NASA CR-66654
FINAL REPORT

CONTRACT NAS1-6561

PERIOD: AUGUST 6, 1966 TO MAY 31, 1968

PREPARED FOR

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION
HAMPTON, VIRGINIA 23365

AUGUST, 1968

DESIGN AND FABRICATION OF A WATER ELECTROLYSIS UNIT FOR AN INTEGRATED LIFE SUPPORT SYSTEM

ALLIS-CHALMERS
ADVANCED ELECTROCHEMICAL
PRODUCTS DIVISION
MILWAUKEE, WISCONSIN 53201

FACILITY FORM 602

N68-34044 (ACCESSION NUMBER)	(THRU)
67 (PAGES)	1 (CODE)
CR-66654 (NASA CR OR TMX OR AD NUMBER)	05 (CATEGORY)

NASA CR-66654

FINAL REPORT

DESIGN AND FABRICATION OF A WATER ELECTROLYSIS UNIT FOR THE INTEGRATED LIFE SUPPORT SYSTEM

Period: August 6, 1966 to May 31, 1968

Contract NAS1-6561

Prepared For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION
HAMPTON, VIRGINIA 23365

ALLIS-CHALMERS
ADVANCED ELECTROCHEMICAL
PRODUCTS DIVISION
MILWAUKEE, WISCONSIN 53201

August, 1968

FOREWORD

The performance period for this contract (NAS1-6561) was from August 6, 1966 to May 31, 1968. Most of the work was performed in the Engineering Department of the Research Division of Allis-Chalmers. However, when the Research Division was reorganized, January 1, 1968, contract supervision was assumed by the Systems Technology Department of the Advanced Electrochemical Products Division of Allis-Chalmers.

Mr. Robert W. Johnson and Mr. Thomas Owens were the technical contract monitors for the NASA, Langley Research Center. Mr. A. P. Antony was the program manager for Allis-Chalmers.

Some results of this program were used in support of a study (Basic Subsystem Module) for the Manned Spacecraft Center under Contract NAS9-6796. This work was partially funded by Modification No. 1 of NAS1-6561. The results of this effort were submitted to Langley Research Center in September, 1967, in Allis-Chalmers' report ACR 096798.

Report Prepared By: A. P. Antony

Approved By:

A. P. Antony

A. P. Antony
Program Manager

G L Reed

G. L. Reed
Manager, Systems Technology Department

ABSTRACT

A four-man water electrolysis unit, which provides 8 pounds per day of oxygen, has been designed, built, and tested under Langley Research Center Contract NAS1-6561. Tests at the contractor's plant included a 250 hour unit demonstration test prior to delivery of hardware. Electrical efficiency for the unit was 76 percent based on average cell voltages and the 1.23 volts per cell theoretically required for water electrolysis. Total power input was 960 watts; 800 watts were used for electrolysis and the remainder for heaters and other accessories. Power sources were 28 volt DC and 115 volt 400 Hertz. Oxygen and hydrogen purities were greater than 99.95 percent based on analysis by gas chromatograph and mass spectrometer.

The unit design is based on zero-g requirements. Potassium hydroxide (KOH) at a nominal concentration of 35 percent is maintained in an asbestos matrix for electrolysis. Water feed is by vapor diffusion across the hydrogen gas passage. The unit consists of 3 modules of 16 cells each. Cell subassemblies are of laminated and bonded polysulfone with "O" ring seals to integral module manifolds for feed water and product gases. Unit weight as fabricated was 160 pounds and occupied a volume of 4.4 cubic feet. Significant reductions could be made in weight and volume for a flight-prototype unit.

TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONTINUED)

SUMMARY

The water electrolysis unit designed, built, tested, and delivered to Langley Research Center, per Contract NAS1-6561, is a system essentially unchanged from the one presented in the original proposal. The choice of 100 amperes per square foot of electrode area was maintained throughout the program and 25.5 volts was attained for the 16-cell module in the final testing. The final 250-hour test run also showed excellent condenser performance, good equilibrium temperatures, very high gas purity, and adequate current control; moreover, no liquid carryover, corrosion or leakage was observed. Accumulation of dissolved gases in the feed water necessitated purging of each module once a day to maintain constant performance.

The unit design allows easy access to all components and provides for ease of operation and maintenance.

The majority of the development effort was devoted to the key component in the system, the electrolysis module. The module evolved from a nickel plate and Teflon gasket design to a completely laminated plastic cell design employing standard "O" ring seals. This design eliminates all metal distribution and backup plates, precluding the possibility of galvanic or chemical corrosion. Assembly time has been substantially reduced, and significant progress was made on the most common industry problem-internal and external sealing.

INTRODUCTION

The objective of the program was to develop a Water Electrolysis Unit employing principles suited to zero-gravity operation to be tested as a part of the Langley Research Center Integrated Life Support System (ILSS) research program. The unit, therefore, must provide the quantity and quality of oxygen required by four men during one year of normal gravity testing on the bench and in open and closed door tests in the ILSS chamber. Major program goals were (1) to achieve a simple, reliable device with long operating life; (2) achieve a design that permits simple maintenance procedures and minimum operational attention; (3) reduce module power requirements to a minimum; and (4) develop a rugged module that eliminates sealing, chemical and galvanic corrosion, and assembly problems.

The primary design specifications to be met were:

Oxygen - 8.0 pounds/day at 15 psig minimum delivery pressure, 70°F maximum delivery temperature with no entrained water, and 99.7 percent minimum purity with less than 0.1 percent hydrogen.

Hydrogen - 1.0 pound/day at 15 psig minimum delivery pressure, 70°F maximum delivery temperature with no entrained water, and 99.0 percent minimum purity.

Services - DC power - 28 ± 1 volt, 3 parallel wires; AC - 115/208 V, 3-phase, 400 cps, 4-wire; coolant - propylene glycol/water mixture at 32°F; and feed water - potable water with approximately 100 ppm of dissolved solids.

Design - Unit to consist of three to six identical modules, and not be larger than 20 x 20 x 37 inches.

SYSTEM DESCRIPTION

BACKGROUND

The basic process of water electrolysis has been known and used for decades, but the requirement for a system to produce essentially dry gas in a zero-gravity environment has occurred only in the last few years. While the basic electrochemical reaction remains the same, the supporting system for the more recent requirement must be substantially revised.

The primary obstacle to be overcome in a zero-gravity environment is the separation of the incoming liquid water and the exit product gases. Two choices of operation are available:

(1) Employ a standard electrolysis design where the gas is formed in the liquid electrolyte and is separated externally by means of a centrifuge or some other device or,

(2) Modify the electrolysis module itself so that the gas produced is removed from the cell with only evaporated and entrained water. This approach offers advantages in size, weight, and power requirements. Success with this type of system design concept in fuel cell applications resulted in its selection by Allis-Chalmers for the ILSS application.

Since the oxygen produced is being fed into a closed environment, the toxicity of the materials employed becomes very important. Coupling this with the zero-gravity environment, the plate and gasket materials and resulting cell sizes, cell construction materials, and sealing design must be tailored for this particular application.

ELECTROCHEMICAL REACTION

The basic system uses a potassium hydroxide electrolyte which is contained in an asbestos matrix held between the working electrodes as shown in Figure 1. Oxygen in each cell is produced at the anode and ported from the cavity behind the electrode to a manifold common to all oxygen cells in the module. The hydrogen is similarly ported to its manifold. The reaction at these electrodes is:

$$\text{Cathode:} \quad 4H_2O + 4e \dashrightarrow 4OH^- + 2H_2 \text{ (gas)}$$

$$\text{Anode:} \quad 4OH^- \dashrightarrow 2H_2O + O_2 \text{ (gas)} + 4e$$

This states that of the four water molecules reacted at the hydrogen electrode, a portion must be diffused back across the cell from the oxygen side and the remainder must be made up from outside the cell to maintain equilibrium. To accomplish this in a zero-gravity environment without 2-phase mixtures, the water is introduced in the vapor phase as described in the following section.

WATER FEED

To provide a means of vaporizing the water, and yet keep the liquid water and hydrogen from mixing, a second asbestos matrix designated the "water transport matrix" is

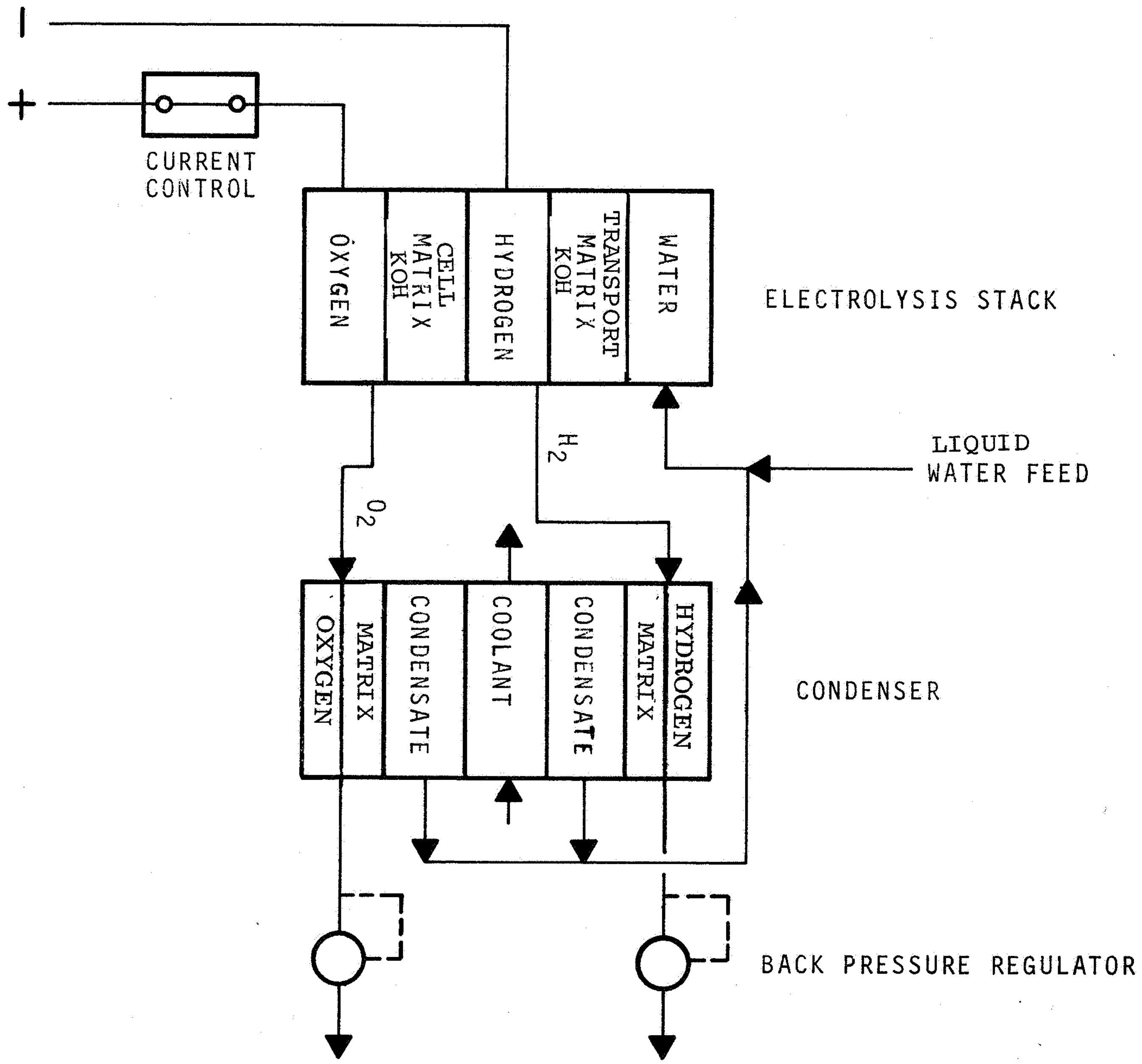


Figure 1. Electrolysis System Schematic

employed in the cell. Its capillary nature prevents the normally higher pressure hydrogen from entering the lower pressure water cavity. The water is vaporized from the surface of this matrix and is transported across the hydrogen electrode and the cell matrix. Proper functioning of this type of system depends on proper control of electrolyte concentration.

Prior to startup, a potassium hydroxide solution is introduced into the cell matrix (asbestos) and into the porous electrodes. (See Figure 1.) This solution serves two purposes: (1) as an electrolyte, and (2) as a source of water to be electrolyzed in the hydrogen electrode. When the system is started up, water is consumed and gases are produced. Since water is being removed from the potassium hydroxide solution, the solution tends to concentrate and the volume of solution shrinks. In addition, the water vapor pressure over this solution decreases. For example, if the normally introduced 35 percent KOH is allowed to concentrate to 40 percent, the vapor pressure will decrease from 2.35 psia to 1.8 psia at a 160°F cell temperature (Figure 2).

Make-up water is supplied to the cell from the water transport matrix. Figure 2 shows that pure water at 160°F has a vapor pressure of almost 5 psia. If the transport matrix was filled with pure water, the large water vapor pressure differential would transfer excess water to the electrode and the cell matrix, and cause flooding of the cell, resulting in the loss of KOH. To establish control, the same concentration of KOH is introduced into the transport matrix, prior to startup, as is introduced into the cell matrix. No water transfer takes place during warmup since the KOH concentrations remain the same. When the electrolysis reaction is started, electrolyte concentration begins and the water vapor pressure gradient gradually increases between the two matrices. The transfer rate of water vapor also increases until equilibrium is reached (normally at several tenths of 1 psi). The size of the gradient depends on the absolute temperature, gas production rate and cell design.

As can be seen in Figure 2, a large change in KOH concentration is required to produce a small vapor pressure change at low temperatures. This large concentration change results in a substantial volume reduction of the KOH solution in the cell and "drying out" of the cell occurs, resulting in higher cell voltages. For this reason, it has been found necessary to operate at temperatures above 120°F. At higher temperatures, substantial water vapor pressure changes occur with small changes in KOH concentration which keep electrolyte volume changes to a minimum, and produce the best cell operating characteristics.

MODULE VOLTAGE

Since power was specified to be at a premium and the current required to produce a given quantity of oxygen is fixed, one of the most important parameters to be controlled is the module voltage that must be applied for the necessary current. The voltage is a function of many variables including (1) electrode catalytic activity or polarization losses, (2) lead losses to bring the current to the electrodes, (3) the quantity of KOH in the cell (as discussed in the preceding paragraph), and (4) the internal resistance. The first two factors are a function of the cell design which are fixed once the cell has been constructed.

The internal resistance, which is not fixed, can be changed as system operating conditions change. The most important effect on the resistivity is the system temperature. As shown in Figure 3, the resistance of 30 percent KOH solution drops by a factor of nearly 3 by increasing the temperature from 80°F to 180°F The KOH electrolyte concentration also affects resistivity at lower temperatures, but is not a factor at high temperatures.

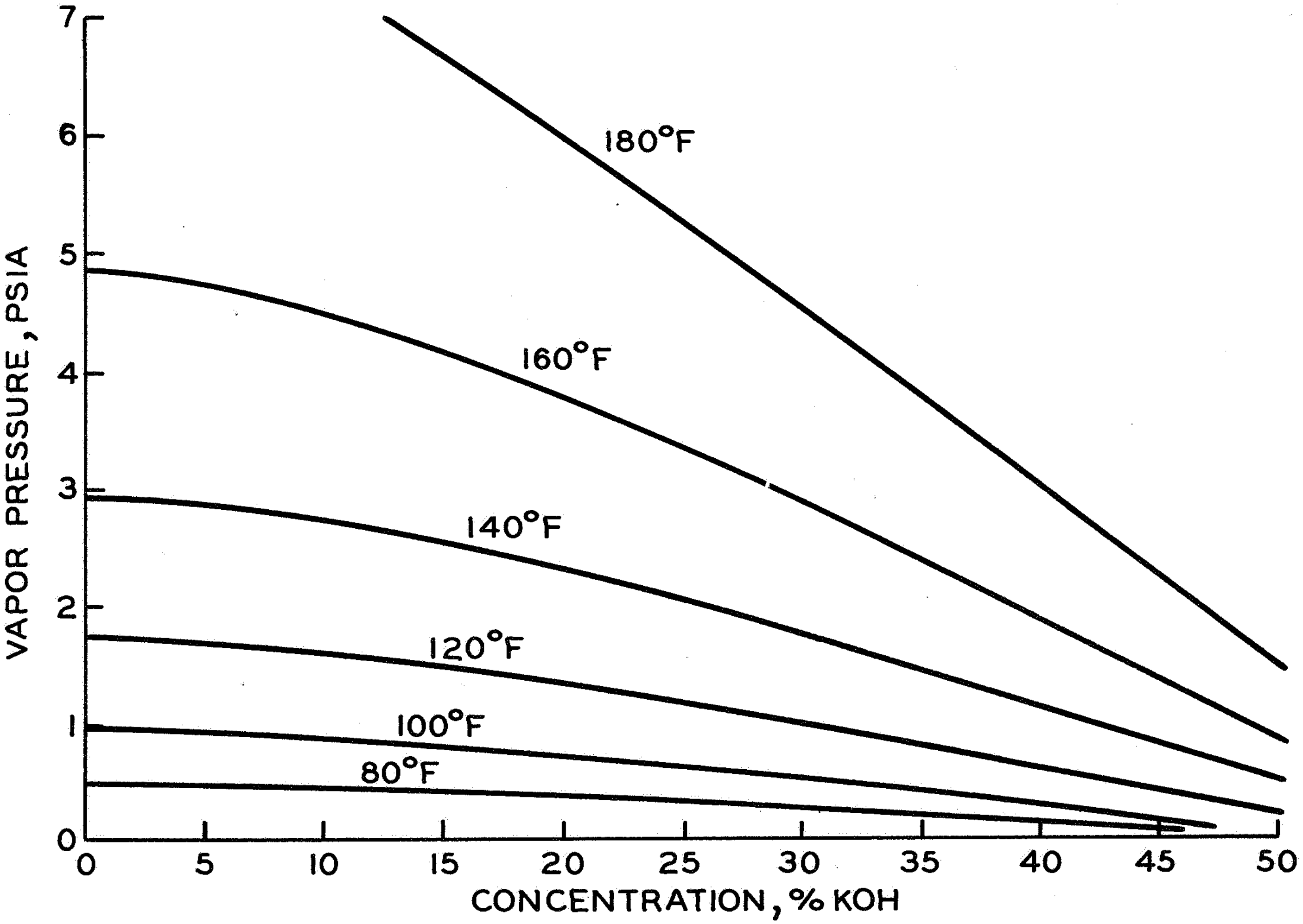


Figure 2. KOH Vapor Pressure Characteristics

To see the absolute effects of this resistance change on module voltage, the remainder of the factors such as line losses must be known. As a basis for further discussion, Figure 4 is included which shows a general relationship of voltage to nominal system temperatures which has been obtained experimentally during the program. This curve is based on data for one module producing one-third of the total system requirements or 0.11 pound of oxygen per hour. This curve shows that there is a significant change in voltage temperature, and from a performance standpoint, high operating temperatures are desirable. The limiting factor on temperature is corrosion and its effect on operating life. Based on testing of previous programs, it has been shown that the desired life can be obtained at temperatures over 200°F, providing the proper materials are chosen. Selection of suitable materials has been accomplished as will be discussed in the hardware design section of this report. Until further testing has been done, a maximum temperature of 200°F was set as an arbitrary upper limit.

SYSTEM THERMAL EFFECTS

It has been established previously that the temperature must be at least 120°F to provide proper water transport; that the maximum temperature allowable is 200°F; and that the module voltage is extremely dependent on operating temperature. Since the temperature is not directly controlled, but allowed to come to equilibrium conditions, the effects of the system design and operating conditions are important. The operating temperatures are influenced by the following:

(1) The module voltage which establishes the heat load. Inefficiency in the electrolysis process results in the generation of waste heat. Based on the higher heating value, the reaction consumes 6832 Btu (or 2000 watts) per pound of liquid water at standard conditions of 65°F and one atmosphere. Since the reaction proceeds at 100 percent current efficiency, this is equivalent to approximately 1.48 volts per cell. The difference between the actual cell voltage and 1.48 volts is released as heat. For a 16-cell module then, heat is produced above 23.68 volts. As shown in Figure 5, the average conditions of 25 to 26 volts obtained during tests on this contract result in an extremely high thermal efficiency with only 50 to 75 Btu/hr produced by a module at the design rate of 0.11 pound of oxygen per hour.

(2) The primary method of heat removal is by absorbing it into the hydrogen and oxygen exhaust streams through water vaporization. The quantity of water vaporized is a function of the total system pressure and the vapor pressure of the KOH solution over which the gases are passing. The vapor pressure, in turn, is a function of the KOH solution concentration and the system temperature. Figure 6 shows the relationship of nominal module temperature as a function of the heat to be removed for various KOH concentrations. Assuming an average heat load of 60 Btu/hr, 30 psia system pressure, and 35 percent KOH solution, the theoretical equilibrium temperature is seen to be approximately 165°F if all the heat is removed by the gas streams. By changing the KOH concentration to 40 percent, the theoretical temperature goes to 175°F; lowering it to 30 percent decreases the temperature to 158°F. The system has the capability of handling more than twice the heat load on this basis and still stay under maximum temperature.

The combined effects of system total pressure and KOH concentration are shown in Figure 7 for one condition of 60 Btu/hr heat removal at design gas flow conditions. This curve indicates the strong effect that total pressure has on system temperature.

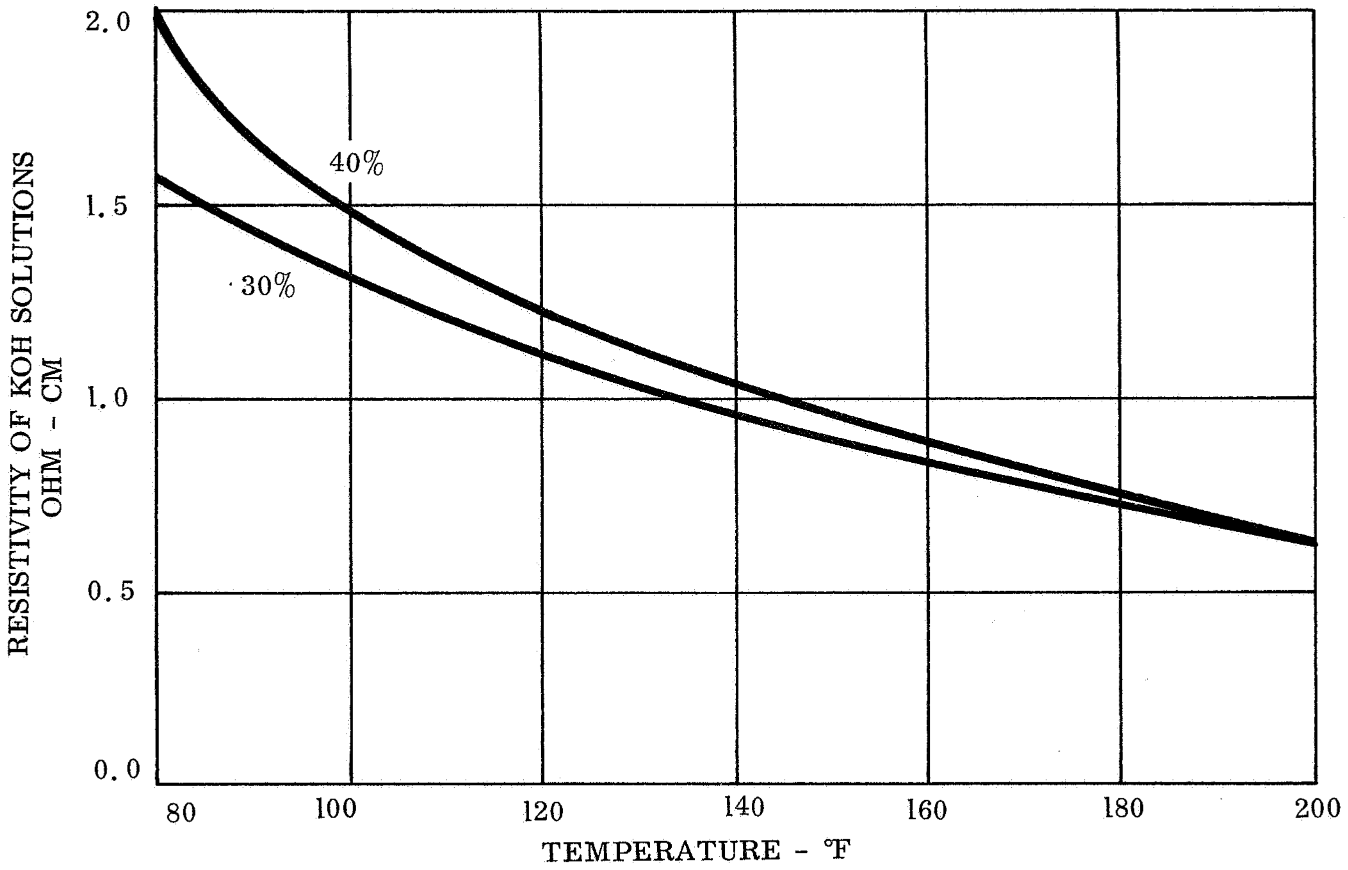


Figure 3. Temperature Vs. Resistivity

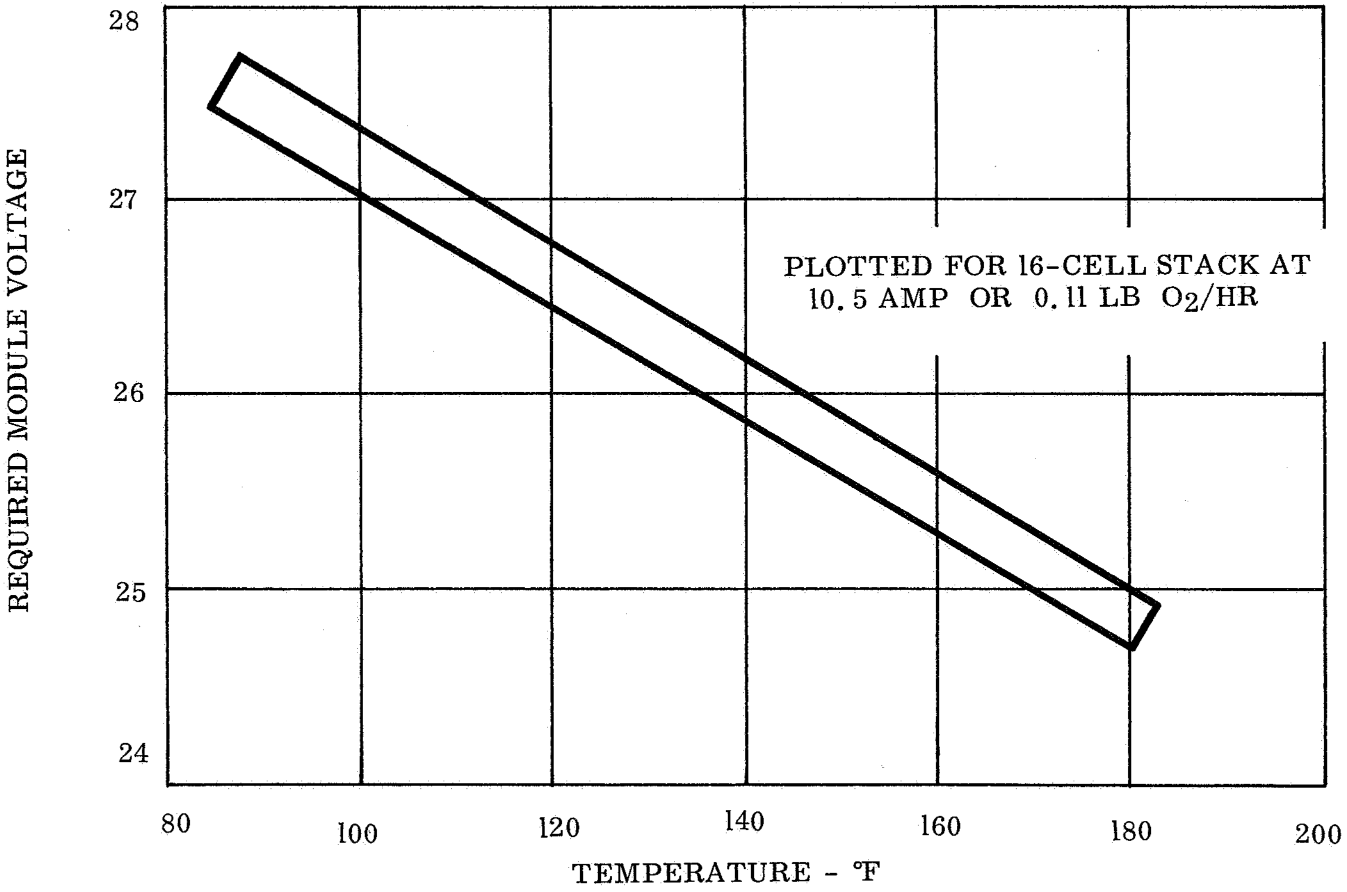


Figure 4. Temperature Vs. Voltage

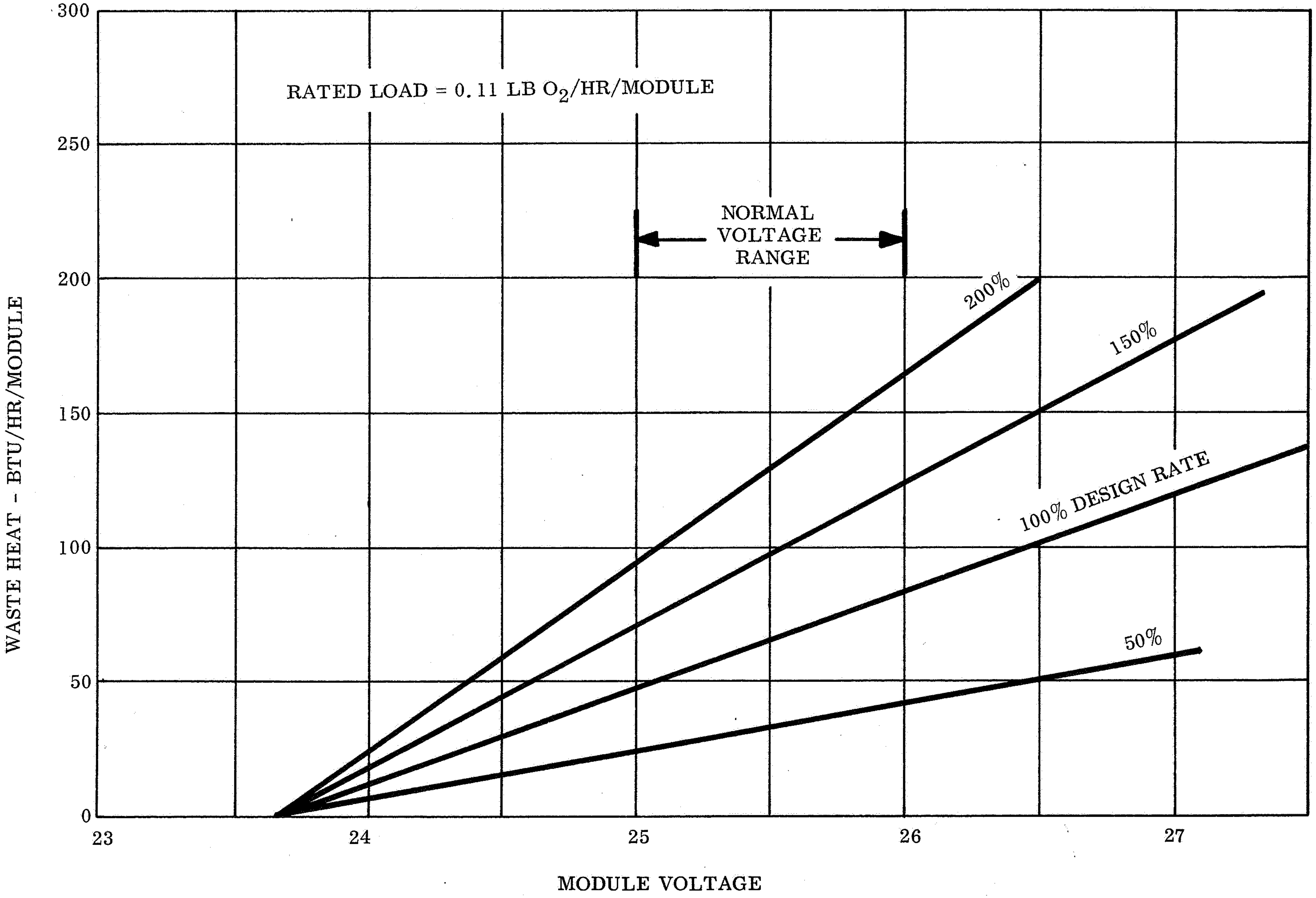


Figure 5. Heat Production Vs. Module Voltage for Various Operating Conditions

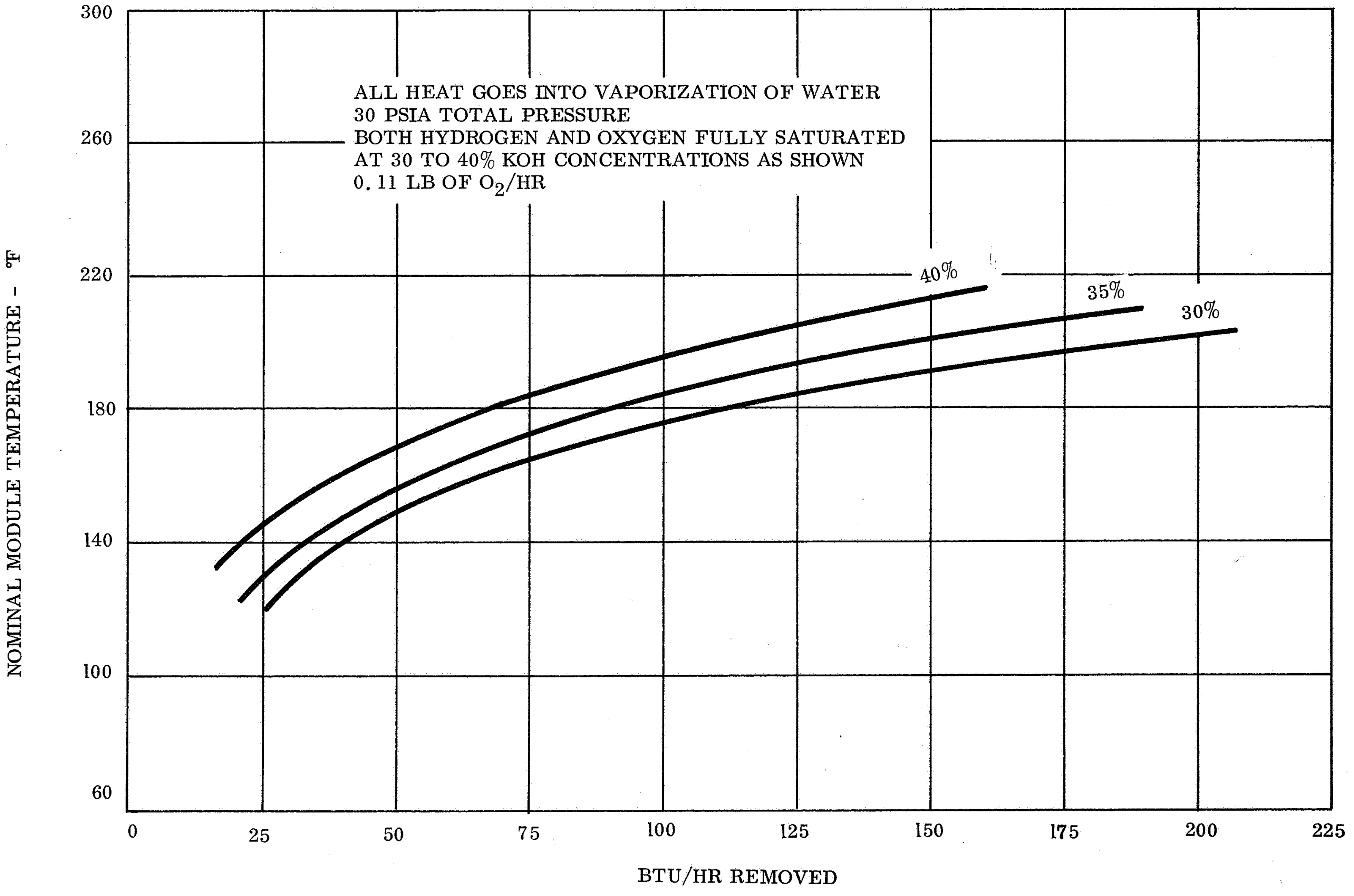


Figure 6. Total Heat Load Vs. Module Temperature

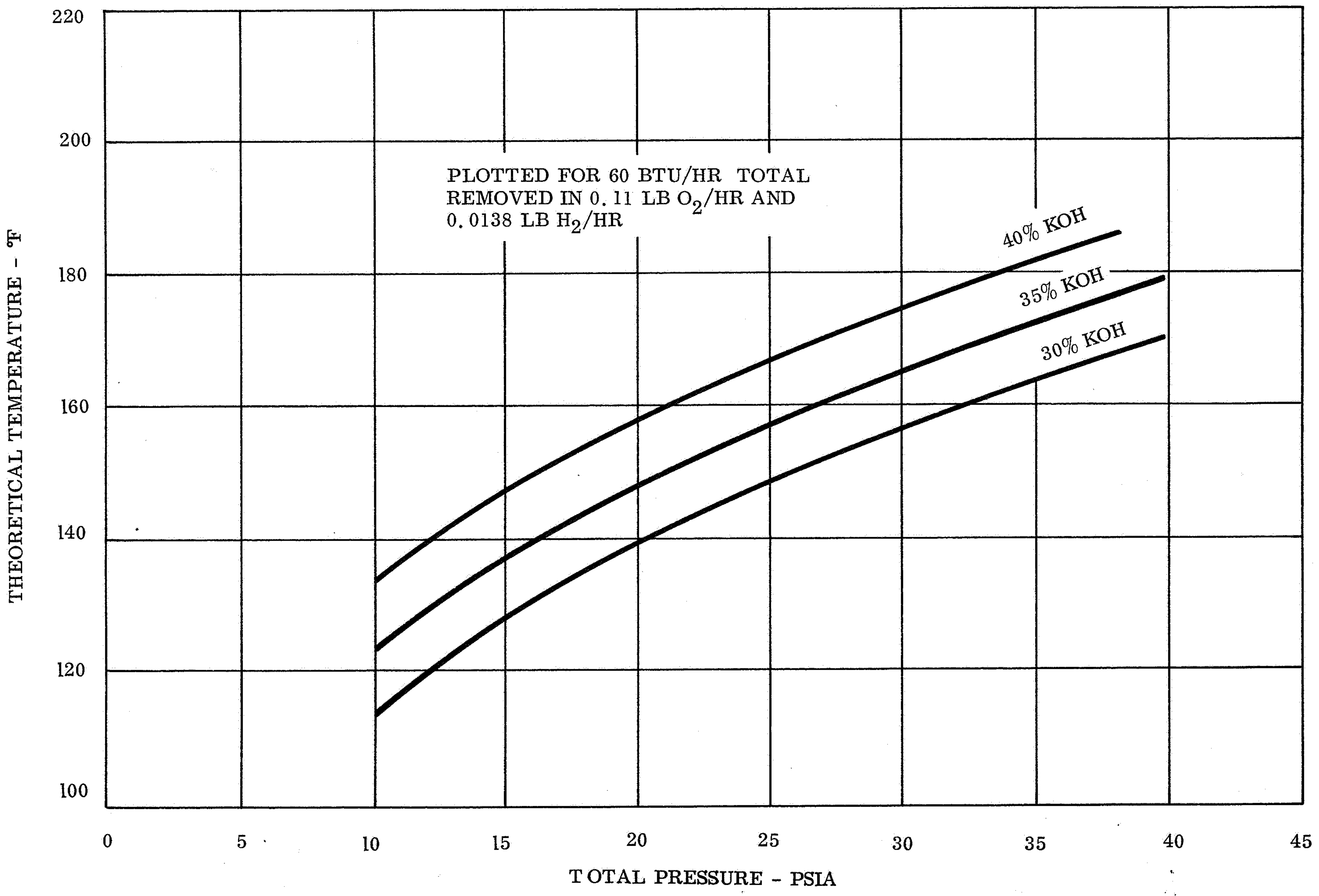


Figure 7. Theoretical Module Temperature As a Function of Total Pressure and KOH Concentration

In addition to the primary water vapor path, some heat will leave the system via conduction and convection, a quantity which is a function of the hardware design. Since some total system pressures produce equilibrium temperatures that are already lower than desired, conduction and convection losses must be kept to a minimum.

Removal of the heat contained in the exit gases occurs in the condensers. Figure 1 indicates how this is accomplished for a zero-gravity design. The wet gas passes through the condenser in a serpentine path in contact with an asbestos matrix. This matrix is cooled by a coolant flowing through a "cold plate". Passages are provided between the gas plate and cold plate which channels condensate out of the condenser. The force required to drive the condensate through the matrix is produced by a differential pressure (normally 1 to 1.5 psi) maintained between the gas and the condensate.

The water removed from the condenser is normally returned to the modules (Figure 1), but the condensate could be collected in an accumulator at any pressure from feed water to cabin pressure.

PRESSURE CONTROL

Fairly close control of the hydrogen, oxygen, and feed water pressure are required to produce the desired results. In practice it has been found desirable to maintain the hydrogen at a slightly higher pressure than the oxygen (approximately 0.5 to 1.0 psig). To provide proper driving force in the condenser, the water pressure must be at least 0.5 pisg lower than the oxygen. Since the pressure is being generated in the unit, back-pressure regulators are usedon each gas stream just before the exhaust connection to bring the gas lines to the proper pressure (Figure 1).

FLOW RATE (CURRENT) CONTROL

Some provisions must be included in the system to establish and maintain the desired oxygen production rate. To understand this, it is necessary to review the voltage-current-temperature relationships. Figure 8 shows the relatively small voltage or temperature changes result in fairly large current changes passed through the cell. Since the gas production rate is directly proportional to this current, a method of holding this current to a fairly constant value must be employed. A device which controls only the applied voltage will not hold the system within the design limits.

For a multi-module system, as specified, the modules will be wired in parallel to the source. Referring again to Figure 8, it can be seen that at a constant voltage, substantial changes in current can occur with changes in temperature. Maintaining total current to the unit at a constant value will not provide equal distribution to the modules. Each module, therefore, must have its own current controller if gross variations are to be avoided.

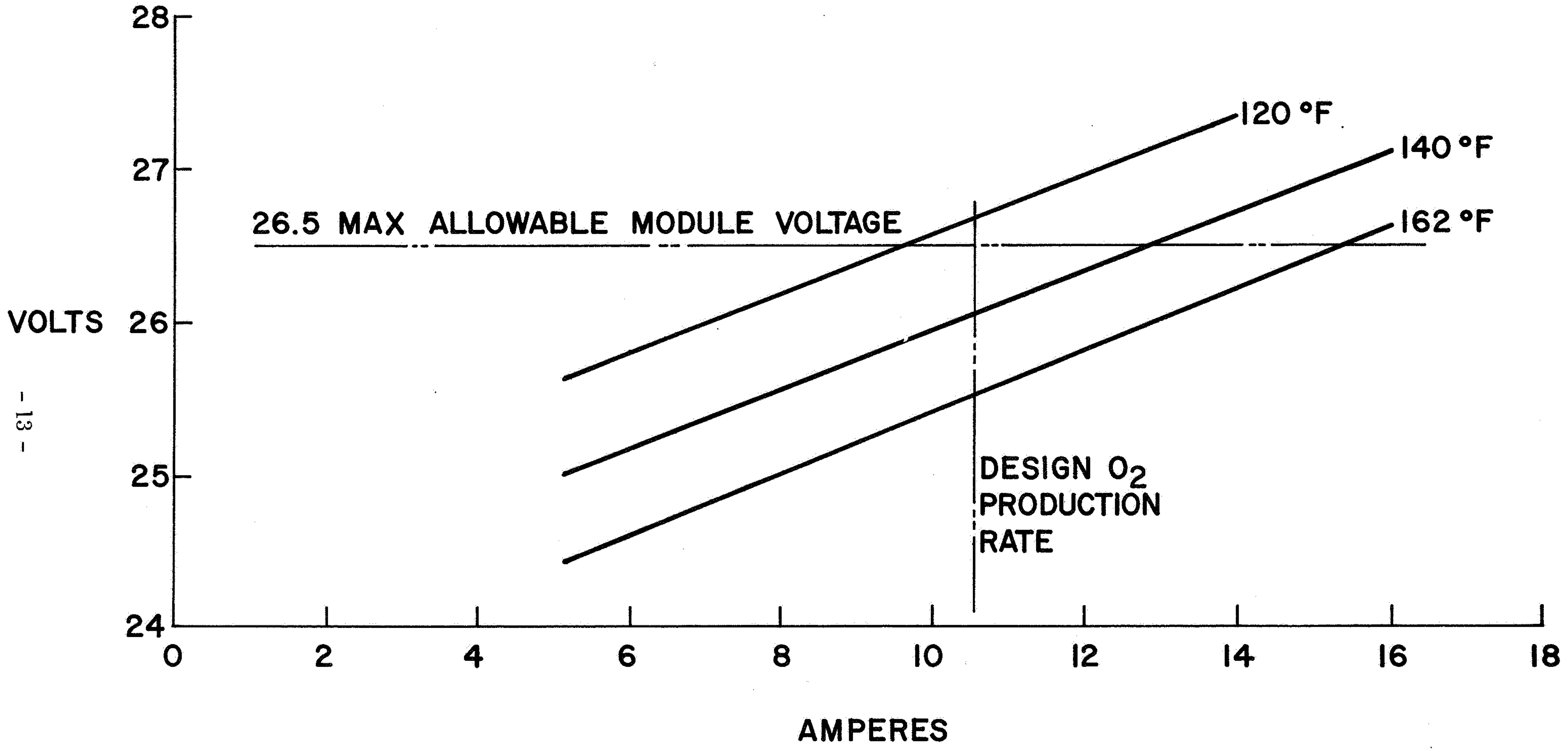


Figure 8. Typical 16-cell Module Performance

HARDWARE DESIGN

GENERAL CONSIDERATIONS

The design of the system and components was based on the following specifications and assumptions made at the outset of the program.

(1) The system would de designed to produce 8 pounds of oxygen per day at a steady rate of 0.333 pound per hour.

(2) The system must produce design oxygen rate at the minimum 27 volts input with proper control. Since the control will have a small loss, the required module voltage should be not more than 26.5 volts.

(3) System pressure should be 15 psig which was specified to be minimum pressure. This pressure permits adequate equilibrium temperatures as discussed in the previous section. It also results in a minimum problem of obtaining module seals which were considered to be a major problem area at the start of the program.

(4) As much of the waste heat as possible should be removed from the unit in the coolant loop.

(5) Maintainability is a prime consideration. Access and simple removal of key components without removal of other components were required.

(6) The current controller should be reliable and perform the required function. Simplicity of construction, operation, and maintenance was or prime consideration while size, weight, and power losses were less important.

(7) Automatic shutdown devices should be minimized to simplify unit startup, operation, and shutdown, maintenance, and repair.

(8) The number of modules operating to produce 8 pounds per day was specified at three to six electrically connected in parallel, and so connected electrically and physically that individual modules may be removed without interfering with the operation of the remainder of the unit.

(9) Components within the unit, and particularly those in contact with the product oxygen must not outgas or produce toxic degradation products.

ELECTROLYSIS MODULE SIZING

The primary task at the start was to establish the number of modules and the desired current density (ASF - amperes per square foot) to the electrodes which determines the cell size. Trade-off studies, which included the 290 pounds/kw power penalty and the 0.01 lb/Btu/hr heat penalty, were performed to arrive at an optimum ASF. To carry out these studies, estimates were made of final module operating voltage, equilibrium conditions accounting for external heat losses, resulting temperature which affects heat production, and hardware weights. Using data derived under this program, Figure 9 represents calculated estimates of equilibrium conditions for any ASF selection. This shows that at the low current densities (20 to 40 ASF) the system will run at temperatures around 120°F when external heat losses are included. This is too low for good water transport as shown previously. At 100 ASF, the equilibrium condition is seen to be approximately 165°F and

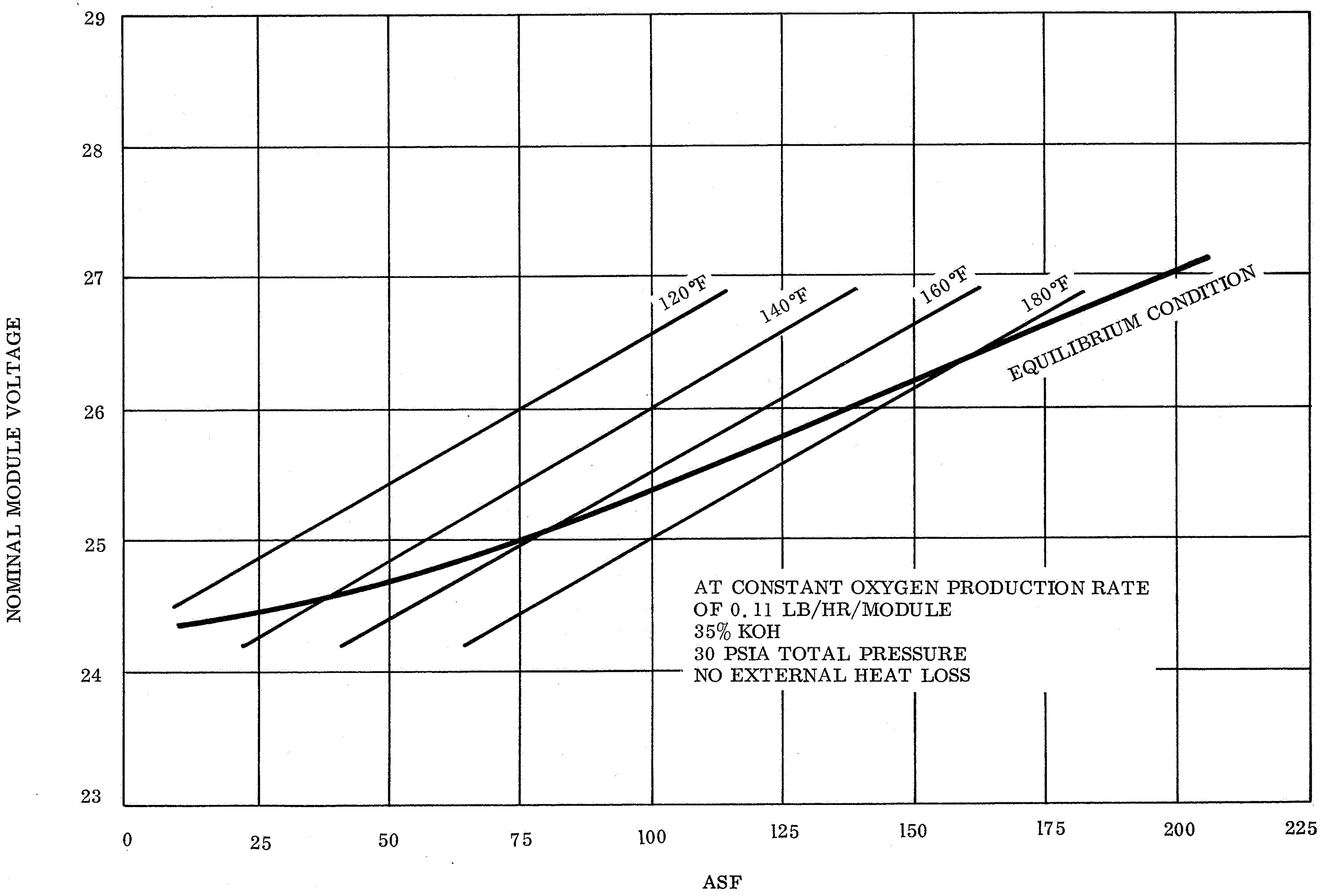


Figure 9. Current Density Vs. Module Voltage

AT CONSTANT OXYGEN PRODUCTION RATE
OF 0.11 LB/HR/MODULE
35% KOH
30 PSIA TOTAL PRESSURE
NO EXTERNAL HEAT LOSS

25.5 volts, which is quite acceptable. The total weight penalty for the module was calculated as a function of ASF for a 3-module system, Figure 10. Included were weights for a 16-cell Polysulfone-type module with end plates, the power penalty at 290 pounds/kw, and the heat penalty at 0.01 pound per Btu. The curve shows a broad minimum from 100 to 175 ASF. Below 50 ASF, the curve shows a steep rise where increased module weight greatly exceeds any savings in power penalty. Above 175 ASF, the module is reduced to such a small size that border and sealing area requirements become a major portion of the total stack and the increase in power penalty exceeds the weight saving.

Equally important to the weight penalty are life characteristics. Although little test data had been obtained prior to the start of the program for an electrolysis system operating in a zero-g mode, a large quantity of information was available from zero-g fuel cell work. Based on this knowledge and the weight penalty trade-offs, 100 ASF was selected as the design point. This was felt to be conservative enough to permit overload conditions of 150 ASF.

At 100 ASF, the effective electrode area per cell required for a three-module system is 16 square inches. A six-module system requires only one-half of this area, but twice as much cell construction, end plate fittings, piping stations, and current controllers greatly complicating the wiring and instrumentation. The three-module system was selected because it appeared to have sufficient overload capability and adequate cell size.

ELECTROLYSIS MODULE CONSTRUCTION

The electrolysis module, consisting of 16 sets of electrolysis cell components, end plates, gasketing, and bolting, is the key component in the water electrolysis unit. Since electrodes and cell matrices were available and electrochemical performance had been previously established, virtually all of the development effort on this program was applied to the module mechanical design to adapt it for the specific problems of zero-g operation. The following factors were considered at the start of the design phase:

(1) Materials used must not produce toxic outgassing or toxic corrosion products.

(2) External seals must not leak hydrogen at 45 psia.

(3) Galvanic corrosion problems must be avoided.

(4) The design must provide positive separation of hydrogen and oxygen, and withstand differential pressure upsets of feed water system pressure to cabin pressure (15 psi).

(5) Stray electrolysis must not occur in water lines which would result in two-phase mixtures.

(6) Stack assembly should be as simple as possible.

All materials used for the electrolysis module during the program were those which had been demonstrated previously in Allis-Chalmers' autoclave or operational tests to be extremely corrosion resistant in an oxygen, hydrogen, and potassium hydroxide environment.

A toxicity analysis is presented in the appendix of this report.

In overcoming some of the problems that arose, the module design evolved in three distinct steps. The initial approach was to use a built-up design with flat Teflon gaskets between components. This allowed component thicknesses to be modified quickly and easily, and represented the least time to begin testing. The design employed metallic current

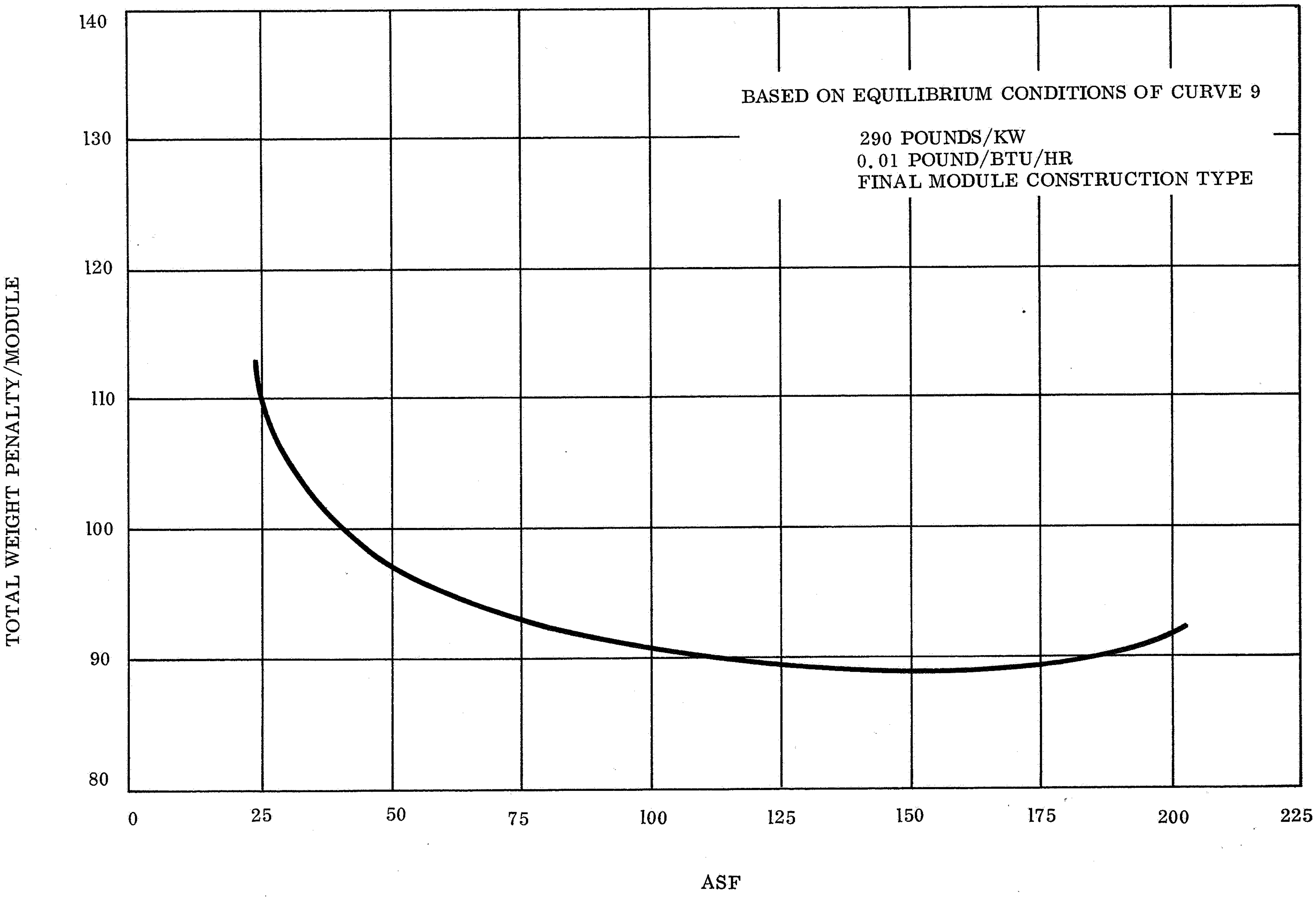


Figure 10. Weight Penalty Vs. ASF

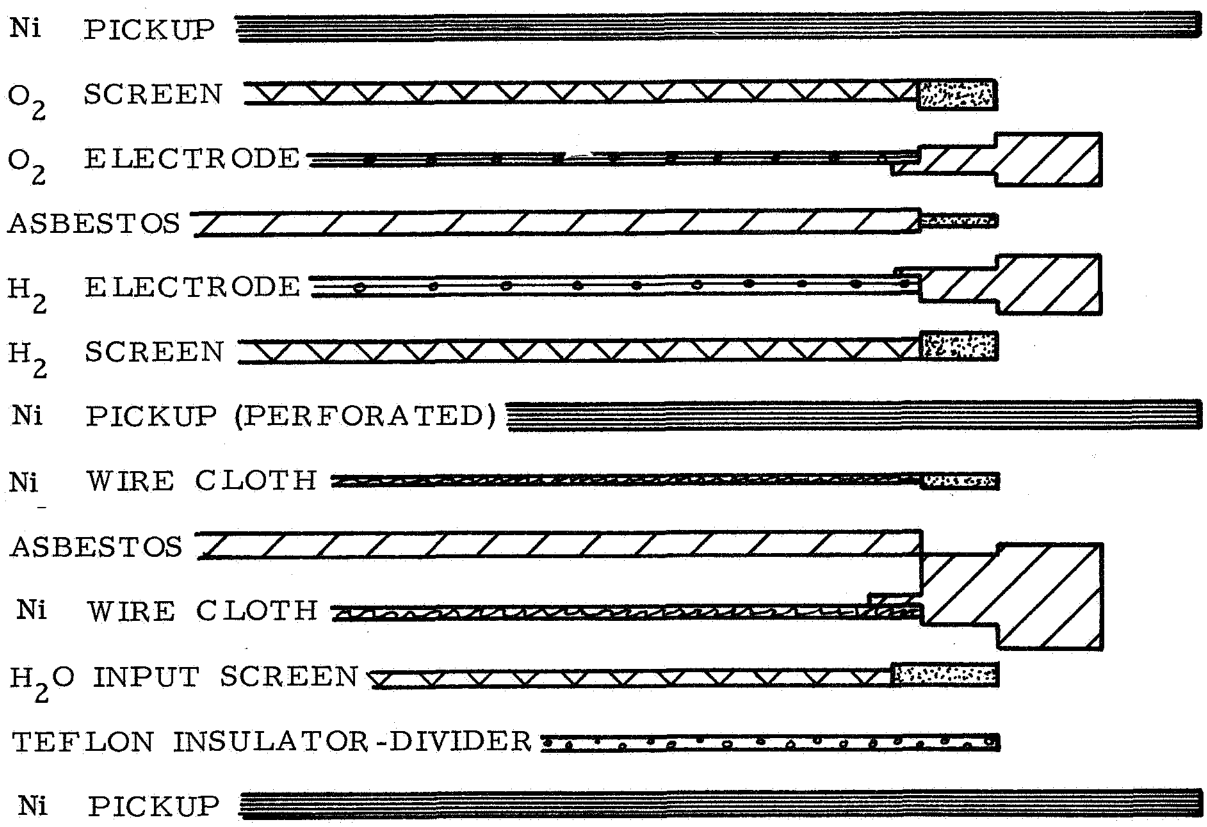


Figure 11. First Generation Cell Design

distribution plates behind the electrodes (Figure 11). This is typical of fuel cell design where "bipolar" plate design cannot be used as the current must be brought to the outside and directed around the insulating water cavity. To avoid the problems of galvanic corrosion which is likely with plated magnesium, 0.025-inch thick pure nickel plates were used. Six Teflon gaskets per cell were required and Polysulfone was used for retainers and spacer plates (Figure 12).

Teflon and nickel are common materials for strong caustic applications. Polysulfone was selected because of its resistance to KOH and for its high temperature properties. Bomb tests run at Allis-Chalmers have shown that no detectable degradation of Polysulfone occurs when it is placed in a combined 25 percent KOH solution and a purge oxygen environment at 250°F. Other tests of Polysulfone showed that it had excellent resistance in autoclave tests at 200°F and 2500 psig oxygen, surpassing all other elastomers and plastics except Teflon. Polysulfone's rigidity at 200°F, makes it desirable as a good structural, electrically-insulating part.

To prevent stray electrolysis in the water manifold, Teflon grommets were placed in the manifold area to prevent the water from contacting the edge of the nickel plate. To locate and properly seal these grommets proved difficult, although useful test results were obtained. Excessive force was required to seal the Teflon gaskets; the large number of parts made assembly difficult. The heavy stack weight from the heavy $\frac{1}{2}$-inch end plates and the large bolts required made it hard to sustain the loading required on the Teflon gaskets.

The second generation design was based on the original proposal. The major difference is that the metal distribution plates are eliminated and the current passes in and out of the cell through the electrode structural screen which extends through the cell (Figure 13). To provide a seal, the screen is bonded into a Polysulfone frame. By this technique, the number of gaskets per cell were reduced to five. After several 4-cell module tests were run, the gaskets were changed from Teflon to EPT (Ethylene - Propylene - Terpolymer). This greatly reduced the gasket load required for sealing and reduced the end plates to $\frac{1}{4}$-inch thickness, resulting in a much lighter module. The nickel screens used to form the cavities were replaced with a Polysulfone "lattice" assembly. Eventually larger portions of the cell were bonded together to form three subassemblies: an oxygen plate, a hydrogen plate, and a water transport plate (Figure 14). This reduced the gaskets required to three and eliminated all metal parts in the cell, except for the electrodes and a 150-mesh nickel screen used for mechanical support of the asbestos in the water cavity. Full size 16-cell modules were constructed with this design for acceptance tests, which demonstrated that most of the criteria had been met. One problem remained, however, which prevented the start of the final acceptance tests. Although theoretically electrically isolated from the cell, the 150-mesh nickel asbestos support screens were supporting stray electrolysis in the water cavity resulting in drying problems. This problem will be discussed in the testing section.

As a result, a third generation design was required which eliminated the metal screens in the water cavity. At the time, substantial progress had been made by Allis-Chalmers' Corporate Plastics Group on bonding complete cell assemblies into one piece. The same techniques were applied to produce parts of the size and properties required for this program. The resulting design is illustrated in Figure 15. The cell parts are bonded together so that when completed, each cell consists of only one piece.

Six standard size "O" rings are used to gasket the manifold holes between cells (Figure 16). The more compact nature of this design reduced the length of the stack by $1\frac{1}{4}$ inches.

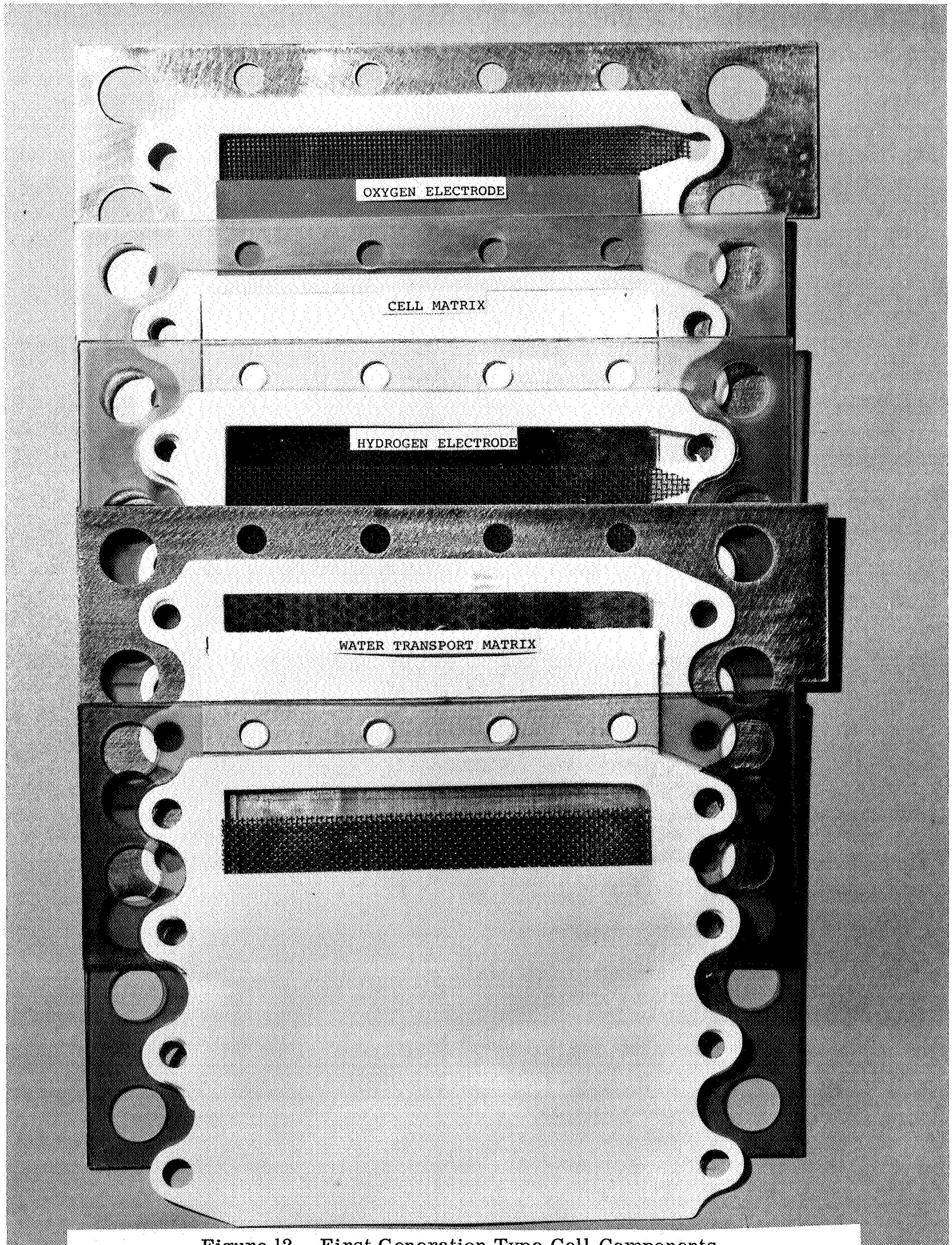


Figure 12. First Generation Type Cell Components

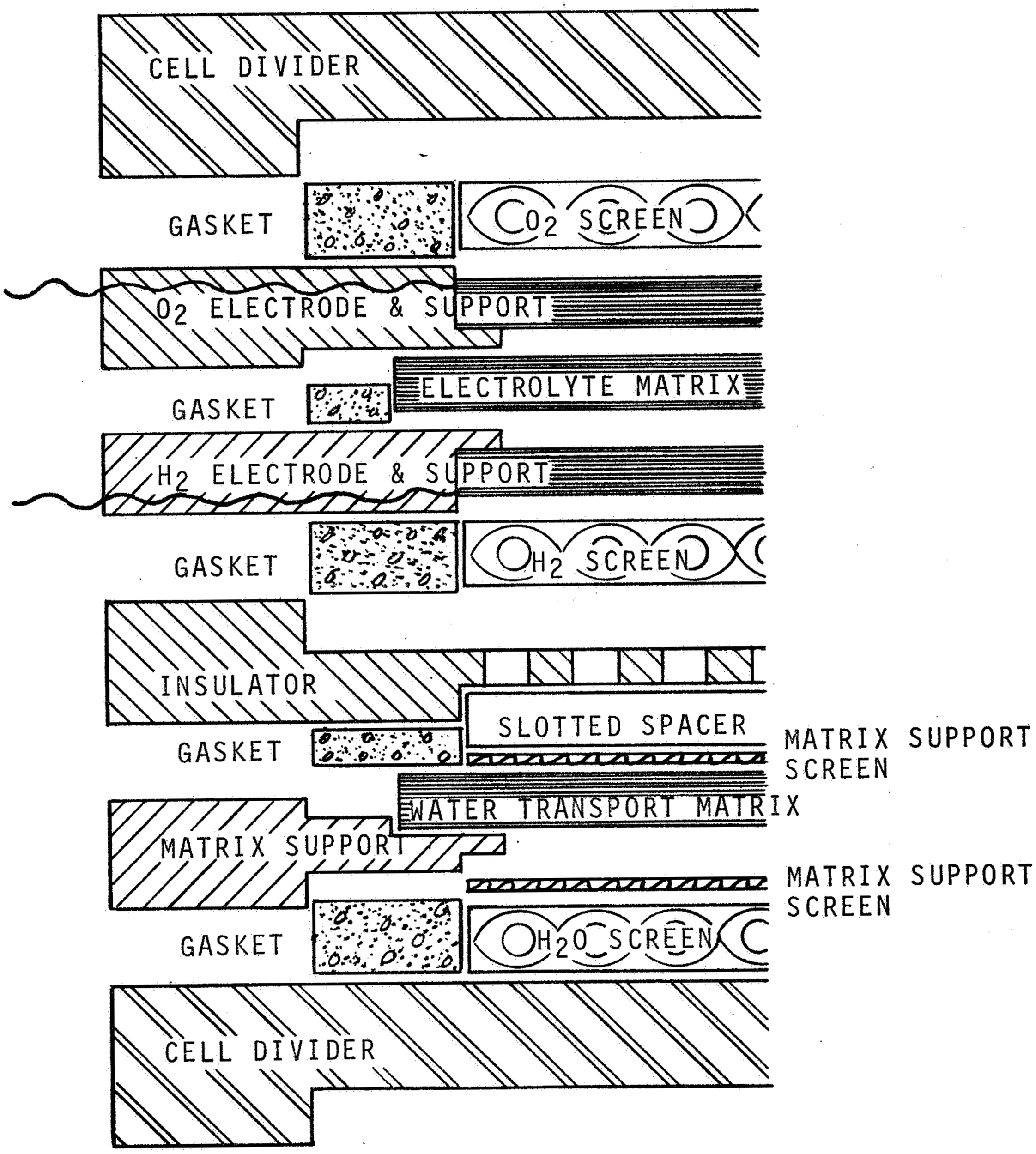


Figure 13. Second Generation Type Cell Design (Tabbed Electrode)

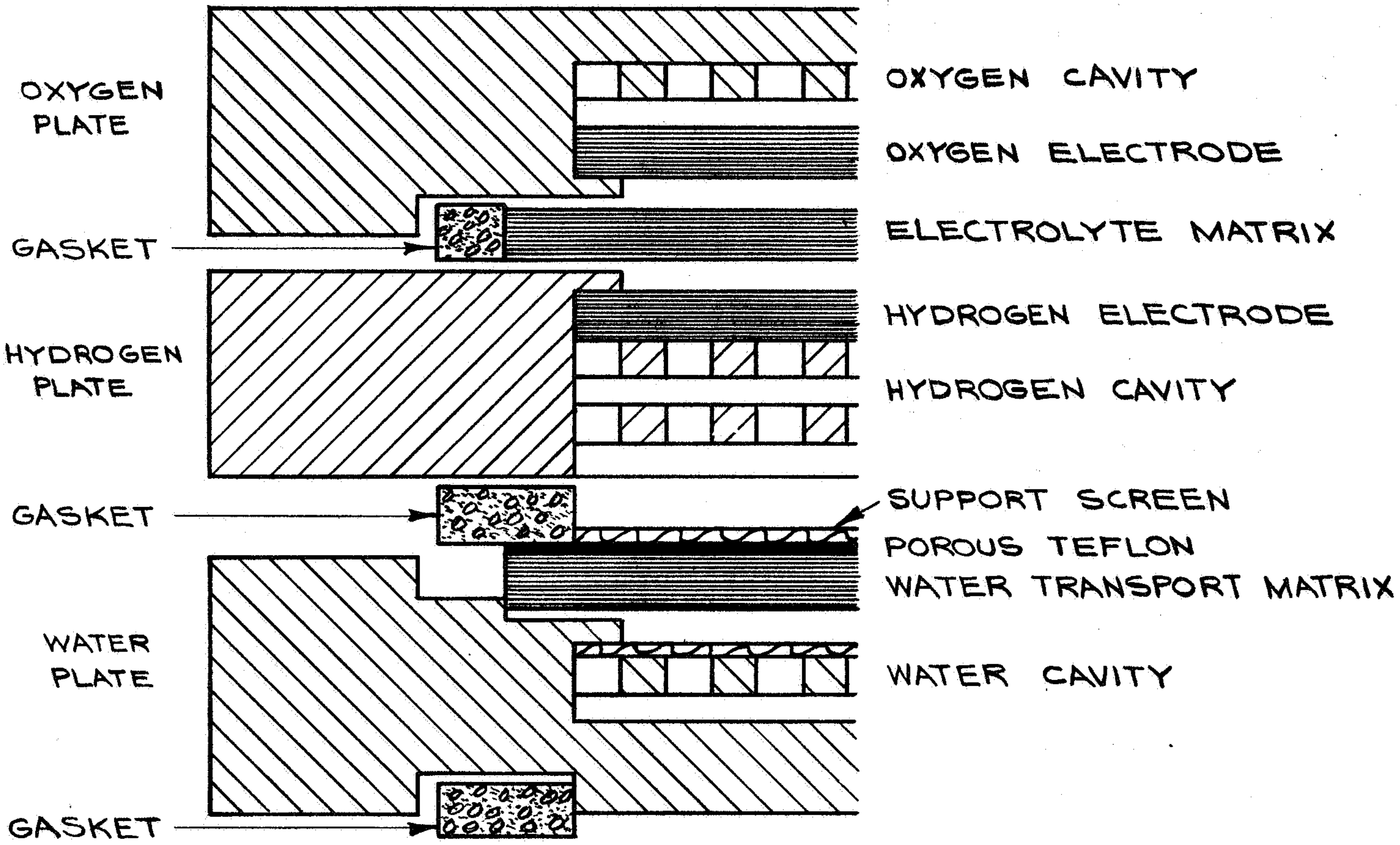


Figure 14. Second Generation Type Cell Design (3 Subassemblies)

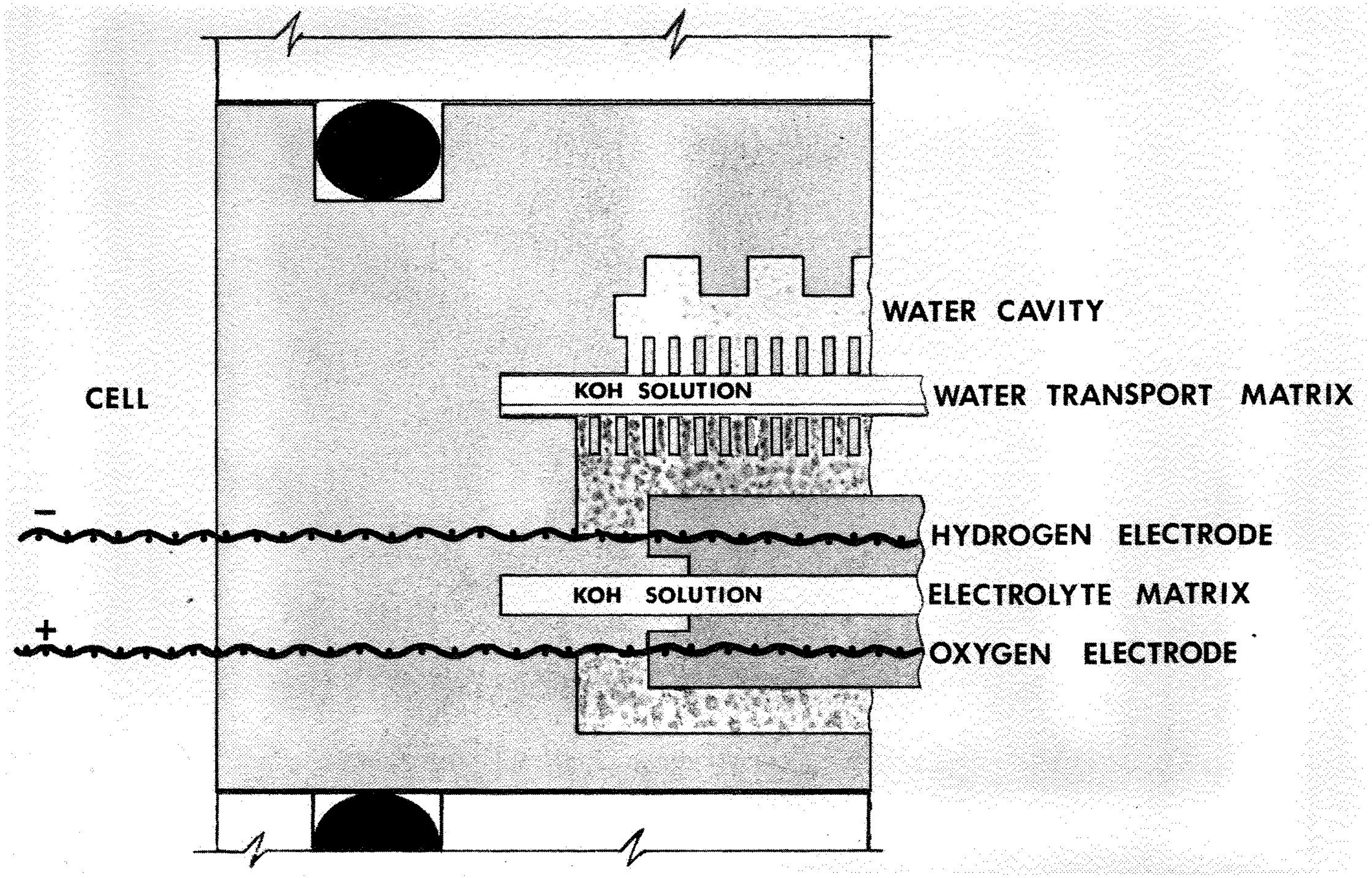


Figure 15. Third Generation Cell Design

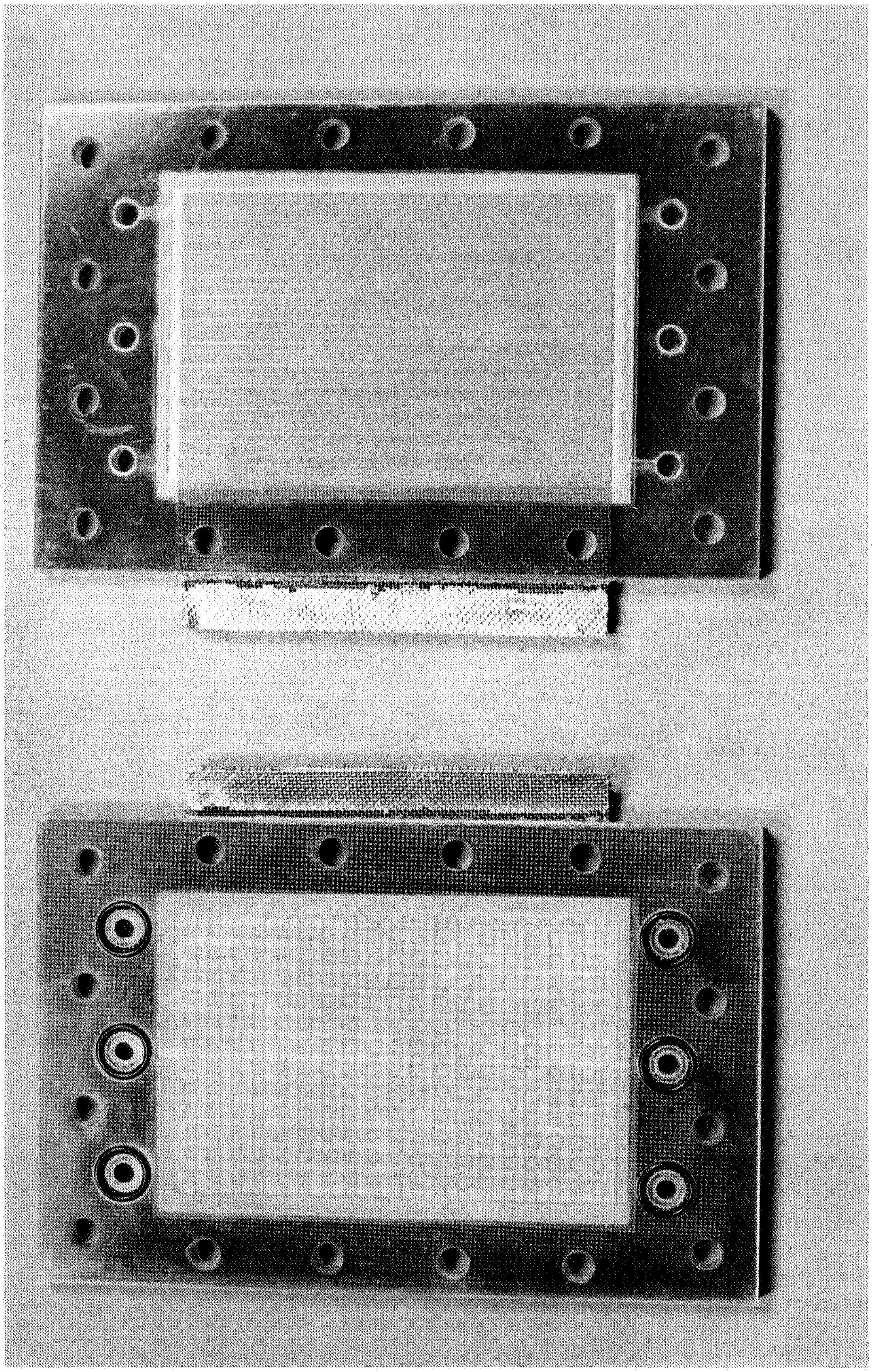


Figure 16. Third Generation Cell Construction

Testing of individual cells repeatedly demonstrated sealing characteristics superior to the previous designs. For the first time, cells could be checked independently before assembly into a stack. Leak checks were made to the exterior by manifolding all three ports together and applying hydrogen at 25 psig pressure (40 psia) with no observed leakage in one hour tests, using a Brooks flowmeter (Size AAA).

A more sensitive test was used for determining cross-leakage of hydrogen across the electrolyte matrix to the oxygen cavity and across the water transport matrix to the water cavity. For this test, the matrices were wetted with KOH solution and hydrogen was applied to the hydrogen cavity at 15 psig. The oxygen and water ports were connected by tubes to water bubblers open to the atmosphere. Most cells showed no bubbles in one hour tests, while a few had one to two bubbles, or a total of approximately 1 cc/hour at 15 psig differential pressure across the matrices. The differential pressure in normal operation is approximately 1 psi across the electrolyte matrix, and 2 to 3 psi across the water transport matrix; the actual leakage, being a function of the pressure squared, can be calculated to be a maximum of 1 cc hydrogen per day on the water side, and less on the oxygen side.

The results also demonstrate the capability of the design to withstand full gas pressures of 15 psig with low water pressures for long periods of time without rupture of the matrix.

The final cell design appears to meet all the major requirements. In addition to solving the stray electrolysis problems, the design eliminates all metal parts other than the electrodes, thereby eliminating galvanic corrosion of structural parts; eliminates special gaskets and reduces sealing loads to a minimum; allows pre-checkout of cells; and results in a simple module assembly which can be assembled quickly.

The outside dimensions of the final cell, dictated by the tooling available from the intermediate development steps, resulted in more bulk than was necessary. A single cell reduced in size by machining away excess border material demonstrated that, with new tooling, the weight of the cells could be cut over 40 percent.

The overall dimensions of the delivered modules are 8 inches high by 5-5/8 inches wide (including tab) by 7-5/8 inches from end plate to end plate. The electrical connector bracket and fittings add an additional 2 inches to the length (Figure 17). The weight of the stack is approximately 25 pounds. Based on the weight and dimensions of the single cell mentioned above, the stack size can safely be reduced in all dimensions and the overall weight cut by almost 50 percent.

CONDENSER DESIGN

The condenser was designed at the same time as the second generation electrolysis module and employs the same Polysulfone bonded components. Like the electrolysis module, Teflon gaskets were used initially, but these were replaced by EPT gaskets. Since no trouble was experienced with the condenser during any portion of the test program, the design was not modified beyond this stage. In any future development work, however, it would be a simple step to go to an all bonded assembly and replace the EPT gasket with "O" rings which are used in the electrolysis module.

Figure 1 shows that the condenser requires several more connections than the module because of the coolant passages. This was accomplished by adding connections to the side through the $\frac{1}{2}$-inch stainless steel end plates (Figure 18).

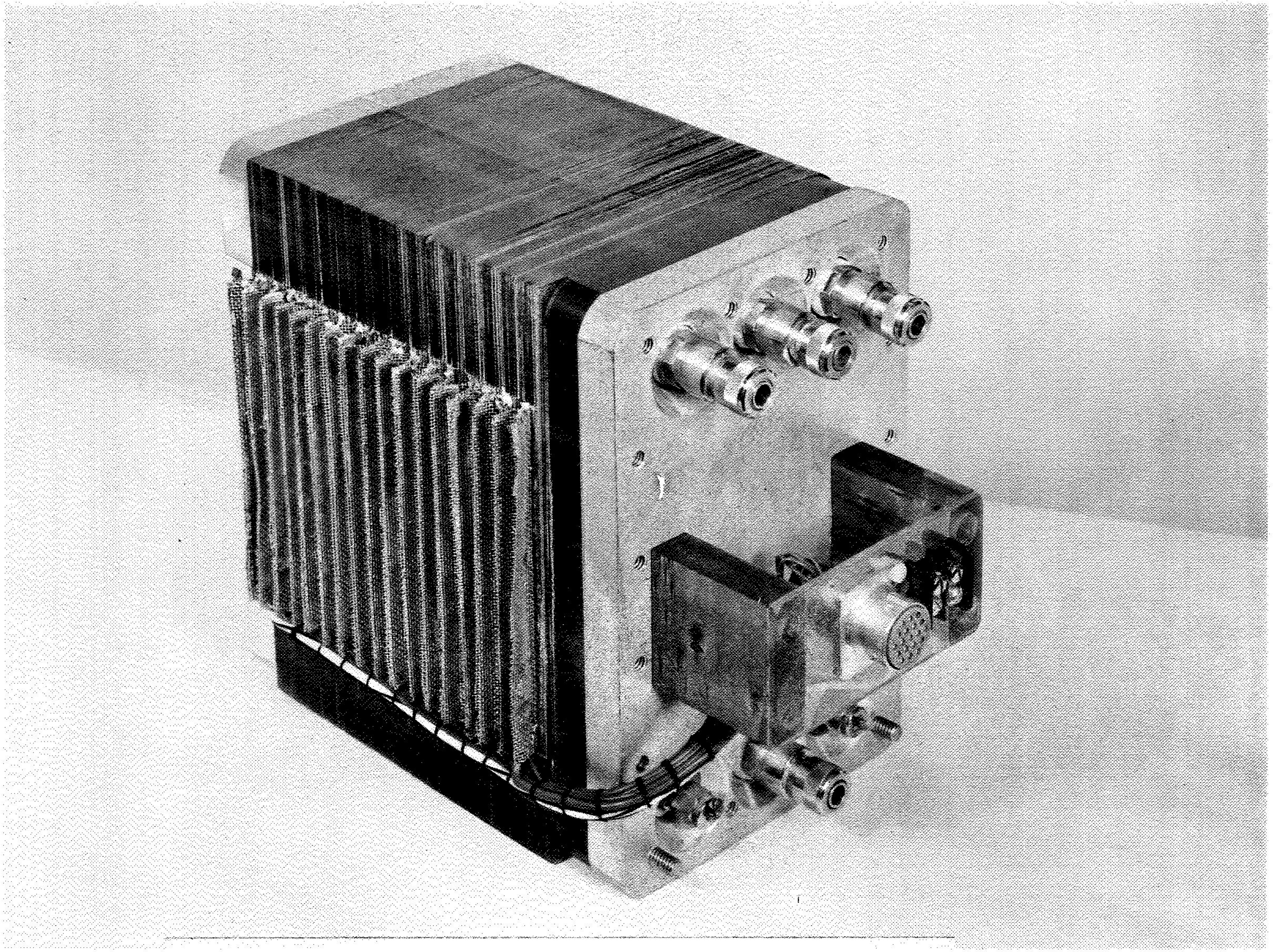


Figure 17. Electrolysis Module (16-Cell)

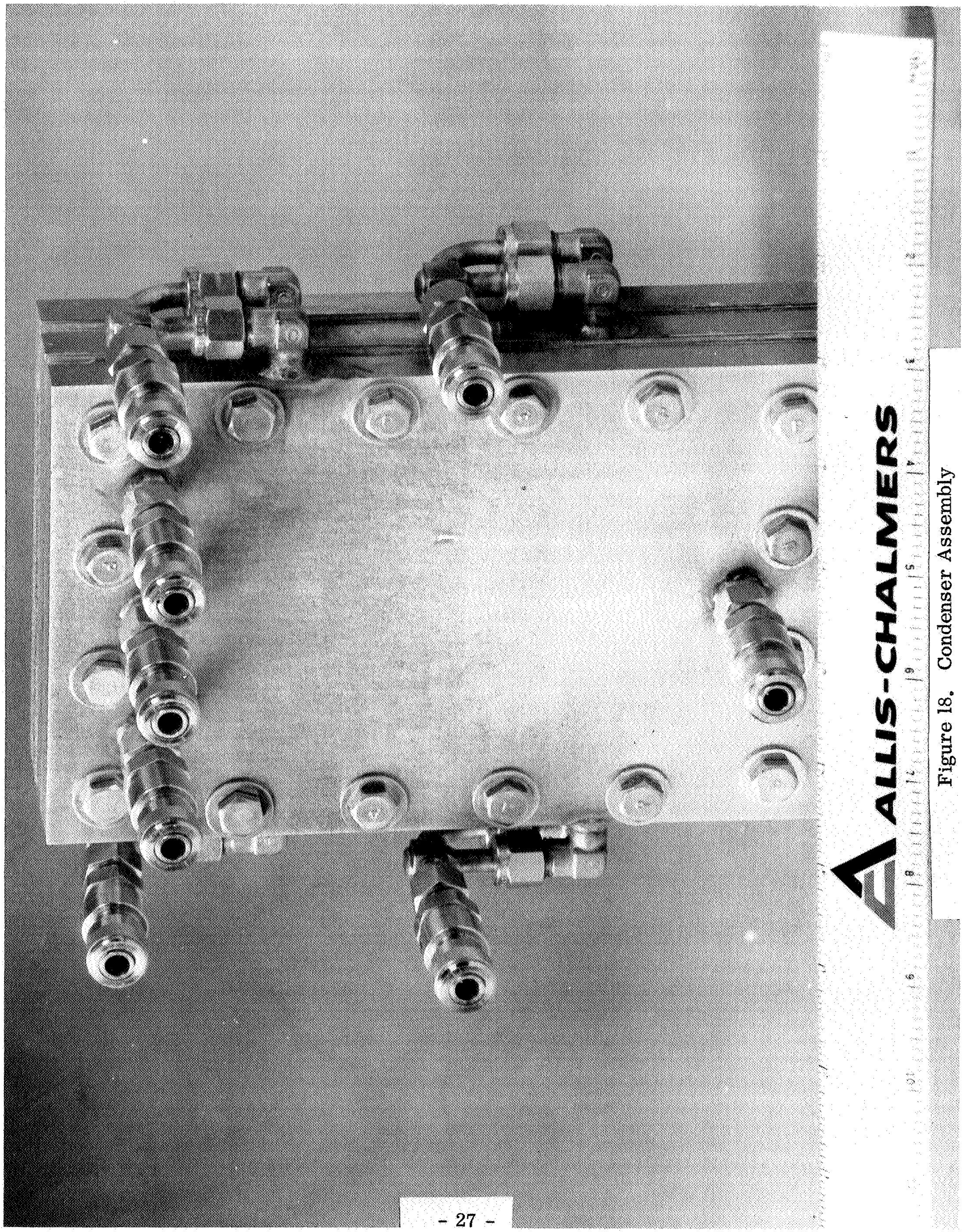


Figure 18. Condenser Assembly

Gas passageways follow a serpentine path in the end plates. This is shown in Figure 19, which is one section of the condenser. The full condenser assembly contains 2 cold plate units having gas passageways on either side. The hydrogen and oxygen product streams from the electrolysis modules are each manifolded through the condenser in two series of parallel paths. No problems were experienced with sealing the condenser after switching from Teflon to EPT gaskets.

The condenser is 8 inches high by $5\frac{1}{4}$ inches wide by $2\frac{1}{4}$ inches long from end plate to end plate. Quick disconnect fittings add an additional 2 inches to the length.

The present weight of the condenser is 20 pounds with $\frac{1}{2}$-inch stainless end plates. With a completely molded design and modified porting arrangement, the condenser weight could be reduced to 5 pounds.

ELECTRICAL CONTROL DESIGN

Electrical control on this unit was held to a minimum. Figure 20 shows all of the controls except the manual readout instrumentation. Three incoming power lines were used to accommodate Langley Research Center's existing system. Each of these lines supplies power to one module and "on-off" power control is provided by 15 ampere, hermetically sealed circuit breakers, CB-1, 2, and 3. The power is directed through normally-open contacts of a hermetically sealed 3-pole power relay to the current controller. The controller essentially drops the excess voltage between line voltage and the voltage required by the module at the desired current setting. This will be described in more detail later in this section.

Automatic shutdown is provided for hydrogen high pressure and water low pressure by hermetically sealed pressure switches. Loss of coolant flow is protected against by a thermostat on the current control cold plate. Power to the shutdown circuit is fed through a circuit breaker, CB-4, which acts as a main DC power switch. An override switch is provided to allow startup of the unit when water pressure is normally below the low pressure switch setting. Lamps maintained by latching relays until released by the operator show all shutdown conditions and are located on the annunciator panel.

Heaters supplied by the 115 volt AC line are included on the module to bring them to minimum operating temperature before gas production startup. Thermostats on the end plates automatically disconnect the heaters from the line when the preset temperature (130°F) is reached.

The current controller is of simple design as shown in Figure 21. A transistor in series with the module dissipates the excess voltage. Current selection is provided by a rheostat in the base circuit. With the exception of these rheostats which are mounted on the front panel, all of the components for three current controllers are mounted on one cold plate (Figure 22). This results in only one set of coolant connections for the electronic apparatus and the least amount of space and complexity.

The current controller is about $13\frac{1}{2}$ inches long by 3 inches high and 1 inch wide. The electrical connectors add an additional 1 inch to the width. The current controller assembly weights about 2 pounds.

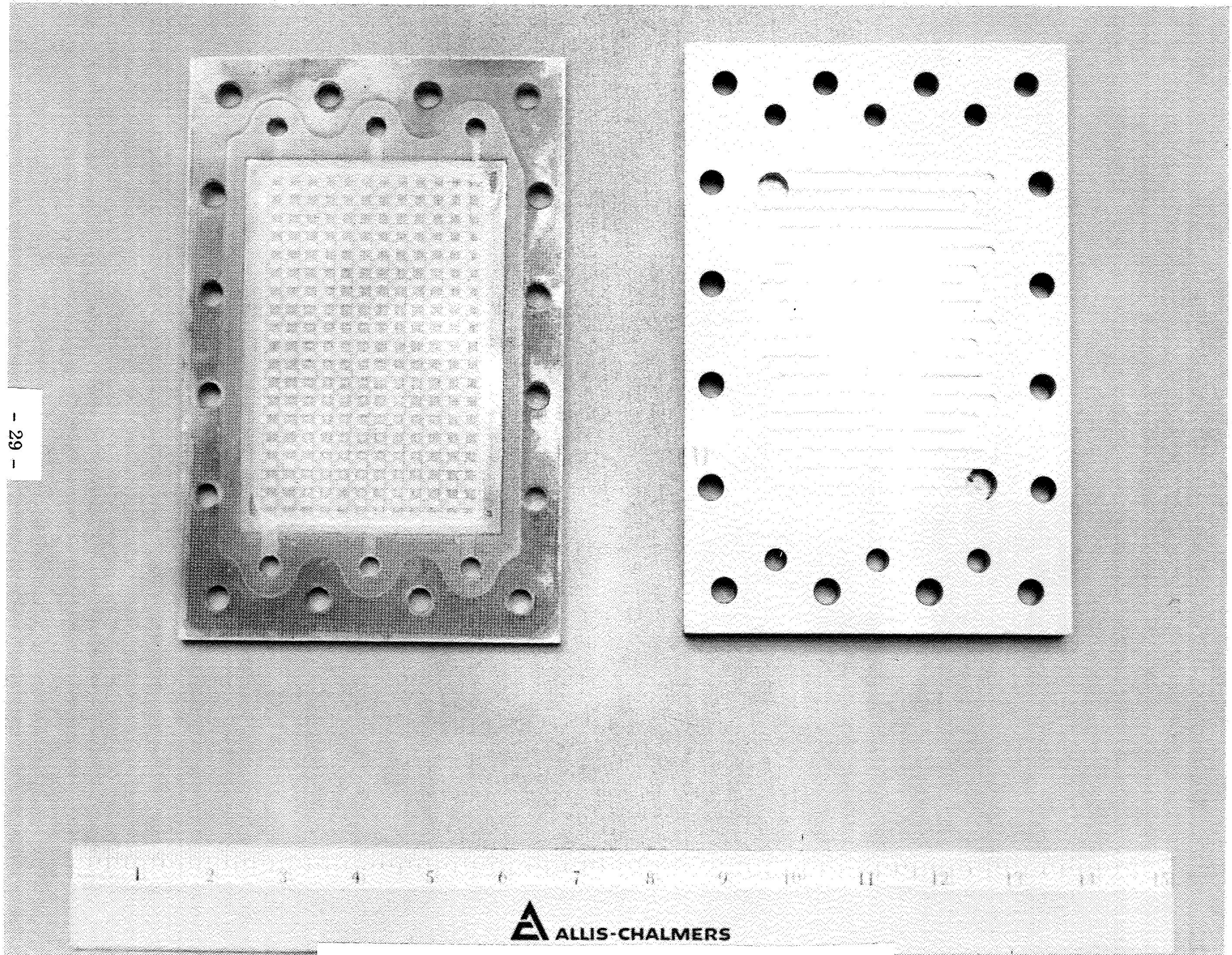
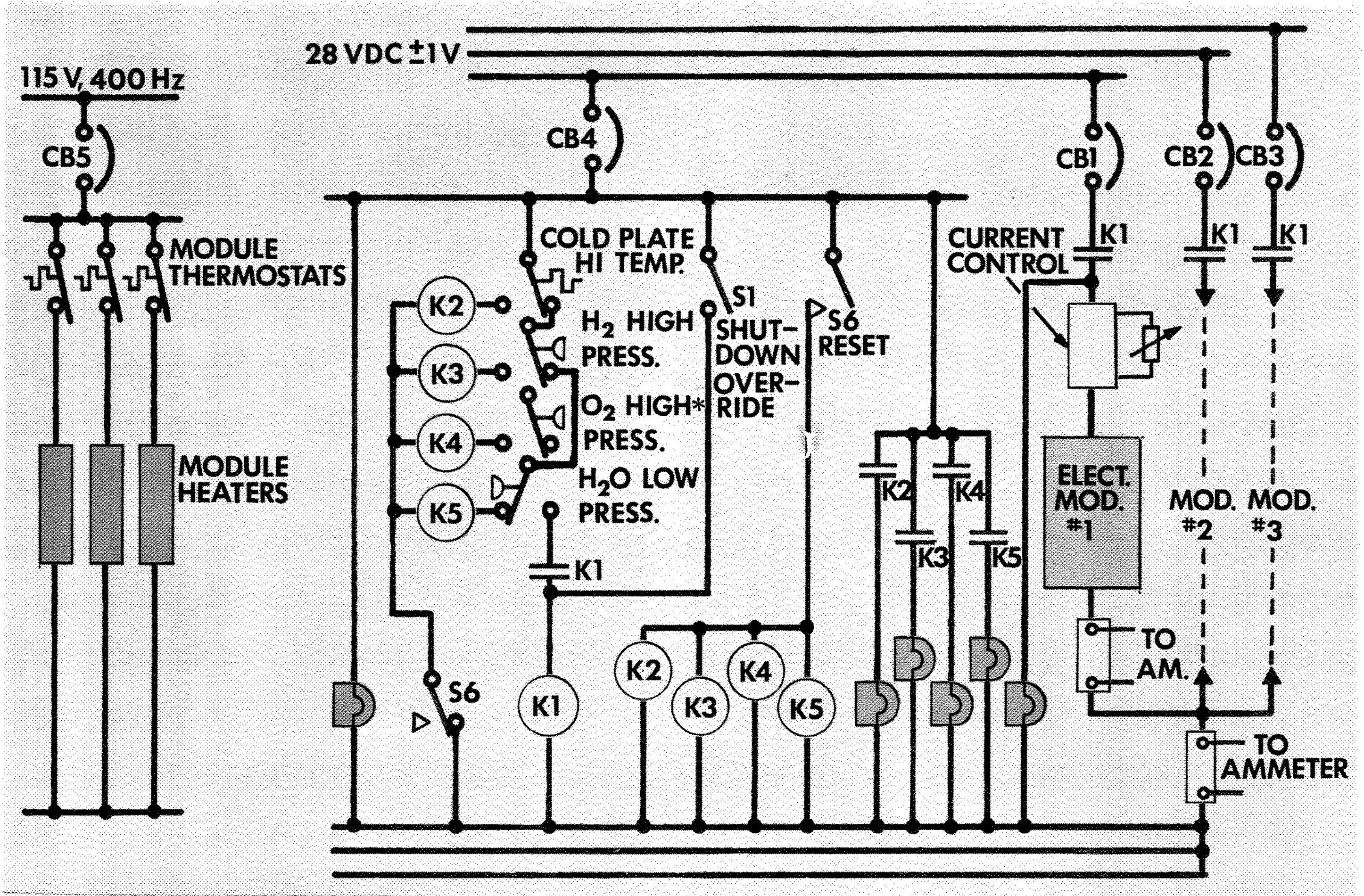


Figure 19. Condenser Gas Passageways in End Plates



*Bypassed in Final Unit Design.

Figure 20. Electrolysis Unit Controls

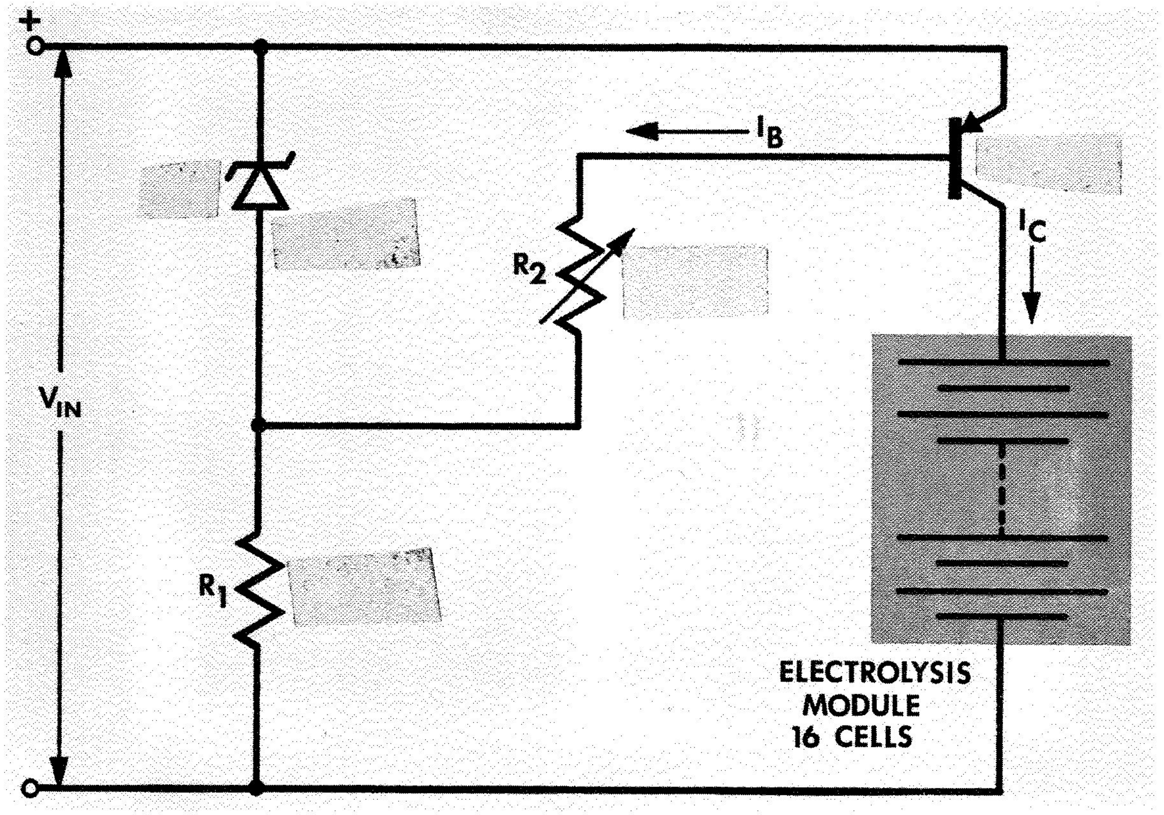


Figure 21. Electrolysis Module Current Control

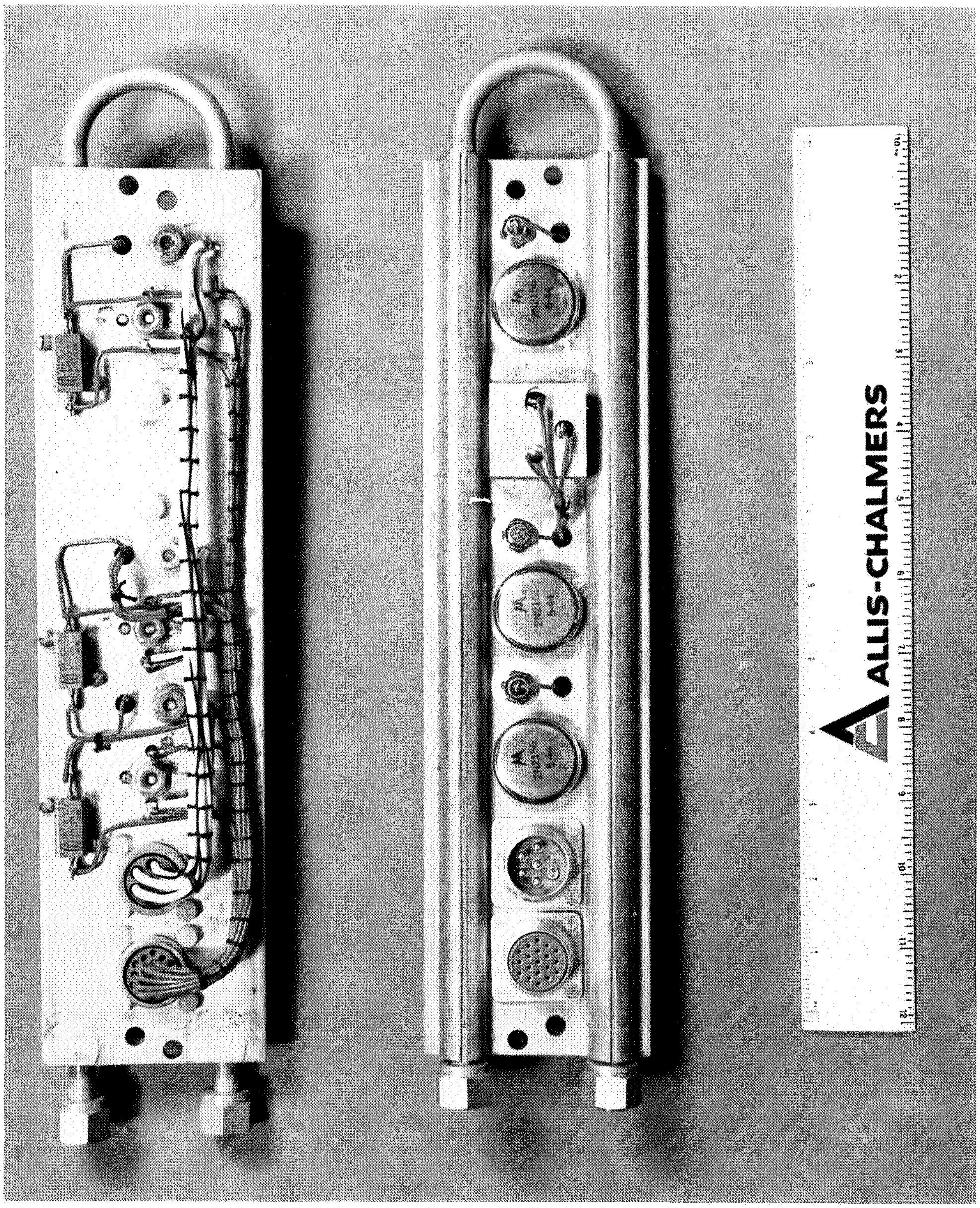


Figure 22. Current Controller Assembly

UNIT LAYOUT

The complete water electrolysis unit consists of three electrolysis modules feeding each gas into a common manifold to a single condenser module (Figure 23). The gases then pass through a moisture knockout pot which was included to provide a visual indication of liquid carry-over if a system upset occurred.

Mechanical back pressure regulators are located just before the gas exhaust from the system. Coolant is piped in parallel to the condenser and cold plate and the flow may be regulated independently to each component by valves at the rear of the unit (Figure 24). The make-up water feed passes through a 15-micron filter before entering the modules. All piping connections to the modules are made through Swagelok "DESO" quick disconnect couplings. Upon opening, these couplings provide isolation on both sides of the parting. Similar quick disconnect couplings are used on the condenser and at the interface between the Water Electrolysis Unit and the remainder of the Integrated Life Support System (Figure 24).

Maintenance accessibility was the major packaging design criterion for the unit and its components; size and weight reduction was of secondary importance. The contract unit design enables the removal of all major components without disturbing any other equipment or the unit piping.

In the early testing stages, the thermal insulation of the individual modules was both cumbersome and inefficient. This was overcome in the final design by fastening permanent insulation inside a structural box which houses the modules (Figure 25). By insulating the box rather than the modules, no additional insulation was required.

Physical removal of the modules is accomplished from the front of the unit. The modules, being mounted on rails, slide out for removal. Other action required for module removal include the release of four piping quick disconnects mentioned previously, one Deutsch electrical connector for the voltage, temperature, and control wiring; in addition, the power leads must be disconnected.

Since the three current controllers are mounted on one cold plate, only two piping connections need to be broken for current controller removal. Coolant isolation is provided by the two quick connect couplings at the unit interface which act as shut-off valves. Electrical power and control wiring to the cold plate is also through Deutsch connections, leaving no loose wires when the controller is removed.

The gas pressure regulating valves are located in the lower right side of the unit within reach of an operator who would be working in front of the unit. All other controls and switches are mounted on the front of the unit (Figure 26).

Overall dimensions of the unit are 20 inches high by 21 inches wide and 19 inches deep. These are based on the second generation module design. The final (third generation) module design is shorter, with these modules being able to fit into a cabinet, 20 X 21 X 16 inches.

Total weight of the unit is 160 pounds which can be reduced considerably in line with the weight reductions of the components discussed previously, and a corresponding reduction in the cabinet frame size.

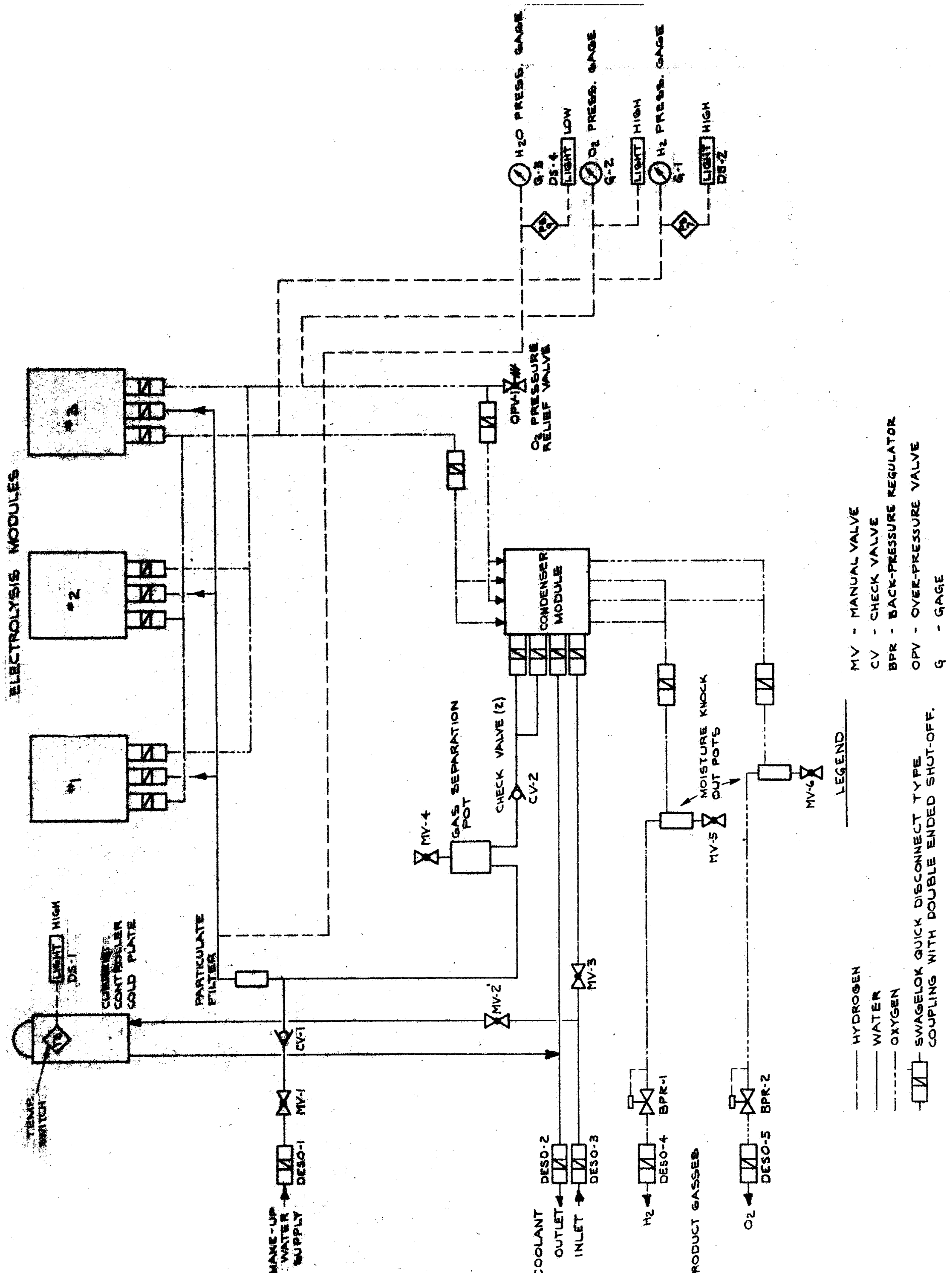


Figure 23. Electrolysis Unit Process Schematic Diagram

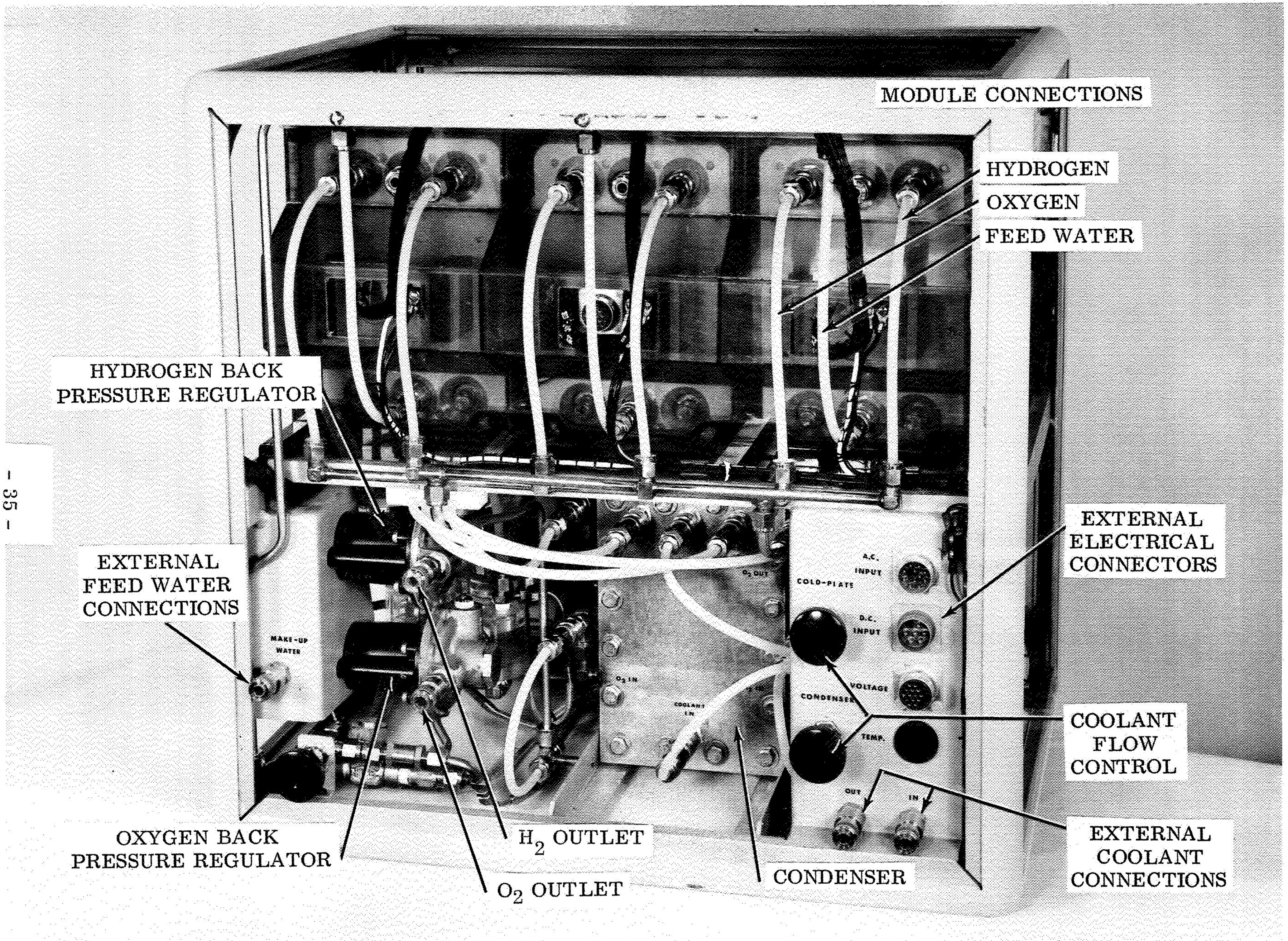


Figure 24. Electrolysis Unit, Rear View

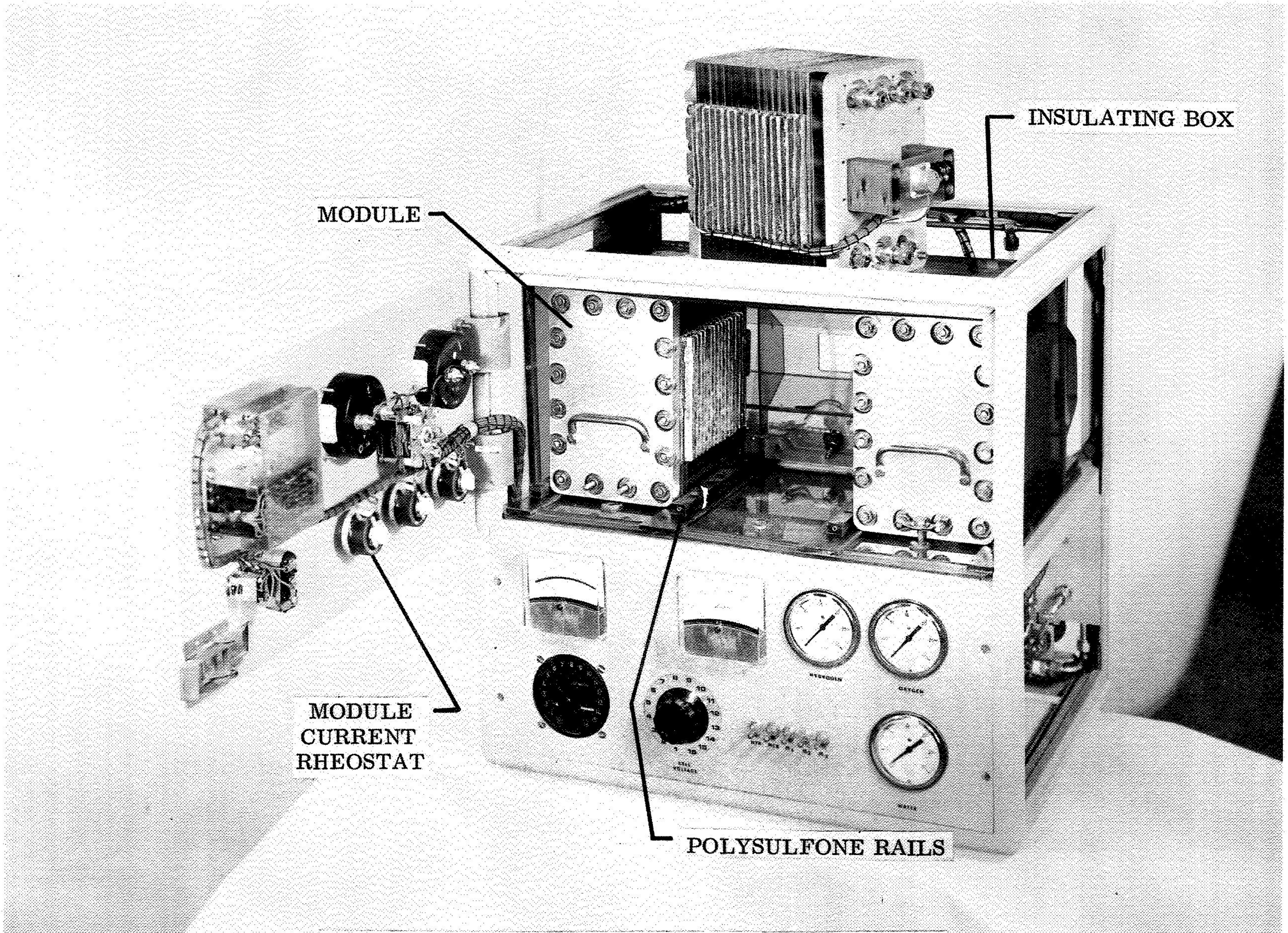


Figure 25. Electrolysis Unit, Exposed Modules View

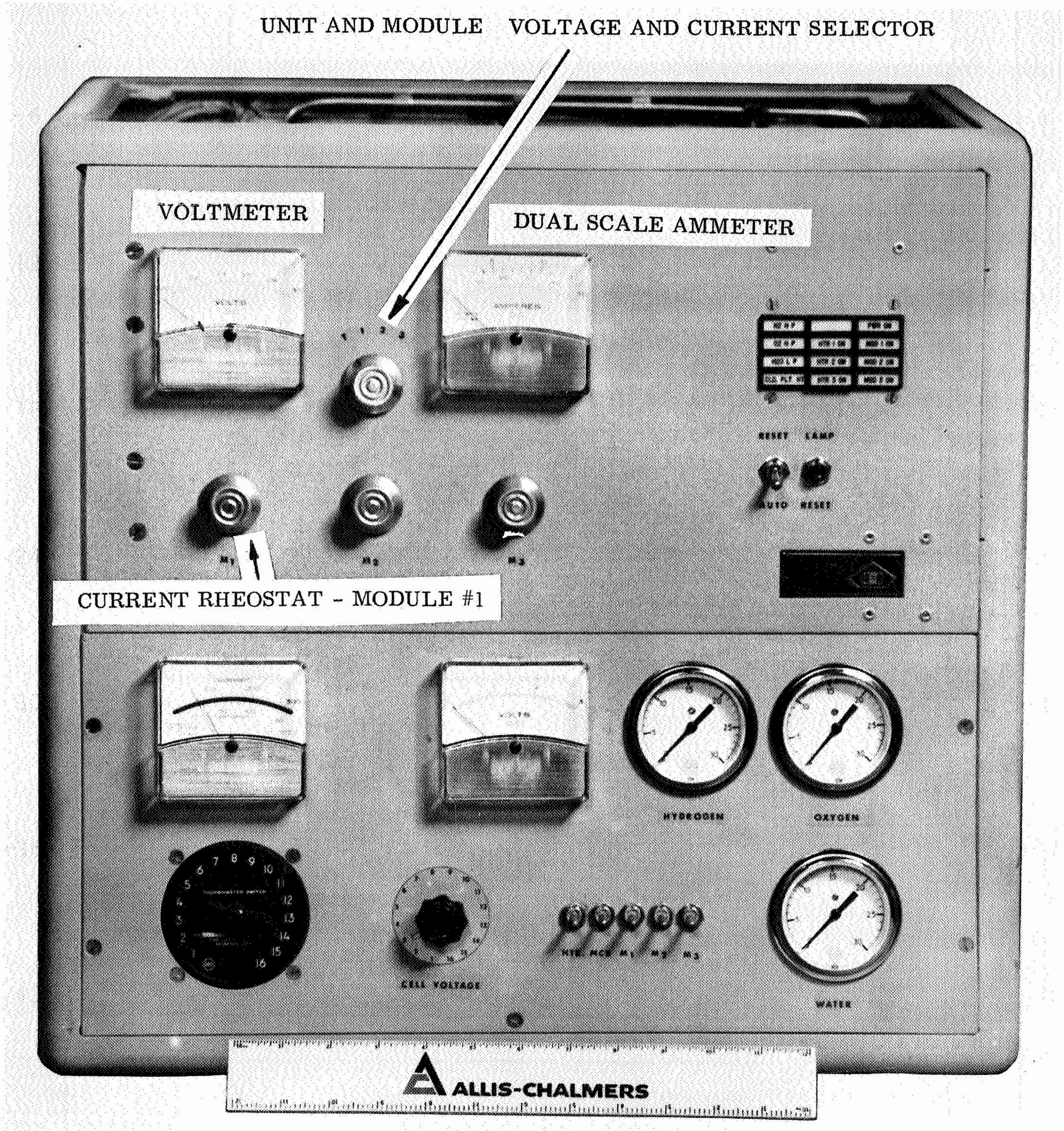


Figure 26. Electrolysis Unit, Front View

TEST RESULTS

DEVELOPMENT PROGRAM TESTING

Throughout the program, testing was employed principally to verify whether the mechanical design of the electrolysis cell was achieving performance requirements. Some of the tests were extended to obtain some life characteristics. Individual tests were performed on the condenser and current controller to establish that design requirements had been met.

Electrolysis Module Testing

Most of the electrolysis cell testing was performed on four-cell modules. At the start of the program, a test bench was assembled to operate four of these modules connected in series simultaneously from a single power supply. A single back pressure regulator for each gas line, set at approximately 15 psig, maintained constant uniform pressure on all modules.

Two of the important variables, current and pressure, were fixed, which permitted comparisons of cell voltages from module to module to determine the effects of construction on performance. Four sets of end plates, bolting, and fittings, along with four sets of 0.025-inch thick nickel plates used to carry the current behind the electrodes were obtained immediately. As described in the construction section, these components were each assembled and disassembled several times with a new module number being assigned for each rebuild with a major component variation. On this basis, 16 modules of the first generation nickel plate/Teflon gasket type were assembled including eleven 4-cell modules, three 1-cell modules and one 16-cell module.

In all of the first generation tests, standard 0.028-inch thick porous nickel anodes, 0.028-inch thick porous nickel with platinum - palladium plated cathodes, and 0.030-inch thick iron-free fuel cell grade asbestos were used. All modules were tested at a nominal 15 psig pressure, and were supplied with pure distilled feed water.

Obtaining both internal and external seals proved to be the major problem area and most of the rebuilds consisted of modifying the Teflon gasket thickness or peripheral dimensions to obtain proper loading and sealing. Seals were obtained at a 10 to 12-ton load on the module. The load was applied with a press and securely held with heavy bolts. This loading for extended periods caused excessive flow of the Teflon into the manifolds holes in many cases, restricting water flow into the water transport cavities, thereby ending useful module life. Most of these modules ran less than 50 hours due to these problems. Toward the end of this phase, the problems were overcome to the extent that two modules were given extended runs. Module 12 operated for 470 hours at an average voltage of 1.60 at 150°F and Module 15 was tested for 669 hours at an average voltage of 1.55 at 160°F. At the end of this latter test, the voltages on two cells were still in the low 1.5-volt range, while plugged ports eventually raised the voltages of the other two cells above 1.8 volts. Figure 27 represents the extended test results for Modules 12, 15, and 18. Variation in operating temperatures for each curve represents most of the variation in cell voltage.

A sixteen-cell module was constructed by combining the parts of several four-cell modules and then was operated over a fairly continuous period of 240 hours. Total module voltage ranged from 26.5 to 27.2 at 140°F. A substantial quantity of gas was produced by stray electrolysis in the water cavity, however, and a continuous purge of the

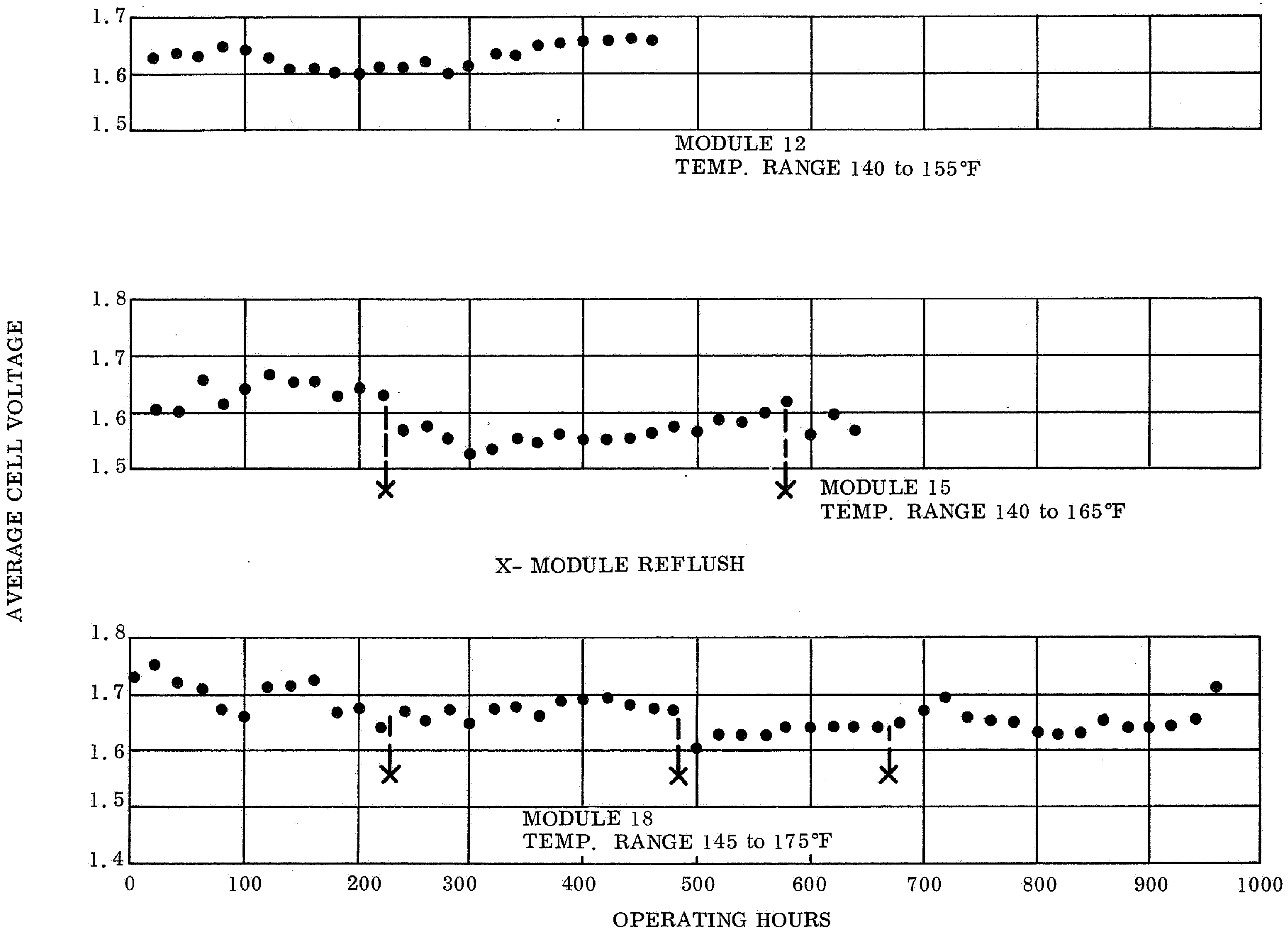


Figure 27. Four-Cell Modules Test Data

cavity to release the gas was required to maintain performance. After the 240-hour run, the module was used to obtain some thermal and pressure effects on performance and to test the current controller. After 320 hours, enough useful information had been gathered and this module was disassembled.

The electrical efficiency of this type of design was excellent as shown in Curve "A" of Figure 28. The average voltage of the 4 cells of Module 6 was approximately 1.54 volts/cell at the design current of 10.5 amperes. These values were achieved repeatedly in the other modules of this general design. The curve is quite flat and shows that less than 1.60 volts were required at 21 amperes (or twice the design capacity rate). The low value reflects the low electrical connection loss between cells with the solid nickel electrode backup plates.

Due to the manifold electrolysis problems and difficulties with sealing, the laminated Polysulfone design was evolved and tested in an additional series of four-cell modules. Typical performance of these modules is shown in Curve "B" of Figure 28 taken on Module 18.

The higher voltages were mostly the result of higher resistance of the "thin" nickel electrode screens that were used to bring the current through the Polysulfone border in place of the solid nickel plates used in the previous tests.

Although Module 18 had higher initial voltage than previous modules, its operation was continued with the test concluding after 981 operating hours. During the last half of this test, the modules were operated on an automatic basis during the second and third shifts of the day and system operational problems and automatic shutdowns caused by the other modules on the common test stand required the cell and transport matrices to be reflushed with fresh KOH solution. This procedure brought the performance back to the initial conditions. Based on the conclusions of these tests, succeeding modules were built using electrodes with heavier screens. Gaskets were changed from Teflon to rubber and three 16-cell modules were constructed of this design. These modules were individually insulated, assembled into a complete unit, and tests were run. These tests indicated:

(1) All aspects of the electrical control system performed as designed.

(2) The safety shutdown devices worked as designed.

(3) The condenser performed as designed.

(4) Approximately 2 hours were required to warm the modules prior to starting electrolysis.

(5) Slightly lower than expected equilibrium temperatures (155 to 150°F) were achieved with the individual insulation on the modules.

(6) The gas generation rate was equal to the theoretical rate at the design current as measured by the displacement of water.

(7) Stray gas was being produced in the water cavities at the end cells to the extent that performance could not be maintained without excessive purging which affected thermal equilibrium. Voltages were in the 1.60 to 1.70 range at the design current.

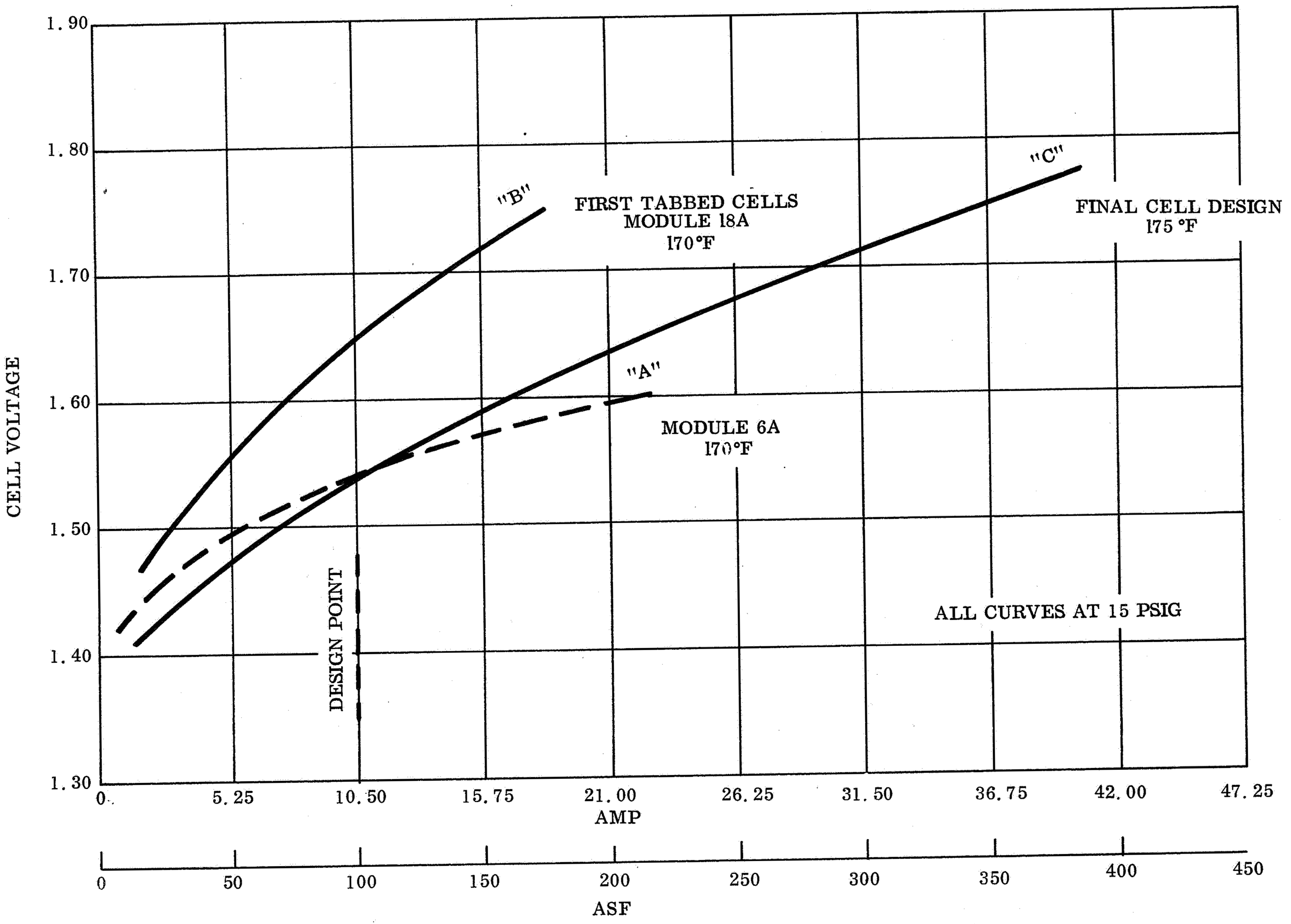


Figure 28. Voltage Vs. Current (Various Modules)

The gas generation problem was traced to the one remaining metal component on the water cavity - a 150 x 150 mesh nickel screen used as a mechanical support of the water transport matrix. Although theoretically isolated from the electrodes by plastic components, a circuit apparently was formed by KOH solution films which bridged the plastic parts. At the low total voltages of the four-cell module tests this phenomenon was not observed, and it was not until the full-size stacks were tested at 27 volts that sufficient potentials were reached to create the problem.

As a result, the third generation design was developed which employed all plastic or asbestos components except for the electrodes. In addition to eliminating the metal screens in the water cavity, the new design utilized some thinner internal plastic plates which improved the water transport properties, and also reduced the overall cell thickness. A performance test run is plotted as Curve "C" on Figure 28. Much of the improvement over Module 18 is due to the heavier electrode screens and a small part is due to improved water transport properties. It is apparent that the screen tabs still account for significant losses at higher current densities (200 ASF) and voltage results are not as good as the heavy nickel plate design. Since the performance obtained at 10.5 amperes was quite acceptable, no further work was done along this line.

Condenser Testing

A prototype condenser module was fabricated which consisted of one of the two parellel sections used in a full-size unit. The section consists of a cold plate in the center with condensate collection chambers and gas distribution plates on each side. The gases were bubbled through hot water to heat and saturate them. Thermal analysis was based on a heat balance study of the cooling water stream, using gas inlet and outlet temperatures to determine logarithmic mean temperature difference. The majority of the tests were run with the gas flow on both faces of the cold plate to determine the maximum heat rejection which could be obtained.

The condenser was tested with air to simulate oxygen (Figure 29). Testing was at atmospheric pressure with flow being varied between 0.50 and 4.0 times the design mass flow. The maximum heat rejection achieved was 125 Btu/hr at a logarithmic mean temperature difference of 34°F and a lower end approach temperature of 18°F using 52°F cooling water. Using 32°F cooling water, this data may be extrapolated to a logarithmic mean temperature difference of 50°F which would produce heat rejection of 187 Btu/hr, or a thermal overload of 3.5.

The unit was tested with hydrogen (Figure 30) at a mass flow rates from 0.50 to 3.0 times normal at atmospheric pressure. The maximum heat rejection rate was 225 Btu/hr at a logarithmic mean temperature difference of 30°F and an approach temperature of 32°F. At design temperatures this would extrapolate to 310 Btu/hr, or a thermal overload of 6.0.

Current Controller Testing

A single current controller was assembled and mounted on a cold plate of the same type used in the final unit. Laboratory water was used as the coolant. Tests were run to establish the range of control setting, stability of setting with varying incoming line voltage, and stratup transient characteristics with no residual voltage on the module.

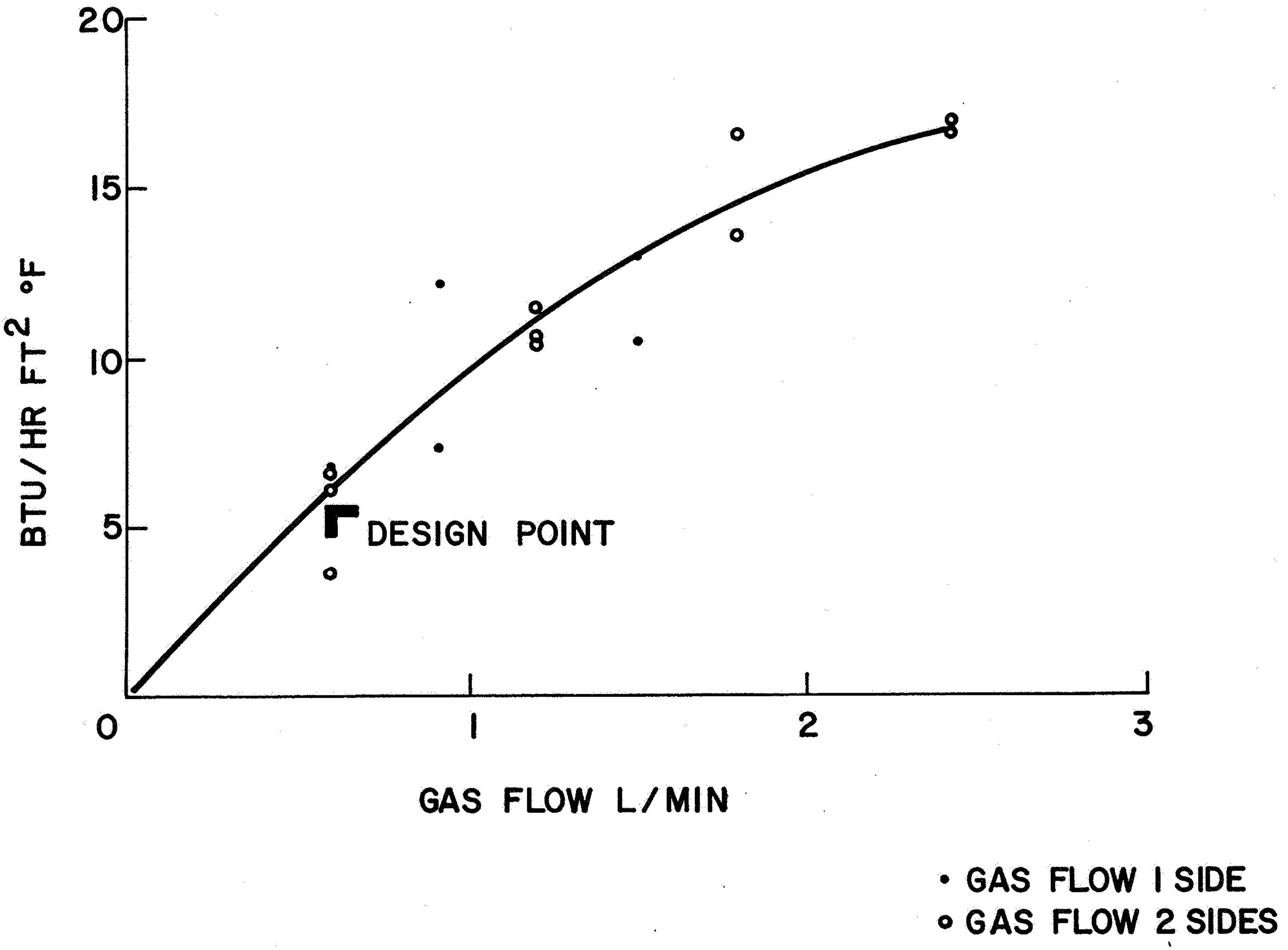


Figure 29. Electrolysis Unit Condenser Performance Using Saturated Air

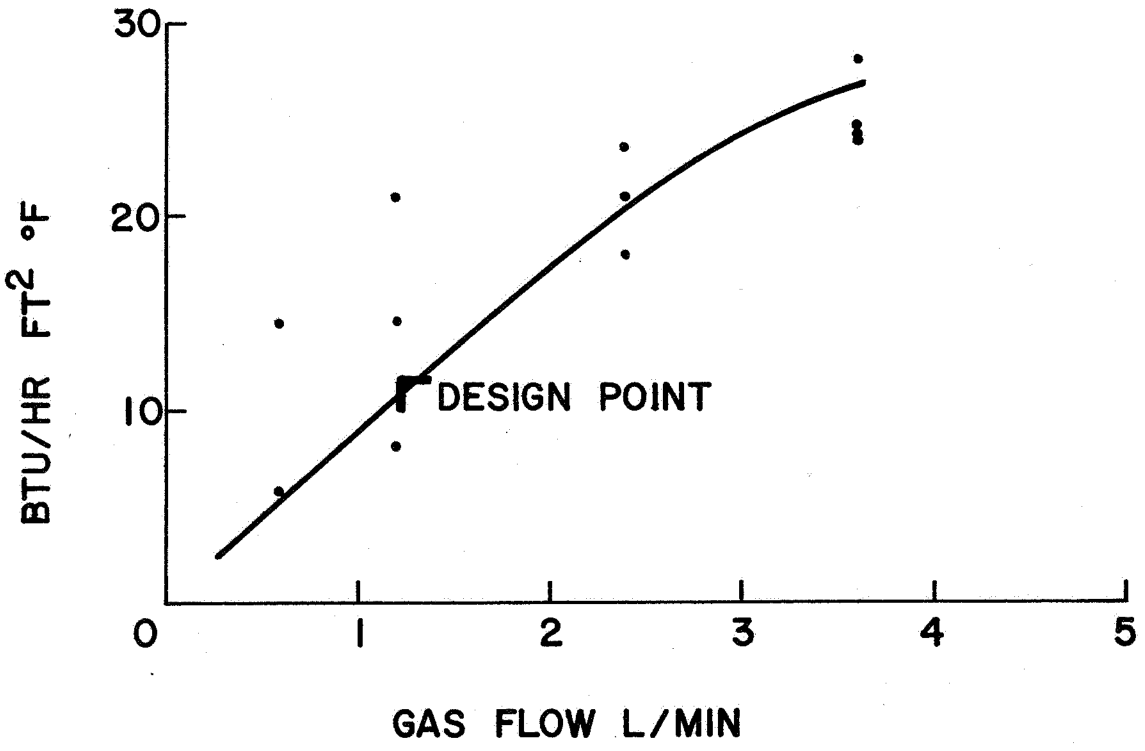


Figure 30. Electrolysis Unit Condenser Performance Using Saturated Hydrogen

The controller demonstrated the ability to be set between 5 and 18 amperes with acceptable stability as shown in Figure 31. At the design current of 10.5 amperes, the current varied approximately ± 0.3 amperes for changes in the supply voltage of ± 1 volt.

A test to ascertain the transient characteristics at startup was performed with a full-size module. Since the electrolysis module has a large capacitive effect, very high currents occur for several seconds if a module is connected to the line without control. Photographs taken on an oscilloscope showed, however, that this type of control regulates almost instantaneously and no current spike is obtained on startup. Figure 32 shows the response at the highest setting on the current controller which is the worst condition. Under normal startup procedures, the setting would be at minimum, and the very small spike would be even less.

ACCEPTANCE TEST

The unit was assembled with three new modules of the third generation design employing "O" ring-type seals and completely bonded cells. The modules were charged with 35% KOH solution and given an initial checkout in the unit. Two problems were experienced at this time.

Transistors in the current controller would work satisfactorily at current up to 10 amperes, but at currents of 11 amperes short-circuits would occur. This was traced to the high ripple on an unfiltered, single-phase power supply being used for the first time. A switch to the three-phase supply eliminated this problem. A leak from the body of the quick disconnect fitting to the water cavity allowed liquid to run down under Module #3 and the heater was short-circuited. This damaged several of the cells in this module, requiring it to be rebuilt.

The 250-hour test was started with Modules #1 and 2. Module #1 was started first and brought to equilibrium conditions. Module #2 was started at 11 hours, the start of the next shift. Module #3 was rebuilt and brought on the line at 71.5 hours. The unit was then run on a continuous basis (Figure 33).

Pressures were maintained at 15 psig on the hydrogen, 14 psig on the oxygen, and 13 psig on the water feed throughout the test.

Equilibrium temperatures were measured by a thermocouple probe which was inserted half-way into the module hydrogen manifold. Temperatures averaged 155 to 160°F which indicated that the "hot box" design was providing better heat retention than the individual module insulation used in previous tests. Box temperatures of 135°F were recorded.

At 186 hours, voltage versus applied current data were taken for all three modules. (See Figure 34.) The voltage deviation between modules were less than 0.15 volt at corresponding currents, so only a single curve was drawn.

Feed water was specially prepared for the test by the Allis-Chalmer's chemistry laboratory to provide the desired conductivity and 100 ppm of dissolved solids. The water was degassed on a batch bases to the solubility level of 28.5" Hg, using the laboratory vacuum system. At this pressure, there is still some dissolved gas in the feed water. To maintain system performance, each module was purged of 5 to 15 cc of gas approximately once each day.

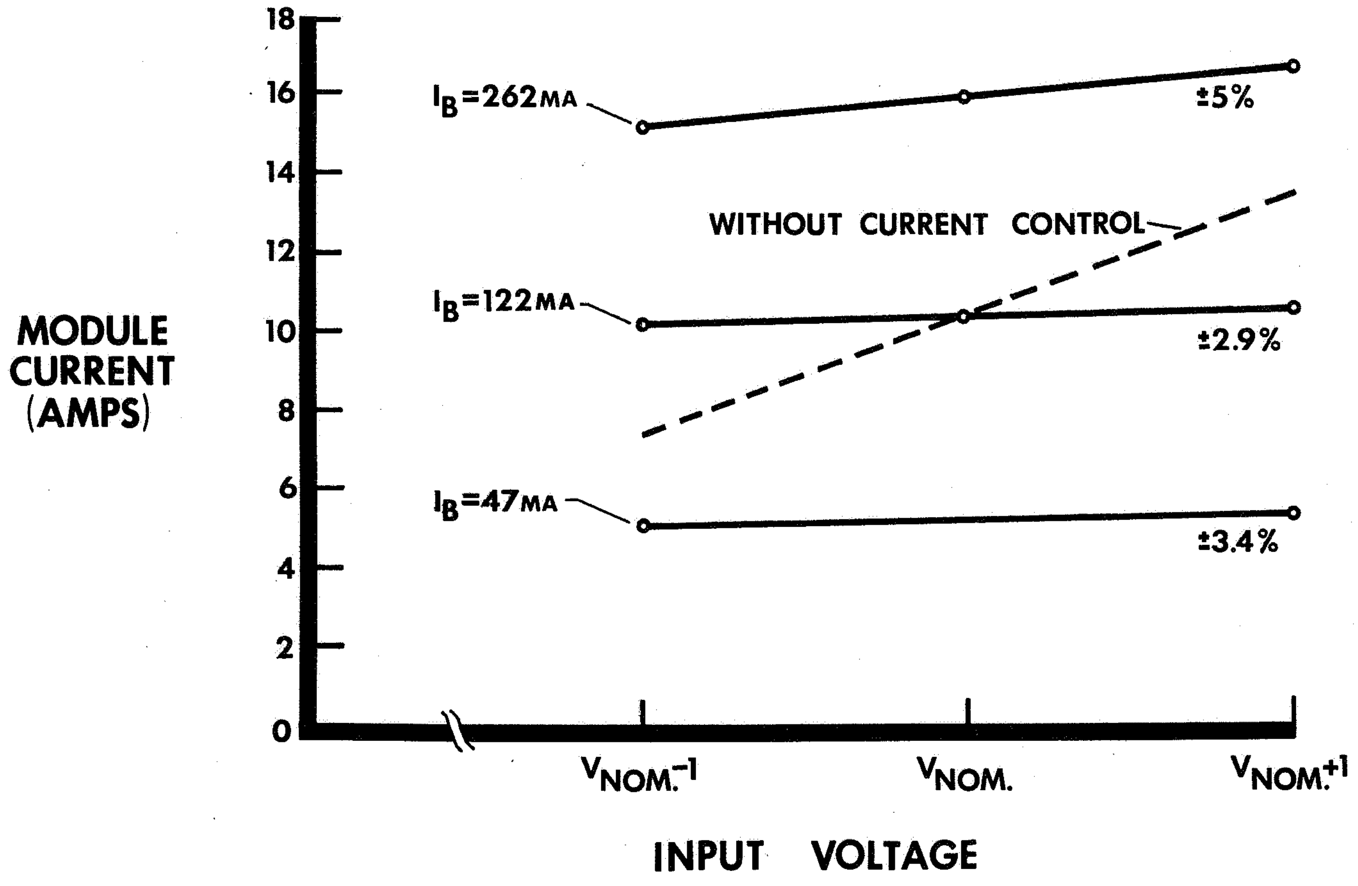


Figure 31. Module Current vs Input Voltage Change

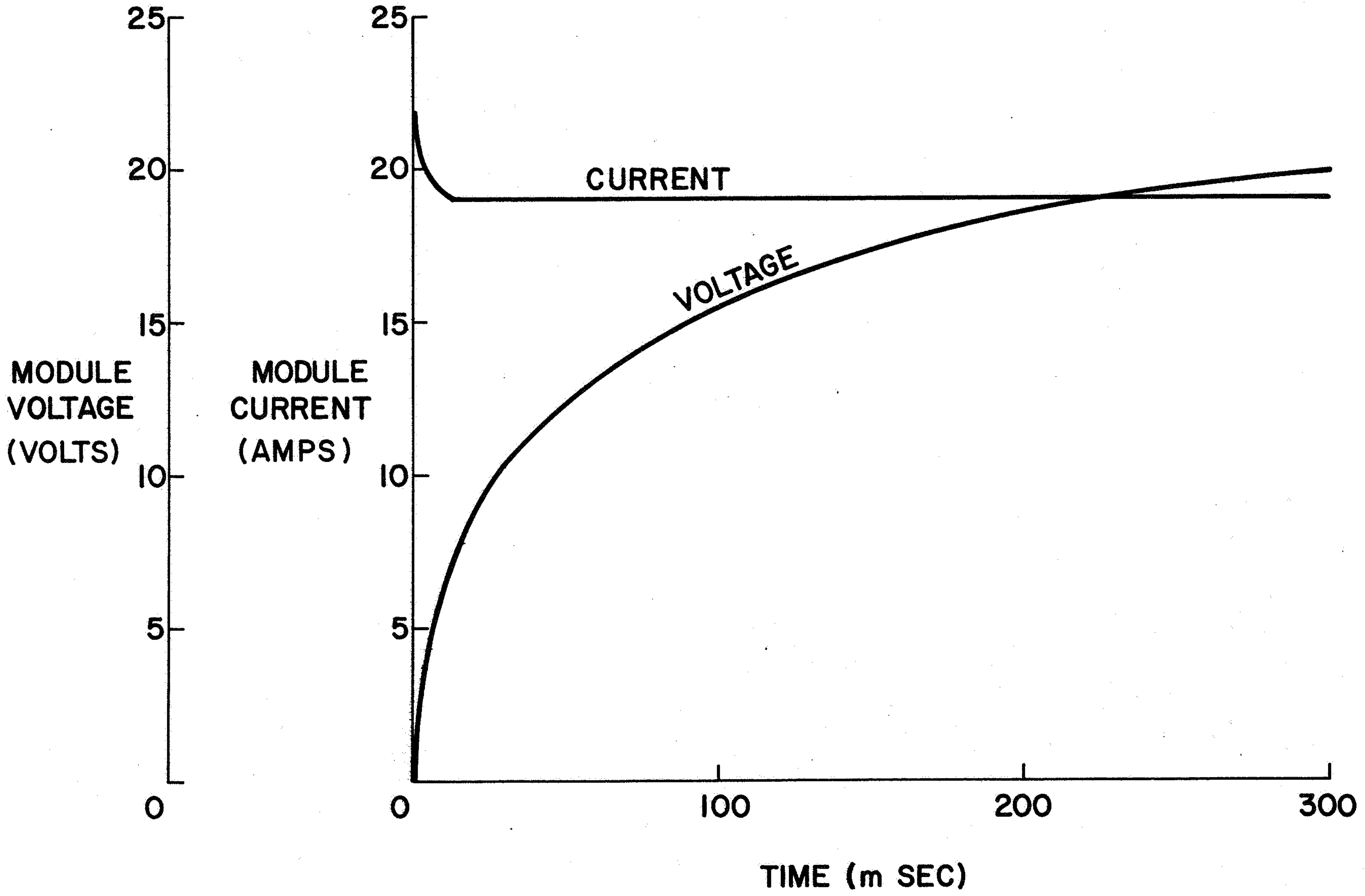


Figure 32. Module Transient Characteristics At High Current Setting

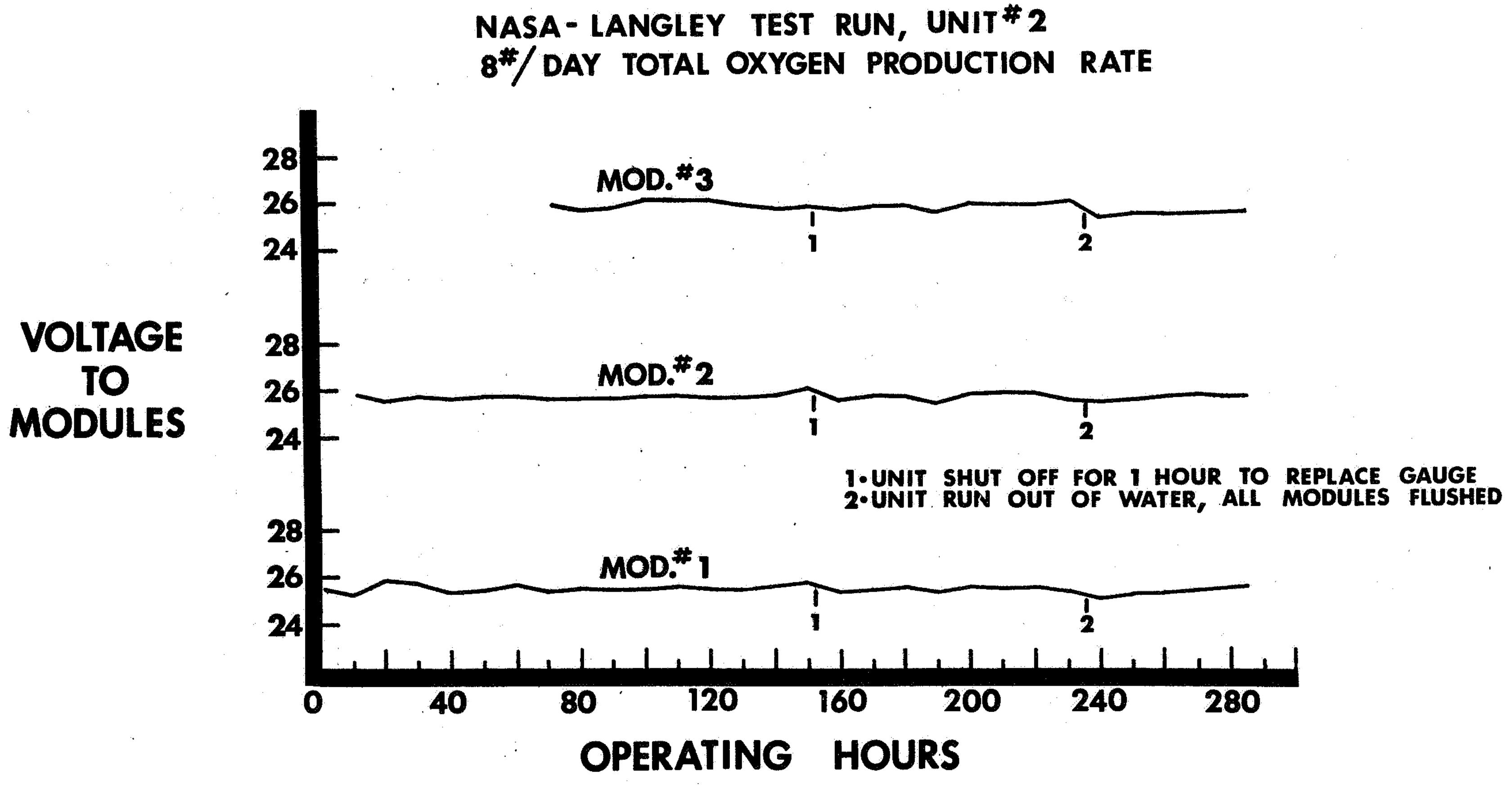


Figure 33. Operating Hours vs Voltage Applied To Modules

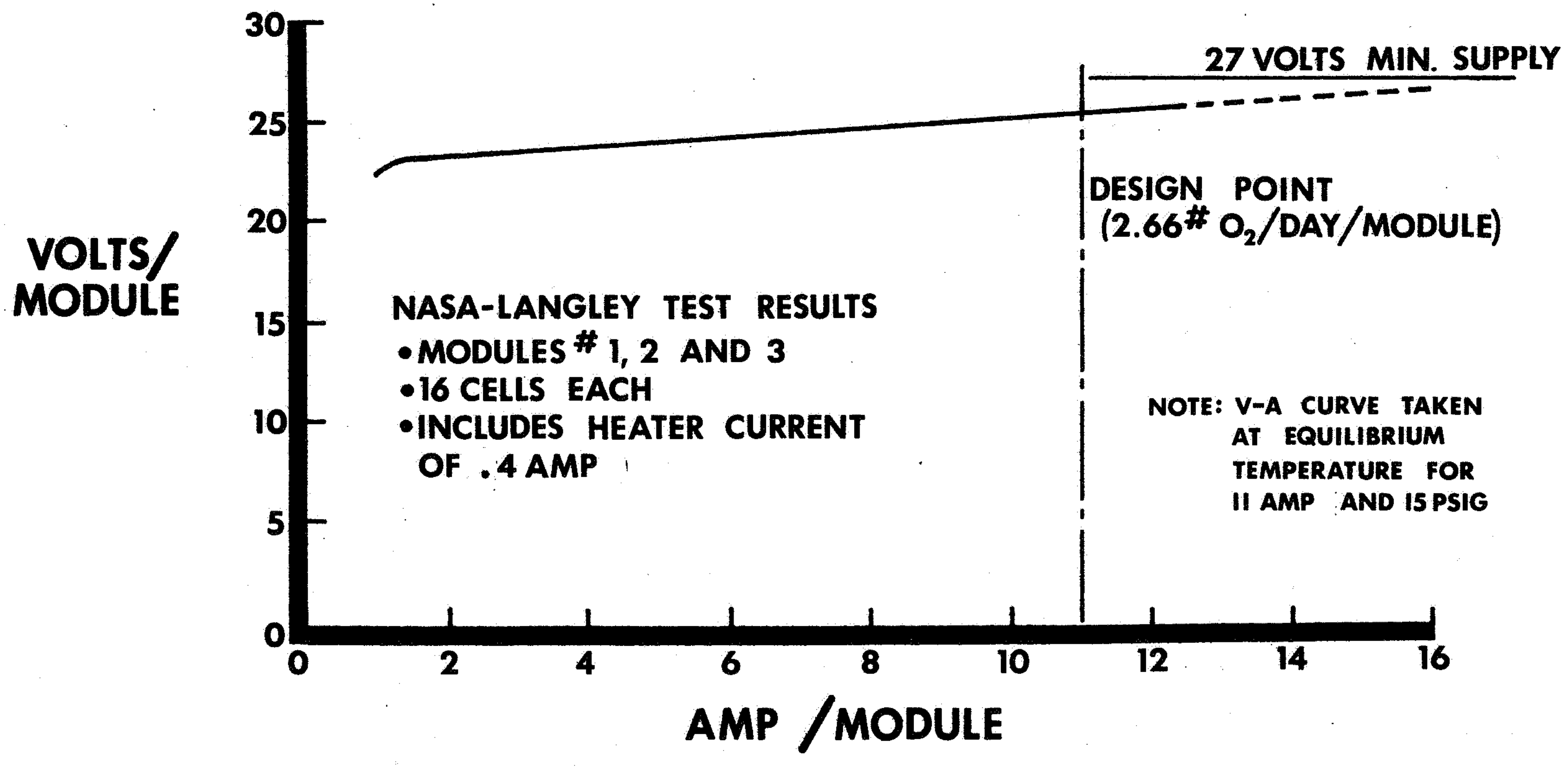


Figure 34. Capacity (amp) vs Applied Voltage

There was no evidence of any stray electrolysis occurring in the feed water cavities. It was concluded that the new cell design was successful in completely eliminating this probelm which had affected all previous testing.

When the test had reached 232 hours, the unit was inadvertently allowed to consume all the water in the supply tank. The unit ran approximately one hour longer after this condition occurred, and the electrolyte concentrated to the point where drying occurred in some cells. At this point, the voltages had risen about 0. 5 volt on all modules. The module were subsequently reflushed with KOH (without disassembly of the module), and put back on test. All modules improved slightly in voltage after the flush.

Module voltages remained consistently low during the test. All modules started up between 25. 5 and 25. 9 volts. Voltages were taken on a digital voltmeter to 2 decimal places. Voltages for various points in the test were as follows:

Hours	Module #1	Module #2	Module #3
50	25. 55	25. 73	-----
100	25. 52	25. 58	26. 03
150	25. 74	25. 95	25. 67
200	25. 48	25. 66	25. 77
250	25. 18	25. 46	25. 26
286	25. 44	25. 62	25. 26

These voltages were substantially lower than the design goal of 26. 5 volts required for adequate current control. The maximum of the hourly recorded voltage was 26. 12 volts.

The condenser was operated in the normal manner with condensate return to the water feed manifold for the first 50 hours with satisfactory results. The condensate lines were then disconnected from the return line, and the condensate collected individually from the hydrogen and oxygen at atmospheric pressure. This resulted in 15 psig differentials across the condenser matrix, but no problems were encountered by operating in this mode.

The condensate was measured and titrated twice a day. Total condensate collected amounted to 5196 cc on the oxygen side and 3174 cc on the hydrogen side. On the first collection, KOH concentration was approximately 6% This was attributed to KOH left in the manifolds after flushing the modules. The concentration immediately dropped to less than 0. 5% and then stayed below 1% for most of the test.

The average of the concentrations recorded was 0. 09%, but the actual value may be lower than this, since these values are approaching the lower limit of detection with the type of titration used. In the normal operating mode, the condensate is returned to the modules and does not leave the system. The condensate collection also shows that a KOH concentration gradient exists in the cell which substantially affects the vapor pressures. The result is that more of the waste heat is dissipated on the oxygen side than the hydrogen side. It is not believed that this is detrimental to operating performance.

All of the safety features were checked either at the start or during the test. The high coolant temperature was checked during operation by shutting off the coolant momentarily. The temperature of the cold plate increased to the 140°F thermostat set point in 10.5 minutes and shut the unit down. The coolant was reapplied and then the unit was restarted immediately.

Gas Purity

Gas samples were taken at 242 hours of the test and analyzed by a mass spectrometer with a lower limit of detection of 0.02%. The results on the hydrogen in mole % were as follows:

Oxygen	< 0.02%
Nitrogen	< 0.02%
Water	~ 0.30%

No other elements were recorded. By subtraction, the hydrogen purity is over 99.96%, well over the minimum requirement of 99%.

The oxygen was also analyzed on the mass spectrometer to observe the full range of impurities. The only constituents indicated by this method were hydrogen, nitrogen, carbon dioxide, and water. Since the process employed potassium hydroxide, the presence of CO_2 was questioned. A second sample was then analyzed on a gas chromatograph on only those gases indicated by the mass spectrometer with the following results in mole %.

Hydrogen	< 0.025%
Nitrogen	< 0.025%
Water	~ 0.200%

In this analysis, CO_2 was not detected on an instrument with a lower limit of detection of 0.005%. By subtraction, the oxygen purity is greater than 99.95%, which again is higher than the required 99.7%. The low hydrogen content indicated that good sealing between the hydrogen and oxygen sides was obtained. Since the unit was run with the hydrogen side 1 psi higher than the oxygen side, and the samples were taken under these conditions, it also indicated that the matrix was accomplishing its secondary function of maintaining separation of the product gases.

Mass and Heat Balance

Due to the type of system employed, the mass and heat balance reflects changes in the input to the unit. This is particularly true of the line voltage which may vary from 27 to 29 volts. This swing in voltage also has a slight effect on the current and gas production rate. Water feed rates and water collection rates, however, were only measured over long periods, so only the average of these values could be obtained.

The mass and heat balance shown in Figure 35 was prepared to show typical conditions, and was arbitrarily selected at 286 hours, the last hour of the test. At this point, the input to the unit was 27.6 volts and 34.8 amperes total.

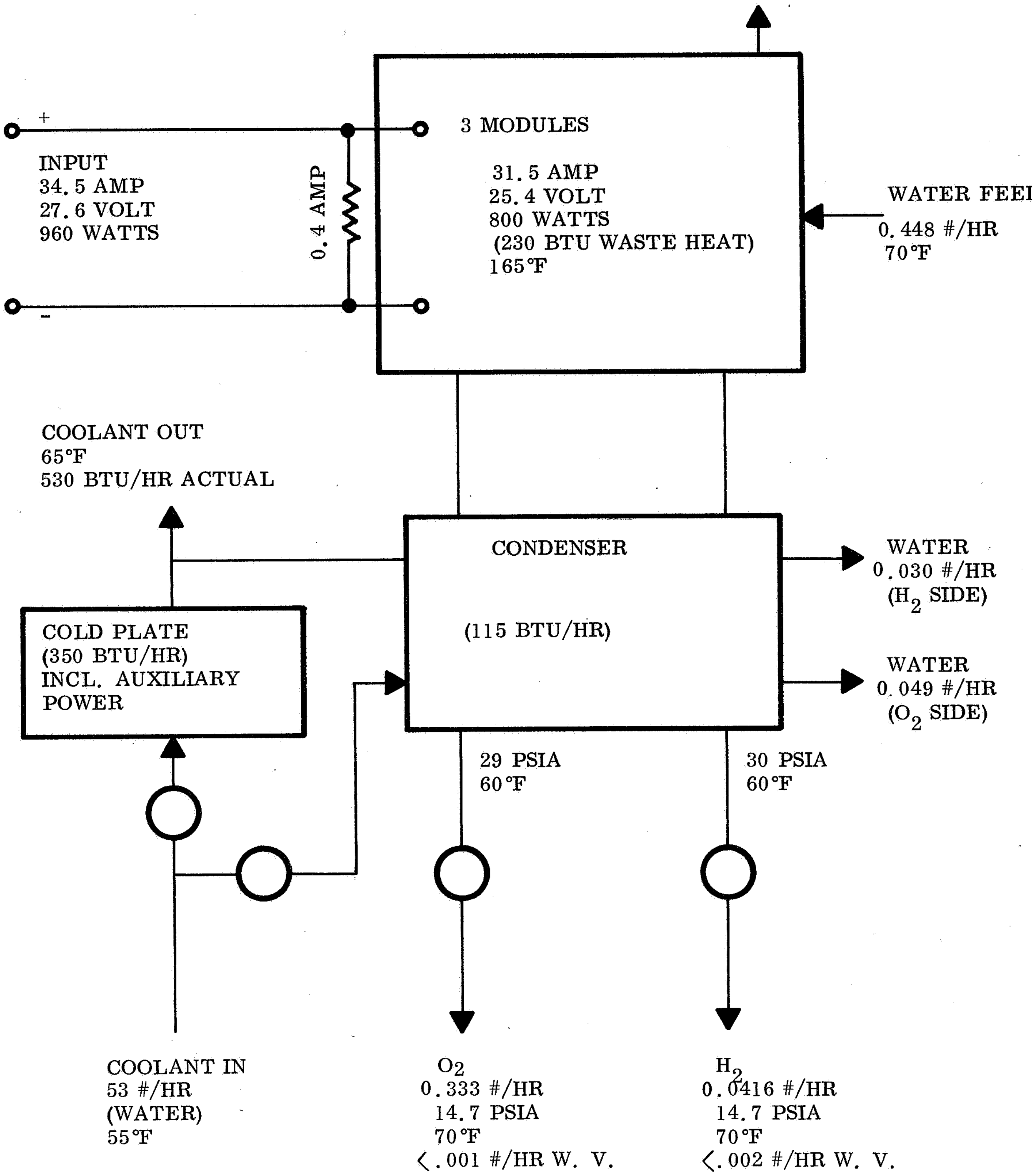


Figure 35. Mass and Heat Balance At 286 Operating Hours

The amperage to each module was maintained at 10.9 amp with 10.5 amp to the electrolysis cells, and approximately 0.4 ampere to the end plate heaters connected in parallel. The voltage required by the modules was 25.4, 25.6 and 25.3 for Modules 1, 2, and 3, respectively, or an average of 25.4 volts. Total power consumed in the electrolysis reaction power was 800 watts plus 30 watts for the heaters. Since the electrochemical reaction required approximately 750 watts, including phase and entropy changes, approximately 70 watts or 230 Btu/hr of heat was produced inside the "thermal box".

Measurement of the quantity of condensate collected by the condenser indicated that 115 Btu/hr were being removed from the modules by water vapor in the gas streams. By subtraction, an equal amount of heat was being rejected by conduction and convection from the Polysulfone to the surroundings.

Thermal efficiency was determined to be about 95 percent, while the electrical efficiency of the electrolysis process was determined to be 76 percent, based on a 1.60 average cell voltage (compared to 1.23 volts theoretically required to dissociate water). The overall unit efficiency, including the inefficiency of the current controller, was 65 percent (based on an ideal power requirement of 627 watts to produce 8.0 pounds/day oxygen and the 960 watts actually used. This latter efficiency could probably be improved with a more sophisticated type of control.

Gas outlet temperatures were approximately the same as room temperature for coolant temperatures of 40 to 55°F. The oxygen gas dropout traps remained dry throughout the test, except for 10 cc withdrawn after the initial startup of Module #1. The hydrogen trap remained dry throughout all phases of the test. This, plus the low water vapor quantities obtained in the gas analysis, indicated dew points of less than 50°F for the gases as they leave the unit.

At 27.6 volts input, approximately 350 Btu/hr were required through the cold plate. With inlet coolant at 55°F and outlet coolant temperature maintained at 65°F, 53 lb/hr were required, indicating that approximately 530 Btu/hr were being removed in the coolant stream. The additional heat was being removed by conduction through the frame from the surroundings and indicated the need for a better thermal isolation of the cold plate.

Feed water to the unit was measured each day and totaled 10,300 cc over the last 51.6 hour period. The average amount was 0.448 lb/hr, which is within 1 percent of the amount required by the reaction, plus the quantities collected and measured from the condenser.

CONCLUSIONS

The constant voltage of 25.5 ± 0.5 in the 250-hour test confirmed that water addition by vapor feed is a suitable method for full-scale systems at the selected current density of 100 ASF. The 1.55 to 1.60 cell voltages obtained are approaching the theoretical limits, and the possibility of further reduction appears remote. Future performance gains, therefore, can be expected to be through increased current densities at present voltage levels.

Maintainability was given prime consideration during components design and system layout. As a result, the final weight of 160 pounds and the final size of 21 x 20 x 19 inches, were greater than was expected, originally. Cell weight reductions and size modifications already achieved indicate that a 4-man, flight-type unit would weigh less than 100 pounds and be less than 3 cubic feet in volume.

Removal of both the current controller and a module for repairs were required during checkout and startup of the 250-hour test. Both of these tasks were accomplished easily, providing some verification of the packaging concepts. The layout for flight-type hardware will be dependent on the mission and access to the unit in the spacecraft for maintenance. The operating and maintenance experience gained during the test makes it reasonable to expect that flight hardware can be designed to be maintained by astronauts using simple tools and procedures.

Typical problems for this type of equipment were experienced throughout most of the program; i.e., internal and external leakage and stray electrolysis. However, these and another typical problem, galvanic corrosion, were not observed during the 250-hour test. The bonded plastic design developed towards the end of the program seems to meet the functional and maintainability requirements.

The one operating problem experienced was the need to purge small amounts of gas, once a day, from the water cavities to maintain operating voltages. This area will require further development for a flight-type system. Purities in excess of 99.9% for both gases indicate the attainment of the required internal sealing.

Testing on this program was limited to the design conditions and, as yet, the limiting factors have not been demonstrated. It may be possible to increase continuous current densities, or provide short-time overload capability.

Although testing on water containing 100 ppm of dissolved solids did not show adverse effects in 250 hours, this period is relatively short compared to the required life. Further testing will be required before positive conclusions can be reached.

APPENDIX

TOXICITY ANALYSIS

All construction materials used in the unit were considered for their outgassing and potential toxic degradation products. The area of most concern was the electrolysis module, operating at temperatures of 150 to 180°F in caustic and pure oxygen environments, and hence, would be most subject to degradation. All the materials selected for the module, however, have been shown to be extremely stable in this environment, and no problems with toxic products are known to exist. The only component in the module which might contribute trace toxic products during abnormal conditions is the rubber "O" ring. The total quantity involved, however, is only 0. 1 pound distributed between three modules. A listing of module materials is shown in Table I.

Other components exposed to the oxygen, hydrogen, and traces of the caustic electrolyte, are the condenser, back pressure regulators, and interconnecting tubing. Components exposed to this environment are shown in Table II.

Materials used for the unit structure and the remainder of the piping and electrical components are also predominately made from materials having non-toxic corrosion products. The paint used on the cabinet was a special low outgassing grade recommended by NASA, LRC. The scope of this program did not permit investigations into the types or properties of paints, coatings or markings used for most of the miscellaneous electrical devices, such as toggle switches, semi-conductors, resistors, and meters. These devices are small and their potential contribution to atmospheric contamination was considered to be negligible.

TABLE I

TOXICITY ANALYSIS - MODULE AND CONDENSER PARTS

Environment I

All parts exposed to oxygen, hydrogen, and KOH solution at temperatures up to 180°F and pressures up to 35 psia internally - cabin atmosphere inside "thermal box" externally.

Material A - Oxygen and Hydrogen Electrodes

a) Function - Electrochemical reaction site

b) Material - Pure sintered nickel powder on a nickel screen with platinum and palladium catalyst applied to the surface.

c) Total Quantity - 9.2 pounds

d) Reaction Product - Non-toxic nickel oxides.

e) Selection Criteria - Optimum electrochemical performance, excellent stability in environment.

Material B - Asbestos Matrix

a) Function - Capillary electrolyte holder, gas/liquid separators.

b) Material - Fuel cell grade asbestos.

c) Total Quantity - 1.7 pounds

d) Reaction Products - Non-toxic magnesium oxide and potassium silicate.

e) Selection Criteria - Optimum product gas separation, minimum resistance, and good chemical stability.

Material C - Polysulfone Spacers, Support Plates and End Plates

a) Function - Channel gases, provide gasket confinement, and support electrodes.

b) Material - Pure Polysulfone resin with no fillers of any type. Chemical formula is Polyarylether.

c) Quantity - 23.0 pounds

d) Corrosion Products - None known at these conditions.

e) Selection Criteria - Excellent resistance to environment, suitable temperature characteristics, desirable bonding and laminating properties.

TABLE I (CONTINUED)

TOXICITY ANALYSIS - MODULE AND CONDENSER PARTS

Material D - Buna "N" Gaskets ("O" Ring-Type)

a) Function - Provide seals between cells at the hydrogen, oxygen, and water ports.

b) Material - Buna "N" - Copolymer of butadiene and acrylonitrite.

c) Total Quantity - 0.1 pound maximum

d) Reaction Products - CO_2, Water, trace amounts light hydrocarbon, SO_2.

e) Selection Criteria - Low compression set, good chemical resistance.

Material E - Stainless Steel Components

a) Function - End plates and bolts - Provide compression on module and condenser.

- Metal Tubing - Pipe oxygen and hydrogen from module to condenser, back pressure regulators and gauges.
- Tube Fittings - Connect tubing runs.
- Pressure Relief Valve - High oxygen pressure.
- Back Pressure Regulator Body - Control H_2 and O_2 pressures.
- Pressure Switches - High H_2 pressure, low water pressure.

b) Material - Type 316 Stainless Steel (Pressure Switch Type 347, Stainless Steel).

c) Total Quantity - 50 pounds

d) Reaction Products - Non-toxic iron oxide, nickel oxide, chromic oxide.

e) Selection Criteria - Excellent corrosion resistance to KOH and oxygen, high strength.

Material F - Flexible Tubing

a) Function - Provide removable piping connections to electrolysis modules and condenser.

b) Material - Low density polyethylene

c) Total Quantity - 0.25 pound

d) Reaction Products - CO_2, water

e) Selection Criteria - Excellent corrosion resistance to oxygen and caustic, good flexibility and resistance to stress cracking.

TABLE I (CONTINUED)

TOXICITY ANALYSIS - MODULE AND CONDENSER PARTS

Material G - Teflon

a) Function - Diaphram for Back Pressure Regulator.

b) Material - Teflon - tetrafluoroethylene.

c) Total Quantity - Less than 0. 1 pound

d) Reaction Products - CO_2 plus toxic vapors above 750°F.

e) Selection Criteria - Inert, flexible, low permeability.

Material H - Acrylic

a) Function - Provide visual indication of system gas or liquid purity.

b) Material - Plexiglass - methyl methacralate

c) Total Quantity - 0. 5 pound

d) Reaction Products - CO_2, water, light hydrocarbons.

e) Selection Criteria - Stable in oxygen and caustic environment, translucent, rigid.

TABLE II

TOXICITY ANALYSIS - OTHER COMPONENTS

Environment II

Parts exposed to cabin atmosphere.

Material I - Aluminum

a) Function - Cabinet - Supporting Structure, instrument panels, mounting brackets.

- Cold Plate - Electrical components heat sink.
- Electrical Connectors - Quick connect of power and voltage reading connections.

b) Material - Primarily Aluminum Alloy Type 6063.

c) Total Quantity - Approximately 20 pounds

d) Reaction Products - Aluminum oxide, aluminum hydroxide.

e) Selection Criteria - Light weight, availability.

Material J - Polysulfone

a) Function - Provide insulation box and slide rails around modules.

b) Material - Pure Polysulfone.

c) Total Quantity - 7 pounds

d) Reaction Products - None known at operating conditions.

e) Selection Criteria - Light weight, bondable, high strength, low thermal conductivity.

NASA CR-66654

DISTRIBUTION LIST

NAS1-6561

NASA Langley Research Center
Langley Station
Hampton, Virginia 23365

	Copies
Attention: Research Reports Division, Mail Stop 122	1
R. L. Zavasky, Mail Stop 117	1
Thomas Owens, Mail Stop 332	2
Robert Bruce, Mail Stop 332	1
Spacecraft Systems Branch, Mail Stop 350	6
Applied Materials & Physics Division, M/S 213	3
Environmental Factors Factors Section, M/S 350	1
Albin O. Pearson, Mail Stop 342	1
David C. Grana, Mail Stop 342	1
ILSS Office, Mail Stop 342	6
Dan C. Popma, Mail Stop 470	1
Robert W. Johnson, Mail Stop 342	10
H. Milton Holt, Mail Stop 258	2
Dr. Thomas O. Wilson, Mail Stop 336	1
Dr. Judd R. Wilkins, Mail Stop 337	1
Dr. James Scow, Mail Stop 310	1
Mr. T. Wayne Holt, Northrop Corporation (Contract NAS1-7399), Mail Stop 344	6

NASA Ames Research Center
Moffett Field, California 94035

Attention: Library, Mail Stop 202-3	1
Dr. Theodore Wydenven, Jr., Mail Stop 239-4	2

NASA Flight Research Center
P. O. Box 273
Edwards, California 93523

Attention: Library	1

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

Attention: Library	1

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Attention: Library, Mail 111-113	1

NASA Manned Spacecraft Center
Houston, Texas 77001

Attention: Library, Code BM6	1
Murline L. Owen, Code EC3	1

NASA CR-66654

DISTRIBUTION LIST

NAS1-6561

	Copies
NASA Marshall Space Flight Center Huntsville, Alabama 35812 Attention: Library	1
NASA Wallops Station Wallops Island, Virginia 23337 Attention: Library	1
NASA Electronics Research Center 575 Technology Square Cambridge, Massachusetts 02139 Attention: Library	1
NASA Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135 Attention: Library, Mail Stop 60-3	1
NASA John F. Kennedy Space Center Kennedy Space Center, Florida 32899 Attention: Library, Code IS-CAS-42B	1
National Aeronautics and Space Administration Washington, D. C. 20546 Attention: Library, Code USS-10	1
NASA Code RB	1
Lockheed Missiles and Space Company 1111 Lockheed Way Sunnyvale, California 94086 Attention: James M. Smith	1
General Electric Company 311 Main Street, Box 1038 Newports News, Virginia 23601 Attention: R. B. Wiley	1
The Garrett Corporation 1120 West Mercury Boulevard Suite 303 Hampton, Virginia 23366 Attention: M. E. Carig	1
McDonnell Douglas Corporation 2013 Cunningham Drive Suite 242 Hampton, Virginia 23366 Attention: Attention: R. D. Heitchure	1

NASA CR-66654

DISTRIBUTION LIST

NAS1-6561

	Copies
NASA Scientific and Technical Information Facility P. O. Box 33 College Park, Maryland 20740	36 plus reproducible