AIRCRAFT EQUIPMENT DIVISION

NASA CR-137689

REPORT

ELECTROCHEMICAL OXYGEN CONCENTRATOR AS AN OXYGEN COMPRESSOR

Contract NAS 2-7676

FINAL TECHNICAL REPORT

Prepared for

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

DIRECT ENERGY CONVERSION PROGRAMS
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GENERAL ELECTRIC

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Foreword

This is a final technical report under Contract NAS 2-7676 covering the total contract period of 21 June 1973 to 31 August 1975. The contract was granted by NASA Ames as a result of General Electric's proposal DE-315 responding to RFP No. 2-21096-2. The goal of the contract was to undertake research and development of a solid polymer electrolyte (SPE) electrochemical oxygen compressor for extra vehicular activity applications on spacecraft.

Effort has been made to use both English and SI units in the text in compliance with NASA publication NASA SP-7012 (1973), Library of Congress Card No. 72-600360. The reader will be familiar with most of the units except possibly for pressure. The units for pressure used here is the

mega Pascal (MPa), equal to $10^6 \quad \frac{\text{Newton}}{\text{Meter}^2}$

Personnel involved in this effort were:

P. D. Quattrone, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, California, the contract monitor.

Mr. Paul Chludzinski, Senior Chemical Engineer, General Electric Company, Direct Energy Conversion Programs, Lynn, Massachusetts, principal investigator responsible for the technical program, system design and testing.

Mr. Ivan Danzig, Chemical Engineer, GE/DECP, responsible for preliminary feasibility and parametric testing.

Mr. William Craft, Senior Mechanical Engineer, GE/DECP, responsible for computer programs and performance optimization studies.

Mr. Robert Jones, Electrical Engineer, GE/DECP, responsible for the design and construction of the ground support test rig and instrumentation.

Mr. Joseph Foley, Specialist - Electrode Development, GE/DECP, responsible for cell manufacture.

Mr. Ellsworth Gibson, Specialist - Responsible for cell manufacture and testing.

Overall program management was provided through May 1974 by Mr. Arnold P. Fickett, and from May 1974 by Mr. Lloyd Chapman, Managers of Engineering.

All test data are recorded in hard bound patent notebooks Numbers 123 and 124, which remain on file at General Electric/DECP.

SUMMARY

Summary

Previous investigators have shown that for EVA missions from spacecraft, a life support system composed of high pressure oxygen bottles is an attractive option provided that oxygen can be stored at about 6000 psi (42 MPa). This could possibly be supplied by a mechanical compressor. The attractive possibility of electrochemically compressing oxygen noiselessly and reliably prompted research and development of such an electrochemical device. Under this contract it was shown that the Solid Polymer Electrolyte (SPE) oxygen compressor is feasible up to generation pressures of 3000 psi (21 MPa). More development must be done to reliably seal multicell stacks, although single cells could be adequately sealed to 5000 psi (35 MPa).

An SPE compressor is composed of an ion exchange membrane containing catalytic electrodes on both sides. By applying electrical power across the electrodes, and introducing low pressure oxygen to the cathode, that oxygen is electrochemically reduced to water. On the electropositive anode the water is oxidized to oxygen at pressures limited only by mechanical strength of materials and diffusion losses in the membrane. The system uses no net water and requires no moving parts.

The General Electric compressor is based on the following components and approaches:

a) Solid Polymer Electrolyte (SPE). This is a cation exchange membrane produced by duPont Corporation and sold under the name of NAFION ®. It has good chemical compatibility and has exhibited capability of withstanding pressure differentials of 5000 psi (35 MPa).

b) Gasketless Sealing. Conventional elastomeric gaskets are probably inadequate for 6000 psi (35 MPa) seals unless very heavy hardware for each cell is used. Since the SPE is of itself an elastomer, a unique approach of metal-to-SPE seals has been borrowed from other GE programs and enlisted on this program. Seals up to 5000 psi (35 MPa) have been effected.

c) Porous Plate Cell Supports. Calculations have shown that for the membrane to withstand a pressure differential of 6000 psi (42 MPa), a support span of not more than 0.007 inch (.18 mm) was needed. It was decided that a porous plate would be the most reliable mechanical support. The intent through the contract was to obtain porous niobium (columbium) or very finely knit niobium woven screens. Because of supplier's limitations, the woven screen was not manufacturable. Another supplier declined to produce porous niobium, but did provide off-the-shelf porous tantalum which was used on the anode side. Porous titanium was used on the low pressure cathode because of its availability and uniformity. Back up screens were obtained from expanded metal screens, 5 Nb 7-6/0 which is a tight screen very difficult to manufacture.

d) Conductive Cooling. Cooling of electrochemical units is usually done in one of two ways:

1) Liquid cooling by a cartridge inserted between cells. This is difficult in the present application since the high pressure differentials tend to crush heat exchangers inserted in the stack.

2) Evaporative cooling. When one reactant stream has a high exhaust flow rate, water may be evaporated in the cell and the heat carried overboard. In this application, the feed stream is pure oxygen, a precious commodity, and would not be used in large excess of that pumped into the EVA tankage. Evaporative cooling was therefore not chosen.

Instead, the metal separator sheets between cells were designed to extend beyond the cells and dissipate heat by conduction from the cell to ambient by virtue of their being heat exchanger fins.

Other results of the program were:

a) A computer program defining the power of the system as a function of current density, temperature, pressure, membrane thickness and water content showed that for minimum power per stage, the cell should operate at 100 to 120°F and 100 to 125 amp/ft^2. Higher current density requires higher voltage, and higher temperature causes parasitic power (diffusional losses) to increase. The hardware was designed to operate at these optimum conditions and to handle pressures up to 10,000 psi (71 MPa) proof pressure.

b) Hardware incorporating hydraulic loading to effect gasketless sealing was built and tested to 6000 psi (42 MPa).

c) Metal-to-metal cathode side (feed side) leakage was only 10% of product output at 50 psi (3.5 MPa), which was judged adequate.

d) With the performance measured and the active area of the cell chosen at .05 ft^2 (46 cm^2), it was estimated that a single stage compressor to provide oxygen at a rate of .24 lb/hr (.1 kg/hr) at 3000 psi (21 MPa) would require about 100 cells and consume 500 to 600 watts. Each cell would run at 5 amp. The weight using standard type flanges, similar to the actual hardware used, would weigh about 100 lb (45 kg). If more sophisticated hemispherical end domes similar to those used on present aircraft oxygen concentrators were used, the weight might approach 20 to 30 lb (9-14 kg).

e) Laboratory cells using open screens and low contact pressure showed base line performance at 100 amp/ft^2 (107 ma/cm^2) of 0.77 volt. Theoretically the voltage would be .05 to .1 volt if the electrodes were reversible. When screens were pressed into the cathode, the voltage increased to 0.80 volt, showing a loss in effective area of about 20%. Such cells performed stably for the chosen life tests of about 7 hours at 107 ma/cm^2. At 214 ma/cm^2, performance was usually unstable with voltages exceeding 1.0 volt. Using porous titanium supports on the cathode, .8 volt was demonstrated as stable. Using the more dense porous tantalum, initial voltage was .9 volt, but not steady. This demonstrated the diffusion polarization of the denser tantalum.

f) Final design cells using porous plates under high contact load showed performance similar to the more ideal lab cells up to about 100 amp/ft^2 (107 ma/cm^2) but showed diffusion polarization above 100 amp/ft^2 (107 ma/cm^2). It was necessary to operate the cathode at 65 psia (4.6 MPa) to achieve performance of lab cells at 15 psia (.1 MPa), probably due to diffusional effects of tightly assembled cells.

g) Operating with the cathode feed saturated with water produced performance similar to dry cathode feed, but required frequent purging to prevent drowning and performance instability. In a real system, the humidity of the gas may have to be reduced below saturation and a continuous cathode purge provided. The majority of testing was done with dry cathode feed.

h) Long term performance stability for periods of 40 hours could be achieved up to generation pressures of 2500 psi (18 MPa), but at 3000 psi (21 MPa) performance deteriorated after about 10 hours. It was possible to achieve steady performance at 3000 psi for 9 hour intervals for 7 days when the cell was shut down overnight with the anode pressure remaining live. It was determined that the performance degradation was not caused by loss of current collector contact, but rather by drying the anode. It must be remembered that normal operation of a cationic compressor tends to pump water from anode to cathode. Intermittent shutdowns seemed to allow the cell to redistribute water to allow more ideal anode and cathode water concentrations for subsequent operation.

i) When cells are first made, they sometimes contain drowned cathode wetproofing, but not always. This tended to confuse some of the data, and made comparisons difficult. It was found that poor performing cells could be conditioned to run well by reverse electrolysis, that is by generating oxygen on the normal cathode, and generating hydrogen on the normal anode. This caused water which was drowning the cathode wetproofing to be quickly pumped to the non wetproofed (normal) anode. Once a cell was properly conditioned, it did not need further electrolysis later in life. If, for example, the cell was run to dryness, water could then be added to the anode whereupon normal resistance was reestablished. Excess water had to be purged from the cell to prevent cathode drowning, but good performance could subsequently be achieved.

j) There were three choices of cathode wetproofing all of which provided cells of comparable characteristics. The wetproofing layers were:

(1) General Electric LNP teflon wetproofing .007 inch (.18 mm) thick manufactured by GE/DECP.

(2) Chemplast Corporation teflon wetproofing DX201-122, .0025 inch (.061 mm) thick. This was later discontinued from that company's product line.

(3) Chemplast Corporation teflon wetproofing E846B-122D, .0025 inch (.06 mm) thick.

Cells were also run without wetproofing and in some cases performed well. In most instances the cathode drowned severely when water was added to the anode. In a practical design, wetproofing films would be needed on the cathode to make it more immune to liquid water in the system.

k) The diffusion loss of cells operating at pressures up to 4500 psi (31 MPa) agreed to that predicted by the computer to within ± 25%. Generally at 3000 psi (21 MPa) the diffusion current density was 15 amp/ft^2 (16 ma/cm^2). Since the cell was designed to operate at 100 amp/ft^2 (107 ma/cm^2) the resulting Faradaic efficiency was about 85%.

l) Cells made with .02 inch (.5 mm) thick SPE (for greater mechanical strength) proved to be far inferior to the standard .01 inch (.25 mm) thick membrane in performance. Again, this probably is because of the greater water gradient and more severe anode drying of the thicker cell. Highly saponified cells .02 inch (.5 mm) did not exhibit improved performance.

m) A cell made with higher water content (35-40%) proved to be too weak to withstand the clamping pressure of the hardware, resulting in tensile failure of the cell and short circuit.

n) A five cell stack was built and tested to 1500 psi (11 MPa). Faradaic efficiency was normal and the center cell, which was thermally most ideal, performed at about 0.1 volt better than the end cells which behaved like normal single cells. Investigation of this stack and others was limited by inability to seal reliably. The hardware was capable of sealing simulated cells (Aclar) in a five cell arrangement to 5000 psi (35 MPa), but five real cells in the same hardware would not seal. This remains the most severe problem of the compressor, and would require more effort to solve before the electrochemical compressor could become practical.

o) The final experiment under this contract resulted in a materials fire, doing major damage to the hardware. The cell being tested was a deviation from the norm in that it had current collector screens on both electrodes. It is believed that the cell operating at 3000 psi suffered a short circuit causing a spark and a leak across the membrane. High pressure oxygen filled the normally low pressure cathode and ignited the porous titanium support. Sparks issued from the hardware and plumbing causing materials errosion. It must be remembered that titanium was being used on the low pressure side because of its availability, low cost, and proper porosity. Titanium should not be considered as a material of construction in a practical system.

Discussion

An electrochemical oxygen compressor based on a solid polymer electrolyte (SPE) will have certain optimum operating conditions for minimum power. In order to qualitatively understand the trade-offs involved, let us look schematically at such a device shown in Figure 1. Low pressure oxygen is fed to the cathode (negative electrode) where it combines with a proton and electron to form water at pressure P_1 according to the reaction:

$$1/2\ O_2\ (P_1) + 2H^+ + 2e^- \longrightarrow H_2O\ (P_1) \qquad (1)$$

At the anode (positive electrode) the water formed in equation (1) is split into oxygen, protons, and electrons at pressure P_2 according to:

$$H_2O\ (P_2) \longrightarrow 2H^+ + 2e^- + 1/2\ O_2\ (P_2) \qquad (2)$$

Adding eq (1) and (2) provides

$$1/2\ O_2\ (P_1) \longrightarrow 1/2\ O_2\ (P_2) \qquad (3)$$

The overall reaction (eq 3) shows that in the system no net water is produced or consumed, but only that oxygen is transported from the cathode to the anode across the SPE (electrolyte) from one pressure to another. If both electrodes were reversible, then the work required would only be that required for theoretical isothermal compression of the oxygen, about 0.05 volt. Since neither electrode is reversible, the practical cell voltage is of the order of 0.7 to 1 volt, depending on current density.

The effect of various parameters on power are:

a) Current Density

Increasing current density causes increased electrode polarization and therefore requires higher power. If no other effects are considered, therefore, it is desirable to operate at low current density. The effects of pressure, however, require that reasonably high current densities be used.

b) Pressure

As the anode pressure increases; that is, the product oxygen pressure increases, some of the oxygen at the anode diffuses back to the cathode because of the pressure differential across the membrane. This amounts to a power loss since the back diffusing oxygen must be recycled back to the anode electrochemically. In other words, let us assume that a

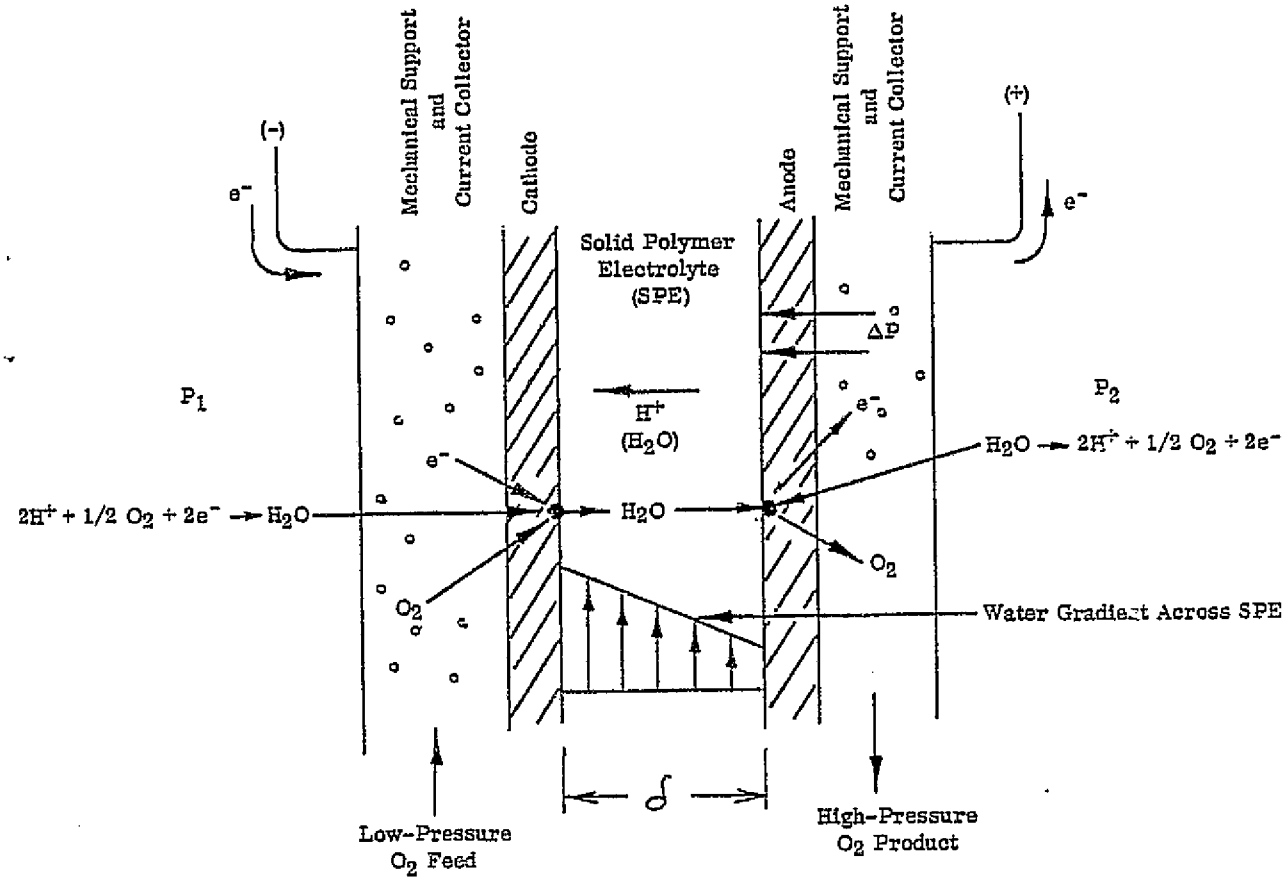


Figure 1. Representation of Electrochemical Oxygen Compressor

generation pressure of 6000 psi the back diffusion of oxygen amounts to 50 amp/ft^2 (ASF). If we operate the cell at a current density of 50 ASF, the anode pressure will be 6000 psi, but diffusion and generation will be equal, resulting in no net transport of oxygen out of the system. In order to create a useful steady state output of high pressure oxygen, the operating current density must be higher than the back diffusion oxygen flux. Therefore, current density and pressure trade-off to result in optimum Faradaic efficiency and minimum power.

c) Temperature

Electrode polarization decreases with increasing temperature, tending to decrease electrical power. However, the membrane permeability to gas increases with increasing temperature, causing back diffusion (parasitic power) to increase. An optimum temperature for minimum power therefore exists, high enough for good electrode performance, yet low enough for minimal back diffusion.

d) Membrane Water Content

High water content gives better ion mobility and therefore requires lower power. Again, however, the membrane permeability increases causing increased parasitic power. Optimum water contents will therefore exist for minimum power. A word about the interrelation of current density and water gradients is important here. As Figure 1 shows, protons flow from anode to cathode in proportion to current density. Protons have a high affinity for water molecules and tend to carry them away from the anode reaction sites, lowering the concentration of water at the anode. As the concentration of water decreases, the anode overvoltage increases, another reason for operation at low current density. A secondary effect also occurs; that is, the shifting of the water content (gradient) lowers diffusional losses.

e) Membrane Thickness

If the membrane thickness, δ, is increased, the ohmic losses increase (power increases), but the diffusional losses decrease. Optimum thickness of the SPE will therefore exist for minimum power.

In order to facilitate system trade-offs which involve many interrelated parameters, a computer program was devised which took into account the performance of the cell as a function of temperature, pressure, thickness, water content and current density. Provisions were made to assess the effects of parasitic losses as a function of these parameters also. The program was set up to evaluate power at various pressures to evaluate the effects of pressure staging.

Figure 2 shows the results of the computer program. Detailed computer output is included in Appendix A. Power optimizes at a current density of about 100 amp/ft^2 (107 ma/cm^2) at 100 F (38 C) for a .01 inch (.25 mm) thick SPE. This requires a total cell area of about 600 in^2 (3871 cm^2). The area can be divided among a number of cells, depending mostly on practical considerations. For example, the total area can be expressed as:

$$A = NA_c \qquad (4)$$

where A is the total area needed to transport oxygen at the required rate and current density.

N is the number of cells in the system.

A_c is the active area of a single cell.

Theoretically, N can equal unity, which results in a single large cell. In this case, the end plates which must support the entire generation pressure, regardless of the value of N, become enormously heavy. At the other extreme, N can be chosen as very large and A_c very small. In this case the end plates are smaller and lighter, but the cell stack core gets heavy because much of the area is taken up by seals which are electrochemically inactive. The computer program does not take into account the system weight versus N and A_c, but some selected hand calculations were made which showed that the stack core weight minimized at about 70 to 100 cells for a single stage compressor.

Other considerations lead to the choice of small cells. For example, thermal gradients along the membrane are minimized, and water transport from hot to cool regions are minimized, thereby achieving more uniform water content in the membrane.

Additional output from the program shows that a power decrease of 15% can be achieved if the membrane thickness is increased to .02 inch (.5 mm). Since most of the basic work in fuel cells and oxygen concentrators has been done with .010 in. (.25 min) SPE, it was used as a base line material in prototype hardware.

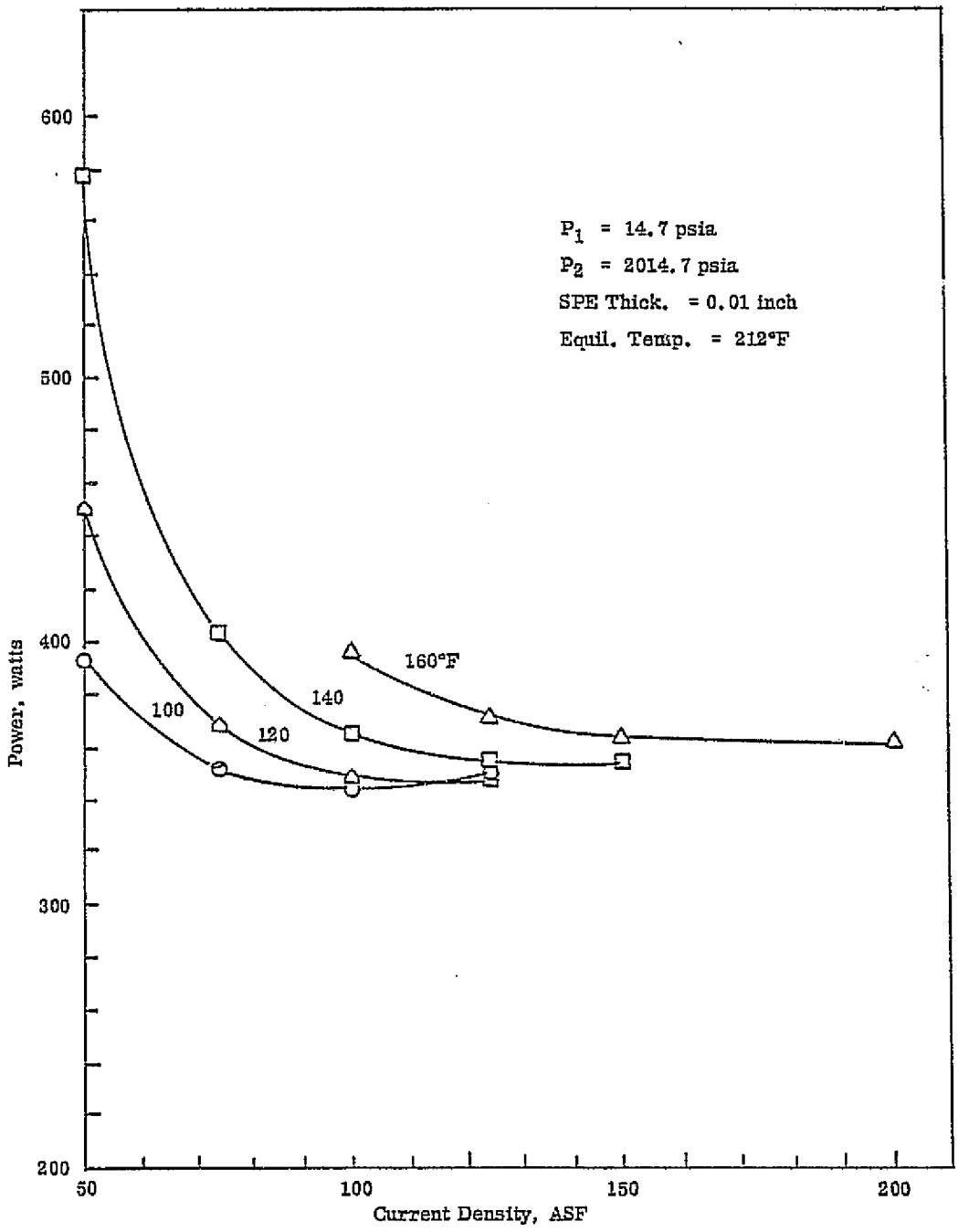


Figure 2. Power Optimization of Electrochemical Oxygen Compressor

Figure 3 shows the power per stage when compressing oxygen to 6000 psi (42 MPa). As the number of stages is increased, the power per stage decreases since the differential pressure across the SPE is lower in each stage and parasitic diffusional because of the need of pumping a constant mass of gas through successive stages. The ideal situation would be to use a single stage, pumping the gas only once, and avoiding successive inputs of power to overcome the irreversible electrochemical reactions in other successive stages. The limitation in achieving single-stage operation, of course, depends on the ability of the SPE to withstand the pressure differential. Hardware was designed to determine the upper mechanical limit of the SPE; that is, the proof pressure was chosen at 10,000 psi (72 MPa) and the burst at 15,000 psi (106 MPa).

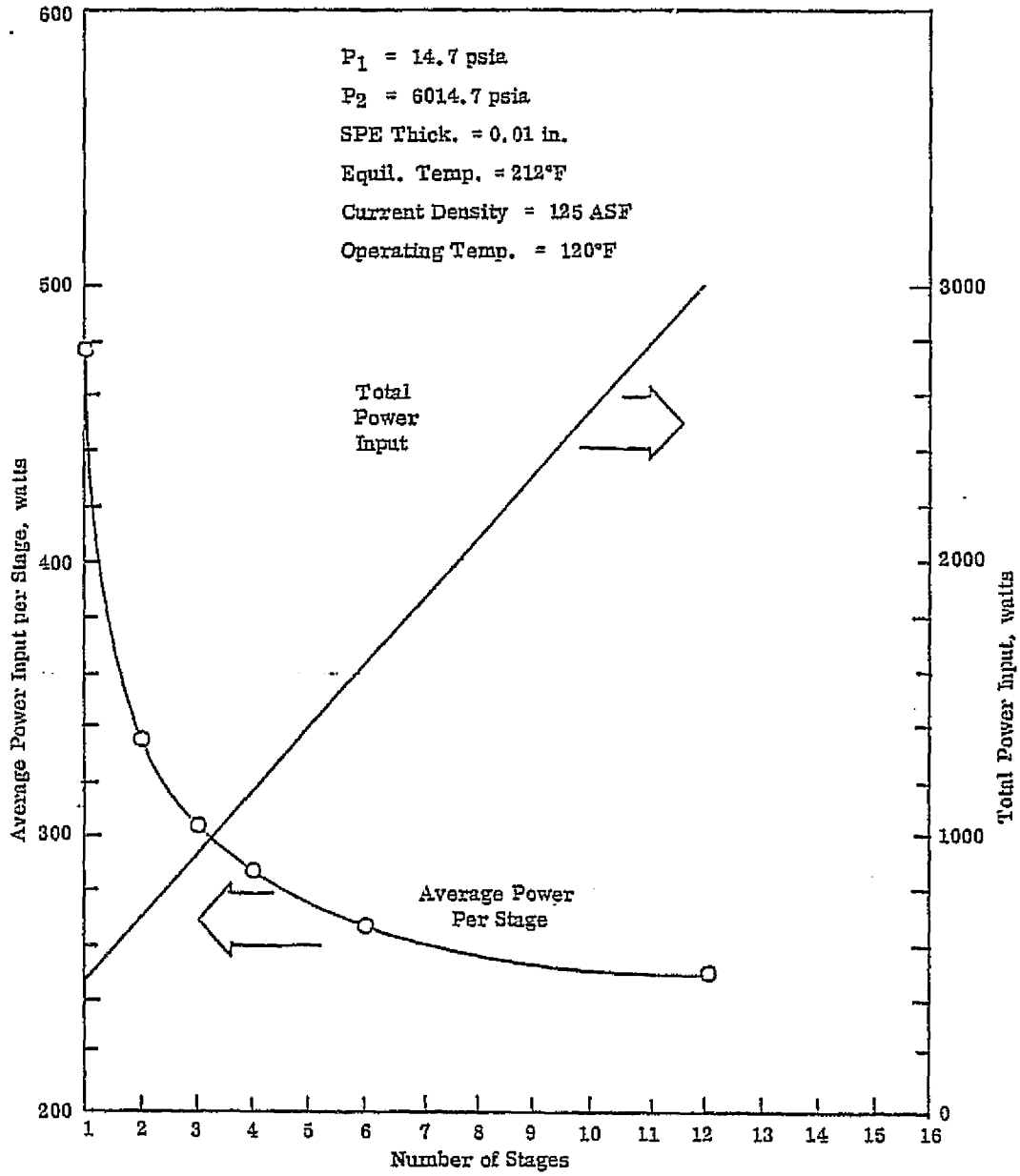


Figure 3. Compressor Power as a Function of Staging

Figure 4. Stress and Strain of SPE (Membrane) Spanning Slots

Hardware Design - Stress Analysis

The major design consideration for the compressor was to provide a proper mechanical support for a membrane having a tensile strength of 2,000 psi (14 MPa) so that it could reliably withstand compressive pressures up to 6,000 psi (42 MPa) without creating tensile stresses greater than half the tensile strength of the membrane. This would provide a safety factor of two.

If the SPE were mechanically restrained so that it was in compression only, it would be able to withstand extremely high pressures without failure. It would act similar to an incompressible fluid which was completely trapped. In the practical case, the SPE must span finite spaces between points on a mechanical support. Calculations were made for an SPE spanning slots of a support. Figure 4 shows that at a pressure loading of 6000 psi (42 MPa) the maximum tensile fiber stress in a 0.01 inch (.25 mm) thick SPE would be 1000 psi (7.1 MPa) at a span of about .005 inch (.13 mm). In other words, if a porous support of about 100 micron (100×10^{-6} m) pore size were used, the stress in the SPE would not exceed half its tensile strength. For the actual hardware, a pore size of 25 micron (25×10^{-6} m) was chosen to keep the stress even lower. For screen supports, niobium screens were chosen using 100 mesh .003 inch (.076 mm) diameter wire having a span of .007 inch (.18 mm). Empirical verification would be needed to show the adequacy of such screens.

It has been stated that the membrane could withstand extreme pressures if it were completely trapped. However, it is not practical to enclose the outer periphery of the membrane, and especially difficult to enclose edges of membrane terminating in manifold seal areas. Therefore, it was of concern that at 6000 psi loading, the membrane would creep and ooze out of the stack and also creep into the manifold areas.

The situation can be pictured as in Figure 5 where pressure acts uniformly on the horizontal surfaces, and no body forces act on the edges (area marked "A_B").

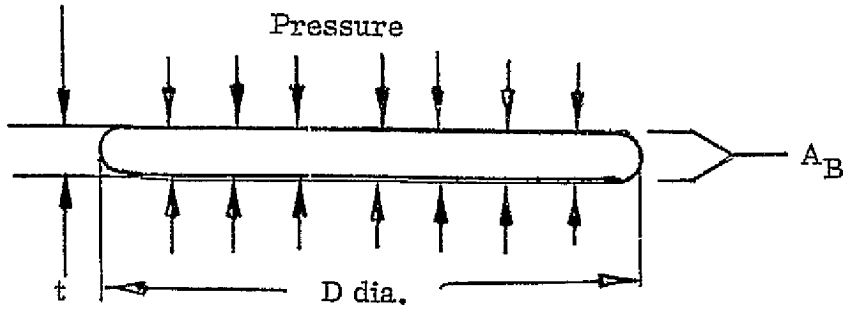


Figure 5. Disk Under Pressure Loading

The edges tend to bulge out radially. If the material is allowed to remain under stress for a period of time, the disk will creep outward. The degree of creep will depend on the Shape Factor, f. The shape factor is defined as the area normal to the compressive force divided by the total "bulge" area of the specimen under load.

$$f = \frac{A}{A_B} = \frac{D}{4t}$$

As the cell gets larger in diameter and smaller in thickness, the shape factor increases, modulus increases, and creep decreases.

Tests were run using a 4 inch (102 mm) diameter equilibrated SPE pressed by a 4 inch (102 mm) diameter metal disk. A hydraulic press at 150 F (66 C) was used to apply the mechanical loading. After applying the pressure for a predetermined time, the SPE was measured for compression set. Results are plotted in Figure 6. The top three curves were previously determined under independent research and development programs. This showed that for a shape factor of 50 at 180 F (82 C), projections of creep at 1000 hours could be as high as 70%. The bottom curve shows the results of the later test at the lower temperature of 150 F (66 C) and higher shape factor (100). Projections showed creep of only 30% after 1000 hours at 6000 psi (42 MPa).

The cell was designed with a shape factor of 100 and was designed to run only at 100-130 F (38 - 54 C), tending to decrease the creep rate.

Another important component requiring stress analysis was the Separator/Heat Exchanger whose function was:

a) Separate the gases between the anode of one cell and the cathode of the next forming a seal between the two. This required that the Separator/Heat Exchanger be subjected to high pressure differentials.

b) Transmit current from one cell to another, requiring an electrical conductor.

c) Transmit heat from the cell to ambient in a conductive mode.

The best material for best weight and material compatibility was niobium which has good corrosion resistance, and high electrical and thermal conductivity per unit weight. Calculations were made for a foil spanning a slot for a chosen stress of 60,000 psi (420 MPa) for niobium alloy. Figure 7 shows that a .014 inch (.36 mm) thick sheet could span a slot whose width was .05 in. (1.3 mm). If we took the more realistic allowable stress of 15,000 psi (108 MPa) for pure niobium, the span must decrease to .010 inch (.25 mm). Actually because of thermal consideration, the thickness of the Separator/Heat Exchanger was dictated at .02 inch (.5 mm), so that mechanical stress was well within allowable limits.

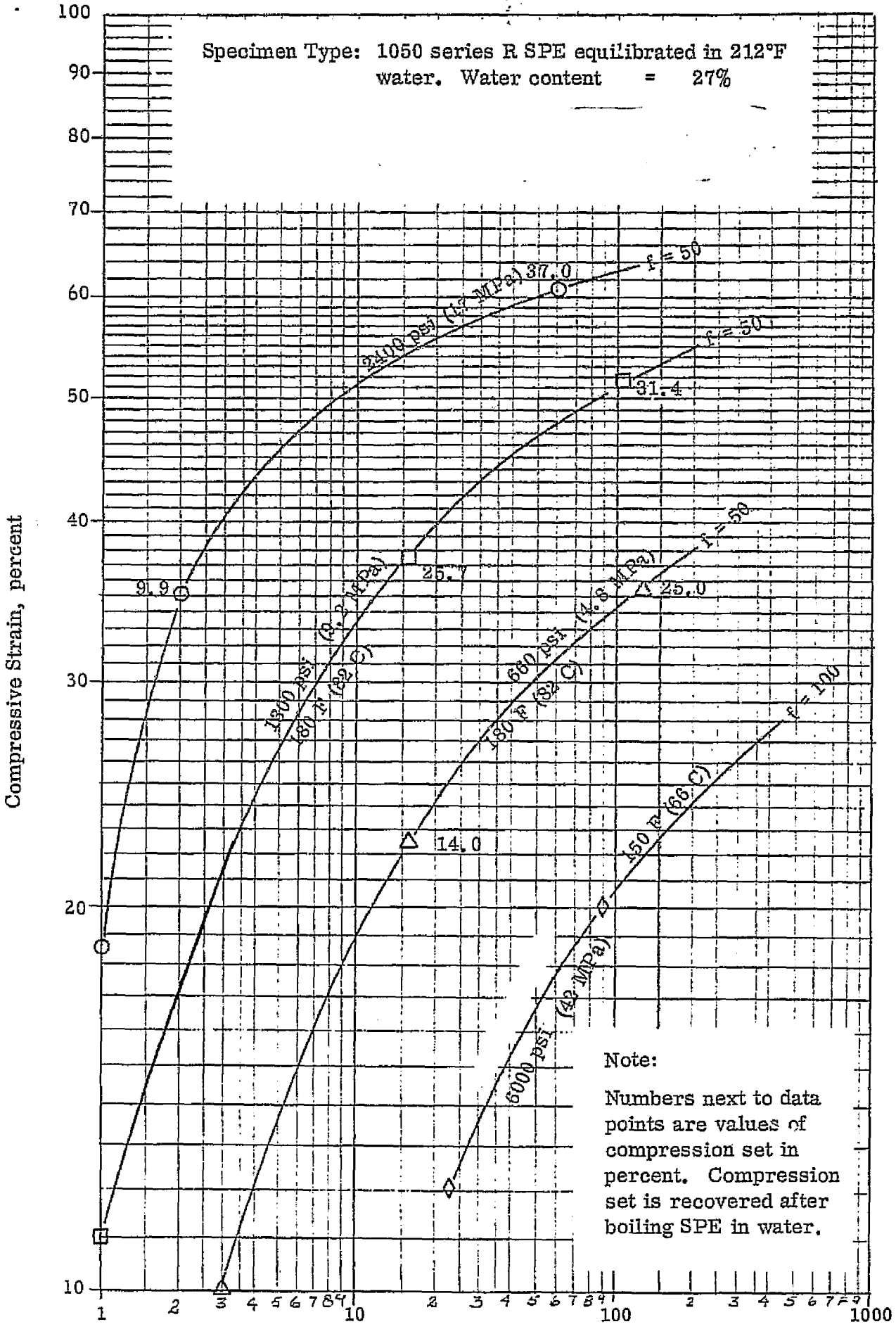
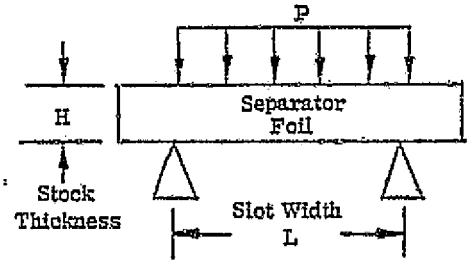


Figure 6. Compression Creep for duPont "R" Membrane (SPE) at 180°F



$$S_{max} = \frac{3}{4}\frac{PL^2}{H^2}$$

$$Y = \frac{10\,S}{48\,E}\frac{L^2}{H}$$

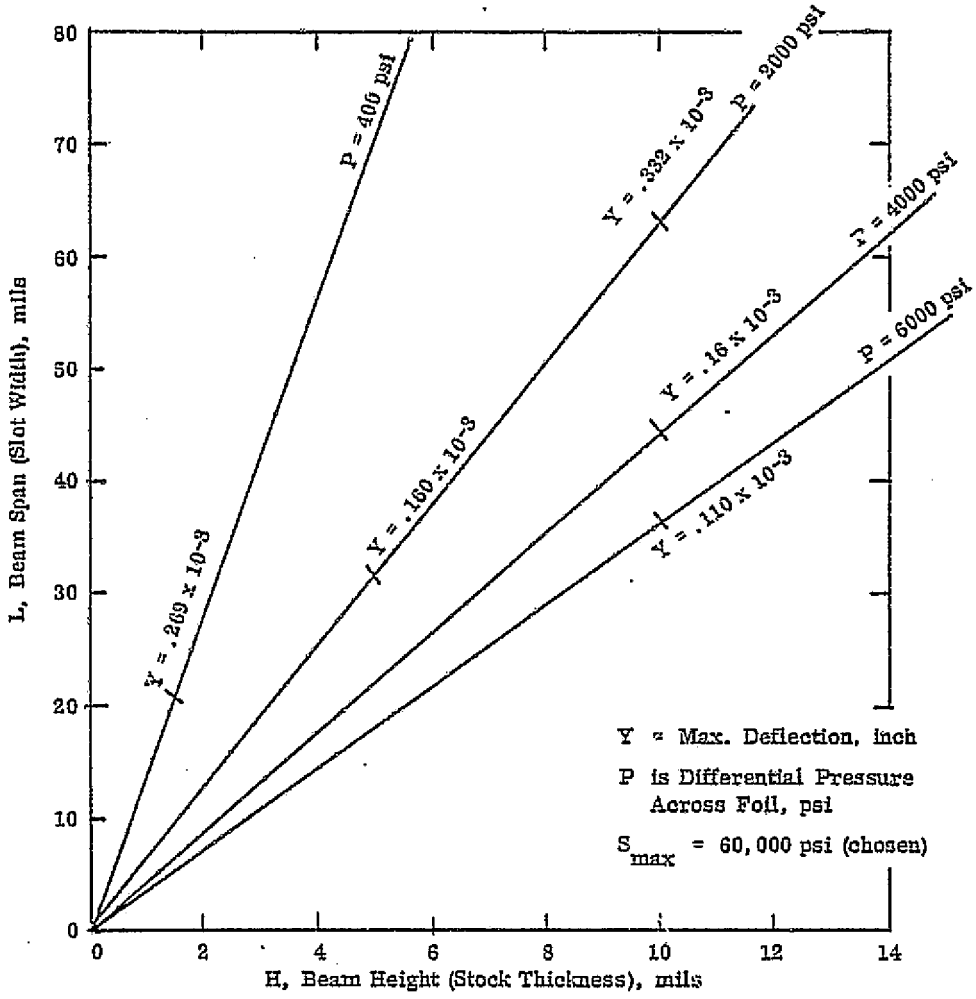


Figure 7. Allowable Span of Separator Foil Over Slotted Support Plate for O_2 Compressor

Hardware Design Details

The layout of the stack is shown in Figure 8. The major components are as follows.

The Pneumatic Cylinder, part (1), houses the piston which applies sealing pressure to the stack. The cylinder was designed for proof pressure of 10,000 psi (71 MPa), and was made of AM 355 steel. It was designed sufficiently thick so that "cocking" produced by the bending moments of the bolts holding the stack was small enough to prevent deflection into the pneumatic piston, part (3). This insured that the piston could move freely to keep sealing pressure on the stack.

The Sealing Plugs, part (4), make the piston somewhat flexible. Slight variances in tolerances in the stackup at the fluid port seals are taken up by independent motion of the plugs.

The Static End Plate, part (2), was designed to deflect .005 inch (.13 mm) at 6000 psi (42 MPa) operating pressure. It has a proof pressure of 10,000 psi (71 MPa) and a burst of 15,000 psi (106 MPa).

The Stack, part (9), is about 8 inches (205 mm) long and 3.9 (99 mm) inches in diameter to the outer sealing ring. Conductive niobium fins extend 0.5 inch (13 mm) beyond the outer diameter of the stack. Cooling is by convective gas or liquid passing over the fins. The length of the stack can be reduced by about 50% if woven screens can be used in place of the present 30 mil porous plates.

Figure 8 also shows an enlarged view of the cell and seal cross-section. All high pressure seals are SPE-to-metal. Internal manifolds are provided for process oxygen, process oxygen purge, product oxygen effluent, and a port for anode water feed, if desired.

The gas separator sheet is 0.02 inch (.5 mm) thick niobium and also serves as the heat exchanger fin. The seals, support structures, and separator sheet are formed in a die so that uniform mechanical loading can be achieved at a high shape factor.

The Overboard Seal, part (16), seals against the SPE (membrane), part (10), in a region where no catalyst exists, thus providing a reliable metal-to-elastomer seal. The seal between part (16) and the separator, part (12), is a metal-to-metal seal, but this is in the low pressure oxygen chamber. These metal-to-metal seals have proved reliable at least to 50 psig (.35 MPa) and leakage on this side is only about 10% of the process feed rate.

The parts list, Figure 8, lists the component parts for the entire stack. At this point, it is advisable to discuss the electrochemical cell itself (part (10), dwg. 73C205849 P1). The cell is composed of the cation exchange membrane manufactured

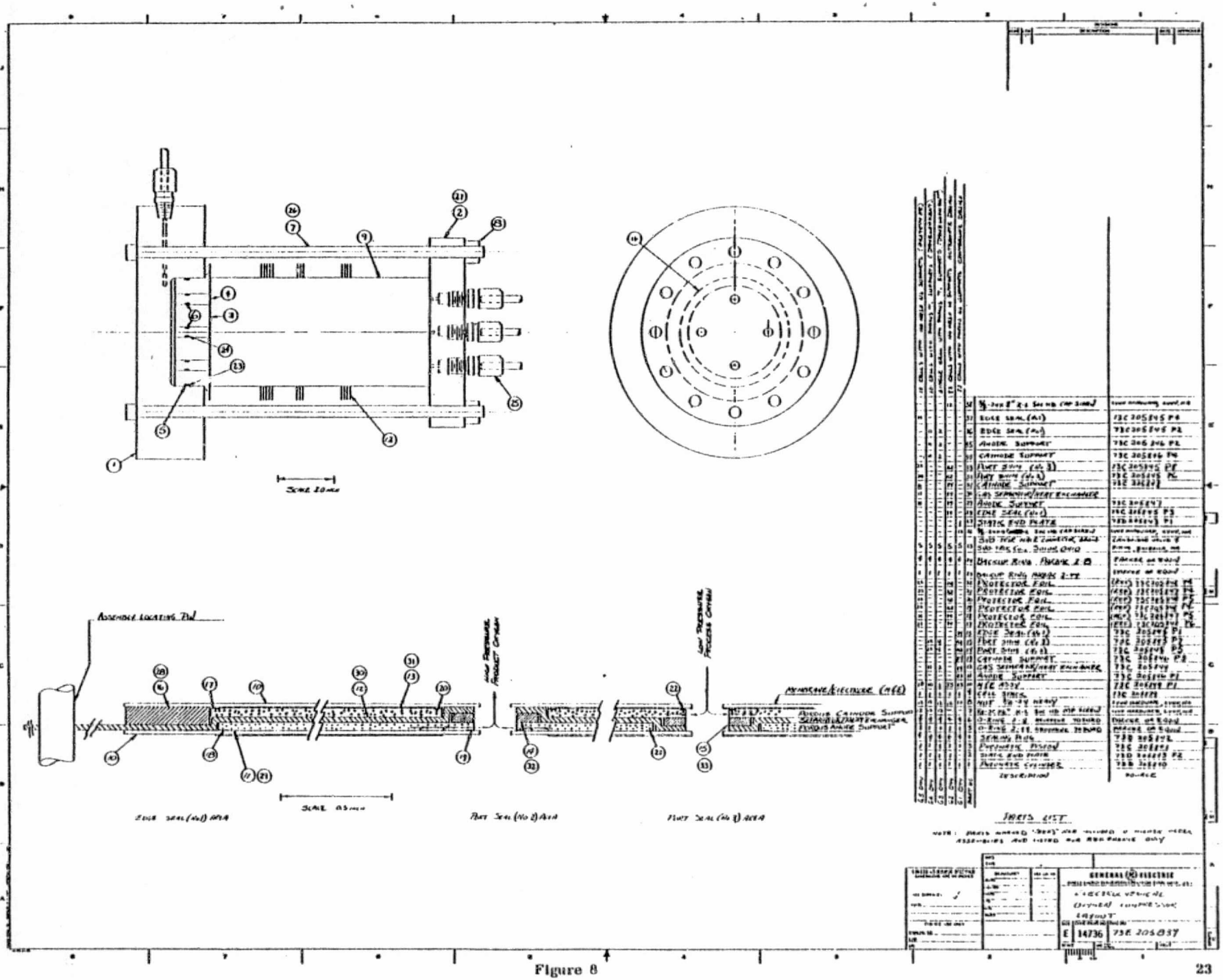
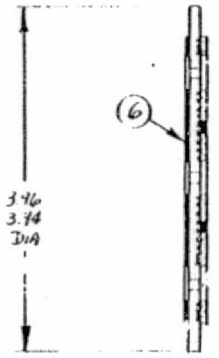
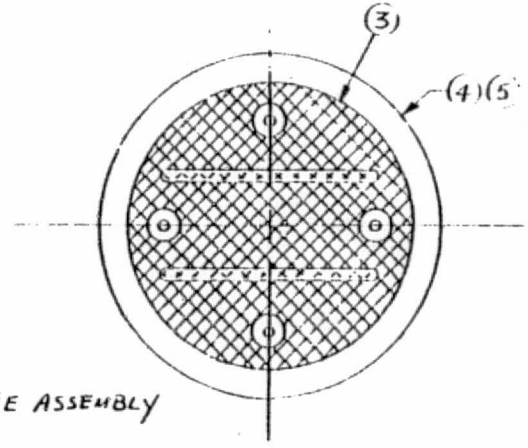


Figure 8

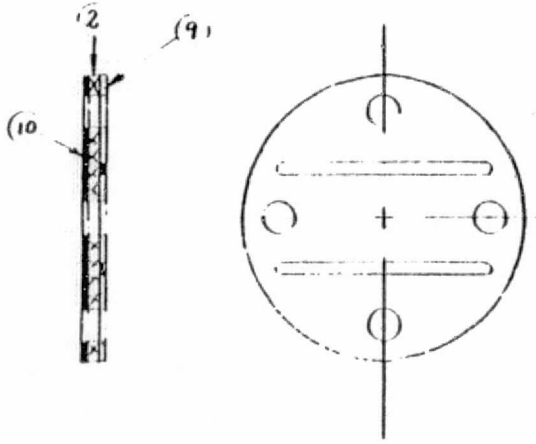
(4) · 1/64 DIA HOLES EQ SP WITHIN 0.002 OF TP ON 1.200 PITCH RADIUS
DIE CUT HOLES AFTER
MEE MANUFACTURE



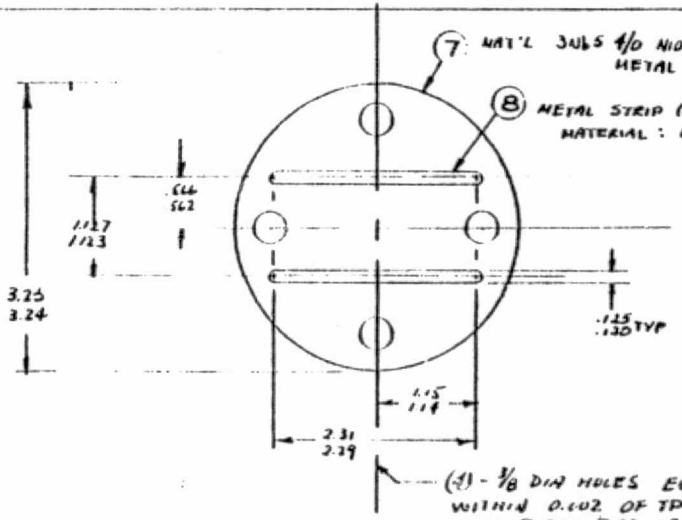


(1) MEE ASSEMBLY

10	CATHODE CATALYST	6 mg/cm² Pt/12.5% TFE CATALYST BLEND
9	CATHODE WETPROOFING LAYER	73C 205850 P2
8	CATHODE CURRENT COLLECTOR STRIP	SEE PART
7	CATHODE ELECTRODE SCREEN	SEE PART
6	ANODE ELECTRODE	73C 205850 P1
5	SAME AS P4 EXCEPT 0.010 THICK	
4	SOLID POLYMER ELECTROLYTE (SPE) DuPONT "NAFION" 2.010 THICK	PROCESS TO DECP MP-000-078
3	CATHODE ELECTRODE	SEE PART
2	CATHODE SCREEN/STRIP ASSEMBLY	SEE PART
1	MEE ASSEMBLY	SEE PART



(3) CATHODE ELECTRODE



7 MAT'L SUBS 4/0 NIOBIUM EXPANDED METAL SCREEN

8 METAL STRIP (2 REQ)
MATERIAL: 0.002 THICK NIOBIUM

(11) - 1/8 DIA HOLES EQ SP WITHIN 0.002 OF TP ON 1.200 PITCH RADIUS

THICK WELD (2) P8 TO P7 EVERY 1/8 INCH

(2) CATHODE SCREEN/STRIP ASSEMBLY

MEE ASSEMBLY & COMPONENTS

GENERAL ELECTRIC CO
DECP LYNN, MASS
M J Chludzinski 10/17/73

73C 205849

by duPont under the trade name "Nafion". Anode catalyst of a proprietary nature is pressed on one side of the SPE. Catalyst is kept free of the various areas where seals occur so that metal to pure SPE contact can be made. This is done since the catalyst is porous and would cause leaks if it extended into the seal regions. On the cathode side, platinum black catalyst is pressed into the SPE. It is necessary to apply a wetproofing layer on top of the cathode catalyst to prevent drowning the catalyst by the action of protons pumping water to that electrode. The wetproofing layer is an electrical insulator. It is therefore necessary to penetrate the layer with metal conductors so that bipolar current transmission can be achieved. This is done by cutting slots in the layer which are filled with metal strips attached to a current conducting screen. The cathode consists, then, of a wetproofing layer, then a screen with metal strips, then the cathode catalyst. This type of geometry has been successfully used in the Navy open loop concentrator on 10-inch diameter cells.

Final Configuration of Oxygen Compressor

During the execution of the contract, many configurations were tried in order to achieve good sealing and good performance. Figure 9 shows the final configuration of a cell and Table I is the parts list showing the thicknesses of various components. The major differences in Figures 8 and 9 are:

a) Anode and cathode supports are composed of composite porous plates against the cell and screens under the plates. This allowed the proper support of the cell by the porous plate, yet allowed gas to circulate under the plate to reduce diffusion losses. Also, the composite structure allowed support thicknesses to be tailored by adding or subtracting screens to various assemblies during the studies.

b) As "detail A" shows, the Separator/Heat Exchanger contained radii at all areas which were formed with the stamping die. These were regions of non-support, and the cell tended to be pushed into these spaces, resulting in leaks or short circuits. For those reasons, the spaces were "potted" with silicone rubber RTV.

c) The overboard seal ring was attached to the Separator/Heat Exchanger using silicone rubber contact adhesive GE SR 537 or equivalent. This served to hold the ring in place for assembly and as a void filler to seal the cathode chamber.

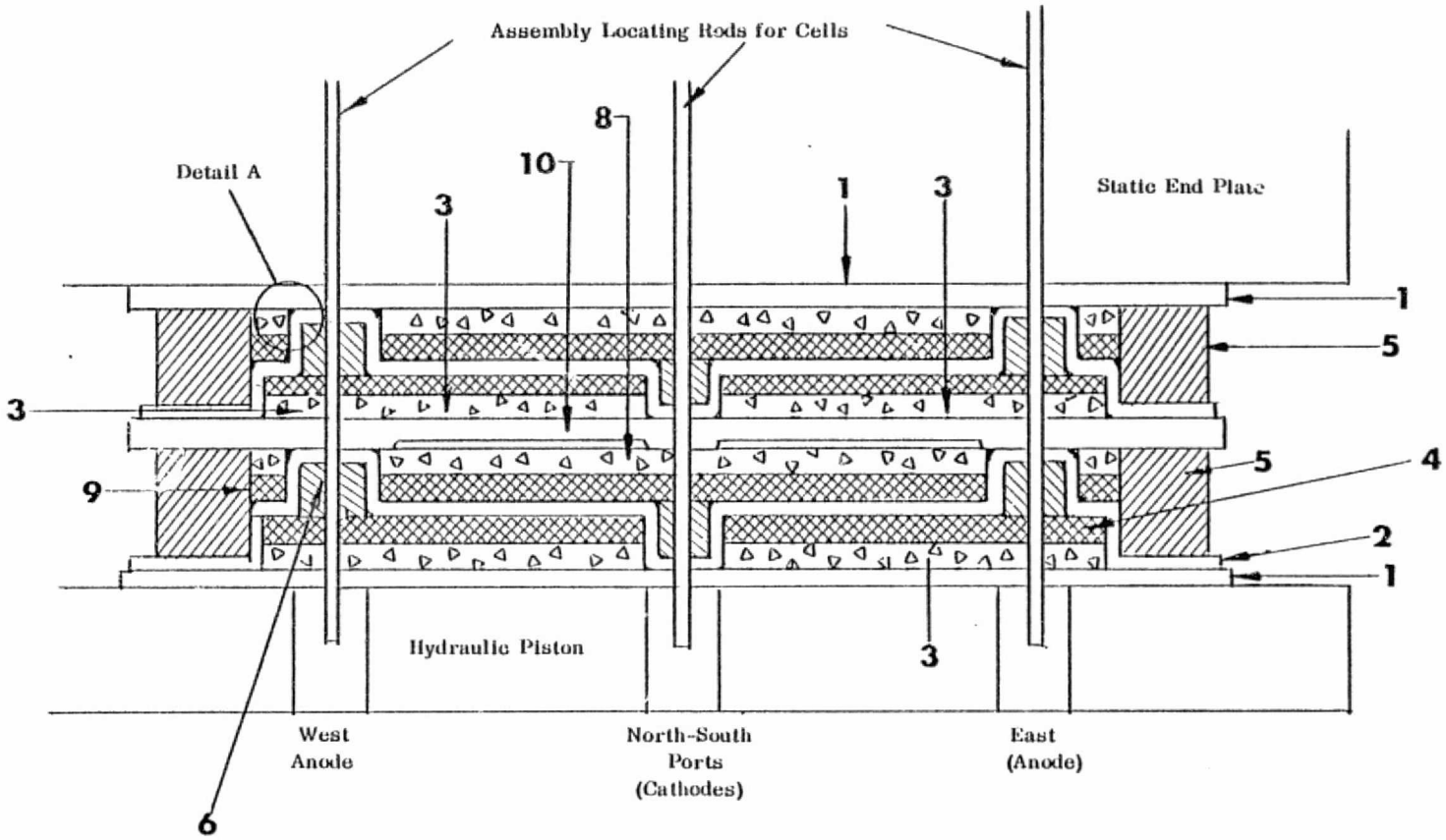
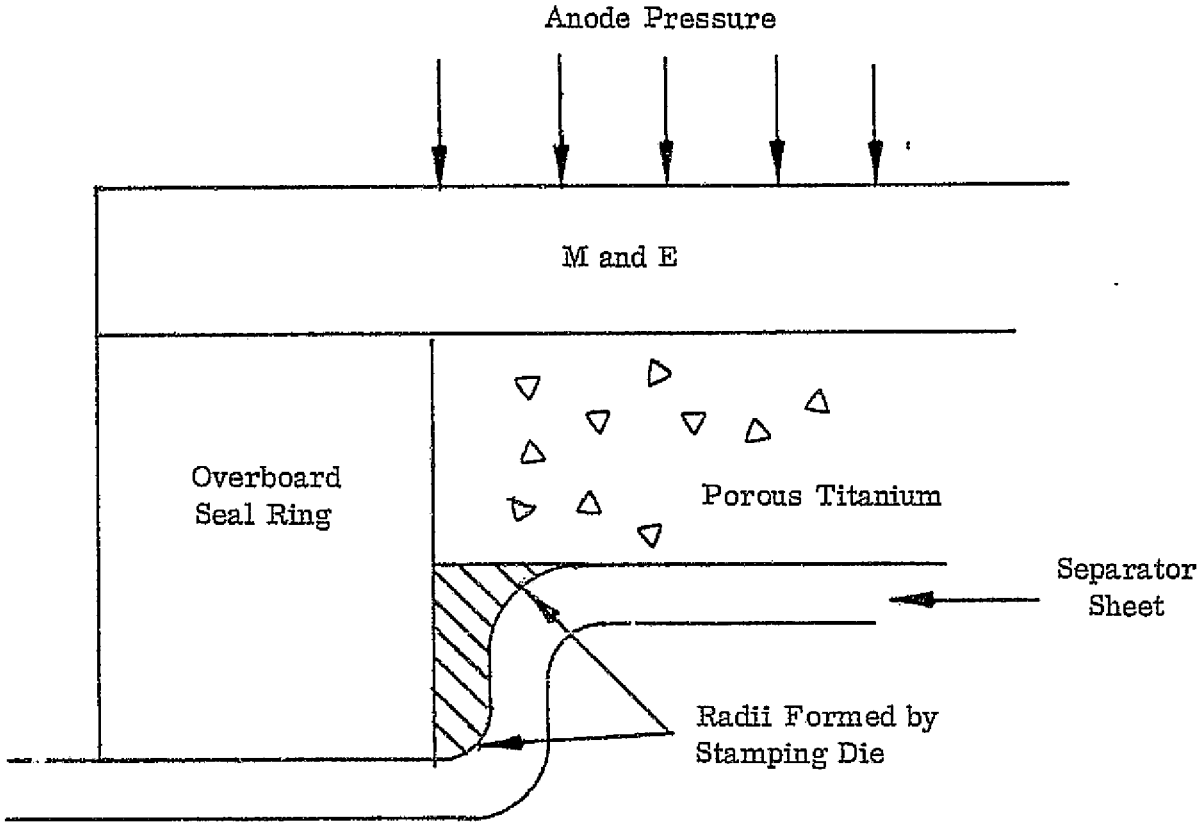


Figure 9. Final Configuration of O_2 Compressor



Silicone Rubber (RTV) Potting Support

Separator Sheet and Cathode Porous Plate
Showing Region of Unsupport

DETAIL A

TABLE I

PARTS LISTING FOR FINAL O_2 COMPRESSOR CONFIGURATION

(1) Aclar Insulator .01 inch (.25 mm) thick

(2) Separator/Heat Exchanger, Drawing 73C205844 .02 inch (.5 mm) thick Niobium

(3) Anode Porous Support, Drawing 73C205846P1, except .018 inch (.46 mm) thick. Porous Tantalum, Kennametal Corporation, Latrobe, Pa.

(4) Screen Support (Anode) 5 Nb 7-6/0 expanded metal screen, Exmet Corporation, Bridgeport, Conn. (2) Layers tack welded together and flattened to .011 inch (.28 mm) thick. Cut to Drawing 73C205846P1

(5) Overboard Seal Ring, Drawing 73C205845P1

(6) Port Shim, Drawing 73C205845P5 (Modified) .048 inch (1.2 mm) thick

(7) Port Shim, Drawing 73C205845P5 (Modified) .043 inch (1.1 mm) thick

(8) Cathode Porous Support, Drawing 73C205846P4. Porous Titanium Grade 6525, 65% porous, 25 micron, Gould Laboratories, Cleveland, Ohio

(9) Screen Support (Cathode). Material same as P4. Cut to Drawing 73C205846P4

(10) Membrane/Electrode Assembly Drawing 73C205849P1

Test Hardware Auxiliaries

A test panel was built to house the stack and contain auxiliary equipment to operate the system. The system schematic is shown in Figure 10. Components and functions are described below.

Cells are mechanically clamped by the pneumatic cylinder loaded with a regulated pressure source. Initially, a high pressure nitrogen bottle was used and later replaced with an Enerpac hand-operated hydraulic pump to eliminate the trapped energy of the gas in the event of mechanical failure. The hydraulic fluid in the pump was replaced by silicone oil to prevent possibility of combustion in the event of mechanical failure.

A fan, Part (4), was available for cell cooling, but was never used. Cooling was always by free convection. Thermocouples were welded to the niobium fins and read out on a meter with selector switch.

Back pressure on the gas generating anodes was regulated by a back pressure regulator, Victor Model BPR 11S22321-F, from Kennet Corp., Newton, Massachusetts. This had capability of regulation from 400 to 7000 psig (.28 to 50 MPa) by manual adjustment during operation.

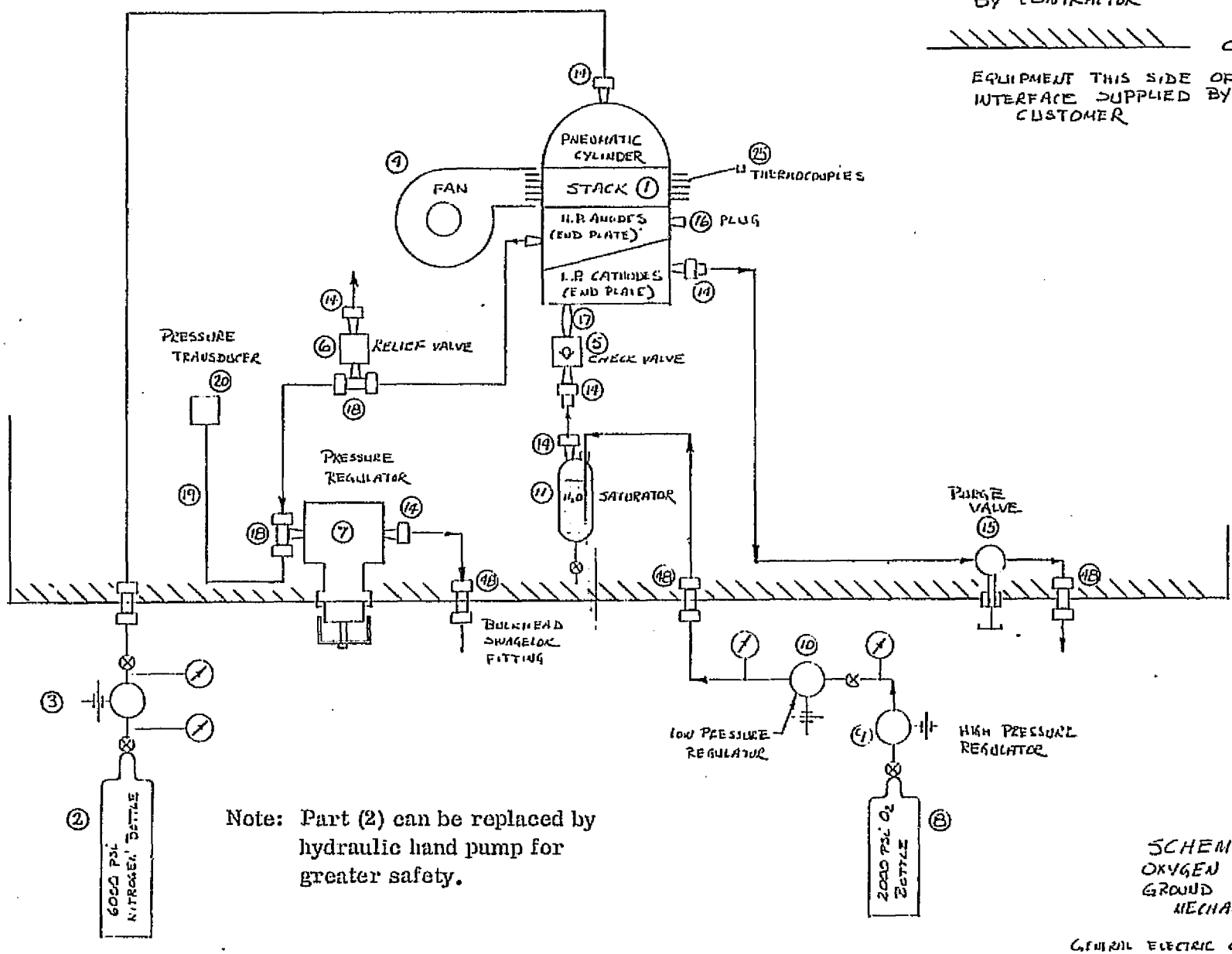
In the high pressure plumbing, there was a relief valve, Circle Seal 5332T-2PP-6500, which was set at 7500 psi. Pressure was sensed by a pressure transducer, Bell and Howell Model 4-326-0001, 0 to 10,000 psig (71 MPa). The signal was read out on a millivoltmeter calibrated in pressure units.

Process oxygen (cathode feed) was supplied by a high pressure oxygen bottle, Part (8), fed through a regulator, through a saturator, check valve and into the cathode manifold port. Purge was provided by a high pressure valve which was a combination fine metering and dead shut-off valve.

The panel layout for supporting the components is shown in Figure 11. The photograph (Figure 12) shows the ground support test rig and instrumentation.

The following is a discussion of the electrical schematic.

The electrical schematic for the system is shown in Figure 13 which includes the components of the system and their interconnections. Primary power for the ground control system was from 115 VAC. This operated the fan and supplied power to the low voltage transformer which in turn supplied power for the current regulator/compressor and the transducer readout circuit board. There were two circuit boards to provide control and readout capability for the system. Temperature readout of various points on the compressor was by iron-constantan thermocouples and a meter readout on the front panel. An ammeter provided an indication of the current supplied



Note: Part (2) can be replaced by hydraulic hand pump for greater safety.

SCHEMATIC
OXYGEN COMPRESSOR
GROUND SUPPORT RIG
MECHANICAL

GENERAL ELECTRIC CO DECP, LYNN, MASS
P.J. Pachuta / R. Jones
3 DEC 73

73C205856

Figure 10. Schematic of Ground Support Rig

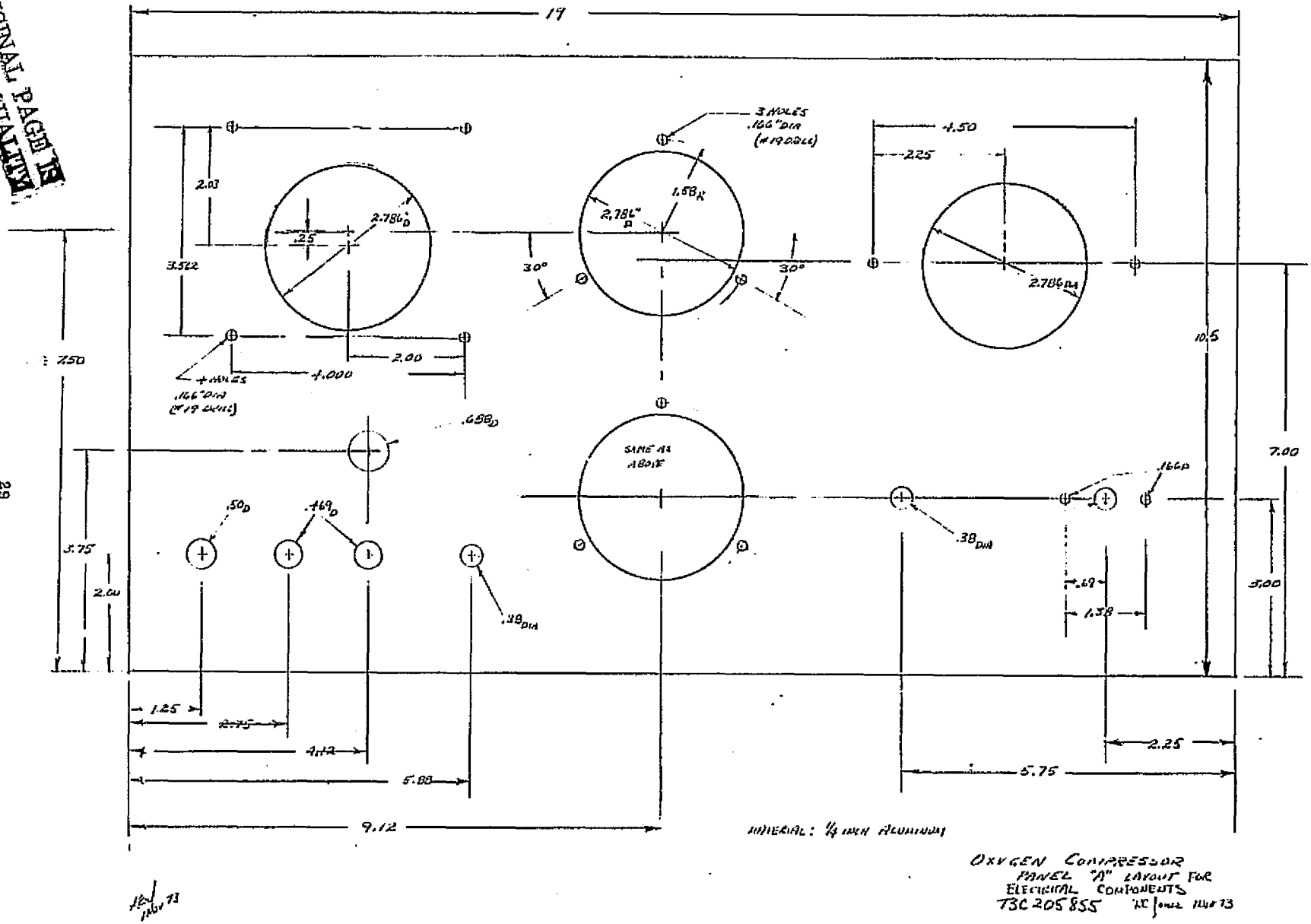


Figure 11. Ground Support Test Rig Mechanical Component Support Panel

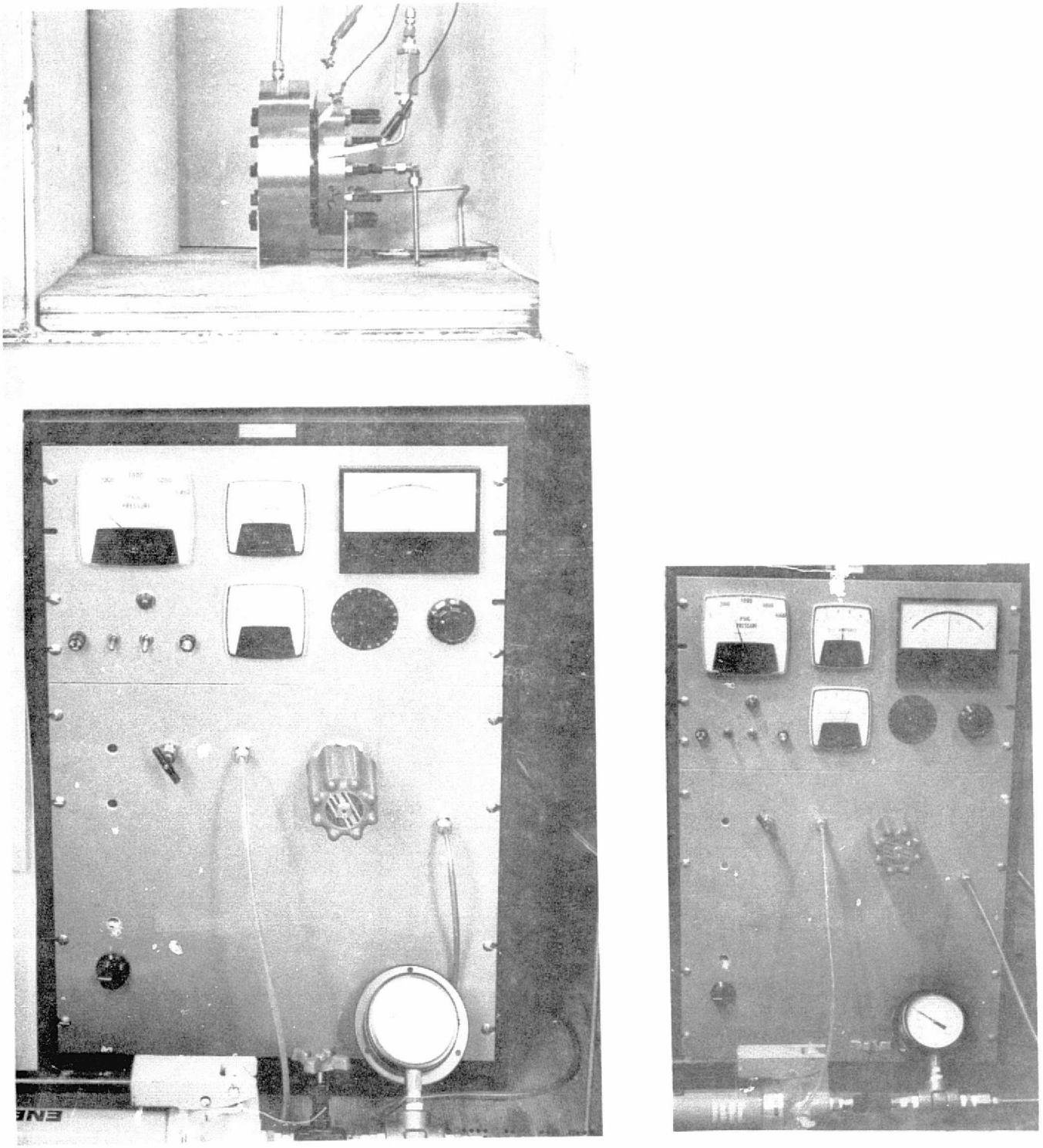


Figure 12. Photo of Ground Support Test Rig

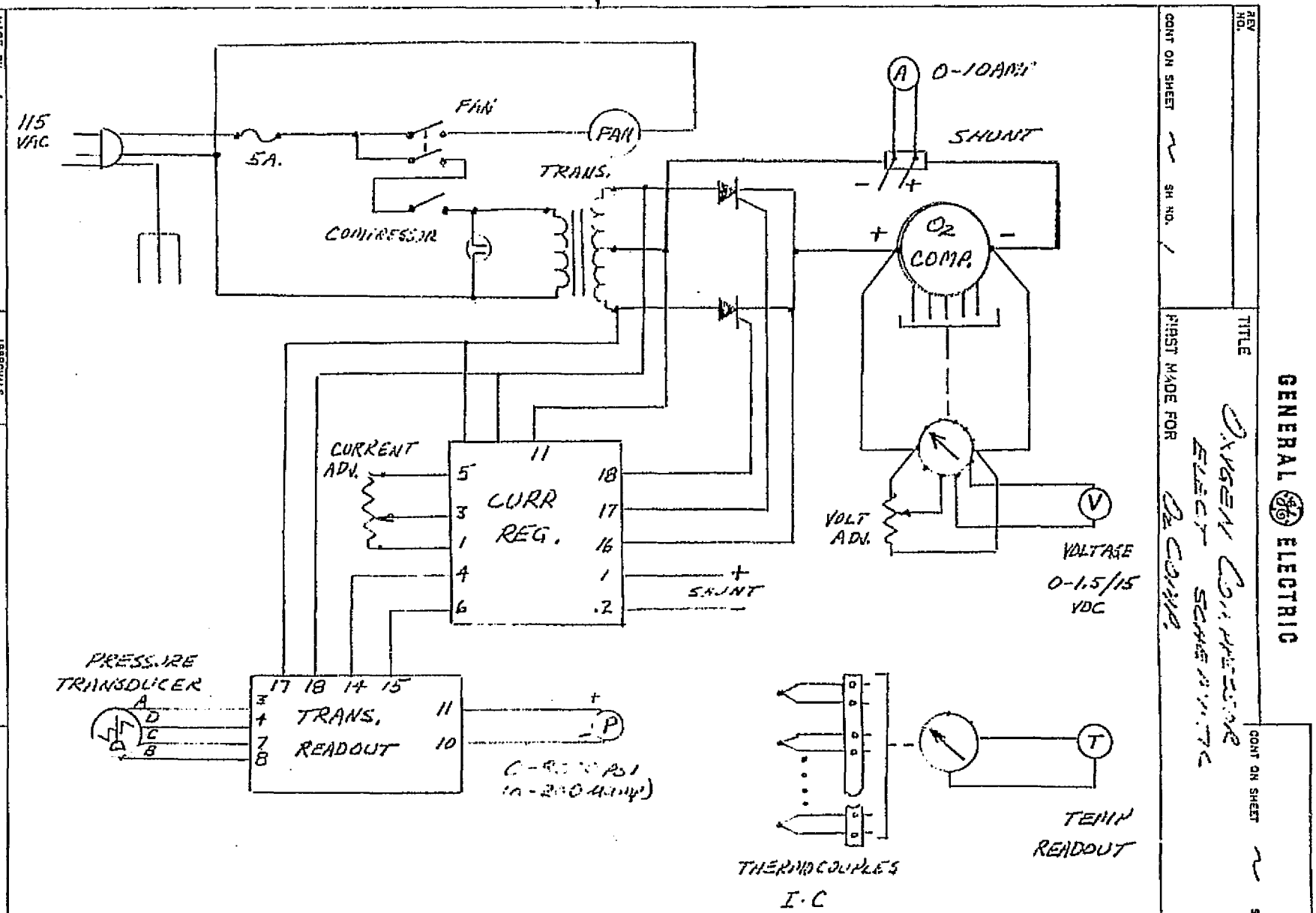


Figure 12.

the compressor. A voltmeter with switch provided a readout of individual cell voltage. A 10:1 voltage divider changed the scale from 1.5 to 15 VDC to enable the readout of the entire stack voltage. The system pressure of the high-pressure oxygen was indicated on the pressure transducer readout.

To accomplish the compression of the oxygen, it was necessary to supply direct current to the stack. This DC was obtained from rectification of the transformer output by the Silicon Controlled Rectifiers (SCR's) operating full wave. The current regulator circuit board regulated the current to the compressor at the value set by the control on the front panel. Figure 14, Drawing No. 107652[a]-515, is a schematic of the board. The shunt provided feedback to the circuit board , maintain the desired current within 1%. On the circuit board, the integrated circuit output was converted by the unijunction oscillator to pulses which in turn drove the SCR's at the desired frequency and phase angle to maintain the current. Nominal current was 8 amps; maximum current of the system was dependent upon the amp/square foot loading desired of the compressor. The electronics were capable of providing in excess of 15 amps, dependent upon transformer voltage and cell back voltage. The current regulator board also contained a circuit that would stop all current to the compressor should the stack voltage exceed a pre-established point (adjustable by potentiometer). This was a latching type circuit and kept all current off the stack until 115 VAC power was removed and then restored. The stop-point was set at approximately 10 volts, some 2 volts above the normal operating point. This circuit protected the stack from continuous current and possible subsequent damage should some problem occur that would cause a high stack voltage.

The transducer readout circuit board (Figure 15) also had two functions. The first was to supply a regulated excitation voltage for the strain gauge transducer (0 - 10,000 psig, 0-71 MPa) and to amplify the output so as to provide a meter readout of the system pressure. Two integrated circuits provided this function. A potentiometer provided calibration capability so that a pressure range of 0 - 8000 psig (0-57 MPa) was displayed full scale on the meter. Another potentiometer provided for adjustment of the meter at zero with zero system pressure. The second function of the circuit board was to provide an adjustable pressure point to operate a relay that in turn would shut off the current to the stack. A potentiometer on the circuit board provided for this adjustment. This controlled the maximum pressure that the system could generate and thereby prevented having to vent oxygen out the relief valve when the generated rate exceeded the demand. This control was equivalent to an electro-mechanical pressure switch and provided for automatic system operation. The pressure transducer thereby performed a dual function. Its output signal was for continuous pressure readout and also for system maximum operating pressure.

An interlock on the fan switch was provided so that this switch had to be ON in order to turn the compressor ON. A pilot light indicated power connected and both switches ON.

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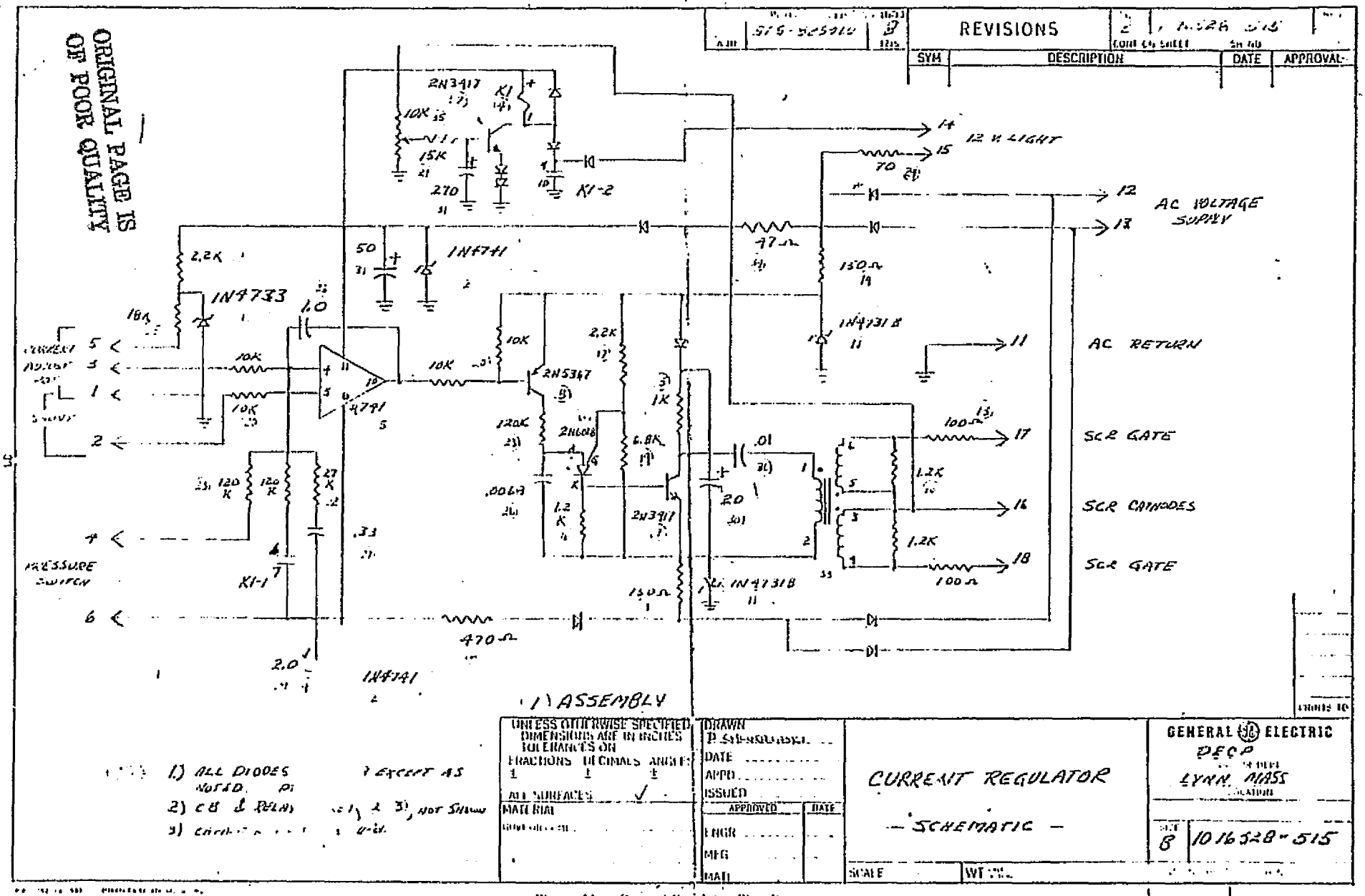

Figure 14. Current Regulator Circuit

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TITLE

TRANSDUCER READOUT

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CONT ON SHEET SH NO.

FIRST MADE FOR O_2 COMPRESSOR

REVISIONS

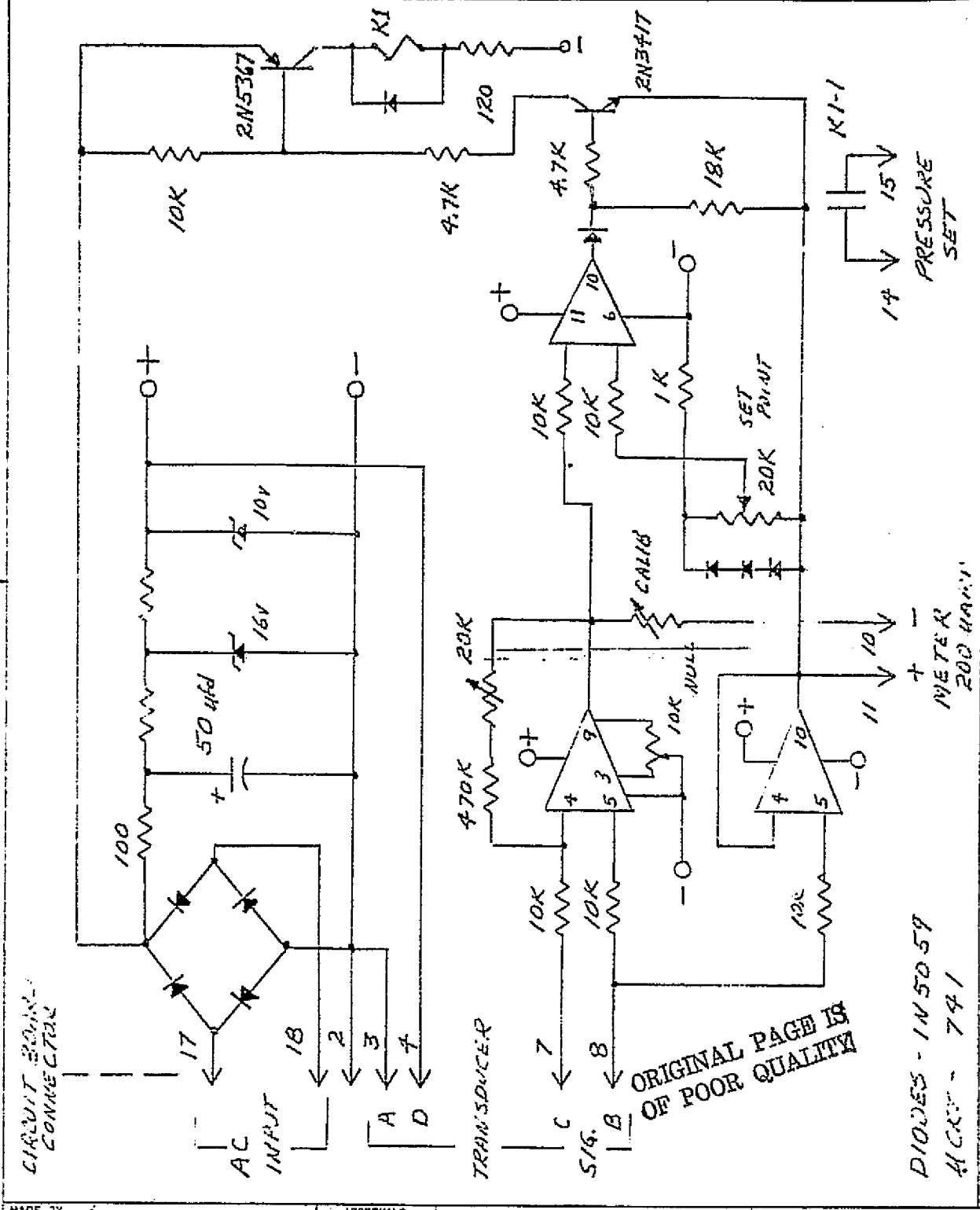

Figure 15, Transducer Readout Circuit Board

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Cell Performance

At the outset of the contract, while hardware was being designed, available low pressure laboratory hardware using a square cell of .05 ft^2 (46 cm^2) active area was used to determine if cells would run at all with a porous plate support against the cathode. The hardware was capable of only 100 psi (.7 MPa) operation, but results nevertheless were considered important before a large commitment of manpower and money should be expended in pursuing high pressure systems. The first tests were performed using open screens as current collectors against both electrodes.

Figure 16 shows performance under the modes of flooded anode (excess water added to the anode side), and saturated cathode (low-pressure cathode saturated with water vapor). Performance was essentially equivalent to that used in the GE proposal to this contract. Flooded anode operation, as expected, was better than saturated cathode by about 50 millivolts.

Of considerable interest was the stability of the cell in the saturated cathode mode. Figure 17 shows that at 200 ASF (215 ma/cm^2) the flooded anode mode was invariant with time, whereas the saturated cathode operation decayed considerably with time due to adverse water activity at the anode.

At 100 ASF, the cell was invariant even in the saturated cathode mode. This was an extremely important result, since stability was achieved at a current density commensurate with that calculated by the computer program for minimum power.

Porous titanium sheets were obtained and tested in 3 x 3 inch laboratory hardware. A porous support was placed against the cathode only, the anode having open mesh screens. The anode pressure was adjusted to 90 psia (.65 MPa) so that the cathode was forced against the porous plate. This was done to verify that the cathode, which is the only electrode subject to diffusion polarization, would operate when lying tightly against a porous plate. It was anticipated that the dense porous plate in intimate contact with the cathode would produce severe gas diffusion polarization, and it was desired to attack this problem as soon as possible.

It was pleasantly surprising to find that the performance with the porous plate was essentially as good as cells run with relatively open gas gaps. Results are shown in Figures 18 and 19, indicating good initial performance and good stability in both the saturated cathode as well as the flooded anode mode. Other cells were run with other porous supports to verify that the results could be reproduced. Additional data can be found in the Appendix, rather than encumber the discussion with too many details. The following table summarizes the results of various tests.

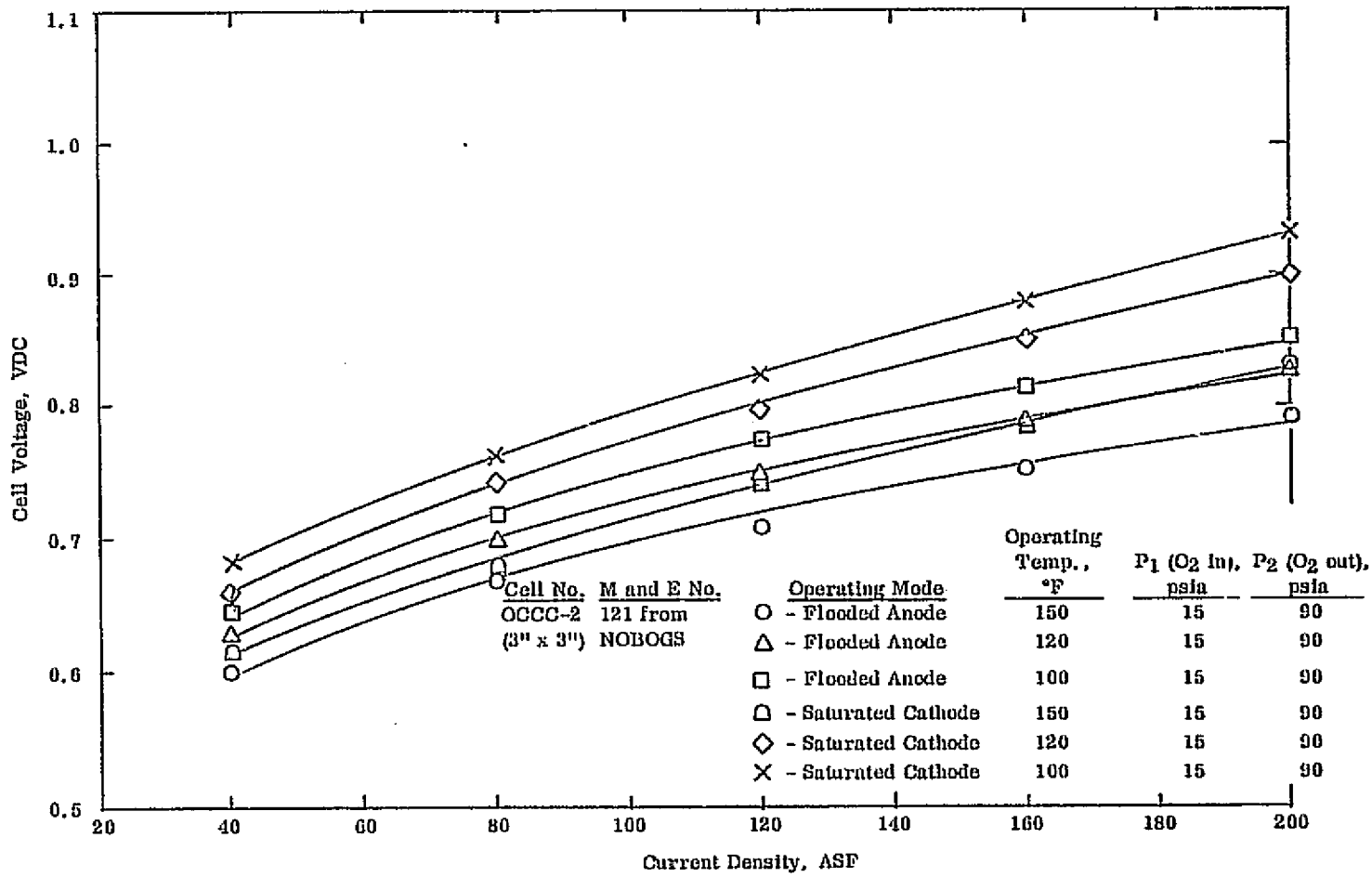


Figure 16. Performance of 3 x 3 Inch Cell in Two Modes of Operation. Standard Open Mesh Screen Supports

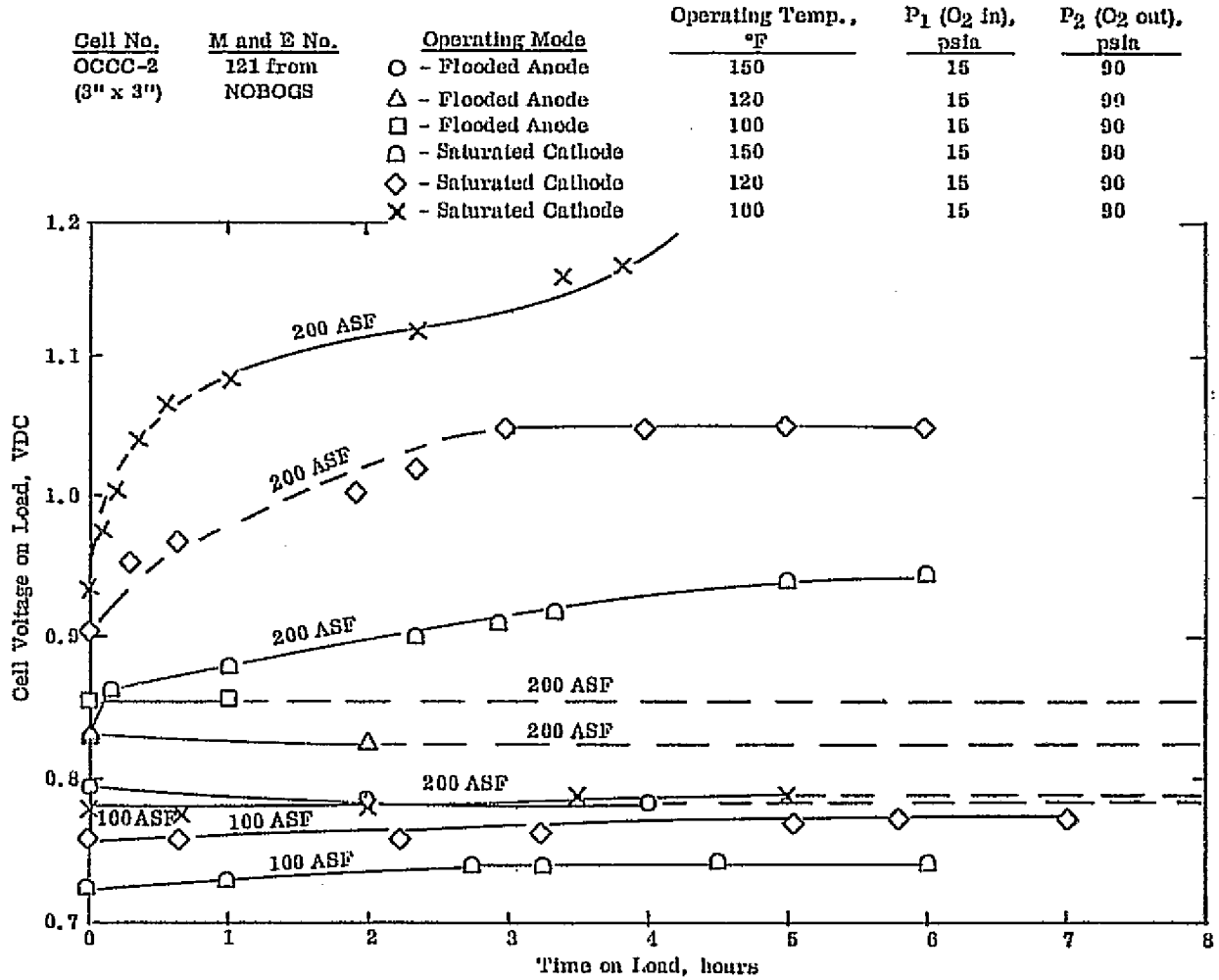


Figure 17. Cell Performance Stability in Two Modes of Operation. Standard Open Mesh Screen Supports

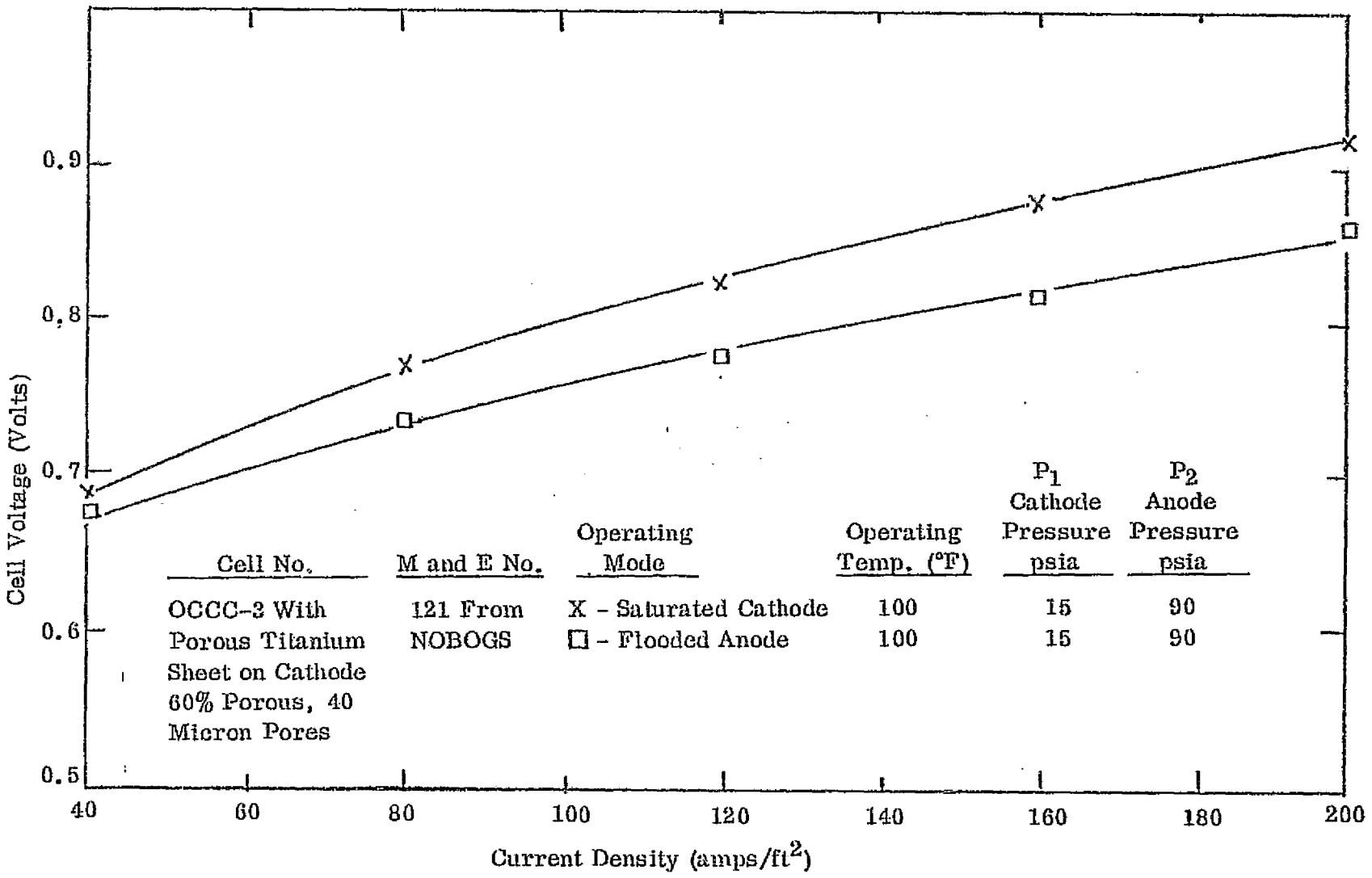
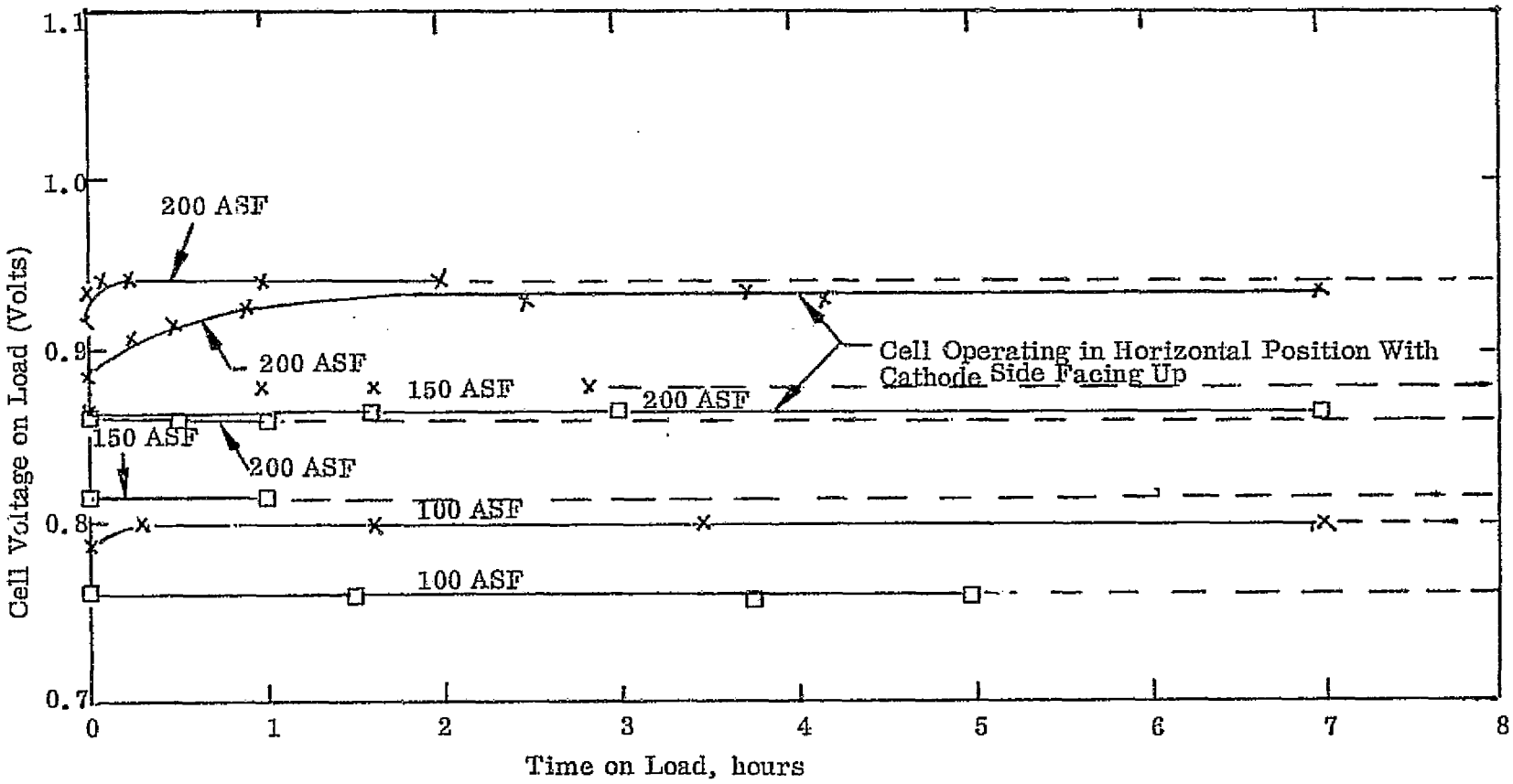


Figure 18. Performance of 3 x 3 Inch Cell in Two Modes of Operation. Porous Titanium Cathode Support



Cell No.	M and E No.	Operating Mode	Operating Temp. (°F)	P_1 Cathode Pressure psia	P_2 Anode Pressure psia
OCCC-3 With Porous Titanium Sheet on Cathode 60% Porous, 40 Micron Pores	121 From NOBOGS	X - Saturated Cathode □ - Flooded Anode	100 100	15 15	90 90

Figure 19. Cell Performance Stability in Two Modes of Operation. Porous Titanium Cathode Support

TABLE II

COMPARATIVE RESULTS OF "3 x 3" INCH (46 cm^2) CELL TESTS IN 100 PSI (.7 MPa) HARDWARE

	Cathode Support Configuration and Stability Comments	Voltage at 100 ASF (107 ma/cm^2) 100 F (38 C) Cathode Mode
A.	Cell OCCC-2 - standard 4/0 expanded Nb screen (open mesh). Stable for 7 hours test @ 100 amp/ft^2 (107 ma/cm^2).	0.795
B.	Cell OCCC-3 - .030 inch (.76 mm) porous Ti sheet, 60% porous, 40 micron pores. Stable for 7 hour test @ 200 amp/ft^2 (215 ma/cm^2).	0.80
C.	Cell OCCC-4 - .030 inch (.76 mm) porous Ti sheet, 65% porous, 25 micron pores. Stable for 4 hour test @ 200 amp/ft^2 (215 ma/cm^2).	0.765
D.	Cell OCCC-5 - .030 inch (.76 mm) Ta porous sheet, 60% porous. Pore size unknown, but less than 25 microns. Unstable in life test.	0.78
E.	Cell OCCC-6 - two layers of woven Ti screen, 80 x 80 mesh, .003 inch (.08 mm) diameter wire strand.	0.775
	E-1 Screens unpressed into cell.	0.775
	E-2 Screens pressed into cell at 2000 psi (14 MPa) Stable at 200 amp/ft^2 (215 ma/cm^2) - 6 hours.	0.785
	E-2 Screens pressed into cell at 6000 psi (42 MPa) Unstable at 200 amp/ft^2 (215 ma/cm^2) after 1 hour. Stable at 100 amp/ft^2 (107 ma/cm^2) after 1 hour.	0.805

It can be seen that in Tests A through C, screen or porous titanium supports ran well in the saturated mode and were stable over relatively long periods. In Test D, a sample of tantalum porous sheet performed well initially, but was unstable. This support was a sample sent in by a vendor who could not define the pore size of the material, but qualitative examination showed that it was much more "dense" than the other porous materials. There seems to be no reason that porous Nb or Ta of the same geometry as the Ti should behave any differently than the Ti sheet. Attempts were made to secure porous niobium of the proper geometry, but only the one vendor could be found who had the technology for porous tantalum. He was reluctant to try niobium at the time for fear of contaminating his dies. Prices quoted for development of niobium were excessive in relation to contract funding, so it was decided to investigate porous titanium with future work to be centered on closely-knit niobium screens to provide the same type of uniform support as the porous plate. Niobium screens were ordered in September 1973, but the order was later cancelled. The vendor who was producing the wire could not anneal it to the satisfaction of the prime vendor responsible for weaving the wire. The program was run, therefore, using only porous plate supports.

In Test E, two layers of Ti 80 mesh woven screen were used. Performance was good. The screens were then pressed into the cell on the cathode side, refixtured and tested. Screens pressed at 2000 psi (14 MPa) performed well and stably at 200 amp/ft^2 (215 ma/cm^2). When the screens were pressed at 6000 psi (42 MPa), performance was good, but instability occurred after one hour of life test at 200 amp/ft^2 (215 ma/cm^2). Stability was good at 100 ASF (107 ma/cm^2).

A comparison of performance of cells in laboratory hardware and final design cells in high pressure hardware is presented in Figure 20. Performance is about the same up to 100 amp/ft^2 (107 ma/cm^2), but the cells in high pressure hardware become diffusion limited above about 120 amp/ft^2 (129 ma/cm^2. This may have been caused by the high clamping pressure, 5000 psi (36 MPa), used in the final design hardware, causing some diffusion polarization. High clamping pressures were needed to seal the cells at high generation pressure, and were used even when the cells were run at low pressure.

It is also important to realize that cells in high pressure hardware needed a higher cathode supply pressure than laboratory cells which could run at essentially ambient pressure. The effects of pressure are discussed elsewhere, but it is noted here that the final design cells all ran with cathode pressure of 65 psia (.46 MPa).

Cathode Side Considerations

In the final design cell there were two possible problem areas. The first was the question of diffusion polarization due to using a porous support directly against the cathode wetproofing layer, and whether or not oxygen could permeate easily enough to the cathode electrode. The second question was the reliability of the overboard sealing ring. This ring sealed the cell on the anode side by contacting the cell membrane

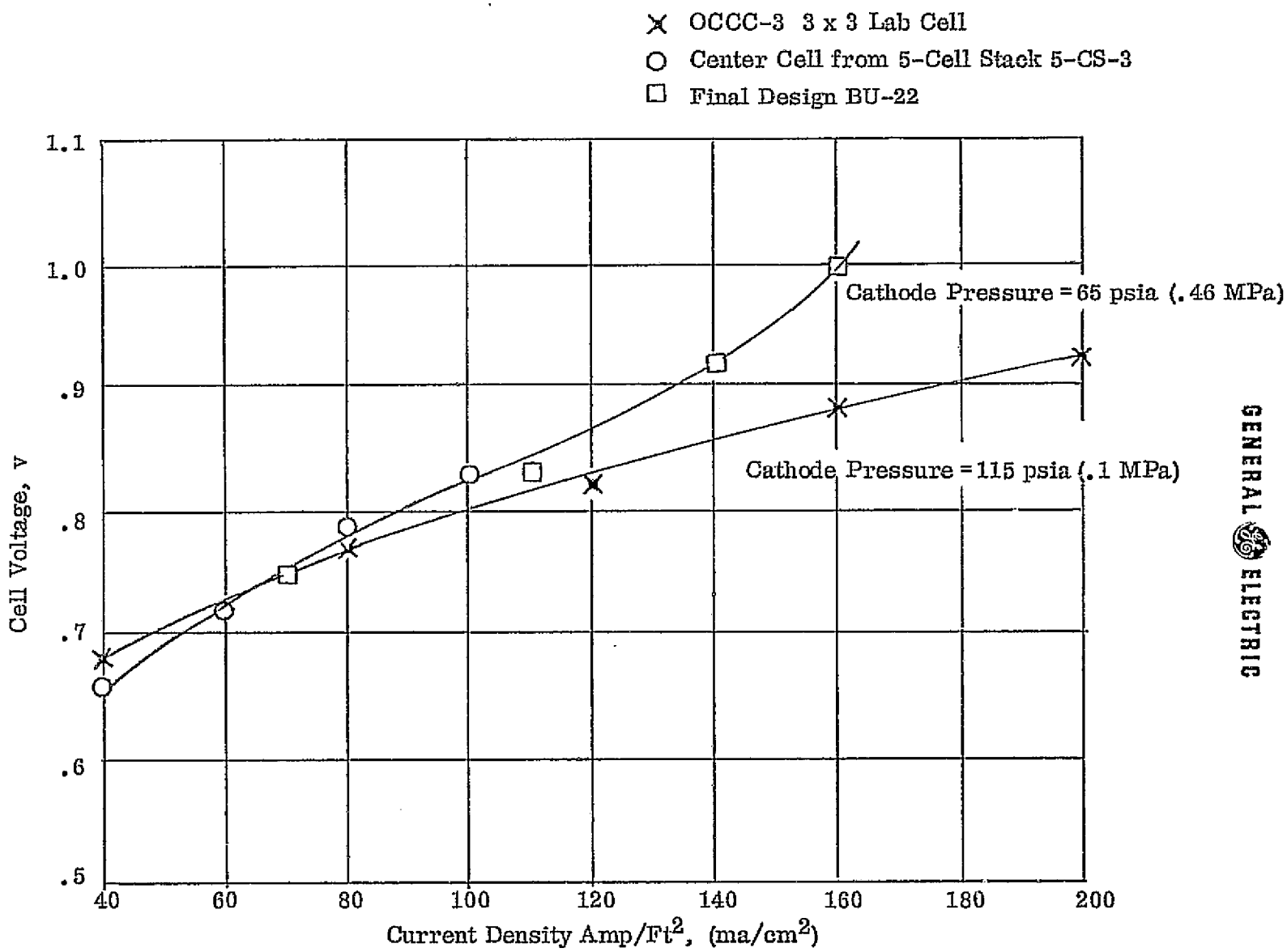


Figure 20. Comparison of Initial Performance of "Lab Cells" and Final Design Cells

itself. This has been shown to be a reliable seal. However, on the cathode side, the seal ring contacted the metal Separator/Heat Exchanger. It was questionable whether the metal-to-metal contact in that region would seal reliably.

Tests on BU-6 answered these questions. Figure 21 shows the effect of cathode pressure on performance. At low pressure, about 10 psig (.07 MPa), the diffusion polarization was severe. As the cathode pressure increased, the losses decreased.

It was next important to know the sealing limitation of the cathode. Figure 22 shows that the overboard leakage rate increased with increasing pressure, as expected. At 50 psig (.35 MPa) the leakage accounted for about 10% of the feed flow or product flow at 5 amp, and was judged satisfactory. The design point of the cathode pressure was therefore taken at 50 psig (.35 MPa) as a compromise between performance and leakage.

Representative Performance of Oxygen Compressor Cell

In this section we will discuss the performance of a final design compressor cell which was run over a period of five days at various pressures. The cell (BU-22) contained Zitex wetproofing DEX 201-122. The cell was shut down overnight and for one weekend during the test. Figure 23 shows the performance. There was about 0.2 volt performance penalty from low pressure to 2650 psig (19 MPa). After about 60 hours on test, the cell lost about 50 mv in performance at a given pressure. Decrease in performance was accompanied by an increase in resistance, as was noted with many other cells. Resistance could be enhanced by adding water to the anode when the cell was shut down, and subsequently blowing out the excess with nitrogen.

Effect of Cathode Wetproofing

The oxygen compressor does not require water from an external source nor does it form water in the overall electrochemical reactions. The water formed at the cathode is used at the anode with no net production or consumption. In theory, then, it should not be necessary to use wetproofed electrodes. If this could be achieved, the construction of the cell could be greatly simplified and made more inexpensive because there would be no need for the wetproofing application, nor for the electrode screen to carry current through the wetproofing.

During the course of the program, attempts were made to run without the wetproofing and also with different types of wetproofing. Figure 24 shows the results of five cells. The cells with the wetproofing, regardless of the type (teflon was the only material used) performed essentially the same, while the cell without the wetproofing layer was considerably poorer in performance. In the case of a sixth cell, BU 18A, without wetproofing, the performance at ambient pressure was as good as the

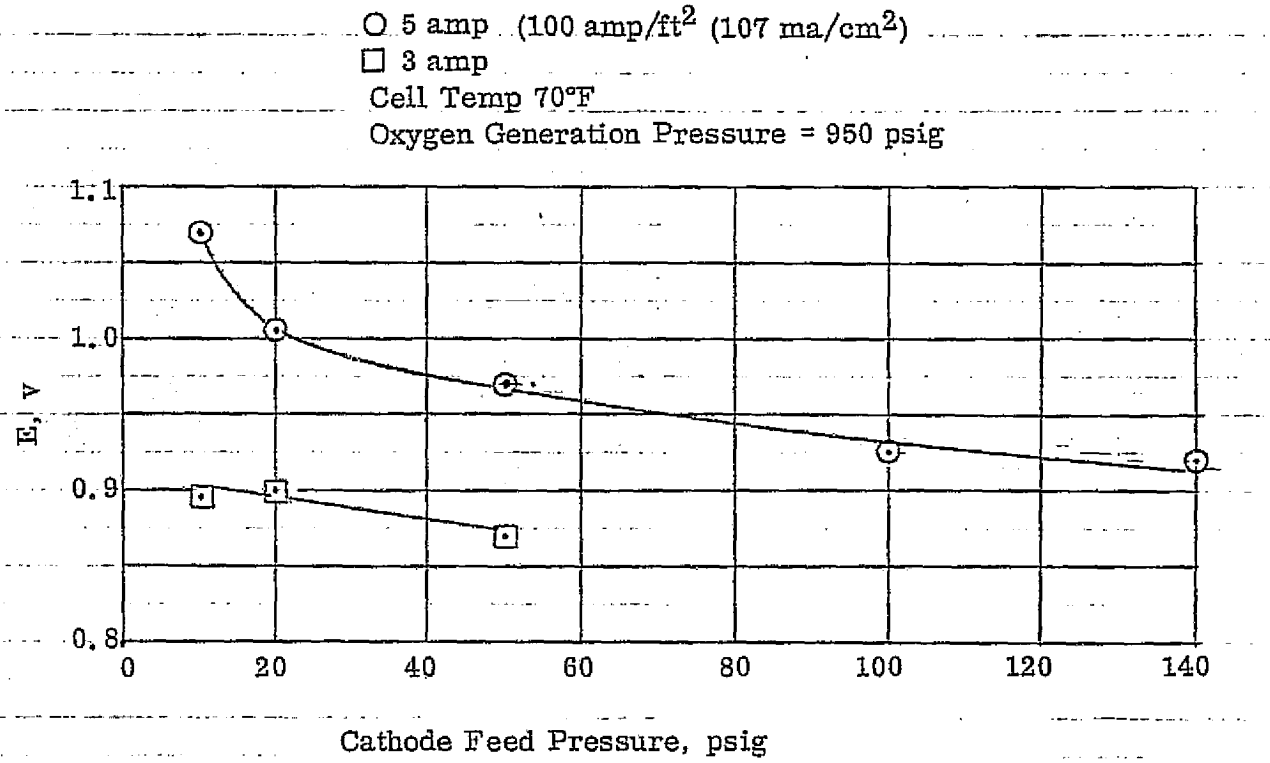


Figure 21. Effect of Cathode Feed Pressure on Oxygen Compressor Performance B/U 6

B/U 6 Single Cell Oxygen Concentrator
Hydraulic Cylinder Pressure = 3000 psig (21 MPa)
Temperature = 70 F (21 C)

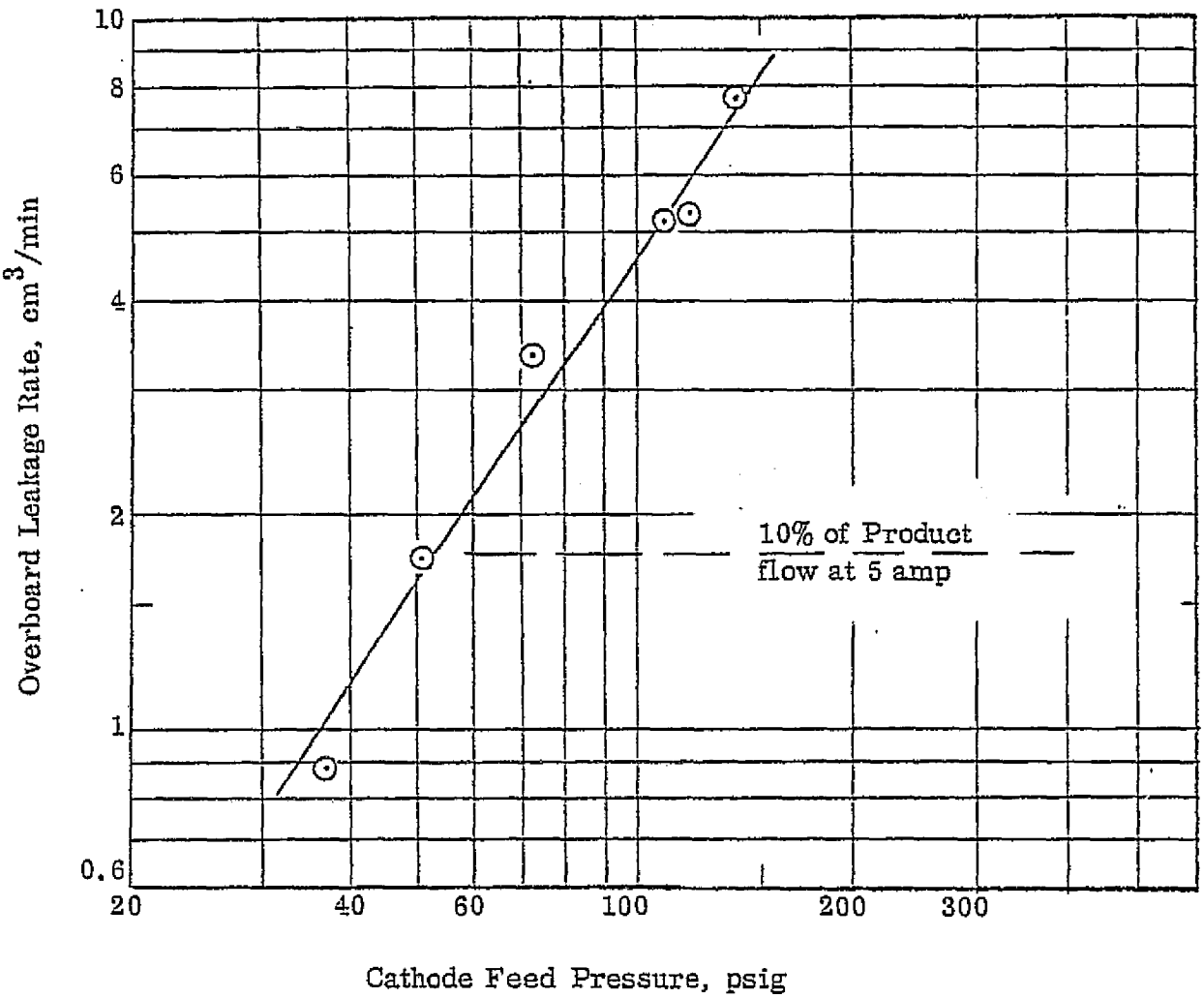


Figure 22. Cathode Overboard Leakage Characteristics

Time at Pressure Hr.	P Anode psig	Date	Time	
0	○ 0	10/3/74	1050	
3.2	□ 850	10/3/74	1404	
4.6	◇ 1620	10/3/74	1528	
10.8	△ 2300	10/4/74	1437	Restart at 0825
27.3	▷ 500	10/7/74	0848	Restart at 0820
30.2	▱ 1900	10/7/74	1115	
31.9	◺ 2400	10/7/74	1255	
52	◇ 1500	10/8/74	0839	Restart at 0816
53.5	◇ 2000	10/8/74	0945	
55.3	△ 2650	10/8/74	1134	
56.8	● 0	10/8/74	1302	
57.6	■ 500	10/8/74	1354	
58.8	◆ 1200	10/8/74	1504	
60	◪ 1900	10/8/74	1617	

Arrows indicate unstable operation

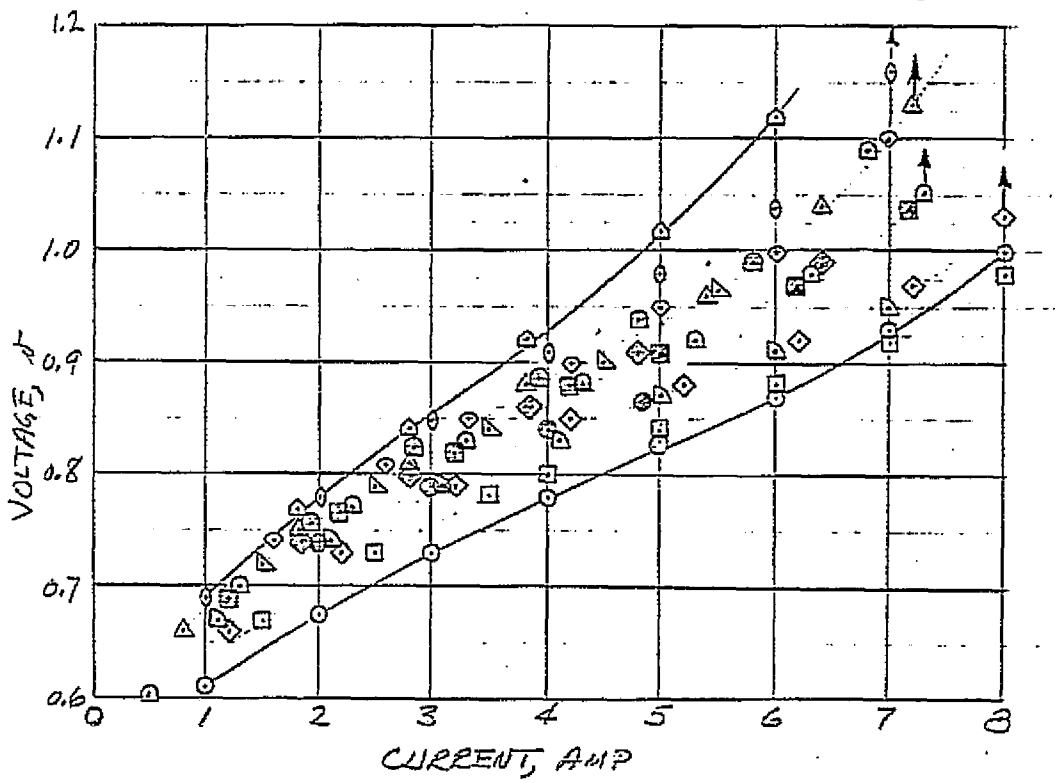


Figure 23. Performance - B/U 22 Single Cell 1/20 Ft^2

○ BU 12 Double Press Cathode, LNP. Ti Pd Screen in Anode 2600 psi (18 MPa)

□ BU 15 Double Press Cathode, LNP. 2500 psi (17.8 MPa)

◺ BU 22 Single Press Cathode, Zitex DEX 201-122. 2400 psi (17 MPa)

△ BU 25 Single Press Cathode, Zitex E846B-122D. 2000 psi (14 MPa)

⌂ BU 7A No Wetproofing 950 psi (6.7 MPa)

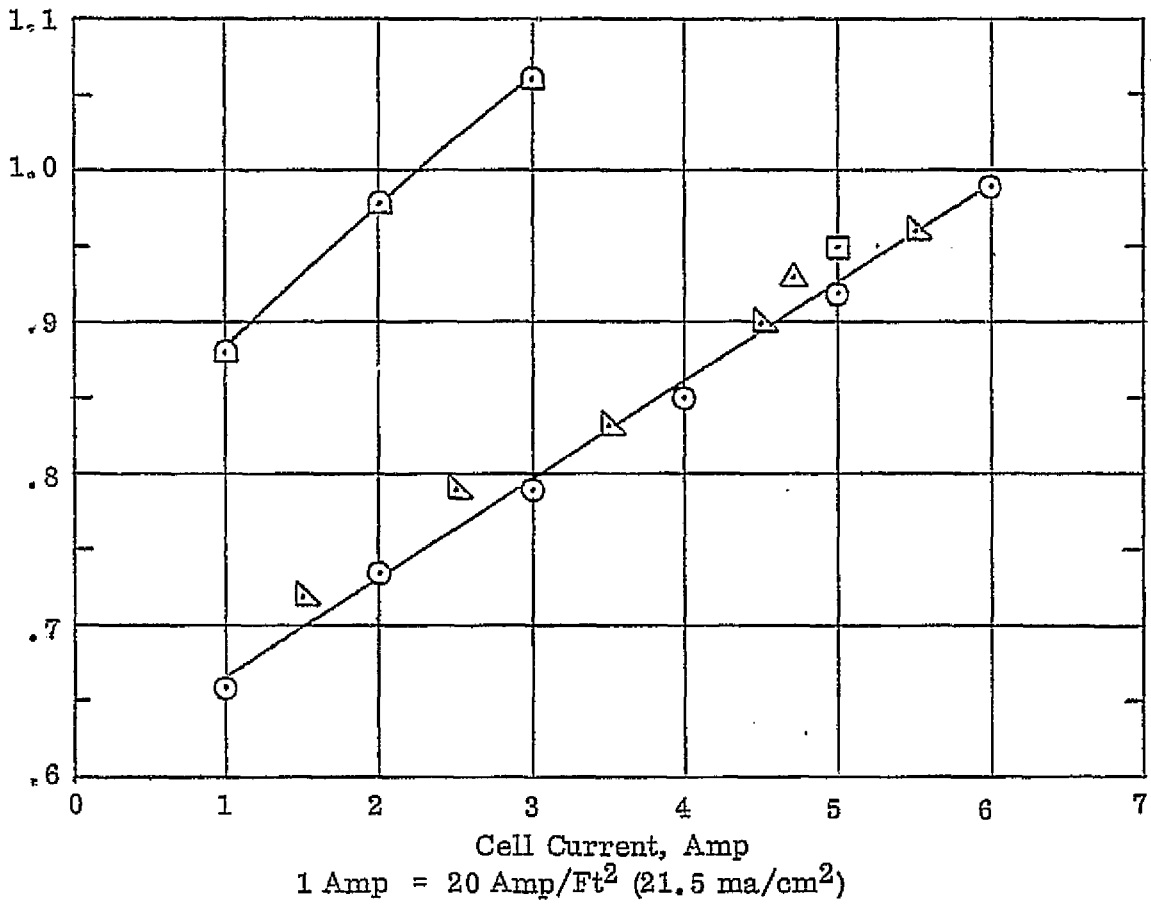


Figure 24. Comparison of Cells with Different Cathode Wetproofing

wetproofed cells, but deteriorated badly at slightly elevated pressures. At this time we must conclude that wetproofing is needed, especially if water is periodically added to the anode

Diffusional Losses

As discussed previously, the computer program predicted the diffusional current due to migration of high pressure oxygen at the anode to the cathode. This is depicted in Figure 25 together with some results of various cells. The measurements of diffusion loss were made by measuring the output from the anode compartment using an ambient pressure wet test meter. Many of the measurements indicated that the diffusional losses were lower than predicted, probably indicating that the cell was drier than normal. The five cell stack showed about 36% higher than normal diffusion and may have been leaking slightly. Overall, the values of Faradaic efficiency were 85% or better based on a design current density of 100 amp/ft^2 (107 ma/cm^2).

Also it is important to note that the diffusion of .02 inch (.5 mm) thick membrane was about equivalent to .01 inch (.25 mm) membrane over a test period of about 16 hours.

Life Testing

Throughout the contract several attempts were made to achieve long term stability at high anode pressure. Rather than encumber this report with chronological descriptions of all cells, two typical cells, one made with the standard General Electric LNP wetproofing two press cycle, and the other made with a single press cycle using Chemplast Corporation Zitex 846B-122D teflon will be discussed.

BU-15 contained a cell made with LNP wetproofing and a two stage application of the wetproofing.

This membrane and electrode assembly was made according to the optimized method used on air/oxygen concentrators. That is, the cathode and anode were applied to the membrane at 750 psig (5.4 MPa) and 350 F (178 C) in a hydraulic mold. The wetproofing layer was then removed and replaced with a new layer applied at 250 (1.8 MPa) psig and 305 F (152 C). The two-stage process was developed under other contracts and the process had the following characteristics:

a) The first stage at high pressure and temperature insured good adhesion of the anode, but compacted the cathode wetproofing layer excessively.

b) The second stage at lower pressure and temperature allowed the new wetproofing layer to remain open to prevent diffusion polarization.

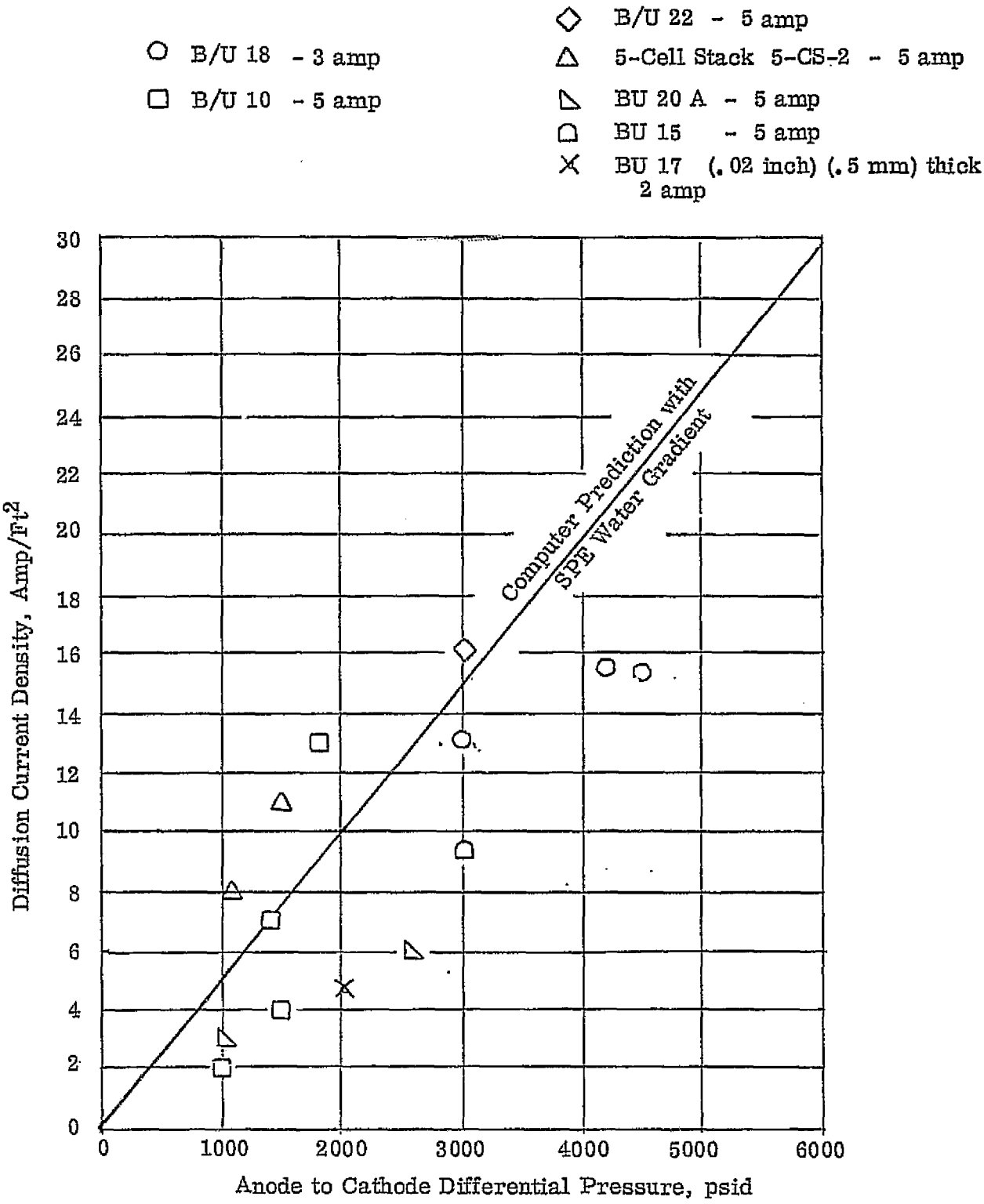


Figure 25. Oxygen Diffusion Losses in Cells

Figure 26 shows the history of BU-15. Performance was fairly stable for periods of about 20 hours up to anode generation pressures of 2500 psi (18 MPa). At 3000 psi (21 MPa) the voltage increased sharply over a period of five hours. The cell resistance increased from an initial 16 m-ohm to 33.5 m-ohm, indicating cell drying. The cell leaked at 3000 psi and testing was discontinued. As with other leaky cells, no sign of damage to the cell could be found, nor could any cell punctures be found.

BU-53 was the next to last cell tested under this contract. This cell contained the standard Chemplast Zitex 846B-122D using a single stage manufacturing process. The process consisted of applying the wetproofing layer at 750 psig (5.4 MPa) and 350 F (178 C) in a hydraulic mold. This cell would not run initially because the wetproofing was drowned during manufacture or storage, a common occurrence. After electrolysis, generating hydrogen on the normal oxygen anode, and generating oxygen on the normal oxygen cathode, the cell performed well. Figure 27 shows the history of this cell. During the first hundred hours of operation, performance deteriorated when the cell was left to operate for periods up to 24 hours. Note that cell resistance rose to 32 milliohm (from an initial 15) at the 106 hour point. The cell was reconditioned by adding water which at first did not improve the cell much, then by electrolysis, which improved the performance. Again allowing the cell to operate for ten hours caused high voltage and resistance. At the 180 to 250 hour interval, fairly stable operation could be achieved at design current density of 100 amp/ft^2 (107 ma/cm^2) at anode pressures from 2000 to 3000 psi (14 to 21 MPa) if the cell were shut down overnight or on weekends. During shutdown the anode pressure was not relieved, but kept active except for normal depressurization because of diffusion through the membrane. These tests show that:

a) Stable performance at high pressure for periods greater than 10 to 20 hours of continuous operation is not readily achievable.

b) Stable performance can be achieved by intermittent shut down periods. The length of the shutdown necessary has not been determined.

c) A degraded cell can be rejuvenated by rewetting and electrolyzing. It is not always necessary to electrolyze.

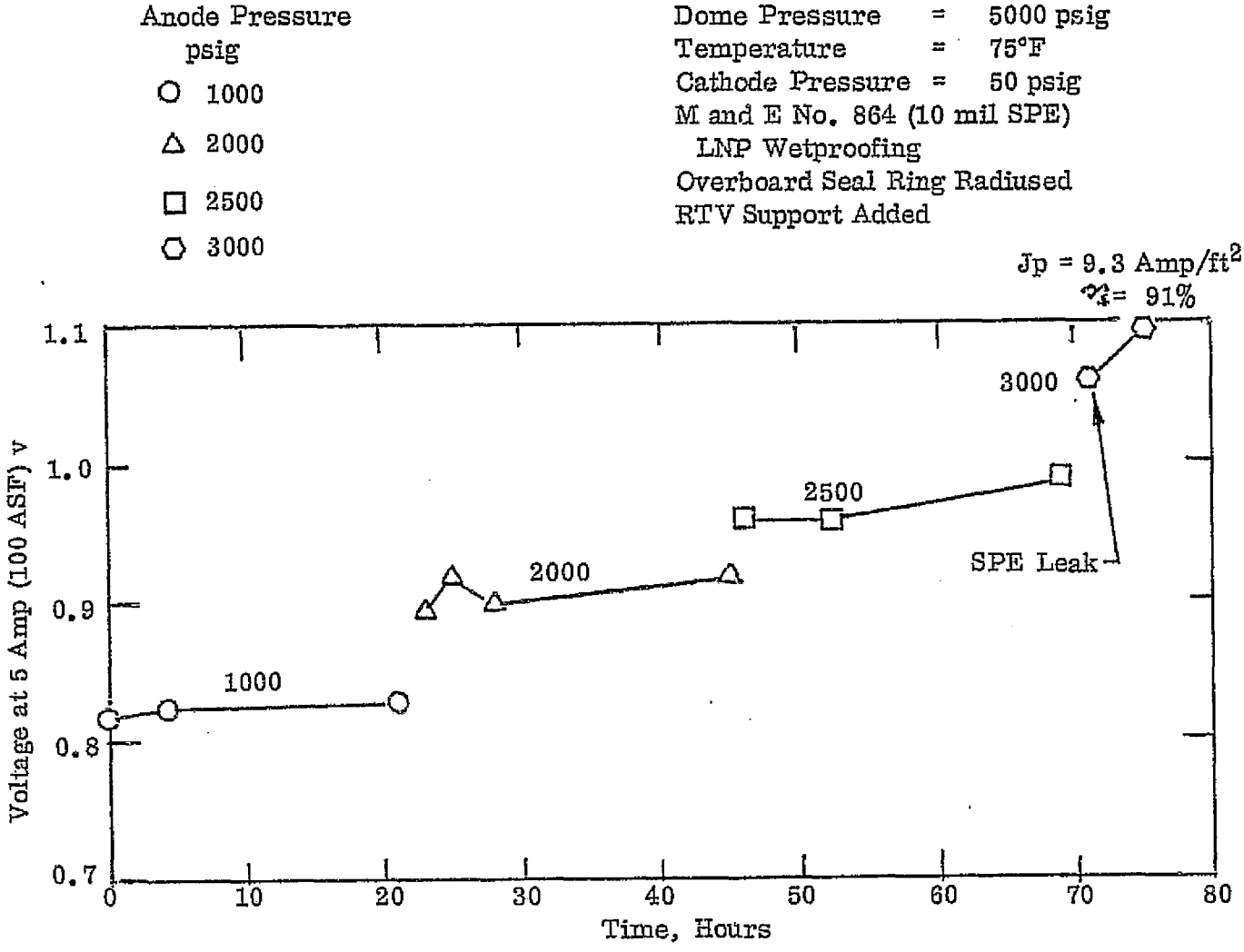


Figure 26. Test History of BU-15

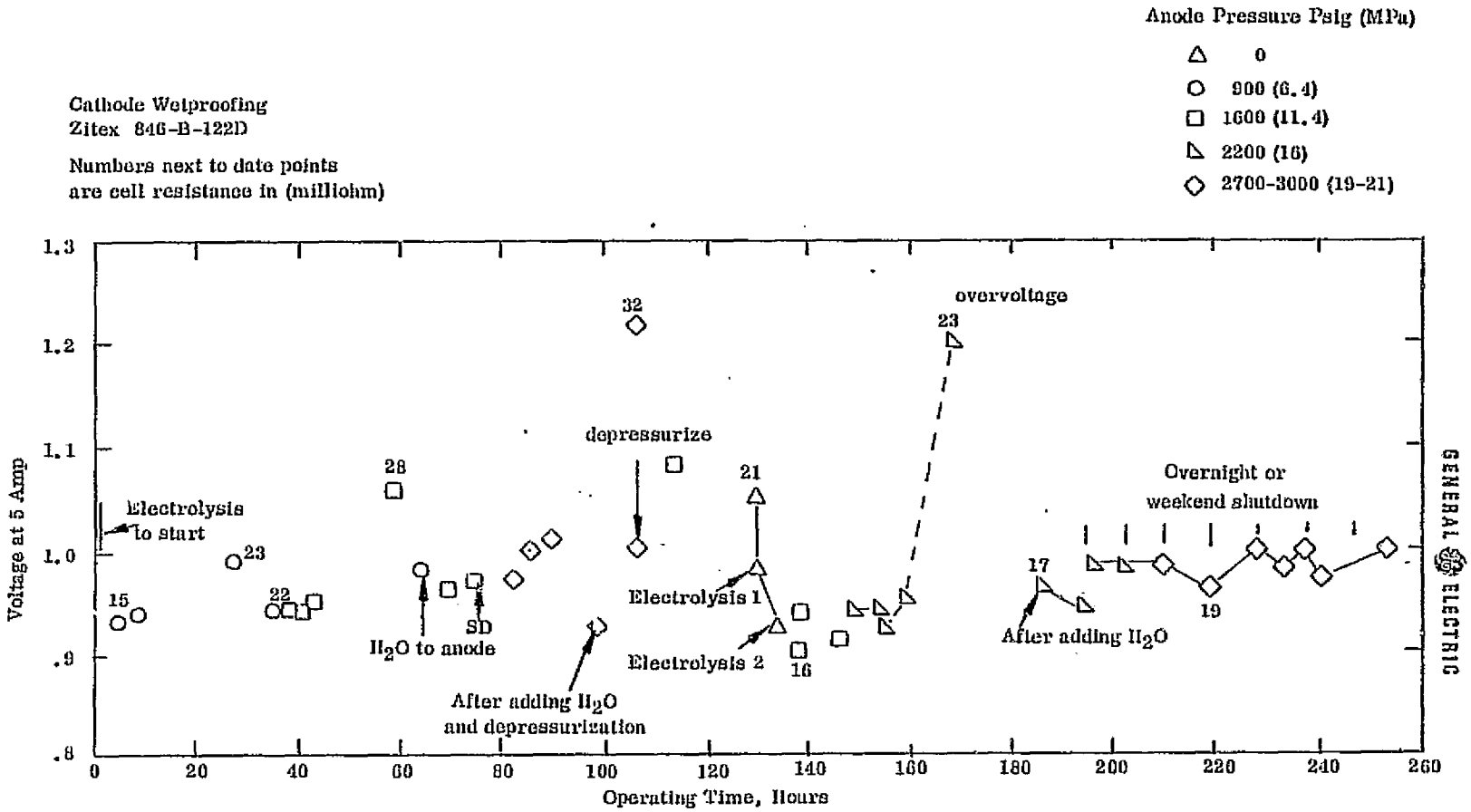


Figure 27. Test History of BU-53

Multi Cell Stack Testing

Five cells were manufactured with the thin wetproofing layer (Chemplast Zitex DX201-122 and assembled in a stack. The first assembly resulted in a short circuit in the center cell (Cell No. 3). The hardware was modified to prevent cell damage by potting unsupported areas with silicone rubber RTV compound. The second assembly with new cells in the number two and three positions did not perform because the new cells were found to contain bad membrane. Finally, a third stack with the number two and three cells replaced again was put on test.

Each cell was equipped with voltage tabs on the gas separator/heat exchangers so that individual cell voltages could be measured. Also, iron constantan surface thermocouples were welded to the gas separators to measure fin temperatures.

Figure 28 shows the performance of cells in the stack. The center cell (Cell No. 3) performed the best and was the highest in temperature. This was expected, since the center cell was more ideally insulated from the heavy end plates than the outboard cells. The fin temperature on the center cell measured 90 F (32 C), while the others were 85 F (29 C). The temperatures remained at those values during steady state operation. The stack performed well up to 1500 psi (11 MPa), the center cell performing close to ideal laboratory cells run at 100 F (38 C). The end cells performed similarly to single cells which ran naturally at lower temperature.

Faradaic efficiency was normal up to 1500 psi (11 MPa) anode pressure.

During the continued testing of the five cell stack, it was found that at 1000 psi (17 MPa), the Faradiac efficiency was 92%, about what would be expected from gas diffusion across the membranes. After about two hours of additional testing, the unit was found on open circuit due to stack voltage above 5.2 volts. Concurrent with this it was found that the Faradaic efficiency thereafter was only 25%, indicating a leak. Leakage was indeed found to be internal, either across the seals or across one or more membranes. Upon depressurizing the stack and then beginning operation again, leakage was minimal at 1000 psi (7 MPa) but began again in two hours. This indicated that the seals were not functioning properly.

The stack was torn down and a test program begun to determine how many cells could be sealed in a stack. It was decided to begin by testing one cell, then adding cells one at a time until leakage appeared. Up to two cells could be sealed adequately. Figure 29 shows the diffusion and leakage characteristics. It shows that leakage does not occur in one or two cell stacks until the anode pressure was 500 psi (3.5 MPa) below dome pressure. This was considered normal, since it takes about 500 psi to flatten the surface of the membrane in the seal area.

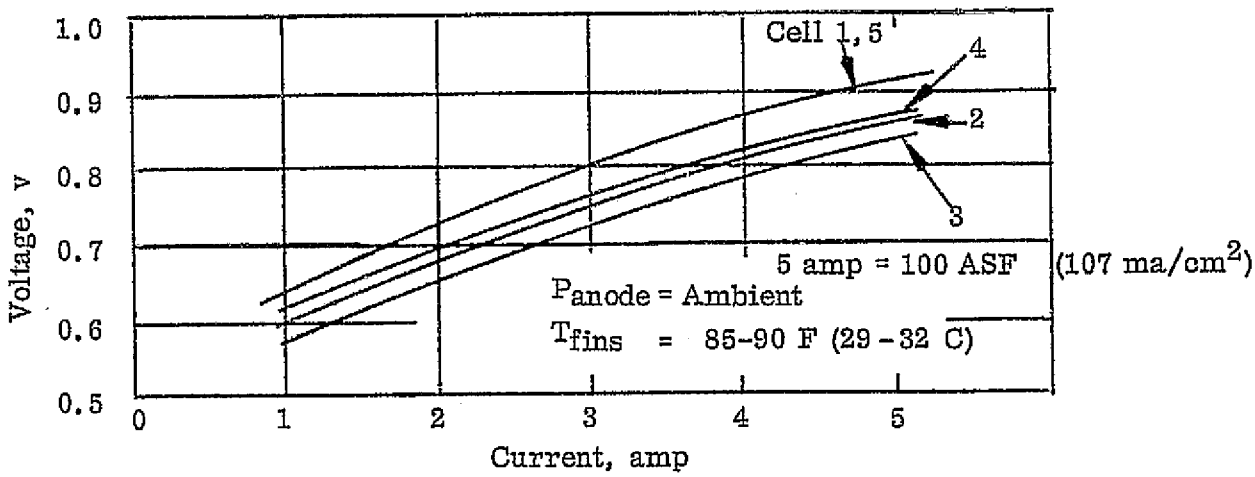


Figure 28a. Performance of 5 Cell Stack 5-CS-3

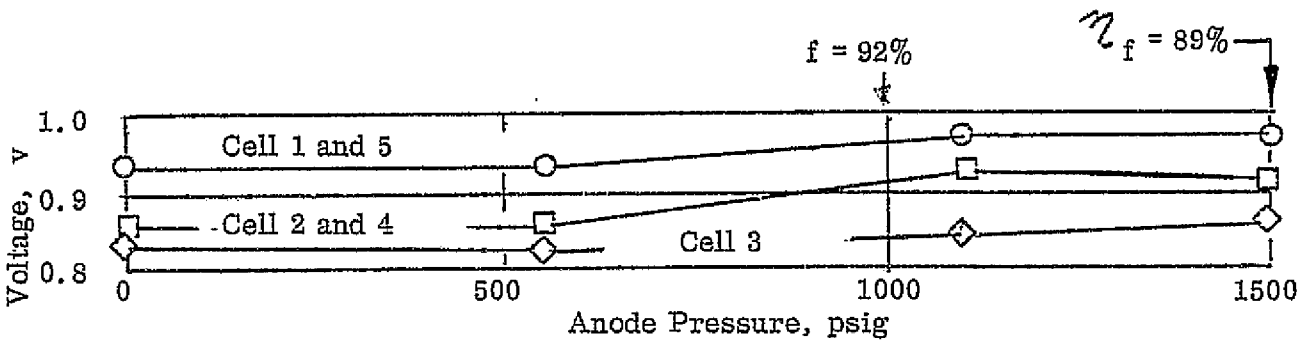


Figure 28b. Performance vs. Generation Pressure

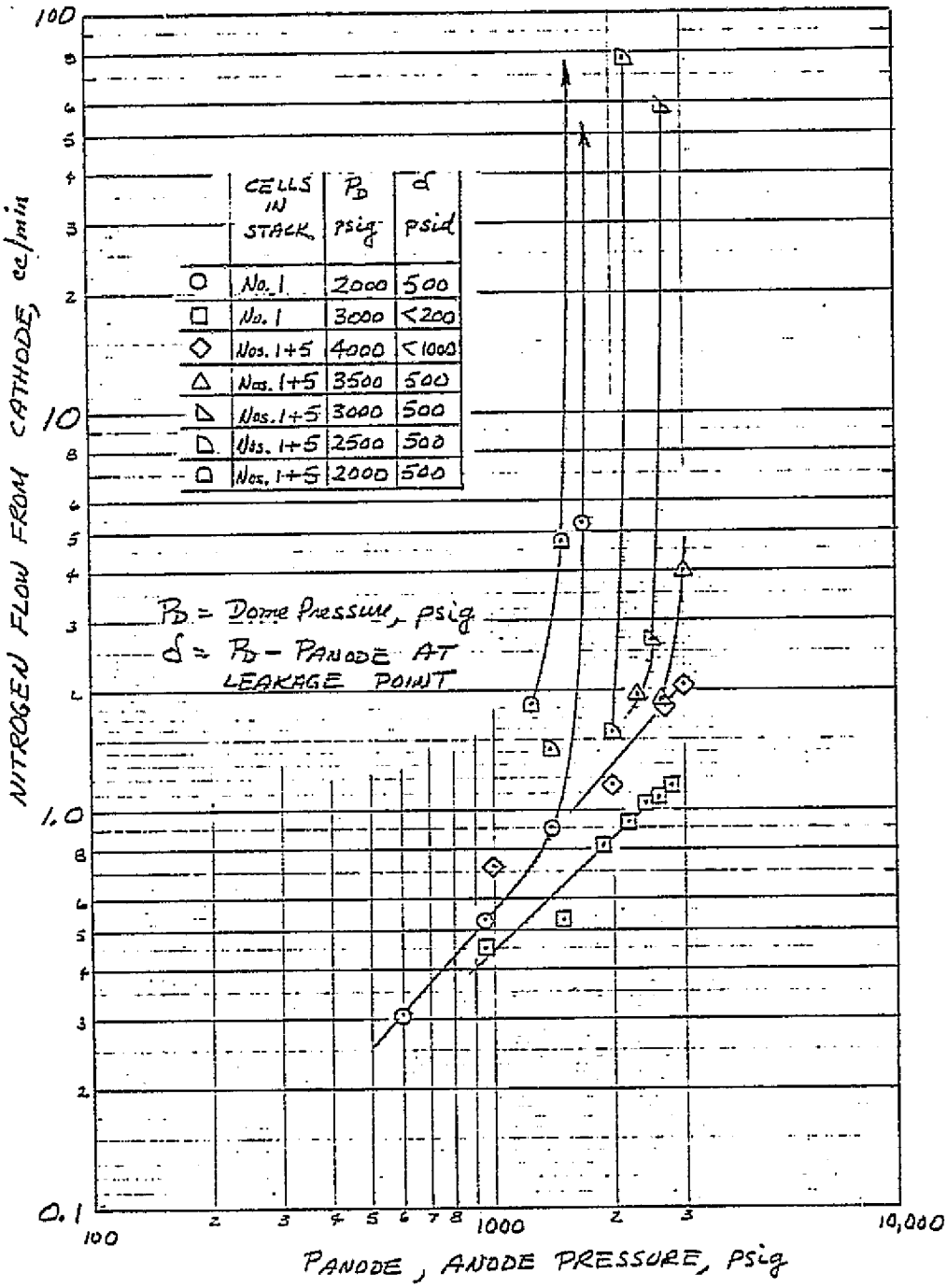


Figure 29. Leakage Characteristics of 1 and 2 Cell Stacks

When a third cell was added to the stack, the stack leaked profusely at about 800 psi (5.7 MPa). The cell was removed and found to seal adequately when tested alone. To this point, then, it was shown that the leakage was due to poor seals, and not to cross membrane leaks. It was theorized that since the separator plates were relatively stiff, they were resisting the pressure applied by the hydraulic pistons on the seal shims. The piston faces were machined to a smaller area where they contacted the shims in order to get force amplification. Also, more shims (Aclar) were added to increase the port seal heights for better contact.

Various combinations of cells were tested and some results are shown in Figure 30. The original stack leakage was high, and once leakage was initiated, the stack did not reseal. The reworked stack sealed up to 1500 psi but leaked above that value. Cell No. 3, which when added to Cells 1 and 5 caused leakage, did not leak as a single cell. Cells 1 plus 5 and 4 leaked similarly to the stack. Cell No. 4 was subsequently tested alone and found to act similarly to the reworked stack, that is, sealing up to 1500 psi and then approaching the full stack characteristic.

Upon examination of the hardware of cell no. 4, the stackups were correct, except that in the region of the high pressure port the porous titanium was about seven mils thinner than normal. This indicated that the porous support was collapsing under the effect of dome pressure, requiring extra shimming to keep pressure on the seal.

More importantly, the electrode screen of cell 4 seemed to be protruding through the membrane. This was caused by the bending of the cell under pressure as shown in Figure 31. The cell was redesigned so that the electrode screen was smaller in diameter and therefore removed from the flex region.

Five new cells were made and assembled in old hardware. The stack, BU-29, was leak tight to 2500 psi, but upon operation, leakage occurred at 600 psi with the hydraulic cylinder at 5000 psi (36 MPa). No short circuits were present, indicating that the screen was not penetrating through the cell. Leakage, therefore was probably due to seals relaxing with time.

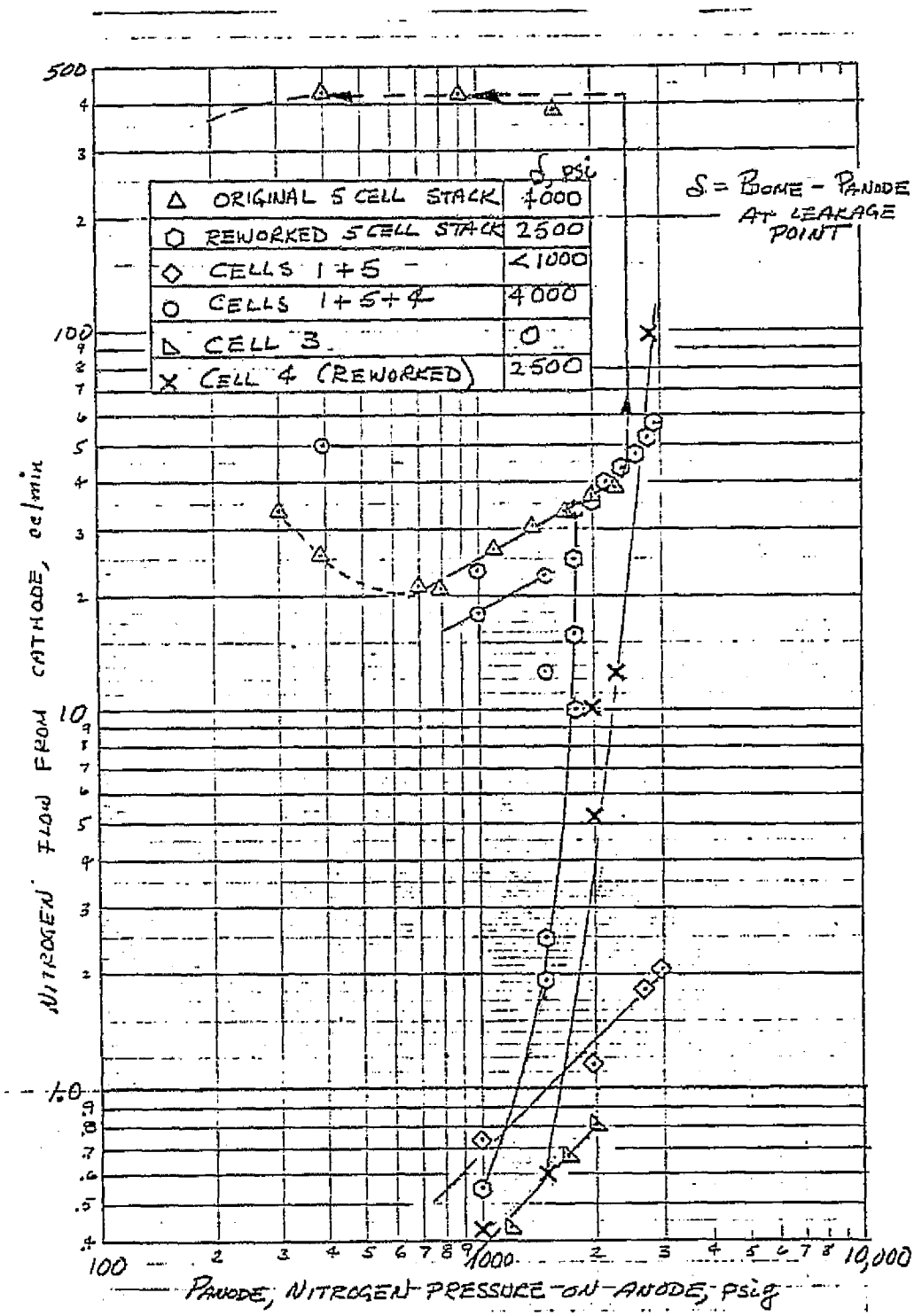


Figure 30. Summary of Stack Leakage

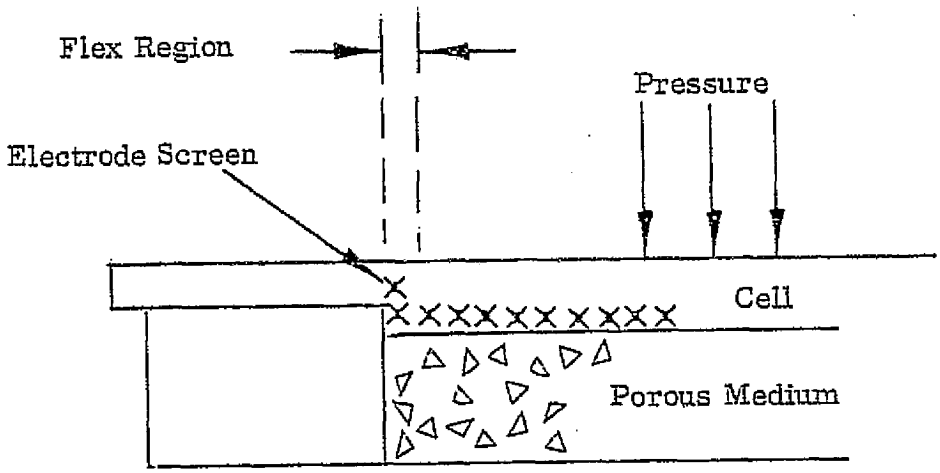


Figure 31. Pictorial Representation of Flexure of Cell and Electrode Screen

Compression tests were run on the porous titanium, indicating that the modulus was rather low and the compression set high. The measurements are discussed elsewhere in the report. The results indicated that increased thickness was needed in the port seal shims.

Consequently, the approach taken was to use additional shims in the port seal areas and to check the sealing on cells simulated by Aclar, a plastic similar in composition to the membrane. A five-cell Aclar stack (BU-30) was assembled using shim thickness (Figure 32) of

t_1 = .038 inch (1.0) mm

t_2 = .043 inch (1.1) mm

This stack leaked. Upon disassembly, the low pressure port seals (t_2) looked proper, since the hydraulic pistons were pushed slightly into the hydraulic end plate, a result of the shims being slightly thicker than necessary. The high pressure port seals looked improper, since the hydraulic pistons protruded out of the end plate indicating the shims were too thin. The next series of Aclar cells were made with

t_1 = .048 inch (1.2) mm

t_2 = .043 inch (1.1) mm

It was also decided to test a single "cell" for sealing capability, then add one "cell" at a time until five together was achieved. BU-32 thru BU-36 were one thru five Aclar cell stacks. They all achieved sealing to 5000 psi (36 MPa) of nitrogen applied to the anode using a hydraulic cylinder pressure of 5000 psi (36 MPa). In general, overboard leaks occurred at 5000 psi (36 MPa) and resealed at 4600 psi (32 MPa). This sealing to within 400 psi (3 MPa) of dome pressure was very encouraging and led to the initiation of the program to achieve the same results at 3000 psi (21 MPa) anode pressure with 5000 psi (36 MPa) hydraulic cylinder pressure on real cells.

The cells used were those previously removed from the five-cell BU-29. A single, two-cell, and three-cell buildup all held 3000 psi (21 MPa) with about 1 cc/min-cell diffusion rate of nitrogen. Pressure was held for 15 minutes and the test discontinued.

BU-40 contained four real cells. This showed the same sealing characteristics (1 cc/min-cell at 3000 psi 21 MPa) and was allowed to remain at pressure. Forty minutes later the stack was checked and found to have an enormous leak, much worse than the usual seal leaks and more likely similar to a torn membrane.

Cell number four was removed from the stack and the remaining three cells tested. The same magnitude of leak occurred, indicating not cell number four, but rather one of the upstream cells was damaged.

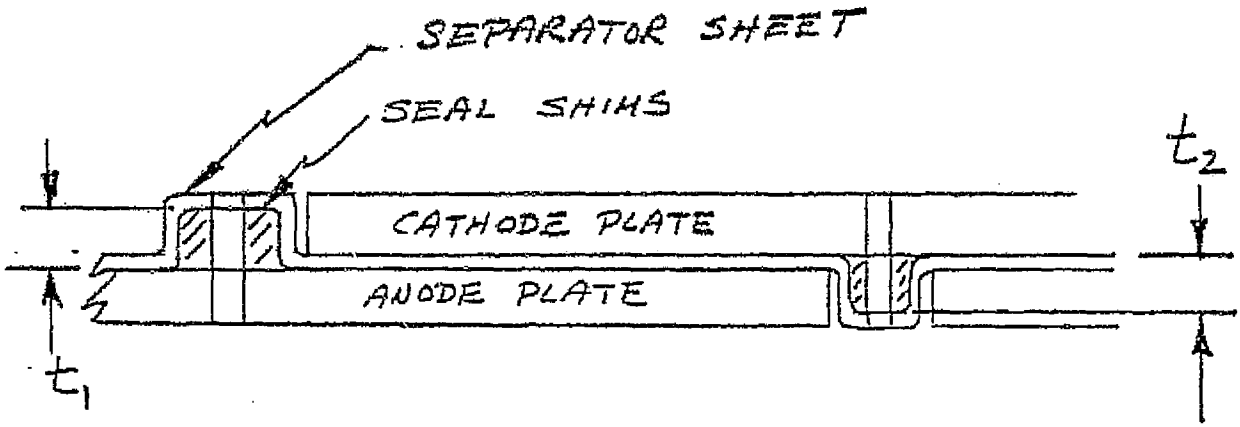


Figure 32. Shim Configuration

It was later found that Cell No. 1 was the leaky cell. Subsequent substitution of Aclar for the cell was leak tight, indicating the hardware seals were probably adequate.

Microscopic examination of Cell No. 1 did not reveal any punctures. An attempt was made to find the hole by applying Bromcresyl Purple indicator to one side of the cell while the other side contacted paper towels saturated with sodium carbonate. When the indicator (yellow on the cathode side) seeped through, it stained the carbonate purple. This technique worked on an old cell deliberately perforated with a pin, but did not show any holes in Cell No. 1. In summary, as far as cell punctures are concerned, no holes have been found in cells. This leads one to conclude that either the holes are too small to detect or that all leaks were seal leaks.

Since contract funding at this point in time was becoming exhausted, no further work was expended on stacks. In order to provide adequate sealing, a few new batches of cells would have to be made, port thicknesses changed and an empirical program run. It was mutually decided that other tasks on single cells would be more productive in generating design data for the compressor.

It can be concluded here that multi-cell sealing can be accomplished using plastic in place of the cells. Sealing of the real cells may be a matter of first using porous niobium instead of porous titanium to increase the compressive modulus, and secondly, adjusting port shim thickness to provide the proper stack-up for the seals.

Strength of Materials Measurements

It was felt that the leakage problem in multi-cell stacks could have been due to inadequate support of the porous supports, specifically the porous titanium, which tended to suffer a permanent deformation under the load of the hydraulically clamped end plates.

Measurements were made of stress-strain and compression set on the porous titanium support.

The measurements were made using the hardware as a compression device as shown in Figure 33. The specimen of known projected area was placed on the hydraulic piston. Lead pellets were placed in three equidistant locations around the specimen and the static end plate was installed parallel to the hydraulic end plate. The hydraulic piston was then pressurized to a selected pressure. After disassembly, the thickness of the lead shot indicated the strain undertaken by the specimen during test, assuming that the lead did not spring back when the end plates were separated. The thickness of the specimen after test was an indication of the compression set of the material under load.

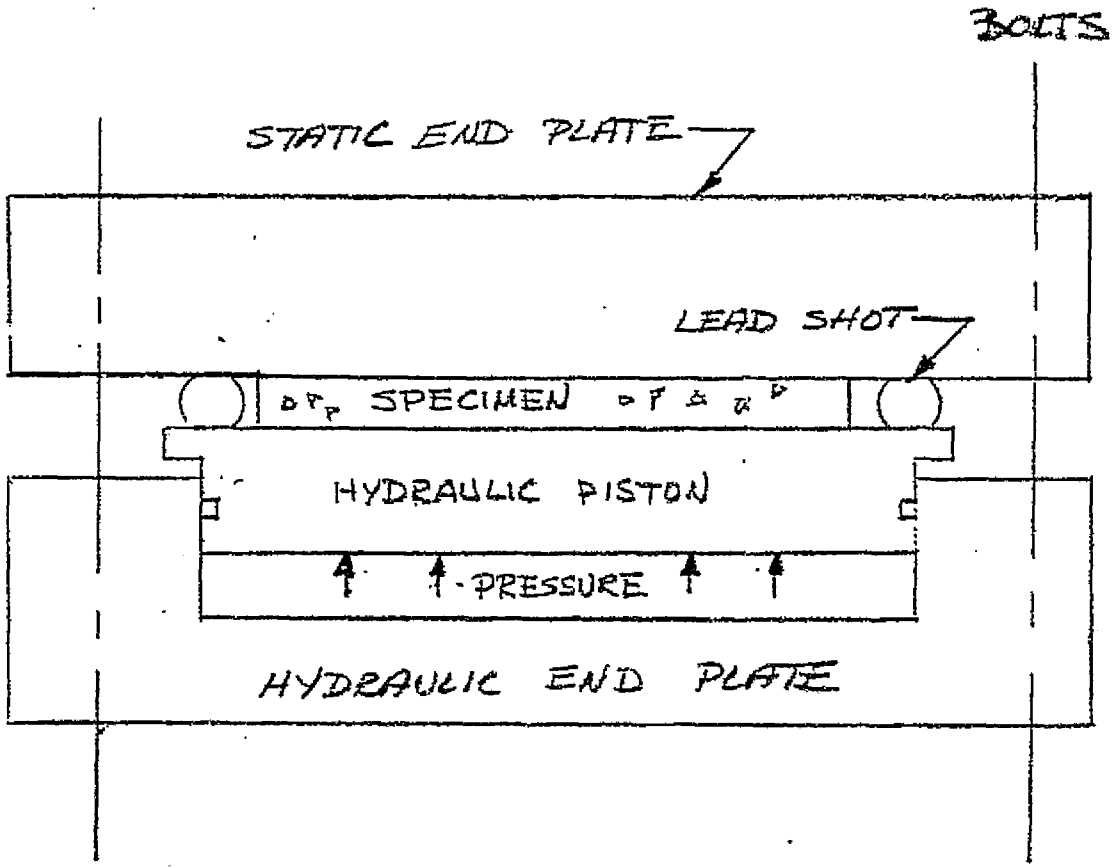


Figure 33. Compression Strain Test Apparatus

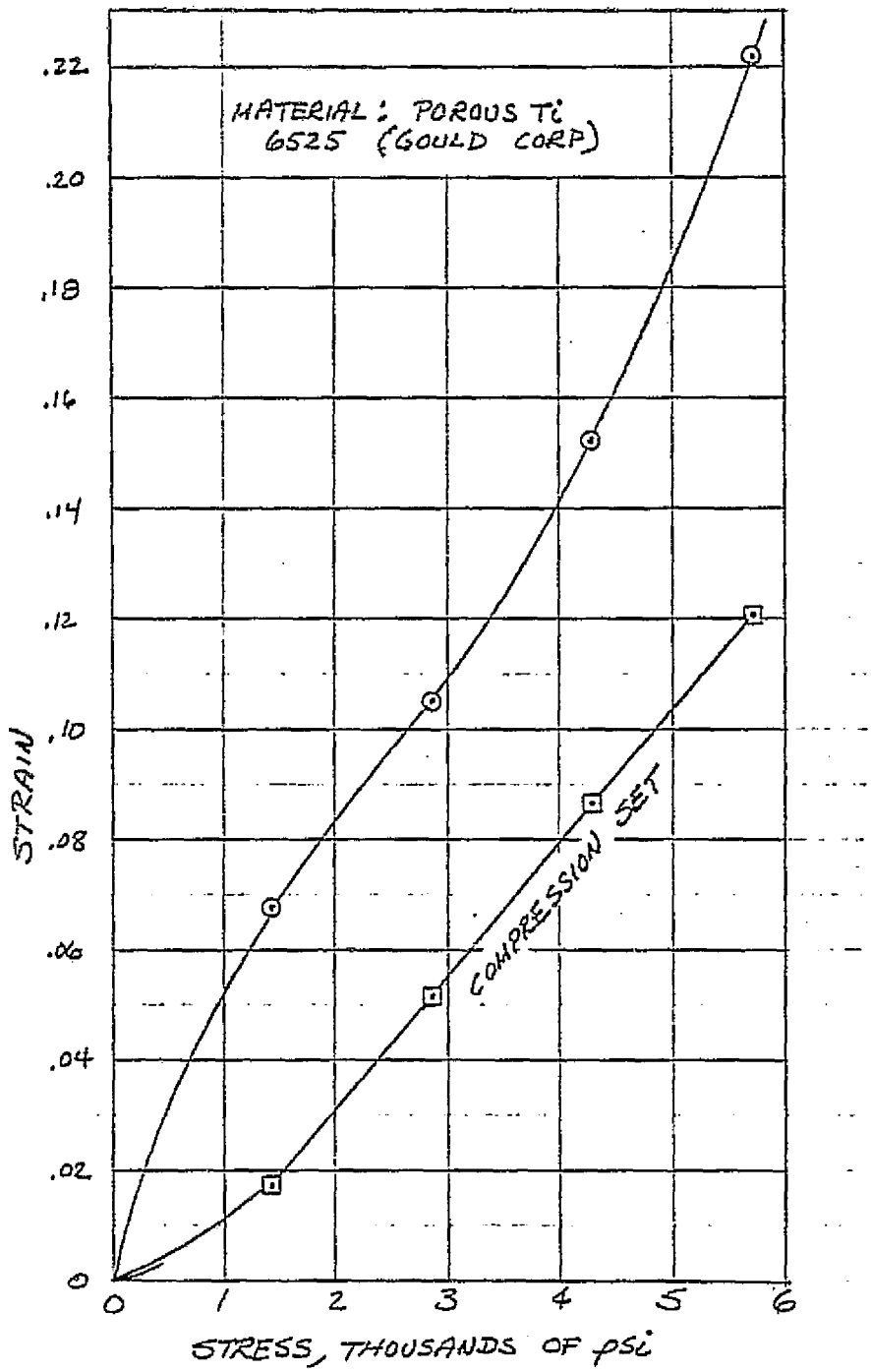


Figure 34. Mechanical Properties of Porous Titanium

Figure 34 shows the results on the porous titanium No. 6525 manufactured by Gould Corporation. Figure 34 indicates that a dome loading of 5000 psi (36 MPa) will strain the material almost 20% and cause compression set of about 10%. This indicated that a .03 inch (.76 mm) thick porous plate would deflect about .006 inch (.15 mm) and therefore would require an additional .006 inch of shim to keep the seal region tight. This corrective action was taken on the cells made later in the contract.

A check of the strength of the porous tantalum was scheduled at a later date, but this was not possible since the hardware was damaged in cell testing in the interim.

Effect of Edge Current Collection from Anode

One possible cause for the loss in performance above anode pressures of 2500 psi (13 MPa) was thought to be loss in contact pressure between the anode electrode and the porous plate serving as the current collector. The theory was that at the high pressure in the anode compartment would tend to separate the cell from the anode support and lose electrical contact. This would result in higher cell resistance and also areas where the cell would not operate, since the untouched catalyst does not conduct electricity along its length very well.

Cells were made with current collector screens imbedded in the anode catalyst. For these types of cells, even if a portion of the cell were not adequately touching the porous support, electrons would still be conducted by the screen to the catalyst.

BU-44 used such a cell. It was found to leak at 2600 psi (18.5 MPa), with no reseal until the pressure was dropped to 1000 psi (7 MPa). This was considered unacceptable and the cell was removed from the hardware and reassembled into new hardware (BU-45).

BU-45 sealed to 2900 psi for a half hour, and was subsequently run on oxygen. Figure 35 shows the results of operating this cell. On a static test of nitrogen pressurizing the anode, the cell resistance remained fairly invariant as compared to a cell with no current collector imbedded in the anode catalyst. Above 1400 psi the resistance increased more rapidly, about three times the rate as at lower pressure.

In the dry mode, that is, with no water injected into the anode, performance was poorer than other standard cells. This may have been due to the fact that this cell had been previously removed from its original hardware. In so doing, the wetproofing layer which tends to stick to the porous plate must be pulled away and may lose its bond to the cathode catalyst.

Inspection of the resistance curves shows that even though the open circuit resistance was not a strong function of pressure, it was a function of pressure when the cell was operated at current. We know that proton pumping will increase the cell

Symbol	Anode Condition	Parameter
□	Dry	Resistance on open circuit
◇	Dry	Peak resistance at 5 amp
◺	Dry	Voltage at 5 amp
△	Dry	Resistance on open circuit after operation
◿	Wet	Voltage at 5 amp

Dome Pressure = 4800 to 5000 psig

Temperature = 70 - 75°F

Numbers near data points are cell resistances, milli-ohm

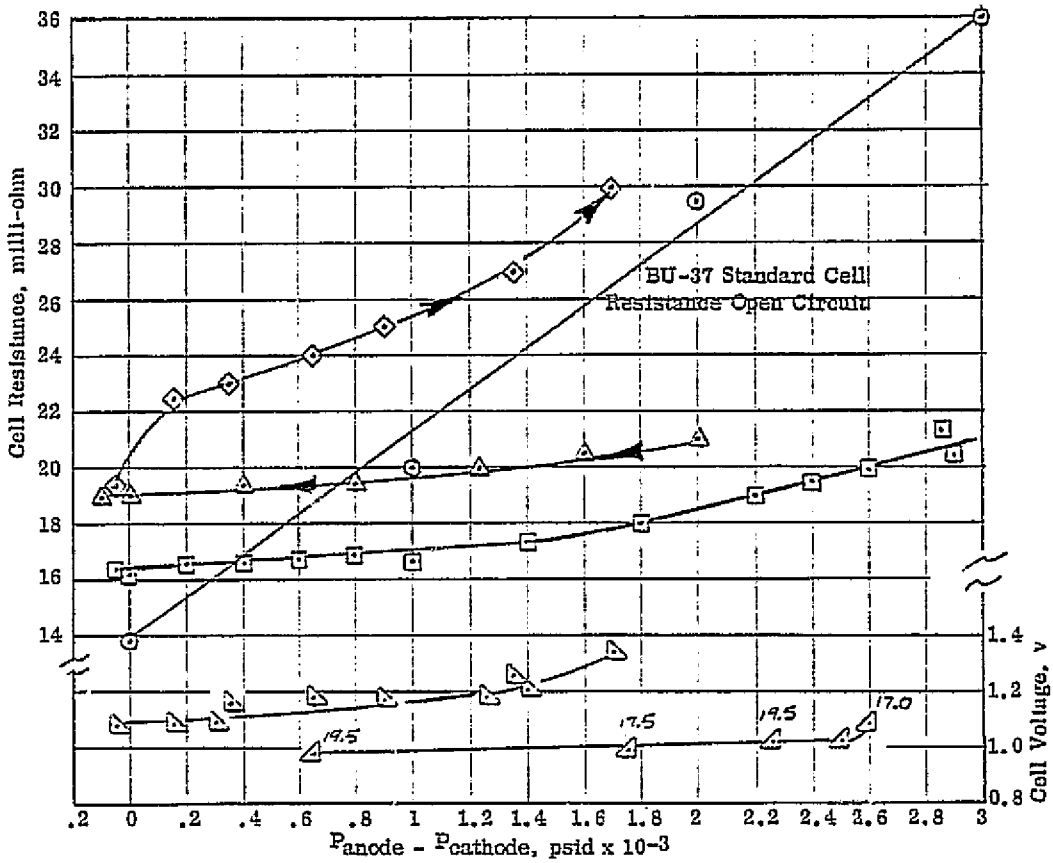


Figure 35. Effect of Pressure and Operating Mode on Resistance and Performance of BU-45 (Edge Collection Anode)

resistance by creating a water gradient (dry anode to wetter cathode). There seems to exist an interrelated effect of pressure combined with operation which aggravates cell resistance.

Figure 36 shows the resistance recovery of the cell after switching to open circuit from a 5 amp load. In two to four minutes, depending on initial current, the water redistributed and the cell approached normal static resistance.

The performance (two lower curves in Figure 35) shows poor performance under dry anode conditions and this may have been diffusion polarization as discussed above. A series of tests were made by injecting water into the anode, first by blowing it in with nitrogen, and then by pumping it in with a positive displacement pump. Under these conditions, performance was much improved. It must be noted, however, that the performance improvement did not come without complications. Once water was injected to a dry anode, performance improved but quickly degraded as the cathode became drowned by protonic pumping. A high cathode purge rate had to be maintained to keep the cell from drowning. This is a complication in a real system, first because a high pressure pump is needed to inject water to the anode, and a high purge rate is needed to keep the cathode clear. The water then must be separated and recycled to the pump.

It was hoped that a small quantity of water could be injected into the anode and then stop the water flow, in a sense, storing enough water to keep the anode wet for a long time. In theory, this is true, a full anode would hold enough water for about four hours. However, the combination of proton pumping, anode gas production and high cathode purge served to expel enough water so that cell voltage tended toward electrolysis within five minutes of water cut off.

A second attempt at improving anode current collection was made with a new cell (BU-50).

This consisted of a cathode with thin (Zitex DX201-122) wetproofing and a current collector screen imbedded in the anode. Performance was fairly steady up to four amps for about 20 hours (Figure 37). The cell would not run at 5 amps stably. It will also be noted that the cell resistance was not helped by the presence of the anode screen, that is, cell resistances of 27 to 32 milliohms were experienced at high pressure, the same as for cells without anode screens. Water was added to the anode at 2800 psi, at which time the cell sprang a leak and testing was discontinued. No high pressure data above 1800 psi could therefore be achieved.

Symbol	Anode Pressure psig	Current just before Setting Open Circuit, amp
○	1750	5
□	2000	3

Cathode Pressure = 50 psig
Temperature: 70-75°F
Anode Condition: Dry (no water injection)

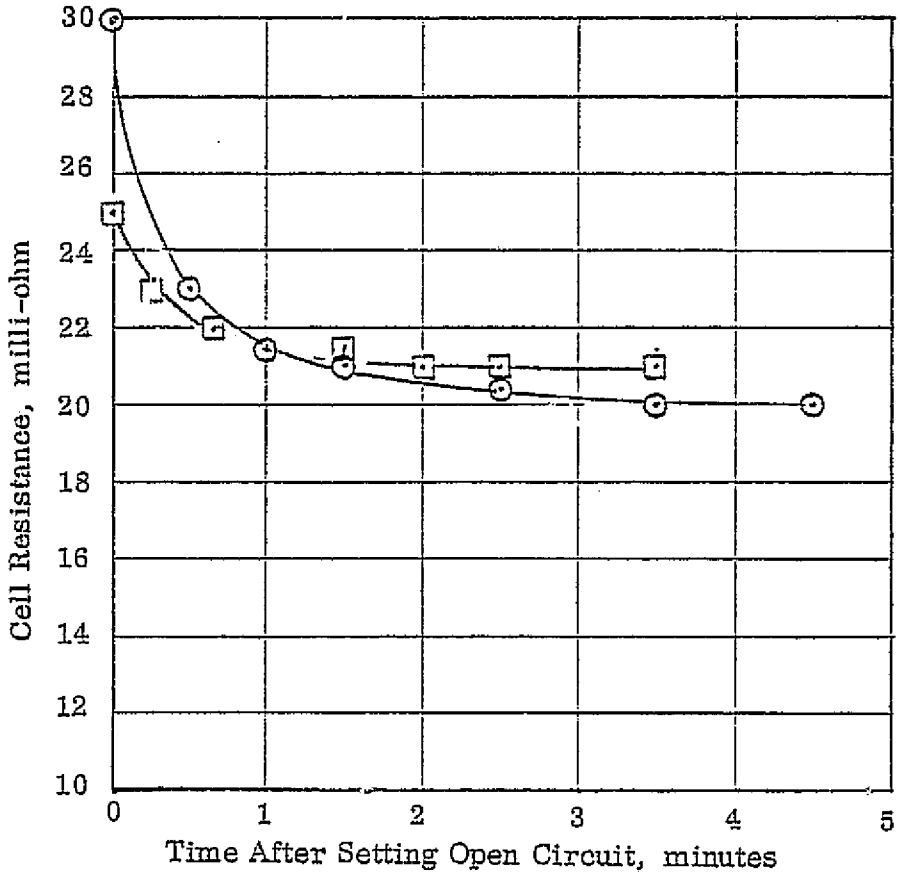


Figure 36. Transient Behavior of BU-45

Figure 37 also shows the oxygen diffusion loss expressed in amps as a function of operating current. It indicates that diffusion increases with increasing current which is the opposite of what one would think. Normally, the cell should run dryer at the higher current because of increased protonic pumping. The dryer the cell, the lower should be the gas permeability. The higher permeability may be indicative of seal leaks due to shrinking of membrane or that the membrane may have become slightly porous under the drying condition.

Effect of Wetproofed Anode

Performance of the cell operating with no external water addition always showed poor performance. Above 2500 psi (18 MPa). Performance could be regained transiently by the addition of water to the anode, sometimes by as much as .25 volt. However, the cell acts as a water pump, the proton flow transporting water from anode to cathode. In so doing, the cathode compartment became flooded and required high cathode purges at frequent intervals to prevent voltage from rising. This, of course, would prove to be a system complication in a practical machine.

Some device was sought which could allow the anode to remain flooded yet prevent excess water from transporting across the membrane to the cathode. The simplest device seemed to be the application of a wetproofing film on the anode electrode itself. Since the wetproofing film is porous teflon, it might repel liquid water, but transport only water vapor to the anode to keep it wet.

A cell was made with a wetproofed anode. Since the wetproofing is also an electrical insulator, the anode had to be made similar to a cathode, that is, it contained a screen and metal strips. The wetproofing was cut so that the metal strips were not covered and could conduct electricity to the porous metal support plate.

Figure 38 shows the performance of the cell in BU-54. Initial performance was good. Water was then added to the anode. After one hour the voltage had risen about 150 mv. Cathode purging returned the performance to normal. In another hour, the voltage rose again and a purge was needed. One hour later the process repeated, whereafter the cell did not need further purging. This indicated that the anode wetproofing did cause water transport to slow down. The cell ran overnight (17 hours) at 1000 psi (7 MPa), with invariant performance and resistance, which was not unusual. The cell then ran for 25 hours at 2300 psi (16 MPa) with an increase in voltage of .08 v and an increase in resistance of 4 milliohms, indicating some cell drying. Water was added with an improvement in performance, but not resistance. Again, cathode purging was necessary to stabilize the voltage. The cell was allowed to operate for 20 hours with a 100 mv performance loss and another gain in resistance. It can be said that the anode wetproofing reduced the water transport, but did not allow performance to be as good as achieved on other standard type cells. The cell was allowed to run at 3000 psi and was invariant for two hours.

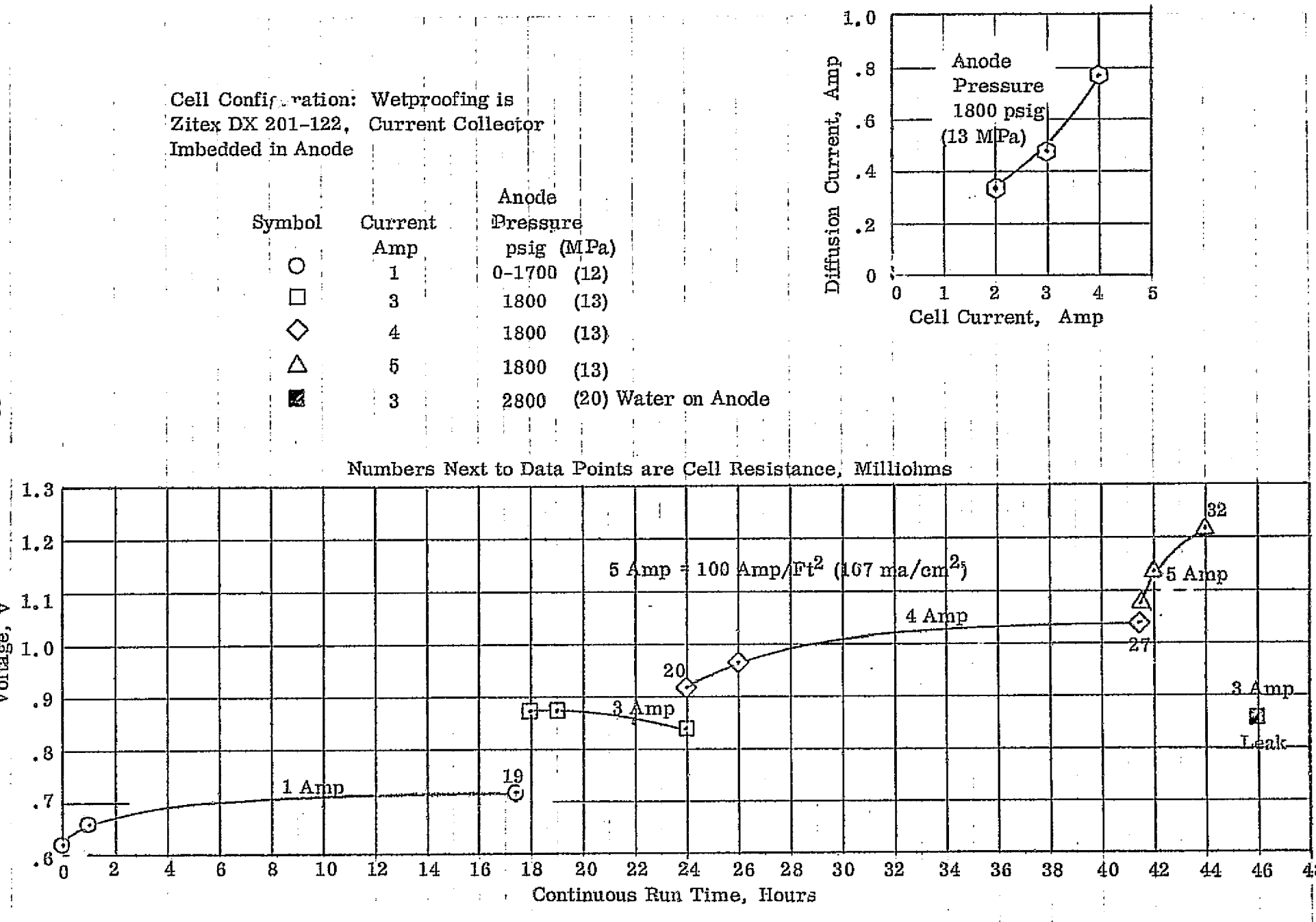


Figure 37, Operating History, BU-50

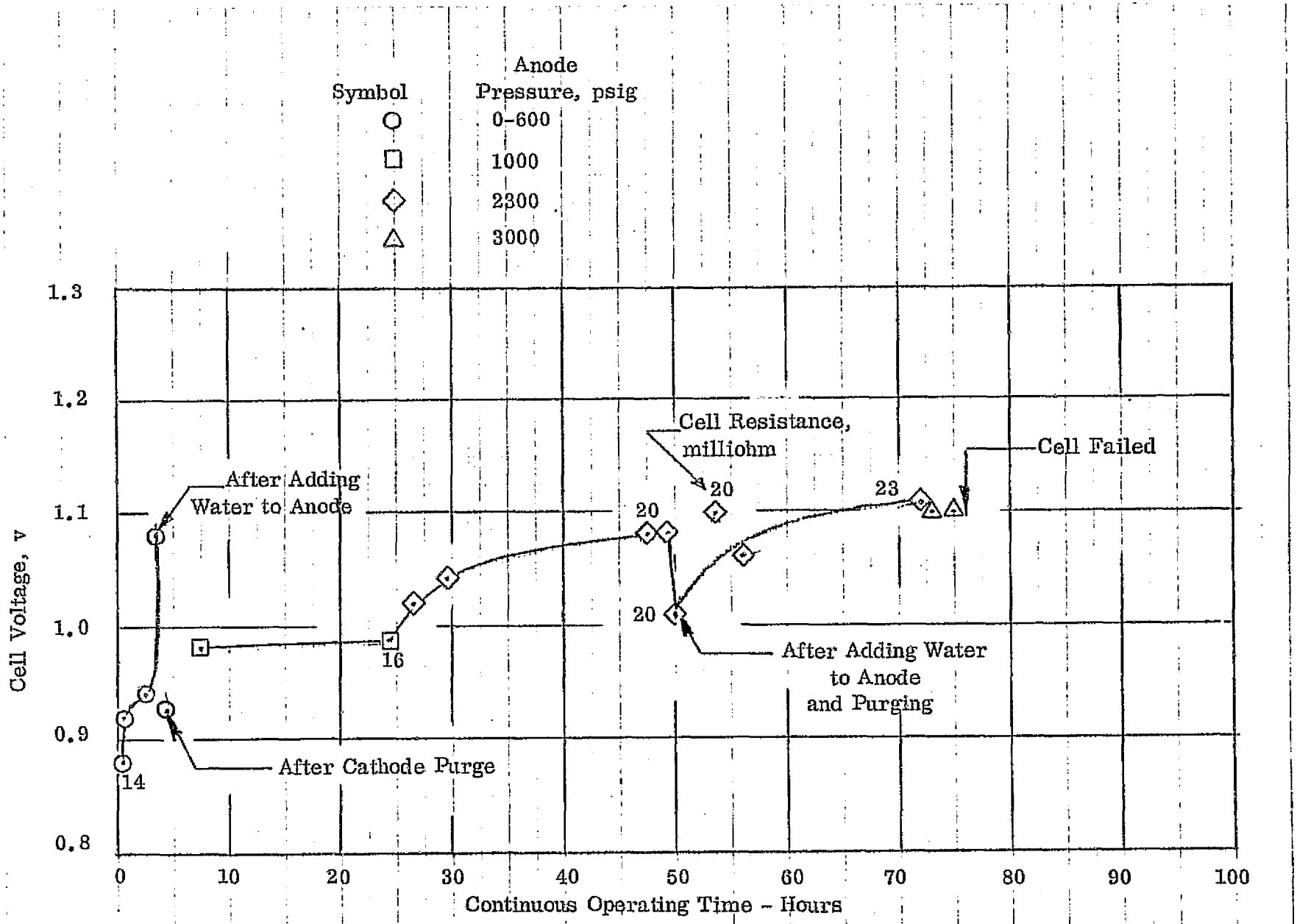


Figure 38. History of BU-54 Wetproofed Anode

Unfortunately, two hours thereafter the cell failed causing extensive damage to the hardware, and further testing was not possible. With the limited data available, we must conclude that the wetproofing layer on the anode did slow down the transport of water from anode to cathode. Performance was inferior to other cells, but it is not known if it was caused by wetproofing the anode.

Failure of Single Cell with Titanium Supports

As discussed under the section "Effect of Wetproofed Anode", it was mentioned that the cell failed in what one could call a catastrophic mode, that is an internal fire was initiated which propagated to the ambient, but no explosion was caused and no personnel were hurt.

The following is an exerpt from an internal safety report written after the incident.

> "On 27 June 1975 at 1440 hours, a single cell oxygen compressor compressing oxygen from 50 psig to 3000 psig failed, causing a short term materials fire spewing sparks and smoke from the test chamber to the adjoining aisle. The fire went out by itself as soon as the stored oxygen was depleted.
>
> Subsequent disassembly showed damage to the test vehicle in the form of eroded stainless steel, essentially complete destruction of the porous titanium support on the low pressure side of the cell and some burning of the niobium porous support on the high pressure side of the cell. Because the porous titanium was very nearly gone from the unit, the titanium itself was probably the fuel for the fire which caused melting and ablating of the other components. Internal damage was so extensive that it was not possible to determine cause and effect for the failure. From the erosion tracks it is evident that the fire was fed from the residual oxygen in the high pressure piping, about 6 liters at standard temperature and pressure (STP). Since other cells have failed pneumatically without fires, it is postulated that this cell failed with a membrane leak and short circuit creating an ignition source. This is likely because this cell was different from the standard cell in that a current collector screen was imbedded in both sides of the membrane (to study the effect of anode wetproofing) and therefore, there was a higher probability of metallic contact during a membrane failure. The hole in the membrane then allowed the high pressure oxygen to dump into the low pressure side which torched to melt the tubing on the low pressure side and the fitting on the end plate."

The cause of the failure was probably due to the configuration of the anode wetproofed cell. This cell had a screen with metal strips on both sides. The thickness of the strip was .003 inch (.076 mm), and two strips pressed tightly into the cell would leave only about .004 inch (.1 mm) of membrane thickness between the opposing strips. At the high anode pressure, it is possible that the strips or screens touched, creating a spark. Once a spark occurred, ignition of the porous titanium support could initiate.

Of course, it was not intended that titanium would be used in final production compressors, but it was used only as a research tool because of its ready availability and desirable pore size. The spectacular results of the failure make it questionable to use titanium in oxygen even at low pressure.

Performance of Thicker Membrane

It was desirable to determine the effect of a thicker membrane on performance, for two reasons. First, the gas diffusion would be decreased, requiring fewer cells for a given gas production rate, and the resistance to puncturing would be far greater than the standard .01 inch (.25 mm) membrane used throughout this contract.

Four cells were built using .02 inch (.5 mm) thick membrane, tested and are discussed below:

a) BU 13 contained a cell with membrane water equilibrated at 212 F (100 C). Otherwise the membrane was as received from the vendor. The cell would not sustain currents above 2 amp even after electrolyzing to clear water from the wetproofing layer. The test was discontinued.

b) BU 16 contained a cell with membrane water equilibrated at 270 F (132 C) to achieve a water content of 35% versus 25% for 212 F (100 C) equilibration. The performance was poor, but the cell would run at 1 amp so that pressure could be built up.

Figure 39 shows BU 16's test history. Performance degraded slightly with time at various pressures, but an encouraging result was that 5000 psi generation pressure was achieved without leaks. At the 5000 psi level, however, voltage increased to the shutdown level of 1.6 volts. A restart showed no shorts or leaks. At restart the pressure was lower because during the period of shutdown, gas diffusion from anode to cathode took place during an overnight period.

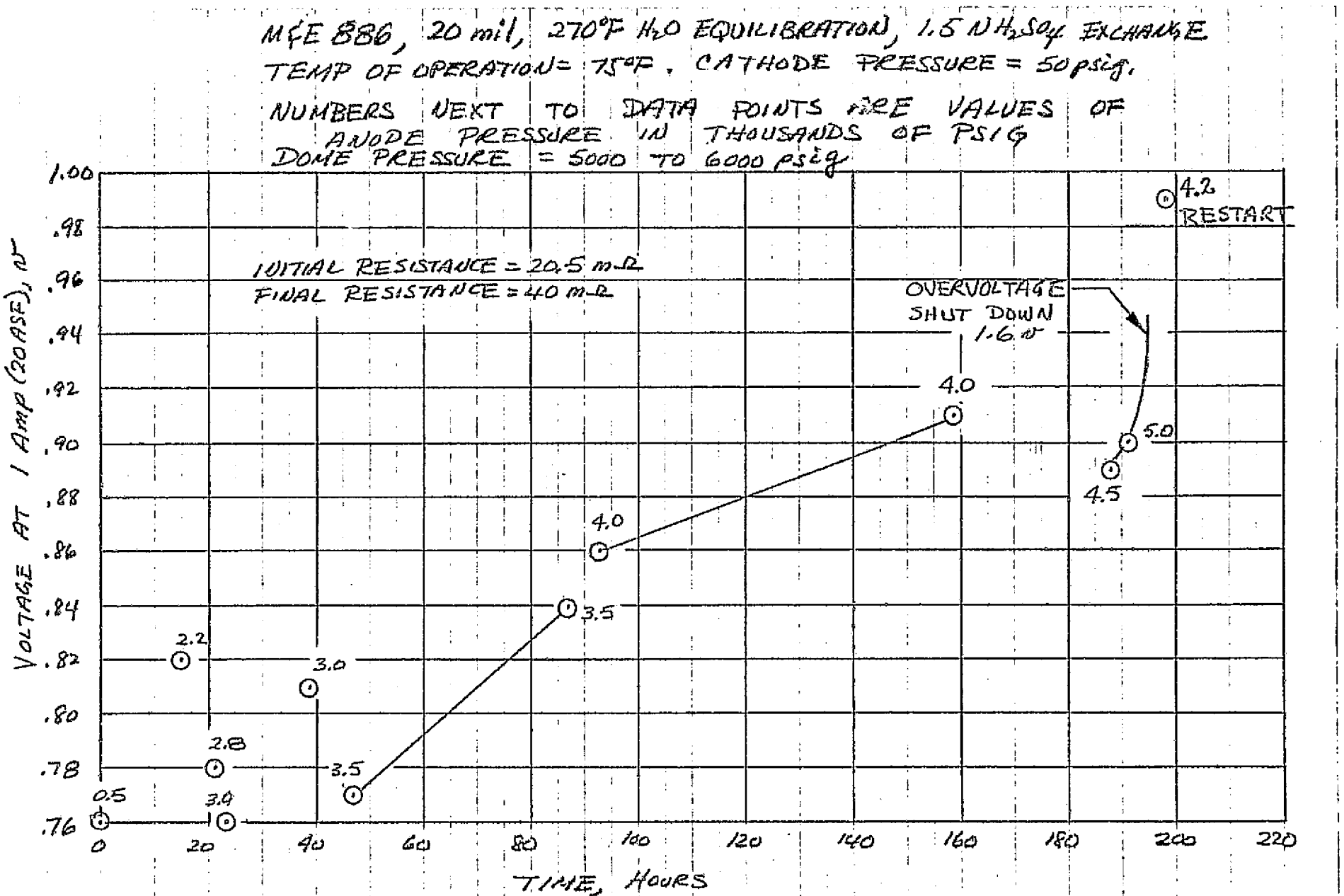


Figure 39. TEST HISTORY OF BU-16

The reason for poor performance could have been that the 20 mil SPE was not fully saponified. At the factory, .020 inch (.5 mm) membrane is treated with NaOH for the same length of time as .010 inch (.25 mm), but the thicker membrane probably requires a longer time for the NaOH to permeate the membrane fully. Therefore, the .020 inch (.5 mm) membrane was re-saponified according to:

$$R - SO_2F + NaOH \longrightarrow R\text{-}SO_3Na + HF$$

This gives additional sites for attachment of protons when acidified subsequently as:

$$2(R\text{-}SO_3Na) + H_2SO_4 \longrightarrow 2RSO_3H + Na_2SO_4$$

The longer saponification time was used to insure that the SO_3H concentration was sufficiently high and uniform throughout the membrane.

c) BU 17 was constructed of membrane resaponified for 64 hours and its test results are shown in Figure 40. The initial polarization curve was much superior to the previous 20 mil cells, but would still not run steadily at 5 amps. Life testing was initiated at various pressure levels at 3 amps, but since the diffusion current was comparable to the thinner membrane, testing was discontinued.

d) BU 23 contained a .020 inch (.5 mm) thick cell resaponified for two weeks, re-equilibrated in H_2SO_4 and water equilibrated at 270 F (132 C). This cell performed essentially the same as BU-17, indicating that the longer saponification did not enhance the membrane properties.

Further work was discontinued on the thicker membrane because the diffusion characteristics were no better than the thin membrane, yet the performance was much poorer.

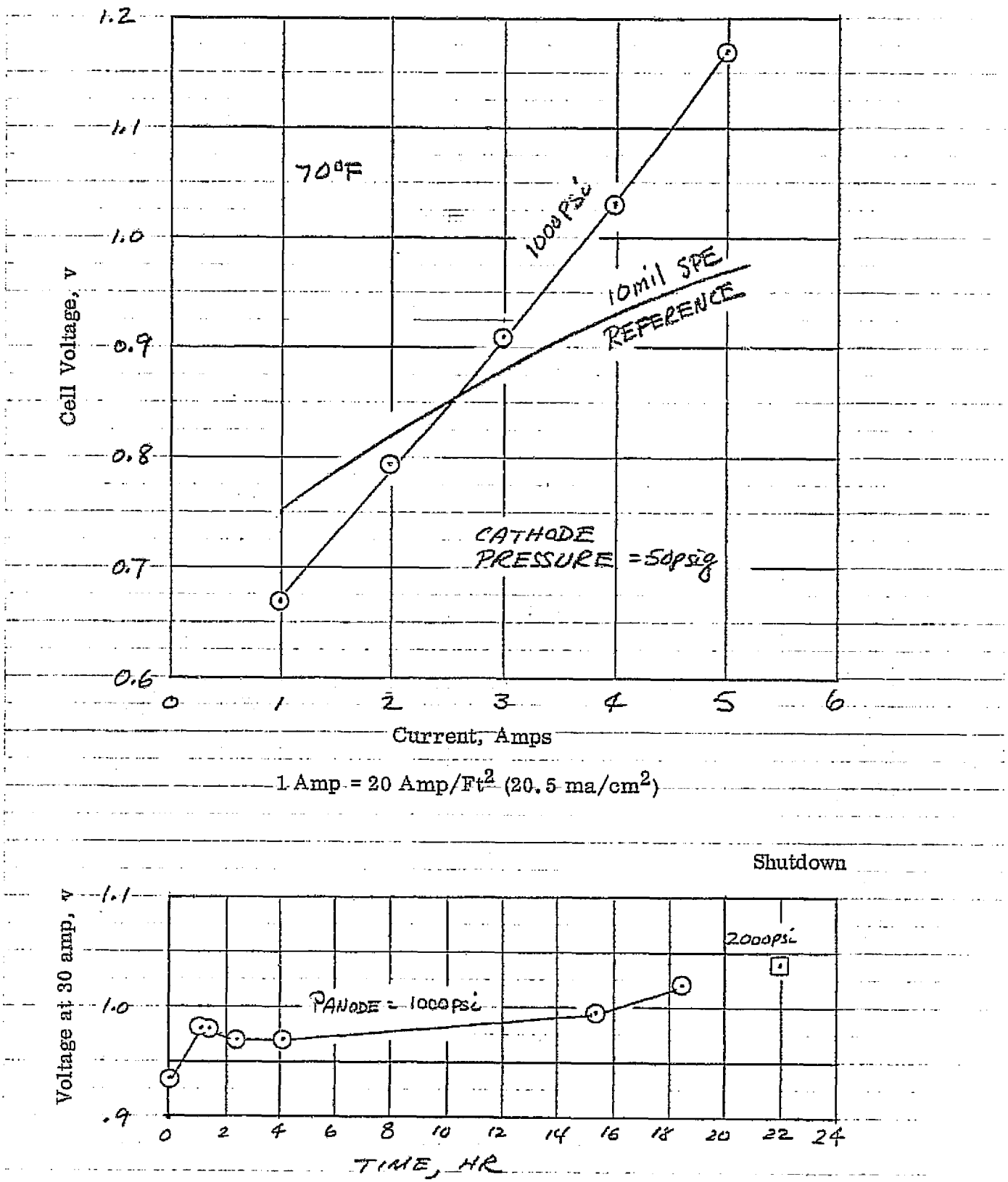


Figure 40. TEST HISTORY OF BU-17 SAPONIFIED SPE

Conclusions

1) A solid polymer electrochemical oxygen compressor has the capability of compressing .24 lb/hr (.11 kg/hr) of oxygen from 65 psia (.46 MPa) to 3000 psia (21 MPa) at the expense of about 500 watts and about 100 lb of system weight. The power requirement is high compared to the isentropic power (20 watts), but the system still has attractiveness if it can be completely static (no pumps or other moving parts). The goal of this contract was to show feasibility of this kind of simple cell.

2) It is probable that a single stage compressor is desirable, since each stage requires high voltages and staging only increases power consumption.

3) Since very high pressure differentials operate on the membrane, the mechanical supports must be adequate to prevent membrane extrusion and failure. Adequate support was provided by porous plates backed up by dense screens. Screens touching the cell are inadequate, causing leaks. This poses materials problems, since only niobium or tantalum are useable at these pressures. We have found only one vendor capable of providing tantalum supports, and a high price would have to be paid for developing porous niobium.

In the execution of this contract, porous titanium was used on the low pressure cathode because of its availability, low cost, and uniform thickness. The possibility of fire was always appreciated, and projections of the design always centered around niobium or tantalum. The titanium proved to be safe in about four or five cell failures where 3000 psi oxygen transported from the anode to cathode. However, at the near conclusion of the contract, a cell failure at 3000 psi was experienced which ignited the titanium.

4) Because of the high pressures involved, the use of gaskets for sealing was discarded. Experience building concentrators for 300 to 500 psi (2.1 to 3.5 MPa) using gaskets proved fruitless, while using a gasketless design was successful. The compressor, therefore, was designed without gaskets, but using the membrane to metal to form a seal. Such seals were adequate to 5000 psi (35 MPa) in single cells.

5) Computer studies have shown that the optimum operating conditions for lowest power is 100 amp/Ft^2 (107 ma/cm^2) at about 100 F (38 C), where diffusional losses become tolerable. Calculations have shown that minimum weight occurs at about 100 circular cells of .05 Ft^2 (46 cm^2) active area. Final design was chosen using that active area.

6) Experimental work on this contract has shown feasibility of a static solid polymer electrochemical compressor for use to 3000 psi (21 MPa). Some developmental problems still exist, namely:

a) Performance stability - Up to 2500 psi (18 MPa) performance was fairly stable for periods of about 30 hours. At 3000 psi (21 MPa), voltage continued to rise at 100 amp/Ft^2 (107 ma/cm^2). This was manifested in cell resistance increase, not caused to a large extent by current collection, but rather by adverse water gradients leaving a dry anode. Adding water to the anode improved performance temporarily, but was ineffective in the long term because the cell pumped water over to the cathode and drowned it. Cells with higher water content were ineffective, since the mechanical strength was inadequate. Methods to hold water on the anode without excessive protonic pumping to the cathode (by wetproofing the anode) were somewhat effective. Water passed through the wetproofing film much more slowly, but drowning still occurred. More work could possibly be done with the wetproofed anode to more closely control the rates of water transport.

b) Sealing in multi-cell stacks - Sealing to 5000 psi has been achieved on single cells. A five "cell" stack using plastic aclar sheets has also sealed to 5000 psi. Real cells in five cell stacks have sealed only to 1500 psi, and then only briefly. This problem should be attacked by changing the stamping die which forms the seal ports, so that more uniform contact is made with the membrane, and more mechanical compliance is built in.

APPENDIX A

Computer Results

Detailed computer results are included in this appendix.

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	100	DEG F
OXYGEN DEW POINT TEMP	94.96	DEG F
CURRENT DENSITY	50	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	24.6654	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	18.3054	AMP/SQ FT
FARADAIC EFFICIENCY	0.6339	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8579	
VAPOR PRESS-SAT WATER VAPOR	0.9503	PSIA
OXYGEN SIDE VAPOR PRESSURE	0.815	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.6859	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.004	VOLTS
CORRECTED CELL VOLTAGE	0.6898	VOLTS
SPE OPERATING RESISTIVITY	56.982	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	45.495	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.024553	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0334	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2616	0.3457
2	0.2391	0.3257
3	0.2195	0.3072
4	0.2024	0.2902
5	0.1873	0.2745
6	0.174	0.26
7	0.1621	0.2466
8	0.1514	0.2342
9	0.1418	0.2227
ANODE 10	0.1332	0.212

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	163.97	SQ IN.
CELL DIAMETER	14.45	IN.
INPUT CURRENT	56.94	AMP
OXYGEN GENERATION RATE	0.2375	lb/hr
STACK POWER INPUT	392.76	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.056	WATTS
TOTAL STACK HEAT GENERATION RATE	380.705	WATTS
FARADAIC EFFICIENCY	0.6339	

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	2014.7	.6898	392.8	380.7
1014.7	3014.7	.5746	327.2	324.5
2014.7	4014.7	.5562	316.7	315.0
3014.7	5014.7	.5454	310.5	309.3
4014.7	6014.7	.5377	306.2	305.2

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	100	DEG F
OXYGEN DEW POINT TEMP	93.82	DEG F
CURRENT DENSITY	75	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	24.6654	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	17.4412	AMP/SQ FT
FARADAIC EFFICIENCY	0.7675	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8283	
VAPOR PRESS-SAT WATER VAPOR	0.9503	PSIA
OXYGEN SIDE VAPOR PRESSURE	0.787	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7394	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0073	VOLTS
CORRECTED CELL VOLTAGE	0.7467	VOLTS
SPE OPERATING RESISTIVITY	59.557	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	45.495	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.023705	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0334	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2585	0.343
2	0.2334	0.3204
3	0.2118	0.2996
4	0.193	0.2805
5	0.1765	0.2628
6	0.162	0.2466
7	0.1493	0.2317
8	0.1379	0.2179
9	0.1279	0.2053
ANODE 10	0.1189	0.1937

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	90.29	SQ IN.
CELL DIAMETER	10.72	IN.
INPUT CURRENT	47.03	AMP
OXYGEN GENERATION RATE	0.2375	lb/hr
STACK POWER INPUT	351.16	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.056	WATTS
TOTAL STACK HEAT GENERATION RATE	339.101	WATTS
FARADAIC EFFICIENCY	0.7675	

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	2014.7	.7467	351.2	339.1
1014.7	3014.7	.6315	297.0	294.3
2014.7	4014.7	.6131	288.3	286.7
3014.7	5014.7	.6023	283.2	282.0
4014.7	6014.7	.5946	279.6	278.7

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	100	DEG F
OXYGEN DEW POINT TEMP	92.54	DEG F
CURRENT DENSITY	100	AMP/SQ FT
GAS PERMEABILITY LOSS, EQUILIBRATED SPE(EQUIV)	24.6654	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	16.5817	AMP/SQ FT
FARADAIC EFFICIENCY	0.8342	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.796	
VAPOR PRESS-SAT WATER VAPOR	0.9503	PSIA
OXYGEN SIDE VAPOR PRESSURE	0.756	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7844	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0119	VOLTS
CORRECTED CELL VOLTAGE	0.7962	VOLTS
SPE OPERATING RESISTIVITY	62.589	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	45.495	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2378	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.022779	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0334	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2554	0.3403
2	0.2278	0.3152
3	0.2042	0.292
4	0.1838	0.2707
5	0.1661	0.2512
6	0.1507	0.2334
7	0.1373	0.2171
8	0.1255	0.2023
9	0.1153	0.1889
ANODE 10	0.1062	0.1767

SUMMARY OF OPERATING CHARACTERISTICS
OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	62.3	SQ IN.
CELL DIAMETER	8.91	IN.
INPUT CURRENT	43.27	AMP
OXYGEN GENERATION RATE	0.2375	
STACK POWER INPUT	344.49	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.056	WATTS
TOTAL STACK HEAT GENERATION RATE	332.436	WATTS
FARADAIC EFFICIENCY	0.8342	

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	2014.7	.7962	344.5	332.4
1014.7	3014.7	.6810	294.6	292.0
2014.7	4014.7	.6626	286.7	285.0
3014.7	5014.7	.6518	282.0	280.8
4014.7	6014.7	.6441	278.7	277.7

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	100	DEG F
OXYGEN DEW POINT TEMP	91.11	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	24.6654	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	15.7368	AMP/SQ FT
FARADAIC EFFICIENCY	0.8741	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.7614	
VAPOR PRESS-SAT WATER VAPOR	0.9503	PSIA
OXYGEN SIDE VAPOR PRESSURE	0.724	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.8286	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.018	VOLTS
CORRECTED CELL VOLTAGE	0.8466	VOLTS
SPE OPERATING RESISTIVITY	66.182	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	45.495	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.021788	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0334	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2523	0.3376
2	0.2223	0.3099
3	0.1968	0.2844
4	0.1749	0.2611
5	0.1562	0.2398
6	0.1401	0.2205
7	0.1262	0.2031
8	0.1142	0.1875
9	0.1039	0.1735
ANODE 10	0.095	0.1611

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	47.56	SQ IN.
CELL DIAMETER	7.78	IN.
INPUT CURRENT	41.29	AMP
OPERATING TEMPERATURE	100	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	349.54	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.056	WATTS
TOTAL STACK HEAT GENERATION RATE	337.484	WATTS

FARADAIC EFFICIENCY 0.8741

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.8466	349.5	337.5
1014.7	3014.7	.7313	302.0	299.3
2014.7	4014.7	.7130	294.4	292.7
3014.7	5014.7	.7021	289.9	288.7
4014.7	6014.7	.6945	286.7	285.8

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	115.13	DEG F
CURRENT DENSITY	50	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	31.3126	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	23.831	AMP/SQ FT
FARADAIC EFFICIENCY	0.5234	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8722	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.478	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.6513	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0032	VOLTS
CORRECTED CELL VOLTAGE	0.6544	VOLTS
SPE OPERATING RESISTIVITY	49.416	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.044529	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

STATION	WATER CONTENT GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2635	0.3474
2	0.2424	0.3287
3	0.2241	0.3116
4	0.2079	0.2957
5	0.1935	0.281
6	0.1807	0.2674
7	0.1693	0.2548
8	0.159	0.2431
9	0.1497	0.2321
ANODE 10	0.1412	0.222

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	198.6	SQ IN.
CELL DIAMETER	15.9	IN.
INPUT CURRENT	68.96	AMP
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	451.27	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.626	WATTS
TOTAL STACK HEAT GENERATION RATE	438.647	WATTS

FARADAIC EFFICIENCY 0.5234

PRESSURE, PSIA INLET	OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	HEAT GEN
14.7	2014.7	.6544	451.3	438.6
1014.7	3014.7	.5336	367.9	365.2
2014.7	4014.7	.5145	354.8	353.1
3014.7	5014.7	.5033	347.1	345.8
4014.7	6014.7	.4953	341.6	340.6

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	114.21	DEG F
CURRENT DENSITY	75	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	31.3126	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	22.9484	AMP/SQ FT
FARADAIC EFFICIENCY	0.694	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8498	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.44	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7025	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0056	VOLTS
CORRECTED CELL VOLTAGE	0.7081	VOLTS
SPE OPERATING RESISTIVITY	51.081	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.043382	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.261	0.3452
2	0.2378	0.3245
3	0.2177	0.3055
4	0.2001	0.2879
5	0.1846	0.2716
6	0.1708	0.2565
7	0.1586	0.2426
8	0.1476	0.2297
9	0.1378	0.2178
ANODE 10	0.129	0.2067

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	99.85	SQ IN.
CELL DIAMETER	11.28	IN.
INPUT CURRENT	52	AMP
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	368.24	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.626	WATTS
TOTAL STACK HEAT GENERATION RATE	355.615	WATTS
FARADAIC EFFICIENCY	0.694	

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	2014.7	.7081	368.2	355.6
1014.7	3014.7	.5872	305.4	302.7
2014.7	4014.7	.5682	295.5	293.7
3014.7	5014.7	.5570	289.7	288.4
4014.7	6014.7	.5490	285.5	284.5

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	113.19	DEG F
CURRENT DENSITY	100	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	31.3126	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	22.0642	AMP/SQ FT
FARADAIC EFFICIENCY	0.7794	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8255	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.399	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7451	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0088	VOLTS
CORRECTED CELL VOLTAGE	0.7539	VOLTS
SPE OPERATING RESISTIVITY	52.972	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.04214	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2585	0.343
2	0.2333	0.3203
3	0.2115	0.2994
4	0.1925	0.28
5	0.1759	0.2622
6	0.1613	0.2457
7	0.1484	0.2306
8	0.1369	0.2167
9	0.1268	0.2039
ANODE 10	0.1177	0.1921

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	66.68	SQ IN.
CELL DIAMETER	9.21	IN.
INPUT CURRENT	46.31	AMP
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	349.11	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.626	WATTS
TOTAL STACK HEAT GENERATION RATE	336.489	WATTS
FARADAIC EFFICIENCY	0.7794	

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	2014.7	.7539	349.1	336.5
1014.7	3014.7	.6330	293.1	290.4
2014.7	4014.7	.6140	284.3	282.6
3014.7	5014.7	.6028	279.1	277.9
4014.7	6014.7	.5948	275.4	274.4

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HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	112.07	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	31.3126	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	21.1849	AMP/SQ FT
FARADAIC EFFICIENCY	0.8305	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.7994	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.355	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0[illegible]	VOLTS
CORRECTED CELL VOLTAGE	0.[illegible]	VOLTS
SPE OPERATING RESISTIVITY	55.128	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.04081	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.256	0.3408
2	0.2288	0.3161
3	0.2054	0.2932
4	0.1851	0.2722
5	0.1675	0.2528
6	0.1521	0.2351
7	0.1387	0.2189
8	0.1269	0.2041
9	0.1166	0.1906
ANODE 10	0.1075	0.1784

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
CELL AREA	50.06	SQ IN.
CELL DIAMETER	7.98	IN.
INPUT CURRENT	43.46	AMP
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	347.3	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.623	WATTS
TOTAL STACK HEAT GENERATION RATE	334.674	WATTS
FARADAIC EFFICIENCY	0.8305	

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.7992	347.3	334.7
1014.7	3014.7	.6783	294.8	292.0
2014.7	4014.7	.6593	286.5	284.8
3014.7	5014.7	.6481	281.6	280.4
4014.7	6014.7	.6401	278.2	277.2

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HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	140	DEG F
OXYGEN DEW POINT TEMP	135.21	DEG F
CURRENT DENSITY	50	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	39.1236	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	30.3759	AMP/SQ FT
FARADAIC EFFICIENCY	0.3925	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8832	
VAPOR PRESS-SAT WATER VAPOR	2.892	PSIA
OXYGEN SIDE VAPOR PRESSURE	2.554	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.6249	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0026	VOLTS
CORRECTED CELL VOLTAGE	0.6274	VOLTS
SPE OPERATING RESISTIVITY	43.418	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	36.035	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.076993	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0369	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.265	0.3487
2	0.2452	0.3312
3	0.2278	0.3151
4	0.2124	0.3002
5	0.1987	0.2864
6	0.1864	0.2735
7	0.1753	0.2615
8	0.1653	0.2504
9	0.1563	0.2399
ANODE 10	0.148	0.2302

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	264.83	SQ IN.
CELL DIAMETER	18.36	IN.
INPUT CURRENT	91.96	AMP
OPERATING TEMPERATURE	140	DEG F
CURRENT DENSITY	50	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	576.95	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.31	WATTS
TOTAL STACK HEAT GENERATION RATE	563.636	WATTS

FARADAIC EFFICIENCY 0.3925

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.6274	576.9	563.6
1014.7	3014.7	.4996	459.4	456.6
2014.7	4014.7	.4799	441.3	439.5
3014.7	5014.7	.4683	430.6	429.3
4014.7	6014.7	.4601	423.1	422.0

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	140	DEG F
OXYGEN DEW POINT TEMP	134.46	DEG F
CURRENT DENSITY	75	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	39.1236	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	29.4786	AMP/SQ FT
FARADAIC EFFICIENCY	0.607	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8658	
VAPOR PRESS-SAT WATER VAPOR	2.892	PSIA
OXYGEN SIDE VAPOR PRESSURE	2.504	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.6745	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0044	VOLTS
CORRECTED CELL VOLTAGE	0.679	VOLTS
SPE OPERATING RESISTIVITY	44.542	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	36.035	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.075475	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0369	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.263	0.3469
2	0.2414	0.3276
3	0.2226	0.3102
4	0.206	0.2938
5	0.1912	0.2786
6	0.1781	0.2646
7	0.1663	0.2515
8	0.1557	0.2393
9	0.1462	0.228
ANODE 10	0.1375	0.2174

SUMMARY OF OPERATING CHARACTERISTICS
OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	114.17	SQ IN.
CELL DIAMETER	12.06	IN.
INPUT CURRENT	59.46	AMP
OPERATING TEMPERATURE	140	DEG F
CURRENT DENSITY	75	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	403.73	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.31	WATTS
TOTAL STACK HEAT GENERATION RATE	390.419	WATTS

FARADAIC EFFICIENCY 0.607

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.6790	403.7	390.4
1014.7	3014.7	.5512	327.7	324.9
2014.7	4014.7	.5315	316.0	314.2
3014.7	5014.7	.5199	309.1	307.8
4014.7	6014.7	.5116	304.2	303.2

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	140	DEG F
OXYGEN DEW POINT TEMP	133.63	DEG F
CURRENT DENSITY	100	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	39.1236	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	28.5768	AMP/SQ FT
FARADAIC EFFICIENCY	0.7142	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8472	
VAPOR PRESS-SAT WATER VAPOR	2.892	PSIA
OXYGEN SIDE VAPOR PRESSURE	2.45	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7154	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0068	VOLTS
CORRECTED CELL VOLTAGE	0.7221	VOLTS
SPE OPERATING RESISTIVITY	45.785	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	36.035	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.073846	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0369	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2609	0.3452
2	0.2377	0.3244
3	0.2174	0.3052
4	0.1997	0.2874
5	0.184	0.2709
6	0.17	0.2557
7	0.1576	0.2415
8	0.1465	0.2284
9	0.1366	0.2163
ANODE 10	0.1277	0.2051

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	72.76	SQ IN.
CELL DIAMETER	9.63	IN.
INPUT CURRENT	50.53	AMP
OPERATING TEMPERATURE	140	DEG F
CURRENT DENSITY	100	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	364.9	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.31	WATTS
TOTAL STACK HEAT GENERATION RATE	351.593	WATTS
FARADAIC EFFICIENCY	0.7142	

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.7221	364.9	351.6
1014.7	3014.7	.5944	300.3	297.5
2014.7	4014.7	.5746	290.4	288.6
3014.7	5014.7	.5630	284.5	283.2
4014.7	6014.7	.5548	280.4	279.3

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	140	DEG F
OXYGEN DEW POINT TEMP	132.73	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	39.1236	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	27.6744	AMP/SQ FT
FARADAIC EFFICIENCY	0.7786	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8273	
VAPOR PRESS-SAT WATER VAPOR	2.892	PSIA
OXYGEN SIDE VAPOR PRESSURE	2.393	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7543	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0097	VOLTS
CORRECTED CELL VOLTAGE	0.764	VOLTS
SPE OPERATING RESISTIVITY	47.165	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	36.035	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.072111	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0369	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2589	0.3434
2	0.234	0.321
3	0.2124	0.3002
4	0.1935	0.281
5	0.1769	0.2632
6	0.1622	0.2468
7	0.1493	0.2317
8	0.1378	0.2178
9	0.1276	0.2049
ANODE 10	0.1185	0.1932

SUMMARY OF OPERATING CHARACTERISTICS
OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	53.4	SQ IN.
CELL DIAMETER	8.25	IN.
INPUT CURRENT	46.35	AMP
OPERATING TEMPERATURE	140	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	354.13	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.31	WATTS
TOTAL STACK HEAT GENERATION RATE	340.816	WATTS

FARADAIC EFFICIENCY 0.7786

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.7640	354.1	340.8
1014.7	3014.7	.6362	294.9	292.1
2014.7	4014.7	.6165	285.7	284.0
3014.7	5014.7	.6049	280.4	279.1
4014.7	6014.7	.5966	276.6	275.5

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS		0.01	IN.
ION EXCHANGE CAPACITY (IEC)		0.825	MEQ/GM
EQUILIBRATION TEMPERATURE		212	DEG F
OPERATING TEMPERATURE		140	DEG F
OXYGEN DEW POINT TEMP		131.75	DEG F
CURRENT DENSITY		150	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)		39.1236	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)		26.7758	AMP/SQ FT
FARADAIC EFFICIENCY		0.8215	
OXYGEN PRESSURE(INLET)		14.7	PSIA
OXYGEN PRESSURE(OUTLET)		2014.7	PSIA
DIFFERENTIAL PRESSURE		2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY		0.8063	
VAPOR PRESS-SAT WATER VAPOR		2.892	PSIA
OXYGEN SIDE VAPOR PRESSURE		2.332	PSIA
CELL VOLTAGE(ATM PRESS DATA)		0.7918	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA		0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE		0.0132	VOLTS
CORRECTED CELL VOLTAGE		0.805	VOLTS
SPE OPERATING RESISTIVITY		48.7	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	0	36. 35	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT		0.2878	GM/GM SPE
		0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT		0.0434	GM/GM SPE
		0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)		0.070275	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION		0.0369	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2569	0.3416
2	0.2303	0.3175
3	0.2074	0.2952
4	0.1874	0.2746
5	0.17	0.2556
6	0.1547	0.2381
7	0.1413	0.2221
8	0.1295	0.2074
9	0.1192	0.194
ANODE 10	0.11	0.1818

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	42.18	SQ IN.
CELL DIAMETER	7.33	IN.
INPUT CURRENT	43.93	AMP
OPERATING TEMPERATURE	140	DEG F
CURRENT DENSITY	150	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	353.65	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.31	WATTS
TOTAL STACK HEAT GENERATION RATE	340.341	WATTS

FARADAIC EFFICIENCY 0.8215

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.8050	353.7	340.3
1014.7	3014.7	.6772	297.5	294.7
2014.7	4014.7	.6575	288.8	287.1
3014.7	5014.7	.6459	283.8	282.4
4014.7	6014.7	.6376	280.1	279.1

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	160	DEG F
OXYGEN DEW POINT TEMP	153.92	DEG F
CURRENT DENSITY	100	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	48.1853	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	36.1984	AMP/SQ FT
FARADAIC EFFICIENCY	0.638	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8636	
VAPOR PRESS-SAT WATER VAPOR	4.745	PSIA
OXYGEN SIDE VAPOR PRESSURE	4.098	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.693	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0054	VOLTS
CORRECTED CELL VOLTAGE	0.6984	VOLTS
SPE OPERATING RESISTIVITY	40.197	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	32.434	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.123612	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0394	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2629	0.3469
2	0.2413	0.3277
3	0.2223	0.3099
4	0.2055	0.2934
5	0.1906	0.278
6	0.1773	0.2638
7	0.1654	0.2505
8	0.1547	0.2381
9	0.145	0.2266
ANODE 10	0.1363	0.2159

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	81.46	SQ IN.
CELL DIAMETER	10.18	IN.
INPUT CURRENT	56.57	AMP
OPERATING TEMPERATURE	160	DEG F
CURRENT DENSITY	100	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	395.08	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	14.209	WATTS
TOTAL STACK HEAT GENERATION RATE	380.87	WATTS
FARADAIC EFFICIENCY	0.638	

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.6984	395.1	380.9
1014.7	3014.7	.5614	317.6	314.6
2014.7	4014.7	.5410	306.0	304.2
3014.7	5014.7	.5290	299.2	297.9
4014.7	6014.7	.5205	294.4	293.3

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	160	DEG F
OXYGEN DEW POINT TEMP	153.18	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	48.1853	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	35.2798	AMP/SQ FT
FARADAIC EFFICIENCY	0.7178	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8481	
VAPOR PRESS-SAT WATER VAPOR	4.745	PSIA
OXYGEN SIDE VAPOR PRESSURE	4.024	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7302	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0075	VOLTS
CORRECTED CELL VOLTAGE	0.7377	VOLTS
SPE OPERATING RESISTIVITY	41.124	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	32.434	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.121392	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0394	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2613	0.3454
2	0.2382	0.3249
3	0.2181	0.3058
4	0.2003	0.2881
5	0.1846	0.2717
6	0.1707	0.2564
7	0.1583	0.2422
8	0.1471	0.2291
9	0.1371	0.2169
ANODE 10	0.1282	0.2057

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	57.93	SQ IN.
CELL DIAMETER	8.59	IN.
INPUT CURRENT	50.28	AMP
OPERATING TEMPERATURE	160	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	370.96	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	14.209	WATTS
TOTAL STACK HEAT GENERATION RATE	356.751	WATTS

FARADAIC EFFICIENCY 0.7178

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.7377	371.0	356.8
1014.7	3014.7	.6007	302.0	299.1
2014.7	4014.7	.5803	291.8	289.9
3014.7	5014.7	.5683	285.8	284.4
4014.7	6014.7	.5598	281.5	280.4

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	160	DEG F
OXYGEN DEW POINT TEMP	152.39	DEG F
CURRENT DENSITY	150	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	48.1853	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	34.3608	AMP/SQ FT
FARADAIC EFFICIENCY	0.7709	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8318	
VAPOR PRESS-SAT WATER VAPOR	4.745	PSIA
OXYGEN SIDE VAPOR PRESSURE	3.947	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7656	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0101	VOLTS
CORRECTED CELL VOLTAGE	0.7757	VOLTS
SPE OPERATING RESISTIVITY	42.134	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	32.434	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.119052	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0394	VOLTS

STATION	WATER CONTENT GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2596	0.344
2	0.2352	0.322
3	0.2139	0.3017
4	0.1952	0.2828
5	0.1788	0.2653
6	0.1642	0.2491
7	0.1513	0.2341
8	0.1398	0.2203
9	0.1296	0.2075
ANODE 10	0.1205	0.1958

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	44.94	SQ IN.
CELL DIAMETER	7.56	IN.
INPUT CURRENT	46.81	AMP
OPERATING TEMPERATURE	160	DEG F
CURRENT DENSITY	150	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	363.15	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	14.209	WATTS
TOTAL STACK HEAT GENERATION RATE	348.94	WATTS
FARADAIC EFFICIENCY	0.7709	

PRESSURE, PSIA INLET	OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	HEAT GEN
14.7	2014.7	.7757	363.1	348.9
1014.7	3014.7	.6387	299.0	296.1
2014.7	4014.7	.6182	289.4	287.6
3014.7	5014.7	.6063	283.8	282.5
4014.7	6014.7	.5978	279.8	278.8

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	160	DEG F
OXYGEN DEW POINT TEMP	150.64	DEG F
CURRENT DENSITY	200	AMP/SQ FT
GAS PERMEABILITY LOSS, EQUILIBRATED SPE(EQUIV)	48.1853	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	32.5334	AMP/SQ FT
FARADAIC EFFICIENCY	0.8373	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.7969	
VAPOR PRESS-SAT WATER VAPOR	4.745	PSIA
OXYGEN SIDE VAPOR PRESSURE	3.781	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.8213	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0167	VOLTS
CORRECTED CELL VOLTAGE	0.838	VOLTS
SPE OPERATING RESISTIVITY	44.44	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	32.434	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.114042	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0394	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2562	0.3411
2	0.2291	0.3164
3	0.2056	0.2935
4	0.1852	0.2723
5	0.1674	0.2527
6	0.1518	0.2347
7	0.1382	0.2182
8	0.1263	0.2032
9	0.1158	0.1895
ANODE 10	0.1066	0.1771

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	31.03	SQ IN.
CELL DIAMETER	6.29	IN.
INPUT CURRENT	43.1	AMP
OPERATING TEMPERATURE	160	DEG F
CURRENT DENSITY	200	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	361.19	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	14.209	WATTS
TOTAL STACK HEAT GENERATION RATE	346.983	WATTS

FARADAIC EFFICIENCY 0.8373

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.8380	361.2	347.0
1014.7	3014.7	.7009	302.1	299.2
2014.7	4014.7	.6805	293.3	291.5
3014.7	5014.7	.6685	288.2	286.8
4014.7	6014.7	.6600	284.5	283.4

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	115.5	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	7.8282	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	6.1712	AMP/SQ FT
FARADAIC EFFICIENCY	0.9506	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	514.7	PSIA
DIFFERENTIAL PRESSURE	500	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8815	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.494	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0067	VOLTS
CORRECTED CELL VOLTAGE	0.793	VOLTS
SPE OPERATING RESISTIVITY	48.017	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 514.7 PSIA)	0.176528	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0255	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2694	0.3524
2	0.252	0.3373
3	0.2356	0.3225
4	0.2203	0.3079
5	0.2058	0.2937
6	0.1923	0.2798
7	0.1797	0.2663
8	0.168	0.2533
9	0.157	0.2408
ANODE 10	0.1469	0.2288

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	43.74	SQ IN.
CELL DIAMETER	7.46	IN.
INPUT CURRENT	37.97	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	301.08	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	9.203	WATTS
TOTAL STACK HEAT GENERATION RATE	291.873	WATTS

FARADAIC EFFICIENCY 0.9506

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	514.7	.7930	301.1	291.9
514.7	1014.7	.6910	262.4	260.7
1014.7	1514.7	.6722	255.2	254.2
1514.7	2014.7	.6610	251.0	250.2
2014.7	2514.7	.6531	248.0	247.4
2514.7	3014.7	.6469	245.6	245.2
3014.7	3514.7	.6419	243.7	243.3
3514.7	4014.7	.6376	242.1	241.8
4014.7	4514.7	.6340	240.7	240.4
4514.7	5014.7	.6307	239.4	239.2
5014.7	5514.7	.6278	238.3	238.1
5514.7	6014.7	.6251	237.3	237.1

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	114.33	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	15.6563	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	11.6893	AMP/SQ FT
FARADAIC EFFICIENCY	0.9065	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	1014.7	PSIA
DIFFERENTIAL PRESSURE	1000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8527	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.445	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0086	VOLTS
CORRECTED CELL VOLTAGE	0.795	VOLTS
SPE OPERATING RESISTIVITY	50.288	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 1014.7 PSIA)	0.086494	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0302	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2648	0.3485
2	0.2438	0.3299
3	0.2246	0.3121
4	0.2071	0.295
5	0.1912	0.2786
6	0.1767	0.263
7	0.1634	0.2482
8	0.1514	0.2342
9	0.1404	0.221
ANODE 10	0.1305	0.2086

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	45.87	SQ IN.
CELL DIAMETER	7.64	IN.
INPUT CURRENT	39.81	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	316.52	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	10.906	WATTS
TOTAL STACK HEAT GENERATION RATE	305.616	WATTS

FARADAIC EFFICIENCY 0.9065

PRESSURE, PSIA INLET	PRESSURE, PSIA OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	POWER, WATTS HEAT GEN
14.7	1014.7	.7950	316.5	305.6
1014.7	2014.7	.6741	268.4	266.7
2014.7	3014.7	.6551	260.8	259.8
3014.7	4014.7	.6439	256.4	255.6
4014.7	5014.7	.6359	253.2	252.6
5014.7	6014.7	.6298	250.7	250.3

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	109.91	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	46.9689	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	29.1233	AMP/SQ FT
FARADAIC EFFICIENCY	0.767	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	3014.7	PSIA
DIFFERENTIAL PRESSURE	3000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.7512	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.273	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0175	VOLTS
CORRECTED CELL VOLTAGE	0.8038	VOLTS
SPE OPERATING RESISTIVITY	60.451	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 3014.7 PSIA)	0.025621	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0378	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2477	0.3335
2	0.2156	0.3033
3	0.1892	0.2766
4	0.1675	0.2528
5	0.1493	0.2317
6	0.1339	0.2129
7	0.1209	0.1963
8	0.1098	0.1816
9	0.1003	0.1685
ANODE 10	0.0921	0.1569

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	54.21	SQ IN.
CELL DIAMETER	8.31	IN.
INPUT CURRENT	47.05	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	378.23	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	13.636	WATTS
TOTAL STACK HEAT GENERATION RATE	364.594	WATTS

FARADAIC EFFICIENCY 0.767

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	3014.7	.8038	378.2	364.6
3014.7	6014.7	.6527	307.1	305.4

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	212	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	103.88	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	93.9379	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	47.0835	AMP/SQ FT
FARADAIC EFFICIENCY	0.6233	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	6014.7	PSIA
DIFFERENTIAL PRESSURE	6000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.6297	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.067	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0352	VOLTS
CORRECTED CELL VOLTAGE	0.8215	VOLTS
SPE OPERATING RESISTIVITY	80.848	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.2878	GM/GM SPE
	0.3677	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 6014.7 PSIA)	0.010762	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.0426	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.2878	0.3676
1	0.2257	0.3131
2	0.1835	0.2704
3	0.1532	0.2363
4	0.1306	0.2087
5	0.1132	0.1861
6	0.0995	0.1674
7	0.0886	0.1518
8	0.0798	0.1388
9	0.0725	0.1278
ANODE 10	0.0665	0.1184

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	66.7	SQ IN.
CELL DIAMETER	9.22	IN.
INPUT CURRENT	57.9	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	475.66	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	15.366	WATTS
TOTAL STACK HEAT GENERATION RATE	460.299	WATTS
FARADAIC EFFICIENCY	0.6233	

PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	6014.7	.8215	475.7	460.3

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.01	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	275	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	113.08	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	36.83	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	24.7363	AMP/SQ FT
FARADAIC EFFICIENCY	0.8021	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.8229	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.394	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0069	VOLTS
CORRECTED CELL VOLTAGE	0.7932	VOLTS
SPE OPERATING RESISTIVITY	48.224	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.3773	GM/GM SPE
	0.4325	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.042009	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.3773	0.4325
1	0.3308	0.4005
2	0.2922	0.3712
3	0.2597	0.3441
4	0.232	0.3191
5	0.2082	0.296
6	0.1876	0.2748
7	0.1696	0.2552
8	0.154	0.2372
9	0.1403	0.2208
ANODE 10	0.1283	0.2059

SUMMARY OF OPERATING CHARACTERISTICS OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.01	IN.
CELL AREA	51.83	SQ IN.
CELL DIAMETER	8.12	IN.
INPUT CURRENT	45	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	356.9	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.626	WATTS
TOTAL STACK HEAT GENERATION RATE	344.279	WATTS

FARADAIC EFFICIENCY 0.8021

PRESSURE, PSIA. INLET	OUTLET	CELL VOLTAGE	POWER, WATTS INPUT	HEAT GEN
14.7	2014.7	.7932	356.9	344.3
1014.7	3014.7	.6723	302.5	299.8
2014.7	4014.7	.6533	293.9	292.2
3014.7	5014.7	.6421	288.9	287.6
4014.7	6014.7	.6341	285.3	284.3

HIGH PRESSURE OXYGEN CONCENTRATOR STACK
OPERATING CHARACTERISTICS
WITH SATURATED CATHODE OPERATION

SPE THICKNESS	0.02	IN.
ION EXCHANGE CAPACITY (IEC)	0.825	MEQ/GM
EQUILIBRATION TEMPERATURE	275	DEG F
OPERATING TEMPERATURE	120	DEG F
OXYGEN DEW POINT TEMP	107.23	DEG F
CURRENT DENSITY	125	AMP/SQ FT
GAS PERMEABILITY LOSS,EQUILIBRATED SPE(EQUIV)	18.415	AMP/SQ FT
GAS PERMEABILITY LOSS WITH SPE GRADIENT(EQUIV)	10.1249	AMP/SQ FT
FARADAIC EFFICIENCY	0.919	
OXYGEN PRESSURE(INLET)	14.7	PSIA
OXYGEN PRESSURE(OUTLET)	2014.7	PSIA
DIFFERENTIAL PRESSURE	2000	PSID
OXYGEN SIDE(ANODE)ACTIVITY	0.6948	
VAPOR PRESS-SAT WATER VAPOR	1.6946	PSIA
OXYGEN SIDE VAPOR PRESSURE	1.177	PSIA
CELL VOLTAGE(ATM PRESS DATA)	0.7864	VOLTS
VOLTAGE CORRECTION FOR ATM PRESS TEST DATA	0	VOLTS
VOLTAGE CORRECTION FOR SPE RESIST CHANGE	0.0676	VOLTS
CORRECTED CELL VOLTAGE	0.854	VOLTS
SPE OPERATING RESISTIVITY	118.229	MOHM-SQ IN.
SPE EQUILIBRIUM RESISTIVITY	40.327	MOHM-SQ IN.
EQUILIBRIUM WATER CONTENT	0.3773	GM/GM SPE
	0.4325	CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	0.0434	GM/GM SPE
	0.0805	CC/CC SPE
VAPOR LOSS RATE (OXYGEN PRESS= 2014.7 PSIA)	0.035465	CC/HR
THEOR VOLTAGE FOR ISOTHERMAL COMPRESSION	0.035	VOLTS

WATER CONTENT

STATION	GM/GM SPE	CC/CC TOTAL
CATHODE	0.3773	0.4325
1	0.3171	0.3905
2	0.2679	0.3512
3	0.2272	0.3145
4	0.1933	0.2808
5	0.1651	0.2501
6	0.1417	0.2226
7	0.1225	0.1984
8	0.1067	0.1774
9	0.0938	0.1593
ANODE 10	0.0833	0.144

SUMMARY OF OPERATING CHARACTERISTICS
OF HIGH PRESSURE OXYGEN CONCENTRATOR STACK

NO. OF CELLS	10	
SPE THICKNES	0.02	IN.
CELL AREA	45.24	SQ IN.
CELL DIAMETER	7.59	IN.
INPUT CURRENT	39.27	AMP
OPERATING TEMPERATURE	120	DEG F
CURRENT DENSITY	125	AMP/SQ FT
OXYGEN GENERATION RATE	0.2375	LB/HR
STACK POWER INPUT	335.37	WATTS
THEOR POWER FOR ISOTHERMAL COMPRESSION	12.626	WATTS
TOTAL STACK HEAT GENERATION RATE	322.747	WATTS

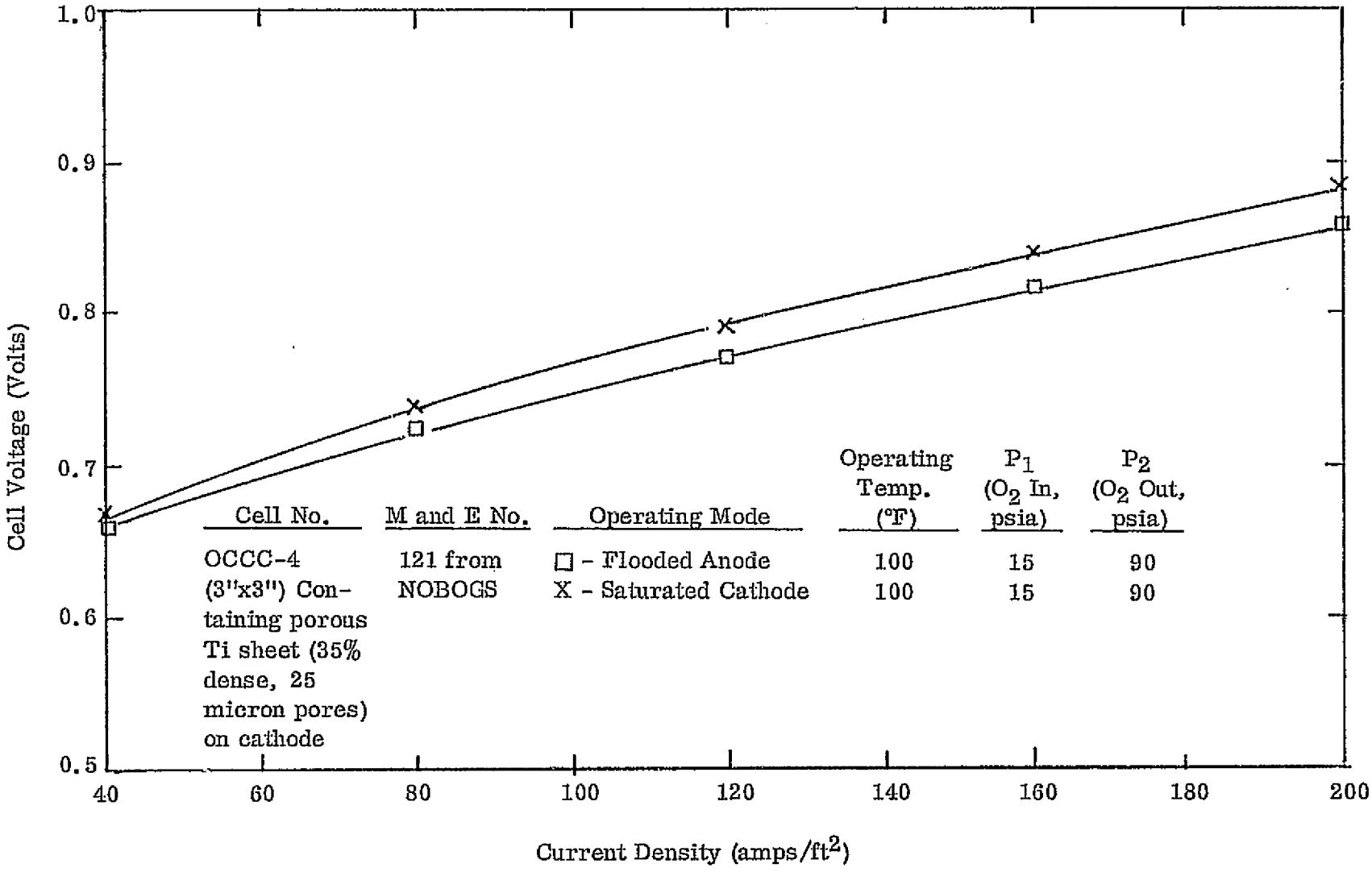
FARADAIC EFFICIENCY 0.919

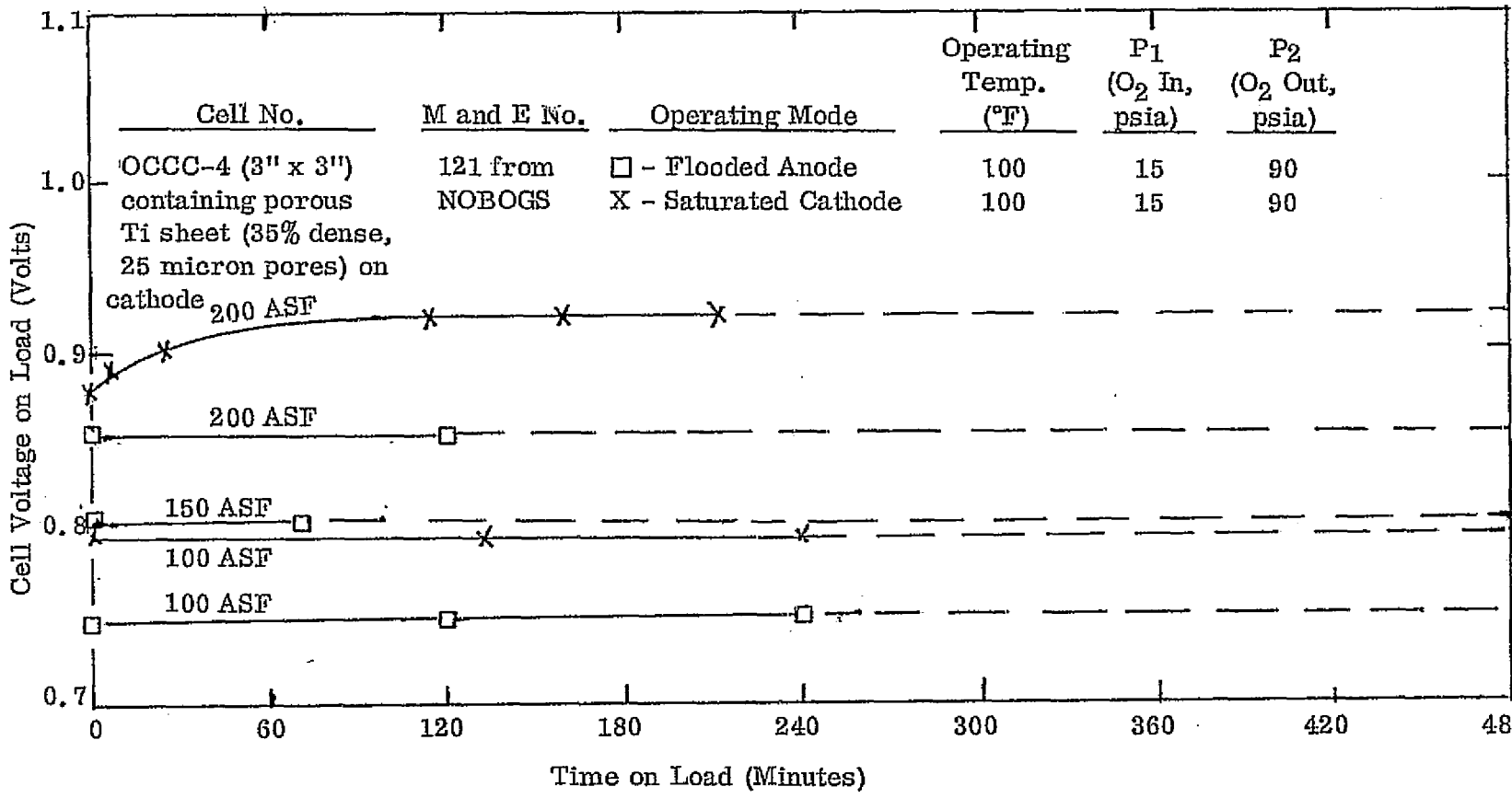
PRESSURE, PSIA		CELL	POWER, WATTS	
INLET	OUTLET	VOLTAGE	INPUT	HEAT GEN
14.7	2014.7	.8540	335.4	322.7
1014.7	3014.7	.7331	287.9	285.2
2014.7	4014.7	.7140	280.4	278.7
3014.7	5014.7	.7029	276.0	274.8
4014.7	6014.7	.6949	272.9	271.9

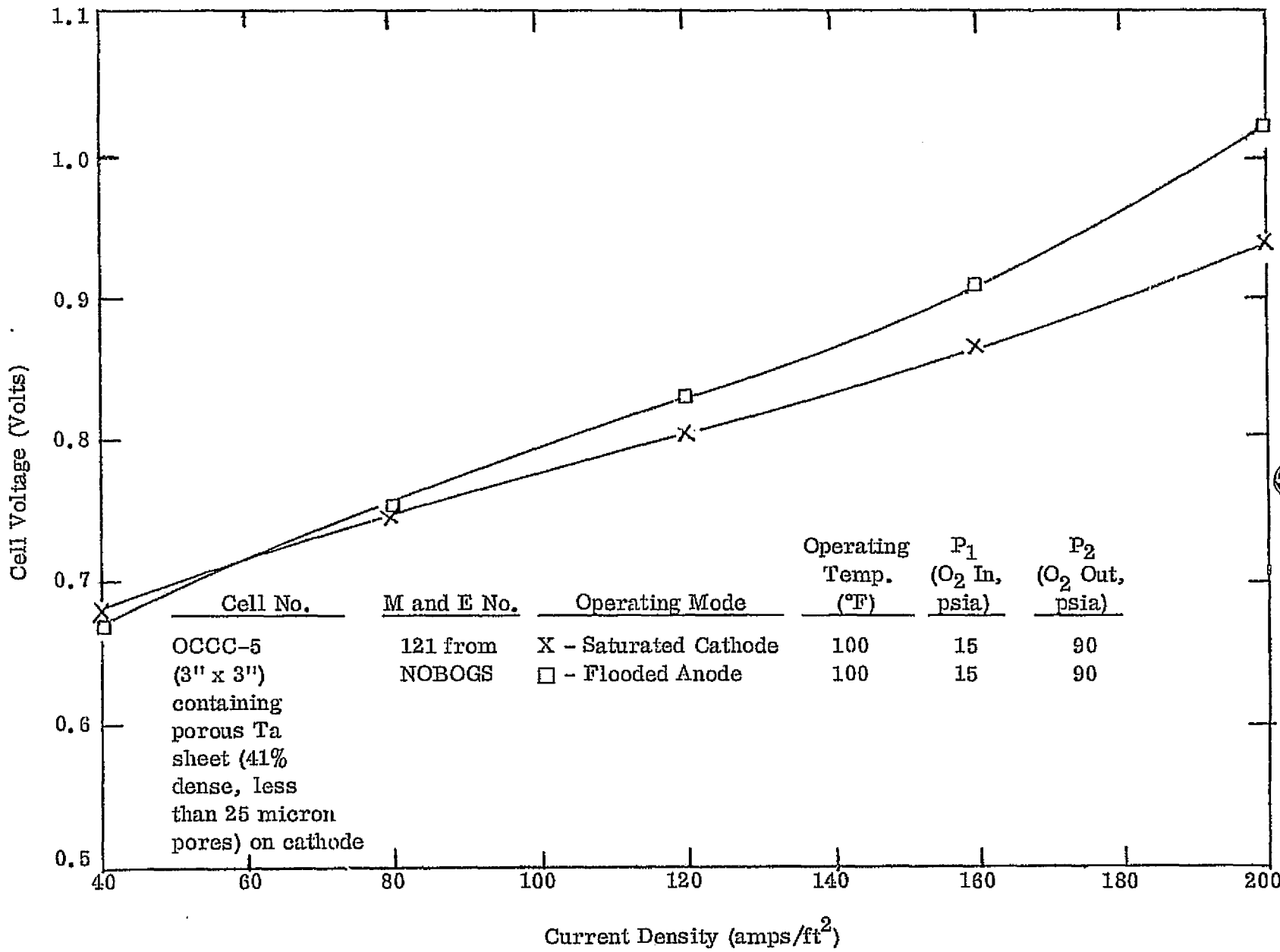
APPENDIX B

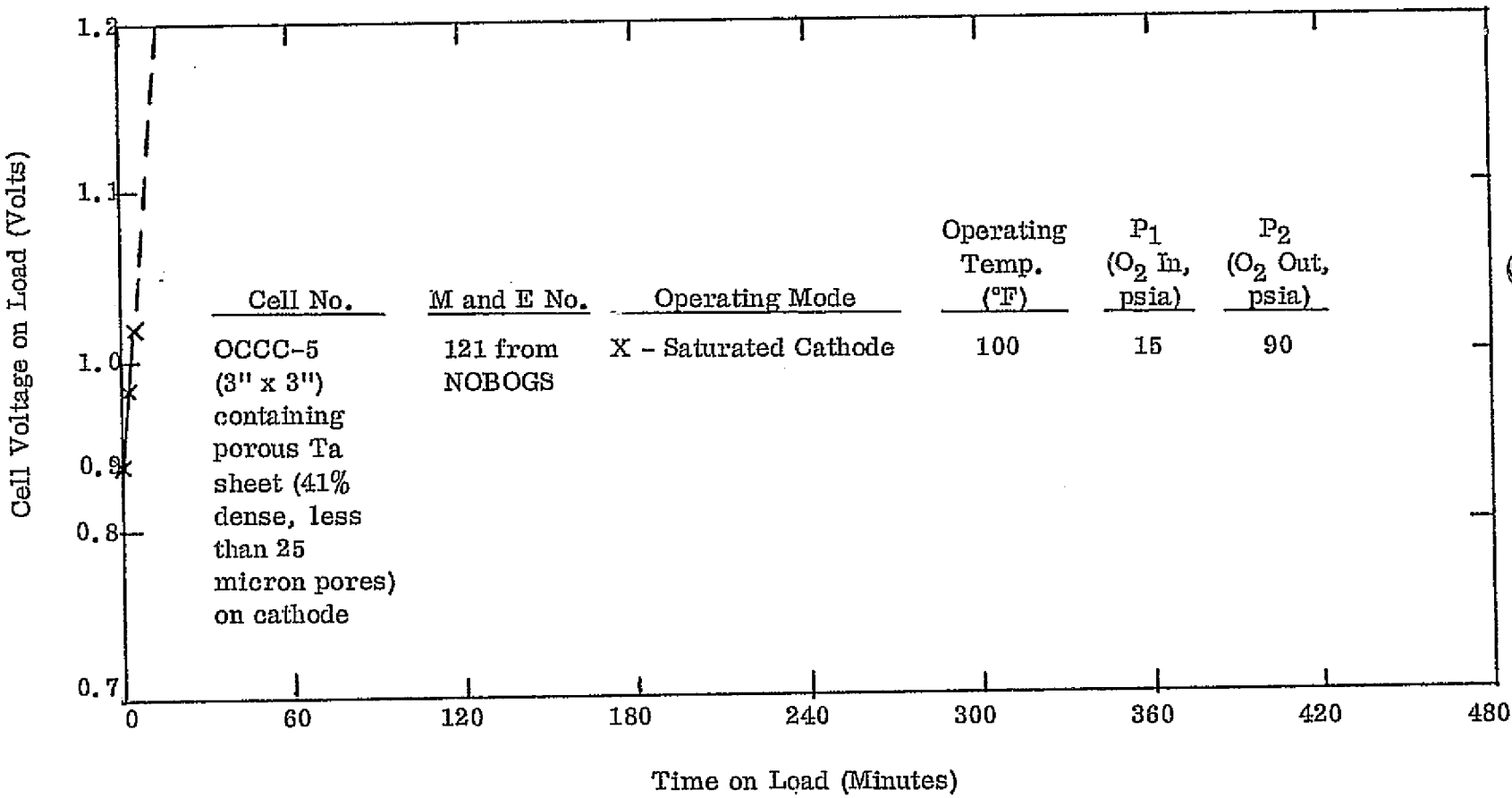
Laboratory Test Data

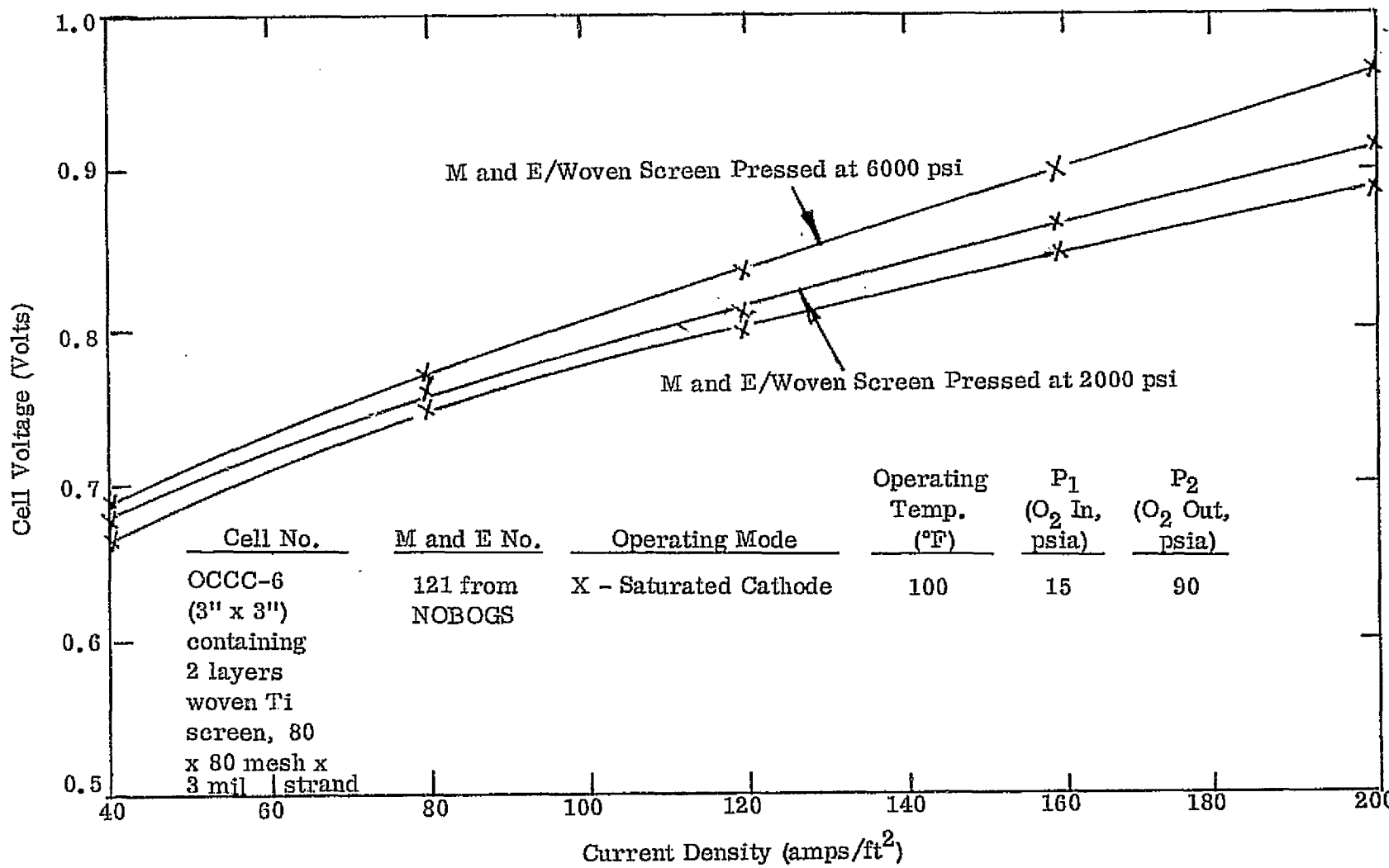
The salient data of preliminary laboratory cells have been discussed in the body of the report. This Appendix includes data on all tests performed in 3 x 3 inch laboratory hardware.

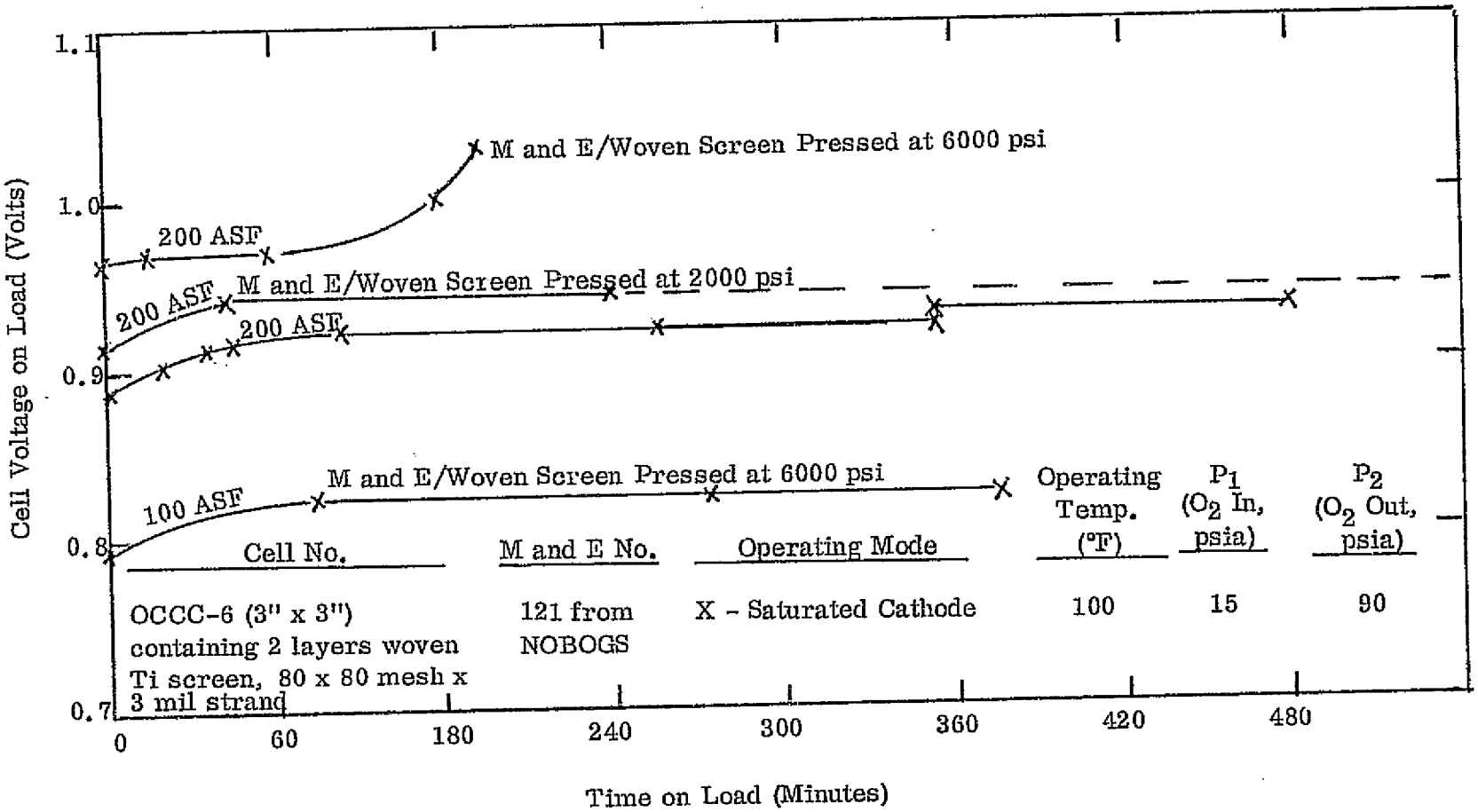

1.0
0.9
0.8
0.7
0.6
0.5
Cell Voltage (Volts)
40
60
80
100
120
140
160
180
200
Current Density (amps/ft^2)
Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P_1 (O_2 In, psia)
P_2 (O_2 Out, psia)
OCCC-4 (3"x3") Containing porous Ti sheet (35% dense, 25 micron pores) on cathode
121 from NOBOGS
□ - Flooded Anode
X - Saturated Cathode
100
15
90
100
15
90


Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P1 (O2 In, psia)
P2 (O2 Out, psia)
OCCC-4 (3" x 3") containing porous Ti sheet (35% dense, 25 micron pores) on cathode
121 from NOBOGS
□ - Flooded Anode
X - Saturated Cathode
100
15
90
100
15
90
200 ASF
200 ASF
150 ASF
100 ASF
100 ASF
Cell Voltage on Load (Volts)
1.1
1.0
0.9
0.8
0.7
0
60
120
180
240
300
360
420
480
Time on Load (Minutes)


1.1
1.0
0.9
0.8
0.7
0.6
0.5
Cell Voltage (Volts)
40
60
80
100
120
140
160
180
200
Current Density (amps/ft^2)
Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P_1 (O_2 In, psia)
P_2 (O_2 Out, psia)
OCCC-5 (3" x 3") containing porous Ta sheet (41% dense, less than 25 micron pores) on cathode
121 from NOBOGS
X - Saturated Cathode
100
15
90
□ - Flooded Anode
100
15
90


Cell Voltage on Load (Volts)
1.2
1.1
1.0
0.9
0.8
0.7
0
60
120
180
240
300
360
420
480
Time on Load (Minutes)
Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P1 (O2 In, psia)
P2 (O2 Out, psia)
OCCC-5 (3" x 3") containing porous Ta sheet (41% dense, less than 25 micron pores) on cathode
121 from NOBOGS
X - Saturated Cathode
100
15
90


1.0
0.9
0.8
0.7
0.6
0.5
Cell Voltage (Volts)
M and E/Woven Screen Pressed at 6000 psi
M and E/Woven Screen Pressed at 2000 psi
Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P1 (O2 In, psia)
P2 (O2 Out, psia)
OCCC-6 (3" x 3") containing 2 layers woven Ti screen, 80 x 80 mesh x 3 mil strand
121 from NOBOGS
X - Saturated Cathode
100
15
90
40
60
80
100
120
140
160
180
200
Current Density (amps/ft2)


1.1
1.0
0.9
0.8
0.7
Cell Voltage on Load (Volts)
M and E/Woven Screen Pressed at 6000 psi
200 ASF
200 ASF
M and E/Woven Screen Pressed at 2000 psi
200 ASF
100 ASF
M and E/Woven Screen Pressed at 6000 psi
0
60
180
240
300
360
420
480
Time on Load (Minutes)
Cell No.
M and E No.
Operating Mode
Operating Temp. (°F)
P1 (O2 In, psia)
P2 (O2 Out, psia)
OCCC-6 (3" x 3") containing 2 layers woven Ti screen, 80 x 80 mesh x 3 mil strand
121 from NOBOGS
X - Saturated Cathode
100
15
90