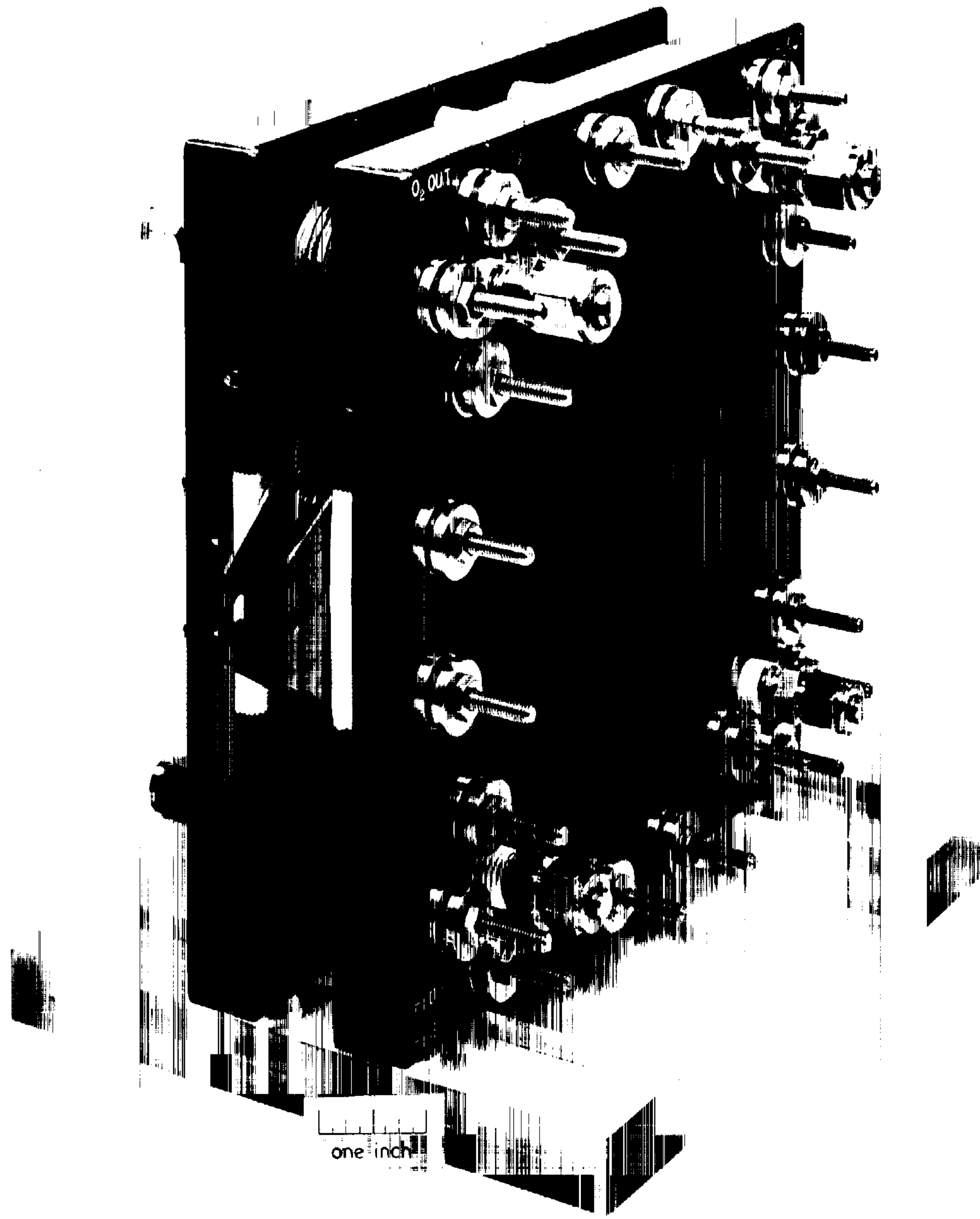


Figure 7. - Seven-Cell Electrolysis Module "A"



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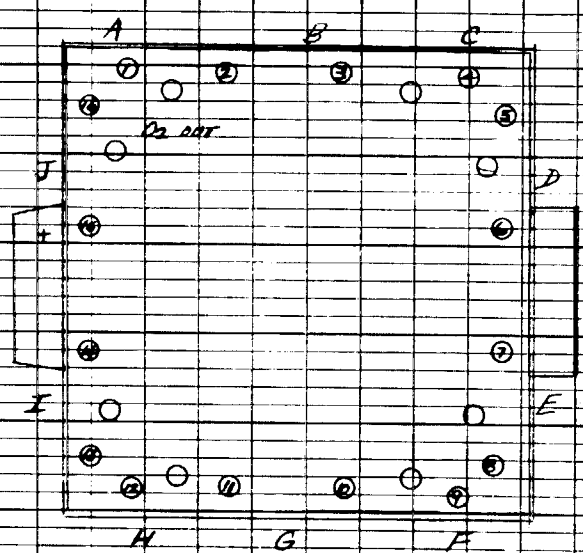
GENERAL ELECTRIC — **TEST LOG** — Page No. 1A

Unit Tested: Retorque of Langley 7-cell module — Test Request No. TASK 3.0 Broadband Ovstons Test — Date 8/16/71 — Headings By: KMD
Type of Test: Endurance – Cathode Fed — Recorder: 1st Shift / 2nd Shift / 3rd Shift
Apparatus Tested: Electrolysis module 7 cells S/N No. "A" — Project: Langley — Stand No. — Bldg. 1-70L — Approval: Test — Engr. — Customer Coordination



Position	Torque in/lbs	Dimension (in)	Torque	Dimen.	Torque	Dimen.	Torque	Dimen.		
1	8.5	.188	15.0	.182	15.0	.167	15.0	.166		
2	9.0	.274		.272	20.0	.258	25.0	.255		
3	8.5	.275		.273	20.0	.256	25.0	.249		
4	8.0	.187		.181	15.0	.171	15.0	.171		
5	7.5	.189		.182	15.0	.166	15.0	.164		
6	8.5	.278		.274	20.0	.268	25.0	.259		
7	9.5	.276		.274	20.0	.260	25.0	.256		
8	7.0	.192		.177	15.0	.166	15.0	.167		
9	8.0	.198		.191	15.0	.178	15.0	.178		
10	10.0	.268		.267	20.0	.252	25.0	.245		
11	9.0	.278		.273	20.0	.255	25.0	.248		
12	6.0	.194		.188	15.0	.172	15.0	.172		
13	8.5	.193		.190	15.0	.170	15.0	.169		
14	11.0	.277		.274	20.0	.259	25.0	.253		
15	10.5	.272		.268	20.0	.259	25.0	.251		
16	7.5	.199		.191	15.0	.178	15.0	.177		
	—	—		—	20.0	—	25.0	—		
A		.889		.887		.868		.864 →	.857	
B		.890		.888		.870		.864 →	.863	
C		.893		.887		.868		.858 →	.858	
D		.897		.892		.870		.863 →	.860	
E		.897		.892		.866		.856 →	.856	
F		.899		.888		.870		.856	.850	opposite No 8
G		.896		.889		.870		.862		
H		.884		.887		.871		.857	.855	opposite No 13
I		.891		.887		.872		.860 →	.861	
J		.885		.884		.871		.863 →	.862	
		1		2		3		4	5	

5 measured 8/17/71 @ 80 psig

NOS 1-16 = washer gap dimensions
LTRS A-J = plate gap dimensions

Inside bolts contain 3 sets of 3 disc springs
Outside bolts (1, 4, 5, 8, 9, 12, 13, 16) contain 3 sets of 2 disc springs

General Notes and Remarks

Figure 8. - Seven-Cell Module "A" Tie Bolt Locations

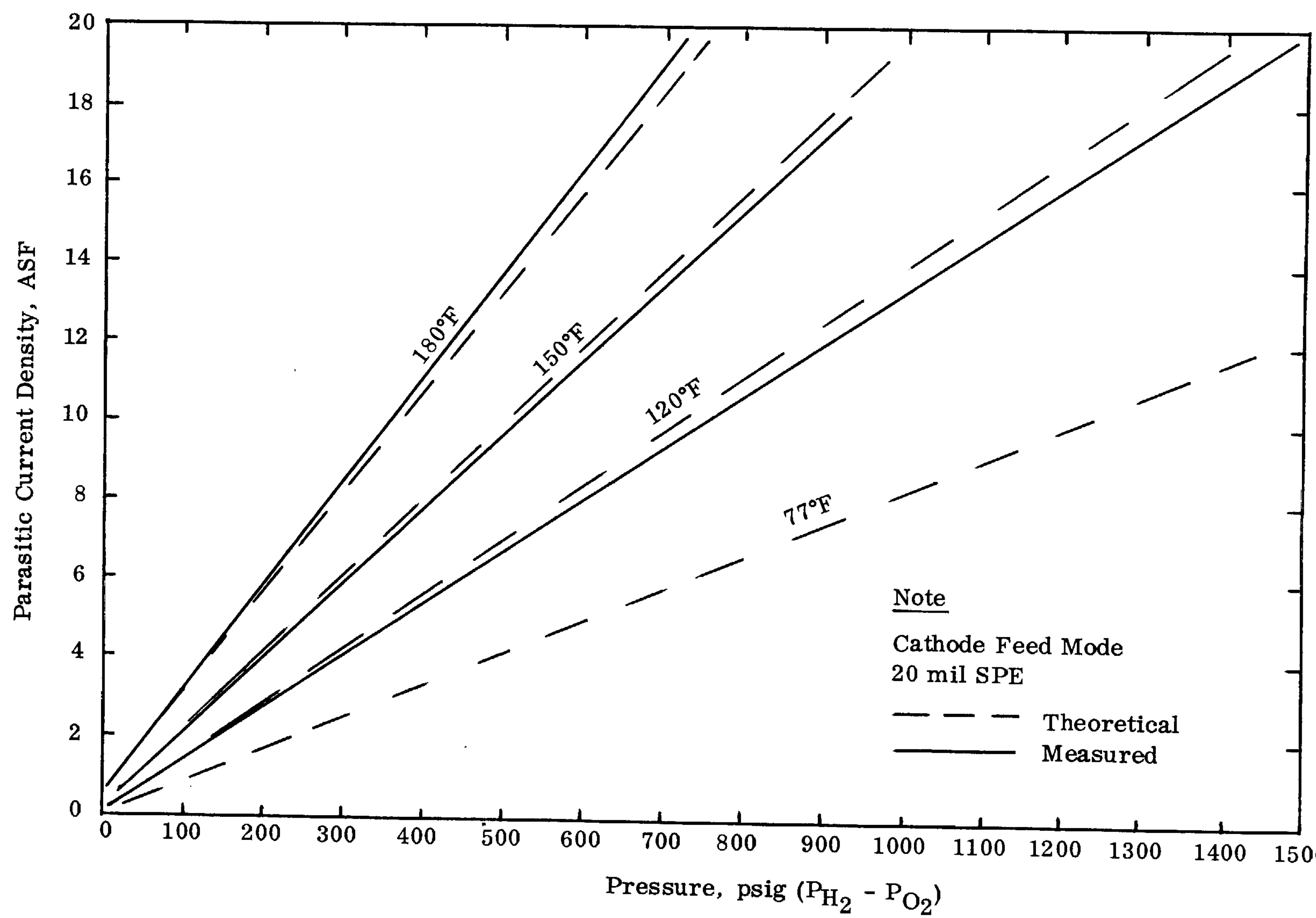


Figure 9. - Parasitic Current Density for 20 mil SPE

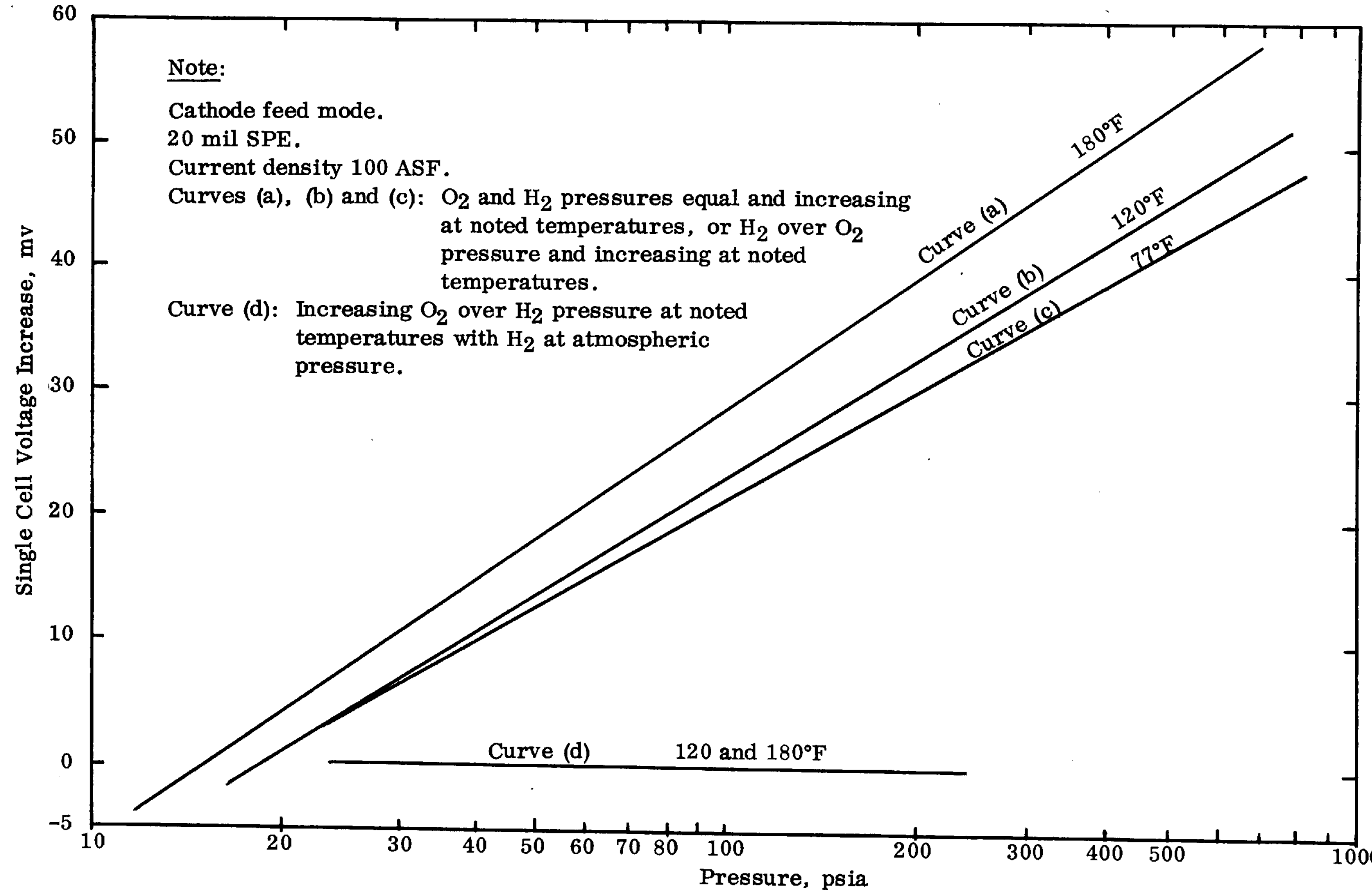


Figure 10. - Effect on Performance Decrease with Pressure

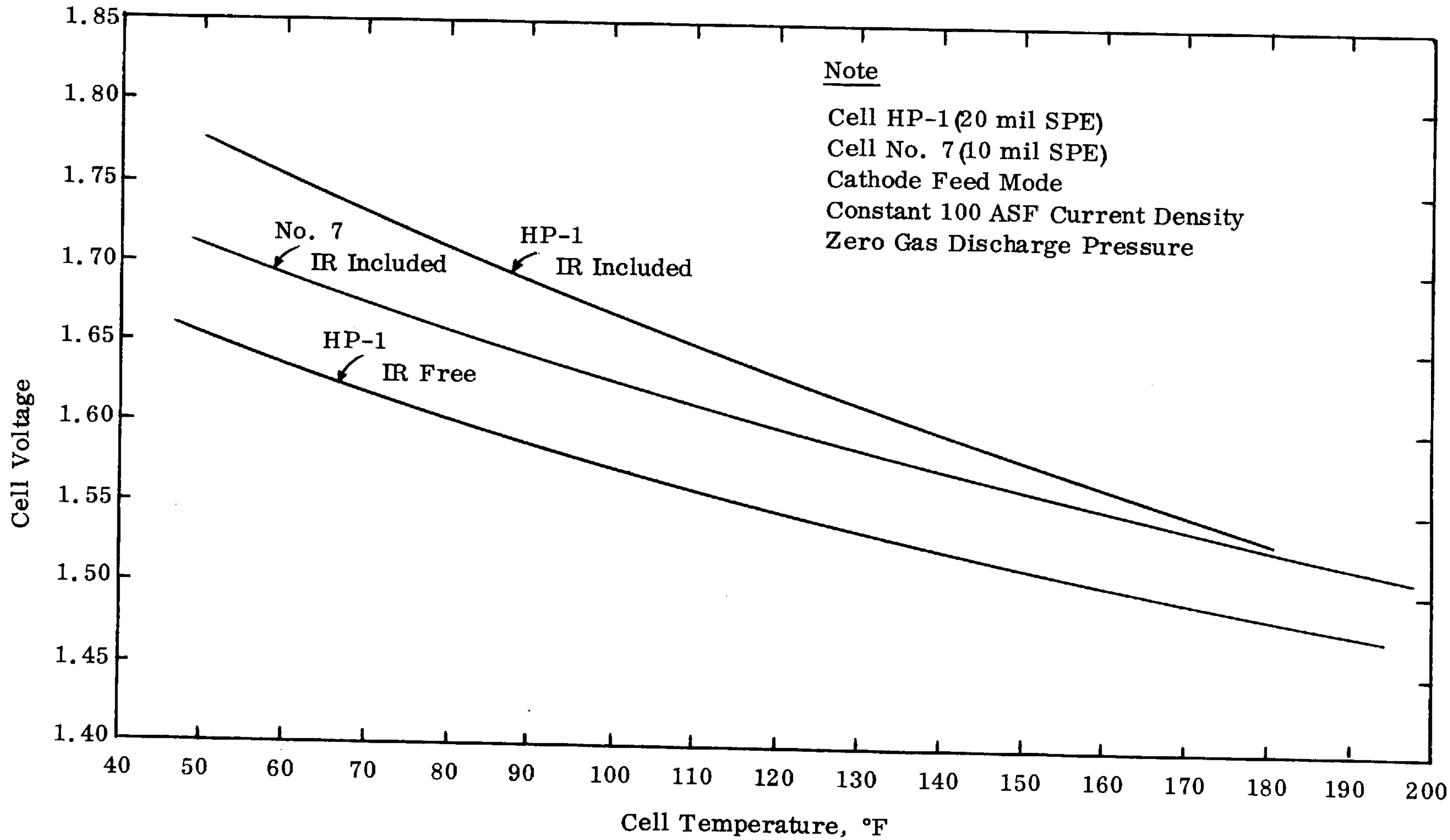
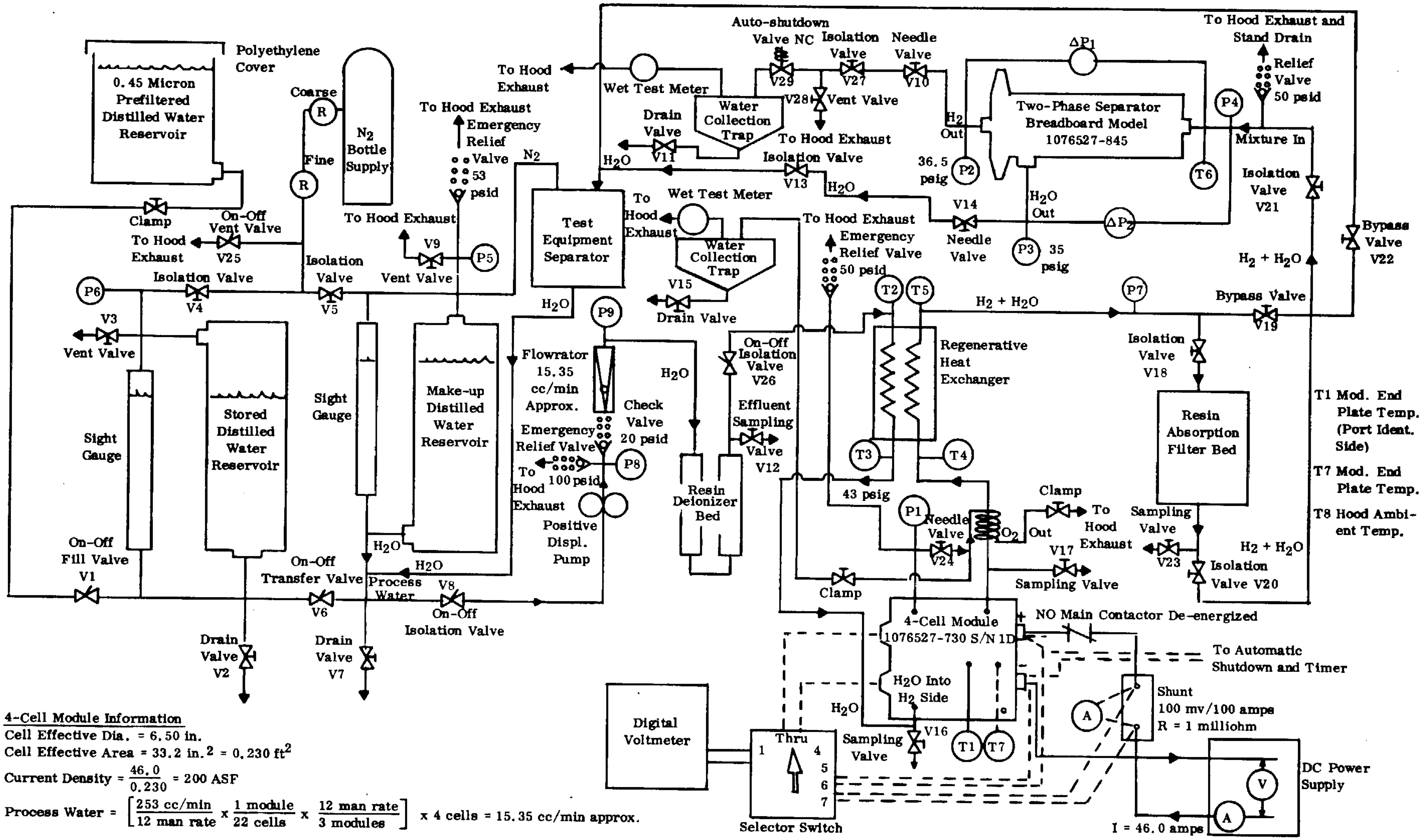


Figure 11. - Effect of SPE Thickness on Performance



4-Cell Module Information

Cell Effective Dia. = 6.50 in.

Cell Effective Area = 33.2 in.^{2} = 0.230 ft^2

Current Density = $\frac{46.0}{0.230}$ = 200 ASF

Process Water = $\left[\frac{253\ \text{cc/min}}{12\ \text{man rate}} \times \frac{1\ \text{module}}{22\ \text{cells}} \times \frac{12\ \text{man rate}}{3\ \text{modules}}\right] \times 4\ \text{cells} = 15.35\ \text{cc/min approx.}$

Note: In the absence of absolute back-pressure type regulators, needle valves V10, V14 and V24 are adjusted during test as necessary to respectively maintain 36.5 psig (P2), 35 psig (P3) and 43 psig (P1).

Figure 12. - Breadboard Water Electrolysis System Test Schematic - Cathode Feed

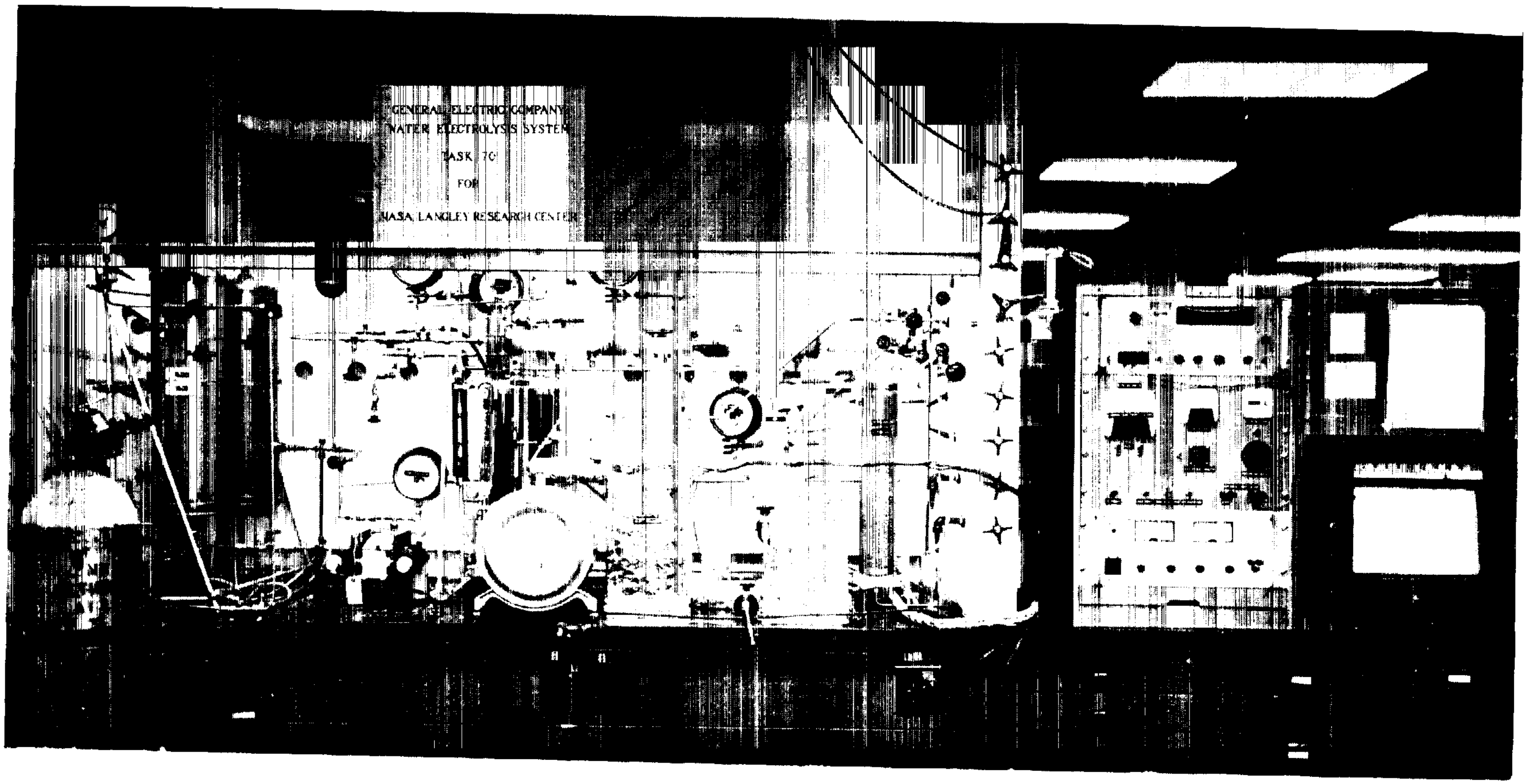
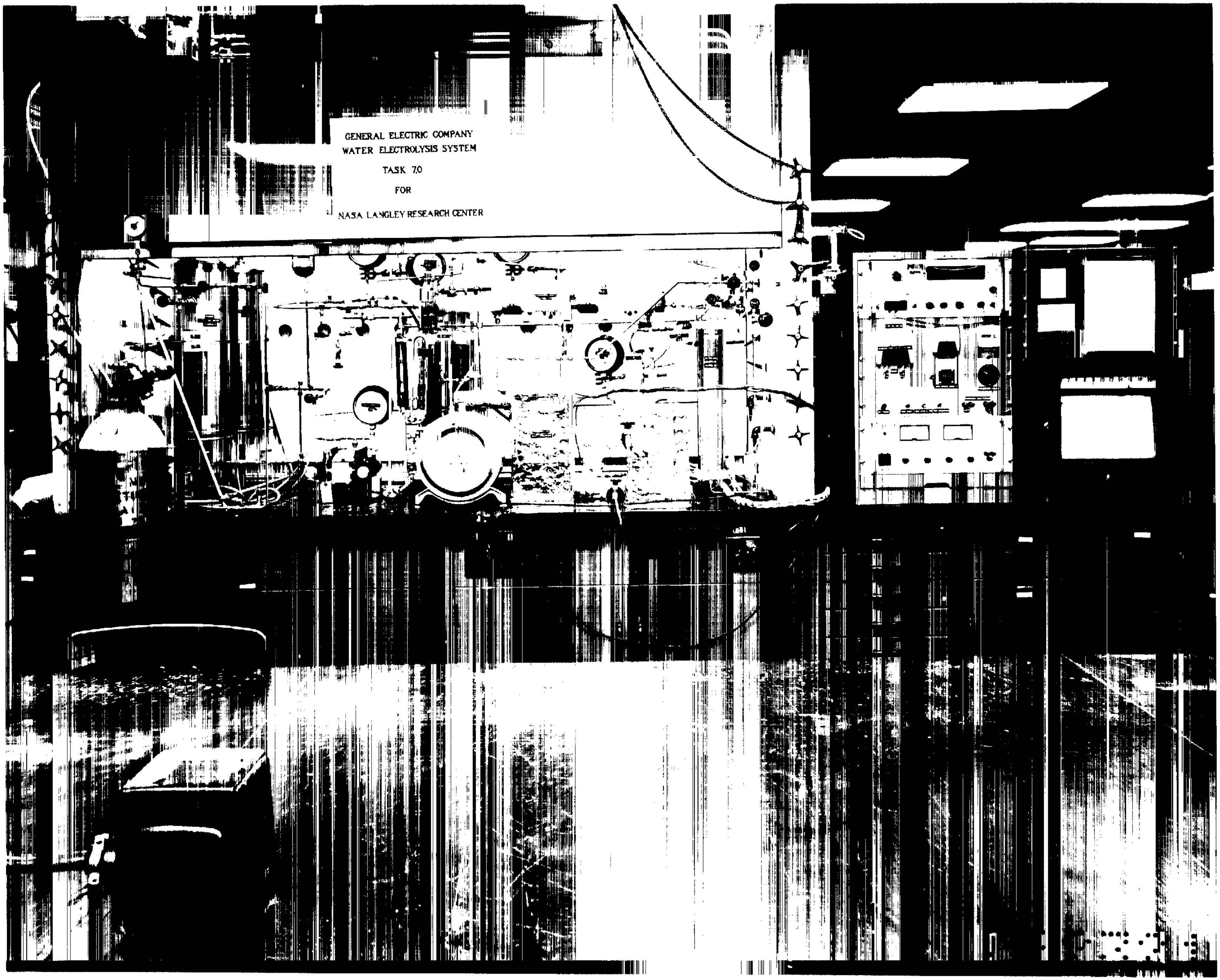


Figure 13. - Water Electrolysis System Test Setup


GENERAL ELECTRIC COMPANY
WATER ELECTROLYSIS SYSTEM
TASK 7.0
FOR
NASA LANGLEY RESEARCH CENTER

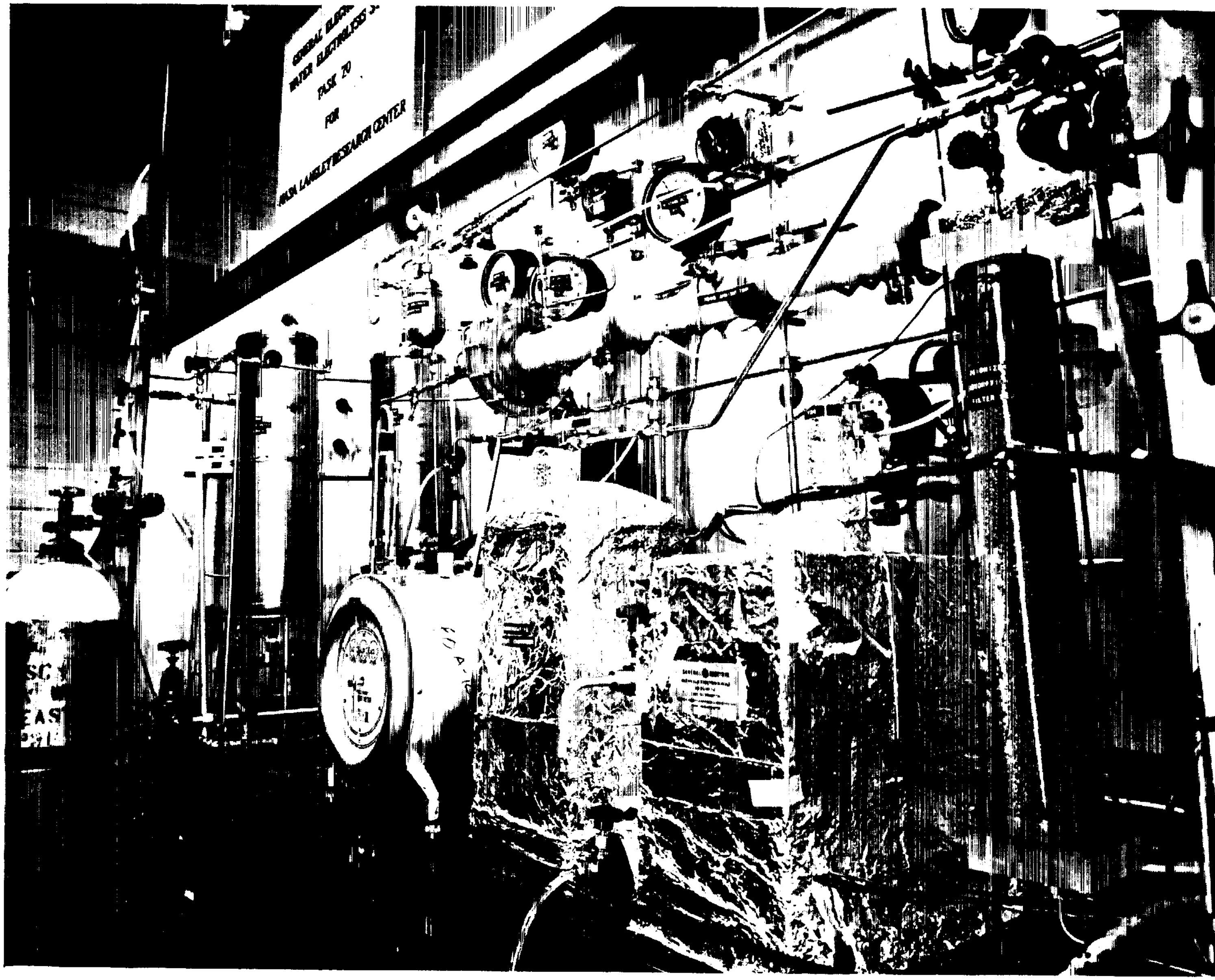
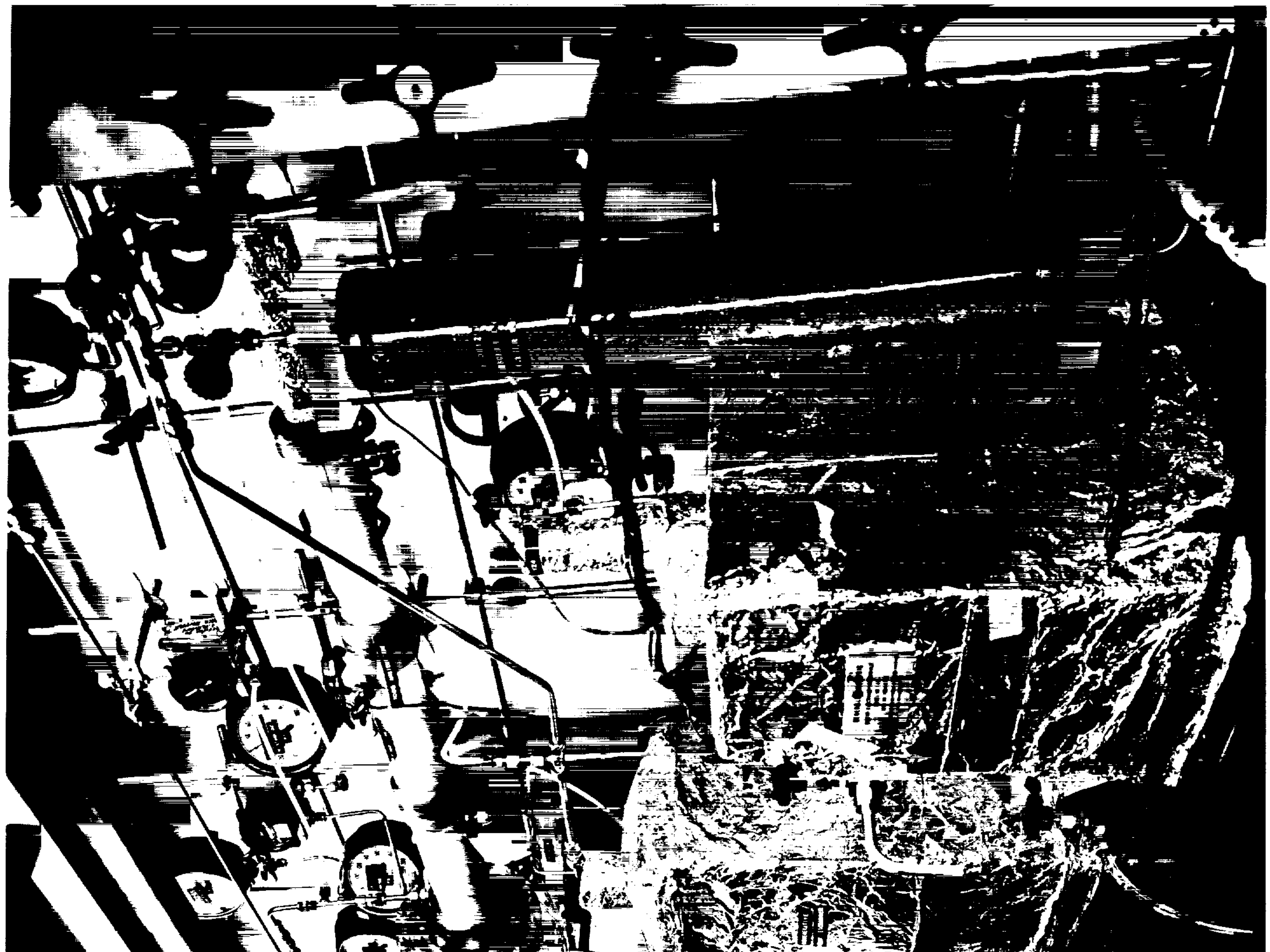


Figure 14. - Water Electrolysis System Test Setup (Closeup)



43 psig O_2 Out and 40 psig H_2 Out Discharge Pressure

Module Condition: Hot

Note: AET = Average Skin Temperature of Two End Plates
Ambient Hood Temperature Variation = 70 to 80°F
Module Thermally Insulated
Module Cathode Feed Water = 15.6 cc/min.
Module Current Density = 200 ASF

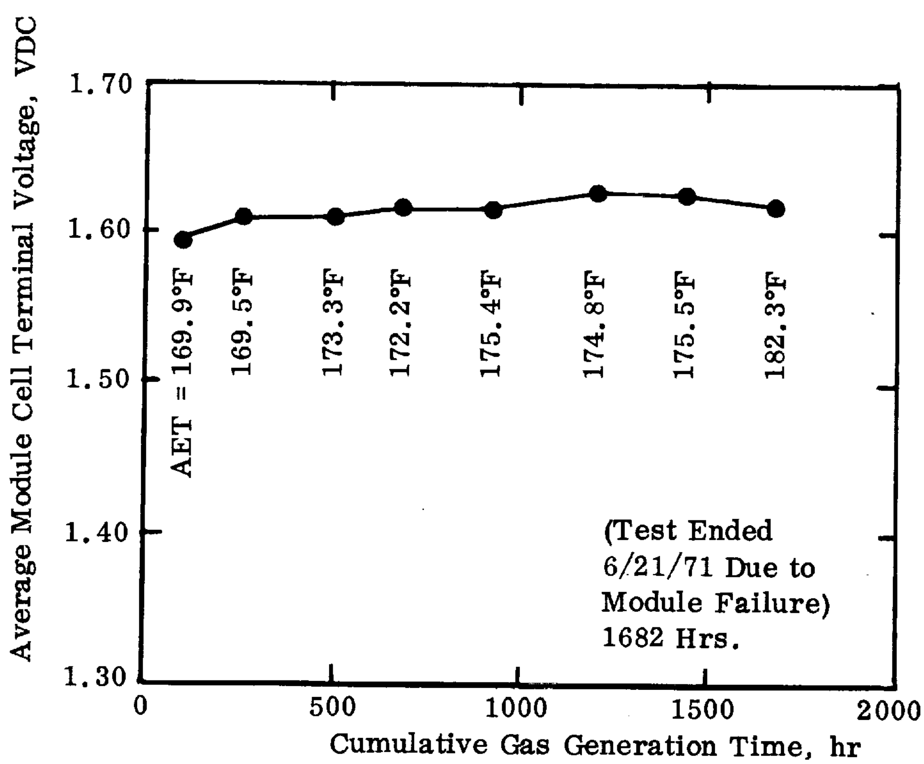


Figure 15. - Four-Cell Module Voltage Plot

	@ 22 Hrs.	@ 26 Hrs.	@ 526.5 Hrs.
Test Date	2/16/71	2/16-17-19/71	5/4/71
O_2 Out Press., psig	0	51	43
H_2 Out Press., psig	-	49	40
Module Condition	Warm	Warm	Hot
Module Insulation	Non-thermal	Non-thermal	Thermal
Module Ambient Temp., °F	77	77	
Module Avg. End Plate Temp., °F			175
Module Cathode Feed Water, cc/min.	15	15	15.6

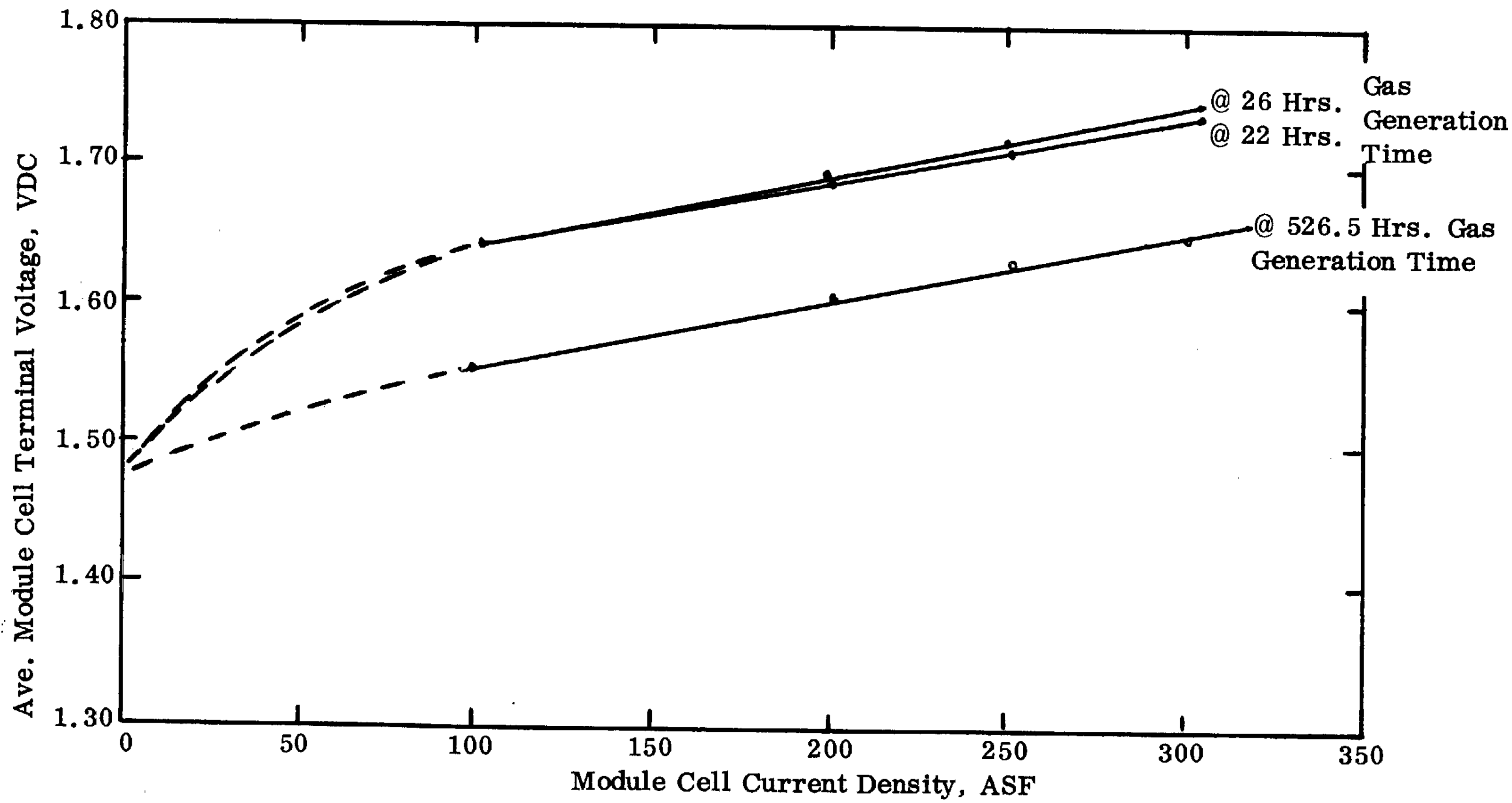


Figure 16. - Four-Cell Module Polarization Data

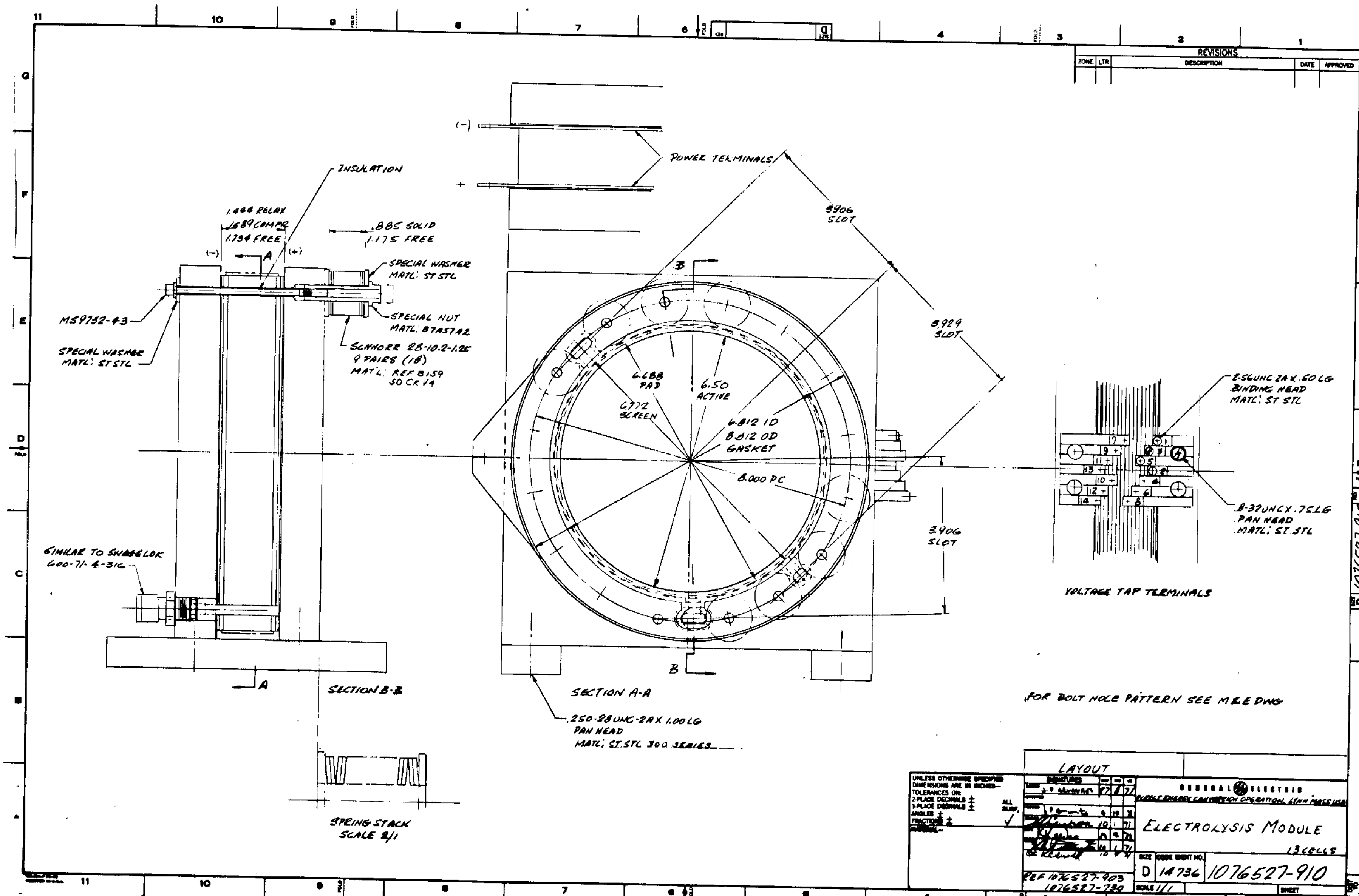
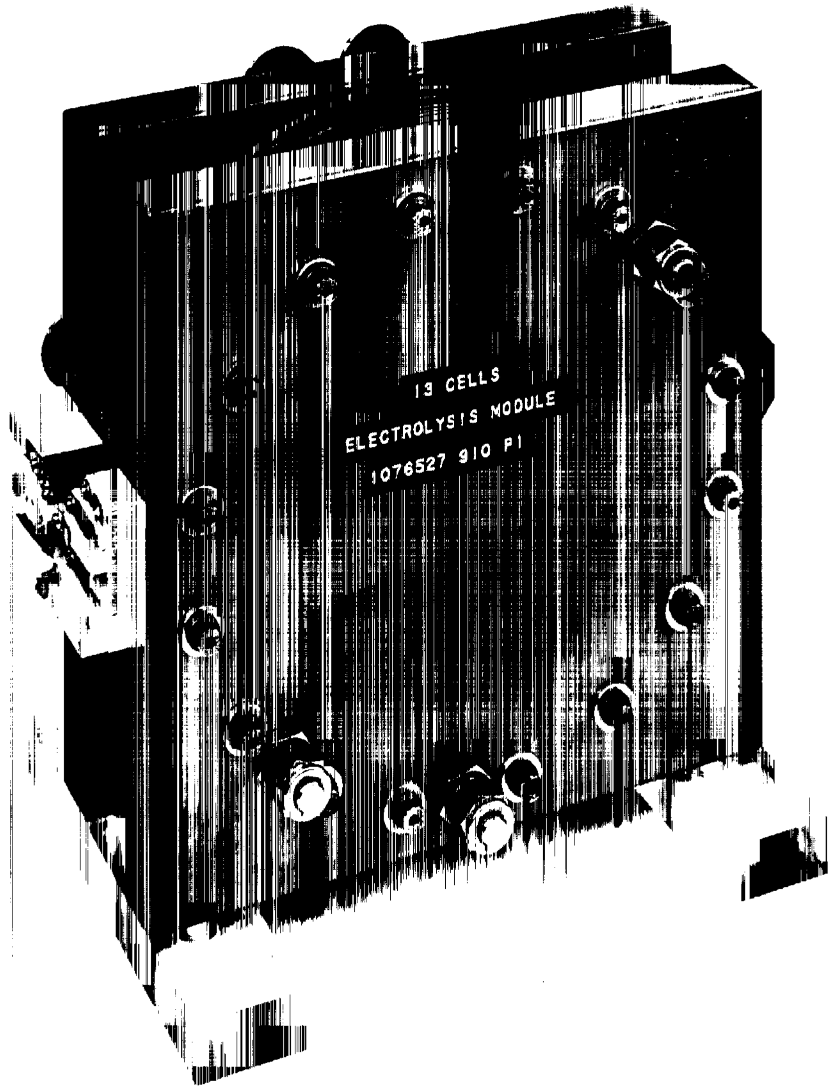

REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
(−)
+
POWER TERMINALS
INSULATION
1.444 RELAX
1.589 COMPR
1.734 FREE
(−)
A
(+)
.885 SOLID
1.175 FREE
SPECIAL WASHER
MATL: ST STL
SPECIAL NUT
MATL. 87A5742
SCHNORR 28-10.2-1.25
9 PAIRS (18)
MATL: REF 8159
50 CR V4
MS9752-43
SPECIAL WASHER
MATL: ST STL
SIMILAR TO SWAGELOK
600-71-4-31C
SECTION B-B
SPRING STACK
SCALE 2/1
3.906
SLOT
3.929
SLOT
6.688
PAD
6.50
ACTIVE
6.772
SCREEN
6.812 ID
8.812 OD
GASKET
8.000 PC
3.906
SLOT
B
SECTION A-A
.250-28UNC-2A X 1.00 LG
PAN HEAD
MATL: ST STL 300 SERIES
2-56UNC 2A X .50 LG
BINDING HEAD
MATL: ST STL
8-32UNC X .75 LG
PAN HEAD
MATL: ST STL
VOLTAGE TAP TERMINALS
FOR BOLT HOLE PATTERN SEE M&E DWG
LAYOUT
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON:
2-PLACE DECIMALS ±
3-PLACE DECIMALS ±
ANGLES ±
FRACTIONS ±
GENERAL ELECTRIC
ELECTROLYSIS MODULE
13 CELLS
REF 1076527-903
1076527-730
SIZE
D
CODE IDENT NO.
14736
1076527-910
SCALE 1/1
SHEET

Figure 17

Figure 18. - 13-Cell Electrolysis Module


13 CELLS
ELECTROLYSIS MODULE
1076527 910 P1

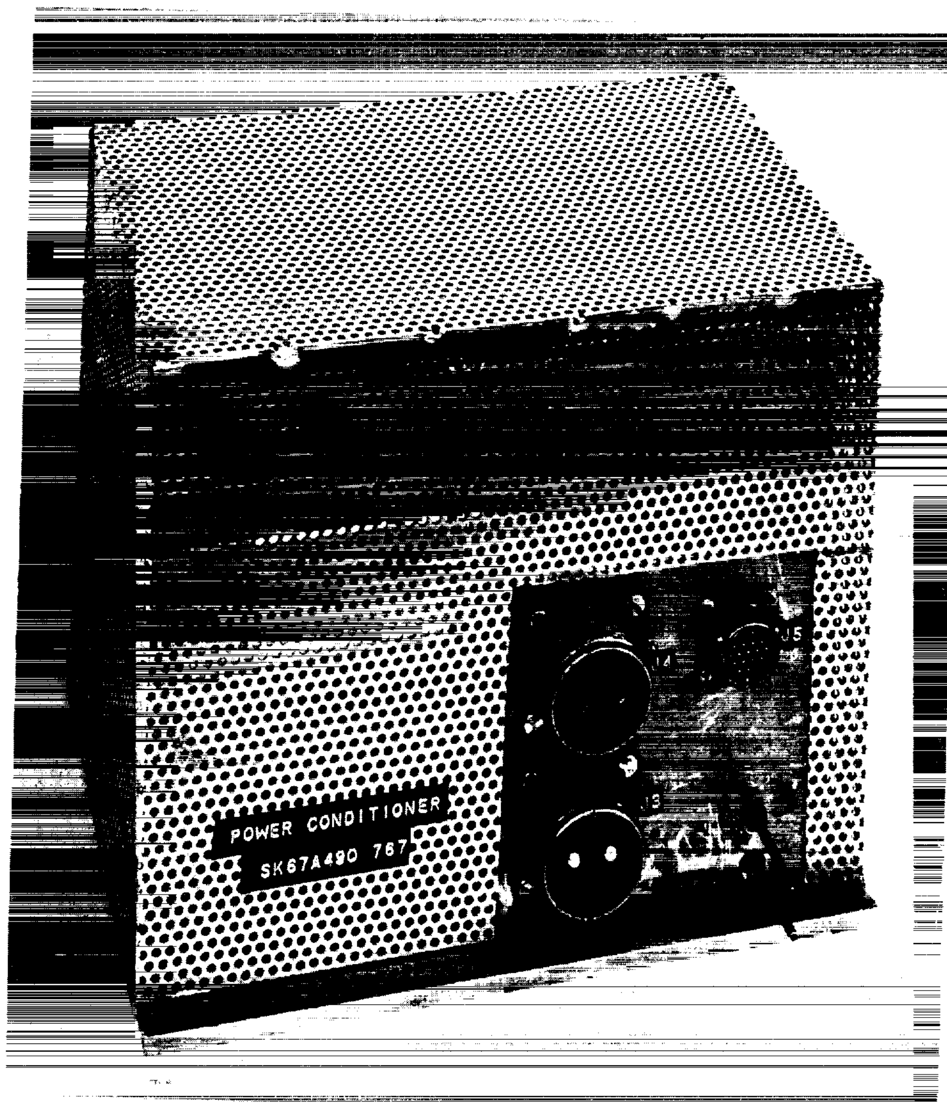
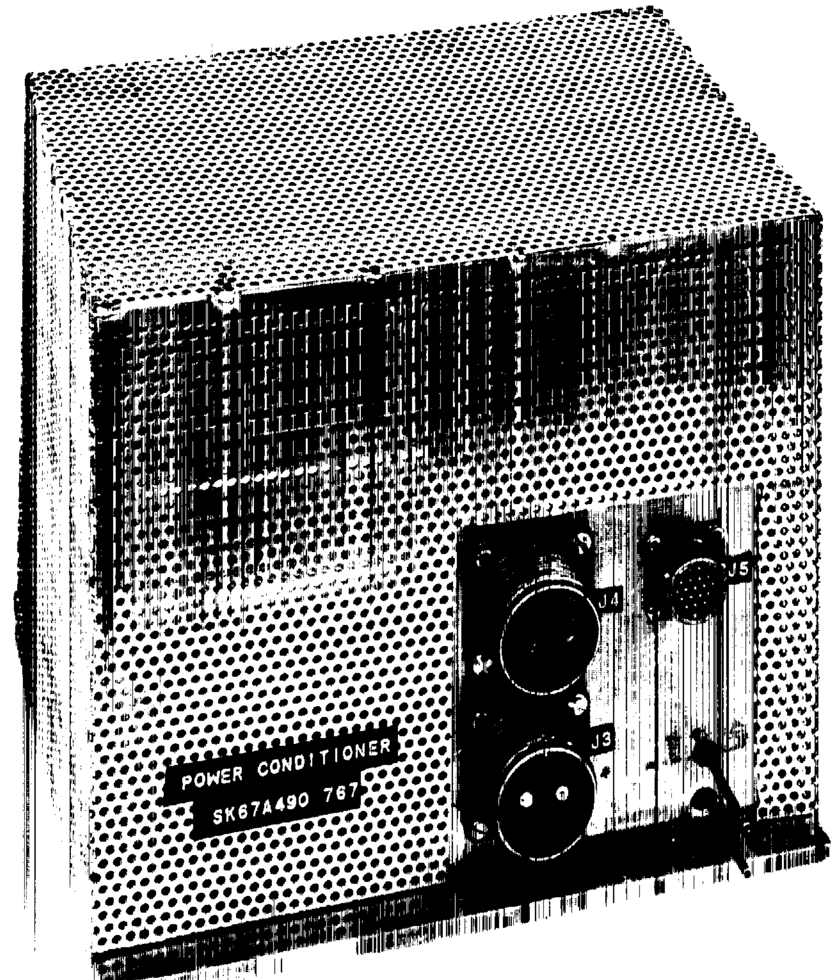
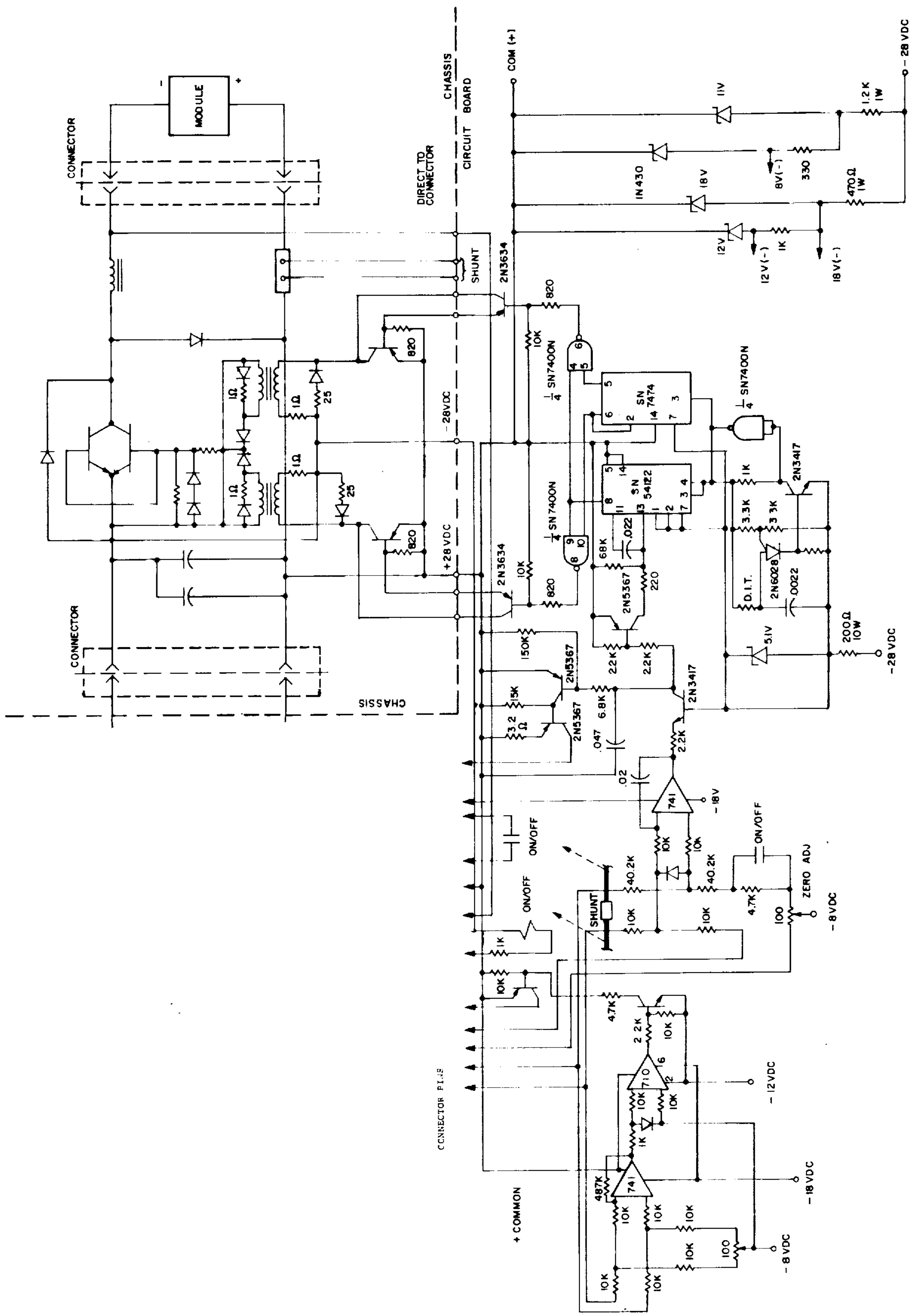


Figure 19. - 75 Amp Power Conditioner


POWER CONDITIONER
SK67A490 767
J4
J5
J3



SK 67A490-767

Figure 20. - Power Conditioner Schematic

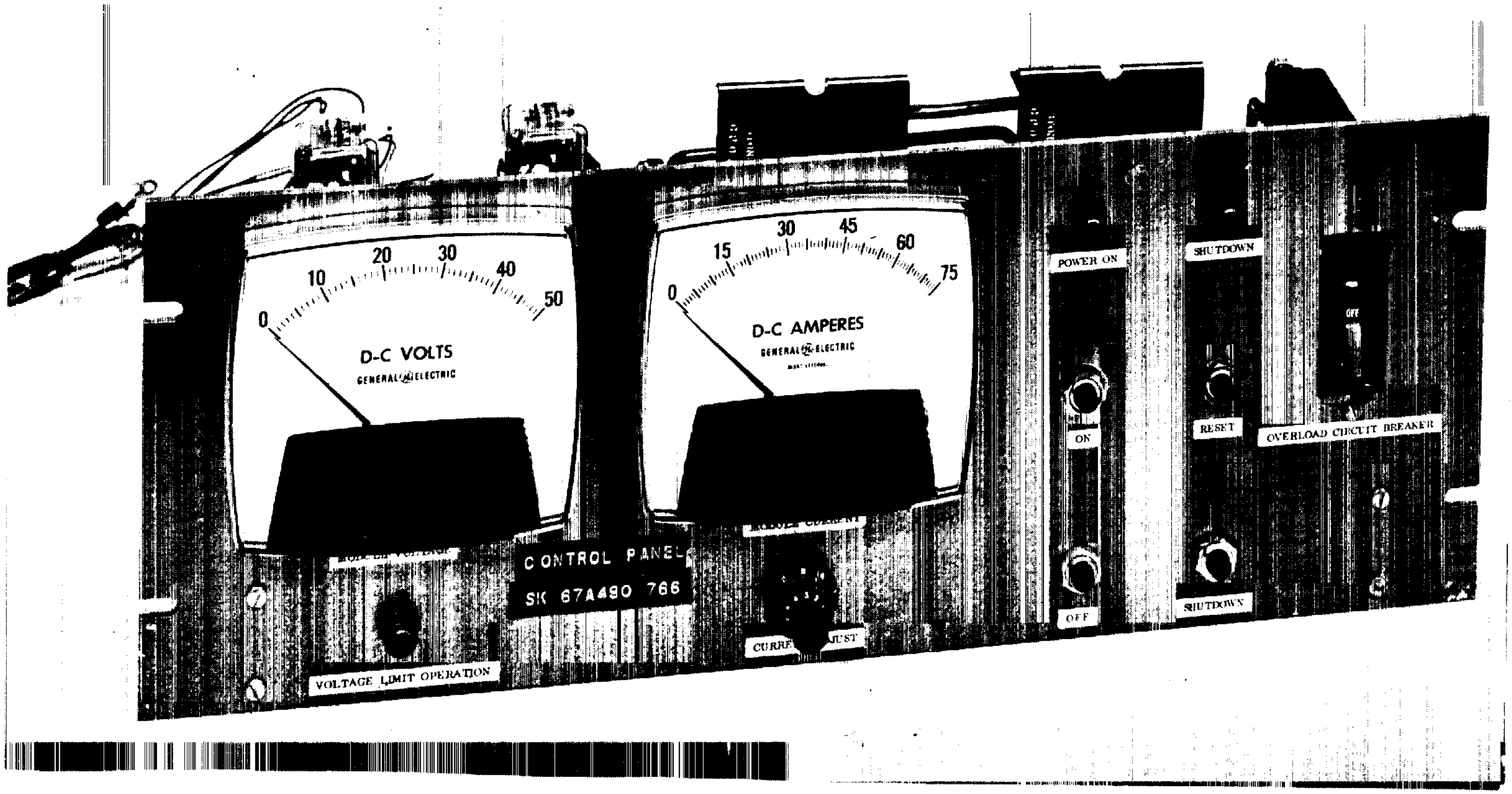
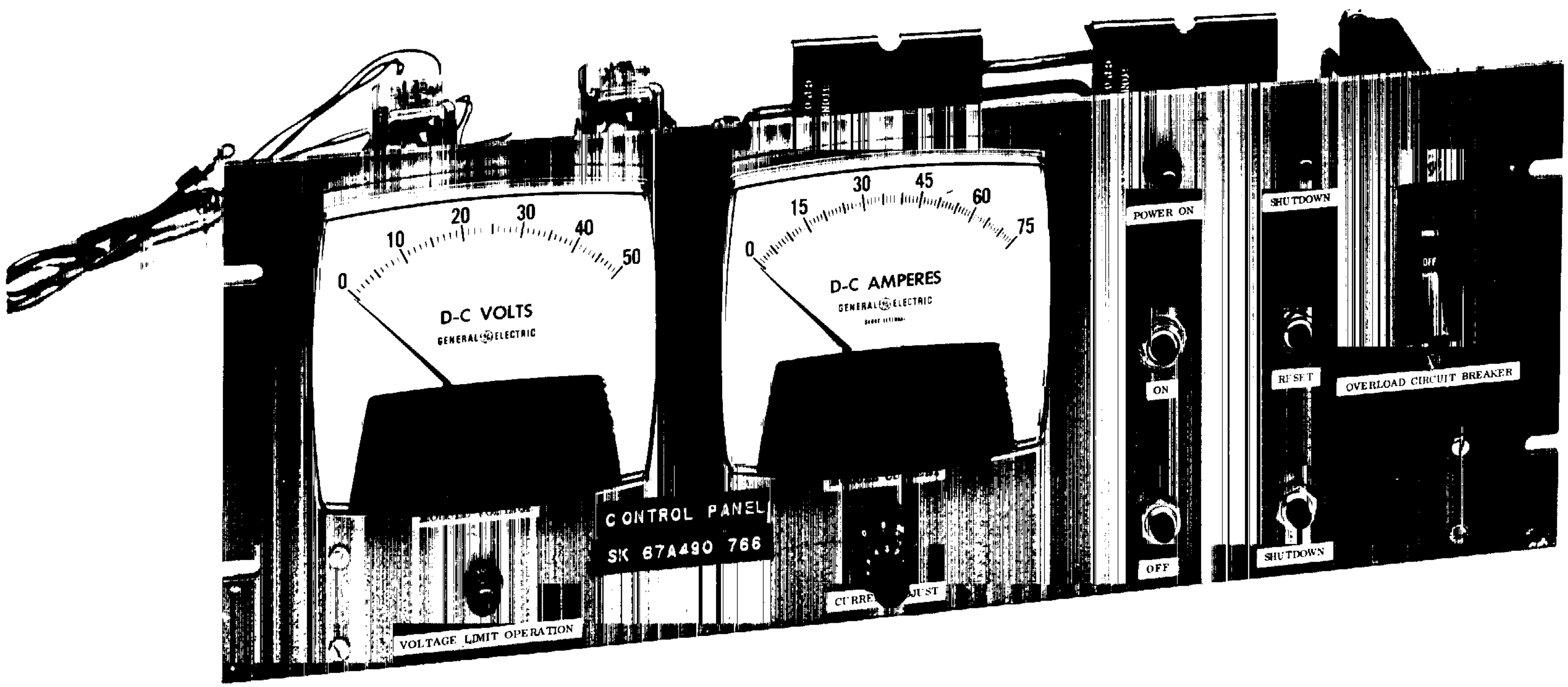


Figure 21. - Control Panel


D-C VOLTS
GENERAL ELECTRIC
VOLTAGE LIMIT OPERATION
CONTROL PANEL
SK 67A490 766
D-C AMPERES
GENERAL ELECTRIC
POWER ON
ON
OFF
SHUTDOWN
RESET
SHUTDOWN
OVERLOAD CIRCUIT BREAKER

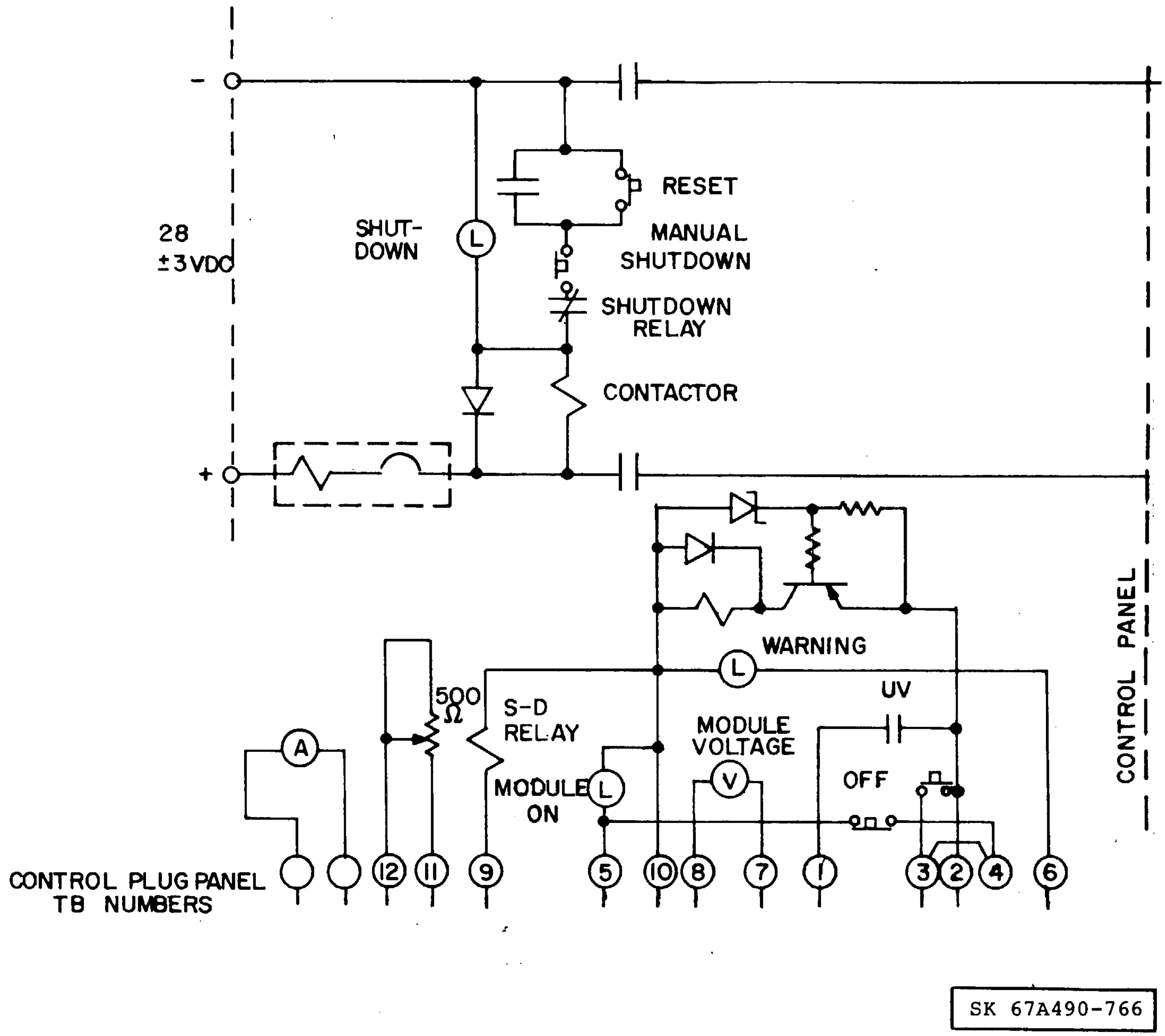


Figure 22.- Control Panel Schematic

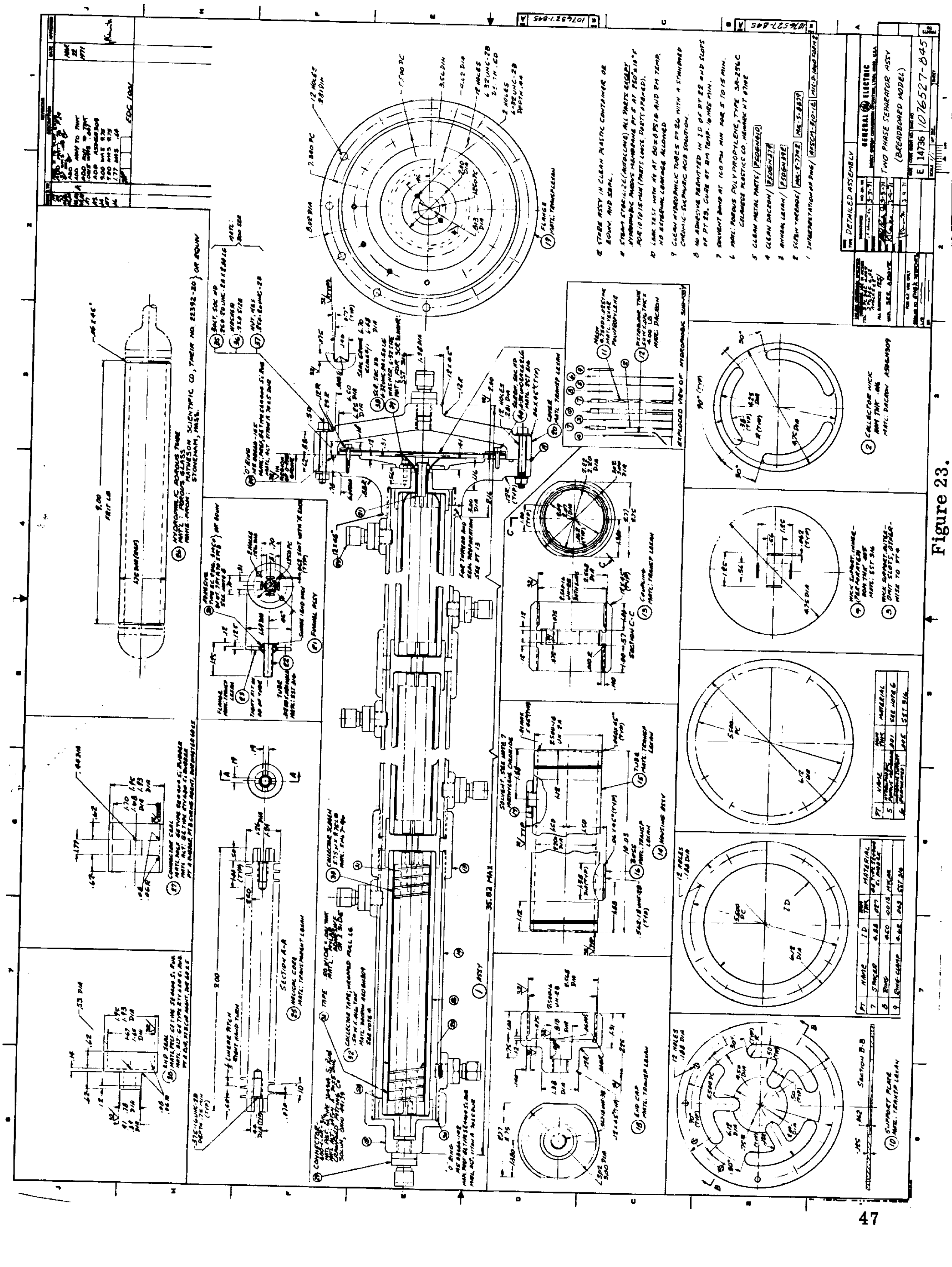

GENERAL ELECTRIC
TWO PHASE SEPARATOR ASSY
(BREADBOARD MODEL)
1076527-845
DETAILED ASSEMBLY

Figure 23.

GENERAL ELECTRIC

PARTS LIST FOR 1076527-845
CONT ON SHEET 2 SH NO. 1

REV NO.

PARTS LIST FOR 1076527-845
CONT ON SHEET 2 SH NO. 1

TITLE TWO PHASE SEPARATOR (BREADBOARD MODEL)
FIRST MADE FOR LANGLEY ELECTROLYSIS

CALC. WEIGHT
SIGN.
DATE

SUBSTITUTIONS REQUIRE ENGINEERING APPROVAL

ITEM	DWG SIZE	IDENTIFICATION NUMBER	DESCRIPTION OR NAME	ZONE	GROUP NO. & QUANTITY
1			ASS'Y		X
2		1076527-845 P2	COLLECTOR WICK		1
3		-845 P3	WICK SUPPORT - OUTER		1
4		-845 P4	WICK SUPPORT - INNER		1
5		-845 P5	HYDROPHOBIC POROUS MEMBRANE		1
6		-845 P6	MEMBRANE SUPPORT		1
7		-845 P7	SPACER		2
8		-845 P8	RING		1
9		-845 P9	RING - CLAMP		1
10		-845 P10	SUPPORT PLATE		1
11		-845 P11	MESH		1
12		-845 P12	DISTRIBUTOR TAPE		4
13		-845 P13	COUPLING		2
14		-845 P14	HOUSING ASS'Y		3
15		SEE DWG.	(INCLUDED IN P14)		
16		SEE DWG.	(INCLUDED IN P14)		
17		SEE DWG.	(INCLUDED IN P14)		
18		-845 P18	END CAP		1
19		-845 P19	FLANGE		1
20		-845 P20	COVER		1
21		-845 P21	FUNNEL ASS'Y		1
22		SEE DWG.	(INCLUDED IN P21)		
23		SEE DWG.	(INCLUDED IN P21)		
24		SEE DWG.	(INCLUDED IN P21)		
25		-845 P25	HELICAL CORE		3
26		-845 P26	HYDROPHILIC POROUS TUBE		3
27		-845 P27	CONNECTOR SEAL		2

SYM	REVISIONS

PRINTS TO

MADE BY J. P. ARVANITES
ISSUED [signature]
APPROVALS [signature] 3/3/71
AEED / DECBS DIV. OR DEPT.
LYNN RIVERWORKS LOCATION

PARTS LIST FOR 1076527-845
CONT ON SHEET 2 SH NO. 1
CODE IDENT NO.

FF-750-D (8-59) Rev. PRINTED IN U.S.A.

Figure 23. (Cont'd.)

GENERAL ELECTRIC

PARTS LIST FOR 1076527-845
CONT ON SHEET FINAL SH NO. 2

REV NO.

PARTS LIST FOR 1076527-845
CONT ON SHEET FINAL SH NO. 2

TITLE TWO PHASE SEPARATOR (BREADBOARD MODEL)

FIRST MADE FOR LANGLEY ELECTROLYSIS

CALC. WEIGHT

SIGN.

DATE

SUBSTITUTIONS REQUIRE ENGINEERING APPROVAL

ITEM	DWG SIZE	IDENTIFICATION NUMBER	DESCRIPTION OR NAME	ZONE	GROUP NO. & QUANTITY 1
28		1076527-845P28	END SEAL		2
29		-845P29	CONNECTOR		8
30		-845P30	O-RING		6
31		-845P31	TAPE		AR
32		-845P32	COLLECTOR TAPE		AR
33		-845P33	COLLECTOR SCREEN		3
34		-845P34	O-RING		1
35		-845P35	BOLT, SOC HD		12
36		-845P36	WASHER		24
37		-845P37	NUT, HEX		12
38		-845P38	SCR, SOC HD		2
39		-845P39	WASHER		2
40		-845P40	SCR, SOC HD		12

SYM | REVISIONS

PRINTS TO

MADE BY J.P. AZVANITIS

ISSUED [illegible]

APPROVALS [illegible] 3/3/71

AEED / DECBS DIV. OR DEPT.

LYNN RIVERWORKS LOCATION

PARTS LIST FOR 1076527-845
CONT ON SHEET FINAL SH NO. 2

FF-750-L (8-59) Rev. PRINTED IN U.S.A.

CODE IDENT NO.

Figure 23.(Cont'd.)

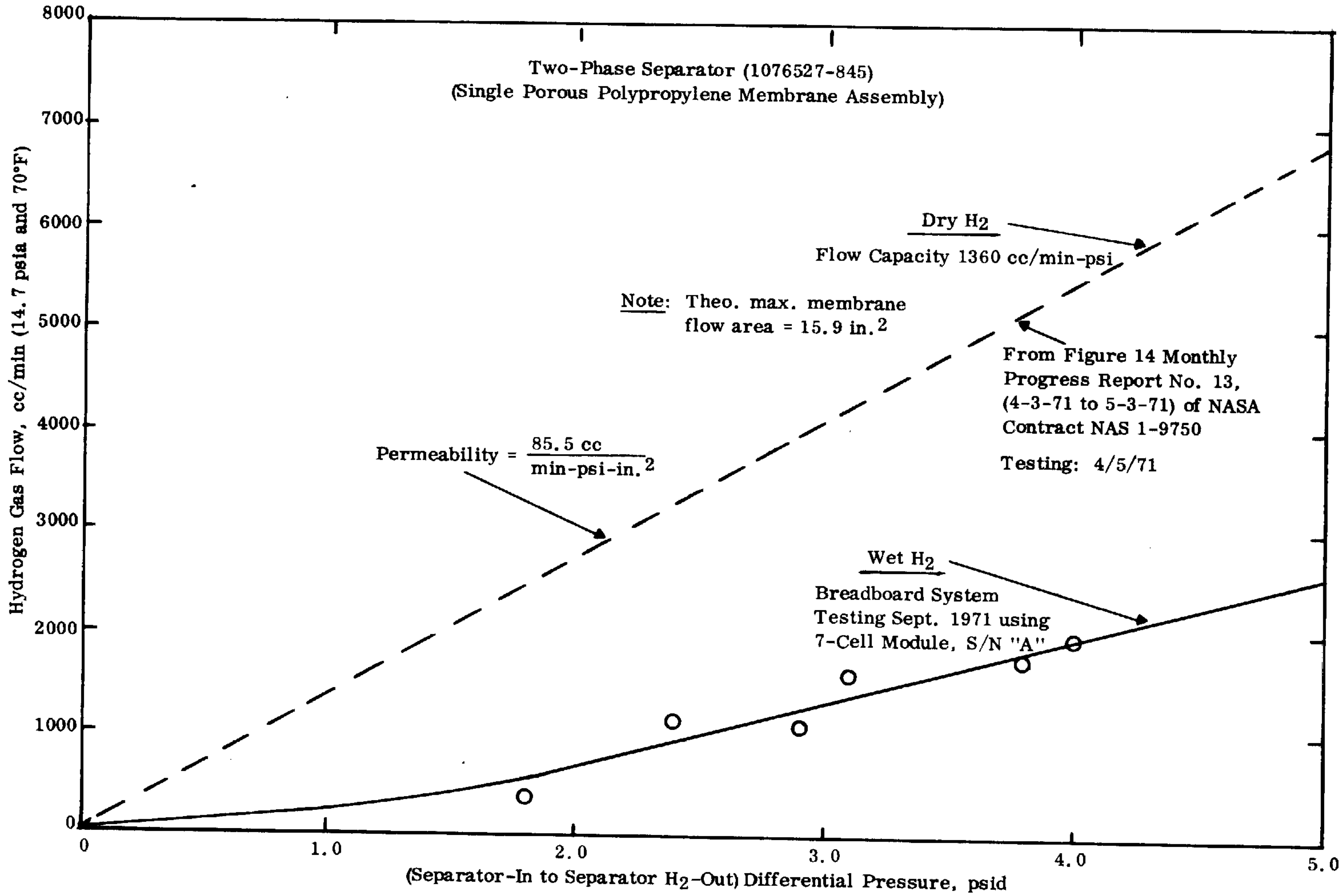


Figure 24. - H_2 Flow vs. Pressure Drop of Two-Phase Separator

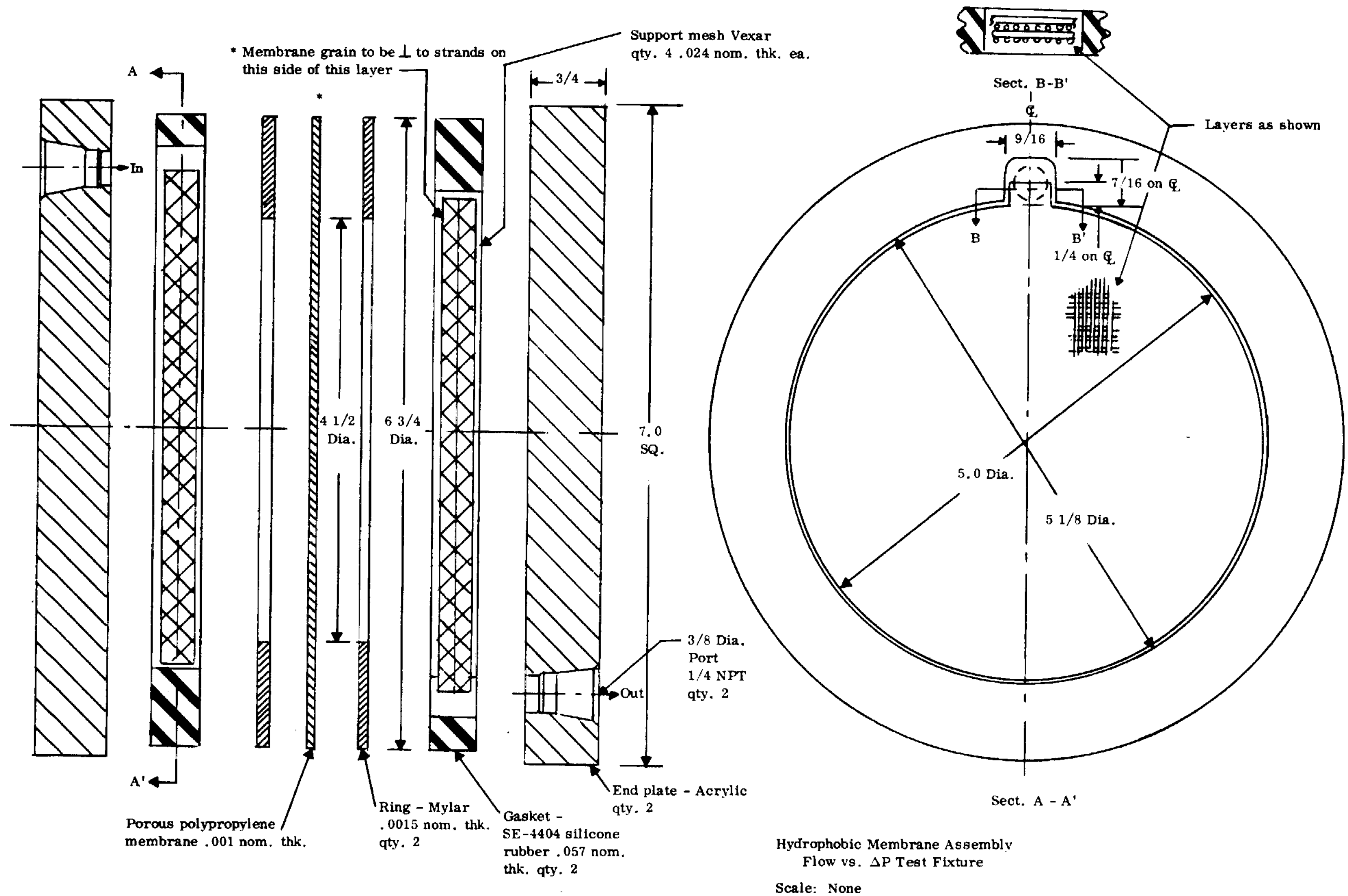


Figure 25. - "Close-Gap" Hydrophobic Subassembly

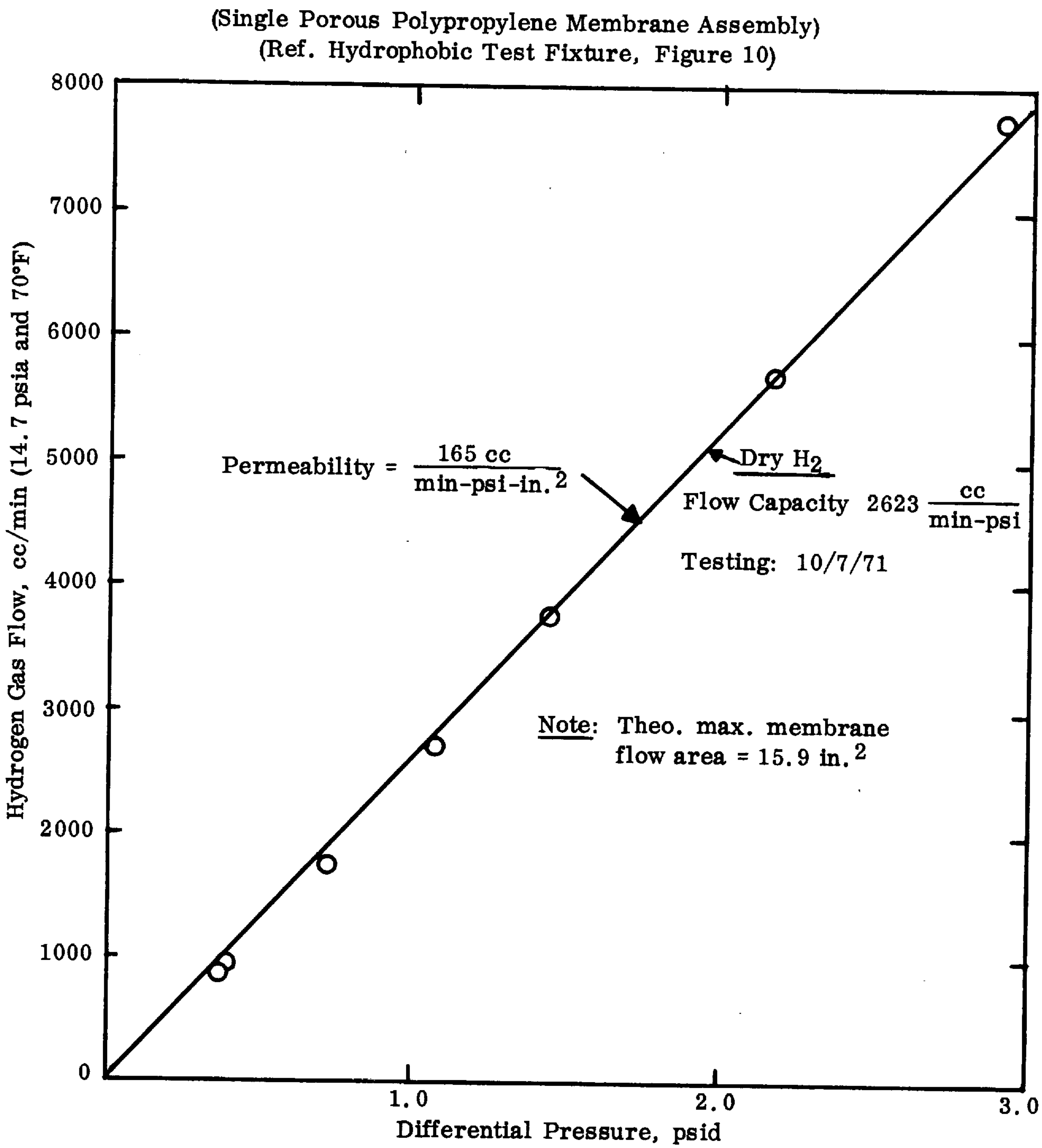


Figure 26. - H_2 Flow vs. Pressure Drop ("Close Gap" Hydrophobic Subassembly)

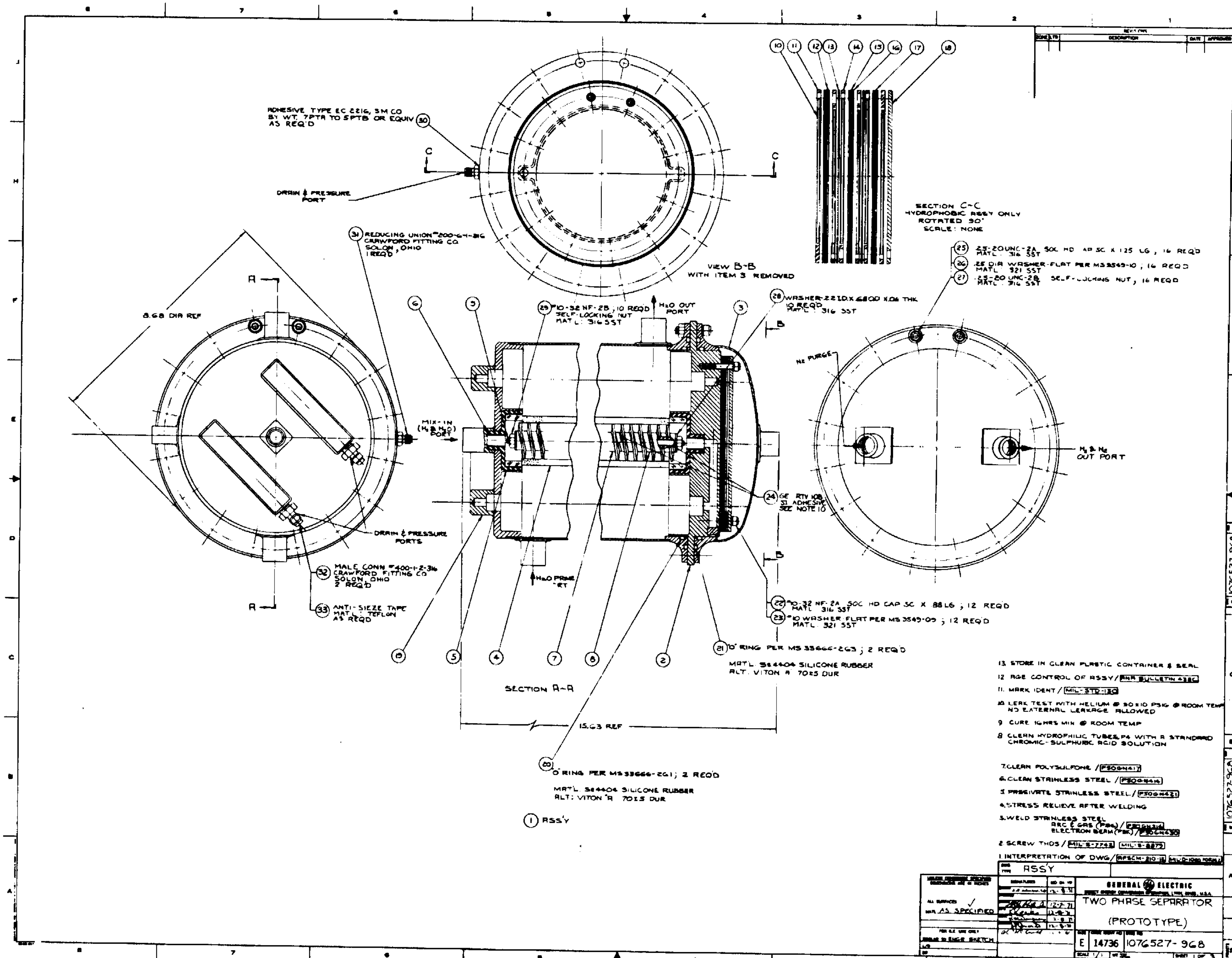

ADHESIVE TYPE EC 2216, 3M CO
BY WT. 7PTA TO 5PTB OR EQUIV
AS REQ'D
DRAIN & PRESSURE
PORT
REDUCING UNION #200-6-1-316
CRAWFORD FITTING CO.
SOLON, OHIO
1 REQ'D
VIEW B-B
WITH ITEM 3 REMOVED
SECTION C-C
HYDROPHOBIC ASSY ONLY
ROTATED 90°
SCALE: NONE
.25-20UNC-2A SOC HD CAP SC X 1.25 LG, 16 REQ'D
MATL: 316 SST
.25 DIA WASHER-FLAT PER MS35649-10, 16 REQ'D
MATL: 321 SST
.25-20 UNC-2B SELF-LOCKING NUT, 16 REQ'D
MATL: 316 SST
8.68 DIA REF
10-32 NF-2B, 10 REQ'D
SELF-LOCKING NUT
MATL: 316 SST
H_2O OUT
PORT
WASHER-.221 ID X .600 OD X .06 THK
10 REQ'D
MATL: 316 SST
N_2 PURGE
MIX-IN
(H_2 & H_2O)
PORT
GE RTV 108
SI ADHESIVE
SEE NOTE 10
H_2 & N_2
OUT PORT
DRAIN & PRESSURE
PORTS
MALE CONN #400-1-2-316
CRAWFORD FITTING CO
SOLON, OHIO
2 REQ'D
ANTI-SIEZE TAPE
MATL: TEFLON
AS REQ'D
H_2O PRIME
PORT
10-32 NF-2A SOC HD CAP SC X .88 LG; 12 REQ'D
MATL: 316 SST
10 WASHER-FLAT PER MS35649-05; 12 REQ'D
MATL: 321 SST
O RING PER MS33666-263; 2 REQ'D
MATL: 3E4404 SILICONE RUBBER
ALT: VITON A 70±5 DUR
SECTION A-A
15.63 REF
O RING PER MS33666-261; 2 REQ'D
MATL: 3E4404 SILICONE RUBBER
ALT: VITON A 70±5 DUR
1 ASS'Y
13 STORE IN CLEAN PLASTIC CONTAINER & SEAL
12 AGE CONTROL OF ASSY
11 MARK IDENT/MIL-STD-130
10 LEAK TEST WITH HELIUM @ 30±10 PSIG @ ROOM TEMP
NO EXTERNAL LEAKAGE ALLOWED
9 CURE 16HRS MIN @ ROOM TEMP
8 CLEAN HYDROPHILIC TUBES, P4 WITH A STANDARD
CHROMIC-SULPHURIC ACID SOLUTION
7 CLEAN POLYSULFONE
6 CLEAN STAINLESS STEEL
5 PASSIVATE STAINLESS STEEL
4 STRESS RELIEVE AFTER WELDING
3 WELD STAINLESS STEEL
ARC & GAS
ELECTRON BEAM
2 SCREW THDS/MIL-S-7742
1 INTERPRETATION OF DWG
ASSY
AS SPECIFIED
GENERAL ELECTRIC
TWO PHASE SEPARATOR
(PROTOTYPE)
E 14736 1076527-968

Figure 27.

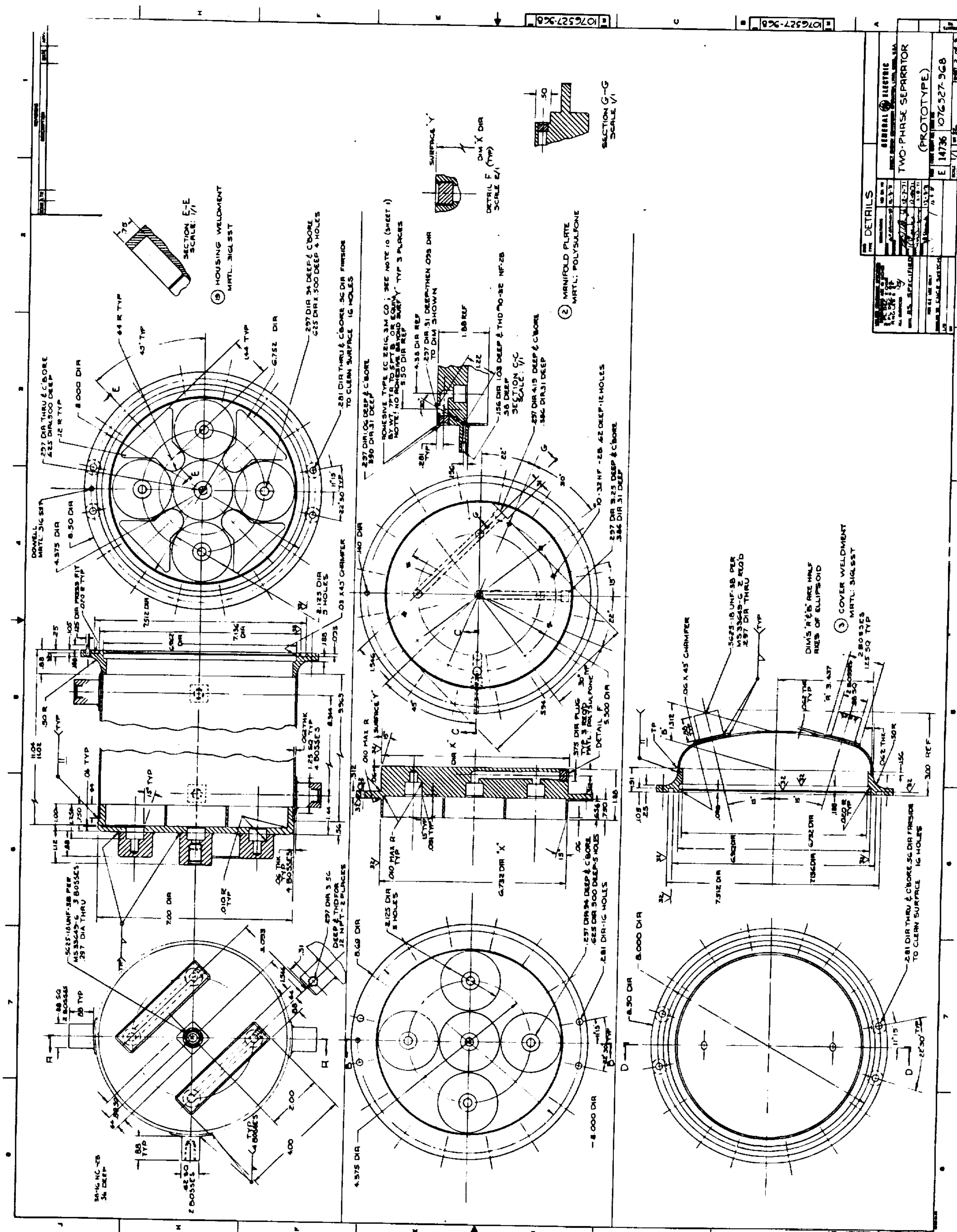


Figure 27. (Cont'd.)

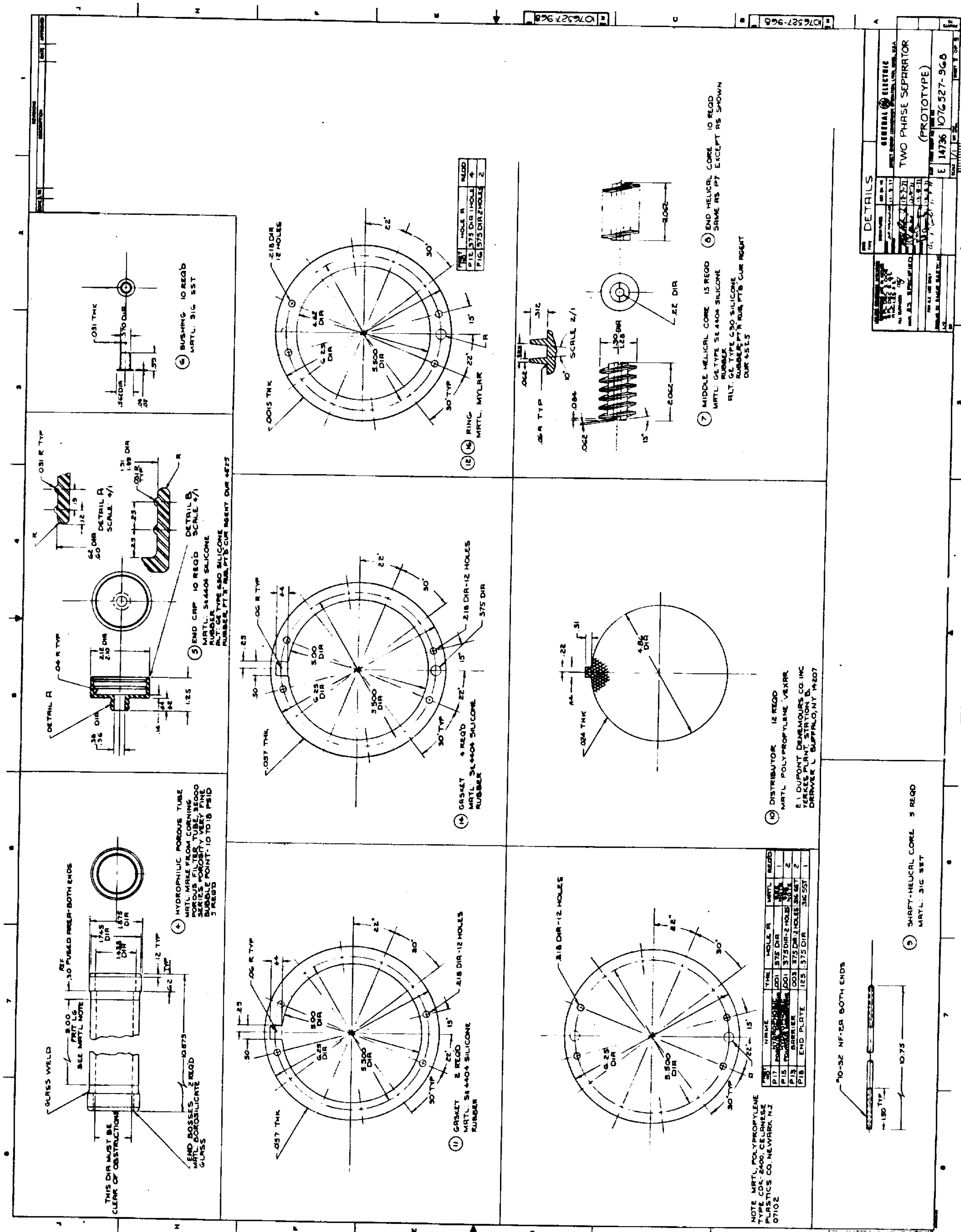


Figure 27. (Cont'd.)

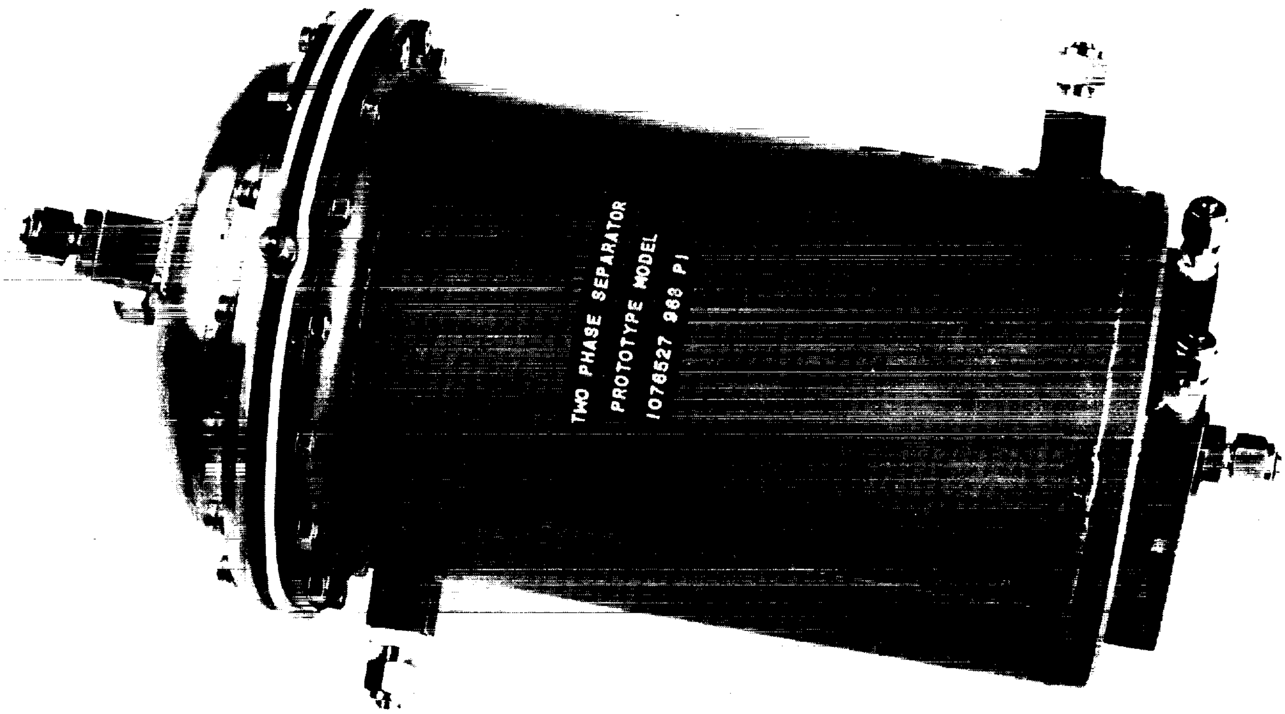


Figure 28. - Two-Phase Separator Prototype Model


TWO PHASE SEPARATOR
PROTOTYPE MODEL
1076527 963 P1

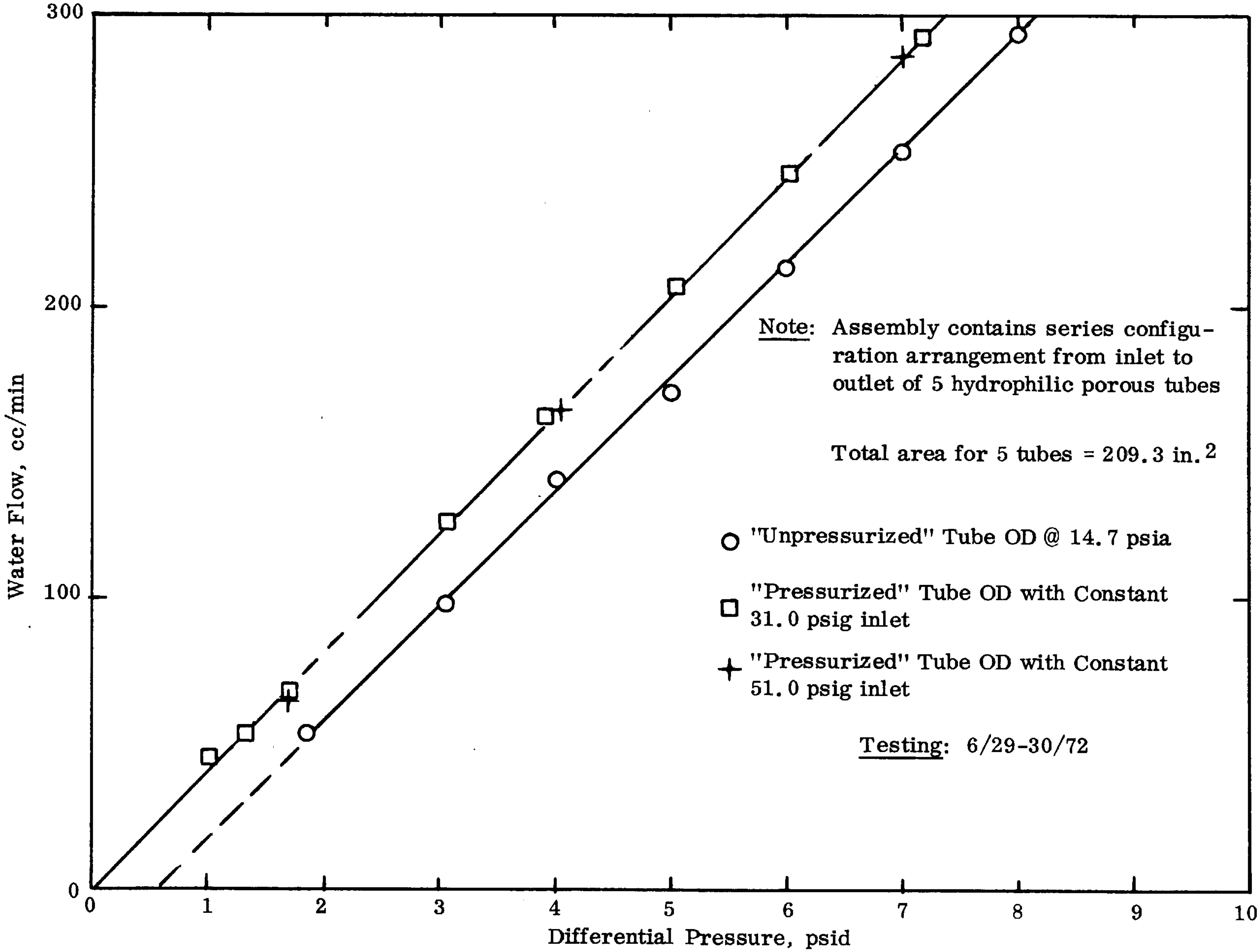


Figure 29. - Water Flow vs. ΔP (Two-Phase Separator Prototype Model 1076527-968P1)

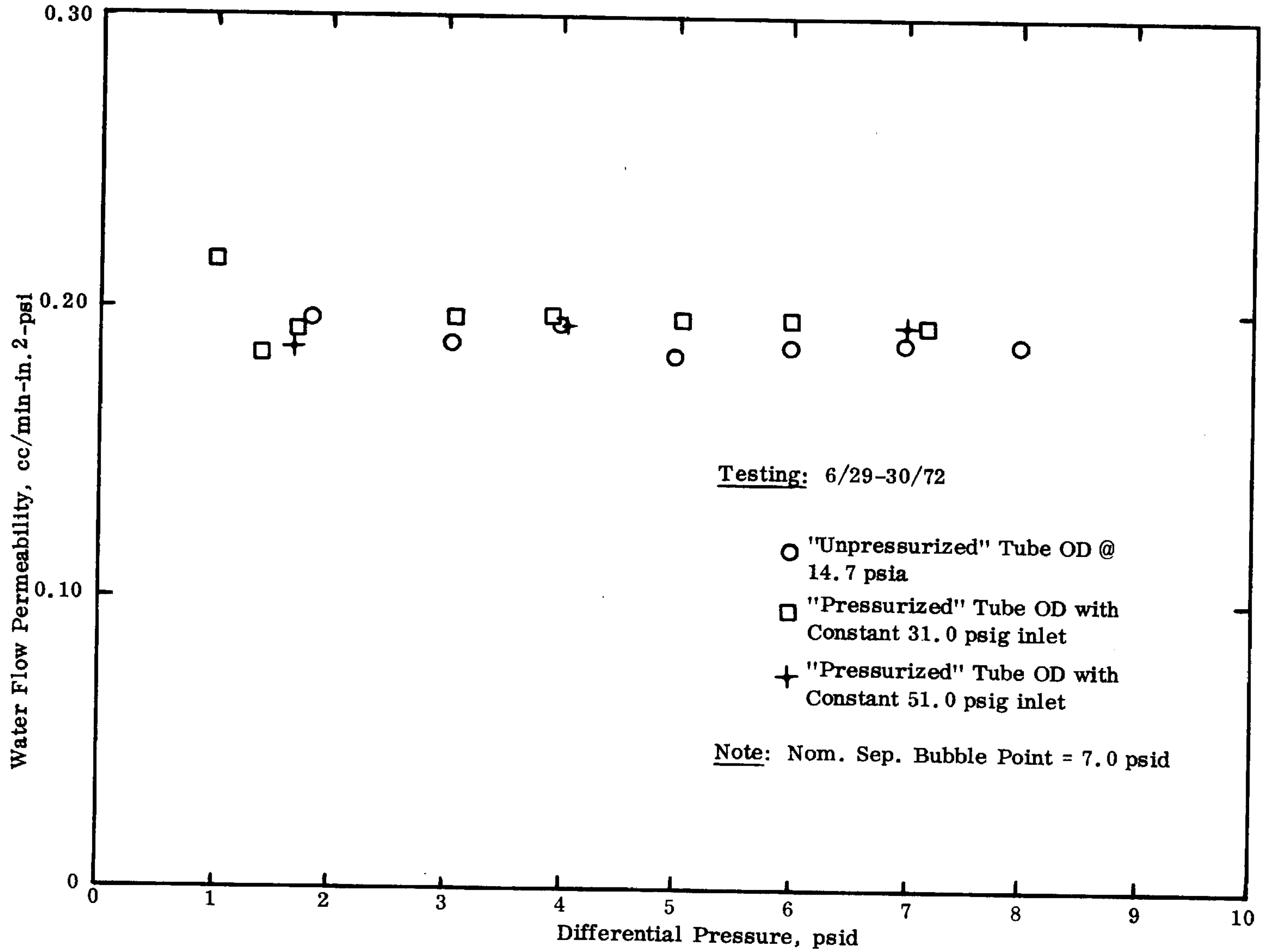
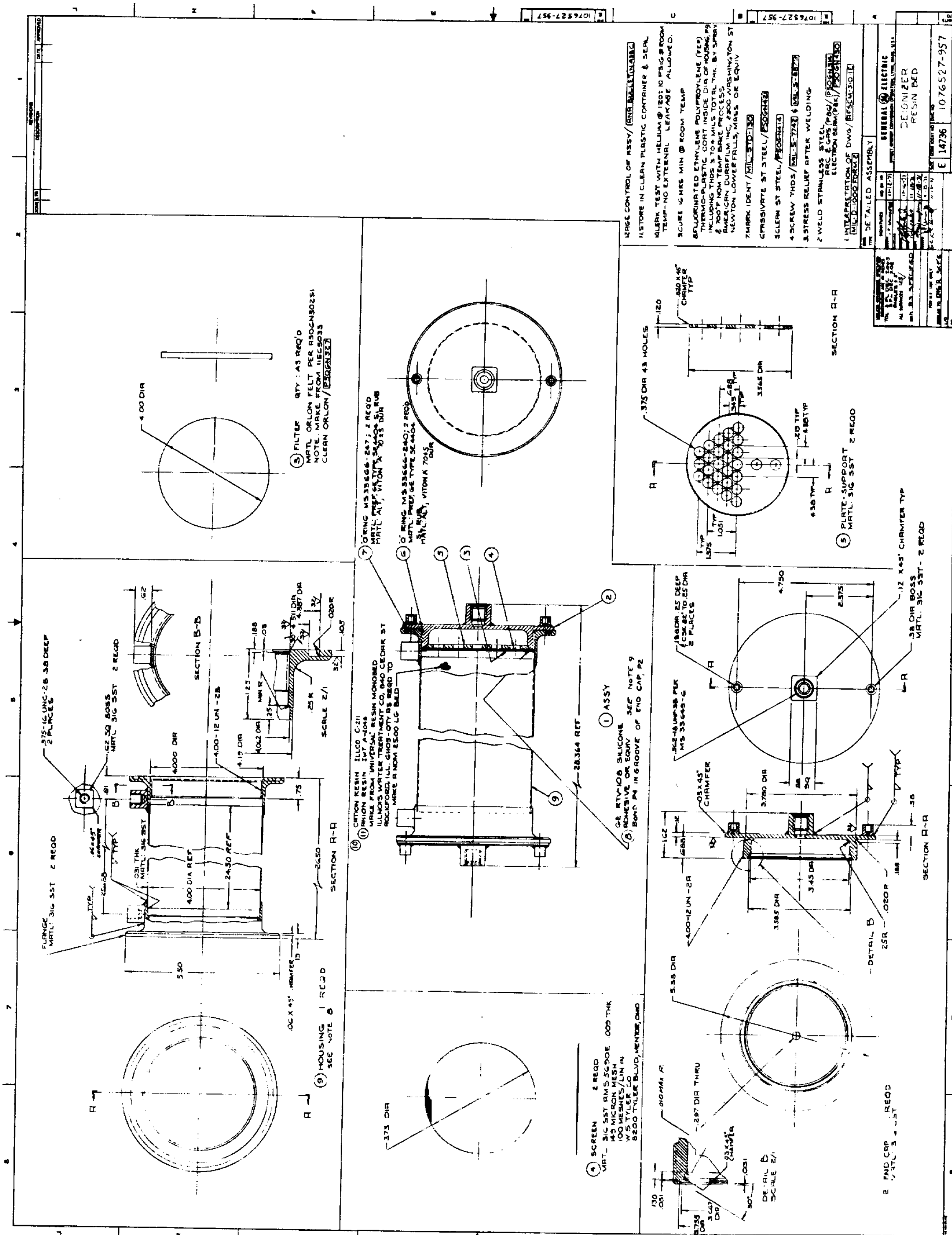


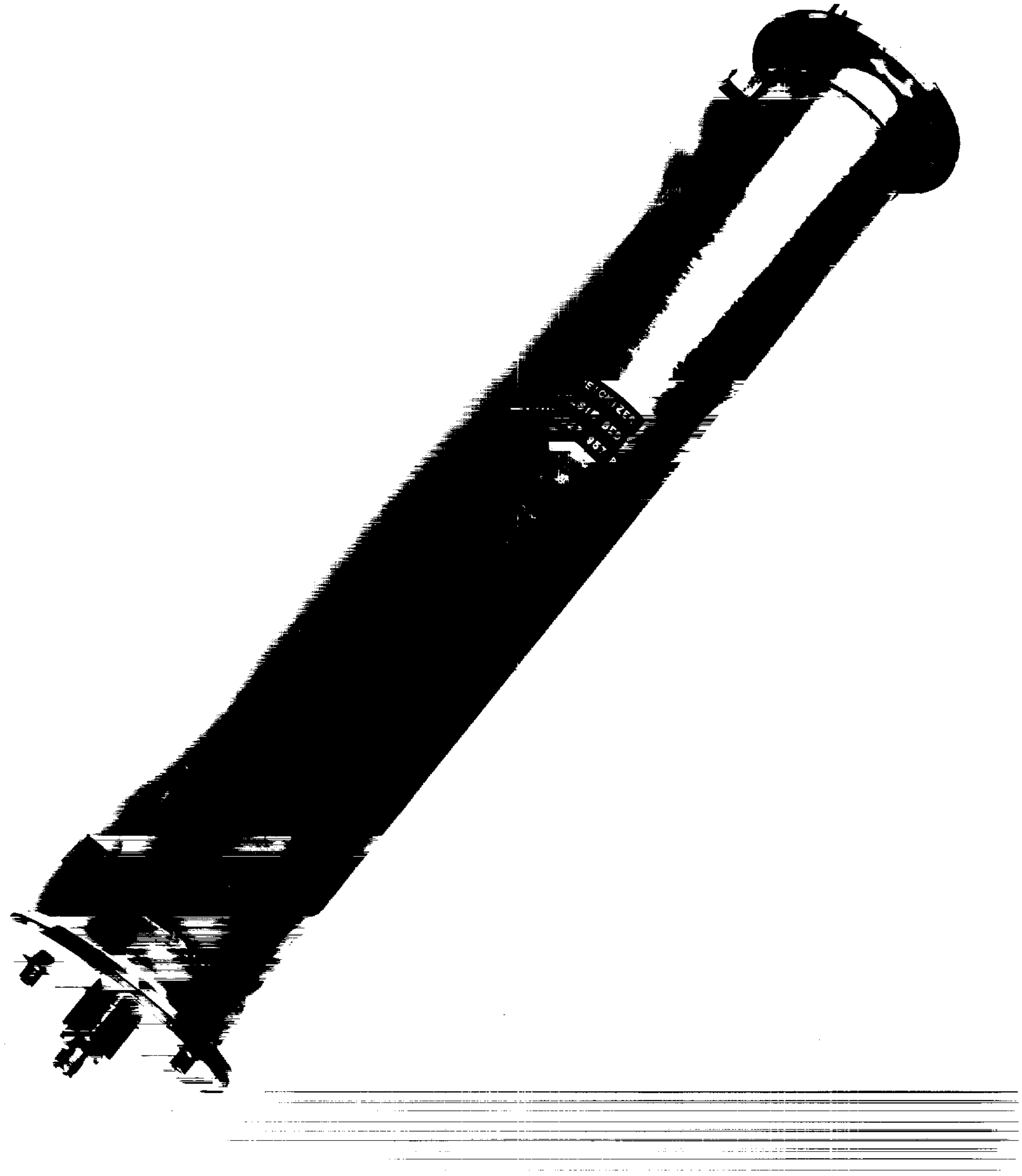
Figure 30. - Water Flow Permeability vs. ΔP (Two-Phase Separator Prototype Model 1076527-968P1)



GENERAL ELECTRIC
DEIONIZER RESIN BED
1076527-957
DETAILED ASSEMBLY

Figure 31.

Figure 32. - Deionizer Resin Bed



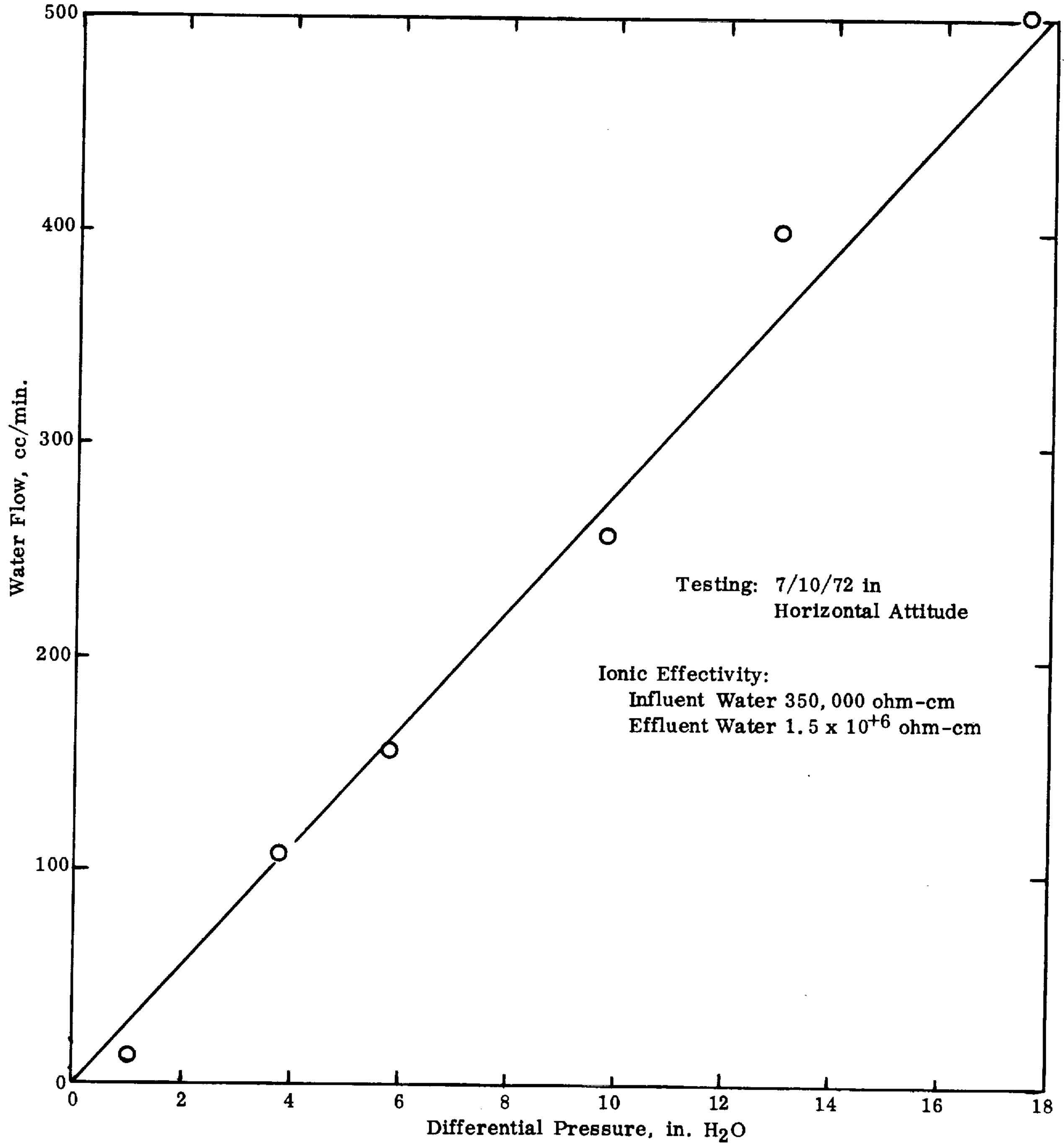
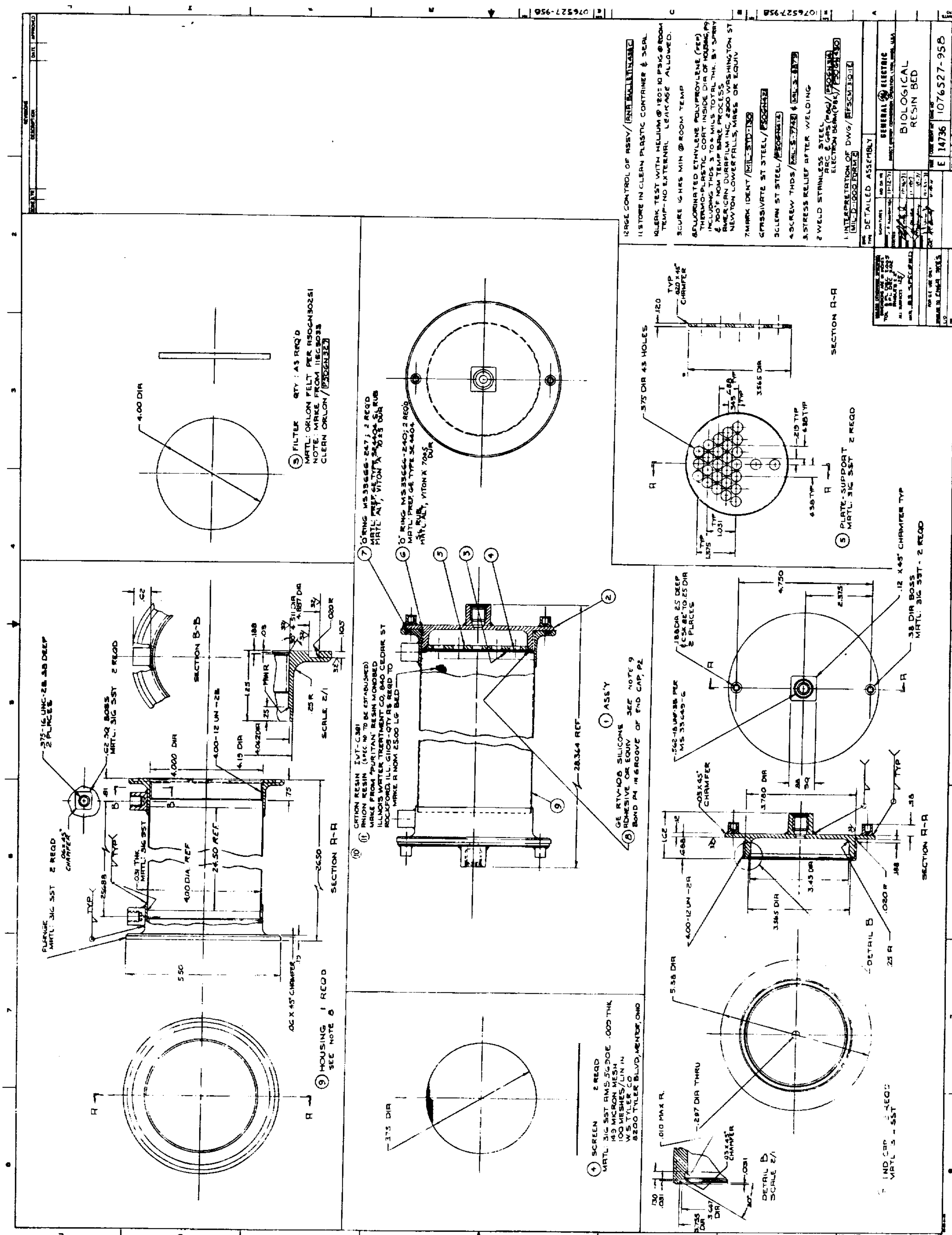


Figure 33. - Deionizer Resin Bed (1076527-968P1) Water Flow vs. ΔP



BIOLOGICAL RESIN BED
1076527-958
DETAILED ASSEMBLY
SECTION A-A
SECTION B-B

Figure 34.

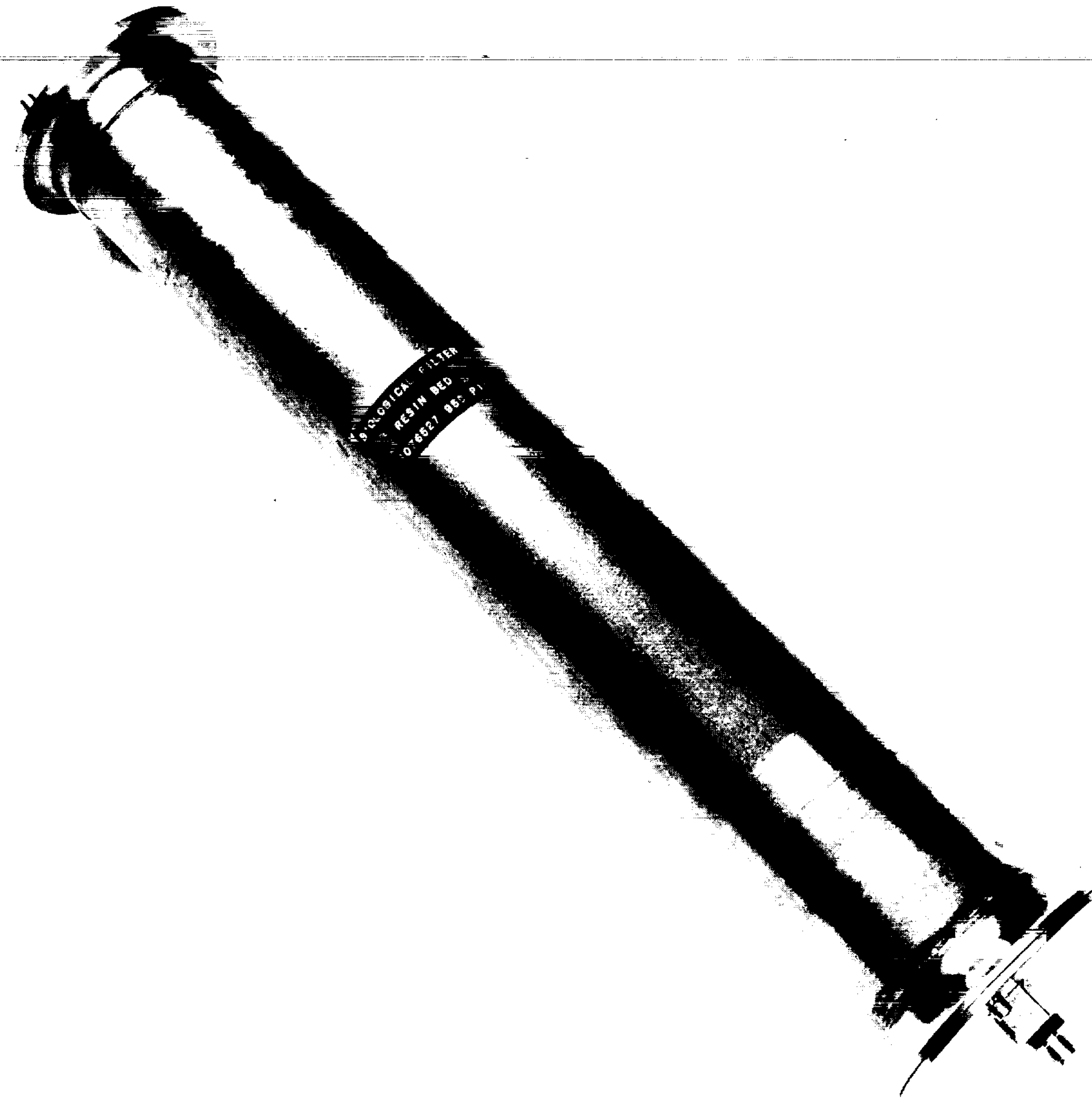


Figure 35. - Biological Filter Resin Bed

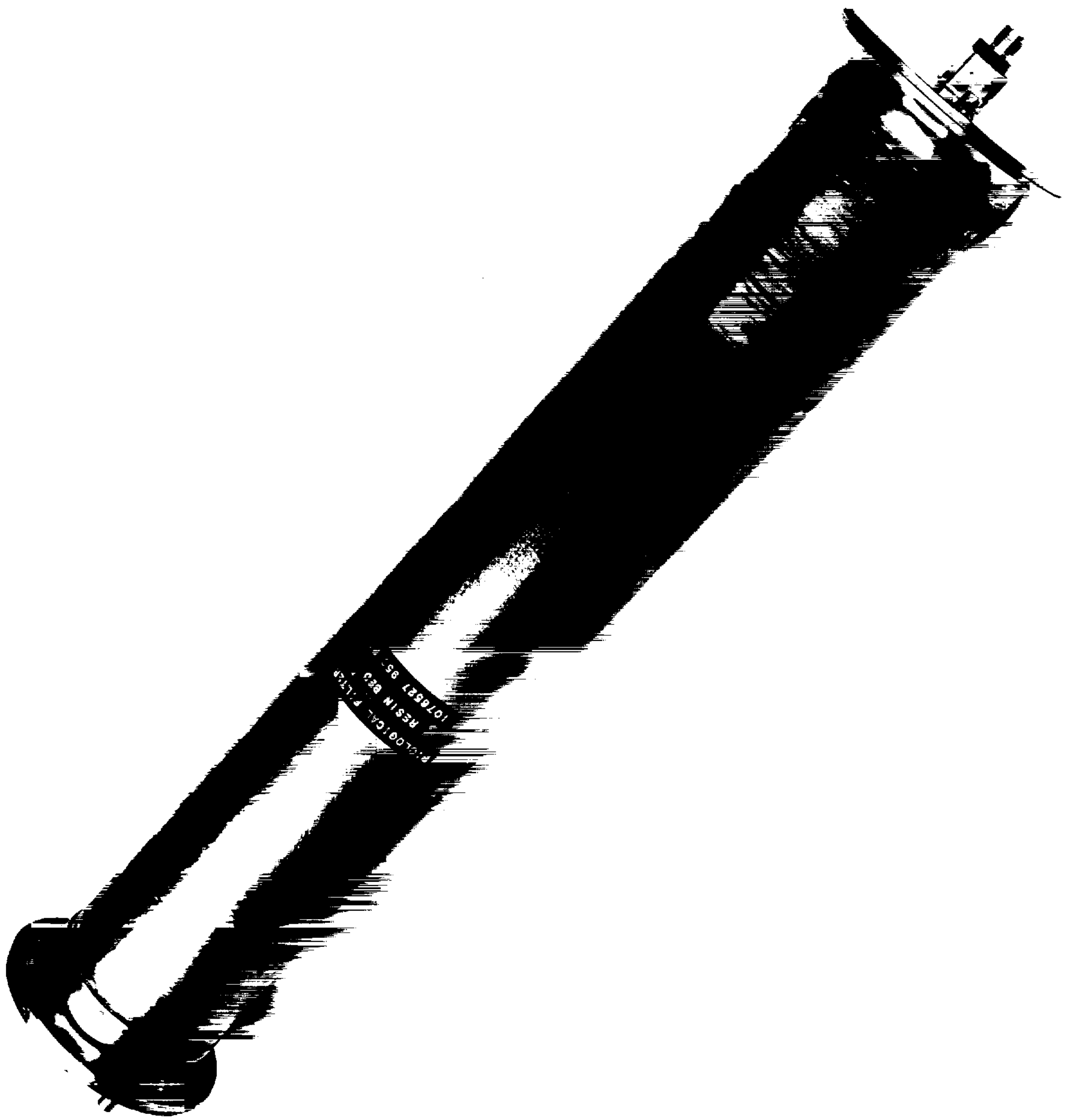

1076527 95
RESIN BED

Figure 36. - Regenerative Heat Exchanger with Thermal Insulation


REGENERATIVE
HEAT EXCHANGER

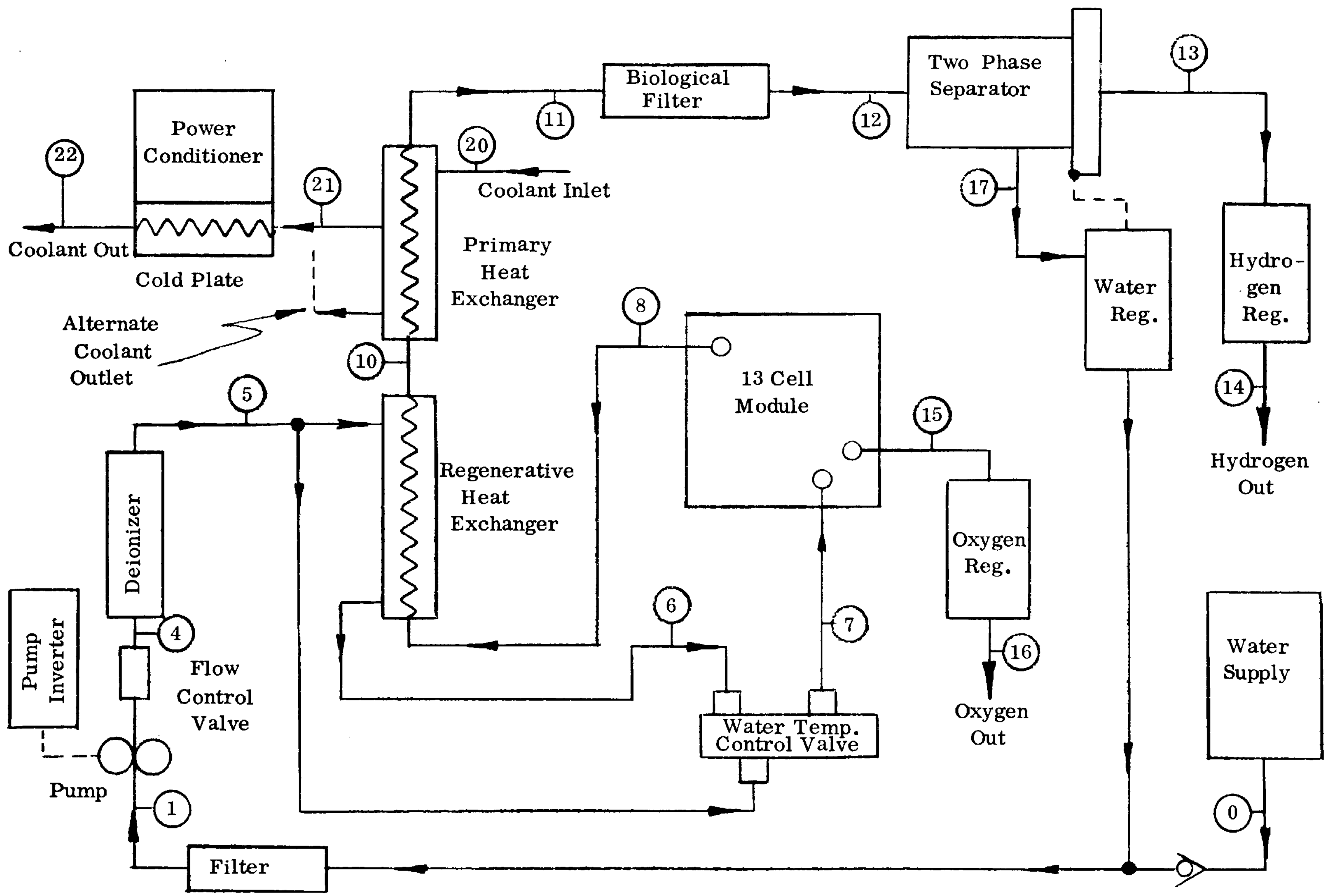
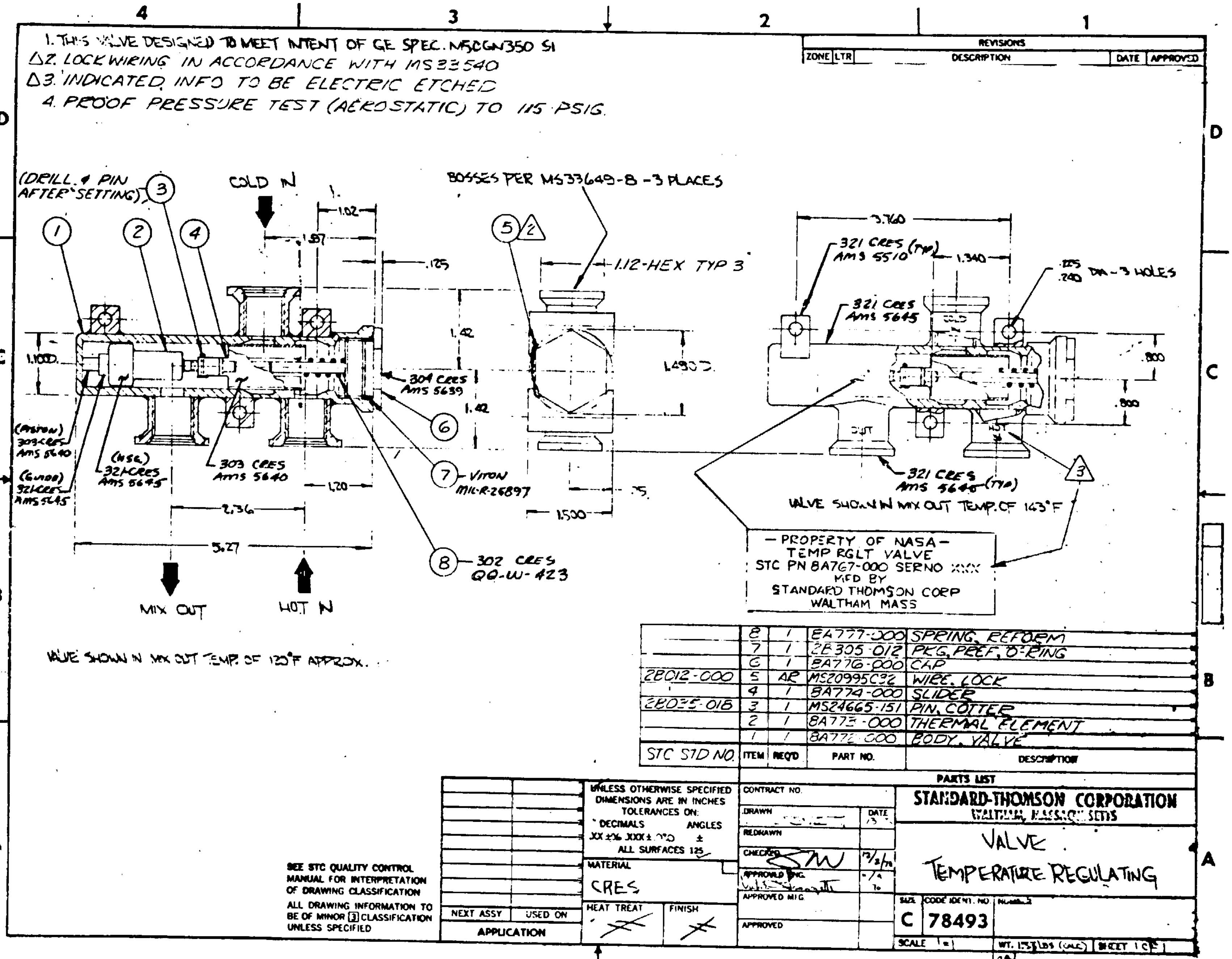


Figure 37. - Typical Electrolysis System Schematic



STC STD NO.	ITEM	REQ'D	PART NO.	DESCRIPTION
	8	1	EA777-000	SPRING, REFORM
	7	1	2B305-012	PKG, PREF, O-RING
	6	1	BA776-000	CAP
2B012-000	5	AR	MS20995C32	WIRE, LOCK
	4	1	BA774-000	SLIDER
2B035-018	3	1	MS24665-151	PIN, COTTER
	2	1	BA773-000	THERMAL ELEMENT
	1	1	BA772-000	BODY, VALVE

Figure 38.

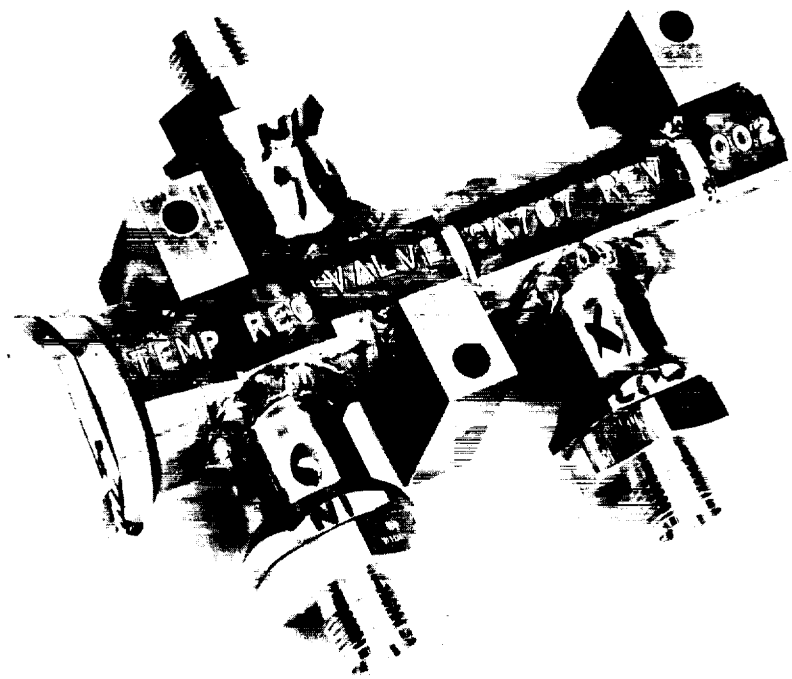
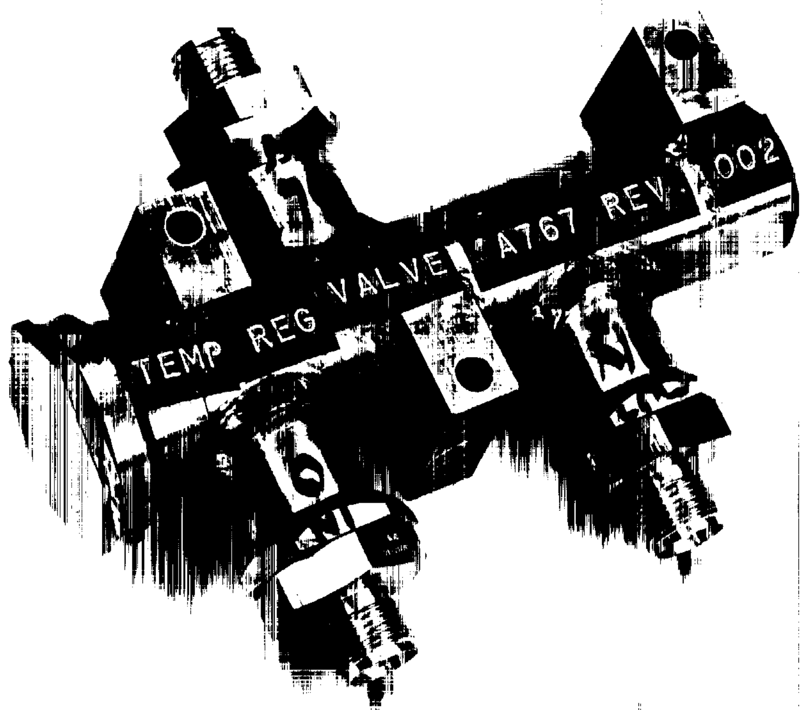


Figure 39. - Water Temperature Regulating Valve (As Procured)



377882

Micropump Model 668D5 (Data abstracted from Micropump Corp. Bulletin No. 700)

Pump Specifications

303 or 316 Stainless Steel
Ceramic (Barium Ferrite)
Delrin AF
Polypropylene
Nitrile (Others available)

Motor Specification

Seal-less, magnetically coupled
3-Phase, 400 Hz, 200 VAC
115 Volts, 400 Hz, 1-Phase Available
4 Leads Including Neutral
Thermal Protection Optional
Total Unit Weight 2.2 Pounds

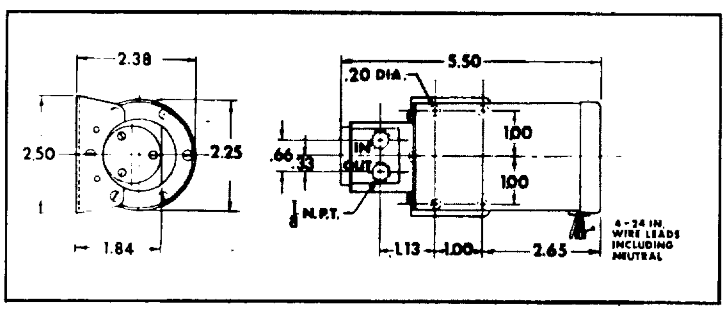
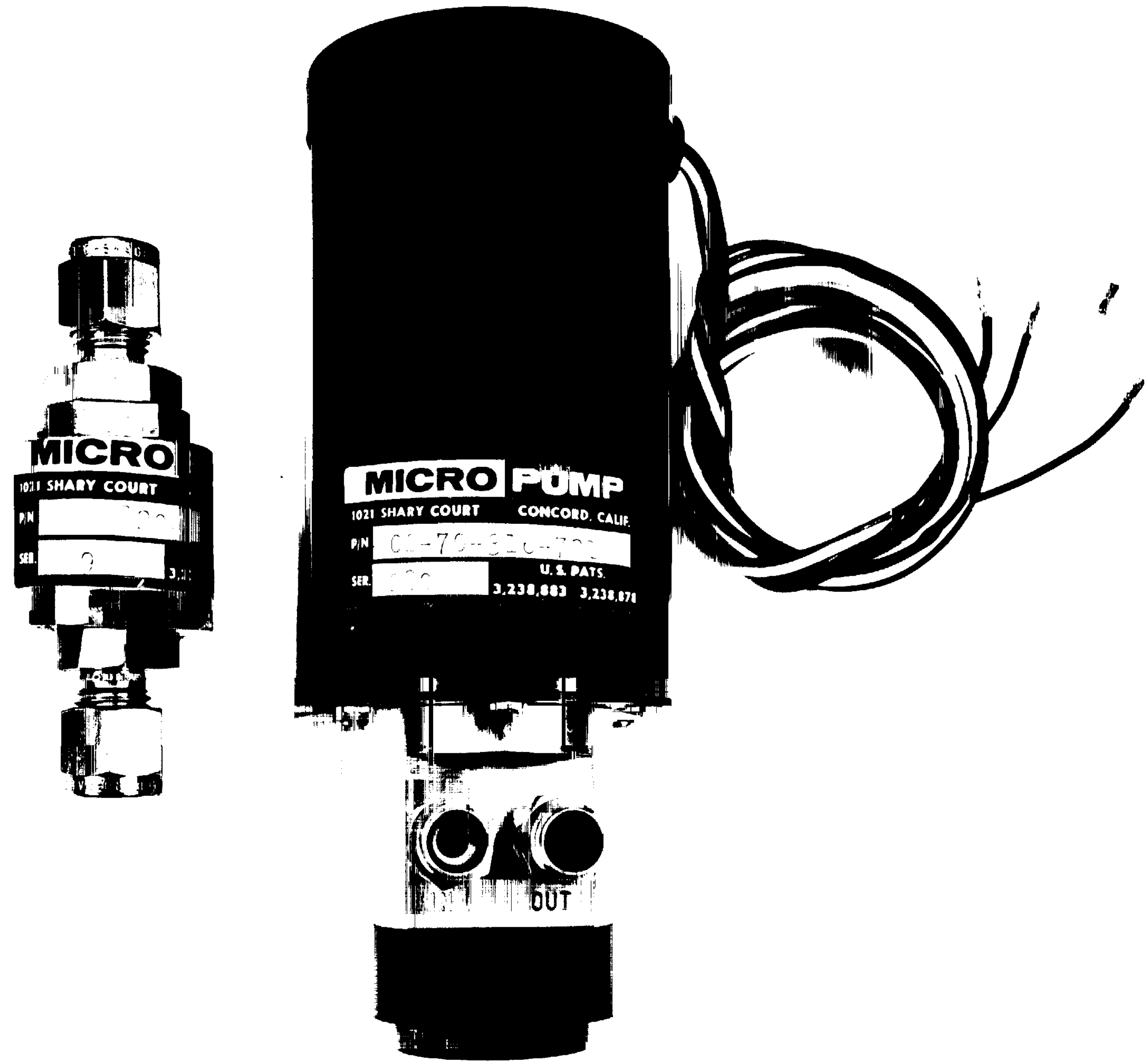


Figure 40. - Process Water Pump Vendor Data

Figure 41. - Water Flow Valve and Process Water Pump


MICRO
1021 SHARY COURT
P/N
SER.
MICRO PUMP
1021 SHARY COURT CONCORD. CALIF.
P/N
SER.
U.S. PATS.
3,238,883 3,238,878
OUT

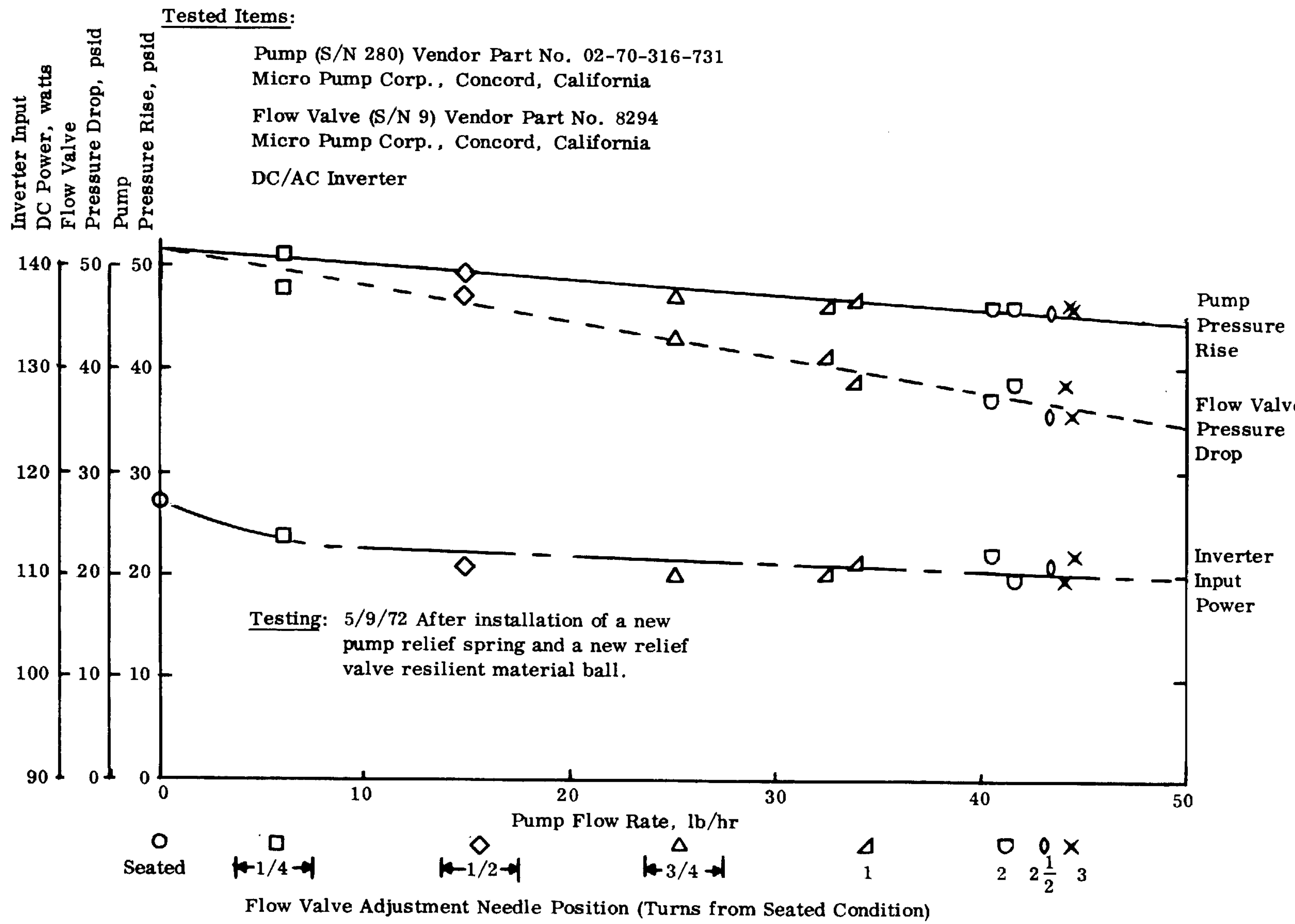


Figure 42. - Inverter, Process Water Pump and Flow Valve Characteristics

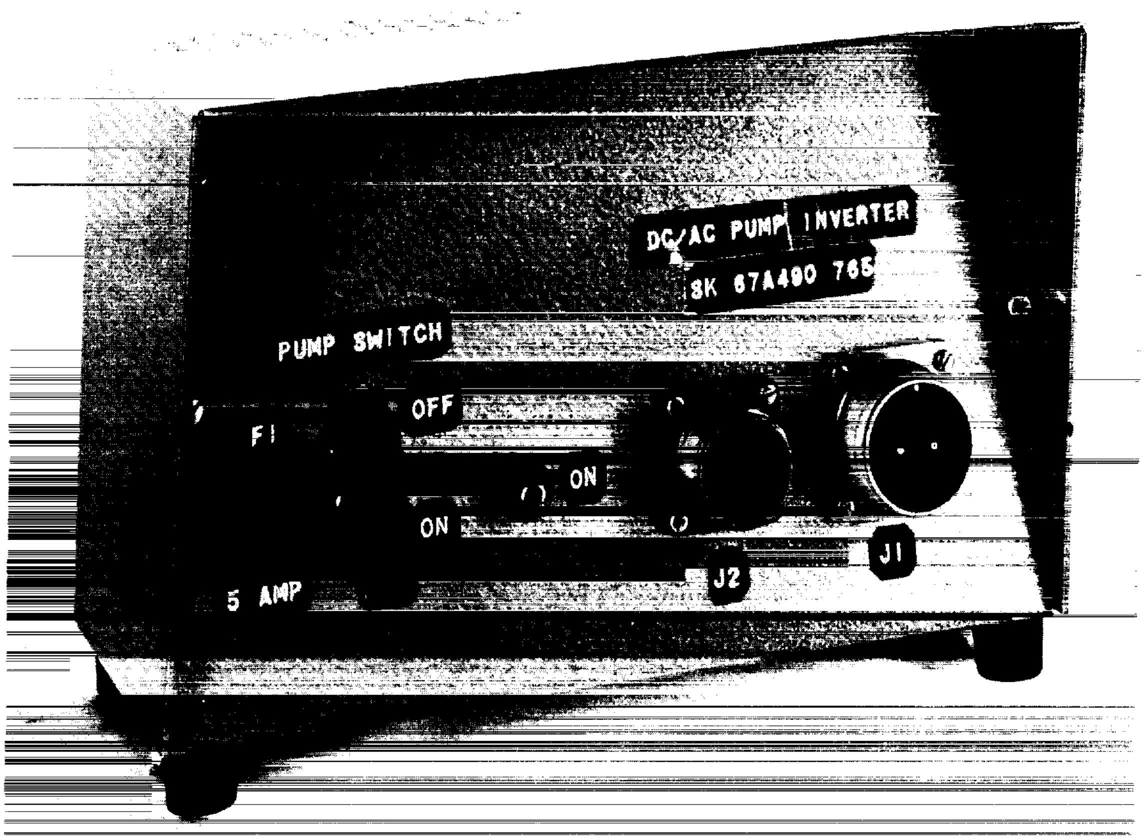
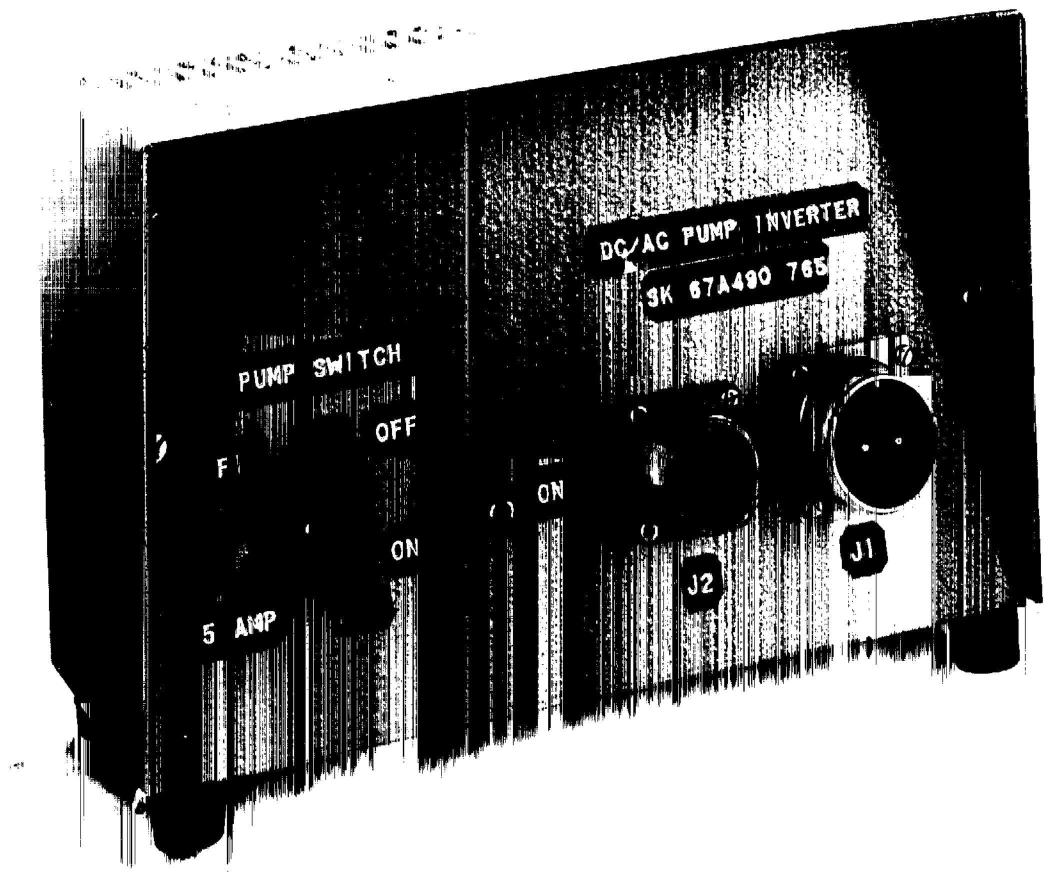


Figure 43. - DC/AC 3-Phase Inverter


PUMP SWITCH
OFF
ON
5 AMP
ON
DC/AC PUMP INVERTER
SK 67A490 765
J2
J1

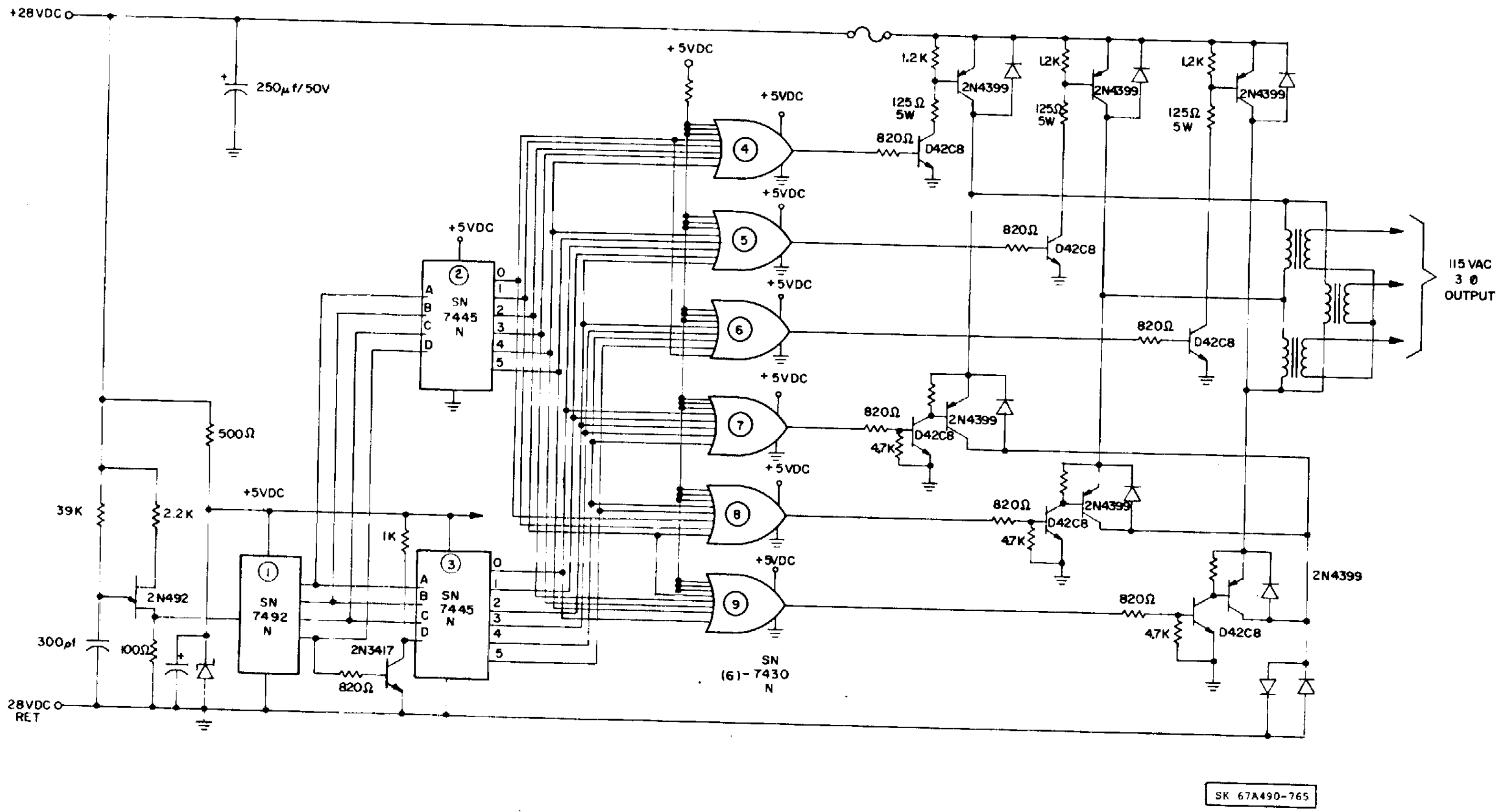


Figure 44. - DC/AC 3-Phase Inverter Schematic

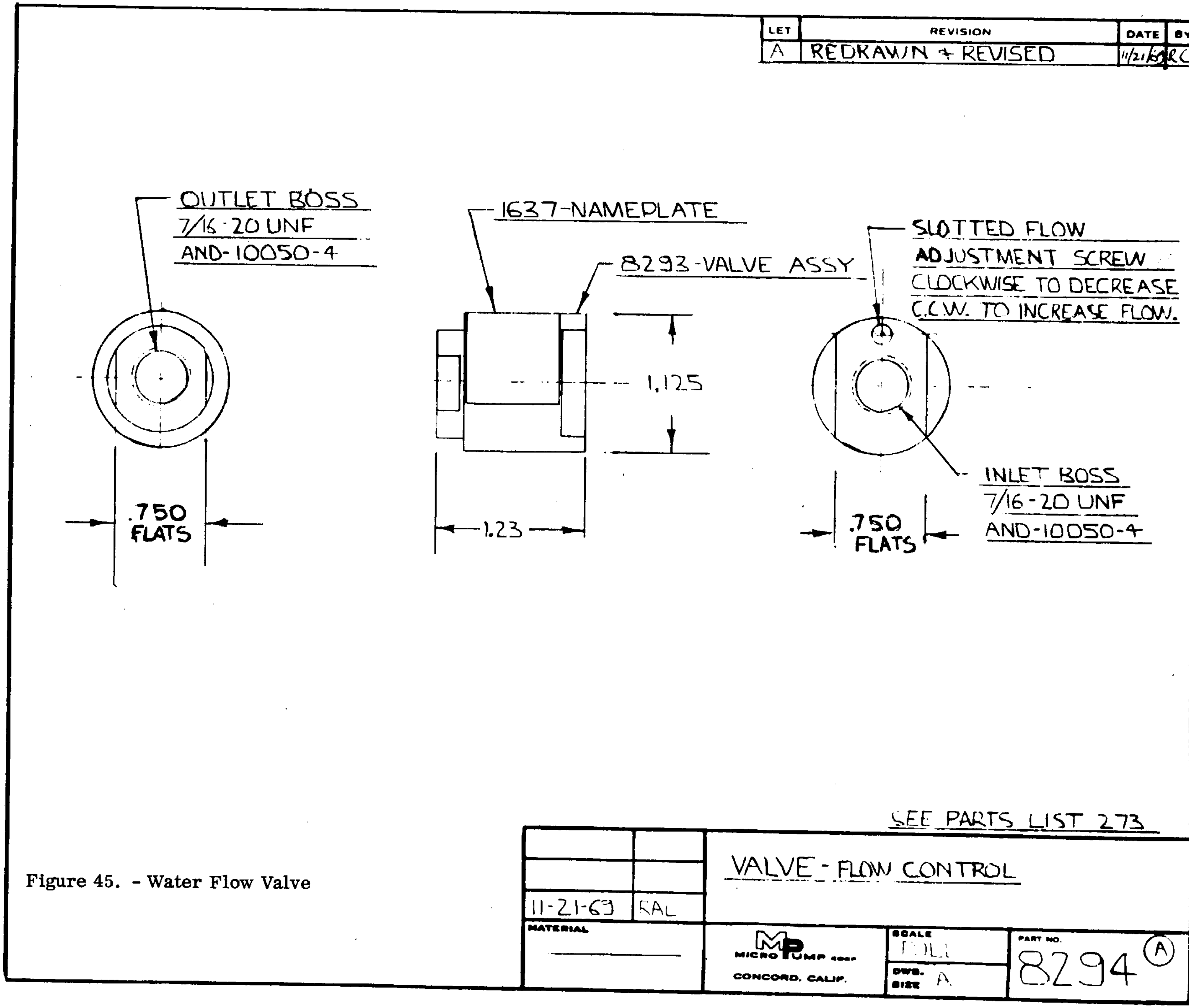


Figure 45. - Water Flow Valve

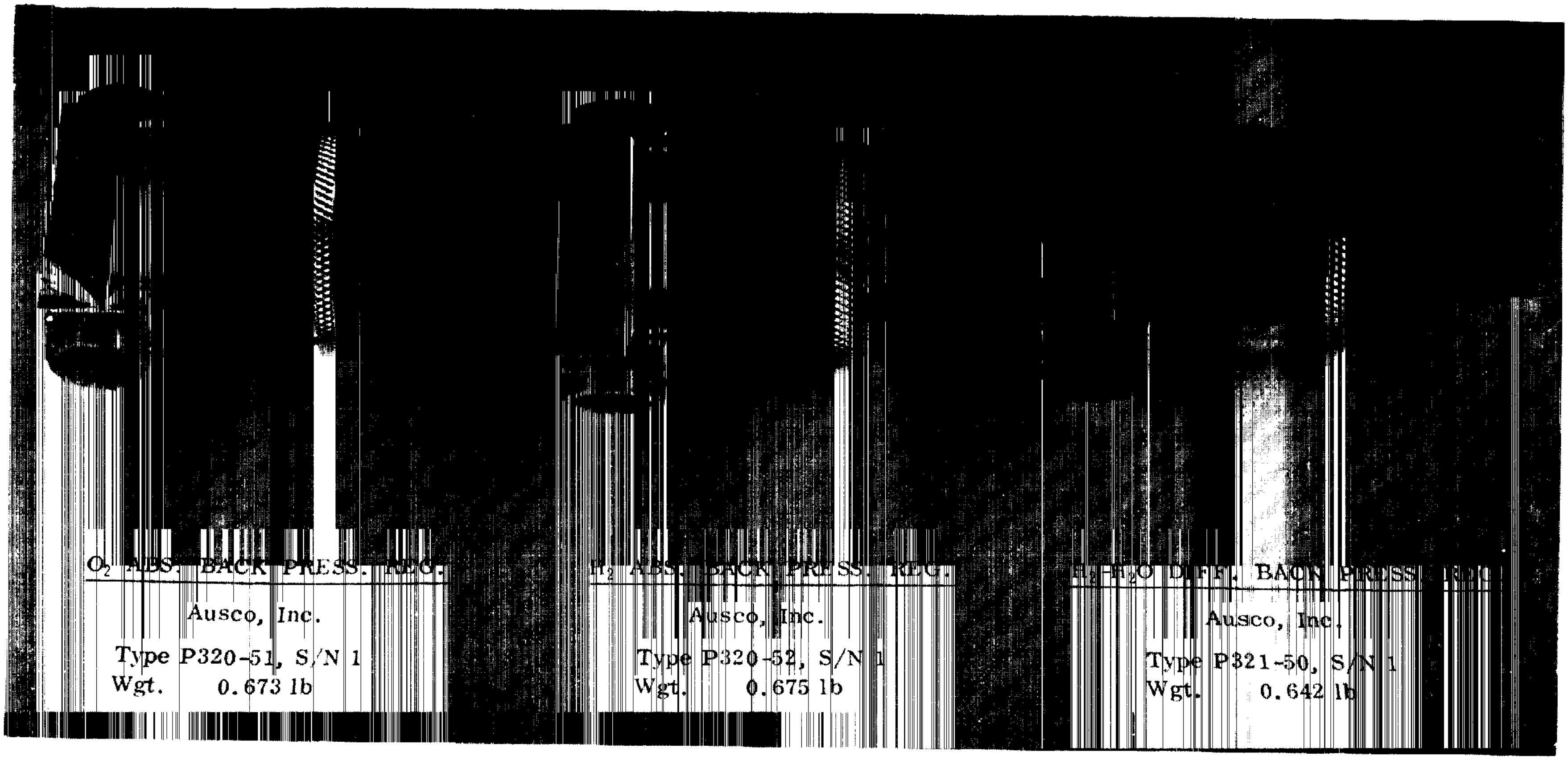
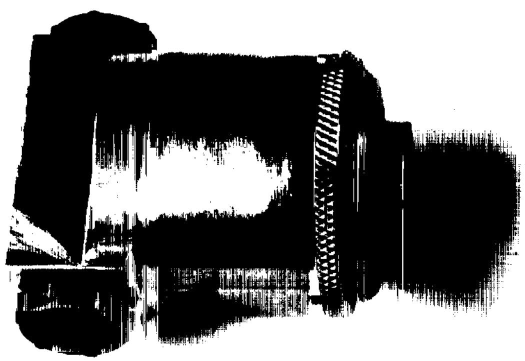

O_2 ABS. BACK PRESS. REG.
Ausco, Inc.
Type P320-51, S/N 1
Wgt. 0.673 lb
H_2 ABS. BACK PRESS. REG.
Ausco, Inc.
Type P320-52, S/N 1
Wgt. 0.675 lb
H_2-H_2O DIFF. BACK PRESS.
Ausco, Inc.
Type P321-50, S/N 1
Wgt. 0.642 lb

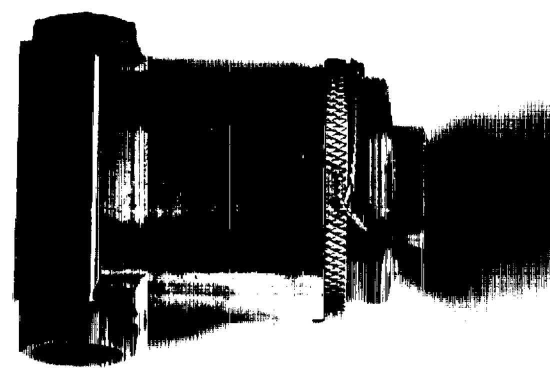
Figure 46



O$_2$ ABS. BACK PRESS. REG.

Ausco, Inc.

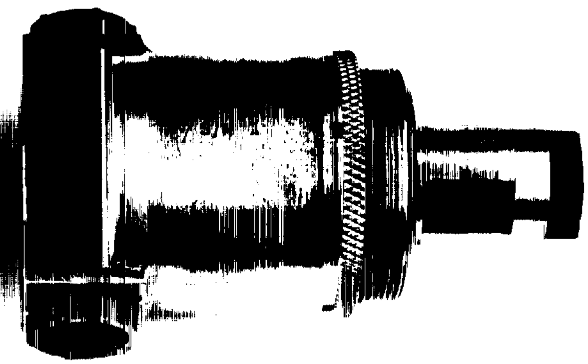
Type P320-51, S/N 1
Wgt. 0.673 lb



H$_2$ ABS. BACK PRESS. REG.

Ausco, Inc.

Type P320-52, S/N 1
Wgt. 0.675 lb



H$_2$-H$_2$O DIFF. BACK PRESS. REG.

Ausco, Inc.

Type P321-50, S/N 1
Wgt. 0.642 lb

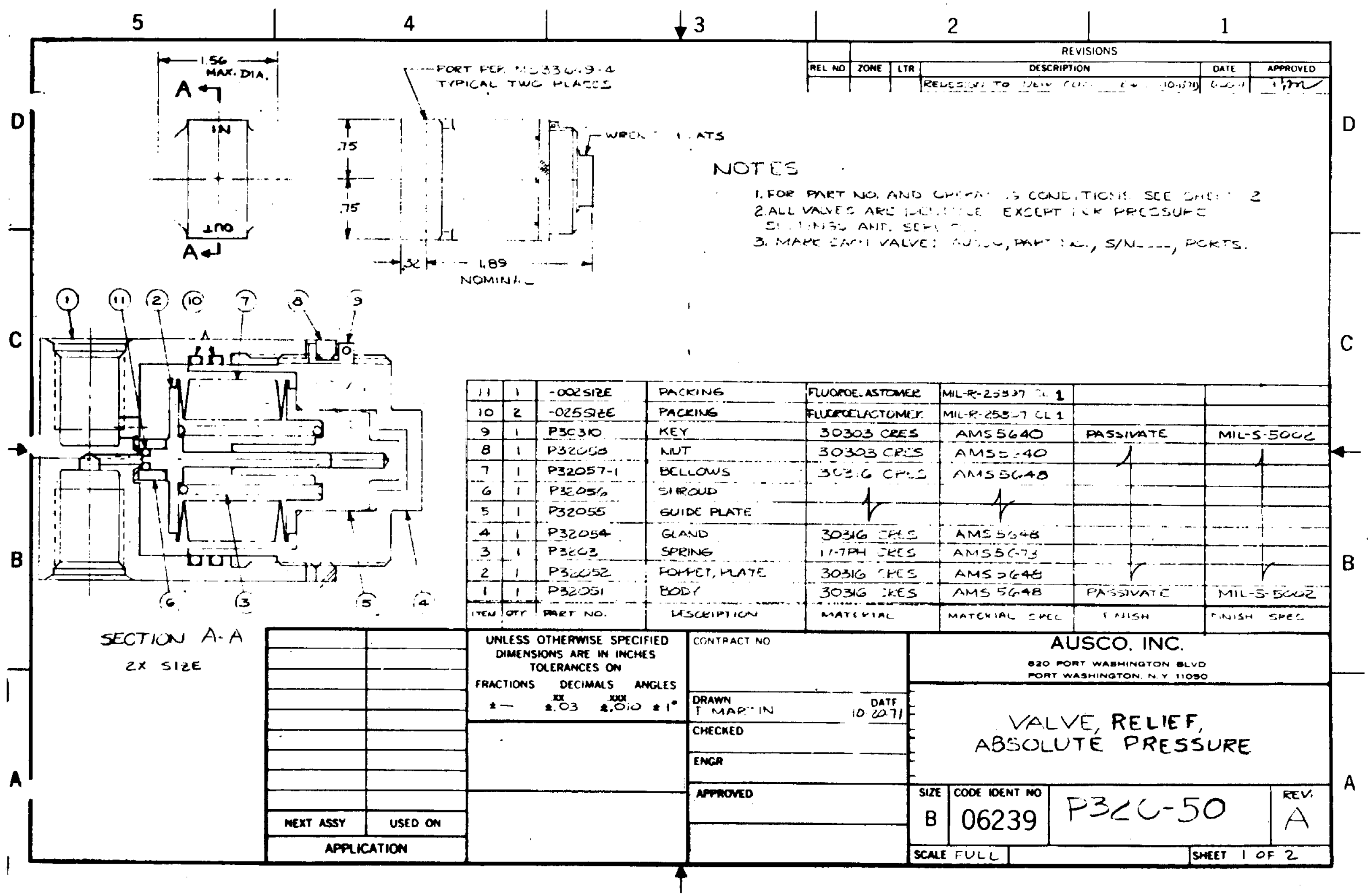

NOTES
1. FOR PART NO. AND OPERATING CONDITIONS SEE SHEET 2
2. ALL VALVES ARE IDENTICAL EXCEPT FOR PRESSURE SETTINGS AND SERIAL NO.
3. MARK EACH VALVE: AUSCO, PART NO., S/N___, PORTS.
SECTION A-A
2X SIZE
1.56 MAX. DIA.
IN
OUT
.75
.75
.32
1.89
NOMINAL
AUSCO, INC.
820 PORT WASHINGTON BLVD
PORT WASHINGTON, N.Y. 11050
VALVE, RELIEF,
ABSOLUTE PRESSURE
SIZE B
CODE IDENT NO 06239
P32C-50
REV. A
SCALE FULL
SHEET 1 OF 2
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON
FRACTIONS ±—
DECIMALS .XX ±.03 .XXX ±.010
ANGLES ±1°
DRAWN T MARTIN
CHECKED
ENGR
APPROVED
CONTRACT NO
NEXT ASSY
USED ON
APPLICATION
REVISIONS
REL NO
ZONE
LTR
DESCRIPTION
DATE
APPROVED
ITEM
QTY
PART NO.
DESCRIPTION
MATERIAL
MATERIAL SPEC
FINISH
FINISH SPEC
11 1 -002 SIZE PACKING FLUOROELASTOMER MIL-R-25897 CL 1
10 2 -025 SIZE PACKING FLUOROELASTOMER MIL-R-25897 CL 1
9 1 P3C310 KEY 30303 CRES AMS 5640 PASSIVATE MIL-S-5002
8 1 NUT 30303 CRES
7 1 P32057-1 BELLOWS AMS 5648
6 1 SHROUD
5 1 P32055 GUIDE PLATE
4 1 P32054 GLAND 30316 CRES AMS 5648
3 1 SPRING 17-7PH CRES
2 1 P32052 POPPET, PLATE 30316 CRES AMS 5648
1 1 P32051 BODY 30316 CRES AMS 5648 PASSIVATE MIL-S-5002

Figure 47.

G.E. ITEM 4

1. NAME ___ O_2 ABS. BACK-PRESSURE R. V.
2. TEMPERATURE ___ AMBIENT 40 TO 110°F., FLUID 100 TO 170°F.
3. PRESSURES ___ PROOF 126 ~~PSIG~~, BURST 252 PSIG.
4. PERFORMANCE ___
   TEMPERATURE ___ 100 TO 170°F.
   CRACK ___ 61 TO 62 PSIA
   FULL FLOW ___ .154 TO 1.750 PPH AT 62 TO 63 PSIA
   RESEAT ___ 60 PSIA MINIMUM
   DOWNSTREAM PRESSURE VARIATION ___ 0 TO 57.0 PSIA
5. WEIGHT ___ 1.25 POUNDS ~~MAXIMUM~~
6. MARKING ___ AUSCO, P320-51 S/N ___, PORTS

G.E. ITEM 5

1. NAME ___ H_2 ABS. BACK-PRESSURE R. V.
2. TEMPERATURE ___ AMBIENT 40 TO 110°F., FLUID 60 TO 80°F.
3. PRESSURES ___ PROOF 84 PSIG, BURST 168 PSIG.
4. PERFORMANCE ___
   TEMPERATURE ___ 60 TO 80°F.
   CRACK ___ 40 TO 41 PSIA
   FULL FLOW ___ .0194 TO .22 PPH AT 41 TO 42 PSIA
   RESEAT ___ 39 PSIA MINIMUM
   DOWNSTREAM PRESSURE VARIATION ___ 0 TO 25 PSIA
5. WEIGHT ___ 1.25 POUNDS ~~MAXIMUM~~
6. MARKING ___ AUSCO, P320-52, S/N ___, PORTS

MATERIAL:

STOCK SIZE:

FINISH:

NOTES:
1. REMOVE ALL BURRS.
2. ___ √ ALL MACHINED SURFACES EXCEPT AS NOTED.

DRAWN: F. MARTIN	AUSCO, Inc. 820 PORT WASHINGTON BLVD. PORT WASHINGTON, N.Y. 11050	SCALE:	
CHECKED:		DATE: 11-9-71	
TOLERANCES FRACTIONS ± 1/64 DECIMALS 2 PL. ± .01 3 PL. ± .005 ANGLE ± 1/2°	VALVE, RELIEF, ABSOLUTE PRESSURE	DWG. NO. P320-50 SHEET 2	REV. A

Figure 47. - Continued

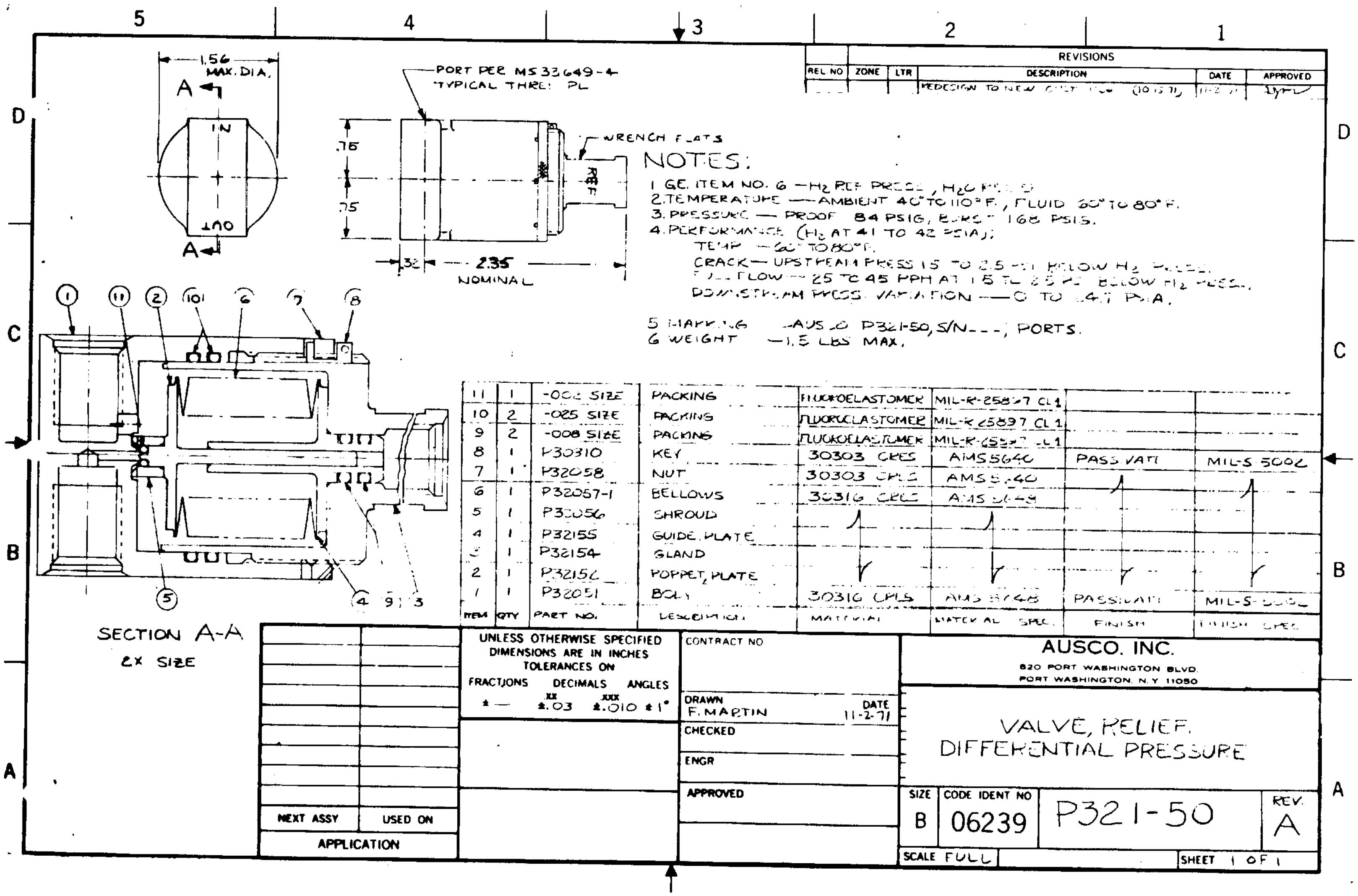

PORT PER MS33649-4 TYPICAL THREE PL
1.56 MAX. DIA.
IN
OUT
.75
.75
.32
2.35 NOMINAL
WRENCH FLATS
NOTES:
2. TEMPERATURE —AMBIENT 40°TO 110°F., FLUID 60°TO 80°F.
3. PRESSURE — PROOF 84 PSIG,
4. PERFORMANCE (H2 AT 41 TO 42 PSIA):
TEMP —60°TO 80°F.
CRACK— UPSTREAM PRESS 15
DOWNSTREAM PRESS VARIATION
6 WEIGHT —1.5 LBS MAX.
SECTION A-A
2X SIZE
REVISIONS
REL NO
ZONE
LTR
DESCRIPTION
DATE
APPROVED
PACKING
KEY
NUT
BELLOWS
SHROUD
GUIDE PLATE
GLAND
POPPET PLATE
ITEM
QTY
PART NO.
P30310
P32058
P32057-1
P32155
P32154
P32051
30303 CRES
30316 CRES
AMS 5640
MIL-S 5002
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON
FRACTIONS
DECIMALS
ANGLES
±.03
±.010
±1°
CONTRACT NO
DRAWN
F. MARTIN
DATE
11-2-71
CHECKED
ENGR
APPROVED
NEXT ASSY
USED ON
APPLICATION
AUSCO, INC.
820 PORT WASHINGTON BLVD.
PORT WASHINGTON, N.Y. 11050
VALVE, RELIEF, DIFFERENTIAL PRESSURE
SIZE
B
CODE IDENT NO
06239
P321-50
REV.
A
SCALE FULL
SHEET 1 OF 1

Figure 48.

TABLE I

GUIDELINE SPECIFICATION FOR FOUR-MAN RATED WATER ELECTROLYSIS SYSTEM (WES)

WES Capacity

10 lb/day oxygen (nominal four-man rate - continuous).

Equivalent 75 amp oxygen generation (maximum) - cyclic usage up to 16 hours "on"/8 hours "off".

WES Gas Purity

Oxygen Generation

99.7% min. O_2
0.1% max. H_2
Remainder - Not defined.

Hydrogen Generation

99.3% min. H_2
0.2% max. O_2
Remainder - Not defined.

NASA-Maintained Downstream Gas Pressures of WES

Oxygen Subsystem: 14.7 psia or less.

Hydrogen Subsystem: 20 ± 5 psia.

Make-up Water (Feed Water) Available to WES

Temperature: +40 to +170°F.

Pressure: 25 ± 5 psia.

Water Purity:
$<$100 ppm by weight solids (assume ionic species).
$<$80 micromhos/cm specific conductance (12,500 ohm-cm max. specific resistance).

Bacteria	- Pseudomonas Aeruginosa	10 counts/cc
	Alcaligenes Faecalis	10 counts/cc
Fungii	- Mucor	1 spore count/cc
Molds	- Not defined.	

Coolant Available to WES

Fluid:	Water with propylene glycol additive to establish a nominal 0°F freezing point.
Temperature:	+40 ± 3°F.
Pressure:	80 psig max.
Flow:	Up to 1 gpm.

Nitrogen Available to WES

Pressure: 80 psia nominal.

Electrical Services Available to WES

28 ± 3 VDC.

115 VAC nominal at 60 Hz.

TABLE II

WES COMPONENT WEIGHTS AND VOLUMES

Component Item	Drawing No.	Ref. Figure No.	Manufacturer	Weight, * lb	Nominal Envelope Size, ** in.	Nominal Envelope Volume, ** in^3	Comments
Power Conditioner	SK67A490-767	2, 3	GE/DECP Lynn, Mass.	17.7	10.0x7.7x8.4	647	Envelope size includes connectors.
Control Panel	SK67A490-766	4, 5	GE/DECP Lynn, Mass.	13.8	19.0x9.0x7.0	1198	Weight with 10 ft cable (1.9 lb).
Prototype Two-Phase Separator	1076527-968P1	10, 11	GE/DECP Lynn, Mass.	21.8 36.5	8.7 dia x 15.6	928	Weight with no water in OD cavity of porous tubes. Weight with full water in OD cavity of porous tubes.
13-Cell Electrolysis Module	1076527-910P1	29, 30	GE/DECP Lynn, Mass.	32.8	11.0x6.0x9.3	614	Envelope size excludes acrylic mounting feet.
Deionizer Resin Bed	1076527-957P1	31, 32	GE/DECP Lynn, Mass.	17.8 21.4	5.5 dia x 28.4	674	Weight with no water. Weight with full water in housing.
Biological Filter Resin Bed	1076527-958P1	34, 35	GE/DECP Lynn, Mass.		5.5 dia x 28.4	674	
Regenerative Heat Exchanger	3101-6, 4-8-6x 316 SST	36	Parker-Hannifin Co. Cleveland, Ohio	11.1	7.3x7.3x16.2	863	Weight with foam thermal insulation.
Water Temperature Regulating Valve	8A767-Rev. 002	38, 39	Standard-Thomson Corp., Waltham, Mass.	1.6	5.5x1.5x2.8	23.1	
Process Water Pump	02-70-316-731	40, 41	Micro Pump Corp., Concord, Calif.	2.4	6.0x2.4x2.5	36	Weight with no port fittings.
DC/AC Inverter	SK67A490-765	43, 44	GE/DECP Lynn, Mass.	4.8	10.0x7.0x6.6	462	
Water Flow Valve	8294	45, 41	Micro Pump Corp., Concord, Calif.	0.2	1.1 dia x 1.2	1.14	Weight with no port fittings.
Abs. H_2 Back-Pressure Regulator	P320-52	46, 47	AUSCO, Inc. Port Washington, NY	0.7	1.5 dia x 2.3	4.06	Weight with no port fittings.
Abs. O_2 Back-Pressure Regulator	P320-51	46, 47	AUSCO, Inc. Port Washington, NY	0.7	1.5 dia x 2.2	3.88	Weight with no port fittings.
Differential Back-Pressure Regulator	P321-50	46, 48	AUSCO, Inc. Port Washington, NY	0.6	1.5 dia x 2.9	5.12	Weight with no port fittings.

* Dry condition unless stated otherwise. ** Port fittings excluded; LxWxH unless stated otherwise.

TABLE III

ELECTROLYSIS UNIT OPERATION HISTORY

Unit	Operating Time, Hours	Comments
Laboratory Cell No. 7	9606	No failure
Laboratory Cell No. 10	9134	No failure
Laboratory Cell No. 11	8971	No failure
Laboratory Cell No. 13	8265	No failure
Single-Cell Module (26.8 in.^{2} cell area)	9344	No failure
Four-Cell Module "B" (33.2 in.^{2} cell area)	6072 which includes 3151 cycles of 60 minutes "on" power and 40 minutes "off" power	No failure
Seven-Cell Module "A" (33.2 in.^{2} cell area)	8313.3 Component testing +2775.4 System testing 11088.7 Total	No failure
Four-Cell Module (S/N 1D) (33.2 in.^{2} cell area)	1682 One-man rated breadboard system test	Rubber gasket relaxation failure caused cell burn-out

Note: This table does not include the cumulative operating time during the special high-pressure electrolysis evaluation under this contract nor does it include the operating time performed on the delivered 4-cell Module "C".

TABLE IV

SEVEN-CELL MODULE "A" TIE-BOLT TORQUE HISTORY

Date	Cumulative Gas Generation Time (hrs)	Torque, lb-in. Tie-Bolt Position 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8/16/71	8313	15	25	25	15	15	25	25	15	15	25	25	15	15	25	25	15
11/2/71	9913	13	17	20	15	15	23	22	12	14	23	22	20	(*)	20	22	(*)
4/27/72	11062	10	12	17	9	8	15	12	8	10	16	13	7	8	15	15	11

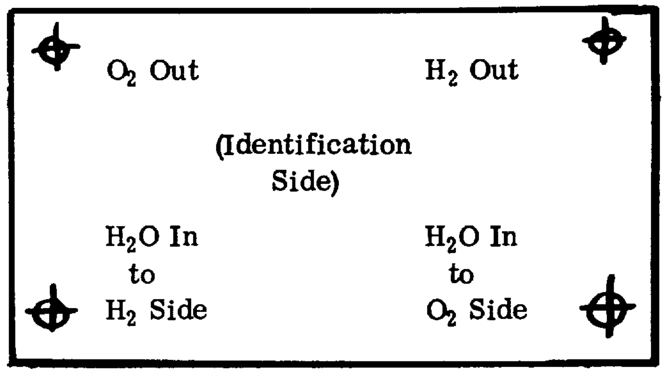
(*) These two positions were inaccessible since the 11/2/71 check was made with the module operating and installed in the breadboard systems test facility.

TABLE V

BREADBOARD 4-CELL MODULE SYSTEM TEST MEASUREMENTS TAKEN AT 1147 HOURS

Measurement	Typical Recorded Data
Cell 1	1.626 VDC
Cell 2	1.630 VDC
Cell 3	1.620 VDC
Cell 4	1.627 VDC
Total Term.	6.562 VDC
Total Sum. Cell	6.492 VDC
Total Shunt Current DC (200 ASF)	45.98 amps
Power Supply	7.3 VDC
Power Supply Current DC	46.0 amps
Module Input Power (Cal.)	301.5 watts
2 ø Sep. Mix. - In to H_2 Out (ΔP_1)	3.5 psid
2 ø Sep. Mix. - In to H_2O Out (ΔP_2)	4.7 psid
Module O_2 Out Press. (P_1)	45.0 psig
Sep. H_2 Out Press. (P_2)	36.0 psig
Sep. H_2O Out Press. (P_3)	35.0 psig
Sep. Mix. - In Press. (P_4)	38.0 psig
Make-Up Water Reservoir Press. (P_5)	33.0 psig
Stored Water Reservoir Press. (P_6)	0 psig
Reg. Heat Exch. Mix. - Out Press. (P_7)	40.0 psig
Pump Disch. Press. (P_8)	56.5 psig
Deionizer Resin Bed Inlet Press. (P_9)	38.5 psig
Deionizer Resin Bed Effluent Specific Resistance	1.10×10^6 ohm-cm
Deionizer Resin Bed Effluent pH	5.67
Module Influent Specific Resistance	not required
Module Influent pH	not required
Module Effluent Specific Resistance	not required
Module Effluent pH	not required
Absorption Resin Bed Effluent Specific Resistance	1.25×10^6 ohm-cm
Absorption Resin Bed Effluent pH	6.25
Water Collected Module O_2 Out	0.325 cc/min
Water Collected 2 ø Sep. H_2 Out	None
Process Water Flow	15.8 cc/min
Hydrogen Flow (wet test meter at STP)	1355 cc/min
Oxygen Flow (wet test meter at STP)	678 cc/min
Cumulative Gas Generation Time	1147.1 hr
Date of Test Events	6/1/71
A and N Time of Events	0820
Comments	Gauge accuracy must be considered.

TABLE V. - Continued



	Measurement		Code	°F
"Light" TC	Module O_2 Out (External Tubing)		T_1	114.5
"Heavy" TC's	Reg. Heat Exch. H_2O - In (Skin)		T_2	69.8
	Reg. Heat Exch. H_2O - Out (Skin)		T_3	149.0
	Reg. Heat Exch. Mix. - In (Skin)		T_4	154.2
	Reg. Heat Exch. Mix. - Out (Skin)		T_5	75.3
	2 Ø Sep. Mix. - In (Skin)		T_6	73.4
	Hood Ambient		T_7	74.6
	Hood Ambient		T_8	75.1
"Light" TC's	Module H_2O - In to H_2 Side (Skin)		T_9	155.2
	Module Mix. - Out from H_2 Side (Skin)		T_{10}	176.5
	Module O_2 - Out (Skin)		T_{11}	167.4
	Module End Plate (Skin) Adj. to H_2O - In Port to H_2 Side	Indent. Side	T_{12}	173.2
	Module End Plate (Skin) Adj. to Mix. - Out Port H_2 Side	Indent. Side	T_{13}	174.6
	Module End Plate (Skin) Adj. to O_2 - Out Port	Indent. Side	T_{14}	174.8
	Module End Plate (Skin) Center	Non-Indent. Side	T_{15}	175.2
	Module End Plate (Skin) Adj. to H_2O - In Port to O_2 Side	Non-Indent. Side	T_{16}	175.2
	Module End Plate (Skin) Center	Non-Indent. Side	T_{17}	174.5
	Module End Plate (Skin) Adj. to O_2 - Out Port	Non-Indent. Side	T_{18}	174.8
	Module End Plate (Skin) Adj. to H_2O - In Port to H_2 Side	Non-Indent. Side	T_{19}	174.3
	Module End Plate (Skin) Adj. to Mix. - Out Port H_2 Side	Non-Indent. Side	T_{20}	176.3
	Module End Plate (Skin(Adj. to H_2O - In Port to O_2 Side	Non-Indent. Side	T_{21}	174.9
	Module Insulation Surface Ident. Side (Center)		T_{22}	103.0
	Module Insulation Surface Non-Ident. Side (Center)		T_{23}	88.8
	Module Insulation Surface (Top)		T_{24}	92.9

TABLE VI
13-CELL WATER ELECTROLYSIS MODULE
SIGNIFICANT DESIGN DATA

Cell Design Parameters	Design Point
Electrode Diameter	6.5 in.
Active Area	33.2 in.^{2} or 0.23 ft^2
Ion Exchange Membrane	Spec: A50GN342
Anode (O_2 Side) Catalyst	E50, 12.5% Teflon
Cathode (H_2 Side) Catalyst	Pt Black, 12.5% Teflon
Cathode Catalyst Support	Expanded Gold Screen .003 in. thick, 6.75 in. dia.
H_2 and O_2 Gas Gap Screening	5 Layers Expanded Screen 5 Nb 7, 3/0, Platinized and Welded Pressed to .022 in. Thick
H_2/O_2 Separator Sheet	.003 in. Thick Niobium Platinized
Gas Gap Gasket Seal	.025 in. Thick GE Silicone SE-4404, Unfilled
H_2 Cell Water Feed Port	.022" Thick Screen Gap x .25" Wide
H_2 and O_2 Cell Outlet Gas Ports	.022" Thick Screen Gap x .38" Wide
Operating Mode	Cathode Water Feed
Normal Current	48.5 amp
Normal Current Density	210 ASF
Normal Cell Voltage	1.81 VDC
Nominal Cell Spacing (Including one pressure pad)	0.110 in.
Module Design Parameters	
Normal Oxygen Generation Rate	10 lb O_2/day
Min. Supply Voltage (Out of Power Conditioner)	23.5 VDC
Number of Modules	One
Number of Cells per Module	13
Nominal End Plate Loading	12,900 lb

TABLE VI (Cont'd.)

13-CELL WATER ELECTROLYSIS MODULE

SIGNIFICANT DESIGN DATA

Module Design Parameters	Design Point
Max. End Plate Center Deflection	.005 in.
End Plate	1 x 9.25 x 9.25 in. 75ST6 Aluminum
Initial Pad Pressure Load (Zero Gas Pressure)	190 psi
Pressure Pad	.055 in. Thick, 6.5 in. Diameter, GE Silicone SE-4404
Manifold Gasket Seal	.045 in. Thick, GE Silicone SE-4404, Unfilled
Module Envelope	5.25 x 9.25 x 9.25 in.
Tie-Bolt Torque	60 lb-in.

TABLE VII

HYDROGEN-WATER VAPOR/WATER SEPARATOR

HYDROPHILIC MATERIAL DATA

Material Description	Pore Size, Micron	Air Bubble Point Test, psid	H_2O Volumetric Flow cc/min-in.[2] @ 14.697 psia and 68°F Discharge Pressure 0.483 psid	0.966 psid	1.932 psid	3.864 psid	9.660 psid	Comments
Stainless Steel Screens								
100 mesh		0.0676						
200 mesh		0.2120						
230 mesh		0.1352						
330 mesh		0.2120						
400 mesh		0.2510						
Porous Metal Plates								
	10 nom	0.3090						
	20 nom	0.3090						
	40 nom	0.3090						
	100 nom	0.1448						
Millipore Glass Filter Paper		2.339						
Nylon Cloth	10 nom	0.675	1388.0	2775.0	5550.0	11100.0	27750.0	(1), (2)
Asbestos Mats								
Manville		14.700	0.46	0.921	1.84	3.69	9.21	
ACCO-1		4.900	7.26	14.53	29.05	58.1	145.3	
Ulti Pore 1		10.300	3.26	6.52	13.04	26.1	65.2	
PVC Membranes								
Synpore 15 mil thk		4.320	33.55	67.10	134.2	268.4	671.0	
Synpore 10 mil thk		5.910	14.20	28.4	56.8	113.6	284.0	
Stainless Steel Filter Cloth								
325 x 2300 mesh		1.737	1322.0	2644.0	5288.0	10576.0	26440.0	
250 x 1370 mesh		1.350	1612.0	3224.0	6448.0	12896.0	32240.0	
200 x 1400 mesh		0.984	2580.6	5161.2	10322.4	20644.8	51612.0	
Rigimesh K		0.945	1995.0	3990.0	7980.0	15960.0	39900.0	
450 x 2750 mesh			2325.0	4650.0	9300.0	18600.0	46500.0	
Porous Glass Tubes								
Fine No. 2	4 to 5.5	5.15	0.75	1.60	4.05	13.40	43.55	
Fine No. 8	4 to 5.5	5.89	0.25	0.60	1.25	3.65	10.80	
Fine No. 9	4 to 5.5	7.61	2.00	4.30	9.25	20.95	55.90	
Fine No. 10	4 to 5.5	6.14	2.40	4.70	9.80	20.95	55.20	
Fine No. 11	4 to 5.5	5.65	2.00	4.30	9.00	19.90	52.60	
Fine No. 12	4 to 5.5	5.89	3.10	6.10	12.00	24.40	61.05	
Very Fine No. 1	2 to 3.5	9.08	0.15	0.32	0.80	2.75	9.40	(3)
Very Fine No. 3	2 to 3.5	9.33	0.20	0.42	0.88	2.10	6.04	
Very Fine No. 4	2 to 3.5	7.86	0.45	0.92	1.96	4.58	12.85	
Very Fine No. 5	2 to 3.5	13.25	0.25	0.52	1.15	2.58	7.25	
Very Fine No. 6	2 to 3.5	8.59	0.30	0.58	1.16	2.22	5.42	
Very Fine No. 7	2 to 3.5	7.86	0.82	1.66	3.34	6.68	16.71	
Fine No. 1E	4 to 5.5	7.50	2.60	3.97	6.68	12.5		
Fine No. 1G	4 to 5.5	5.25	2.27	3.00	6.12	10.7		(4)
Fine No. 1H	4 to 5.5	7.50	5.13	6.45	11.30	20.4		
Acropor AN-3000	3	1.5 to 4.3						
Acropor AN-800	0.8	>10	9.66					Gelman Instrument Co. PVC on a nylon cloth support.
Acropor AN-450	0.45	>10	3.86					
E610-222/L Zitex	2 to 5	1.0						Chemplast Inc.
GE-EH 2038 Nuclepore	3	1.0						
GE-RU 1703 Nuclepore	1	10	24.15					
GE-MC 1588 Nuclepore	0.8	>10	19.32					Poly-carbonate membranes.
GE-UC 1788 Nuclepore	0.6	>10	12.08					
GE-300 Nuclepore	3	2 to 3						
GE-100 Nuclepore	1	<1.0						
Micro-Por 100 Tube		<1.0						ABS Thermoplastic.
Metricel Type VM-1	5	1.0						Gelman Instrument Co.
Metricel Type VM-100	10	<0.5						Gelman Instrument Co.
Microweb (1 Layer)	3	2.6	3.44		18.88	36.1		Millipore Type WSWP (Sample No. 1)
Microweb (2 Layer)	3	4.4						Millipore Type WSWP
Microweb (1 Layer)	3	2.4			9.44	27.7		Millipore Type WSWP (Sample No. 2)
DAWP 04700	0.65	>10	14.99					Millipore Cellulose
HAWP 04700	0.45	>10	9.66					Millipore Cellulose
WHWP 14200	0.45	>10	5.80					Millipore Cellulose with nylon cloth support
Porous Polypropylene with Surfactant	0.1	100.0			0.0353			Celanese Plastic Co. published data.
AMICON XM300		5.0						Lexington, Mass.
AMICON XM300A		5.0						
Type 100-25AA		5.0						
Type 100-25A		3.0						Balston Co., Lexington, Mass. asbestos cylinders with epoxy impregnation.
Type 100-25B		1.0						
Type 100-25C		1.3						

TABLE VII (Cont'd.)

NOTES:

(1) Converted flow data from Figures 16 thru 26 of Lockheed Missiles and Space Co., Sunnyvale, Calif., Report No. NASA CR-66922, dated 5/18/70 for Contract NAS 1-8228.

(2) After initial water wetting of material by passing water through material and with a light water film on one side and air applied to other side, observe for first bubble indication on water film side. Converted data from Tables 4 and 6 of Lockheed Missiles and Space Co., Sunnyvale, Calif., Report No. NAS CR-66922, dated 5/18/70 for Contract NAS 1-8228.

(3) After initial water wetting of material on ID and OD and with OD to ambient air, observe for first bubble indication in ID when a vacuum is applied to ID. Converted data from 10/28/70 tests made at GE/DECP, Lynn, Mass. Corning filter tube type 5/8" OD x .45" ID x 4" lg, Pyrex Laboratory Glassware, Corning Glass Works. Mean lateral area =

$$(3.1416) \left[\frac{.625 + .450}{2}\right] (4) = 6.75 \text{ in.}^2.$$

(4) After initial wetting of material on ID and OD and with ID to pressurized air, observe for first bubble indication on OD (immersed in water). Corning filter tube type 1" OD x 3/4" ID x 8" lg. Mean lateral area = 22 in.^{2}.

TABLE VIII

HYDROGEN/WATER SEPARATOR

HYDROPHOBIC MATERIAL DATA

Material Description	Pore Size, Micron	Water Initiation Point, psid	H_2 + Water Vapor Volumetric Flow cc/min-in.^{2} @ 14.697 psia and 68°F Discharge Pressure 0.483 psid	0.966 psid	1.932 psid	3.864 psid	9.660 psid	Comments
Coated 230 Mesh Screens								
Teflon TFE		0.367						
Teflon FEP		0.213						
Teflon S		0.154						
Kynar		0.213						
Vydax		0.019						
Zitex Membranes								
E610-122		2.320	1062.0	2120.0	4250.0	8480.0	21200.0	
H662-123		1.312	1942.0	3880.0	7750.0	15520.0	38800.0	
H622-124		1.526	2060.0	4120.0	8250.0	16500.0	41200.0	
K233-222		0.483	2160.0	4320.0	8650.0	17320.0	43200.0	
E610-122+H662-123		5.150	619.0	1238.0	2470.0	4950.0	12380.0	
E610-122 2 Ply		6.620	505.0	1008.0	2015.0	4020.0	10100.0	
E610-122 3 Ply		8.330	255.0	510.0	1020.0	2040.0	5100.0	
E610-122 6 Ply		7.110	203.0	407.0	813.0	1628.0	4060.0	(1), (2)
E610-122 12 Ply		5.380	230.0	460.0	920.0	1840.0	4600.0	
E610-122C		8.100	232.0	464.0	926.0	1850.0	4630.0	
E610-122C+E610-122 6 Ply		9.320	55.8	111.5	223.0	446.0	1115.0	
E610-122C 2 Ply + E610-122 3 Ply + H662-123 2 Ply		14.697	47.3	94.5	189.0	378.0	944.0	
12-104		14.697	53.3	106.6	213.0	426.0	1066.0	
Pallflex Products								
TV20 A40		1.197	1430.0	2850.0	5720.0	11400.0	28500.0	
TV20 A60		1.968	1501.0	3000.0	6100.0	12000.0	30000.0	
TS-1GC-32		8.100	89.7	179.6	359.0	718.0	1795.0	
TX40 H80		8.330	15.78	31.5	63.0	126.0	314.0	
Saunders Engineering								
S-20 Teflon Tape		28.95	66.6	133.5	267.0	534.0	2140.0	
S-22 Teflon Tape		28.95	35.6	71.2	142.3	284.0	712.0	
Aquapel (Type SSHP)	3	5.0						Millipore Corp. 5 mils thk.
Armalon (Type 406A-116)		15.0					0.054/ 0.124(3)	duPont Teflon coated glass fabric (6 mils thk.)
Mitex (Type LCHP)	10	3.0						Millipore Corp. 5 mils thk.
E248-122D (Zitex)		0.5						Chemplast Inc.
H201-122D (Zitex)		0.5						Chemplast Inc.
Unsintered Teflon Sample No. 3		40.0	215(4)	435(4)	865(4)			W. S. Shamban Co. (7 mils thk.) (Improved quality)
E610-222 (Zitex)	2 to 5	1.0						Chemplast Inc.
E610-122D Bonded to a 40 x 40 Nickel Mesh Screen		1.0						Chemplast Inc. 5 mils thick.
H662-123 (1 Layer)		0.8						Chemplast Inc.
H622-123 (2 Layers)		1.5						Chemplast Inc.
Porous Polypropylene (Type SR * 256C)		500	192(4)	386(4)	775(4)			Celanese Plastics Co. 0.9 mil thick.
E606-223/35 (Zitex)		3.0						Chemplast Inc.
E606-223/5.0 (Zitex)		3.25						Chemplast Inc.
E606-222/5.0 (Zitex)		4.00						Chemplast Inc. (Zitex)
Armalon (Type 403G-108)		3.0						duPont; Teflon coated glass fabric; 3 mils thick.
Armalon (Type 405A-112)		3.0						duPont; Teflon coated glass fabric; 5 mils thick.
Armalon (Type 408-128SC)		2.5						duPont; Teflon coated (one side) on glass fabric; 8 mils thick.
Armalon (Type 95-502)		0.5						duPont; Teflon coated glass fabric: 27 mils thick.

NOTES:

(1) Converted flow data from Figures 27 thru 45 of Lockheed Missiles and Space Co., Sunnyvale, Calif., Report No. NASA CR-66922, dated 5/18/70, for Contract NAS1-8228.

(2) After applying a light water film to one side of material and applying air pressure above this film, observe for first water indication on other side of material. Converted data from Tables 5 and 7 of Lockheed Missiles and Space Co., Sunnyvale, Calif., Report No. NASA CR-66922, dated 5/18/70, for Contract NAS1-8228.

(3) Airflow magnitude/H_2 flow magnitude.

(4) H_2 flow magnitude.

TABLE IX

ANION EXCHANGE RESIN DATA (DEIONIZER)

(Illinois Water Treatment Co. Specification IWT-A-204G)

This is an intermediate base, high capacity anion exchange resin. This resin is manufactured in granular form. It is shipped in 2 ft^3 bags or 7 ft^3 fiber drums in a partially dried form.

<u>Chemical and Physical Properties</u>

Ionic Form Supplied	Hydroxide Form
Moisture Content	53 to 57%
Shipping Weight	17 lb/ft^3
Total Anion Exchange Capacity	2.50 meq/ml - based on $SO_4^=$ form 7.40 meq/dry gm - based on $SO^{4=}$ form
Economical Usable Exchange Capacity	20 to 25 kg/ft^3, $CaCO_3$ equivalent
Effective Size	0.4 to 0.7 mm
Screen Grading	14 to 50 mesh U.S. Standard screens
Hydraulic Expansion	see below

Hydraulic Expansion

Upflow Rate, gpm/ft^2	% Expansion at 70°F
2	22
3	45
4	68
6	110

Pressure Drop

Flow Rate, gpm/ft^2	Pressure Drop, psi/ft of bed depth
4	0.45
5	0.58
6	0.70

Swelling	8% from OH^- to Cl^- form
Regeneration Levels	3 to 5 lb $NaOH/ft^3$ - 4 to 6% by wt. 5 to 7 lb Na_2CO_3/ft^3 - 5 to 7% by wt.
Solubility	Insoluble in acids, bases and all common organic solvents
Usable pH Range	0 to 8.5
Service Flow Rate	1 to 2.5 gpm/ft^3 for water treatment
Regenerant Flow Rate	0.5 to 1.0 gpm/ft^3

TABLE IX (Cont'd.)

ANION EXCHANGE RESIN DATA (DEIONIZER)

(Illinois Water Treatment Co. Specification IWT-A-204G)

Chemical and Physical Properties

Rinse Flow Rate	0.5 to 2.0 gpm/ft^3
Rinse Volume	50 to 80 gal/ft^3
Maximum Operating Temperature	130°F in hydroxyl cycle

TABLE X

CATION EXCHANGE RESIN DATA (DEIONIZER)

(Illinois Water Treatment Co. Specification ILLCO-C-211)

This is a cation exchange resin, manufactured in bead-like particles from styrene and divinylbenzene. The active exchange group (sulfonic) is added after polymerization of the bead by sulfonation.

Chemical and Physical Properties

Ionic Form Supplied	Sodium Form. Hydrogen form can also be supplied.
Moisture Content	45 to 50%
Shipping Weight	53 lb/ft^3
Cation Exchange Capacity	Minimum of 2.0 meq/ml - based on sodium form - 4.5 meq/dry gm.
Economical Usable Exchange Capacity	10 to 25 kg/ft^3, $CaCO_3$ equiv.
Effective Size	0.45 to 0.60 mm
Screen Grading	16 to 50 mesh (wet) U.S. Std. screens
Hydraulic Expansion	see below
Pressure Drop	see below
Swelling	7% from Na^+ to H^+ form
Regeneration Levels	2.5 to 20 lb 66° Be' H_2SO_4/ft^3 -2 to 10% by wt. 5 to 30 lb 30% HCl/ft^3 - 5 to 10% by wt. 4 to 15 lb $NaCl/ft^3$ - 10% by wt.
Solubility	Insoluble in acids, bases, and all common organic solvents
Usable pH Range	1 to 14

Hydraulic Expansion

Upflow Rate, gpm/ft^2	% Expansion at 70°F
2	12
4	33
6	54
8	75

Pressure Drop

Flow Rate, gpm/ft^2	Pressure Drop, psi/ft of bed depth
4	0.40
6	0.65
8	0.82
10	1.10

TABLE X (Cont'd.)

CATION EXCHANGE RESIN DATA (DEIONIZER)

(Illinois Water Treatment Co. Specification ILLCO-C-211)

Chemical and Physical Properties

Service Flow Rate	1 to 50 gpm/ft^2 for water treatment
Regenerant Flow Rate	0.50 to 1.5 gpm/ft^3
Rinse Flow Rate	0.50 to 1.5 gpm/ft^3
Rinse Volume	50 to 75 gal/ft^3
Maximum Operating Temperature	250°F
Cross-linkage	8% divinylbenzene

TABLE XI

ANION EXCHANGE RESIN DATA (BIOLOGICAL FILTER)

(Illinois Water Treatment Co. Specification IWT-A-704A)

Type		Strong base
Structure		Macroporous styrene divinylbenzene matrix
Ionic form		Hydroxide
Physical form		Spheres
Standard mesh		20-50
Usable pH range		0-8.5
Solubility		Insoluble in acids, bases, and all common organic solvents
NH_3 exchange capacity		0.56
SO_4 exchange capacity		3.46
Total ion exchange capacity		4.02 meq/gm
Moisture holding capacity		72%
Skeletal density		1.203 g/cc
Apparent density		0.555 g/cc
Copolymer swelling ratio (ethylene dichloride)		2.75
Microanalysis	% Cl	13.0
	% N	5.5
Surface area		7.3 m^2/g
Radius at max pore volume		70,000 Å
Pore radius range		25,000-250,000 Å

Columnar Removal of Colloidal Silica From Water

Flow Rate	2 gpm/ft^3
Temperature	50°C
Bed Volume	50 ml
Breakpoint	1 ppm total SiO_2

Influent Conc. in ppm Colloidal SiO_2	Bed Volume Thruput
2.4	1234
5.2	490
10	35

TABLE XII

CATION EXCHANGE RESIN DATA (BIOLOGICAL FILTER)

(Illinois Water Treatment Co. Specification IWT-C-381)

This is a macroreticular sulfonic type cation exchange resin.

Chemical and Physical Properties

Ionic Form Supplied	Sodium form. Hydrogen form can also be supplied.
Moisture Content	47 to 53%
Shipping Weight	50 lb/ft^3
Cation Exchange Capacity	1.80 meq/ml, Na^+ form, 4.30 meq/dry gm
Economical Usable Exchange Capacity	10 to 20 kg/ft^3, $CaCO_3$ equivalent
Effective Size	0.4 to 0.5 mm
Screen Grading	16 to 50 mesh (wet) - U.S. Standard screens
Hydraulic Expansion	

Upflow Rate, gpm/ft^2	% Expansion at 70°F
2	5
4	25
6	45
8	60
10	80

Pressure Drop

Flow Rate, gpm/ft^2	Pressure Drop, psi/ft of bed depth
2	0.1
4	0.2
6	0.4
8	0.5
10	0.7

Swelling	5% from Na^+ to H^+ form
Regeneration Levels	2.5 to 20 lb 66° Bé H_2SO_4/ft^3 - 2 to 10% by wt. 5 to 30 lb 30% HCl/ft^3 - 5 to 10% by wt. 4 to 15 lb $NaCl/ft^3$ - 10% by wt.
Solubility	Insoluble in acids, bases, and all common organic solvents
Usable pH Range	1 to 14

TABLE XII (Cont'd.)

CATION EXCHANGE RESIN DATA (BIOLOGICAL FILTER)

(Illinois Water Treatment Co. Specification IWT-C-381)

Chemical and Physical Properties

Service Flow Rate	1 to 50 gpm/ft^3 for water treatment
Regenerant Flow Rate	0.50 to 1.5 gpm/ft^3
Rinse Flow Rate	0.50 to 1.5 gpm/ft^3
Rinse Volume	50 to 75 gal/ft^3
Maximum Operating Temperature	250°F

TABLE XIII

SUMMARY OF COMPUTER CASE STUDIES FOR ELECTROLYSIS SYSTEM

Computer Case No.	Coolant (See Code Below)	Fraction of Pump Flow Bypassing Regen H/E	Process Water (Pump) Flow Rate, lb/hr	Primary H/E Coolant Inlet Temp., °F	Gas Generation Rates			Electrolysis Module Input Current, amp	Power Conditioner Input, kw
					Oxygen, lb/day	Oxygen, lb/hr	Hydrogen, lb/hr		
103	TW	0.75	22	75	15.33	0.639	0.0804	75.0	2.22
114	PG	0.68	22	36	15.33	0.639	0.0804	75.0	2.22
115	PG	0.80	22	44	15.33	0.639	0.0804	75.0	2.22
132	PG	0.6	10.6	36	10.00	0.417	0.0524	49.1	1.44
143	PG	0.45	10.6	40	6.67	0.278	0.0350	32.8	0.98
145	PG	0.18	10.6	40	3.33	0.139	0.0175	16.6	0.53

Coolant Code: TW - Tap Water
PG - Propylene glycol - water (40-60 pct by weight)

TABLE XIV

COMPARISON OF DESIGN COOLING CRITERIA AND REQUIREMENTS FOR GE/DECP AND NASA/LRC FACILITIES FOR ELECTROLYSIS SYSTEM TESTING (1)

Facility	Computer Case	Coolant	Freezing Point, °F	Coolant Inlet Temp, °F	Coolant Flow Rate, pph	Process Outlet Temp (Primary H/E), °F	Electrolysis Module Temperatures, °F Inlet (3)	Electrolysis Module Temperatures, °F Outlet	Primary Heat Exchanger Capacity, UA (4)	Regenerative Heat Exchanger Capacity, UA	Fraction of Pump Flow Bypassing the Regenerative H/E
NASA/LRC	115	Propylene-glycol-water 40-60% (2)	-5	44	150	83.9	107.2	147.4	20 B/hr-°F	80 B/hr-°F	0.80
GE/DECP	103	Filtered tap water	32	75	150	80.1	106.9	147.2	60	80	0.75

NOTES:

(1) The primary heat exchanger design was based on the maximum power input conditions of 75 amp input to the electrolysis module.

(2) A 37-63% propylene glycol-water mixture gives a 0°F freezing point. The 40-60% mixture was selected for a conservative design and to avoid interpolation of available property data.

(3) The values of the electrolysis module inlet and outlet temperatures are typical, and are those corresponding to the computer calculations. The water temperature control valve will cause the module inlet temperature to vary from 98 to 110°F, depending on the operating conditions and valve hysteresis effects.

(4) The heat exchanger capacity is the product of the overall heat transfer coefficient between the two heat exchanger fluids and the total heat exchanger surface area.

TABLE XV

WATER TEMPERATURE REGULATING VALVE SPECIFICATION

1. Functional Description: The water temperature regulating valve mixes the process water which is heated by the regenerative heat exchanger with water bypassing the same heat exchanger. The water temperature regulating valve provides an essentially constant mixing temperature over the range of operating conditions.

2. Mechanical Description: The water temperature regulating valve consists of a sleeve mixing valve actuated by a eutectic wax linear actuator. The proprietary wax mixture that is selected for the actuator causes the actuator to be linear for a total temperature range of 20°F over approximately 80% of the total travel. Only a travel corresponding to 8-10°F is selectdd to produce full heated flow or full bypass flow.

3. Weight: 1.6 lb (max)

4. Port Configuration: MS33649-8.

5. Mounting Provisions: The water temperature regulating valve will be surface mounted.

6. Predominant Materials: All parts in contact with the fluid will be AISI 316 or 17-4 PH stainless steel and compatible elastomeric compounds. The wax in the linear actuator is completed sealed by a compressed elastomeric seal.

7. Performance Requirements:

Maximum hot flow at not less than 97°F

Maximum cold flow at not less than 107°F

Total water flow rate	0.85-33 lb/hr
Pressure loss	less than 0.25 psid
Nominal working pressures	60-65 psia
Fluid temperatures	40-110°F
Leakage	Zero external leakage
Proof pressure	140 psig
Burst pressure	280 psig

8. Life: Life of 2 years including 5514 temperature cycles.

TABLE XVI

PROCESS WATER PUMP SPECIFICATION

1. Functional Description: To provide circulation of the make-up and process water in the electrolysis subsystem. A portion of the water circulated is lost due to either electrolysis of water or to saturate the effluent gases. The remaining water which is circulated by the pump is utilized as the principal medium for cooling the electrolysis module.

2. Mechanical Description: The pump shall be a positive displacement, self-priming type with an induction motor. The pump shall incorporate a bypass pressure relief valve to prevent operation of the pump at an excessive differential pressure.

3. Weight: 3.75 lb (max).

4. Port Configuration: 1/8 NPT female ports.

5. Mounting Provisions: The pump assembly shall be supported principally by a motor bracket.

6. Predominant Materials: The water pumped by this component will be exposed to the following materials: AISI 316 stainless steel, polypropylene or Delrin AF (gears and hydrodynamic bearings), barium ferrite (magnetic drive), and silicone rubber or Viton A elastomeric seals.

7. Electrical Requirements: 70 watts, 208 volts, 3 phase, 400 Hz, with neutral ground.

8. Performance Requirements: 0.85 to 33 lb/hr.

9. Working Fluid: Potable Water.

10. Allowable Leakage:

External

No external leakage

Internal

Bypass relief valve 1 cc/min

11. Normal Working Fluid Pressures:

Pump inlet pressure	14.7 to 24.7 psia
Pump pressure rise	27 to 39.5 psid
Normal working fluid temperatures	40 to 100°F

TABLE XVI (Cont'd.)

PROCESS WATER PUMP SPECIFICATION

12. Internal Relief: A bypass relief valve shall prevent the pumping elements from exceeding a differential pressure of 45 psid.

13. Proot Pressure: 140 psig

14. Burst Pressure: 280 psig

15. Duty Cycle: 5514 cycles of operation for 55 minutes and shutdown for 39 minutes (94 minute orbit) for 180 day (4320 hr) mission.

16. Reliability: Life of 2 years.

TABLE XVII

WATER FLOW VALVE SPECIFICATION

1. Functional Description: The water flow valve is connected at the outlet of the process water pump to maintain an essentially constant process water flow rate.

2. Mechanical Description: The water flow valve maintains a constant flow by regulating the pressure drop $\geq$ 5 psid across an external adjustable orifice. The water flow valve maintains the flow within ± 5% of the set point with $\geq$ 5 psid pressure loss.

3. Weight: 1.3 lb (max).

4. Port Configuration: MS 33649-4.

5. Mounting Provisions: The water flow valve will be line mounted.

6. Predominant Materials: AISI 304 stainless steel and silicone or Viton "A" elastomeric seals.

7. Performance Requirements:

    Flow Rate: 0.85 to 33 lb/hr.

    Adjustable to within ± 10% of set point at min flow rate and to within ± 5% of set point at high flow rate.

    Pressure Loss: 10 psid (max)

8. Working Fluid: Potable water.

9. Allowable Leakage: No external Leakage.

10. Normal Working Fluid Conditions:

Inlet Pressure:	69 psia (max)
Temperature:	40 - 100°F

11. Proof Pressure: 140 psig

12. Burst Pressure: 280 psig

13. Duty Cycle: 5514 cycles of operation for 55 minutes and shutdown for 39 minutes (94 minute orbit) for 180 days.

14. Reliability: Useful life - 2 years.

TABLE XVIII

HYDROGEN ABSOLUTE BACK-PRESSURE REGULATOR SPECIFICATION

1. Functional Description: To establish a controlled pressure level on the hydrogen discharge side of a hydrogen-water separator assembly.

2. Mechanical Description: Spring-loaded evacuated bellows (aneroid) with resilient material seat.

3. Weight: 1.25 lb max.

4. Port Configuration: MS 33649-4 inlet and outlet ports.

5. Electrical Interfaces: None.

6. Mounting Provisions: In-line tubing installed.

7. Predominant Materials: 17-7 PH and 316 SST: Viton "A" and/or unfilled silicone seal material.

8. Max. Overall Envelope Dimensions: 1.56 in. dia. x 2.50 in. long.

9. Performance Requirements: With 60 to 80°F mixture of hydrogen and water vapor supplied to the inlet, the upstream cracking pressure shall be 40 to 41 psia independent of the downstream pressure. The regulator shall be capable of controlling the upstream pressure to 41 to 42 psia, when passing a 60 to 80°F saturated mixture of 0.0194 to 0.220 lb/hr of hydrogen independent of the downstream pressure. The regulator shall reseat (shut off hydrogen flow) at 39 psia minimum.

10. Working Fluid: Hydrogen and water vapor.

11. Allowable Leakage Rate: No internal leakage after the reseating condition has been reached; no external leakage. Note: Redundant seals shall be provided for all external hydrogen leak paths except on inlet and outlet "MS" ports.

12. Downstream Working Fluid Pressures: Min. 0 psia; max. 20 psia; normal 14.7 psia.

13. Upstream Working Fluid Temperature: Min. 60°F; max. 80°F; nominal 70°F.

14. Proof Pressure: 84 psig.

15. Burst Pressure: 168 psig.

16. Temperature Environment Requirements: 40 to 140°F.

17. Continuous Mission Rate Duty: Steady-state flows for 6 months varied within a hydrogen range of 0.0194 to 0.220 lb/hr of 80°F saturated.

18. Cyclic Mission Rate Duty: 5514 cycles of hydrogen/water vapor flow "on and off", i.e., one cycle equals 55 min. of 80°F saturated hydrogen "on" flow time at 0.220 lb/hr and 39 min. of no flow.

19. Reliability: Useful life - 2 years.

TABLE XIX

OXYGEN ABSOLUTE BACK-PRESSURE REGULATOR SPECIFICATION

1. Functional Description: To establish a controlled pressure level on the oxygen discharge side of a water electrolysis subsystem.

2. Mechanical Description: Spring-loaded evacuated bellows (aneroid) with resilient material seat.

3. Weight: 1.25 lb max.

4. Port Configuration: MS 33649-4 inlet and outlet ports.

5. Electrical Interfaces: None.

6. Mounting Provisions: In-line tubing installed.

7. Predominant Materials: 17-7 PH and 316 SST; Viton "A" and/or unfilled silicone seal material.

8. Max. Overall Envelope Dimensions: 1.56 in. dia. x 2.50 in. long.

9. Performance Requirements: With 100 to 170°F mixture of oxygen and water vapor supplied to the inlet, the upstream cracking pressure shall be 61 to 62 psia independent of the downstream pressure. The regulator shall be capable of controlling the upstream pressure to 62 to 63 psia, when passing a 100 to 170°F saturated mixture of 0.154 to 1.750 lb/hr of oxygen independent of the downstream pressure. The regulator shall reseat (shut off oxygen flow) at 60 psia minimum.

10. Working Fluid: Oxygen and water vapor.

11. Allowable Leakage Rate: No internal leakage after the reseating condition has been reached. No external leakage.

12. Downstream Working Fluid Pressures: Min. 0 psia; max. 36 psia; normal 14.7 psia.

13. Upstream Working Fluid Temperature: Min. 100°F; max. 170°F; nominal 143°F.

14. Proof Pressure: 126 psig.

15. Burst Pressure: 252 psig.

16. Temperature Environment Requirements: 40 to 110°F.

17. Continuous Mission Rate Duty: Steady-state flows for 6 months varied within an oxygen range of 0.154 to 1.750 lb/hr at 170°F saturated.

18. Cyclic Mission Rate Duty: 5514 cycles of oxygen/water vapor flow "on and off", i.e., one cycle equals 55 min. of 170°F saturated oxygen "on" flow time at 1.75 lb/hr and 39 min. of no flow.

19. Reliability: Useful life - 2 years.

TABLE XX

H_2-H_2O DIFFERENTIAL BACK-PRESSURE REGULATOR SPECIFICATION

1. Functional Description: To establish a controlled pressure level on the water discharge side of a hydrogen-water separator assembly.

2. Mechanical Description: Spring-loaded bellows (aneroid) referenced to a set pressure and with resilient material seat.

3. Weight: 1.50 lb max.

4. Port Configuration: MS 33649-4 inlet, outlet and reference ports.

5. Electrical Interfaces: None.

6. Mounting Provisions: In-line tubing installed.

7. Predominant Materials: 17-7 PH and 316 SST, Viton "A" and/or unfilled silicone seal material.

8. Max. Overall Envelope Dimensions: 1.56 in. dia. x 3 in. long.

9. Performance Requirements: With 60 to 80°F water supplied to the inlet along with a supplied referenced pressure, the upstream water cracking pressure shall be 1.5 to 3.5 psi below any set referenced pressure up to 42 psia and be independent of the downstream water pressure. The regulator shall be capable of controlling the upstream water pressure 1.5 to 3.5 psi below a set reference pressure of 39 to 42 psia when passing 60 to 80°F water of 25 to 45 lb/hr and be independent of the downstream water pressure.

10. Working Fluid: Water and hydrogen reference gas.

11. Allowable Leakage Rate: No internal leakage after the reseating condition has been reached; no external leakage. Note (1): Redundant seals shall be provided for all external hydrogen leak paths except on reference "MS" port. Note (2): Redundant seals shall be provided for all internal hydrogen-to-water side leak paths.

12. Downstream Working Fluid Pressures: Min. 0 psia, max. 24.7 psia; normal 16 psia.

13. Upstream Working Fluid Temperature: Min. 60°F, max. 80°F, nominal 70°F.

14. Proof Pressure: 84 psig.

15. Burst Pressure: 168 psig.

16. Temperature Environment Requirements: 40 to 110°F.

17. Continuous Mission Rate Duty: Steady-state flows for 6 months varied within a water range of 25 to 45 lb/hr at 80°F and with a reference pressure of 42 psia.

18. Cyclic Mission Rate Duty: 5514 cycles of water flow "on and off", i.e., one cycle equals 55 min. of 90°F water "on" flow time at 45 lb/hr and with a reference pressure of 42 psia and 39 min. of no flow.

19. Reliability: Useful life - 2 years.

SECTION 6. APPENDIX

HEAT TRANSFER STUDY DATA

TABLE XXI

WES*2 CASE 103

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO.CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.777	VOLTS
MODULE TERM VOLTAGE	23.1	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	74.99	AMP
DESIGN CURRENT DENSITY	323.8	ASF
PERM LOSS(EQUIV J)	1.41	ASF
OPERATING CURRENT DENSITY	325.2	ASF
ELECT MOD TEMP RISE	40.3	DEG F
MEAN CELL TEMP	127	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	1021.4	B/HR
MOD HEAT LOSS TO CABIN	76.75	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.639	LB/HR
OXYGEN PRODUCTION(LB/DAY)	15.33	
OXYGEN HEAT LOSS RATE	14	B/HR
O2 END PLATE HEAT LOSS RATE	1.74	B/HR
HYDROGEN FLOW RATE	0.0804	LB/HR
WATER PUMPING RATE	22	LB/HR
WATER SUPPLY RATE	0.733	
REGEN H/E EFFECT	1	
C(COLD) 5.5		B/HR-DEG F
C(HOT) 22.4		B/HR-DEG F
HEAT TRANS RATE	283	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	16.5	LB/HR
BYPASS FLOW RATIO	0.75	
H/E EFFECT WITH BYPASS CORR	0.25	
PRIM H/E EFFECT	0.914	
SPECIFIC HEAT OF COOLANT	1	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 22.104		B/HR-DEG F
HEAT TRANS RATE	1211.3	B/HR
HEAT TRANS FACTOR	60	B/HR-DEG F
POWER COND EFF(MIN)	0.812	
MAX CURRENT	84.06	AMP
HEAT GENERATION RATE	1368	B/HR
POWER COND LOSS, WATTS	400.8	
REG POWER FOR CONTROL(28VDC)	0.15	
POWER INPUT(MAX)	2.221	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL,PCT	10.7	

WEIGHT AND PENALTY SUMMARY

TOTAL CELL WEIGHT	5.4	
END PLATE WEIGHT	7.8	
MISC HARDWARE WT	5.3	
INSULATION WT	1.2	
STK COVER & SUPPORT	3.2	
OVERALL ELEC MOD DIAM	10.14	
OVERALL LENGTH	4.21	
TOT ELEC MOD WT	23	
POWER COND WT	10	
ELEC MODULE VOL	340.4	
POWER COND VOL	170	
CELL STK HEIGHT	1.56	
END PLATE & B.C. DIAM	8.94	7.78
END PLATE THICKNESS	0.727	
INSULATION THICKNESS	0.6	
INSULATION VOLUME	151.1	
WEIGHT PENALTIES		
REGULATED POWER	1312.4	
COOLANT LOOP	139.3	
CABIN HEAT REJECTION	11.6	
TOT PENALTY(3 MOD)	1562.3	

OPERATING CONDITIONS AT VARIOUS STATIONS

Reference Figure 37

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	WATER*MASS*FLOW VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.73				
PUMP	1	13.7	79.9		22.00				
REGEN H/E	5	53.0	93.5		22.00				
REGEN MIX	6	52.0	147.2		5.50				
ELEC MOD	7	51.0	106.9		22.00				
REGEN H/E	8	49.0	147.2		21.22	.0547		16.460	3.148
PRIM H/E	10	48.0	134.9		21.23	.0400		16.196	2.861
PHASE SEP	11	46.0	80.1		21.27	.0080		14.843	2.193
H2 REG	13	41.5	80.1	77.0	.00	.0080	.902		
	14	14.7	80.1	47.6	.00	.0080	.320		
		25.0	80.1	62.2	.00	.0080	.543		
O2 REG	15	62.5	115.0	103.0	.00	.0061	.707		
	16	14.7	127.0	58.7	.00	.0061	.119		
		25.0	127.0	74.0	.00	.0061	.202		
PRIM H/E	20		75.0		150.00				
COLD PLATE	21		83.1		150.00				
	22		95.6		150.00				

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO.CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.775	VOLTS
MODULE TERM VOLTAGE	23.08	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	74.99	AMP
DESIGN CURRENT DENSITY	323.8	ASF
PERM LOSS(EQUIV J)	1.43	ASF
OPERATING CURRENT DENSITY	325.3	ASF
ELECT MOD TEMP RISE	39.9	DEG F
MEAN CELL TEMP	128	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	1015.9	B/HR
MOD HEAT LOSS TO CABIN	78.22	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.639	LB/HR
OXYGEN PRODUCTION(LB/DAY)	15.33	
OXYGEN HEAT LOSS RATE	14.42	B/HR
O2 END PLATE HEAT LOSS RATE	1.73	B/HR
HYDROGEN FLOW RATE	0.0804	LB/HR
WATER PUMPING RATE	22	LB/HR
WATER SUPPLY RATE	0.733	
REGEN H/E EFFECTIVENESS	0.9997	
C(COLD) 7.04		B/HR-DEG F
C(HOT) 22.741		B/HR-DEG F
HEAT TRANS RATE	416.1	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	14.96	LB/HR
BYPASS FLOW RATIO	0.68	
H/E EFFECT WITH BYPASS CORR	0.32	
PRIM H/E EFFECTIVENESS	0.5758	
SPECIFIC HEAT OF COOLANT	0.89	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 22.038		B/HR-DEG F
HEAT TRANS RATE	1191.4	B/HR
HEAT TRANS FACTOR	20	B/HR-DEG F
POWER COND EFF(MIN)	0.812	
MAX CURRENT	83.99	AMP
HEAT GENERATION RATE	1368.1	B/HR
POWER COND LOSS, WATTS	400.9	
POWER INPUT(MAX)	2.219	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL, PCT	10.7	

OPERATING CONDITIONS AT VARIOUS STATIONS
REFERENCE FIGURE 37

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.73				
PUMP	1	13.7	75.8		22.00				
REGEN H/E	5	53.0	89.3		22.00				
REGEN MIX	6	52.0	148.0		7.04				
ELEC MOD	7	51.0	108.1		22.00				
REGEN H/E	8	49.0	148.0		21.22	.0559		16.505	3.172
PRIM H/E	10	48.0	129.9		21.24	.0348		15.965	2.755
PHASE SEP	11	46.0	75.8		21.27	.0070		14.712	2.170
H2 REG	13	41.5	75.8	72.8	.00	.0070	.902		
	14	14.7	75.8	43.9	.00	.0070	.320		
		25.0	75.8	58.2	.00	.0070	.543		
O2 REG	15	62.5	116.1	104.4	.00	.0063	.713		
	16	14.7	128.0	59.8	.00	.0063	.121		
		25.0	128.0	75.2	.00	.0063	.205		
PRIM H/E	20		36.0		150.00				
COLD PLATE	21		43.9		150.00				
	22		53.1		150.00				

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO.CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.777	VOLTS
MODULE TERM VOLTAGE	23.1	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	74.99	AMP
DESIGN CURRENT DENSITY	323.8	ASF
PERM LOSS(EQUIV J)	1.41	ASF
OPERATING CURRENT DENSITY	325.2	ASF
ELECT MOD TEMP RISE	40.2	DEG F
MEAN CELL TEMP	127.3	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	1020.1	B/HR
MOD HEAT LOSS TO CABIN	77.1	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.639	LB/HR
OXYGEN PRODUCTION(LB/DAY)	15.33	
OXYGEN HEAT LOSS RATE	14.1	B/HR
O2 END PLATE HEAT LOSS RATE	1.74	B/HR
HYDROGEN FLOW RATE	0.0804	LB/HR
WATER PUMPING RATE	22	LB/HR
WATER SUPPLY RATE	0.734	
REGEN H/E EFFECTIVENESS	1	
C(COLD) 4.4		B/HR-DEG F
C(HOT) 22.689		B/HR-DEG F
HEAT TRANS RATE	219.9	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	17.6	LB/HR
BYPASS FLOW RATIO	0.8	
H/E EFFECT WITH BYPASS CORR	0.2	
PRIM H/E EFFECTIVENESS	0.5739	
SPECIFIC HEAT OF COOLANT	0.89	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 22.153		B/HR-DEG F
HEAT TRANS RATE	1190.8	B/HR
HEAT TRANS FACTOR	20	B/HR-DEG F
POWER COND EFF(MIN)	0.812	
MAX CURRENT	84.04	AMP
HEAT GENERATION RATE	1368	B/HR
POWER COND LOSS,WATTS	400.8	
POWER INPUT(MAX)	2.22	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL,PCT	10.7	

OPERATING CONDITIONS AT VARIOUS STATIONS
REFERENCE FIGURE 37

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.73				
PUMP	1	13.7	83.6		22.00				
REGEN H/E	5	53.0	97.2		22.00				
REGEN MIX	6	52.0	147.4		4.40				
ELEC MOD	7	51.0	107.2		22.00				
REGEN H/E	8	49.0	147.4		21.22	.0550		16.471	3.154
PRIM H/E	10	48.0	137.7		21.23	.0432		16.328	2.923
PHASE SEP	11	46.0	83.9		21.27	.0091		14.961	2.216
H2 REG	13	41.5	83.9	80.7	.00	.0091	.902		
	14	14.7	83.9	50.9	.00	.0091	.320		
		25.0	83.9	65.7	.00	.0091	.543		
O2 REG	15	62.5	115.2	103.3	.00	.0061	.708		
	16	14.7	127.3	59.0	.00	.0061	.119		
		25.0	127.3	74.3	.00	.0061	.203		
PRIM H/E	20		44.0		150.00				
COLD PLATE	21		51.9		150.00				
	22		61.1		150.00				

TABLE XXIV

CASE 132

DESIGN POINT

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO. CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.704	VOLTS
MODULE TERM VOLTAGE	22.15	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	49.06	AMP
DESIGN CURRENT DENSITY	211.2	ASF
PERM LOSS(EQUIV J)	1.56	ASF
OPERATING CURRENT DENSITY	212.8	ASF
ELECT MOD TEMP RISE	38.7	DEG F
MEAN CELL TEMP	123.9	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	518.1	B/HR
MOD HEAT LOSS TO CABIN	72.25	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.417	LB/HR
OXYGEN PRODUCTION(LB/DAY)	10	
OXYGEN HEAT LOSS RATE	9.34	B/HR
O2 END PLATE HEAT LOSS RATE	1.09	B/HR
HYDROGEN FLOW RATE	0.0524	LB/HR
WATER PUMPING RATE	10.6	LB/HR
WATER SUPPLY RATE	0.475	
REGEN H/E EFFECTIVENESS	1	
C(COLD) 4.24		B/HR-DEG F
C(HOT) 10.923		B/HR-DEG F
HEAT TRANS RATE	273.6	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	6.36	LB/HR
BYPASS FLOW RATIO	0.6	
H/E EFFECT WITH BYPASS CORR	0.4	
PRIM H/E EFFECTIVENESS	0.8381	
SPECIFIC HEAT OF COOLANT	0.89	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 10.514		B/HR-DEG F
HEAT TRANS RATE	723.1	B/HR
HEAT TRANS FACTOR	20	B/HR-DEG F
POWER COND EFF(MIN)	0.805	
MAX CURRENT	52.76	AMP
HEAT GENERATION RATE	901	B/HR
POWER COND LOSS, WATTS	264	
POWER INPUT(MAX)	1.438	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL, PCT	10.7	

OPERATING CONDITIONS AT VARIOUS STATIONS
REFERENCE FIGURE 37

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.48				
PUMP	1	13.7	50.4		10.60				
REGEN H/E	5	53.0	78.7		10.60				
REGEN MIX	6	52.0	143.3		4.24				
ELEC MOD	7	51.0	104.6		10.60				
REGEN H/E	8	49.0	143.3		10.09	.0321		22.294	3.043
PRIM H/E	10	48.0	118.1		10.11	.0162		21.218	2.551
PHASE SEP	11	46.0	49.3		10.12	.0018		19.104	2.076
H2 REG	13	41.5	49.3	46.5	.00	.0018	.902		
	14	14.7	49.3	21.9	.00	.0018	.320		
		25.0	49.3	33.5	.00	.0018	.543		
O2 REG	15	62.5	112.3	106.7	.00	.0044	.851		
	16	14.7	123.9	61.8	.00	.0044	.145		
		25.0	123.9	77.3	.00	.0044	.246		
PRIM H/E	20		36.0		150.00				
COLD PLATE	21		40.8		150.00				
	22		46.8		150.00				

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO.CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.665	VOLTS
MODULE TERM VOLTAGE	21.65	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	32.83	AMP
DESIGN CURRENT DENSITY	140.9	ASF
PERM LOSS(EQUIV J)	1.51	ASF
OPERATING CURRENT DENSITY	142.4	ASF
ELECT MOD TEMP RISE	20.8	DEG F
MEAN CELL TEMP	114.3	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	296.3	B/HR
MOD HEAT LOSS TO CABIN	58.26	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.278	LB/HR
OXYGEN PRODUCTION(LB/DAY)	6.67	
OXYGEN HEAT LOSS RATE	5.46	B/HR
O2 END PLATE HEAT LOSS RATE	0.39	B/HR
HYDROGEN FLOW RATE	0.035	LB/HR
WATER PUMPING RATE	10.6	LB/HR
WATER SUPPLY RATE	0.317	
REGEN H/E EFFECTIVENESS	0.9991	
C(COLD) 5.83		B/HR-DEG F
C(HOT) 10.655		B/HR-DEG F
HEAT TRANS RATE	270.3	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	4.77	LB/HR
BYPASS FLOW RATIO	0.45	
H/E EFFECT WITH BYPASS CORR	0.55	
PRIM H/E EFFECTIVENESS	0.8383	
SPECIFIC HEAT OF COOLANT	0.89	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 10.506		B/HR-DEG F
HEAT TRANS RATE	523.4	B/HR
HEAT TRANS FACTOR	20	B/HR-DEG F
POWER COND EFF(MIN)	0.799	
MAX CURRENT	34.3	AMP
HEAT GENERATION RATE	608.5	B/HR
POWER COND LOSS, WATTS	178.3	
POWER INPUT(MAX)	0.977	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL, PCT	10.7	

OPERATING CONDITIONS AT VARIOUS STATIONS
REFERENCE FIGURE 37.

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.32				
PUMP	1	13.7	50.3		10.60				
REGEN H/E	5	53.0	78.5		10.60				
REGEN MIX	6	52.0	124.6		5.83				
ELEC MOD	7	51.0	103.9		10.60				
REGEN H/E	8	49.0	124.6		10.27	.0128		13.863	2.645
PRIM H/E	10	48.0	99.4		10.28	.0062		13.333	2.327
PHASE SEP	11	46.0	49.6		10.28	.0012		12.554	2.077
H2 REG	13	41.5	49.6	46.9	.00	.0012	.902		
	14	14.7	49.6	22.2	.00	.0012	.320		
		25.0	49.6	33.8	.00	.0012	.543		
O2 REG	15	62.5	108.0	104.9	.00	.0028	.913		
	16	14.7	114.3	60.3	.00	.0028	.179		
		25.0	114.3	75.7	.00	.0028	.305		
PRIM H/E	20		40.0		150.00				
COLD PLATE	21		43.5		150.00				
	22		47.5		150.00				

ELECTROLYSIS SYSTEM PERFORMANCE SUMMARY

NO.CELLS	13	
ELEC MOD STKS IN PARALLEL	1	
CELL ACT AREA	33.2	SQ IN.
CELL DIAM(ACTIVE)	6.5	IN.
CELL VOLTAGE	1.614	VOLTS
MODULE TERM VOLTAGE	20.98	VOLTS
AVAIL MOD INPUT VOLTS	22	VOLTS
MODULE INPUT CURRENT	16.55	AMP
DESIGN CURRENT DENSITY	70.3	ASF
PERM LOSS(EQUIV J)	1.45	ASF
OPERATING CURRENT DENSITY	71.8	ASF
ELECT MOD TEMP RISE	6.7	DEG F
MEAN CELL TEMP	103.8	DEG F
SUBSYSTEM OPERATING MODE	CONTINUOUS	
HEAT GEN RATE	121.3	B/HR
MOD HEAT LOSS TO CABIN	43.11	B/HR
MOD HEAT LOSS FACTOR	1.447	B/HR-DEG F
OXYGEN OUT TEMP FACTOR	0.2	
OXYGEN FLOW RATE	0.139	LB/HR
OXYGEN PRODUCTION(LB/DAY)	3.33	
OXYGEN HEAT LOSS RATE	2.21	B/HR
O 2 END PLATE HEAT LOSS RATE	0.06	B/HR
HYDROGEN FLOW RATE	0.0175	LB/HR
WATER PUMPING RATE	10.6	LB/HR
WATER SUPPLY RATE	0.158	
REGEN H/E EFFECTIVENESS	0.9588	
C(COLD) 8.692		B/HR-DEG F
C(HOT) 10.571		B/HR-DEG F
HEAT TRANS RATE	262.7	B/HR
HEAT TRANS FACTOR	80	B/HR-DEG F
BYPASS FLOW RATE	1.91	LB/HR
BYPASS FLOW RATIO	0.18	
H/E EFFECT WITH BYPASS CORR	0.788	
PRIM H/E EFFECTIVENESS	0.8372	
SPECIFIC HEAT OF COOLANT	0.89	B/LB-DEG F
C(COLD) 150		B/HR-DEG F
C(HOT) 10.547		B/HR-DEG F
HEAT TRANS RATE	374.3	B/HR
HEAT TRANS FACTOR	20	B/HR-DEG F
POWER COND EFF(MIN)	0.79	
MAX CURRENT	16.32	AMP
HEAT GENERATION RATE	315.2	B/HR
POWER COND LOSS, WATTS	92.4	
POWER INPUT(MAX)	0.527	KW
NOM POWER SUPPLY VOLTAGE	28	VOLTS
SUPPLY VOLT TOL, PCT	10.7	

OPERATING CONDITIONS AT VARIOUS STATIONS

REFERENCE FIGURE 37.

COMPONENT	ENTRANCE STA	PRESS PSIA	TEMP DEG F	DEW POINT	WATER*MASS*FLOW LIQUID	VAPOR	REL HUM	VOL RATIO GAS/LIQ	MOL WT
CHK VALVE	0	14.7	74.0		.16				
PUMP	1	13.7	47.3		10.60				
REGEN H/E	5	53.0	75.5		10.60				
REGEN MIX	6	52.0	105.9		8.69				
ELEC MOD	7	51.0	100.4		10.60				
REGEN H/E	8	49.0	107.1		10.44	.0038		6.528	2.400
PRIM H/E	10	48.0	82.4		10.44	.0018		6.320	2.199
PHASE SEP	11	46.0	46.9		10.44	.0005		6.138	2.071
H2 REG	13	41.5	46.9	44.2	.00	.0005	.902		
	14	14.7	46.9	20.1	.00	.0005	.320		
		25.0	46.9	31.4	.00	.0005	.543		
O2 REG	15	62.5	101.8	100.4	.00	.0012	.960		
	16	14.7	103.8	56.5	.00	.0012	.213		
		25.0	103.8	71.7	.00	.0012	.361		
PRIM H/E	20		40.0		150.00				
COLD PLATE	21		42.5		150.00				
	22		44.6		150.00				