AIRCRAFT EQUIPMENT DIVISION

REPORT

SOLID POLYMER ELECTROLYTE WATER ELECTROLYSIS SYSTEM DEVELOPMENT

Contract NAS 9-13430

FINAL TECHNICAL REPORT

Prepared for

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
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GENERAL ELECTRIC

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SECTION 1.0 INTRODUCTION

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

In March, 1970, NASA Langley Research Center awarded a contract (NAS 1-9750) to General Electric Company, Direct Energy Conversion Programs, Wilmington, Massachusetts (then located in Lynn, Massachusetts) to investigate the use of the solid polymer electrolyte (SPE) technology in a water electrolysis system to generate oxygen and hydrogen for manned space station applications. The long life and stable performance of the SPE electrolysis concept was demonstrated by four separate laboratory cells operating approximately 9000 hours each and a seven cell module (two-man O_2 rate) accumulating 11,000 operating hours all without failure. Under this program, a one-man rated breadboard SPE water electrolysis system (WES) was developed and demonstrated the performance/life characteristics of the SPE electrolysis technology. In addition, the program culminated in the fabrication of the major components for a four-man rated breadboard oxygen generation system. This program was completed in August 1972, with results documented in a final report NASA CR-112183 dated August 1972.

In October 1972, the present program, consisting of two phases, was initiated. Phase I utilized the previously fabricated major components, where appropriate, and fabricated and tested a four-man rated, low pressure breadboard WES with the necessary instrumentation and controls. A photograph of this system is shown in Figure 1. Phase II encompassed the development of a six-man rated, high pressure, high temperature, advanced preprototype WES. This configuration included the design and development of an advanced water electrolysis module, capable of operation at 2758 kN/m^2 (400 psig) and 366.5K (200°F), and a dynamic phase separator/pump in place of a passive phase separator design. Major components and instruments meeting design requirements of this system, were utilized from previous WES contract work. The six-man rated advanced WES was contained in the control cabinet and fluid package shown in Figure 2. Evaluation of this system demonstrated the goal of safe, unattended automatic operation at high pressure and high temperature with an accumulated gas generation time of over 1000 hours. Work under this contract was concluded in June 1975.

During the period of this contract (approximately 2 1/2 years), support was also provided to two other water electrolysis development programs of NASA. System performance mapping tests were performed on the four-man WES, including

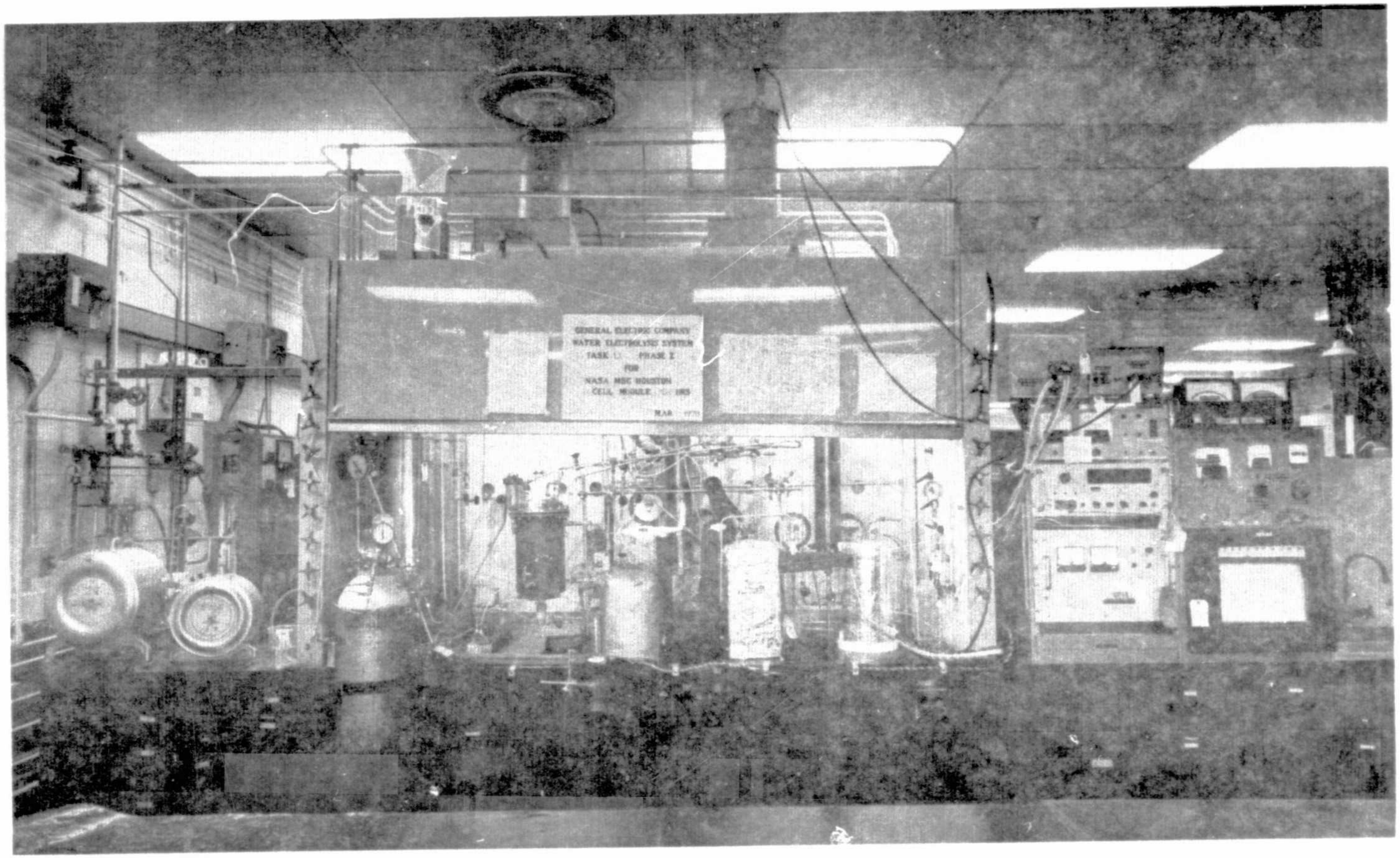

Figure 1. Four-Man Breadboard WES Facility

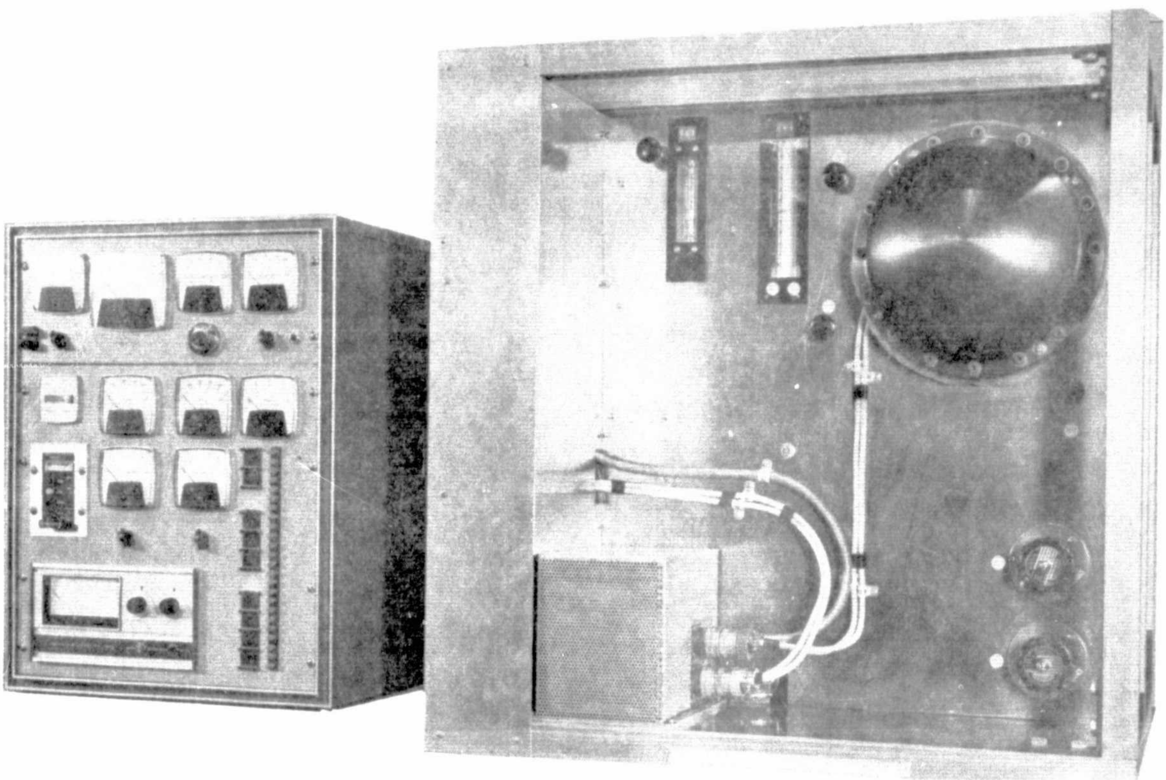

Figure 2. Six-Man Advanced Water Electrolysis System Control Cabinet and Fluid Package

exploratory, off-design conditions to provide design data in support of the Space Station Prototype (SSP) Oxygen Generation Subsystem design. Also, the six-man WES was tested in different operating modes to provide design information in support of the development of the WES demonstrator unit for the Life Sciences Payload Program, Contract No. NAS 9-14205.

SECTION 2.0 LOW PRESSURE BREADBOARD, WATER ELECTROLYSIS SYSTEM (WES)

The WES components developed and fabricated under Contract NAS 1-9750 were designed to be capable of continuous oxygen generation equivalent to a nominal four-man rate basis of 4.54 kg/day (10 lb O_2/day), with a maximum nominal capacity equivalent to a six-man rate. Wherever possible and as directed by the contract, standard commercial materials and components were selected to provide functional demonstration compliance at minimal cost and delivery schedule. It should be noted therefore, that these breadboard components would require modification and redesign in order to provide flight-worthiness to withstand "hard" environment launch vibration, shock and acceleration along with weight and volume reductions, mounting configuration, producibility and maintainability considerations.

2.1 Specification

A "guideline" specification for design capability of the four-man rated, low pressure breadboard WES is outlined in Table I.

2.2 Configuration

Figure 3 is a fluid schematic of an SPE water electrolysis system showing the basic arrangement of the breadboard components. It should be realized that additional control components and instrumentation would be necessary for automatic control, performance monitoring, fault isolation, shutdown and safety considerations.

Primary fluid and electrical interfaces to the WES are:

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

As shown in Figure 3, feed water is supplied to the WES at a make-up water rate of approximately 5.13 kg/day (11.3 lb/day) and 69 kN/m^2 (10 psig) for an oxygen generation rate of 4.5 kg/day (10 lb/day). The water enters the WES through a check value which prevents reverse flow when the system is shutdown at normal

TABLE I

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

WES Capacity

10 lb/day (4.54 kg/day) oxygen (nominal four-man rate - continuous).

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

WES Gas Purity

Oxygen Generation

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

Hydrogen Generation

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

NASA-Maintained Downstream Gas Pressures of WES

Oxygen Subsystem: 14.7 psia (101.4 kN/m^2) or less.
Hydrogen Subsystem: 20 $\pm$ 5 psia (137.9 $\pm$ 35 kN/m^2).

Make-up Water (Feed Water) Available to WES

Temperature: +40 to +170°F (277.6 to 350K).
Pressure: 25 $\pm$ 5 psia (172 $\pm$ 35 kN/m^2).

Water Purity:		$<$ 100 ppm by weight solids (assume ionic species). $<$ 80 micromhos/cm specific conductance (12,500 ohm-cm max. specific resistance).	
Bacteria	-	Pseudomonas Aeruginosa	10 counts/cc
		Alcaligenes Faecalis	10 counts/cc
Fungii	-	Mucor	1 spore count/cc
Molds	-	Not defined.	

Coolant Available to WES

Fluid:	Water with propylene glycol additive to establish a nominal 0°F (273K) freezing point.
Temperature:	+40 $\pm$ 3°F (277.6 $\pm$ 1.7K).
Pressure:	80 psig (552 kN/m^2) max.
Flow:	Up to 1 gpm (3.78 l/min.)

Nitrogen Available to WES

Pressure: 80 psia (552 kN/m^2) nominal.

Electrical Services Available to WES

28 $\pm$ 3 VDC.
115 VAC nominal at 60 Hz.

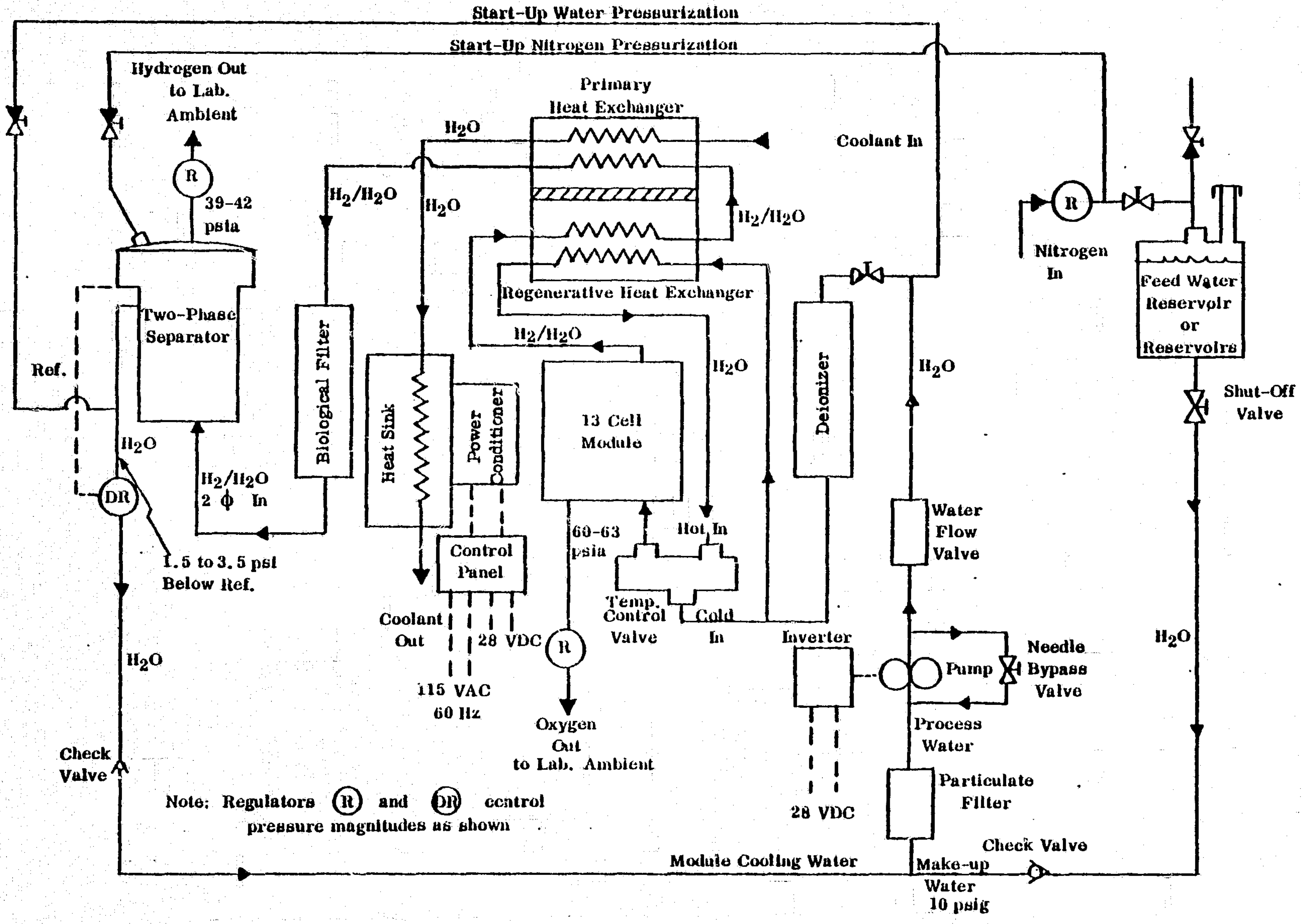

Figure 3. "4-Man" Breadboard Water Electrolysis System Fluid Schematic

working pressures. The feed water is mixed with recycled module cooling water upstream of the particulate filter to the water pump. This process water is circulated throughout the WES by a gear-type pump with quantity regulation maintained by the water flow control valve and needle bypass valve. The pump design includes an internal relief valve which becomes functional if an internal dead-ended condition arises within the pump. Pressurization of the feed water to 69 kN/m^2 (10 psig) reduces the pump pressure rise and subsequent journal bearing load and also prevents the relief valve from continuously relieving. Excess pump capacity is delivered through the needle bypass valve. An orifice could be used in place of the needle valve for a flight designed system. The water pump is powered through a DC to 3-phase AC inverter with a 28 VDC input. Downstream of the pump, the water flows through a deionizer resin bed which reduces the ionic contamination level to acceptable WES purity limits of $\geq$ 400,000 ohm-cm.

The water then passes through a regenerative heat exchanger prior to mixing in a temperature regulating valve which controls the supply temperature to the electrolysis module at approximately 311K (100°F). This temperature control maintains electrolysis module performance essentially independent of coolant and environmental temperature variations. The process water is delivered to the cathode (hydrogen generating) side of the 13-cell electrolysis module. Since the electrolysis occurs at the anode, water required for this reaction diffuses through the solid polymer electrolyte at a rate just equal to that required for oxygen generation. (A cross section showing the SPE electrolysis cell concept and a description of operation are provided in the Appendix.) The generated oxygen will be saturated at the cell temperature and pressure [approximately 322K (120F) and 428 kN/m^2 (62 psia)], but will contain no liquid water when discharged to ambient pressure. The free liquid water required for cell cooling will remain on the cathode side and will exit with the hydrogen as a two-phase mixture. This heated mixture passes through the regenerative heat exchanger to transfer its heat to the incoming colder process water. The two-phase mixture (hydrogen and module cooling water) leaving the regenerative heat exchanger is then cooled to approximately room temperature in the primary heat exchanger which transfers heat to the interface coolant fluid. Waste heat from the power conditioner is removed by the attached heat sink through which the interface coolant is also circulated. A biological resin bed filter is installed immediately upstream of the two-phase separator to remove micro-organisms (i.e., bacteria, molds, fungi, yeast) and particulate matter by three possible mechanisms, namely: electrostatic attraction to the resin beads; particulate matter depth filtration through the resin bed column; and retardation or actual destroying of bacteria and mold growth by any localized acidified water within the resin bed column.

The two-phase mixture, therefore, has been pre-cleaned prior to entry into the two-phase separator. The life of the hydrophilic tubes with a pore size of 2 to 3.5 microns within the separator is therefore increased since pore clogging is minimized. The H_2/H_2O phase separator provides a passive means of separating liquid from a gas in a zero gravity environment using both hydrophilic and hydrophobic separation elements. Primary separation is accomplished by removing water slugs from the two-phase mixture (hydrogen and water) with five hydrophilic porous glass tubes connected in a series fluid flow path. The hydrophilic elements permit the water to pass through the tube wall under a controlled differential pressure to the housing side of the assembly. Gas leaving the last tube, which is normally free of entrained water, passes through three parallel hydrophobic membranes located in the separator cover. The hydrophobic membranes, by their ability to pass only gas, serve as a trap to prevent water carryover to the hydrogen outlet stream in the event of porous tube failure and/or differential water regulator failure. The pressure differential across the hydrophilic elements is controlled by a differential back-pressure regulator which is referenced to the inlet side of the hydrophobic membranes. The water leaving the differential back-pressure regulator (module cooling water) is mixed with the feed water and returned to suction side of the pump through the particulate filter.

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

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

The major components developed and fabricated under Contract No. NAS 1-9750 were:

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

These breadboard components were individually acceptance tested as part of the aforementioned contract. Installation and operation of these components as part of an integrated four-man rated system was accomplished under Phase I of Contract No. NAS 9-13430.

Figure 1 illustrates the four-man rated breadboard WES which resulted from modification of the NASA/LRC facility (ref. Figure 13 of Report NASA CR-112183). The modification required complete teardown of the one-man rated WES to install the four-man rated breadboard components previously listed.

In addition, the installed system and facility were modified to include start-up pressurization capability, increased make-up water reservoir capacity, primary heat exchanger, city water coolant system and automatic shutdown capability with a fault detection and isolation panel. A 100 amp DC power supply along with facility wiring and temperature, pressure, current and voltage readout was also provided.

2.3 Component Testing

As previously described, the fourteen major components listed on Page 9 had been designed, fabricated and some individually bench tested under Contract NAS 1-9750. Component descriptions, specifications, drawings and check-out test data are included in the Final Report NASA CR-112183 under that contract.

Component checkout tests were completed under the current program, most of which required installation with instrumentation as part of an electrolysis system in order to obtain meaningful operating conditions and test data. The following component checkout activities were undertaken.

2.3.1 13-Cell, Low Pressure, Electrolysis Module

A 13-cell, low pressure (434 kN/m^2, 100 psi, maximum operating pressure), electrolysis module design, as shown in Figure 4 and pictured in Figure 5, was designed to meet requirements of a four-man rated low pressure WES under Phase I of this program. As reported under Phase II, most of the cell parts were salvaged for modification and incorporation into a six-man rated, high pressure (2758 kN/m^2, 400 psi) advanced electrolysis module design. A satisfactory proof-pressure leakage test was performed on the low pressure module design (10/17/72) submerged in water and under 690 kN/m^2 (100 psig) nitrogen pressure common to oxygen and hydrogen sides. There was no indication of external leakage. Subsequently, a satisfactory cross-membrane leakage test was performed with 345 kN/m^2 (50 psig) nitrogen to the hydrogen side and atmospheric pressure on the oxygen side. Measured gas leakage was within acceptable SPE permeability limits.

Module flow-pressure drop characteristics of the cathode side were measured with "solid" water flowing respective of a non-operating condition as shown in Figure 6. Two tests were performed, of which the 11/21/72, data is considered more appropriate because some residual gas may have been trapped by screens in the cells for the 11/20/72 evaluation.

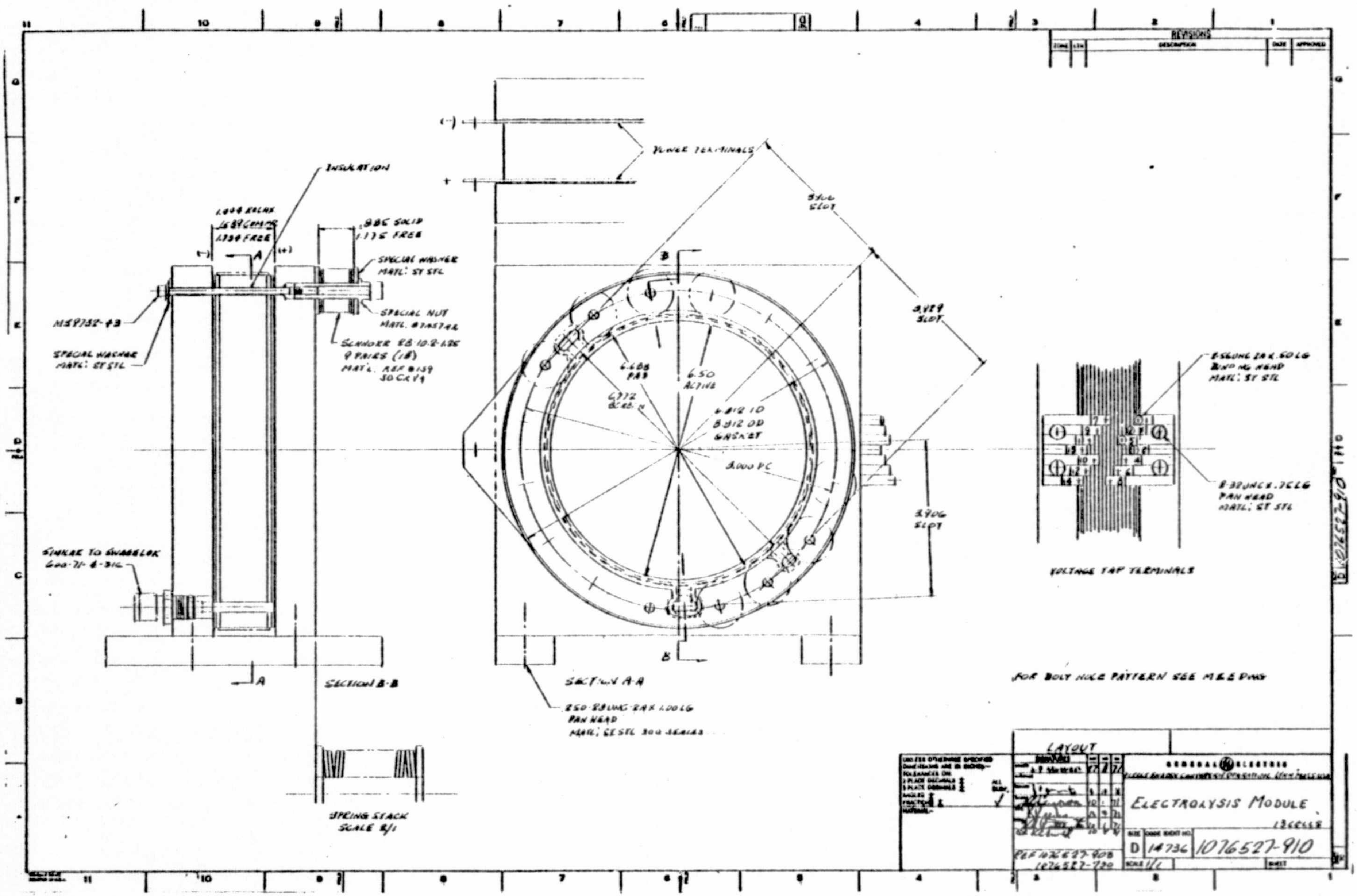

Figure 4.

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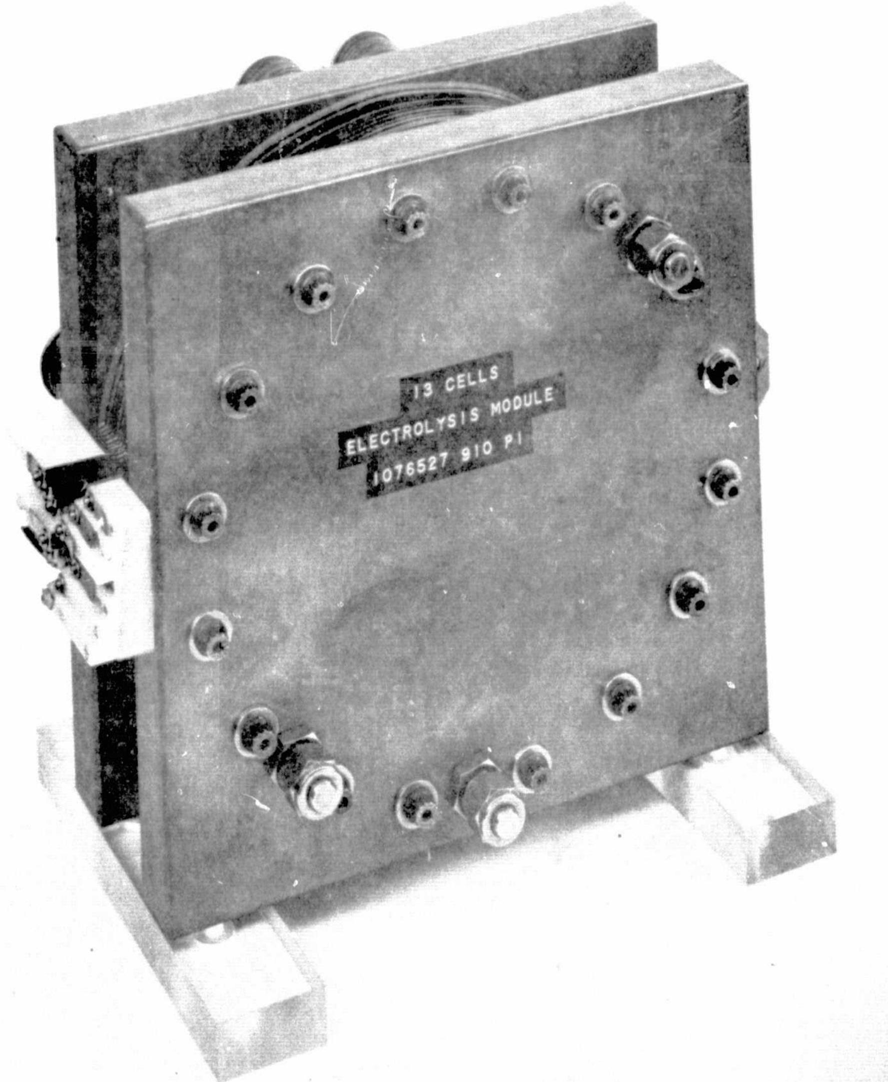


Figure 5. 13-Cell Electrolysis Module

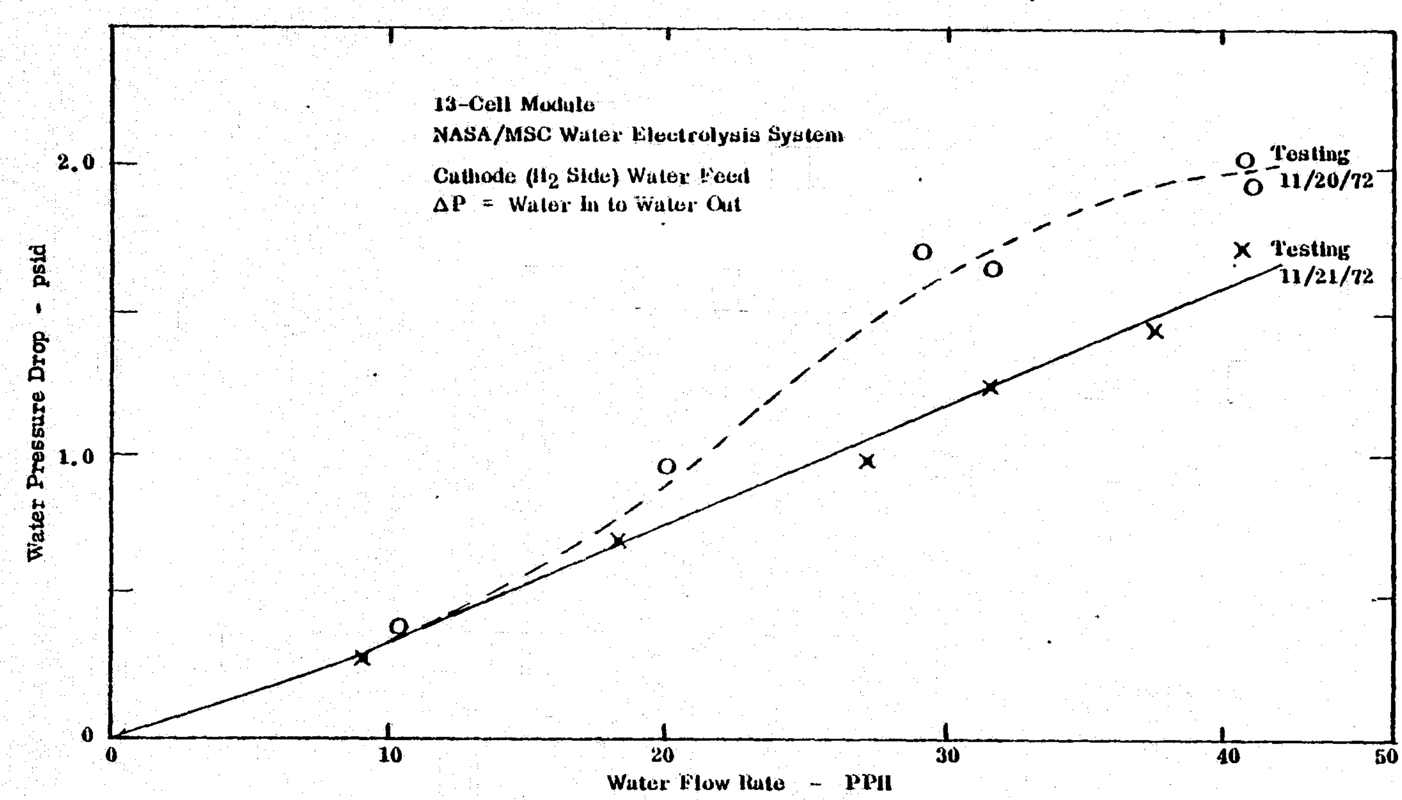


Figure 6. Water ΔP Versus Flow Characteristics

The module demonstrated satisfactory steady state performance on 11/27/72. This was at four-man rated design point conditions of 49.1 amps, current density of 230 mA/cm^2 (213 ASF), a process water feed rate of 80 cc/min at 311K (100°F), two-phase mixture (hydrogen plus liquid water) outlet temperature of 331.7K (137.5°F) and nominal operating pressure of 75.8 kN/m^2 (11 psig). Typical voltage performance at these conditions was as follows:

Voltage, VDC

at 49.1 Amps, 230 mA/cm^2

Cell No.													Total	Total
1	2	3	4	5	6	7	8	9	10	11	12	13	Sum.	Term.
1.690	1.682	1.678	1.691	1.682	1.661	1.674	1.669	1.668	1.675	1.680	1.670	1.672	21.82	21.85

Immediate gas generation was demonstrated during push-button starts at pre-selected current settings from a nominal 5.6 amps to 49.1 amps. During cyclic operation under typical space-station orbit conditions of a nominal 55 minutes "on" and 39 minutes "off", the oxygen was delivered during the instantaneous start-up transient and thereafter, free of liquid water. Liquid-free oxygen delivery was observed during pushbutton starts following shutdown periods of up to 16 hours. However, with shutdown periods of approximately 24 hours, or longer, some water will be delivered with the oxygen during a subsequent start transient (10 to 30 cc of water). The start transient is that elapsed time from a pushbutton start (at a pre-selected current setting) for the module oxygen-side pressure to reach a steady-state level as set by the absolute oxygen back-pressure regulator. In this four-man rated system, the regulator is set at a nominal 310 kN/m^2 (45 psig). This water discharge, only at start-up, is caused by the hydraulic permeability of the SPE membrane which allows the gradual transport of water from the flooded hydrogen side to the oxygen side over an extended shutdown period.

2.3.2 Power Conditioner and Control Panel

The power conditioner and control panel checked-out satisfactorily for all steady state, start and stop transient conditions up to the four-man design point of 49.1 amps (230 mA/cm^2). In addition, satisfactory operation was demonstrated at above design point conditions up to 75 amps (350 mA/cm^2).

The automatic current limit shutdown feature of the power conditioner was satisfactorily demonstrated at approximately 80 amps.

2.3.3 Temperature Regulating Valve

This valve, Model No. 8A767 - Rev. 002, manufactured by Standard-Thomson Corp., is factory set to control the outlet water temperature of the valve 313 ± 2.2K (104 ± 4F). However, during WES testing in October - December 1972, there was observed occasional upward shifting of the controlled mixture-out temperature (cold water plus hot water) to as high as 313K (140°F). It has been hypothesized that residual gas bubbles in the water at the 80 cc/min. process water rate would tend to collect in the vicinity of the "wax" actuator internally in the valve, causing poor heat transfer characteristics with subsequent "out-of-spec" control of the temperature. During WES operation, when temperature regulation was out-of-spec, it was demonstrated that manually tapping the valve would clear the gas and re-establish proper temperature control at the nominal 311K (100F) setting.

On 1/3/73, the valve was removed from the WES for a bench evaluation. The results of this investigation demonstrated satisfactory performance of the temperature regulating valve with "solid" water flows of more than 100 cc/min.

In the WES, process water is delivered to the module cathode side for electrolysis and module cooling. A two-phase mixture of water-hydrogen gas sluglets therefore exits from the module at module pressure and temperature. This water also contains dissolved hydrogen gas.

The downstream passive separator removes the water sluglets from this mixture with subsequent return circulation of the water to the pump suction side. In the WES, pressure-drop of components in the return circulating loop (water differential back-pressure regulator, check valve, etc.) have been kept low to minimize the release of dissolved gas in the water "from coming out of solution", due to expansion from a high pressure region to a lower region. It is possible, therefore, that some dissolved gas may come out of the water (effervescent effect) which will be recirculated by the pump. It was concluded, therefore, that the temperature regulating valve had previously failed to control because of this gas mixture condition.

The evaluation of the problem resulted in the following corrective action:

1) For gravity operation, the valve must be mounted at a 45° attitude to provide internal gas clearage from the wax-actuator end of the valve. This facility change was incorporated on 1/24/73. A configuration design change to the valve is possible to remove the attitude sensitivity.

2) To enhance gas clearance through the valve, the process water rate was increased by 50% (from 80 to 120 cc/min.).

After introducing these corrective actions, performance of the temperature regulating valve was satisfactory.

2.3.4 Absolute Oxygen Back-Pressure Regulator

Regulator performance of the controlled upstream pressure was evaluated on Ausco Inc. regulator, type P320-51. Figure 7 presents the results of this investigation. Compliance with GE/DECP requirements was satisfactory.

2.3.5 Absolute Hydrogen Back-Pressure Regulator

Regulator performance of the controlled upstream pressure was evaluated on Ausco Inc. regulator, type P320-52. Figure 8 presents the results of this evaluation. Compliance with GE/DECP requirements was somewhat marginal due to the controlled setting being near the lower specification limit. Actually, the results confirm the setting of this component as it was originally received from the vendor. The setting is readily changeable and was adjusted to bring the control point up to approximately 172 kN/m^2 (25 psig) from a nominal 165 kN/m^2 (24 psig).

2.3.6 Differential Back-Pressure Water Regulator

Regulator performance of the controlled upstream water pressure below a nominal hydrogen reference pressure of 165 kN/m^2 (24 psig) was evaluated on Ausco Inc. regulator, type P321-50. Figure 9 presents the results of this investigation. Compliance with GE/DECP requirements was satisfactory.

Figure 10 presents the adjustment characteristics of this regulator as investigated from the original as-received setting.

2.3.7 Inverter, Process Water Pump and Flow Valve

These components were always operated together in bench testing and for the delivery of process water in the WES. A second pump, Micropump Corp. Model No. 02-70-316-986, which included a plastic poppet-type relief valve in place of the ball-type and a 316 SST gear housing in place of a plastic housing, was purchased for this program as a back-up to the original pump (Model No. 02-70-316-731). The performance characteristics of these two pumps are presented in Figure 11. Component evaluation also occurred during systems testing of the WES which identified a number of pump problems that were investigated. A summary of these problems with corrective actions is presented as follows:

1) Uncoupling of the magnetic drive between the motor and pump was resolved by drilling pressure balancing holes in the Teflon hub of the driven magnet.

NASA/MSC Water Electrolysis System - 13-Cell Module (1076527-910P1) (0.23 Ft^2/Cell)

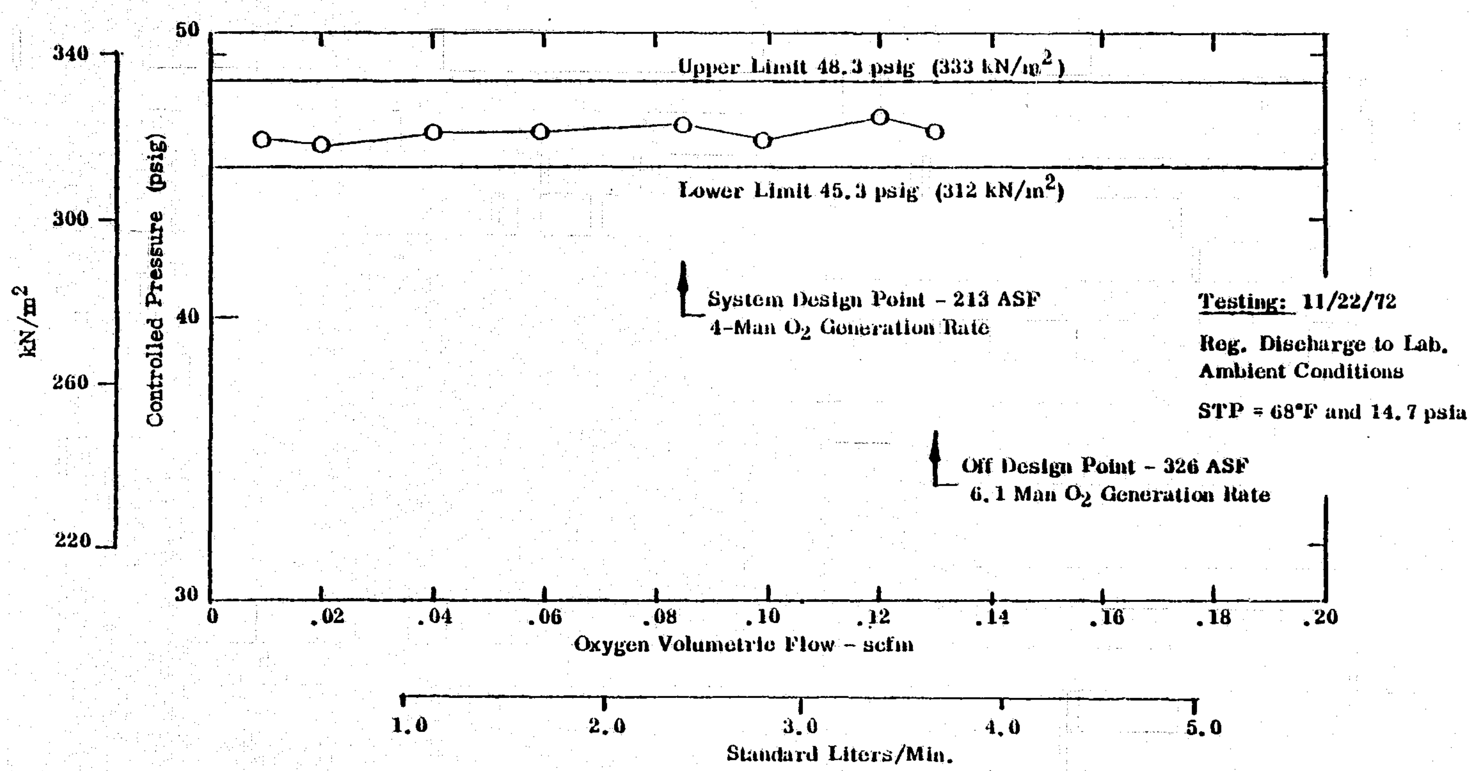


Figure 7. Oxygen Regulator (Absolute Type) Performance Controlled Upstream Pressure vs. Flow

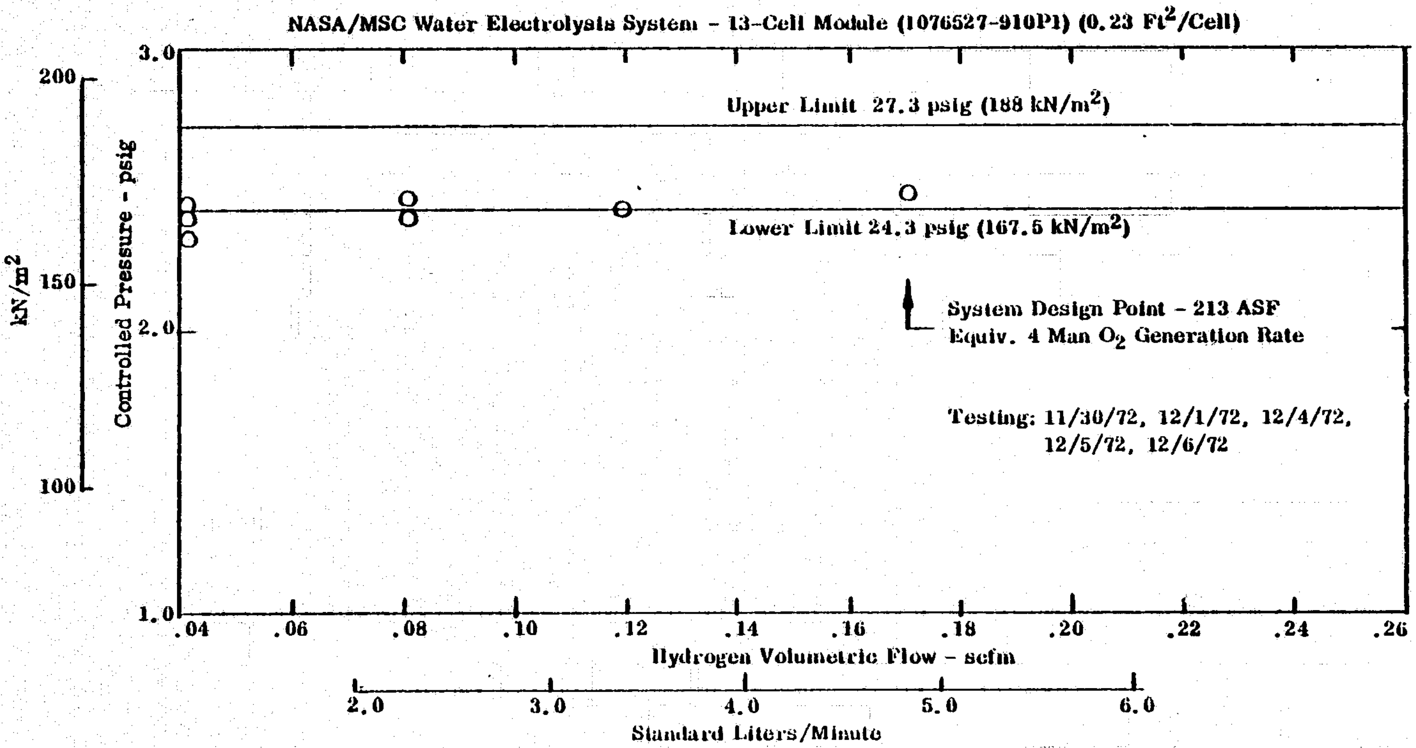


Figure 8. Hydrogen Regulator (Absolute Type) Performance - Controlled Upstream Pressure vs. Flow

NASA/MSC Water Electrolysis System - 13-Cell Module (1076527-910P1) (0.23 Ft^2/Cell)

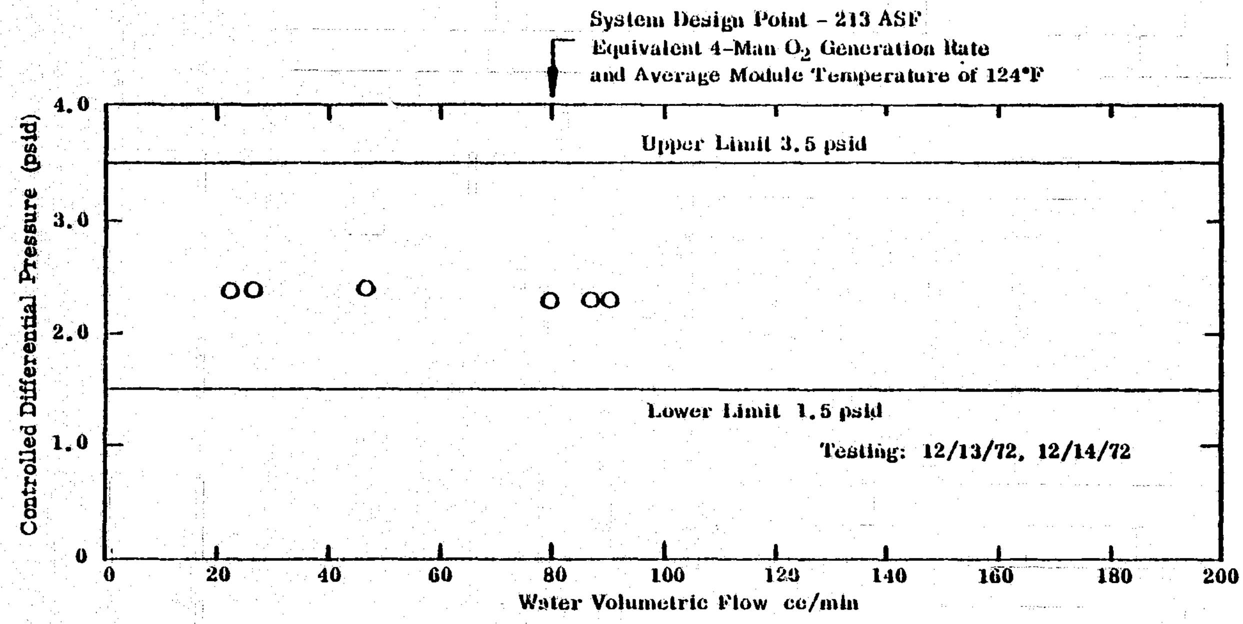


Figure 9. Water Differential Regulator Performance - Controlled Upstream Water Pressure Below a Nominal 24 psig H_2 Ref. vs. Flow

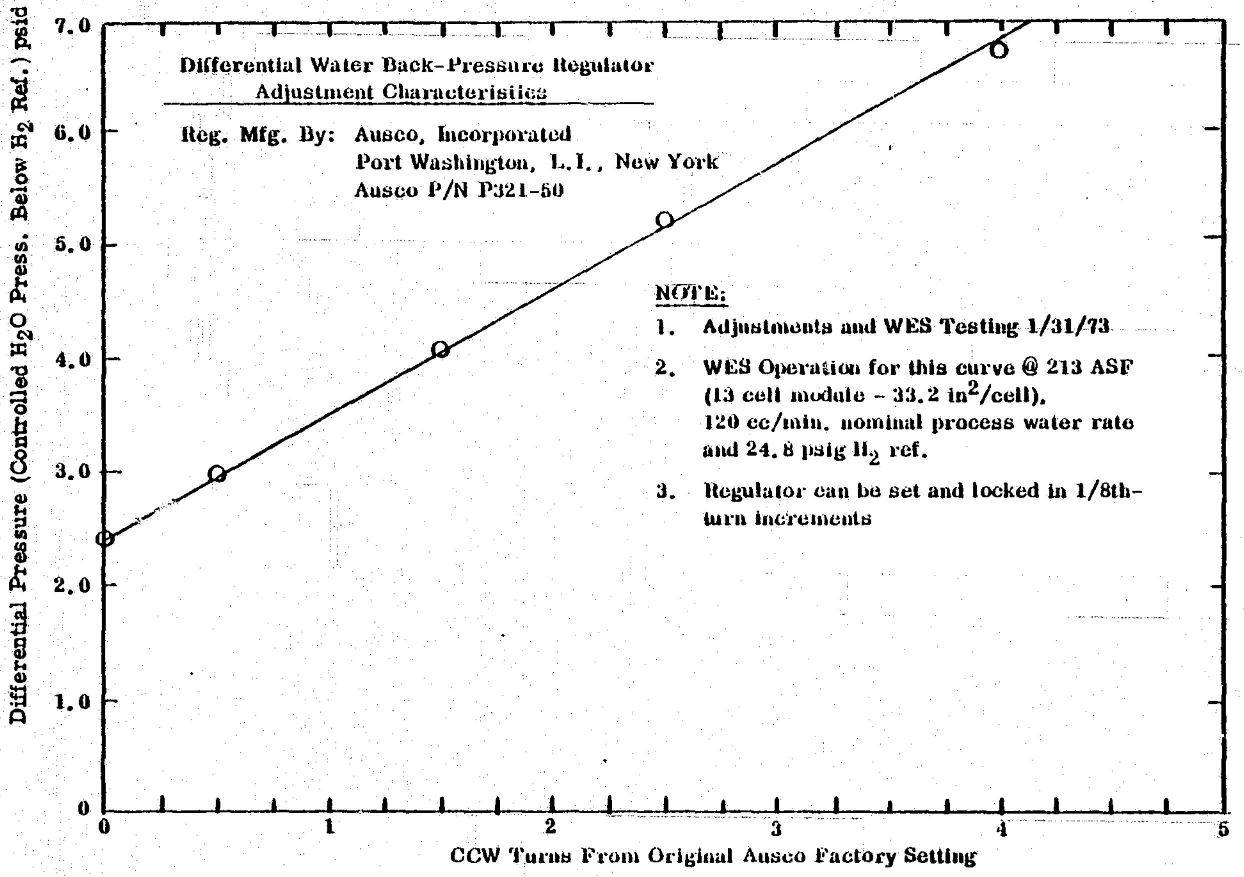


Figure 10. Steady State WES Operation

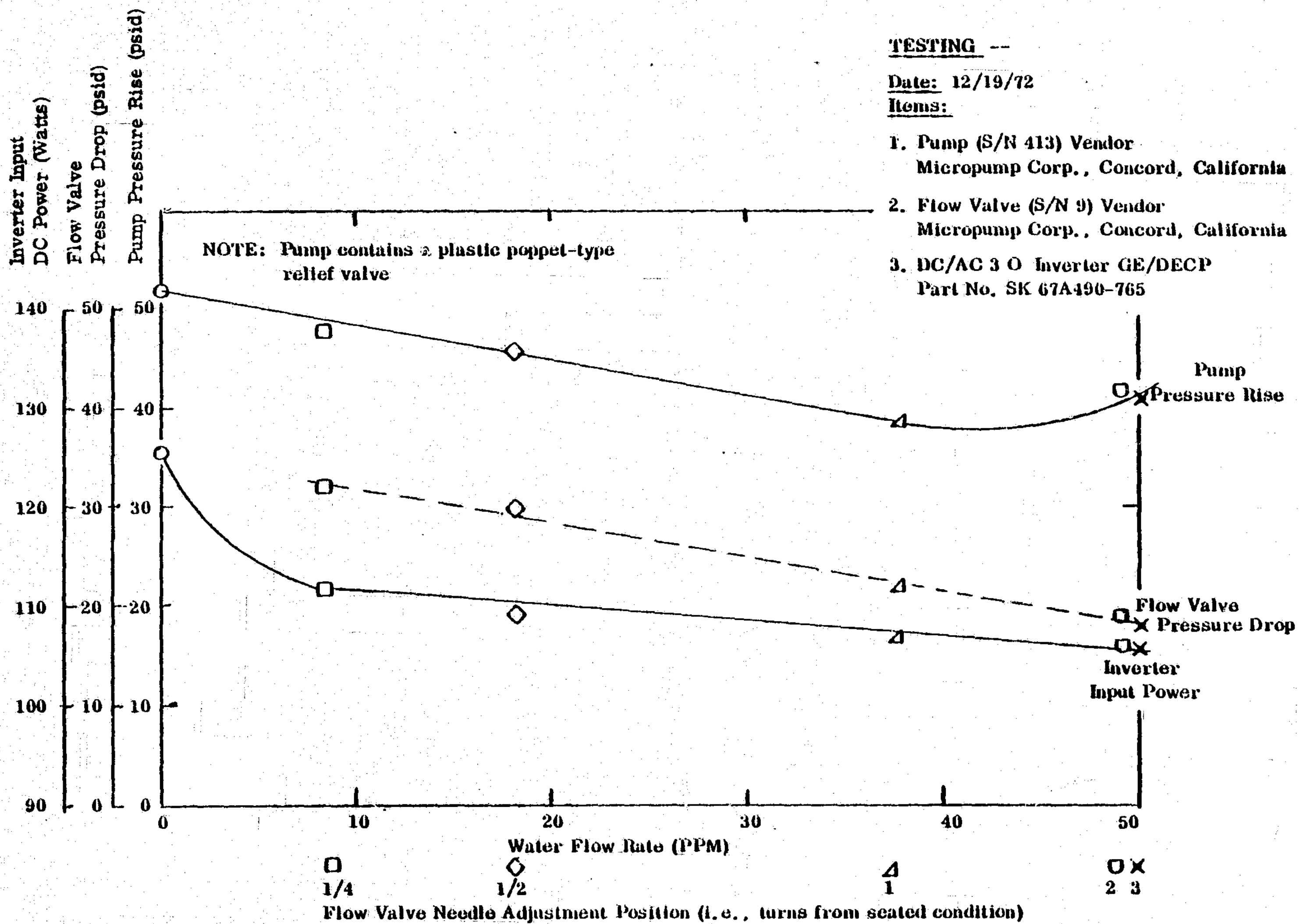


Figure 11. Inverter, Pump and Flow Valve Performance NASA/MSC Water Electrolysis System

2) Oscillations in pump discharge pressure had resulted in breakage in the internal relief valve spring. Tried a vendor recommendation of relief valve ball material change from Teflon to rubber, but spring breakage continued. A change from a ball-type to a poppet-type relief valve design configuration did reduce pressure fluctuations and resulted in no spring breakage.

3) Pump cavitation was caused by entrained gas in the pump suction resulting from dissolved gas (the water is saturated with hydrogen at the operating pressure of the phase separator) coming out of solution at reduced pressure and increased temperature. An attempt to reduce pump pressure fluctuations with an external by-pass to deliver excess flow (approximately 75% of input flow) externally to the pump rather than internally through the relief valve increased the cavitation problem. Cavitation was reduced by raising pump suction pressure, reducing pump suction water temperature and by increasing water pump throughput rate from 80 to 120 cc/min which forced out residual gas.

4) The audible noise emitted by the pump was reduced by a material change of the pump-gear housing from plastic to stainless steel.

5) External pump leakage was eliminated by a design change to gaskets in place of an O-ring seal.

2.3.8 Passive Phase Separator

Operating characteristics of the prototype, five-tube passive phase separator were evaluated during transient and steady-state operation of the four-man rated electrolysis system. A photograph, drawings and a complete description of this assembly is provided in Report NAS CR-112183. This is a passive phase separation device (a dynamic phase separator was developed and tested under Phase II of this program) which utilized five hydrophilic fritted glass tubes for water transport/ gas blockage and hydrophobic polypropylene membrane material for gas transport/ water blockage.

During system startup, a transient high pressure differential existed momentarily across the hydrophilic tube walls which resulted in some bubble-point breakthrough. This was resolved by replacing two tubes with bubble points of 47 kN/m^2 (6.8 psid) and 59 kN/m^2 (8.5 psid) with tubes of higher bubble points such that all five tubes were greater than 62 kN/m^2 (9.0 psid).

Flooding of the hydrophobic assembly also occurred which was attributed to loss of water permeability of the hydrophilic tubes due to pore contamination and the effects of higher water viscosity and insufficient hydrophilic ΔP margin when operating with a cold (278-283K) (40-50°F) two-phase mixture. Corrective action included (1) discontinuation of the tubes capable of reclamation which resulted in higher water flow permeability of the separator assembly, (2) increasing the hydrophilic Δ P by adjusting the water differential regulator from 16.5 kN/m^2 (2.4 psid) to 42.7 kN/m^2 (6.2 psid), (3) thoroughly draining and flushing the system to remove contamination (particulate matter and/or microbiological species), and (4) repacking of the deionizer and biolcgical filter resin beds with new beads after thermoplastically coating (with FEP) the inside of the housings to eliminate a possible corrosion contamination source. Test data showing the water flow permeability of the refurbished separator assembly is provided in Figure 12.

2.4 System Evaluation and Test Results

2.4.1 System Checkout Tests

WES system checkout was essentially performed during evaluation of components, as described in Section 2.3, such as the electrolysis module, power conditioner, static phase separator, water pump, pressure regulators, etc., under various conditions of module current or gas generation rate, process water rates, process water temperature, city water coolant temperature, etc.

As part of WES testing, electrolysis module operation prior to April 4, 1973, had been exclusively operated in the cathode water feed mode with the oxygen side pressure greater than the hydrogen (cathode) side pressure. This $O_2 > H_2$ pressure condition was selected to minimize water carryover to the oxygen side by hydrodynamic permeability through the SPE cell from the flooded hydrogen side when the electrolysis module was shutdown. In support of a parallel engineering design effort on the oxygen generation subsystem for the Space Station Prototype (SSP) it was necessary, for overall life support system considerations, to learn the effects of electrolysis module operation and deactivation with a $H_2 > O_2$ pressure condition. Laboratory experiments have verified that electrolysis cell performance (i.e., cell voltage) is independent of oxygen pressure, but that cell voltage increases about 30 millivolts for each tenfold increase in hydrogen absolute pressure in agreement with the theoretical Nernst equation. Because of protonic pumping (Ref. Appendix) of water from the anode to the cathode in the SPE cell under load, there would be no water transport to the oxygen side even with a $H_2 > O_2$ pressure differential as was evidenced by test. The effects of a deactivated electrolysis module were studied during the typical orbital "off" period of 39 minutes, and also for extended shutdown periods up to 90 hours. The effects of diffusion and the consumption of gases (H_2 and O_2) in the "fuel cell" mode were demonstrated after shutdown. Module total voltage decreased from an operating value of about 22 VDC to less than 2 VDC within 2 hours of shutdown for either $H_2 > O_2$ or $O_2 > H_2$ pressure condition. Because the trapped gas volume on the oxygen side of the electrolysis module is considerably smaller than that on the hydrogen side, which includes the heat exchangers, biological filter resin bed and phase separator, the oxygen pressure decays more rapidly than the hydrogen pressure after shutdown. The results of measuring oxygen side pressure decay are plotted in Figure 13.

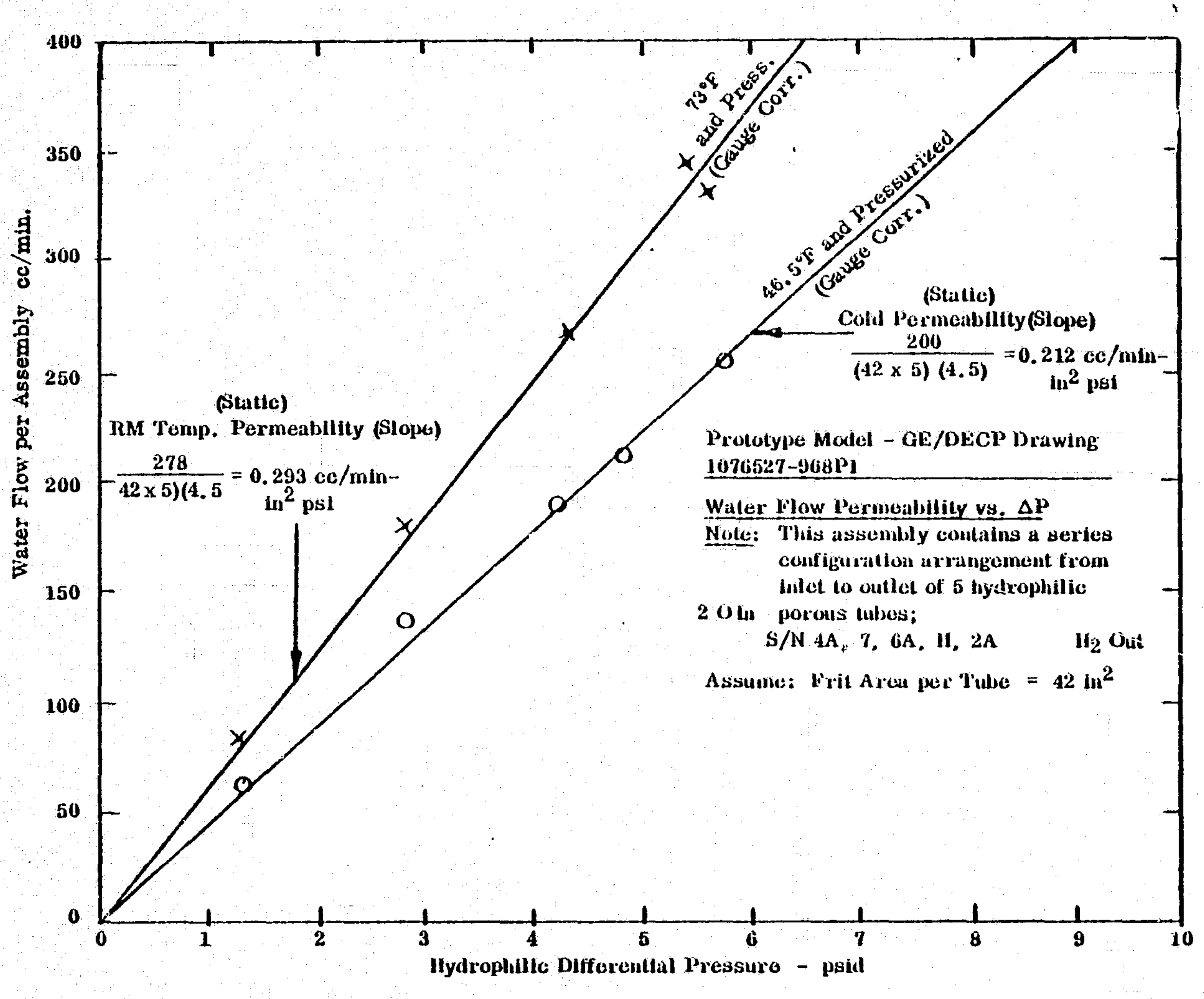
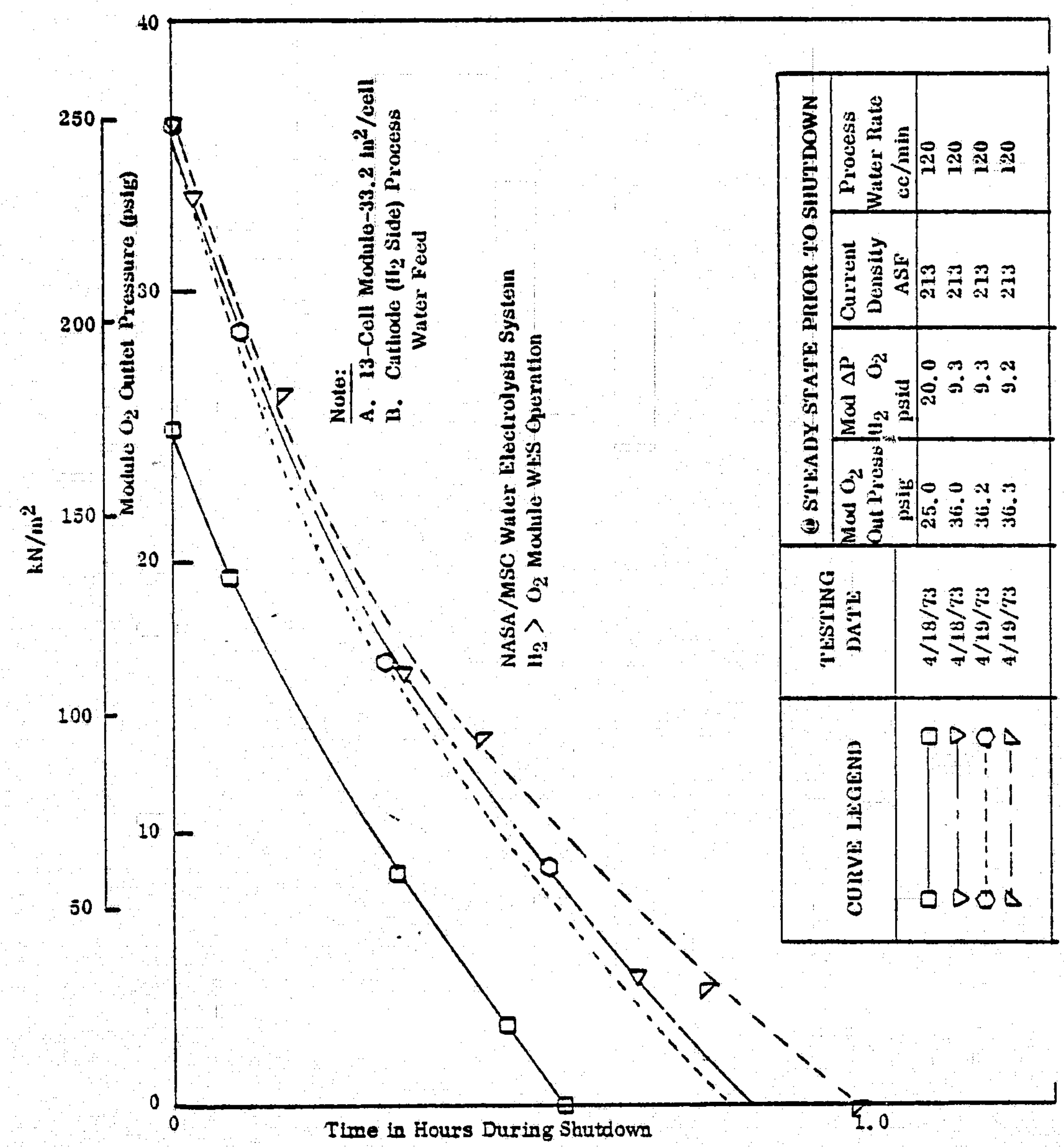


Figure 12. Two-Phase Separator Assembly



CURVE LEGEND	TESTING DATE	@ STEADY STATE PRIOR TO SHUTDOWN			
		Mod O_2 Out Press psig	Mod ΔP H_2 O_2 psid	Current Density ASF	Process Water Rate cc/min
□———□	4/18/73	25.0	20.0	213	120
▽—— - ——▽	4/18/73	36.0	9.3	213	120
○- - - - - -○	4/19/73	36.2	9.3	213	120
◁ —— —— ◁	4/19/73	36.3	9.2	213	120

Figure 13. Module O_2 Side Pressure Decay vs. Shutdown Time

Water accumulation on the oxygen side after shutdown depends upon initial $H_2 > O_2$ pressure conditions and the time interval for water transport. The water discharged from the oxygen side was measured on the subsequent start-up. In summary, the water discharged at start-up after a 39 minute orbital shutdown amounted to about 2 to 3 cc. After an extended 90 hour shutdown about 90 cc of water was discharged at start-up. This is greater than the total calculated volume of all 13 cells on the oxygen side of the electrolysis module, indicating eventual complete flooding with time.

For module operation with $O_2 > H_2$ pressure conditions, the discharge of water from the oxygen side on start-up is substantially reduced. No water was ever delivered out the oxygen side for any orbital cycle start-up (39 min. "off" period) and for any extended shutdown period up to 16 hours. The following quantities were measured after the shutdown periods cited: 10 cc in 24 hours, 15 cc in 72 hours, 63 cc in 12 days.

2.4.2 SSP Mapping Tests

Exploratory system testing was conducted in support of anticipated SSP operating requirements which represented conditions of overstress outside the design point of the four-man rated WES capability of 4.54 kg/day (10 lb/day) oxygen generation rate. Steady state electrolysis module voltage performance is shown in the following table at the four-man rated WES design point represented by a current of 49.1 amps (230 mA/cm^2), module controlled water inlet temperature of 311K (100°F) and two-phase (H_2/H_2O) outlet temperature of 327.7K (130°F) obtained from a process water flow of 120 cc/min, 326 kN/m^2 O_2 pressure, and 174 kN/m^2 hydrogen pressure.

Voltage, VDC

at 49.1 Amps, 230 mA/cm^2

	Cell No.													Total	Total
Date	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum.	Term.
1/29/73	1.715	1.707	1.708	1.713	1.709	1.685	1.705	1.692	1.712	1.697	1.704	1.692	1.695	22.17	22.14

Five simulated orbital cycles were demonstrated, each consisting of a 55 minute "on" power period and a 39 minute "off" period. Design point operating conditions were identical to those cited above except that module H_2/H_2O outlet temperature of 321.2K (128.5°F) was slightly lower reflecting a shorter warm-up period.

At essentially the same operating pressures, but at a minimum load condition of 5.7 amps (27 mA/cm2), module water inlet temperature of 282.6K (85°F) and H_2/H_2O outlet temperature of 303.7K (86.8°F) the following steady state voltages were measured.

Voltage, VDC

at 5.7 Amps, 27 mA/cm^2

Date	Cell No. 1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum.	Total Term.
2/2/73	1.562	1.563	1.562	1.564	1.562	1.559	1.564	1.559	1.563	1.561	1.565	1.558	1.562	20.31	20.31

With the O_2 and H_2 pressure regulators maintaining design operating pressures as before, and with the temperature regulator controlling water inlet temperature to the module at 311.5K (100.9°F), off design conditions were established for a load of 75 amps (350 mA/cm^2). A module two-phase outlet temperature of 343.2K (158F) was established at the same process water flow of 120 cc/min. Cell voltage performance was measured as follows.

Voltage, VDC

at 75 Amps, 350 mA/cm^2

Date	Cell No. 1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum.	Total Term.
2/2/73	1.788	1.772	1.770	1.780	1.776	1.730	1.763	1.748	1.785	1.760	1.765	1.747	1.750	22.99	22.94

Two simulated orbital cycles, each of nominal 55 minutes "on" and 39 minutes "off", at the off design condition of 75 amps were also successfully completed, as was the minimum load condition of 5.7 amps.

An evaluation of electrolysis module operation at higher temperature was made with the water inlet temperature manually controlled at a nominal 399K (150°F) and at design load of 49.1 amps. Steady state module H_2/H2O outlet temperature was measured at 348K (166.8°F) with the following improved corresponding voltage performance.

Voltage, VDC

at 49.1 Amps, 230 mA/cm^2

Date	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum.	Total Term.
2/6/73	1.645	1.638	1.637	1.638	1.636	1.619	1.636	1.622	1.638	1.628	1.637	1.626	1.636	21.27	21.23

2.4.3 Breadboard System Unattended Test

Following component and system checkout tests, the WES breadboard configuration and operating conditions were sufficiently defined to specify requirements for automatic control, fault monitoring detection with automatic safe shutdown allowing unattended operation. A Failure Mode and Effects Analysis of the WES was made to identify single point failures and determine where redundancy or fault detection of components was required in the system. A Fault Detection and Isolation Analysis (FDIA) identified the monitoring instrumentation and control requirements for automatic WES shutdown capability. Wherever possible, commercial "off-the-shelf" components were purchased to minimize the cost of the FDIA instrumentation.

Table II is a summary of those monitoring devices installed to detect out-of-limit component operating conditions which result in an automatic shutdown. An emergency controller shown in Figure 14 was designed and fabricated which monitored sensor signals and provided conditioning and logic for automatic emergency shutdown of the WES.

After complete installation and checkout of all fault detection and isolation instrumentation, breadboard system operation at design point conditions was initiated on 8/7/73. Typical electrolysis module voltage performance logged on the following at 49.1 amps (230 mA/cm^2) with temperatures of 310.8K (99.7°F) water-in, 328K (130.8°F) H_2/H_2O out, 121 cc/min process water rate, 165.4 kN/m^2 (24.7 psig) O_2 pressure and 265.5 kN/m^2 (38.5 psig) H_2 pressure was as shown in the following table.

Table II

FDIA Automatic Shutdown Summary

WES Component Functional Description	Monitoring Device	Fault Isolation Device	WES Result
Low Module Current (Pwr. Cond.)	Meter	Red light on	Automatic Shutdown
High Module Current (Pwr. Cond.)	Meter	Red light on	
High Two-Phase Module Outlet Temperature	Meter	Red light (3) on	
High H_2 Concentration in O_2 Outlet	Meter	Red light on	
Low City Water (Coolant) Flow	Flowrator	Red light on	
Loss 28 VDC Supply Voltage	Meter	Green light out	
Loss 115 VAC Supply Voltage	--	Green light out	
High Power Conditioner Input Current (Circuit Breaker)	SW Pos.	Red light on	
High Pump Outlet Pressure	Meter	Red light on	
High Separator Hydrophilic ΔP	Meter	Red light on	
High Separator Hydrophobic ΔP	Meter	Red light on	
High Module O_2 Outlet Pressure	Meter	Red light on	
High Separator H_2 Outlet Pressure	Meter	Red light on	
High Deionizer Effluent Conductivity	Meter	Red light on	

Note:

a) All circuitry communicates through electronic controller to be designed under Tasks 1.1.9 and 1.1.10.

b) All automatic shutdowns simultaneously remove power to the module and the pump.

c) Data recording is manual.

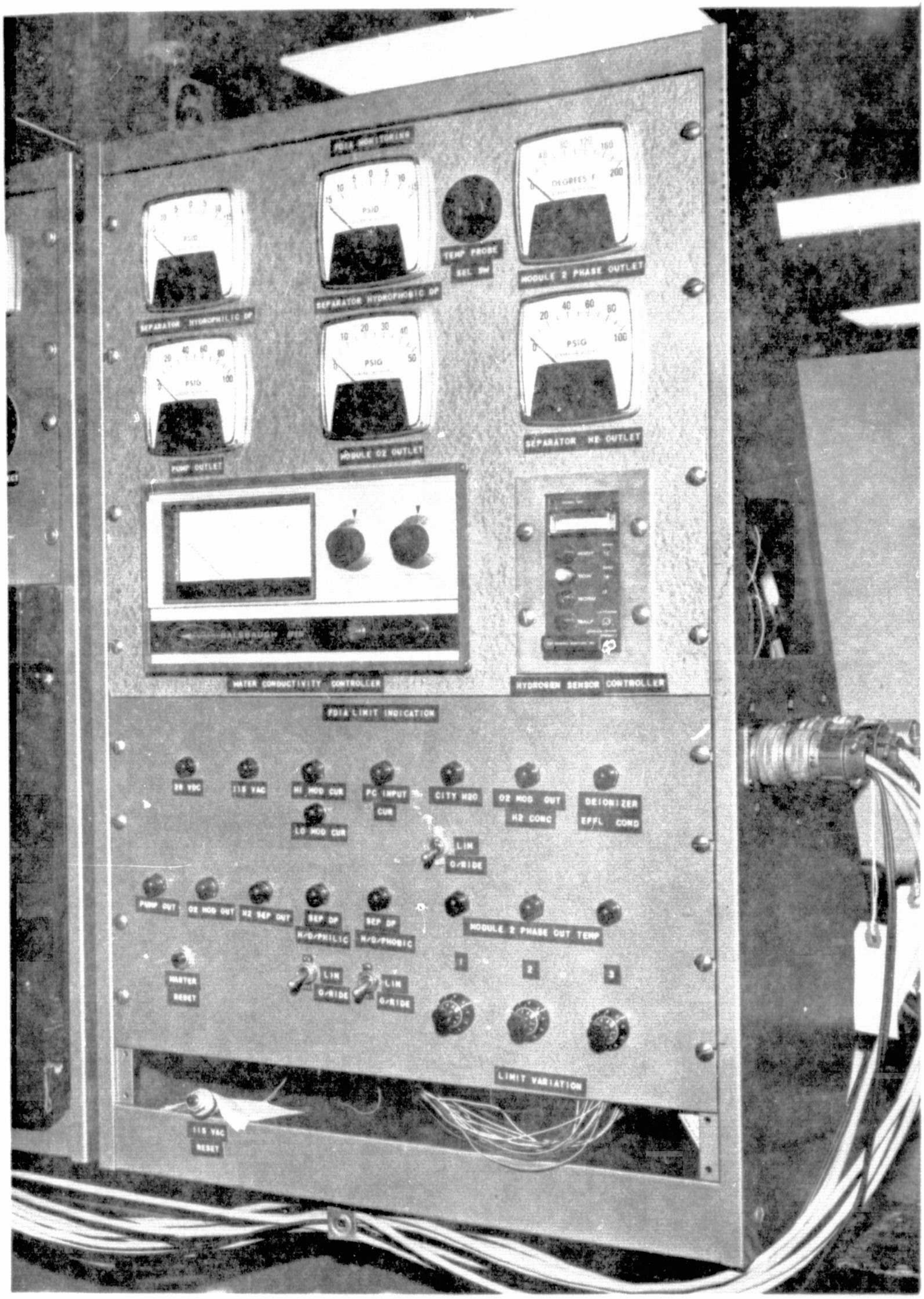


Figure 14. Instrumentation and Controller Unit

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Voltage, VDC

at 49.1 Amps, 230 mA/cm^2

Date	Cell No. 1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum.	Total Term.
8/8/73	1.724	1.719	1.717	1.714	1.716	1.696	1.717	1.702	1.721	1.705	1.716	1.700	1.705	22.22	22.26

System operation was conducted on an unattended daily basis with minimum data logging and/or operator surveillance. Four hours after morning start-up on 8/9/73 with 18.8 cumulative hours of unattended operation, the system was found automatically shutdown with the "Low Module Current" light illuminated on the FDIA panel. Subsequent investigation revealed that a 10 micron, in-line pump filter (Circle Seal type P/N 43115-2XTN) was severely plugged with anion resin material. A previous failure of the anion resin (degraded into a fine powder) in the biological filter had caused plugging of hydrophilic tubes of the passive phase separator. At that time (5/1/73) the biological filter was removed from the system which was drained and flushed to remove this residual degraded resin. It was hypothesized that the in-line filter was plugged with fine resin material not previously flushed from the system.

After cleaning the in-line filter, a differential pressure transducer was installed in the system to monitor the pressure drop across the filter during WES operation. Also, the water reservoir facility was drained and fresh distilled water added.

While remaining in the breadboard test setup, the 13-cell electrolysis module was checked for possible damage. A cross-membrane, nitrogen permeability test revealed no leakage as evidence damage. A 1000 Hz impedance check did show Cell No. 5 was 0.00142 ohm or 47.6% higher than the average of the other 12 cells. The high cell impedance was attributed to water starvation and subsequent drying prior to emergency shutdown caused by the plugged water filter during WES operation. Attempts to restore the performance of Cell No. 5 with low current density operation ($\sim$ 50 mA/cm^2) was not fruitful. Retesting of the module at design point conditions previously cited, revealed the following voltage performance at 49.1 amps (230 mA/cm^2).

Voltage, VDC

at 49.1 Amps, 230 mA/cm^2

Date	Cell No. 1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum.	Total Term.
8/14/73	1.714	1.709	1.705	1.716	1.978*	1.695	1.711	1.691	1.710	1.698	1.711	1.698	1.704	22.45	22.50

* Note that the voltage of Cell No. 5 is 0.273 volt higher at 230 mA/cm^2 than the average of the other twelve cells.

Loss of water supply to one or more cells of the electrolysis module results in drying of the SPE cell membrane and an increase in cell impedance. At a given load this results in a higher cell voltage. The power conditioner voltage/current control established an upper module voltage limit about 1.5 VDC below supply voltage of 28 VDC. Once this voltage limit was reached a further increase in cell or module impedance would reduce input current to the module. An automatic shutdown "low" limit of 5 amps was pre-set for WES operation. It was hypothesized that Cell No. 5 was more sensitive to the condition of low water supply, increased impedance and temperature at the sustained load of 5 amps sufficient to change the SPE water equilibrium such that normal water content impedance and performance could not be restored as in the other cells.

Corrective action was planned to include, for Phase II, the replacement of Cell No. 5 with a new cell when the 13-cell electrolysis module was disassembled, modified and reassembled for high pressure operation. Also, the "low current" shutdown for module protection would be changed to a "high voltage" shutdown condition in the event of water starvation or performance loss. The latter type of shutdown protection had been used successfully on laboratory cells and modules, but had been altered to the former for system incorporation to prevent inadvertent module shutdown at high initial current settings with a "cold" module.

SECTION 3.0 DEVELOPMENT OF AN ADVANCED WATER ELECTROLYSIS SYSTEM (WES) WITH COMBINATION WATER PUMP, PHASE SEPARATOR

3.1 Specification

A guideline specification for the design of a six-man rated, high pressure and temperature WES is outlined in Table III. The primary goals of the advanced WES were the development of an electrolysis system capable of operating at 2758 kN/m^2 (400 psig) and incorporating a combination water pump/dynamic phase separator, and with an electrolysis module capable of operating up to 366°K (200°F), and 350 ma/cm^2 (326 ASF).

3.2 System Description

The complete six-man rated, preprototype water electrolysis system is contained within two packages pictured in Figure 15. The control cabinet (53 x 53 x 66 cm) on the left contains operating controls, meter displays and fault detection and isolation lights. The fluid components and large electrical components of the system are contained in the package (91 x 91 x 61 cm) shown at the right. The electrical and fluid interface connections are located on the left face of this package and an electrical harness interconnects the two packages. A more complete description of these packages with component identification and location will be provided later. A list of the major components installed in the two packages of the system is provided in Table IV. These are identified by item number and shown in the system schematics in Figures 16 and 17. Fluid and electrical service interface connections are shown at the left side of Figure 16 with nominal maintained values in accordance with the guideline specification of Table III. A functional description of the system follows and the basic functional components described are identified by respective item numbers in parenthesis as referred to Table IV and Figures 16 and 17.

Power is delivered to the 13-cell electrolysis module (1) from a 28-VDC supply through a power conditioner (11) which acts as a current regulator for maintaining a selected gas production rate. The power conditioner which operates at about 92 percent efficiency, rejects waste heat to a cold plate through which externally supplied coolant is circulated.

Water is delivered to the hydrogen side of the electrolysis module at a controlled maximum temperature of 339 K (150° F) maintained by the temperature regulating valve (10). Some of this process water is dissociated into hydrogen and oxygen by electrolysis, whereas the excess amount is discharged with the hydrogen produced and carries off the module waste heat. Temperature rise of the process water through the module is proportional to the applied load which at 75 A produces a module outlet temperature of 366 K (200 F) at a water flow rate of 9 kg/hr (20 lb/hr). The two-phase mixture of hydrogen and water passes through the regenerative heat exchanger (12). to release heat to water delivered to the hot side of the temperature regulating valve. The two-phase mixture is further cooled to about room temperature

Table III

Guideline Specification for Breadboard Six-Man Rated Advanced Water Electrolysis System (WES)

(*Revised 11/30/73)

WES Capacity

15 lb/day (6.8 kg/day) oxygen (nominal six-man rate);
Equivalent 75 amp maximum oxygen generation;
Continuous or cyclic orbital duty of 55 minutes "on" power and 39 minutes "off" power.

WES Gas Purity

Oxygen Generation - by volume
99.7% min. O_2
0.1% max. H_2
Remainder - not defined.

Hydrogen Generation - by volume
99.3% min. H_2
0.2% max. O_2
Remainder - not defined.

NASA-Maintained Downstream Gas Pressures of WES

Oxygen Subsystem: 14.7 psia (101.4 kN/m^2) nominal
Hydrogen Subsystem: 14.7 psia (101.4 kN/m^2) nominal

Make-Up Water (Feed Water) Available to WES

Fluid: Industrial distilled water
Temperature 75± 5 F. (275 ± 2.8K)
*Pressure: 2 to 10 psig. (13.8 to 68.9 kN/m^2)
*Water Purity
Microorganism species: Not defined.
Total dissolved solids: 5 ppm max.

*Particulates:

Particulate Size Range	No. of Particles per 500 mi.
0 - 10 microns	Unlimited
10 - 25 microns	1000
25 - 50 microns	200
50 - 100 microns	10

Table III (Cont'd)

Guideline Specification for Breadboard Six-Man Rated

Advanced Water Electrolysis System (WES)

(*Revised 11/30/73)

Coolant Available to WES

Fluid: "City" water.
Water Purity (i.e. ionic and microorganism species): Not defined.
Temperature: 48 ± 7 F (289 ± 3.9 K).
Pressure: 75 psig (517 kN/m^2) max.
Flow: Up to 10 gpm (37.8 l/min).

Nitrogen Available to WES

Pressure: Selectable to 500 psig (3448 kN/m^2) maximum

Electrical Services Available to WES

28 ± 5% VDC.
115 ± 5% VAC, 60 Hz, single phase.

Component Design Stress Considerations

Proof Pressure: 1.5 times maximum operating pressure.
Burst Pressure: 2.5 times maximum operating pressure.

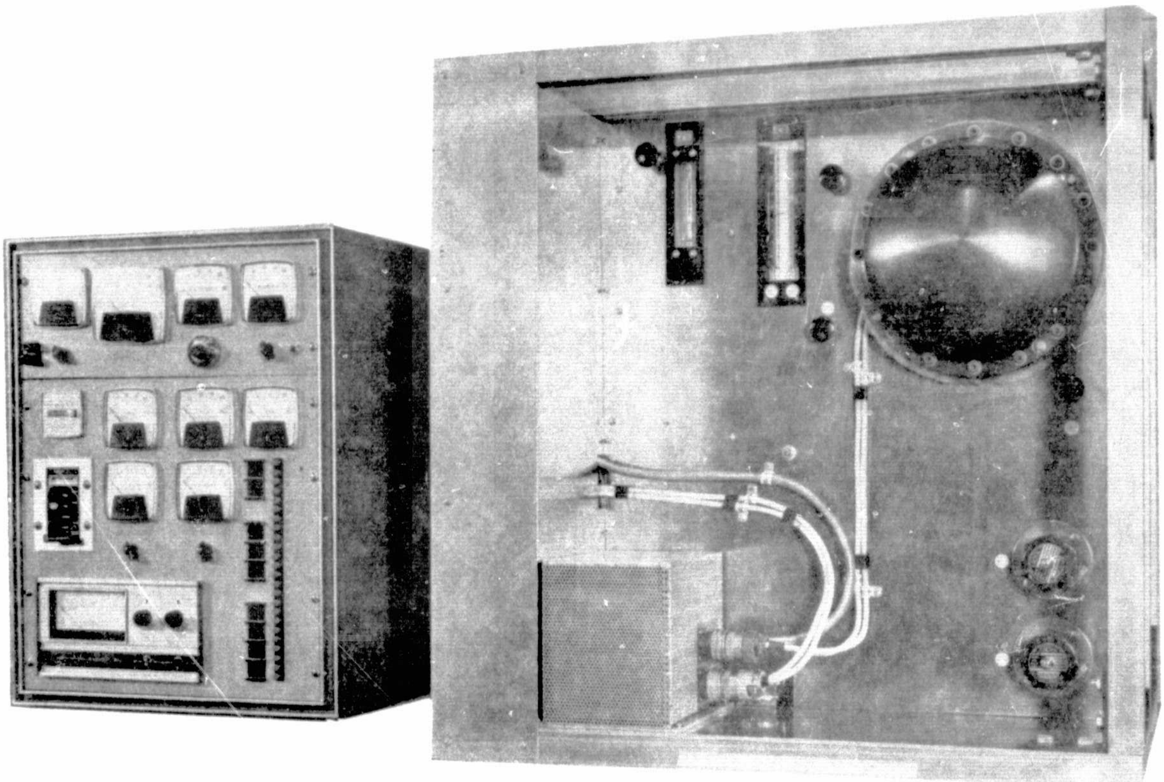


Figure 15. Six-Man Advanced Water Electrolysis System Control Cabinet and Fluid Package

Table IV

Major Components List

6-Man Advanced Preprototype Water Electrolysis System (WES)

Fluid Package

Item No.	Component Title	Installed Quantity
1	Water Electrolysis Module	1
2	Check Valve	6
3	Make-Up Water Filter	1
4	Make-Up Water Pump	1
5	Coolant Water Filter	1
6	Separator/Pump Electronic Controller	1
7	Deionizer Resin Bed	1
8	Two-Phase Dynamic Separator/Pump	1
9	Cooling Water Flowmeter	1
10	Temperature Regulating Valve	1
11	Power Conditioner/Cold Plate Assembly	1
12	Regenerative Heat Exchanger	1
13	Primary Heat Exchanger	1
14	Absolute O_2 Back-Press. Regulator	1
15	Absolute H_2 Back-Press. Regulator	1
16	Water Accumulator	1
17	Pressure Transducer, 0 - 500 psig (0 - 3448 kN/m^2)	5
18	Differential Press. Trans., ± 100 psid (± 689 kN/m^2)	1
19	Pressure Switch	1
20	Differential Back Press. Regulator	1
21	Module Outlet Temperature Sensor	1
22	Combustible Gas Detector Sensing Probe	1
23	Dual O_2 and H_2 Flowmeter	1
24	Conductivity Sensor Probe	1
25	Coolant Flow Switch	1
26	In-Line Relief Valve	4
27	Manual N_2 Pressure Regulator	2
28	Manual Shut-Off Valve	7
29 *	Differential Pressure Test Gage, 0 - 30 psid (0 - 207 kN/m^2)	2
30	Needle Valve	2
31	Flow Orifice	1
32	Catalytic O_2/H_2 Mixture Sensor	2
33	Circuit Breaker, 80 amp	1
34 *	Differential Pressure Test Gage, 0-200 "WC (0 - 50 kN/m^2)	1

* Non-deliverable instrumentation for check out only

Table IV (Cont'd)

Major Components List

6-Man Advanced Preprototype Water Electrolysis System (WES)

Control Cabinet

Item No.	Component Title	Installed Quantity
40	Module Terminal Voltage Meter, 0-50 VDC	1
41	Module Current Meter, 0 - 100 amp	1
42	Module Cell Voltage Meter	1
43	Module Cell Voltage Selector Switch, 13 Pos'n	1
44	Temperature Elec. Display Meter, 0 - 250°F	1
45	Temperature Sensor Selector Sw., 3 Pos'n	1
46	Combustible Gas Detector Controller/Meter	1
47	Conductivity Sensor Controller/Meter	1
48	Press. Trans. Elec. Display Meter, 0 - 500 psig	2
49	Accumulator Δ P Trans. Elec. Disp. Meter, ± 100 psid	1
50	Electric Display Meter, 0 - 5 VDC	2
51	Elec. Meter Selector Switch, 3 Pos'n	2
52	Elapsed Timer	1
53	Module Current Adjust, Potentiometer	1

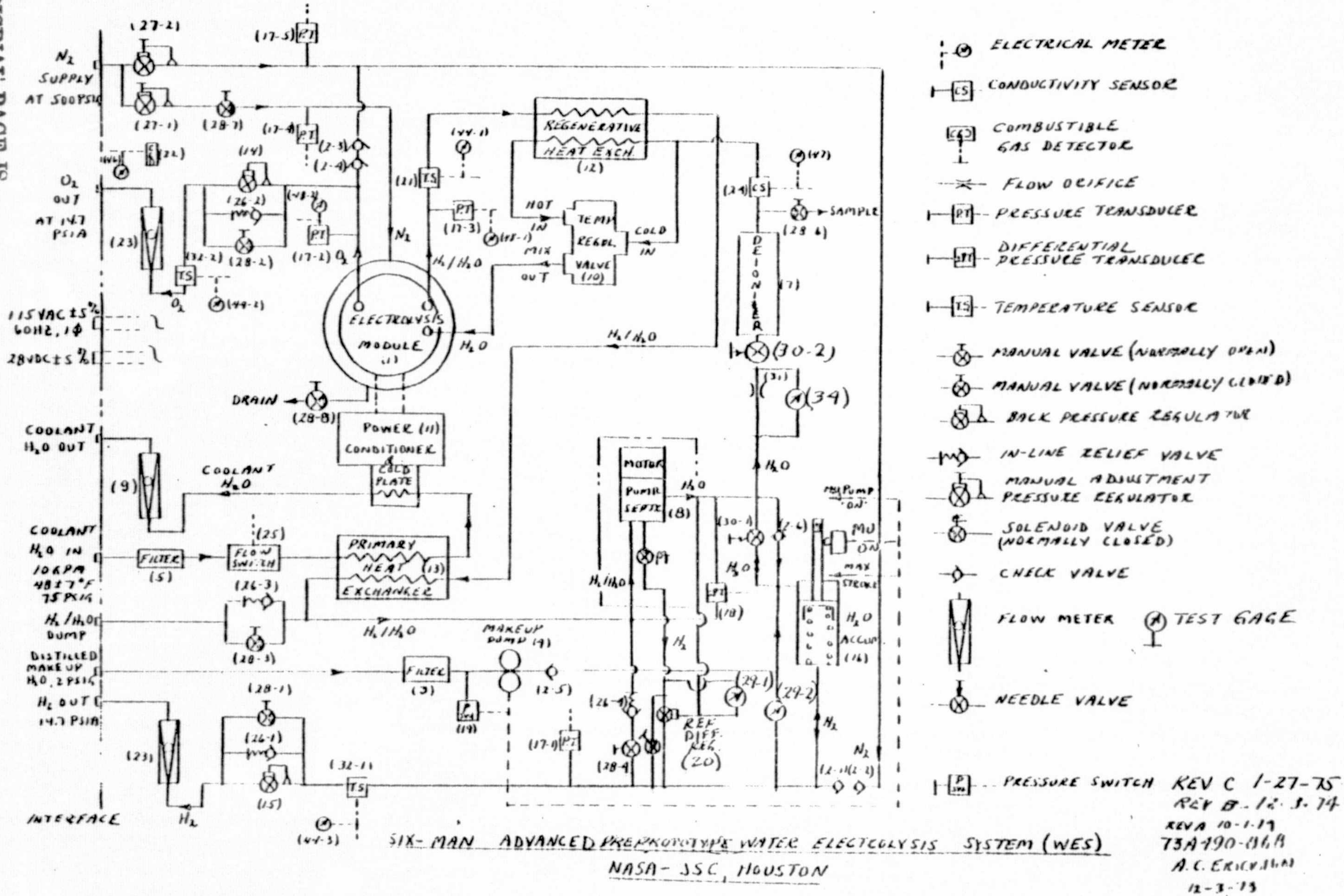
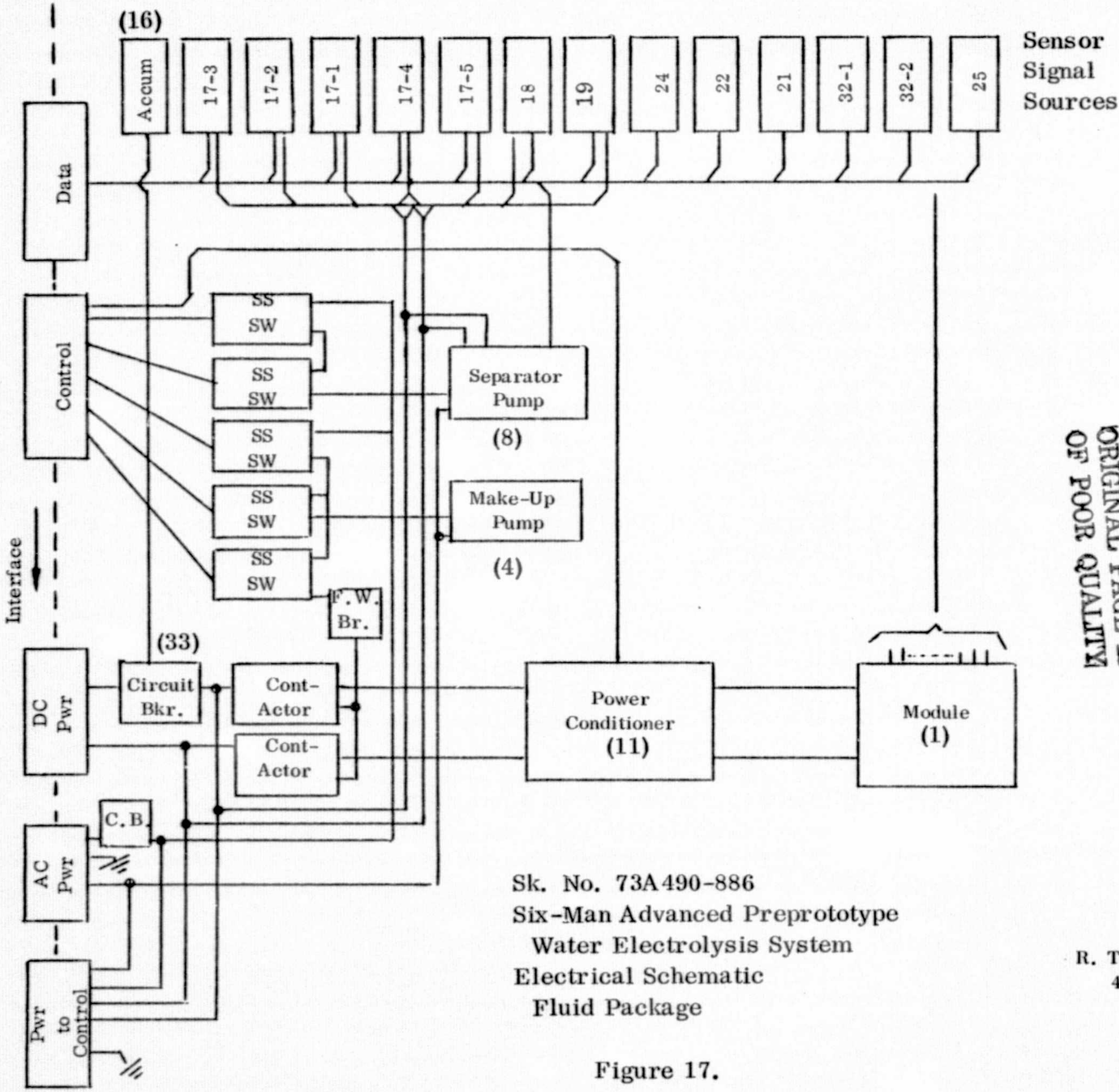

N2 SUPPLY AT 500PSIG
O2 OUT AT 14.7 PSIA
115VAC±5% 60HZ, 1Ø
28VDC±5%
COOLANT H2O OUT
COOLANT H2O IN
H2/H2O DUMP
DISTILLED MAKEUP H2O, 2 PSIG
H2 OUT 14.7 PSIA
INTERFACE
DRAIN
REGENERATIVE HEAT EXCH (12)
HOT IN
COLD IN
MIX OUT
TEMP REGUL VALVE (10)
ELECTROLYSIS MODULE (1)
POWER CONDITIONER (11)
COLD PLATE
COOLANT H2O
FILTER (5)
FLOW SWITCH
PRIMARY HEAT EXCHANGER (13)
MAKEUP PUMP (4)
FILTER (3)
SAMPLE
DEIONIZER (7)
MOTOR
PUMP SEPTR (8)
REF DIFF REG (20)
H2O ACCUM (16)
MAX STROKE
ELECTRICAL METER
CONDUCTIVITY SENSOR
COMBUSTIBLE GAS DETECTOR
FLOW ORIFICE
PRESSURE TRANSDUCER
DIFFERENTIAL PRESSURE TRANSDUCER
TEMPERATURE SENSOR
MANUAL VALVE (NORMALLY OPEN)
MANUAL VALVE (NORMALLY CLOSED)
BACK PRESSURE REGULATOR
IN-LINE RELIEF VALVE
MANUAL ADJUSTMENT PRESSURE REGULATOR
SOLENOID VALVE (NORMALLY CLOSED)
CHECK VALVE
FLOW METER
TEST GAGE
NEEDLE VALVE
PRESSURE SWITCH
REV C 1-27-75
REV B 12-3-74
REV A 10-1-74
73A190-11GB
A.C. ERICKSON
12-3-73
SIX-MAN ADVANCED PREPROTOTYPE WATER ELECTROLYSIS SYSTEM (WES)
NASA-JSC, HOUSTON

Figure 16.



Sk. No. 73A490-886
Six-Man Advanced Preprototype
Water Electrolysis System
Electrical Schematic
Fluid Package

R. Torkildsen
4/4/74

Figure 17.

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in the primary heat exchanger (13) where heat is rejected to the externally supplied coolant.

The H_2/H_2O mixture is delivered to the dynamic phase separator-pump (8) which provides separation of the gas and water. This device was developed by the Fluid Dynamics Corp., Chester, California, to provide positive separation of hydrogen and water in a zero gravity environment as well as pumping capability for the process water circuit. It is basically a centrifugal pump operating with a gas core of a diameter controlled by the operation of an internal pickup or sensor causing venting of hydrogen through an integral solenoid valve.

An ion exchange column, or deionizer (17), is located between the phase separator-pump and the electrolysis module to eliminate any system generated contaminants within the circulating process water loop and impurities from the makeup water feed. Hydrogen vented from the phase separator-pump through the differential pressure regulator (20) is further regulated at an absolute pressure by the hydrogen back pressure regulator (15) and is discharged from the system. The latter pressure regulator contains a spring adjustment capable of manual settings between 790 and 2860 kN/sq m (115 to 415 psia). The oxygen back pressure regulator (14) receiving the gas supply directly from the electrolysis module is a similar device which controls oxygen absolute pressure at a level set about 345 kN/sq m (50 psi) higher than hydrogen absolute pressure. This assures a positive pressure differential of oxygen greater than the two-phase mixture of hydrogen and water in the module such that no water is hydraulically transported to the oxygen side and eliminates entrained water in the oxygen discharged from the system.

A feed water makeup pump (4) and water accumulator (16) are also provided in the system. The latter contains a spring-loaded piston and rod-actuated position switch. As water is consumed by electrolysis, the piston travels to a position actuating the switch subsequently starting the makeup pump which is energized for two minutes adding water to the system from the supply at ambient or cabin pressure. The water accumulator also accommodates changes in the quantity of water contained in the process water loop due to system startup and load transients associated particularly with cyclic load operation which will be further discussed under "System Development and Test Results."

The nitrogen supply at 3550 kN/m^2 (515 psia) is utilized to pressurize the electrolysis module pressure vessel or domed enclosure subsequently discussed, and to maintain a regulated system base pressure under regulated hydrogen pressure. The oxygen and hydrogen sides of the system are initially pressurized with nitrogen to a base pressure of 234 kN/m^2 (340 psia) with a hand loading pressure regulator (27 - 2) through dual check valves (2-1, 2-2, 2-3, and 2-4). During automatic start up oxygen and hydrogen are generated and internal pressures built up until the O_2 and H_2 back pressure regulators discharge gas at their pre-set regulated settings. When the system is electrically deactivated at elevated pressure the nitrogen base pressure serves as a "floor" to which internal pressures gradually decay and maintains a safe condition in the event of an automatic shutdown. The nitrogen also serves as an inert gas for purging the system during depressurization.

In addition to the aforementioned basic functional components, the schematic in Figure 16 also shows relief valves for overpressure protection and manual valves for venting, bypass, sampling, etc. Sensors for measurement of voltage, current, pressure, temperature, water conductivity, etc. provide output to display meters on the control panel as well as to the emergency controller with preset fault detection limits which activates an automatic safe system shutdown.

The packaged system was designed for automatic operation at any preset pressure level from 790 to 2860 kN/m^2 (115 to 415 psia). Operating controls include 0 to 75 amp load adjustment, mode selection switches for continuous, cyclic (simulated near-earth orbital conditions) or standby operation as well as override switches for independent makeup pump, phase separator-pump or power conditioner (including electrolysis module) operation. Control by manual valves permits operation at low pressures close to atmospheric pressure as well as allows "bootstrap" operation by self pressurization of both O_2 and H_2 sides under load to maximum operation pressure.

A frontal view of the control cabinet is shown in Figure 18. The rectangular meters display module current (with potentiometer for load adjustment) and terminal voltage, individual cell voltage with selector switch, module two-phase outlet temperature, O_2 in H_2 and H_2 in O_2, temperatures sensing gas mixtures, accumulated hours and the following pressures: H_2 and O_2 regulated back pressures, accumulator piston Δp, two-phase (module), N_2 dome, N_2 base, phase separator-pump Δp, and water flow orifice Δp. The nine rectangular push buttons in a vertical line respective from top to bottom provide the following operating functions: Mode selection for (1) Continuous or (2) Cyclic operation, (3) Automatic start up (4) Standby operation (5) Shutdown and the override switches for independently energizing the (6) Contactor (7) Power Conditioner (including electrolysis module) (8) Phase separator-pump and (9) Makeup pump. The 24 small round lights in a vertical line identify which one of 22 fault detection sensor limit conditions was activated during an automatic shutdown. The fault conditions and sensor limits are listed in detail in Table X. To the left center of the control cabinet in Figure 18 is located a controller and meter for a combustible gas detector, Model 180, manufactured by General Monitors, Inc., Costa Mesa, California which detects external hydrogen leakage to ambient from piping and components in the fluid package. At the lower left corner of the control cabinet is the controller and meter, for a water conductivity sensor Model 915M-SC manufactured by Balsbaugh Laboratories, Inc., South Hingham, Massachusetts for monitoring the quality of process water.

Inside the control cabinet are located three circuit boards which contain the logic elements for automatically controlling sequential functions of start up,

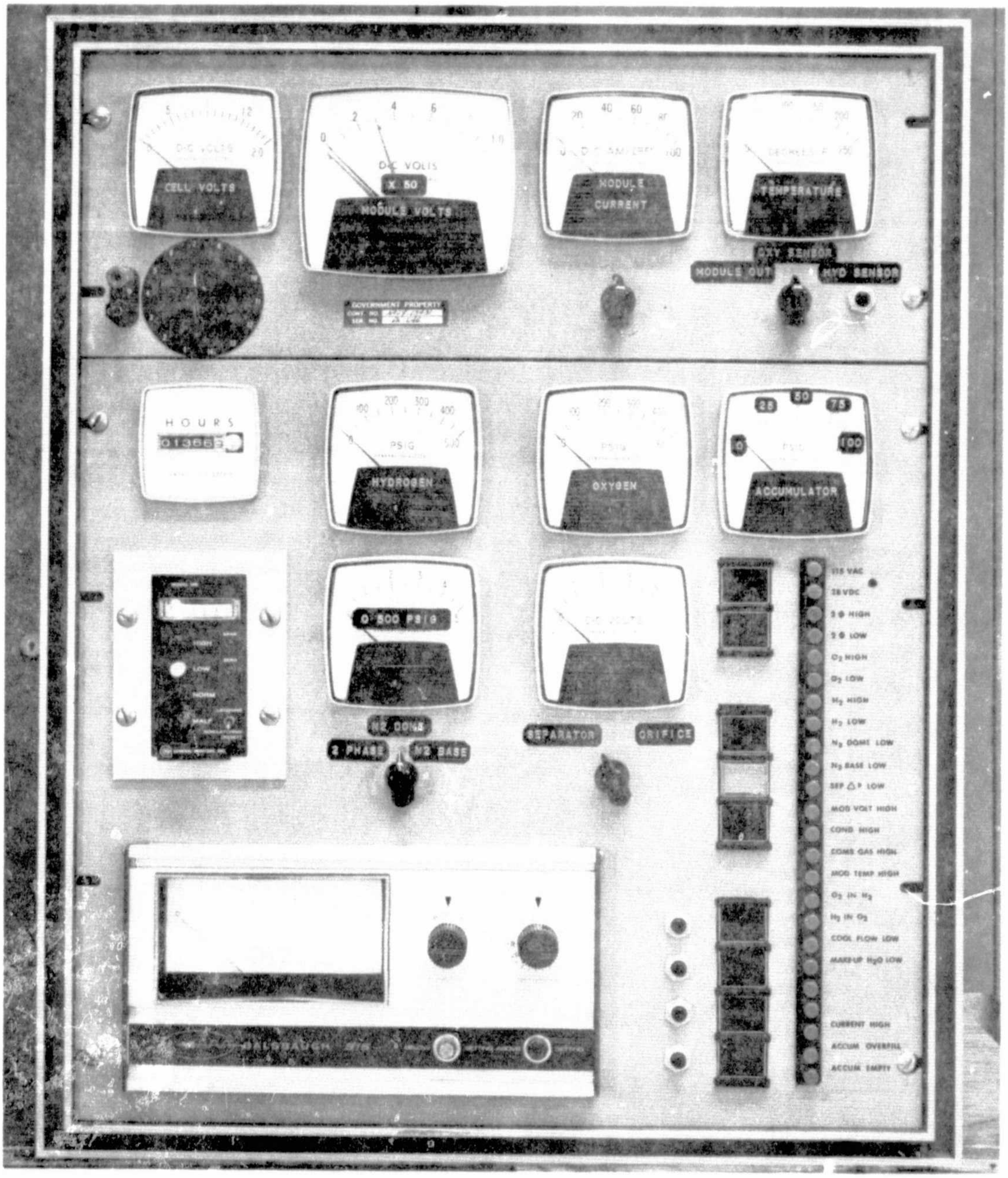


Figure 18. Water Electrolysis System Control Cabinet, Front

shutdown, continuous, cyclic and standby system operation as well as the requirements for an automatic safe emergency shutdown. Also contained within the cabinet are eight adjustable potentiometers for each of the FDIA pressure limit conditions which permits pre-setting these limits for any selected system operating pressure between 790 and 2860 kN/m^2 (115 to 415 psia). Also inside is located an emergency shutdown bypass switch which allows low pressure system checkout below the established high pressure regulator and potentiometer limit settings.

A frontal view of the fluid package is provided in Figure 19. Locations of the major components are shown and denoted by item numbers identified in Table IV and Figure 16. The electrolysis module is shown with its thermal insulation removed.

A photograph of the rear view of the fluid package is given in Figure 20. The locations of many of the basic components identified in Table IV and Figure 16 are shown. Thermal insulation applied to those components operating at elevated temperature such as the temperature regulating valve, module outlet temperature sensor and associated lines has been removed. The primary and regenerative heat exchangers shown consist of off-the-shelf concentric tube dual heat transfer coils, P/N 3101-6, 4-8-6X, manufactured by Parker Hannifin, Cleveland, Ohio, which were foamed-in-place into insulating cylinders of polyurethane foam covered with aluminum foil.

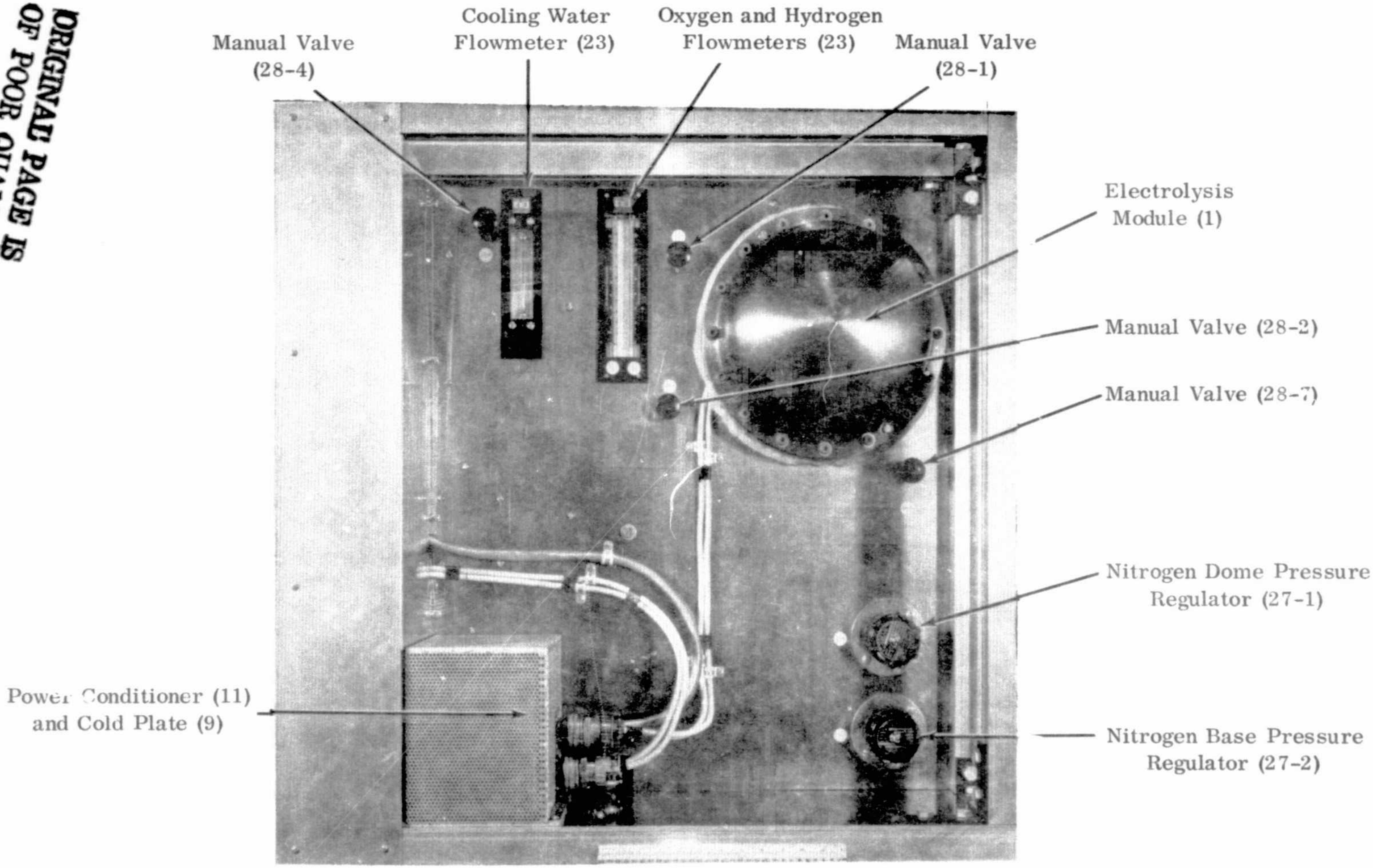
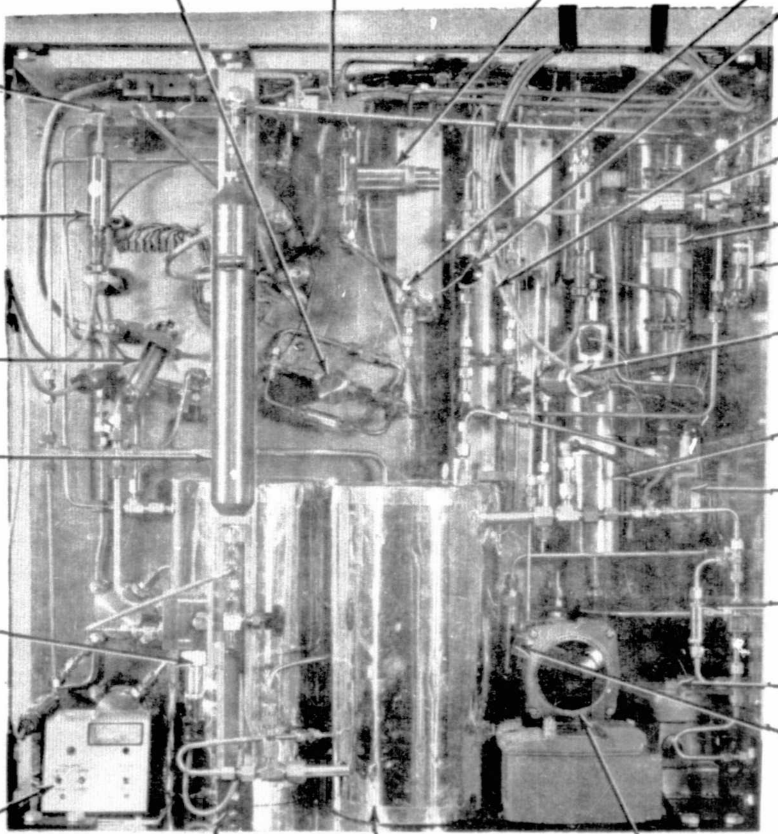


Figure 19. Water Electrolysis System Fluid Package, Front View



igure 20. Water Electrolysis System Fluid Package, Rear View

3.3 Component Development

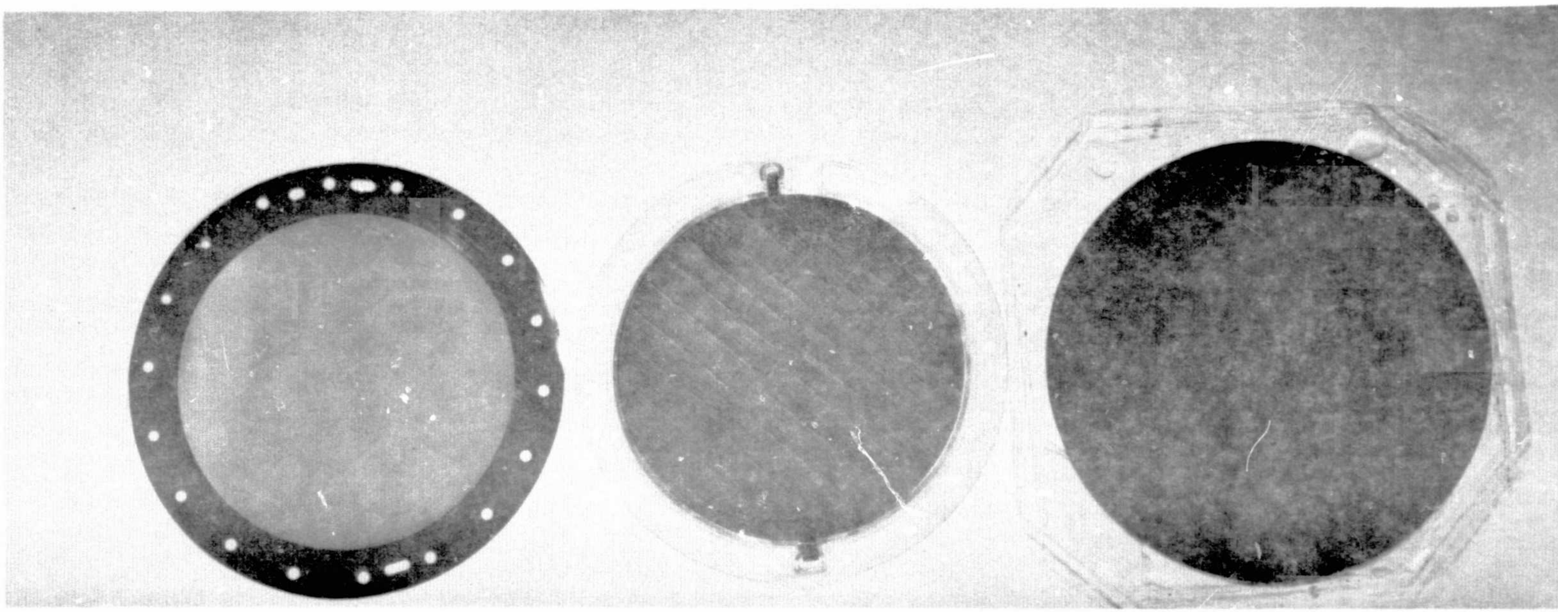
Available components from the low pressure, breadboard WES developed under Phase I were utilized wherever possible in the high pressure, advanced, preprototype WES. Also, standard commercial materials and components were selected where applicable to avoid unnecessary developmental costs and minimize procurement time. Specifications were prepared for definition and development of those components having operating requirements particular to the needs of the advanced WES system. A discussion of these components including specifications, drawings, and test results from bench checkout and/or system operation follows.

3.3.1 13-Cell, Advanced Electrolysis Module

A primary objective under Phase II of the program was to increase the capacity of the 13-cell, 4-man rated, low pressure module tested under Phase I to a six-man rated, high pressure, high temperature module design. Disassembly of the four-man rated module revealed that all cell parts exhibited no corrosion and were otherwise in a physically good condition. Twelve of the membrane and electrode assemblies were reusable whereas one required replacement because of high electrical impedance, attributed to water starvation during Phase I testing, to make up a 13-cell module. All of the cell screen assemblies and separator sheets were found reusable. A photograph of these cell components is shown in Figure 21. Two screen/gasket assemblies are required for each single cell to form the anode and cathode fluid compartments.

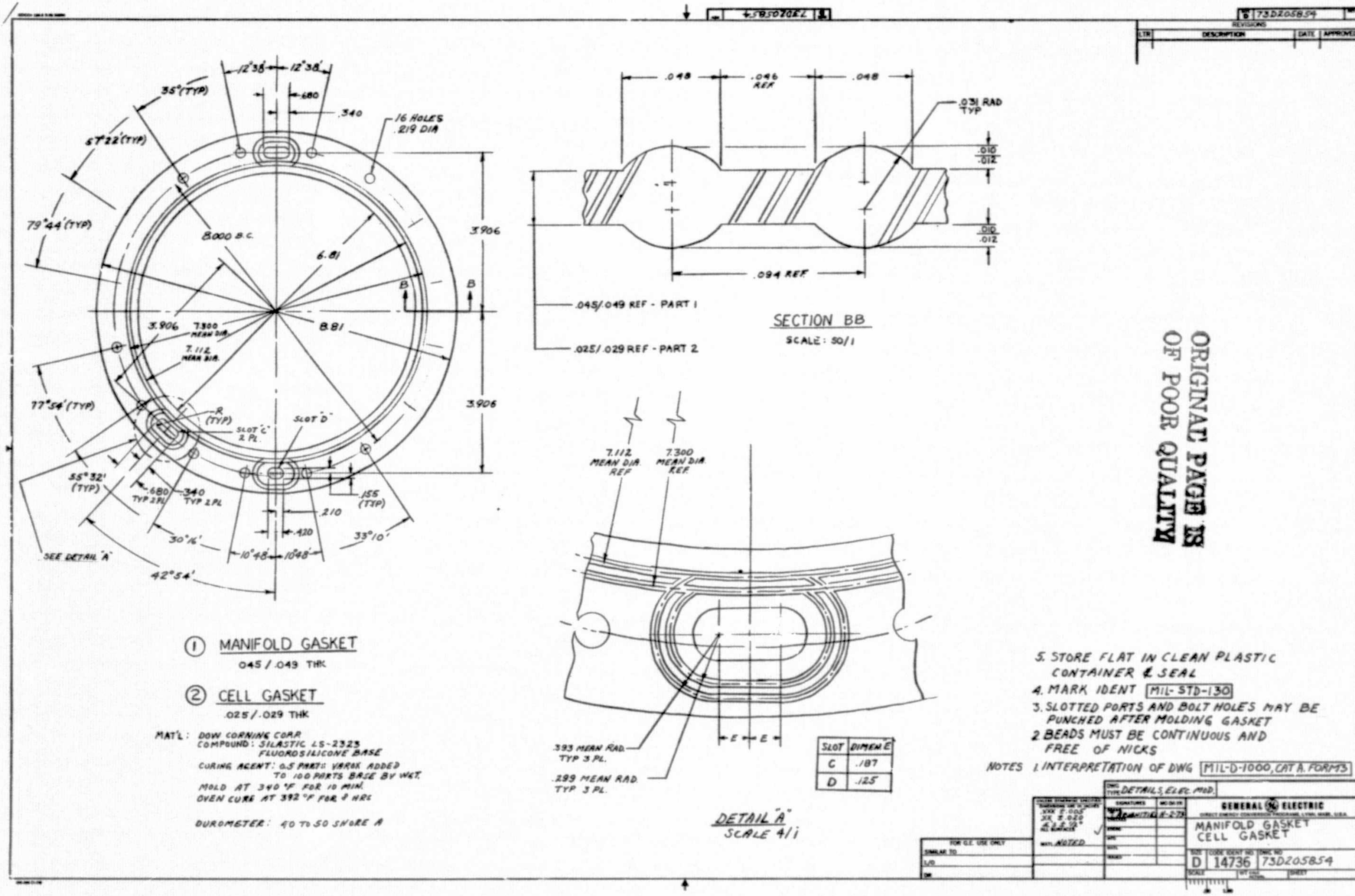
Laboratory compatibility tests were conducted with various gasket materials contacting the SPE membrane for 1400 hours at 361K (190°F) and 2758 kN/m^2 (400 psi). Fluorosilicone rubber showed excellent resistance to acid attack as did silicone rubber faced with a thin film of teflon (TFE) on the side adjacent to the SPE membrane. Both were considered alternate approaches for the high temperature design with the former incorporated into a molded gasket configuration with dual peripheral beads on each face shown in Drawing 73D205854, Figure 22. Tie bolt holes in all cell components were enlarged from a 10-32 to a 5/16 - 24 screw size to accommodate the higher pressure capability. The basic cell design was otherwise unchanged to increase module operating performance from a Four-man to a Six-man capability (current density from 213 to 350 MA/cm^2) resulting from attaining lower cell voltage and improved performance at higher operating temperature. Basic design parameters of the SPE electrolysis cell are listed in Table V.

The design approach to a high pressure module configuration was to enclose the compressed stack of 13 cells into a pressure vessel. A photograph of the module is shown in Figure 23.



Cell Compartment Separator Sheet | Cell Compartment Screen/Gasket Assy. | SPE Electrolyte with Electrodes

Figure 21. SPE Electrolysis Cell Components


73D205854
REVISIONS
LTR
DESCRIPTION
DATE
APPROVED
12°38'
12°38'
.680
.340
35°(TYP)
16 HOLES
.219 DIA
67°22'(TYP)
79°44'(TYP)
8.000 B.C.
6.81
3.906
B
B
3.906
7.300
MEAN DIA.
8.81
7.112
MEAN DIA.
77°54'(TYP)
R
(TYP)
SLOT "C"
2 PL.
SLOT "D"
3.906
35°32'
(TYP)
.680
TYP 2 PL
.340
TYP 2 PL
.155
(TYP)
.210
.420
30°16'
33°10'
10°48'
10°48'
SEE DETAIL "A"
42°54'
.048
.046
REF
.048
.031 RAD
TYP
.010
.012
.010
.012
.094 REF
.045/.049 REF - PART 1
.025/.029 REF - PART 2
SECTION BB
SCALE: 50/1
7.112
MEAN DIA.
REF
7.300
MEAN DIA.
REF.
E
E
.393 MEAN RAD.
TYP 3 PL.
.299 MEAN RAD.
TYP 3 PL.
SLOT
DIMEN E
C
.187
D
.125
DETAIL "A"
SCALE 4/1
(1) MANIFOLD GASKET
.045 / .049 THK
(2) CELL GASKET
.025 / .029 THK
MAT'L: DOW CORNING CORP.
COMPOUND: SILASTIC LS-2323
FLUOROSILICONE BASE
CURING AGENT: 0.5 PARTS VAROX ADDED
TO 100 PARTS BASE BY WGT.
MOLD AT 340 °F FOR 10 MIN.
OVEN CURE AT 392 °F FOR 8 HRS
DUROMETER: 40 TO 50 SHORE A
5. STORE FLAT IN CLEAN PLASTIC
CONTAINER & SEAL
4. MARK IDENT MIL-STD-130
3. SLOTTED PORTS AND BOLT HOLES MAY BE
PUNCHED AFTER MOLDING GASKET
2. BEADS MUST BE CONTINUOUS AND
FREE OF NICKS
NOTES 1. INTERPRETATION OF DWG MIL-D-1000, CAT A, FORM 3
DETAILS, ELEC. MOD.
GENERAL ELECTRIC
MANIFOLD GASKET
CELL GASKET
D
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73D205854
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Figure 22.

TABLE V

13-CELL ADVANCED WATER ELECTROLYSIS MODULE

SIGNIFICANT DESIGN DATA

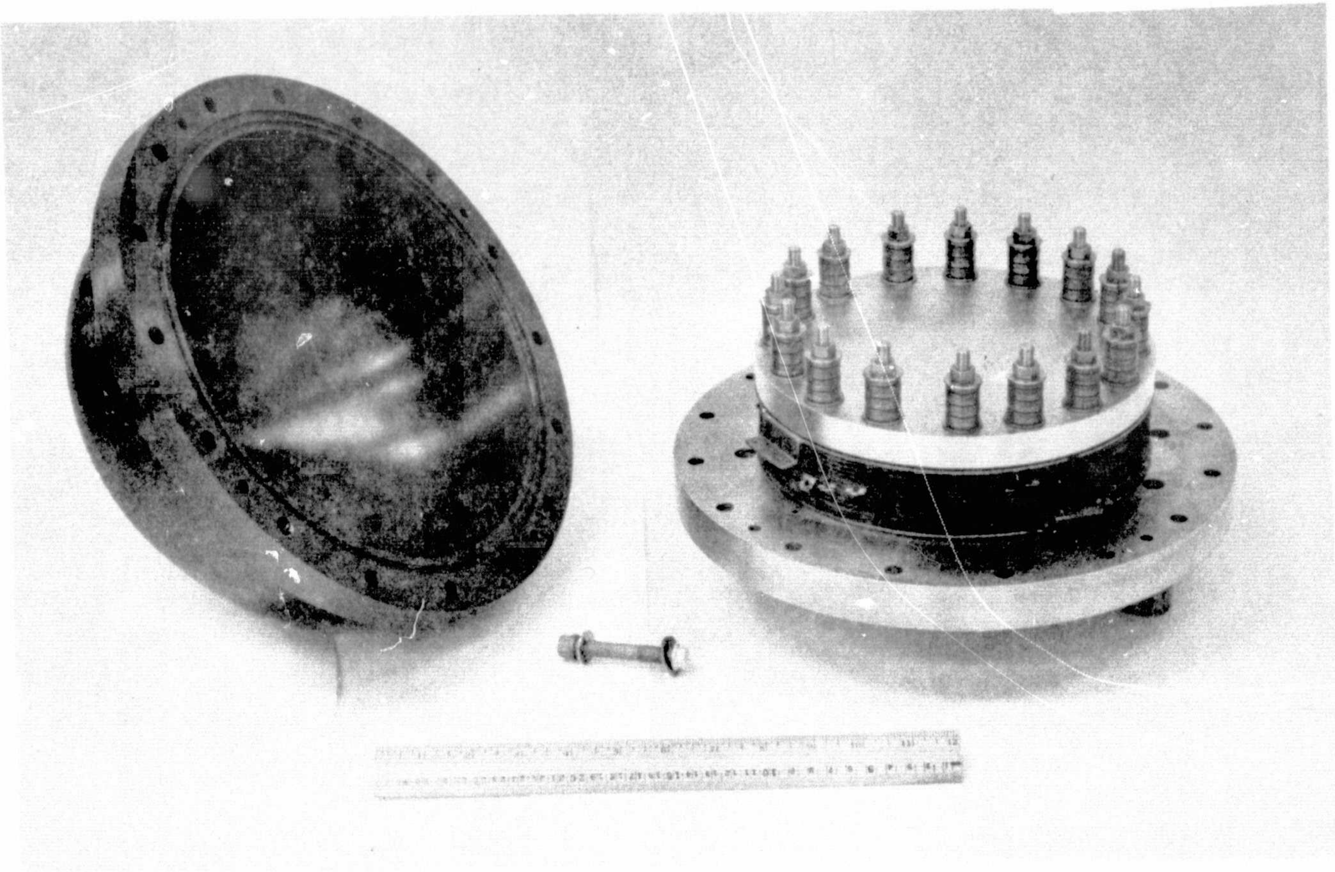
Cell Design Parameters	Design Point
Electrode Diameter	16.5 cm (6.5 in.)
Active Area	214 cm^2 (33.2 $in.^2$)
Ion Exchange Membrane	G.E. Spec: A50GN342
Anode (O_2 Side) Catalyst	E50, 12.5% Teflon
Cathode (H_2 Side) Catalyst	Pt Black, 12.5% Teflon
Cathode Catalyst Support	Expanded Gold Screen .076 mm (.003 in.) thick, 17.15 cm (6.75 in.) dia.
H_2 and O_2 Gas Gap Screening	5 Layers Expanded Screen 5 Nb 7, 3/0, Platinized and Welded Pressed to .56 mm (.022 in.) Thick
H_2/O_2 Separator Sheet	.076 mm (.003 in.) Thick Niobium Platinized
Cell Gasket Seal	.69 mm (.025 in.) Thick TFE Faced or Fluorosilicone Rubber Unfilled
H_2 Cell Water Feed Port	.56 mm (.022") Thick Screen Gap x 6.4 mm (.25") Wide
H_2 and O_2 Cell Outlet Gas Ports	.56 mm (.022") Thick Screen Gap x 9.6 mm (.38") Wide
Manifold Gasket Seal	1.19 mm (.047") Thick Silicone or Fluorosilicone Rubber Unfilled
Pressure Pad	1.40 mm (.055") Thick, 16.5 cm (6.5 in.) Diameter Perforated G.E. Silicone Rubber SE-4404
Operating Mode	Cathode Water Feed
Maximum Current	75 amp
Maximum Current Density	350 mA/cm^2
Maximum Outlet Temperature	367K (200°F)
Cell Voltage (at Maximum Current, Nominal Pressure and Temperature)	1.72 VDC
Nominal Cell Spacing (Including one pressure pad)	2.8 mm (0.110 in.)

TABLE V (Cont'd)

13-CELL ADVANCED WATER ELECTROLYSIS MODULE

SIGNIFICANT DESIGN DATA

Module Design Parameters	Design Point
Oxygen Generation Rate	6.8 kg/day (15 lb O_2/day)
Min. Supply Voltage (Out of Power Conditioner)	23.5 VDC
Number of Modules in System	One
Number of Cells per Module	13
Maximum Cell Pressure	2861 kN/m^2 (415 psia)
Nominal/Maximum Cell or Gasket Pressure Differential	345/690 kN/m^2 (50/100 psid)
Maximum Dome Pressure	3206 kN/m^2 (465 psia)
Proof Pressure	4654 kN/m^2 (675 psig)
Top End Plate	23.2 cm (9.125") Dia x 1.9 cm (.75") thick, 7075-T651 Alum. with .15 mm (.006") thick epoxy coating
Internal Studs	Sixteen, 5/16" - 24 Type 316 S.S.
Belleville Washer Assy.	7 nests of 3 in parallel per Stud, P/N B0750-040-S Assoc. Spring Co.
Bottom Enclosure Plate	33.02 cm (13.00") Dia x 26.8 cm (1.055") Thick Type 316 S.S.
Domed Enclosure Head.	33.02 Cm (13.00") Dia. x 152 cm (6.0") Deep 6061-T651 Alum., Anodized.
Flange Bolts	Sixteen, 3/8" - 24 per MS9559-28
Total Assembled Weight	W/O Insulation 72.5 lbs.



13-Cell Advanced Electrolysis Module
(With Pressure Dome Removed)

Figure 23.

The configuration consists of 13 cells with projecting terminal plates compressed with 16 tie bolts, spring-loaded with Belleville washers, between rigid end plates. A flanged elliptical dome is fastened to the larger bottom plate to enclose the stack assembly.

The photograph was taken before internal wiring was connected to the terminal plates and the cell voltage tabs. These tabs of .08 mm (.003") niobium were embossed with a diamond pattern to a thickness of (.16) mm (.006") and inserted between the separator sheet and manifold gasket into the pressure pad cavity of each cell. They provided a dual function of individual cell voltage measurement and gas breathing between the pressure vessel and pressure pad cavity thus preventing possible gasket blowout during rapid module depressurization. A layout of the module assembly is pictured in Figure 24. Module design parameters are listed in Table V.

The module pressure vessel is pressurized with nitrogen to approximately 345 kN/m^2 (50 psid) greater than cell internal operating pressures to eliminate gasket blowout from high pressures while providing an inert gas blanket in the event of a module gasket failure. Cell gasket thermal expansion at high operating temperatures is accommodated by the stack of Belleville washers on the tie rods which permit axial displacement of the top end plate while maintaining axial load.

The advanced module was assembled initially with FEP film/silicone rubber (GE Compound SE - 4404 unfilled) gaskets since delivery of the molded gaskets was later. With the domed enclosure head removed the 13-cell stack assembly was proof pressure tested at 690 kN/m^2 (100 psi) internal pressure and cross membrane gas diffusion at 345 kN/m^2 (50 psid) was measured within acceptable permeability limits.

The aluminum dome was satisfactorily proof pressure tested at 4827 kN/m^2 (700 psig) using a special stainless steel test plate and filling the dome with water prior to pressurization for safety. The electrolysis module was then completely assembled with the dome and leak checked. With the dome pressurized with nitrogen at 345 kN/m^2 (50 psig) leakage to the oxygen and hydrogen cell cavities at atmospheric pressure was measured respectively as zero and 13.2 standard cc/hour. Calculated dome-free volume from a pressure decay test was 4320 cc. Electric checkout for shorts and cell impedance measurements were found satisfactory.

Operational checkout of the electrolysis module coincided with initial low pressure checkout of the system on June 4, 1974. All cells performed satisfactorily. Module performance, at a nominal operating pressure of 690 kN/m^2 (100 psig), exhibited during warmup at varied load settings is shown in Figure 25 on June 13, 1974. Over a 429 hour endurance test period at a nominal system pressure of 690 kN/m^2 (100 psig) module performance was very stable.

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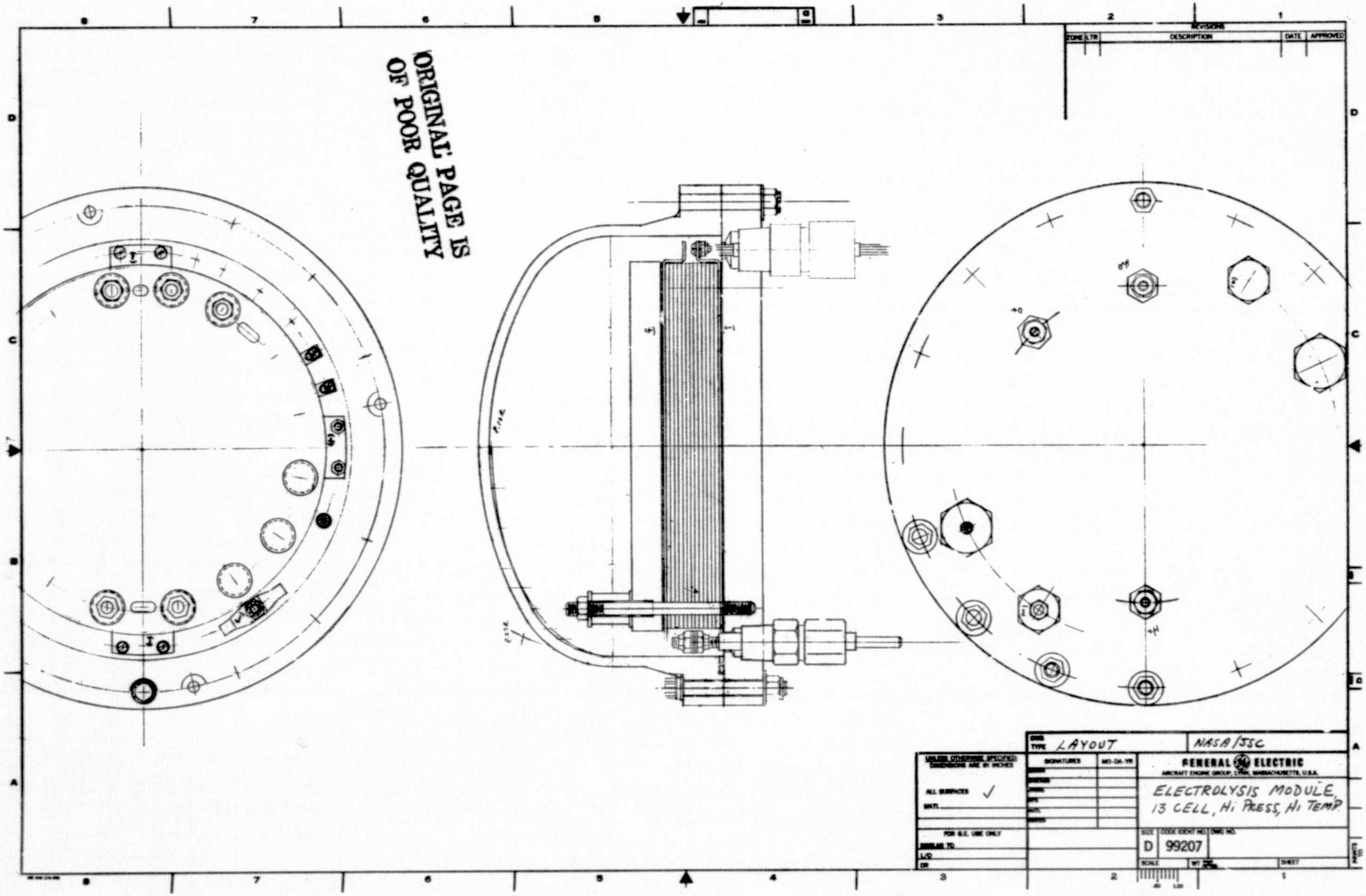


Figure 24.

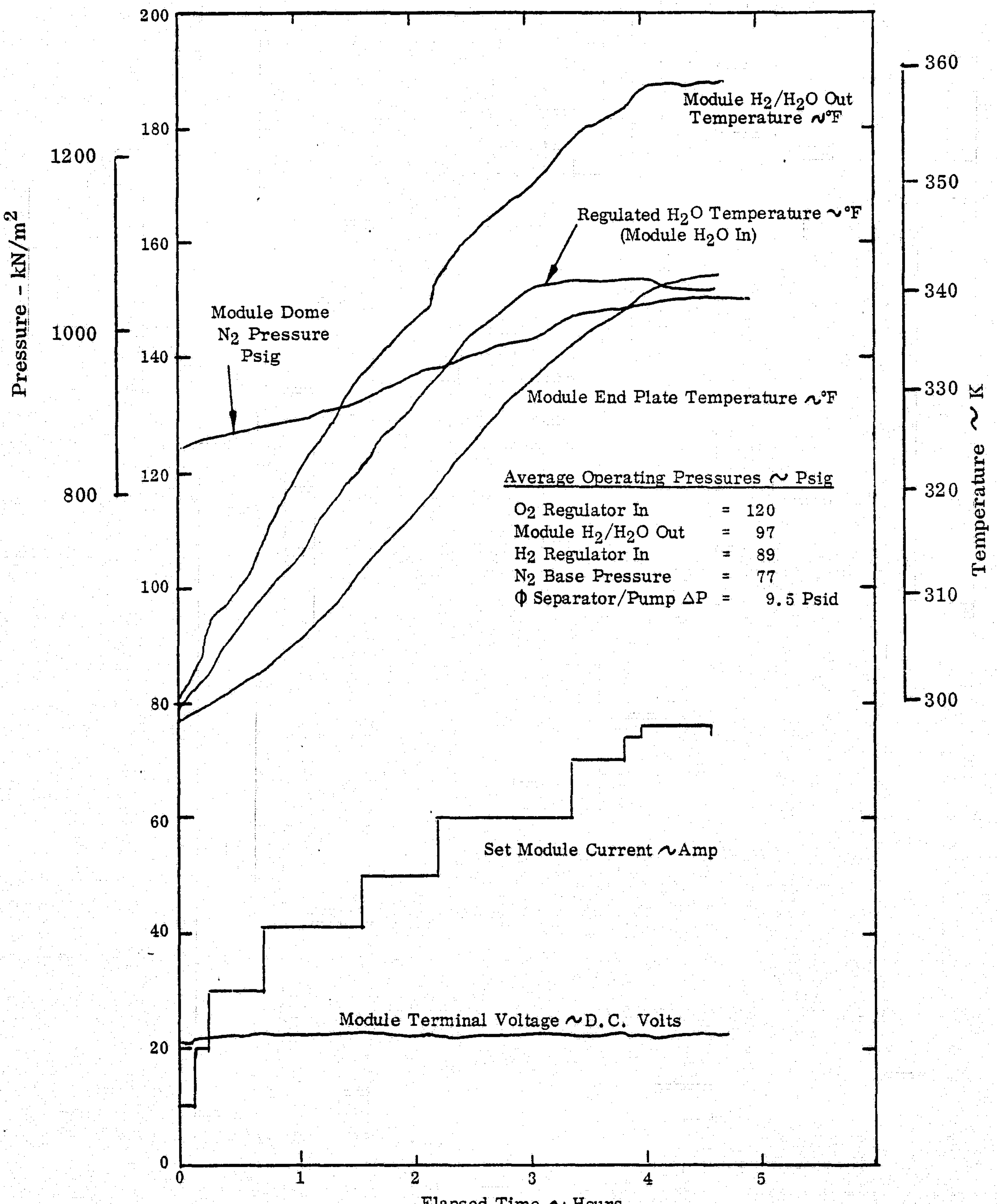


Figure 25. WES Test Run On June 13, 1974

Tabulated below are the individual cell voltages which were recorded after one and seven days, respectively, of continuous unattended system operation at 75 amps (350 ma/cm^2), 827 kN/m^2 (120 psig) O_2, 655 kN/m2 (95 psig) H_2/H_2O pressures, 339 k (150°F) H_2O inlet and 361 k (190°F) H_2/H_2O outlet temperatures at the module.

Voltage, VDC

at 75 Amp, 350 ma/cm^2

Cell Number

Date	1	2	3	4	5	6	7	8	9	10	11	12	13	Total Sum
6-20-74	1.734	1.730	1.711	1.717	1.716	1.710	1.694	1.714	1.710	1.694	1.712	1.698	1.795	22.34
6-27-74	1.751	1.730	1.730	1.730	1.714	1.716	1.699	1.719	1.716	1.697	1.716	1.692	1.796	22.40

The change in module temperatures and voltage during reductions in load following the endurance test period is plotted in Figure 26.

The end cells, Nos. 1 and 13 exhibit higher voltages because the measurement, as wired, includes IR drop across the terminal plates.

Following system endurance testing at 690 kN/m^2 (100 psig) and prior to initial testing at 1724 kN/m^2 (250 psig), a nitrogen dome leakage check disclosed leakage from a Conax gland sealing module cell voltage lead wires through the end plate. This teflon gland seal becomes hot ~ 339 k (150°F) during module operation and evidentally some permanent set and contraction allowed leakage at room temperature. Upon commencement of module tests at 1724 kN/m^2 (250 psig) it was discovered that cell voltage readout on cell numbers 12 and 13 was not possible although module operation and total voltage was otherwise normal. The common voltage tab between cells 12 and 13 was evidentally loosened or pulled out when the nut and gland was rotated to effect a seal on the lead wires.

Measurements of module temperature and voltage over a load profile from 20 to 75 amperes at a nominal operating pressure of 1724 kN/m^2 (250 psig) are plotted in Figure 27.

Coincident with this test run at a module current of 75 amps (350 ma/cm^2) the following cell voltages were recorded.

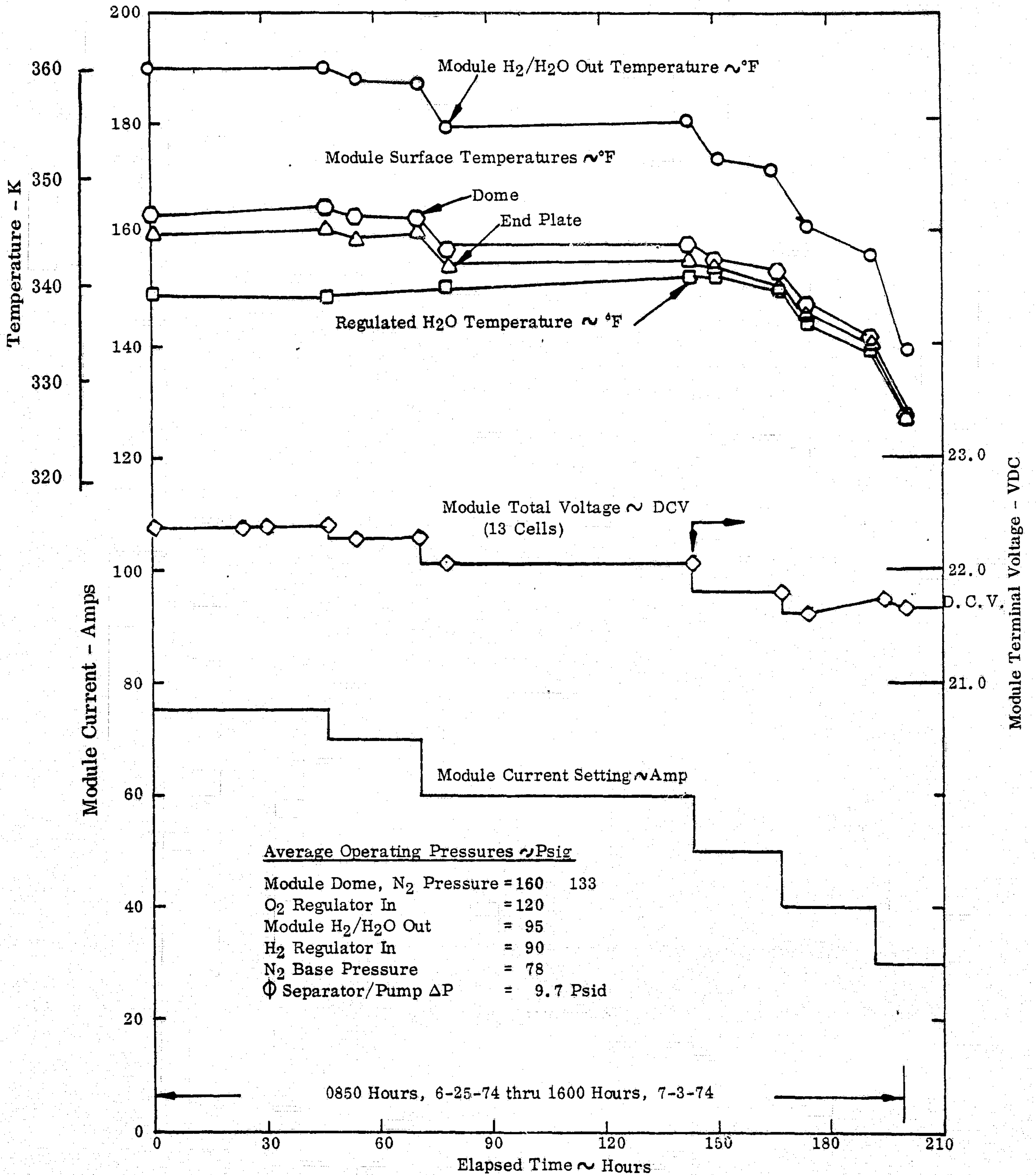


Figure 26. WES Unattended Endurance Test Steady State Load/Temperature Evaluation

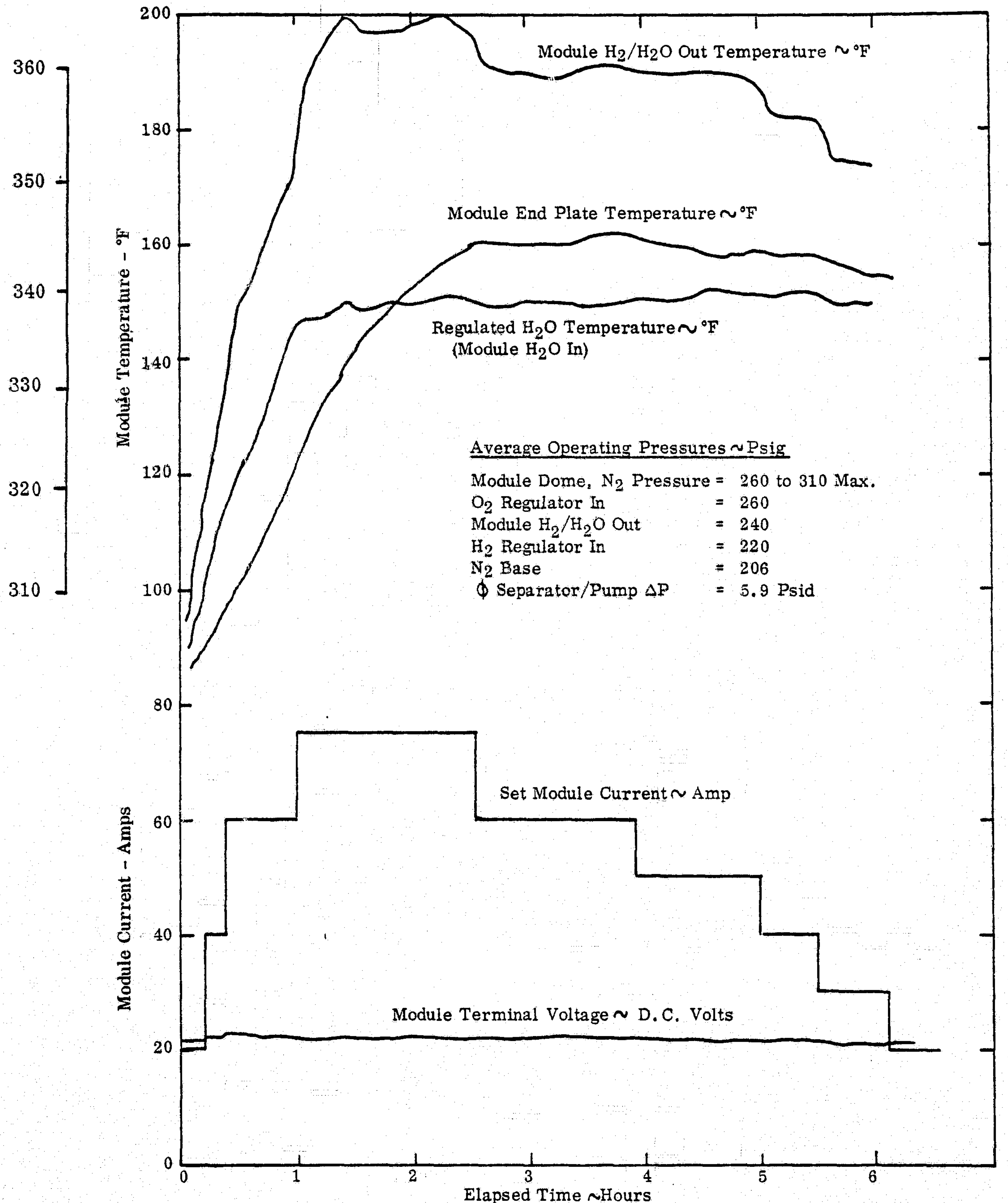


Figure 27. WES Test Run onAugust 20, 1974

Voltage, VDC

at 75 Amps, 350 mA/cm^2

Cell No

1	2	3	4	5	6	7	8	9	10	11	12	13	Terminal
1.734	1.710	1.697	1.696	1.688	1.684	1.680	1.691	1.692	1.673	1.679	*	*	22.4

* No cell voltage measurement capability on
Cell numbers 12 and 13

Module performance at design point conditions of 75 amp (350 mA/cm^2) load, 2860 kN/m^2 (415 psia) nominal pressure and 367 K (200°F) outlet temperature was satisfactorily demonstrated by the following operating conditions on 11-7-74.

TABLE VI

Measured Parameter	Operation Value
Module Current, Amp	75
Module Current Density	350 mA/cm^2 (325 ASF)
Module Terminal Voltage, VDC	22.4
Module Dome N_2 Pressure	2965 kN/m^2 (430 psig)
Regulated O_2 Pressure	2772 kN/m^2 (402 psig)
Module H_2/H_2O Outlet Pressure	2578 kN/m^2 (374 psig)
Regulated H_2 Pressure	2482 kN/m^2 (360 psig)
Regulated N_2 Base Pressure	2275 kN/m^2 (330 psig)
Phase Separator - Pump Δ P	53.8 kN/m^2 (7.8 psig)
Mean Process Water Flow Rate	8.07 kg/hr. (17.8 PPH)
Regulated Module Water Inlet Temp.	339 k (151°F)
Module H_2/H_2O Outlet Temp.	372 k (210°F)
Module Dome Skin Temp.	350 k (170°F)
Module End Plate Skin Temp.	347 k (165°F)

Voltage, VDC

at 75 amp, 350 mA/cm^2

Cell No

1	2	3	4	5	6	7	8	9	10	11	12	13	Terminal
1.734	1.717	1.708	1.714	1.695	1.693	1.691	1.714	1.699	1.678	1.691	*	*	22.4

* No cell voltage measurement capability on

Cell numbers 12 and 13

Because of reduced pumping Δ P of the phase separator-pump at high system operating pressure which reduced process water flow rate and increased module outlet temperatures, module operating loads greater than 50 amperes (233 mA/cm^2) could not be sustained for periods of time exceeding six hours.

After 550 hours of module operation which included high pressure and high temperature operation, the assembly was rechecked for internal leakage with nitrogen. At 345 kN/m^2 (50 psid) pressure differential, N_2 dome to O_2 side and N_2 dome to H_2 side leakage rates were measured 3.13 SCCM and 3.81 SCCM respectively. Cross membrane cell diffusion of nitrogen at 345kN/m^2 (50 psid) O_2 to H_2 side was measured at 8.3 SCC/hr/cell which was under the 10 SCC/hr/cell allowable diffusion for new cells. Nitrogen leakage from the dome to the cell prevented locking in nitrogen pressure during unattended operation and was attributable to difficulty in sealing the manifold port locations which was experienced during assembly. The O_2 to H_2 side sealing capability was effective in the cells so testing was contained without servicing the module.

The performance characteristics of the 13-cell electrolysis module at these pressures (shown by the relationship of cell voltage, current and operating temperature), are shown in Figure 28. These data are taken from mapping and parametric testing of the system over a period of time rather than from a single run evidenced by Table VI. Lines of constant current or cell current density are drawn which show the linear decrease in cell voltage as the module H_2/H_2O outlet temperature would increase during a warm-up period at constant load settings.

Satisfactory electrolysis module performance was also demonstrated during the orbital cyclic mode of WES operation. Because of parasitic losses caused by gas diffusion through the SPE cell at high temperature and pressure, a load of 5 amps or greater is required to sustain a net gas production such that the O_2 and H_2 back pressure regulators maintain system pressures. During a period of seven days or 170 hours of continuous unattended system operation in the automatic cyclic mode, the module was cycled between loads of 6 and 20, 30, 40 and 50 amperes. A recorded trace of module terminal voltage over an 11 hour period on 1-28-75 is provided in Figure 29. Maximum voltage occurs immediately after the 40 amp load is

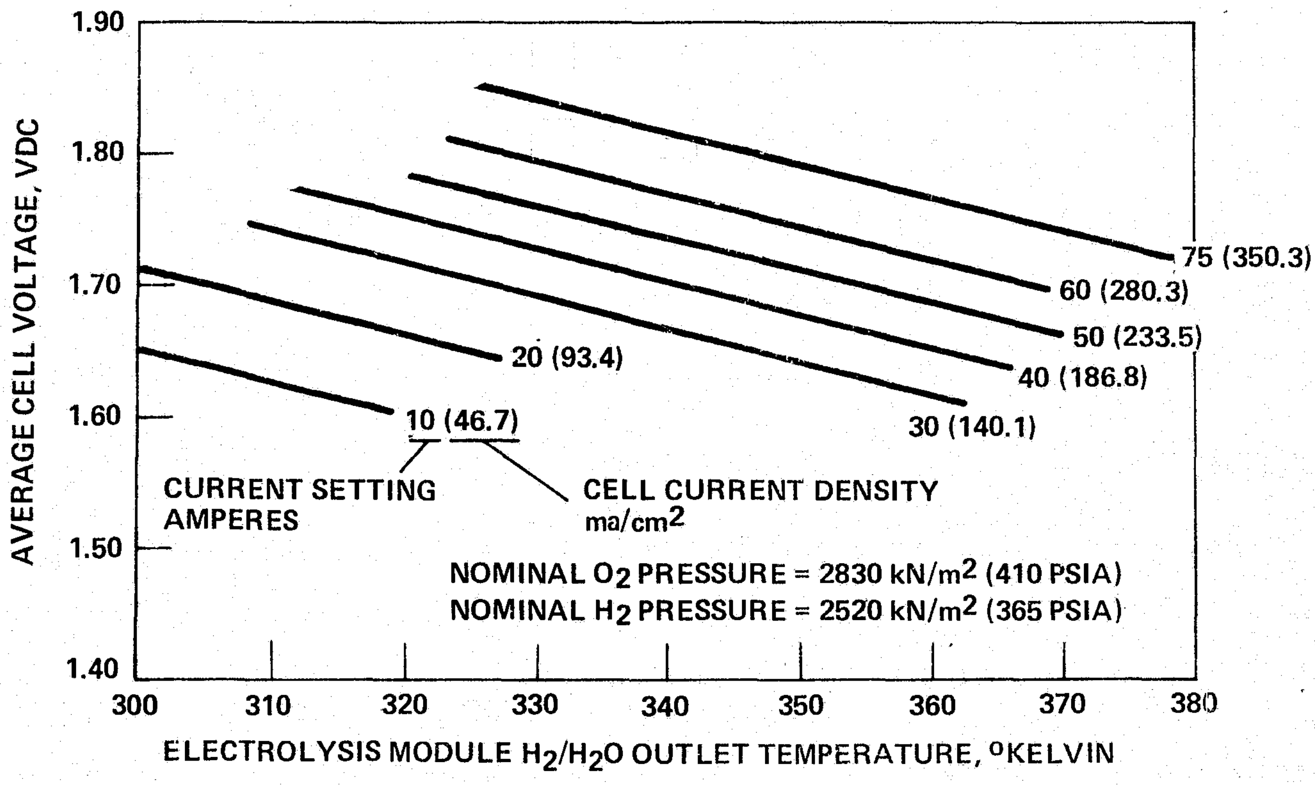
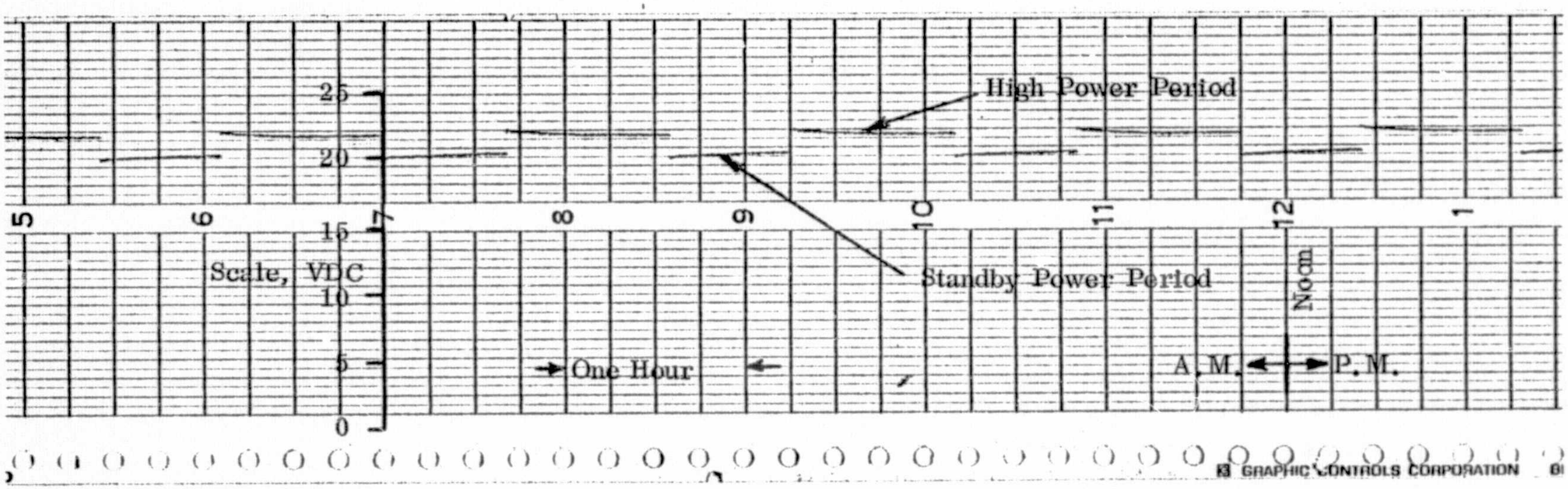


Figure 28. 13-cell Electrolysis Module Performance Characteristics



Test Date: 1/28/75
0300 to 1400 Hours

Figure 29. Electrolysis Module Terminal Voltage During Cyclic (Orbital) Operating Mode: 54.7 Min High Power at 40 Amp
40.7 Min Standby Power at 6 Amp

instantaneously applied and decays slightly during the warm up period at high load. Minimum voltage occurs immediately after the load change from 40 to 6 amps and increases very slightly as some cooling of the module occurs at the low standby load.

After an accumulated gas generation time of over 1040 hours on the module as part of advanced WES testing, it was removed from the system to be disassembled for inspection and installation of molded fluorosilicone gaskets in place of the FEP film/silicone gaskets as initially assembled. In addition to the new gasket configuration, the electrolysis module will be reassembled with seven, instead of thirteen, cells reflecting the three-man oxygen generation requirement of a WES Test Demonstration Unit for the Life Sciences Payload Program under Contract No. NAS 9-14205. The advanced breadboard system will serve as a test bed to evaluate performance and endurance of the new module configuration as well as other components incorporating modifications for the Test Demonstration Unit.

3.3.2 Power Conditioner

The 75 amp power conditioner was developed on previous Contract NAS 1-9750 and adapted for use on this system. The unit is of open construction (Figure 30) with water cooling of the main power handling components. The output is directly coupled to the electrolysis module and the output can be controlled from a remote potentiometer to give from 0 to 75 amps to the module.

The power conditioner circuitry is shown schematically in Figure 31 It is basically a step-down, time-ratio-control current regulator.

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

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

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

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

One of the drawbacks of adapting this power conditioner from a previous contract was the floating negative module bus. Direct overvoltage shutdown protection divider circuitry was found to be overly sensitive to operating transients causing erratic shutdowns. Replacement with a meter relay which did not require the negative common reformer eliminated this problem. The same result could have been accomplished by using PNP switching transistors and a common negative bus, however, it did not seem practical to redesign and rebuild the power conditioner just to overcome this limitation when a meter relay was available and worked very satisfactorily.

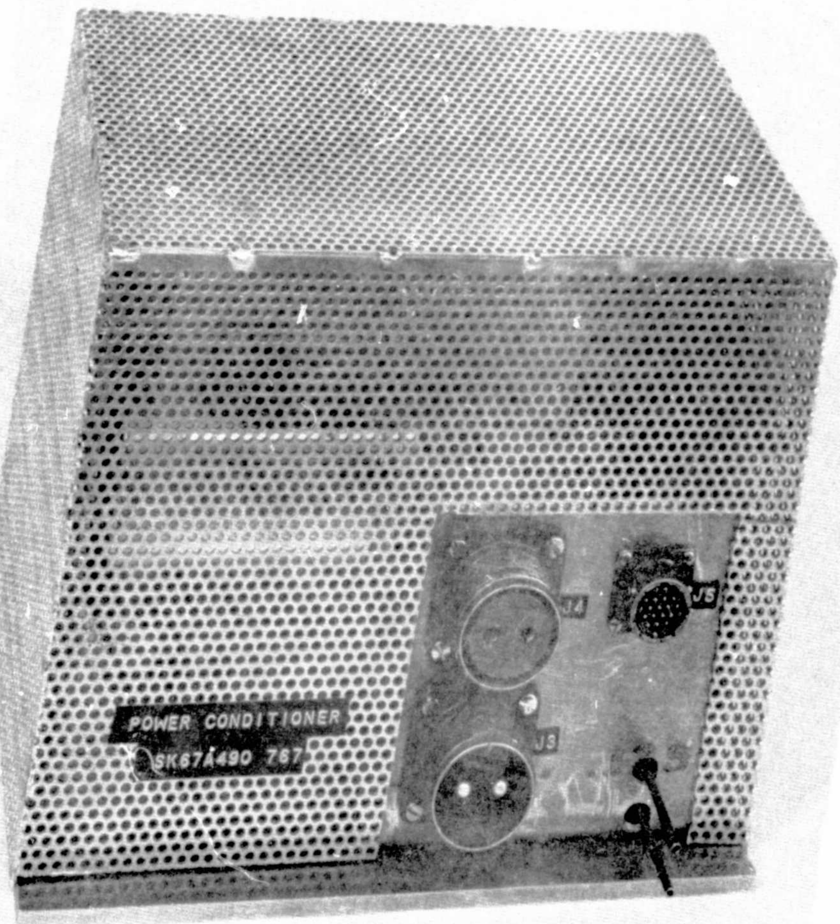


Figure 30. 75 Amp Power Conditioner

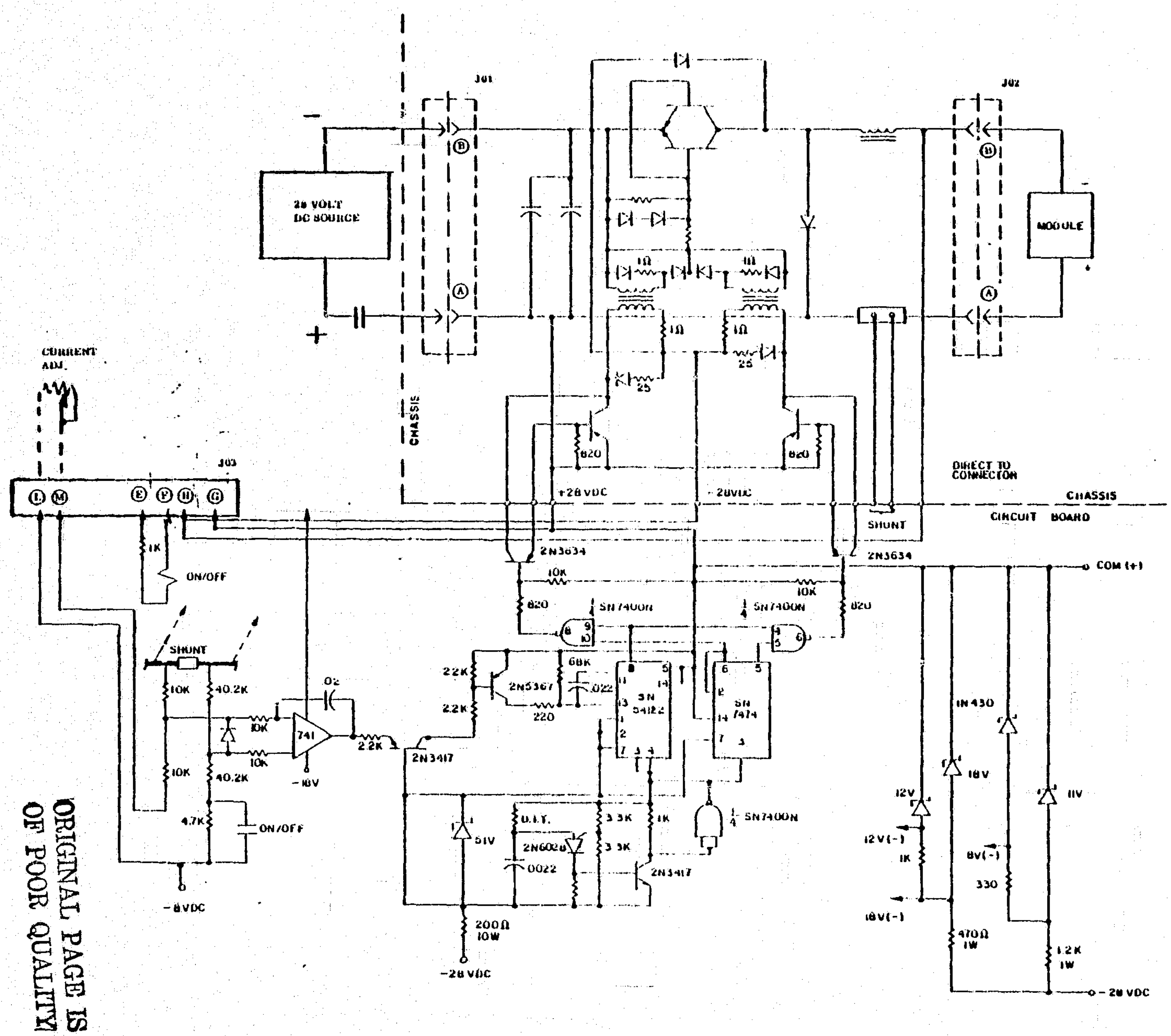


Figure 31. Power Conditioner Schematic

C.3.3 Dynamic Phase Separator-Pump

Important to the design of an advanced, high pressure water electrolysis system utilizing a cathode feed SPE module design, was the need for reliable H_2/H_2O phase separation and process water circulation essentially insensitive to system operating pressure and its possible variations with operation conditions in a 1 g or zero gravity environment. Experience in low pressure electrolysis systems with passive means of phase separation and available pumps had shown the vulnerability of these devices to system pressure changes resulting in loss of positive separation and/or pump cavitation. A successful centrifugal phase separation device had been developed by the Fluid Dynamics Corporation, Chester, California. An advanced design for the high pressure WES application required increased pumping pressure differential, higher gas volume rates and high line pressure capability. Analyses were made from WES component test data in Phase I to predict H_2/H_2O separation and process water flow requirements to define a specification for a combined phase separator-pump. This specification, No. 73A49-828, is included in the appendix.

An outline drawing of the phase separator-pump developed by Fluid Dynamics Corporation under Phase II of this program is provided in Figure 32.

The phase separator-pump assembly consists of a single phase, 115VAC, 60 Hz synchronous motor, permanent magnet drive coupling, pump impeller, speed-sensing pickup impeller, H_2 outlet solenoid valve, overboard relief valve and accompanying electronic control. The permanent magnet on the motor armature engages and spins a concentric magnet sealed inside and attached to the pump impeller thus avoiding a shaft seal. Protruding radial vanes on the pump impeller cause the liquid in the separator spin chamber to form a rotating hollow cylinder which creates a separating force in excess of 200 g's on the incoming fluid. The lighter fluid of a two phase mixture, consisting in this case, hydrogen and water, is separated by moving to the center or core of the spin chamber. The heavier fluid is drawn into the centrifugal pump impeller and is discharged into a chamber connected to the water outlet port.

As a mixture of hydrogen (saturated with water vapor) and water is delivered to the separator, the gas and vapor will be forced to the center core while the liquid will be discharged out of the pump section.

As more gas is separated the center core grows in size and must be vented to allow the separating action to continue. A secondary, or sensor, impeller is mounted in such a way as to face the driving impeller and the rotating mass of liquid causes this impeller to rotate with the fluid. Since the diameter of the sensor impeller is smaller than the spin chamber, the rotating liquid moves out of contact with sensor impeller blades as the gas core grows in size. The sensor impeller, through various components, activates a logic circuit which determines a rotating or non-rotating signal. A non-rotating signal causes the logic circuit to open a solenoid valve allowing the gas in the core to be vented. Since the separator is operated at a pressure higher than the

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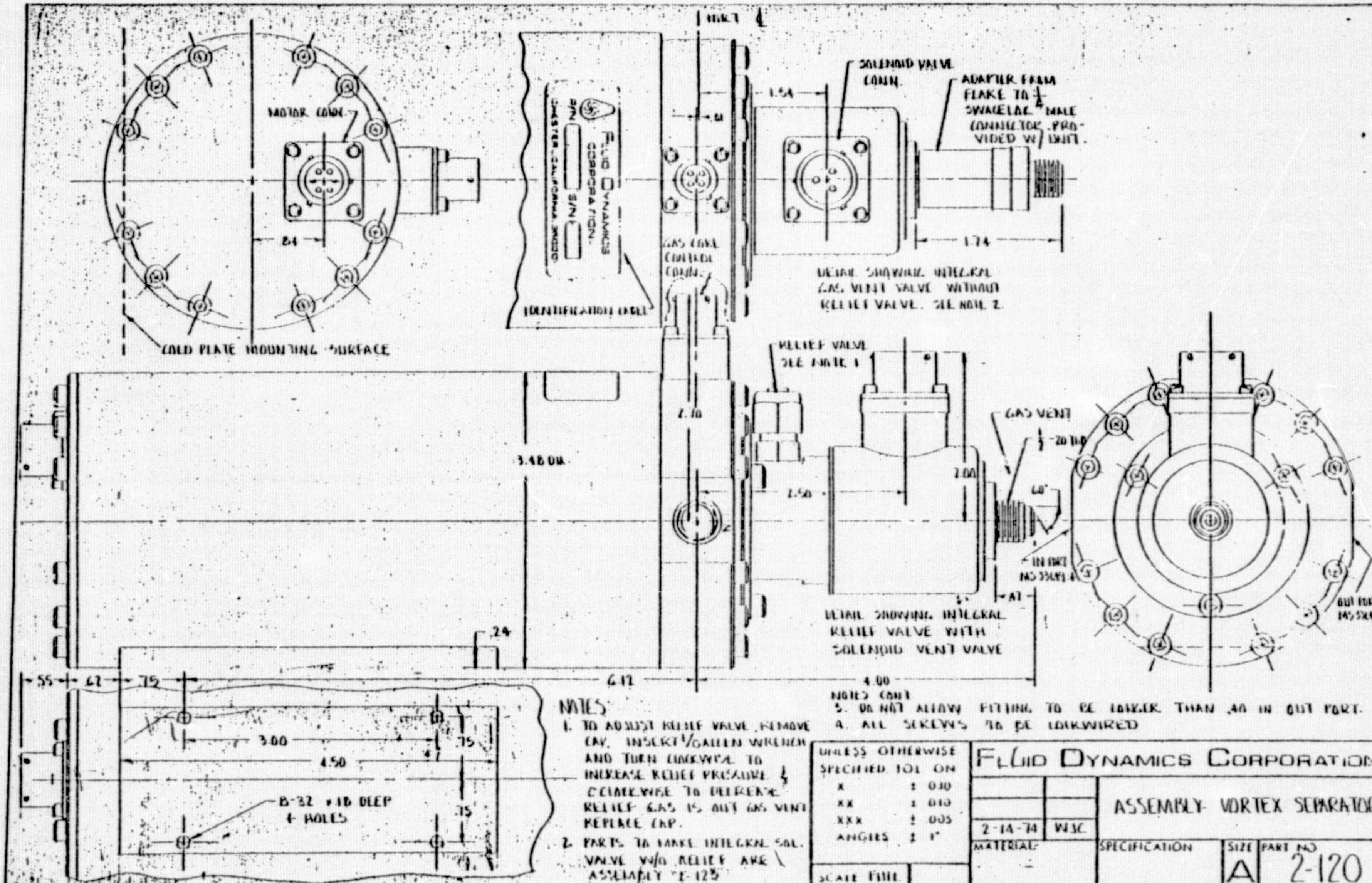

Figure 32.

discharge point, gas is forced out of the separator. This causes the gas core to shrink, and the spinning liquid engages the sensor impeller causing the logic circuit to close the solenoid valve. More gas enters, is separated, the gas core grows until the sensor impeller slows, the vent valve is opened, the core shrinks, the sensor impeller rotates, and the valve closes. Cycling of the solenoid valve is continuous with a steady input of gas increasing in frequency to about ten cycles per minute at maximum volumetric hydrogen generation rate whereas water flow rate is determined by H_2O outlet minus 2 Φ inlet ΔP and the flow impedance of the recirculation loop.

The phase separator/pump and its electronic control box was bench tested at low pressure using a seven-cell electrolysis stack as a source of two-phase H_2/H_2O flow. Operation was found satisfactory except that measured pump pressure rise was 63.4 kN/m^2 (9.2 psid) instead of 69 kN/m^2 (10.0 psid) as specified and 71.7 kN/m^2 (10.4 psid) as obtained by Fluid Dynamics Corporation (see Figure 33) at low system pressure. A subsequent proof pressure test showed excessive leakage at the bolted flange or end plate which attaches the solenoid valve and relief valve to the separator/pump housing. Recommendation by Fluid Dynamics Corporation was made to reduce a 0.4 mm (.016" shim) to about .30 mm (.012 inch) thickness to increase the compression on two O-ring face seals. This was accomplished and the separator/pump assembly successfully passed a proof pressure test of 3840 kN/m^2 (557 psig) without evidence of external leakage. Subsequent bench testing to re-evaluate separator/pump operation showed an increase of pump differential to 71.7 kN/m^2 (10.4 psid) probably due to reduced internal running clearance. The setting of the built-in relief valve was increased from 124 to 138 kN/m^2 (18-20 psid) to 290 kN/m^2 (42 psid) cracking pressure, 207 kN/m^2 (30 psid) reseat pressure.

Performance of the phase separator/pump was satisfactory over a 429 hour test period which included system checkout at low pressure and continuous operation for over 300 hours at a phase separator/pump inlet pressure of 655kN/m^2 (95 psig) and an H_2O out minus 2 Φ inlet ΔP of 64.8kN/m^2 (9.4 psid). When system pressures were adjusted for operation at a nominal level of 250 psig, phase separator/pump operation was found to have dropped to under 41kN/m^2 (6.0 psid) thereby reducing process water flow rate. With the concurrence of Fluid Dynamics Corporation, the manufacturer, it was decided to obtain system performance data at maximum system pressure of 2860kN/m^2 (415 psia) before returning the separator/pump for vendors examination and correction. At this pressure level decoupling of the magnetic drive sometimes occurred as well as leakage of the solenoid valve and integral relief valve. Removal and inspection of the solenoid valve revealed from wear-marks that the open coil of the return spring evidently snagged in the longitudinal groove of the plunger thus preventing its return and proper seating. Correction was accomplished by reversing the coil spring such that the open coil faced the shoulder on the plunger. An improper O-ring seal was found in the relief valve which was corrected by removing the spring and inserting a 1/4 inch tube spacer. This, however, left the relief valve non-functional, but was not considered necessary for WES safe operation. It was also learned that normal pumping ΔP was restored at low pressures. The unit was removed from the system and sent to Fluid Dynamics Corporation on 9-11-74 for high pressure evaluation and corrective modifications as necessary.

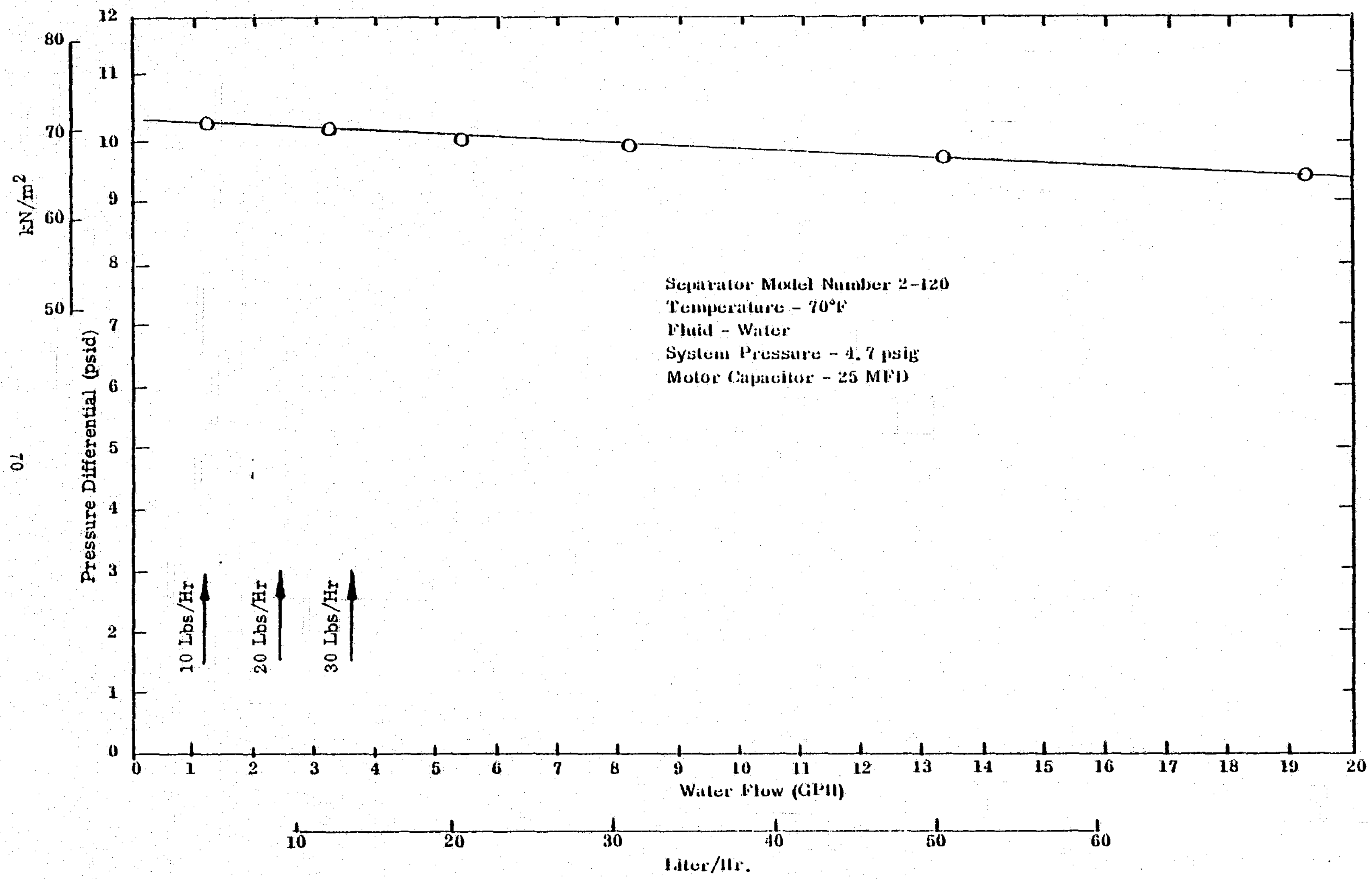

Figure 33. Liquid Flow as Measured Against Pressure Rise Across Vortex Separator

As evaluated by the vendor, loss of pumping pressure differential at high operating pressure was attributed to excessive thrust bearing friction causing loss of motor speed and at times decoupling of the magnet drive to the pump element. The thrust bearing was altered to include improved relative slip between a glass-filled teflon thrust washer and a stainless steel ring inserted in the impeller. Recommendations by Fluid Dynamics Corporation for a more improved redesign, not possible within the configuration of the current unit, would include substitution of graphite for teflon for further reduction of friction and increasing the torque capacity of the magnet drive from 22 to 35-inch-ounces. To prevent magnet uncoupling on the present unit the motor speed was reduced slightly at high torque with the change of a capacitor in its circuit to increase motor slip.

Phase separator/pump operation was satisfactory when re-installed in the system, although it did exhibit some sensitivity to system pressure by a ΔP reduction from about 9.5 to 8.0 psid between respective operating pressures of about 138kN/m^2 (20 psig) and 2480kN/m^2 (360 psig). Two occurrences of component malfunction during system evaluation resulted ultimately in a bearing seizure of the separator/pump which required additional repair. During system depressurization and drainage of the process water loop without the separator/pump operating, reversal of water flow through the deionizer caused dislodging of resin beads into the separator/pump water discharge line (which was subsequently flushed) and some inadvertently into the impeller cavity. During unattended system operation a broken solder joint on a water accumulator switch prevented makeup water addition to the process water circuit. This ultimately resulted in fault shutdown of "low" separator/pump ΔP equal to 24kN/m^2 (3.5 psid). The low ΔP resulted from an enlarged gas core which reduced water lubrication of the impeller thrust bearing, and some deionizer resin particles had settled in the .010 inch clearance between the thrust bearing and impeller, thus interferring with rotation. Normally, the pump could handle this foreign material as a centrifugal pump with adequate water flow. However, with reduced water flow rate the gas core enlarged in diameter and exposed dry regions of the thrust bearing which eventually picked up the resin particles and bound up. New bearings were fabricated and the separator assembly was bench tested at low and high pressure by Fluid Dynamics Corporation.

The repaired phase separator/pump was re-installed in the system on 12-3-74. Subsequent system evaluation revealed at the nominal operating pressure of 2413kN/m^2 (350 psig) that pressure rise across the circulating pump element was 51.7kN/m^2 (7.5 psid) as opposed to 69kN/m^2 (10 psid) measured by a vendor bench test. The difference was later attributed to possible deflection of the pump housing at elevated pressure which increased the impeller clearance and reduced pump performance.

Because a few drops of water had been observed in the glass tube hydrogen flowmeter, a translucent 1/4" diameter nylon line was installed at the hydrogen outlet of the phase separator. During system operating conditions with a full water accumulator, a pressure differential of about 159kN/m^2 (23 psid) can exist across the closed solenoid valve. Water slugs up to 2.5 cm long were periodically observed discharged with the hydrogen when the solenoid valve was opened. Apparently, the surge of hydrogen from the gas core at high differential allowed some carry-over of water to the outlet. This condition was corrected later in the program by an internal modification which prevented the sensing impeller from picking up water/gas interface during venting at high differential pressure.

On 12-31-74, the system was automatically shutdown caused by a "high" two-phase pressure fault condition resulting from a failed bellows in the hydrogen back pressure regulator. The poppet of this component continuously cycles between an open and almost closed position as the solenoid valve on the phase separator is energized cyclically. The frequency, dependent upon gas generation rate, was about 10 cycles per minute at 30 amperes. It was estimated that 400,000 cycles were accumulated to this failure point with a WES accumulated gas generation time of 629 hours. Subsequently the system was installed with a repaired hydrogen back pressure regulator and an electrical counter which was energized simultaneously with the solenoid valve on the phase separator/pump.

As reported in Para. 3.4.3 a differential H_2 back pressure regulator was added downstream of the separator solenoid valve with a reference to separator/pump H_2O outlet pressure. This device has reduced the continuous cyclic operation of the solenoid valve and no water discharge was evidenced in the translucent H_2 outlet line. During an extended period of over 200 hours of system operation the pressure rise of phase separator/pump gradually diminished from 7.6 to about 6.0 psid which required readjustment of the differential pressure regulator to "hold" the solenoid valve open.

On February 10, 1975, the phase separator was removed from the system and disassembled. Inspection of the pump revealed that the teflon washer shim between the impeller and housing had been worn and frayed. This was replaced with a .13 mm (.005") thickniobium metallic washer. The separator/pump was then reassembled and bench tested with a pressurized water reseroir up to 2413kN/m^2 (350 psig) and with circulated water flow (without two-phase input capability). A pump $\Delta P$of about 62kN/m^2 (9.0 psid) was measured in this set up. After re-installation of the separator and subsequent operation in the system at design pressure for a few hours its measuredΔP changed to about 51.7kN/m^2 (7.5 psid).

Additional system tests were conducted to determine the variance of phase separator/pump ΔP with low and high pressure operation with solid water or two-phase flow separation, etc. Provision was made with a "tee" inserted in the two-phase line at the separator/pump inlet to inject nitrogen gas. Gas injection at this point took the form of small bubbles swept by the continuous water stream; whereas, electrolysis operation usually results in alternate cylindrical bubbles and water slugs. The "tee" was, therefore, relocated to the two-phase inlet of the primary heat exchanger. In passing through about 6.1 meters (20 feet) of 1/4 inch diameter tubing of the heat exchanger as well as working against a 25 to 38 cm (10 to 15 inch) water column, a more slug-like flow was established. A differential gage was also installed to measure separator Δp, i.e., (H_2O OUT minus 2 Ø IN). Separator pressure differential was measured under a variety of conditions, i.e., 103 to 2413 kN/m^2 (15 to 350 psig) 0 to high injection rates of N_2 or H_2 gas as well as with electrolysis module generation. At low pressure a differential of 59 to 62kN/m^2 pf (8.5 to 9.0 psid) was usually experienced which fell off to 51.7 to 55kN/m^2 (7.5 to 8.0 psid) at design operating pressure of 2413kN/m^2 (350 psig). This change was sometimes erratic and sudden, however, particularly at high pressure or by stopping and restarting. Although a Δp of 51.7kN/m^2 (7.5 psid) was normally realized at 2413kN/m^2 (6.5 psid). Two phase operation of 12 hours or more resulted in a reduction to about 45kN/m^2 (6.5 psid). The phase separator/pump was not disassembled or removed from the system installation to further ascertain the cause; but, as previously hypothesized these variations were probably due to changes in internal impeller clearance causing variation in internal leakage which affects pump performance.

Operation of the phase separator/pump with the differential pressure regulator, whereby the solenoid valve is maintained continuously open, usually results in generation of a repeating pulse or dip in pump ΔP lasting one to two seconds. Periods of steady operation may be up to an hour, but once triggered by a load change, operation of the makeup pump or some flow transient, the pulse is sustained at a frequency of usually two to seven times per minute. During this pulse the pump ΔP drops from a normal 48 to 50kN/m^2 (7 to 8 psid) to about 34kN/m^2 (5 psid) and then returns to the higher value. A change in water flow coincides with the change in ΔP and motor speed increases sharply as ΔP is reduced by a larger core diameter. Because the operation of the phase separator pump, differential pressure regulator and water accumulator are inter-related, the exact cause was not apparent. By isolating the water accumulator and differential pressure regulator with valves and by elimination of water in the H_2 discharge with a trap, the causes of possible instability could be determined. It was found that pulses could occur when the solenoid valve was powered open, even with the differential regulator and water accumulator ineffective in the fluid circuit by valving. It appears that the core diameter may be oscillating slightly (noted by slight ΔP oscillations) which becomes unstable probably due to a speed increase as the core diameter grows and the motor becomes unloaded (possibly aggravated by the built-in slip condition). At low pump ΔP a churning sound is heard for about one second and then the motor speed is reduced and high ΔP is restored as the core collapses. Pulsations have been observed during system operation at low and high pressures and at low and high loads. Observations were also noted during a shutdown condition with the phase separator/pump "on" when the two-phase loop was being drained. That is, pulsations could occur when the solenoid valve was powered open, as caused by a partially drained separator with an enlarged core. Although disconcerting, the pulsations noted are less frequent and no more detrimental to system components than those oscillations caused by a constantly cycling solenoid valve. Further phase separator testing and development should investigate whether pulsations are prevented by a synchronous speed or whether the vortex region or the pump impeller should be modified with baffles to retard free-surface oscillations of the core.

In summary, the technical difficulties experienced with the development of the dynamic phase separator/pump were primarily related to the undersize torque rating of the magnetic coupling which required the reduction in motor speed to prevent decoupling. The modified speed-torque characteristic resulted in a speed and ΔP output sensitivity to impeller torque variations with clearance and bearing friction. Positive aspects of the component development were that the unit provided effective H_2/H_2O separation over the wide range of system operating pressures and gas production rates and was proven functionally compatible with the automatic start, stop and cyclic operating requirements of the system. Centrifical separation with a hollow core and with gas venting capability completely eliminated pump cavitation problems and no gas was ever entrained in the water discharge. For this reason, the phase separator was operated continuously during system depressurization to effectively separate and handle H_2 outgassing of process water in the two-phase loop as pressures were reduced.

3.3.4 Water Accumulator

The water accumulator provides the dual function of accomodating the changes in the quantity of water in the two-phase region of the process water loop due to sudden changes in load or hydrogen generation rate, and, it also provides the sensing means for adding makeup water periodically as it is consumed by the electrolysis module. Bench tests with a seven-cell electrolysis stack verified the changes in water "held up" in the hydrogen cavity of the cells at various applied loads. Also, the quantity of water contained as cylindrical slugs with two-phase flow in fluid lines depended on rates and the volume ratio of gas and liquid. Anticipated volumes of fluid components handling two-phase flow were calculated with the electrolysis module, primary and regenerative heat exchangers making up the largest portion of total volume for sizing the water accumulator.

Requirements for the design of a water accumulator meeting the volume displacement requirements and the switching logic for makeup water addition are provided in Spec. No. 73A490-862 contained in the appendix. Commercially available accumulators or hydraulic cylinders could not be modified to meet these requirements primarily because materials used were not suitable for water service. Response to quotations were received from four vendors but cost and delivery in all cases were beyond program plans.

The design of the water accumulator specially made for the WES requirements is shown in cross section on Drawing No. 73A490-873 in Figure 34. It consists of a customary hydraulic actuator design with piston, rod, return spring, hollow cylinder and square end plates sealed with O rings and secured with four tie rods. The piston design shown was for incorporating TFE coated "Quad" rings. An alternate split-piston design suitable for chevron-type teflon seal rings was also fabricated. The cylinder bore and piston rod were honed to an 8 RMS finish to minimize friction. All metal parts are made from 300 series stainless steel. The water storage capacity of the unit is 261 cc consistent with a full stroke of 7.62 cm (3 inches). A .635 cm (.25 inch) square by 2.54 cm (1.00 inch) long magnet is contained in the end of the piston rod, which actuates proximity switches, fastened to the surrounding bracket, at zero and full stroke positions. The number of internal washers (one inch diameter bolt size) located on the tubular piston stop can be varied to adjust spring force for various operating pressures.

Bench tests were performed on the accumulator to evaluate both piston seal designs and to set pre-load on the return spring. The teflon seal, of a chevron-type having a captured expansion spring, demonstrated lower friction but allowed a small amount of water leakage (H_2O to H_2 outlet) which was considered unsatisfactory. The TFE coated "Quad" ring exhibited a 20.6 to 34.5kN/m^2 (3 to 5 psid) pressure differential due to friction, but maintained a leak-proof seal. The piston was assembled with only one ring to limit friction. Typical accumulator performance during a bench test is shown in Figure 35 with the hydrogen side of the piston at atmospheric pressure. At elevated system H_2 pressure, the pistion pressure differential

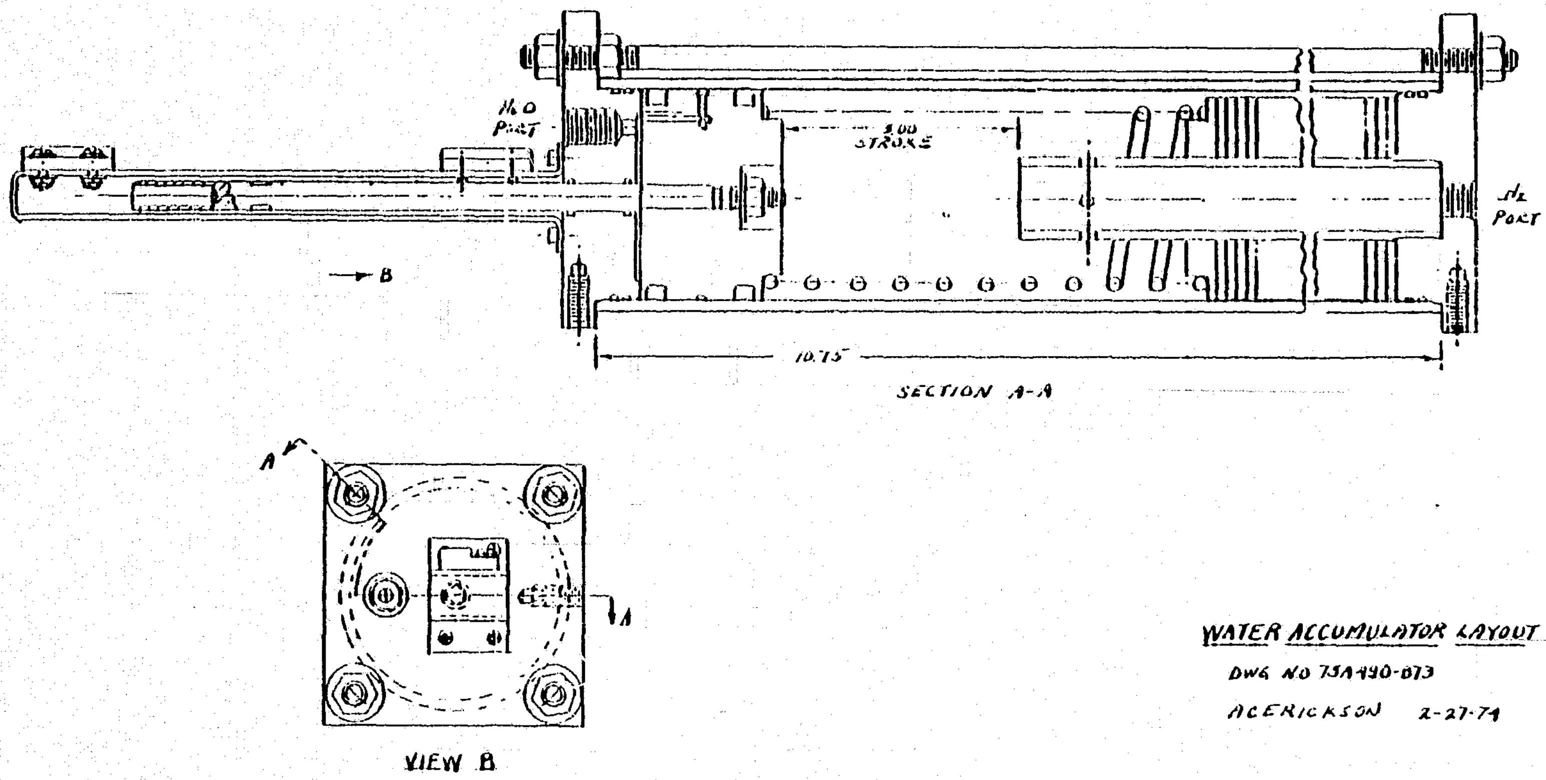
H_2O PORT
5.00 STROKE
N_2 PORT
B
10.75"
SECTION A-A
A
A
VIEW B
WATER ACCUMULATOR LAYOUT
DWG NO 73A490-873
A C ERICKSON 2-27-74

Figure 34.

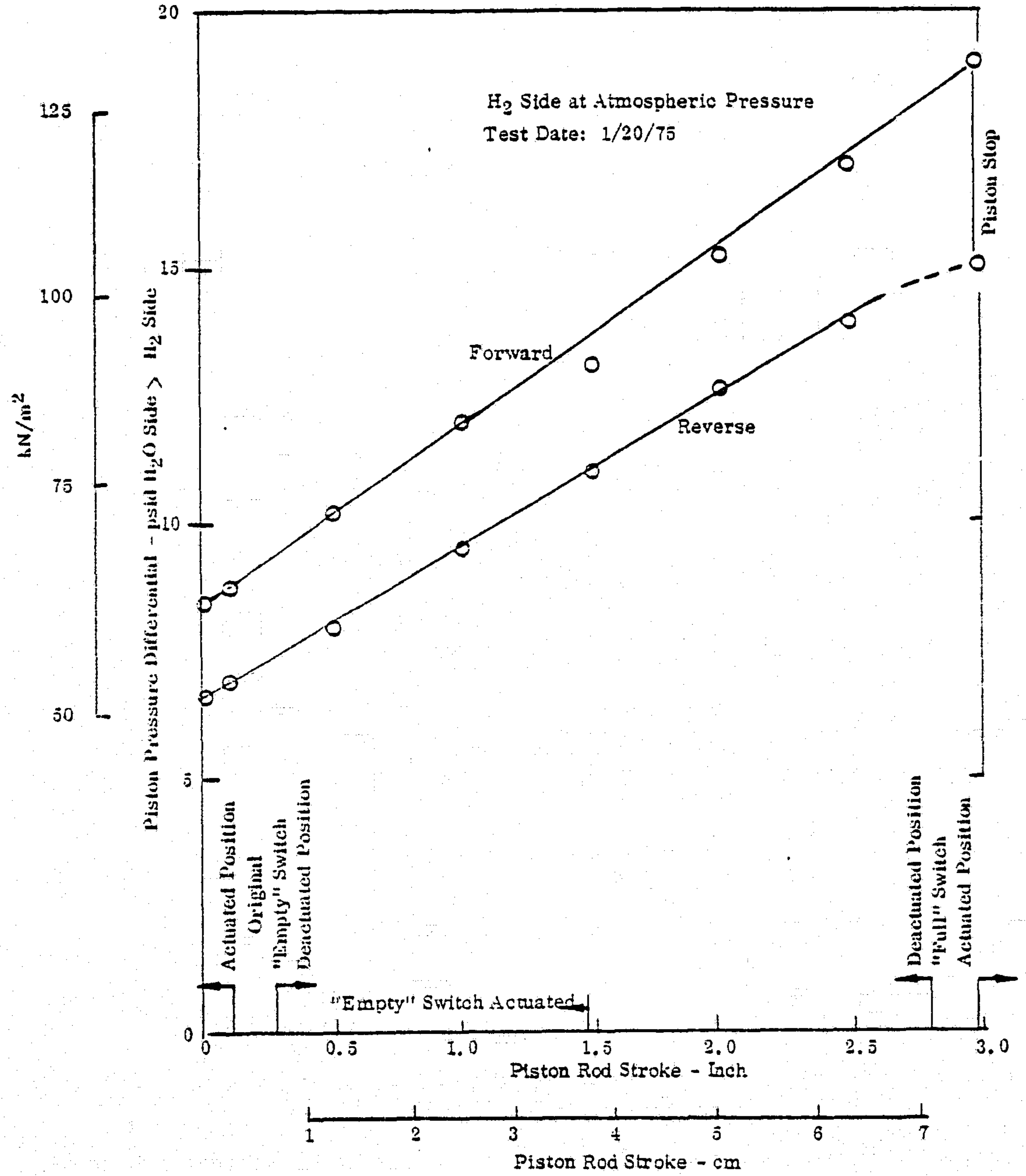

Figure 35. Water Accumulator Bench Test

($H_2O - H_2$) increases because of the imbalance caused by the piston rod area.

Accumulatior performance during the extended period of system operation exhibited a minimum of difficulty. On one occasion the WES was automatically shut down due to a broken solder joint on the "empty" position switch. After over 550 hours of WES operation the water accumulator was observed to stick near the "empty" position. The component was disassembled and the teflon coating on the "Quad" ring seals was observed to be worn off and deposited on the cylinder wall near the "empty" position where most of the cyclic stroking occurs (from phase separator solenoid valve cycling). The seals were replaced and Dow Corning silicone grease and "Apiezon" pure hydrocarbon grease were evaluated as lubricants. The latter gave smoother stroking results so was used in the assembly.

The function of the accumulator was evaluated during load and pressure transients as well as during the cyclic mode of WES operation. During system operation at high load the high-volume components of the two-phase loop (primarily the electrolysis module and two heat exchangers) are filled with a mixture of hydrogen and water having a greater portion of hydrogen. At a low gas production rate in the standby mode the mixture changes to mostly water in these components. The difference in the quantity of water in the two-phase loop caused by load change must be accommodated by the water accumulator. Parametric tests of cyclic operation were conducted between a standby current of 6 amperes and selected currents of 20, 30, 50, and 75 amperes which provide the data in Figure 36. As current is changed from low load to high load, water is added to the accumulator from the two-phase loop. At load reductions water is removed from the water accumulator by the return spring in the piston. At maxumum load differential, piston displacement approximates 3.8 cm (1.5 inch). To accommodate this displacement it was necessary to relocate the "empty" switch of the water accumulator to the center position of the 7.62 cm (3.00 inch) maximum stroke. This was done with the addition of a button-actuated switch which was actuated by the piston rod for any stroke position between 0 and 3.70 cm (0-1.46 inch); refer Figure 35. From this position, maintained by water addition from the makeup pump, the water accumulator will tend to fill with water for a load increase or almost empty to the zero stroke position for a large load reduction. In the latter case, the makeup pump is on for about eight minutes during the standby period to return the piston to the mid-position. It was therefore necessary to increase the ESD delay time for an "empty" water accumulator from 4.5 to 9.0 minutes.

From all piston positions a continuous feed of sufficient water is always available to the two-phase loop such that pressure decay is minimized and normal phase-separator/pump pressure rise is also maintained during load changes.

It had been concluded after system checkout that the accumulator check valve (Item 2-6, Fig. 16) was not a necessary system component. To verify this by test this component was removed from the WES. One result was that the makeup pump was noisier but otherwise system operation at low pressures and high pressures

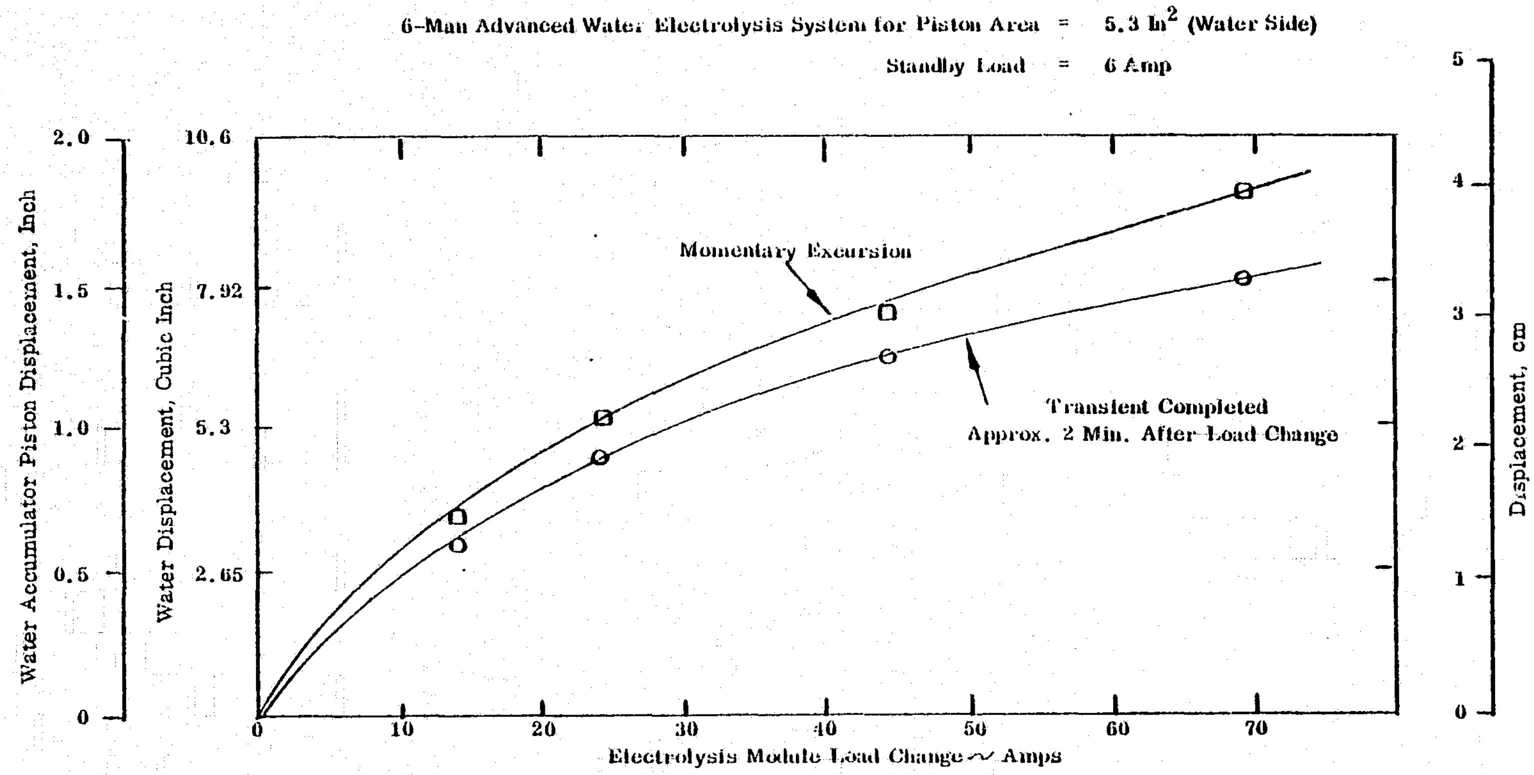

Figure 36. Water Accumulator Change In Piston Position With Change In Electrolysis Module Current

was basically the same. Throttling of the accumulator metering valve (Item 30-1, Fig. 16) does diminish the magnitude of the piston stroke during cyclic operation of the solenoid valve on the phase separator/pump.

The same check valve was inserted in the water outlet line of the phase separator/pump to learn if it might reduce the pressure flow excursions caused by cyclic operation of the solenoid valve on the phase separator/pump. It was determined that the check valve was effective in controlling the water flow direction during priming of the system but did not alter system operation or reduce pressure-flow excursions. It appears that rather than the gas core being collapsed by reverse water flow when the solenoid valve is opened, there is a sudden rush of two-phase flow into the phase separator/pump supplied by the reservoir of two-phase fluid in the electrolysis module and heat exchangers. Pressure drop across the check valve in the flow direction was about $6.9 kN/m^2$ (1 psid) so that water flow rate was reduced. The conclusion was to leave the check valve out of the system for either function.

3.3.5 Oxygen Absolute Back-Pressure Regulator

An oxygen absolute back-pressure regulator P/N 356-01 was designed and fabricated by Ausco, Inc., Port Washington, N. Y. in accordance with the requirements of Specification No. 73A490-831 Rev. B contained in the appendix. A drawing of this unit is provided in Figure 37.

The valve is of the direct acting, bellows loaded poppet type. The evacuated bellows acts to oppose the ambient pressure force to hold the poppet seated until crack pressure is reached, then allows the poppet to lift off its seat for flow. Adjustment of the crack pressure over the range of pressure from 690 to 3448kN/m^2 (100 to 500 psi) is accomplished by turning the gland into the body; then the key type lock is brought into the mating slot in the body by the knurled nut. This gives a positive lock between the body and gland so that vibration, etc. will not alter the pressure setting. This regulator controls oxygen back-pressure on the electrolysis module in the WES. Vendor bench tests with N_2 gas on the unit prior to delivery are included in Table VII.

Performance of the unit during all WES testing was excellent at the adjusted levels of 827, 1793 and 2758kN/m^2 (120, 260, and 400 psig) regulated oxygen pressure used during automatic system operation. No seat leakage was ever observed below set cracking pressure.

3.3.5 Hydrogen Absolute Back-Pressure Regulator

A unit identical in design to the oxygen absolute back-pressure regulator was fabricated by Ausco, Inc. as P/N 356-02 to meet requirements for a hydrogen absolute back-pressure regulator per Specification No. 73A490-830 Rev. B contained in the appendix.

Vendor bench tests with helium gas on the unit prior to delivery are included in Table VIII. Adjusted levels of regulated hydrogen pressure were established at 620, 1517, and 2413kN/m^2 (90, 220, 350 psig) during automatic system operation. Pressure regulation and poppet sealing at lock-up conditions was observed to be excellent.

A regulator failure occurred on 12-31-74 at 2413kN/m^2 (350 psig) operating pressure after 619 hours of operation and an estimated 400,000 open/close cycles caused by cyclic operation of the solenoid valve on the phase separator. Disassembly of the valve assembly revealed a cracked bellows. The bellows manufacturer attributed failure to cyclically applied high stress condition on the diaphragm. Recommendations for substantially increased cycling capability would be to increase diaphragm thickness from .152 to .178 cm (.006 to .007 inch).

A spare bellows assembly was installed in the failed regulator which was re-installed in the WES for resumption of testing on 1-3-75. Because this assembly continued the original bellows design, efforts were made to reduce the cyclic nature of phase separator solenoid valve operation as discussed in Para. 3.3.2.

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DIRECT ENERGY CONVERSION PROGRAMS

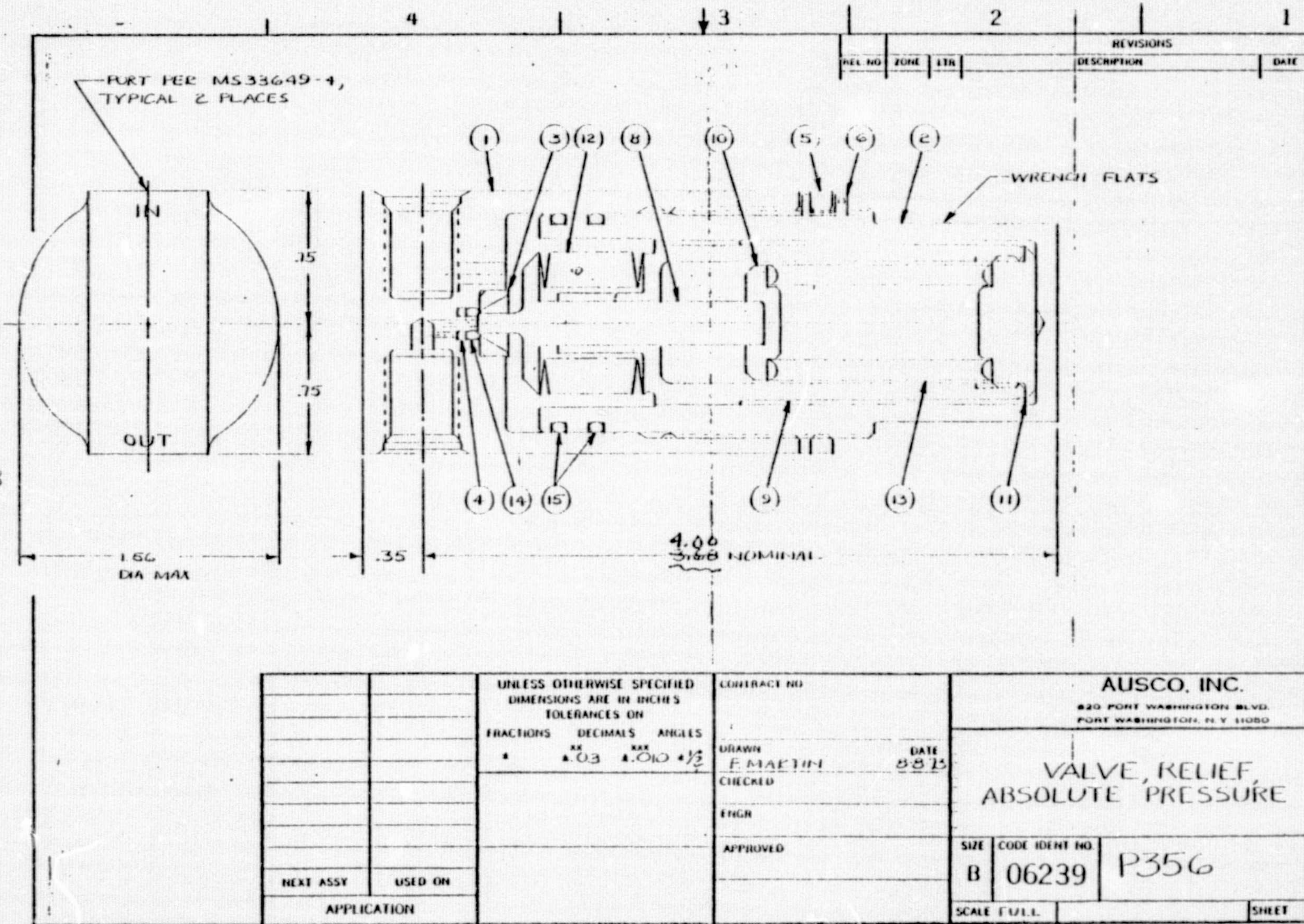

Figure 37.

GENERAL ELECTRIC

Table VII

FORM #D5

AUSCO, INC.

VALVE ASS'Y. FUNCTIONAL TEST TRACEABILITY REPORT

ASS'Y. # P356-01 ASS'Y. LOT # SERIAL # 2

ASS'Y. DWG # P356 REV. B DATE 3-25-74

DESCRIPTION OF TEST GE 73A490-831 REV. B

ITEM S/N	PROOF 653 psig		CRACK	FULL FLOW *	RESEAT				UNIT S/N
TST 1			91	93	90			PSIG	
TST 2			490	500	485				
TST 3			410	415	405				

* UNIT TESTED ON N_2 ; .329 CU FT/MIN OF N_2 IS EQUIVALENT TO 1.75 LB/HR OF O_2

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Table VIII

FORM #D5

AUSCO, INC.

VALVE ASS'Y. FUNCTIONAL TEST TRACEABILITY REPORT

ASS'Y. # P356-02 ASS'Y. LOT # 1 SERIAL # 1

ASS'Y. DWG # P356 REV. B DATE 3-25-74

DESCRIPTION OF TEST G.E. 73A490-830

(Unit) S/N	Proof 512 psig		Crack	Full Flow *	Reseat			Unit S/N
	✓							
Test 1			95	97	94	PSIG		
Test 2			510	518	495	PSIG		
Test 3			355	359	345	PSIG		

* UNIT TESTED WITH He: .987 $\frac{cu\ ft}{min}$ OF He IS EQUIVALENT TO .22 $\frac{LB}{HR}$ OF H_2

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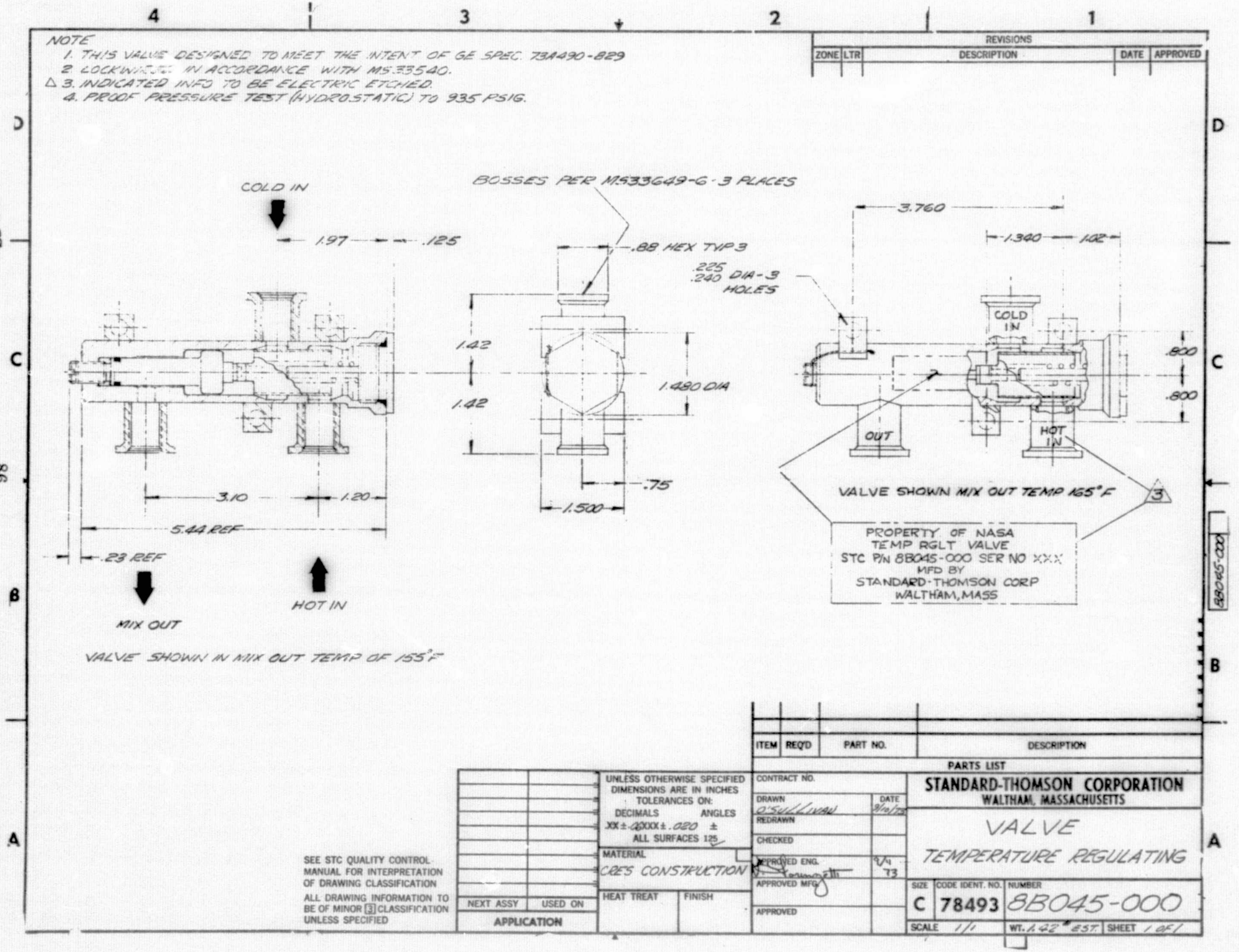
3.3.6 Water Temperature Regulating Valve

The water temperature regulating valve controls the process water temperature entering the electrolysis module. This valve mixes the water heated by the regenerative heat exchanger with a portion of the process water which bypasses the regenerative heat exchanger to maintain essentially constant temperature leaving the valves. Electrolysis module performance is improved by the higher operating temperature, remains independent of changes in coolant and ambient temperature at high load and module warm-up time is reduced. The water temperature regulating valve was designed and fabricated by Standard-Thomson Corp., Waltham, Massachusetts in accordance with Specification No. 73A490-829 Rev. B contained in the appendix. A drawing of the unit is shown in Fig. 38. Valve function is performed by an internal spool or actuator which contains a hermetically sealed eutectic wax. Expansion and contraction of the wax due to temperature variations results in valve displacement and subsequent proportioned mixing of "hot" and "cold" entering water.

Performance of the temperature regulating valve installed in the WES was excellent throughout system testing at all water flow conditions. Water discharge temperature was controlled usually within 2K (3.6°F). of the regulated setting of 339K (150°F). This controlled temperature is maintained for all module loads greater than 50 amps which provide a module heat rejection sufficient to raise the temperature of process water flowing through the regenerative heat exchanger and to the "hot" water inlet part of the temperature regulator to a value above 339K (150°F). At module loads below 50 amps the temperature regulating valve is closed to the "cold" water inlet part so no process water by-passes the regenerative heat exchanger and module water inlet temperature see's a lower level of thermal equilibrium (See Figure 26).



NOTE
1. THIS VALVE DESIGNED TO MEET THE INTENT OF GE SPEC. 73A490-829
2. LOCKWIRE IN ACCORDANCE WITH MS33540.
3. INDICATED INFO TO BE ELECTRIC ETCHED.
4. PROOF PRESSURE TEST (HYDROSTATIC) TO 935 PSIG.
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
COLD IN
1.97
.125
BOSSES PER MS33649-G-3 PLACES
.88 HEX TYP 3
.225
.240 DIA-3 HOLES
3.760
1.340
1.02
COLD IN
1.42
1.42
1.480 DIA
.800
.800
OUT
HOT IN
.75
1.500
3.10
1.20
5.44 REF
.23 REF
VALVE SHOWN MIX OUT TEMP 165°F
3
PROPERTY OF NASA
TEMP RGLT VALVE
STC P/N 8B045-000 SER NO XXX
MFD BY
STANDARD-THOMSON CORP
WALTHAM, MASS
MIX OUT
HOT IN
VALVE SHOWN IN MIX OUT TEMP OF 155°F
8B045-000
ITEM
REQ'D
PART NO.
DESCRIPTION
PARTS LIST
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON:
DECIMALS
ANGLES
XX ± .03 XXX ± .020 ±
ALL SURFACES 125
CONTRACT NO.
DRAWN
O'SULLIVAN
DATE
REDRAWN
CHECKED
APPROVED ENG.
APPROVED MFG.
APPROVED
73
STANDARD-THOMSON CORPORATION
WALTHAM, MASSACHUSETTS
VALVE
TEMPERATURE REGULATING
MATERIAL
CRES CONSTRUCTION
HEAT TREAT
FINISH
SEE STC QUALITY CONTROL MANUAL FOR INTERPRETATION OF DRAWING CLASSIFICATION
ALL DRAWING INFORMATION TO BE OF MINOR 3 CLASSIFICATION UNLESS SPECIFIED
NEXT ASSY
USED ON
APPLICATION
SIZE
CODE IDENT. NO.
NUMBER
C
78493
8B045-000
SCALE 1/1
WT. 1.42 EST.
SHEET 1 OF 1

Figure 38.

3.3.7 Process Water Deionizer

On the basis of makeup water supplied to the WES having total dissolved solids of 5 PPM (Refer Guideline Spec. in Table III), a mixed deionizer bed size of about 80cc was determined for water consumption of 7.7Kg (17 lb.) /day for 60 days at 50 percent bed efficiency. Because of internal generated metal ion contaminants resulting from slight corrosion of stainless steel (primarily type 316) components in the process water loop, the bed size was increased to 500 ML utilizing a commercially available, high pressure gas sampling cylinder as a container. (Model No. 6-645-2520, Matheson Gas Products, Type 304SS, 1800 psig rating). This container was machined with 9/16-18 UNF female threads on each end and internally coated with .15mm (.006") thick gray durathane by American Durifilm Co., Inc., Newton Lower Falls, Massachusetts for corrosion resistance. To the internal face of a commercial outlet fitting was spot welded 100 mesh, type 310 stainless steel screen A '^ micron in-line filter P/N 20666-4-40, Mectron Industries, Inc., South El Monte, California was installed in the outlet line. The container was filled with Universal I monobed resin, Illinois Water Treatment Co., Rockford, Illinois and with glass wool packed between the resin bed and fitting at each end. The results of these water flow pressure drop tests on 2-5-74 are plotted in Fig. 39.

Because of reduced water flow rate on 11-11-75 the deionizer in-line filter was removed and found plugged with fines from the resin bed. Further inspection revealed many dionizer beads in the water line between the phase separator/ pump and inlet to the deionizer. The latter was expected to occur a few days previous during which rapid depressurization from 2413kN/m^2 (350 psig) of the system without the phase separator/pump operating because of a leaky H_2 vent valve (Item 28-1). Rapid venting of hydrogen and water from the two-phase region causes flow surges, and in this case, high flow reversal through the deionizer thus dislodging the beads into the inlet line. Inspection of the resin bed indicated considerable anion resin material had degraded to a fine powder.

The inlet fitting of the deionizer was also provided with 100 mesh screen filter to retain resin beads in the event of flow reversal. The container was re-filled with Mixed Bed Resin AG501-X8 from BIO-RAD Laboratories, Richmond, California having a 20-50 mesh bead size which was used with good results in other laboratory work. The degraded resin from Illinois Water Treatment Co., was evidently the result of a quality control problem. The result of a water flow pressure drop test on this configuration is also plotted in Fig. 39.

Following a WES test demonstration on 2-11-75 the system was depressurized without the phase separator/pump operating and with water flow control valve (Item 30-2) inadvertently closed. This condition resulted from trapping rather than expelling from the process water the hydrogen outgassed during depressurization. Subsequent system start up revealed a reduced water flow rate. A bench flow test with water indicated no problem with the deionizer as the data

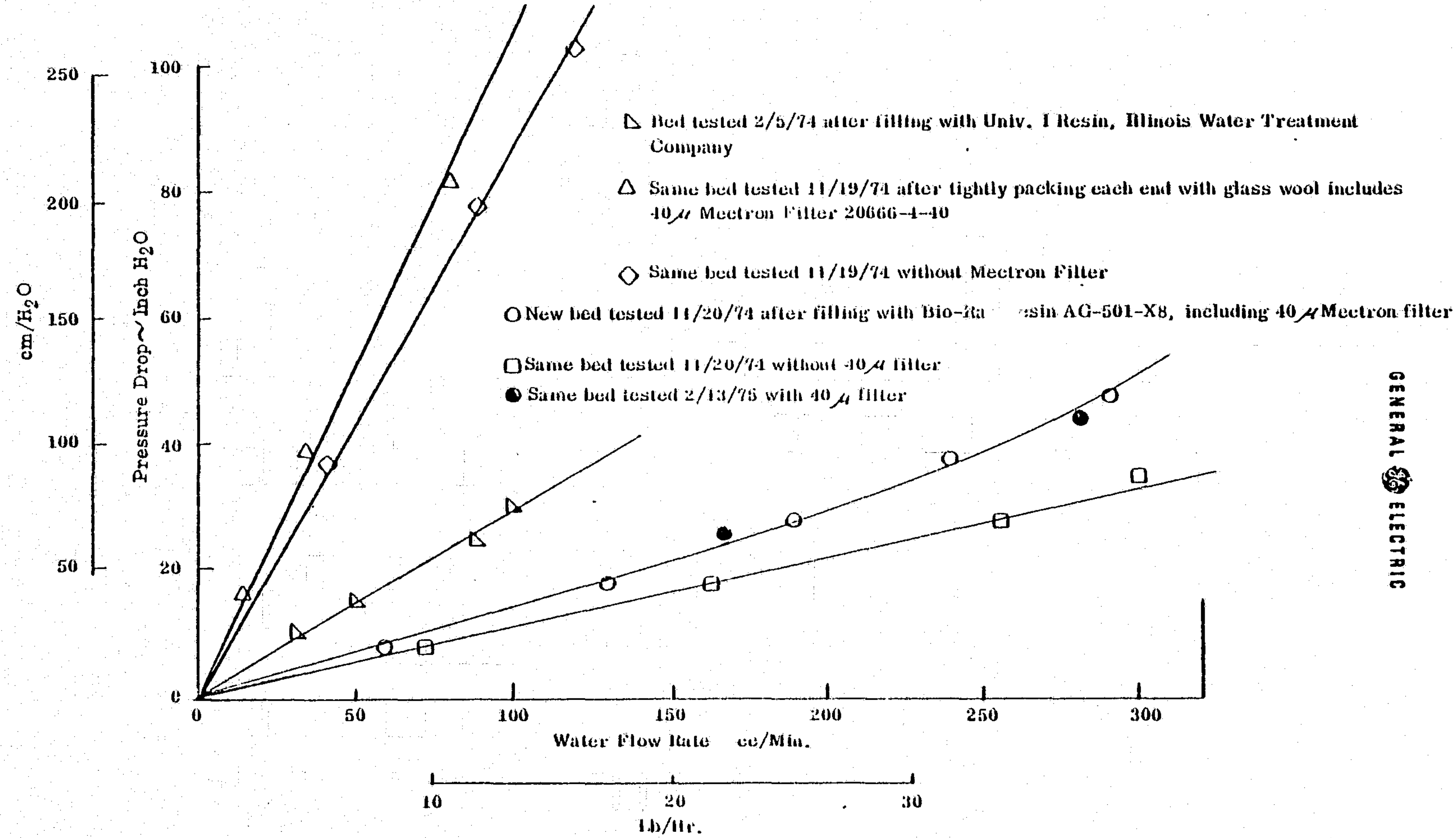


Figure 39. Deionizer Bed Pressure Drop Versus Water Flow Rate

shown in Fig. 39. Checks on other components of the process water circuit also revealed no problem. Further evaluation of the deionizer showed that a gas bound deionizer bed can initially block water flow (top to bottom at 1g) up to 12.5kN/m^2 (50" H_2O) but that gradual water seapage and recirculation will remove the entrained gas. This condition was never experienced again during repeated WES depressurizations with the phase separator/pump operating and circulating the process water to remove entrained hydrogen evolved at low pressure.

3.3.8 O_2/H_2 Mixture Sensor

Although a General Monitors Corp. combustible gas detector (Item 22, Table I) was used in the WES to sense external hydrogen leakage to ambient, there remained a need for a sensor for detecting potential mixtures of O_2 and H_2 existing in internal lines resulting from possible internal electrolysis module leakage. Operation at high system pressure compounded the problem.

A catalytic sensor was devised by attaching a platinum electrode (as used in SPE fuel and electrolysis cells) to a stainless steel sheathed platinum resistance temperature probe which could be exposed to an O_2/H_2 mixture in a high-pressure fluid line. A successfully tested configuration consisted of a pressed electrode made with platinum black and expanded tantalum screen which was wrapped around and tack welded to a .64 cm (1/4 inch) dia. sheath x 14 cm (5-1/2 inch) long resistance temperature detector P/N GP70-A1-P200-B manufactured by RDF Co., Hudson, N. H. This catalytic sensor probe was inserted in the horizontal leg of a 3/8 inch Swagelok Tee and fastened and sealed with a 3/8 to 1/4 reducer.

The O_2/H_2 mixer sensor was bench tested with various mixtures of oxygen and hydrogen injected in the vertical leg of the Tee. The flow of gas mixture impinged on the sensing probe, which was heated by combination of O_2 and H_2 on the platinum black surface and ejected out one horizontal leg of the Tee. Measured sensor temperatures versus the percentage of O_2 in H_2 or H_2 in O_2 are plotted in Fig. 40. Two sensors were installed in the system. The O_2 in H_2 mixture sensor (Item 32-1) was installed in the hydrogen upstream of the hydrogen back pressure regulator to prevent exposure to air during shutdown. The H_2 in O_2 mixture sensor (Item 32-2) was installed in the oxygen output line between the oxygen back pressure regulator and O_2 flowmeter. Automatic emergency shutdown was set for 333K (140°F) for the O_2 in H_2 sensor and 359K (187°F) for the H_2 in O_2 sensor. The latter setting was higher because oxygen leaving the insulated oxygen regulator can reach about 327K (130°F)

Inspection of these sensors after about 1000 hours operation showed that the platinum black had spalled off particularly the O_2 in H_2 sensor. This erosion was caused by water impringement at rather high velocity when present in the discharge lines. Recommended modifications would be to improve the adhesion of the catalyst with more binder and a smaller screen grid. Also, erosion would be reduced with a baffle or shield in the impact zone and probe installation in a 1/2 inch Tee size to reduce local gas velocities.

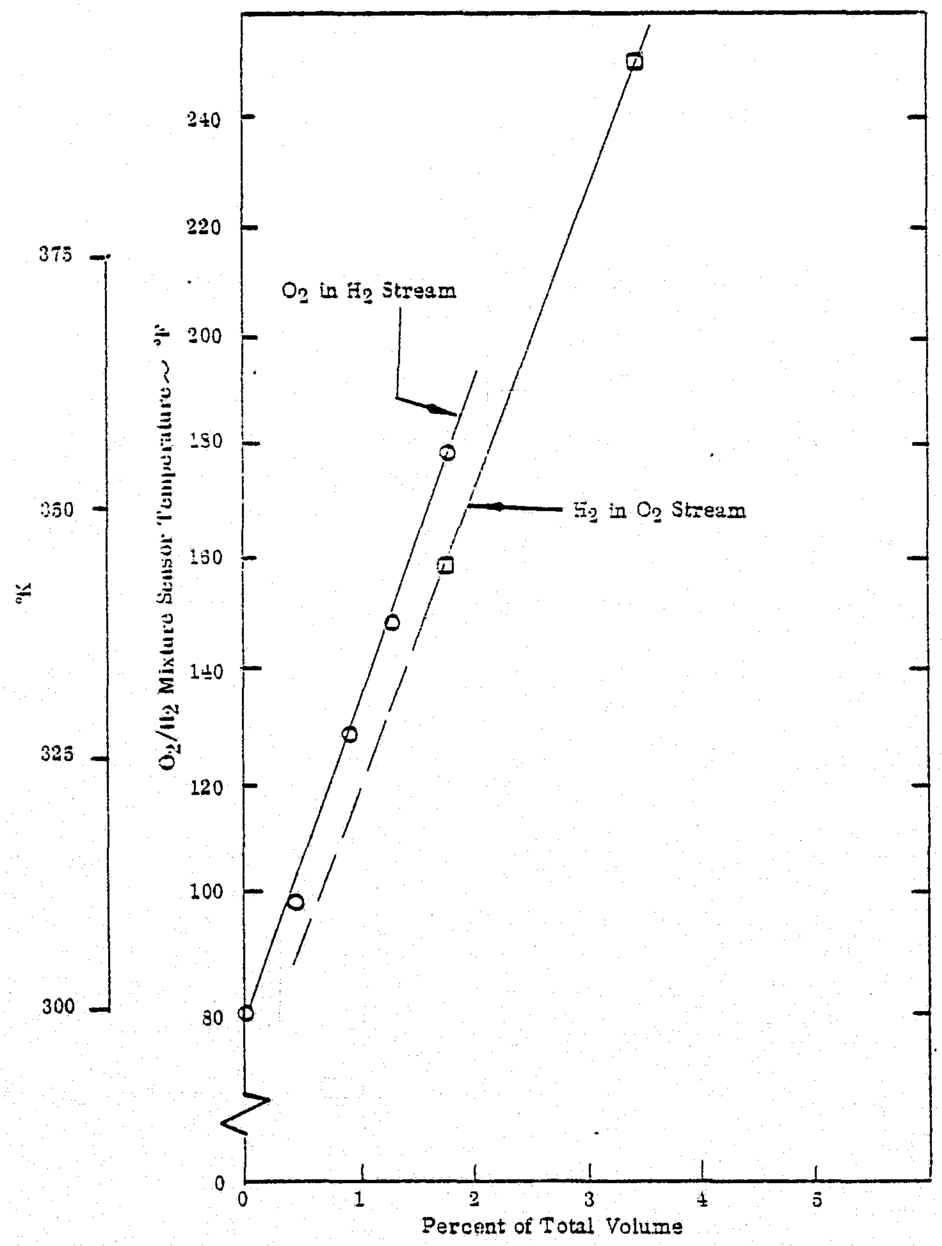


Figure 40. Gas Mixture Temperature vs. Percent by Volume in O_2/H_2 Mixture Sensor

3.4 System Development and Test Results

3.4.1 System Design Analysis

Advance system development under Phase II of the subject contract included the design, fabrication and procurement, assembly and test of a six-man rated pre-prototype WES. Various proposed systems were studied which would include an advanced electrolysis module capable of six-man oxygen generation rate and a dynamic phase separator. With the concurrence of Mr. R. B. Martin, NASA/JSC, Contract Technical Monitor, the system selected included an advanced electrolysis module, a dynamic phase separator/pump and other ancillary components to provide pure oxygen and hydrogen generation at high pressure (nominal 2860kN/m^2, 415 psia) and (nominal 355K, 180° F) module average temperature. This system would include, where possible for cost effectiveness, former NAS1-9750 contract components with necessary modifications and off-the-shelf commercial components meeting functional requirements. The existing 13-cell electrolysis module would be modified for operation at high pressure, high temperature and accompanying high current density to increase capacity from a four-man to a six-man rating. This pre-prototype water electrolysis system would be packaged and contain suitable controls and display for safe, unattended operation.

Tests on the four-man breadboard WES were conducted to provide data for predicting pressure drop in the water and two-phase circuit at high pressure conditions. Figure 41 shows measurements of pressure drop versus electrolysis module current for process water flow rates of 4.53, 6.79 and 9.16kg/hr.(10, 15 and 20 lb/hr.). Differential pressure was measured across a series of components in combination: (1) deionizer, water temperature regulator and electrolysis module in one group; and (2) check valve, regenerative heat exchanger and primary heat exchanger in another group. Pressure drop of Group (1) was essentially independent of hydrogen generation rate or module current exhibited by flow through screens in the cells. Pressure drop in Group (2) was dependent upon both water and hydrogen flow caused by two-phase slug flow in the tubing of the heat exchangers. Nominal line pressure was 310kN/m^2 (45 psia).

From the test data, hydrogen and water volumetric flow rates were calculated to generate Figure 42, which shows pressure drop in the two-phase region (Group (2) components in series) as a function of hydrogen/water volume ratio. The significance of this volume ratio is illustrated by Figure 43 at design water flow rate, mean fluid temperature at various system operating pressures. As indicated by the dashed line, at constant water flow the hydrogen volumetric rate at 23 amps, 690kN/m^2 (100 psia), is equivalent to 75 amps at 691kN/m^2 (350 psia). A map of predicted system pressure-flow characteristics are given in Figure 44 with estimated performance of the phase separator/pump.

Analysis of the water electrolysis module was made to predict performance at 2760kN/m^2 (400 psia) oxygen pressure, 2413kN/m^2 (350 psia) hydrogen

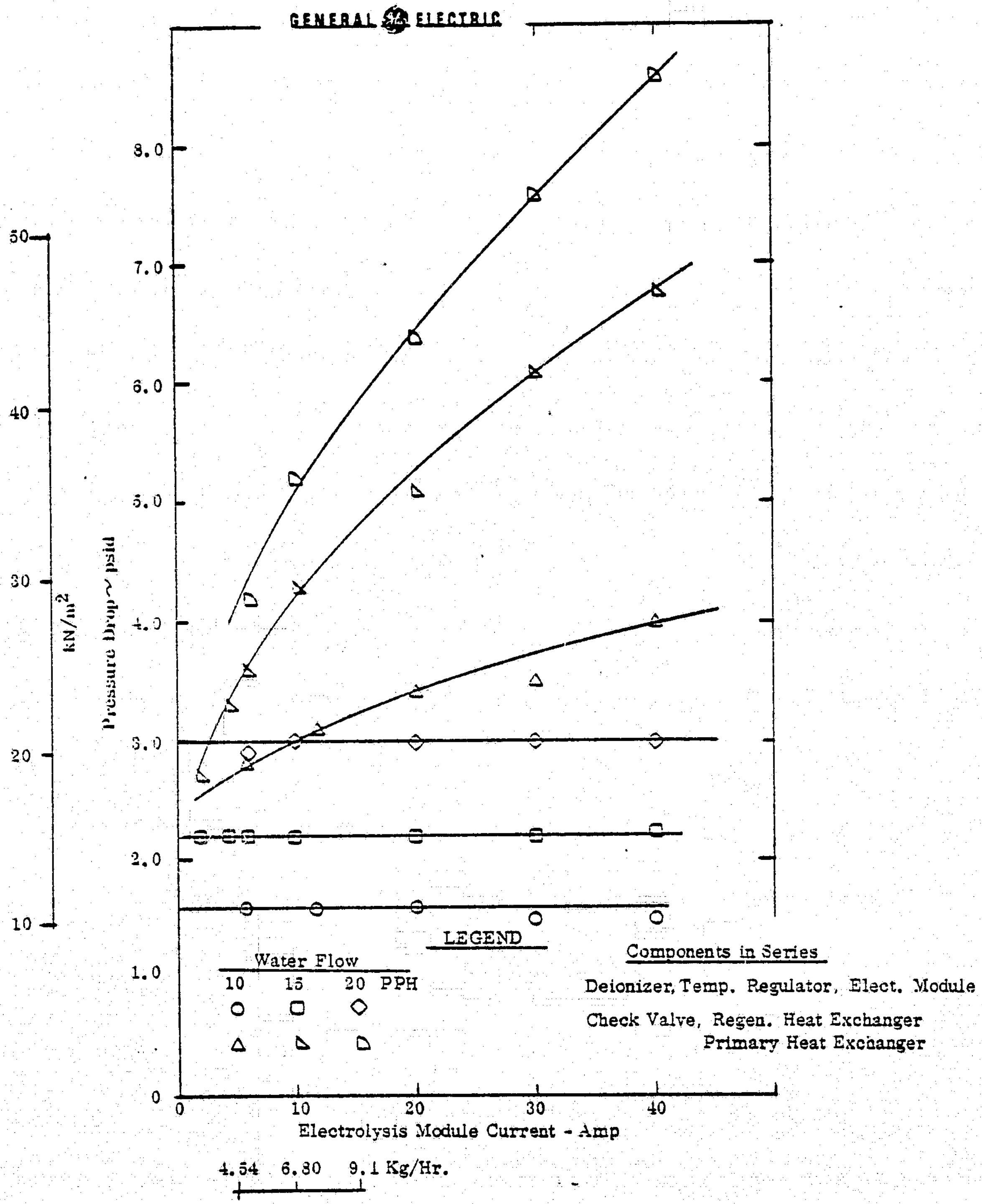


Figure 41. WES Components Pressure Drop Vs. Electrolysis Module Current at Constant Water Flow

C. 2

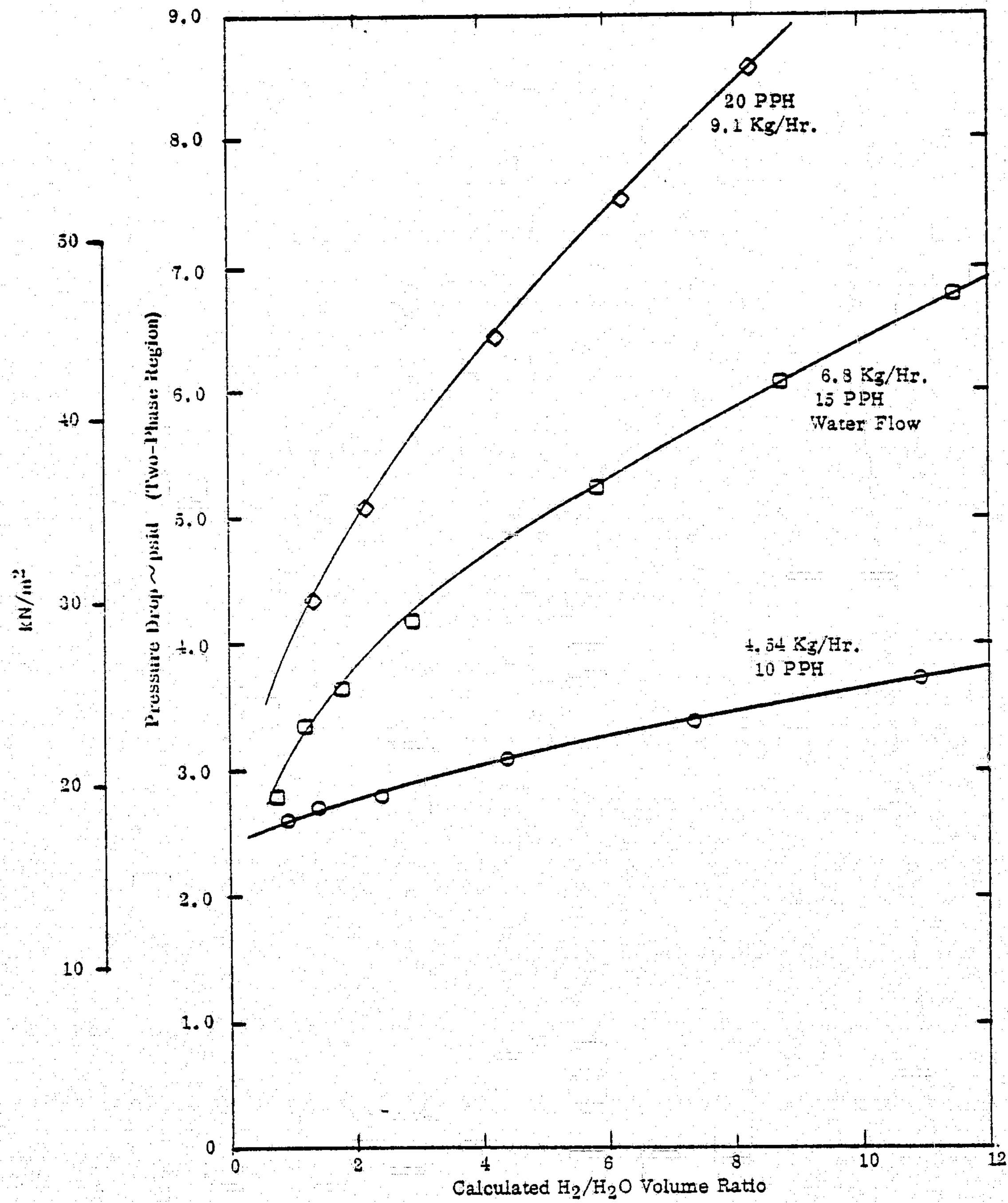


Figure 42. WES Two-Phase Components Pressure Drop Versus Calculated Gas/Liquid Volume Ratio at Constant Water Flow

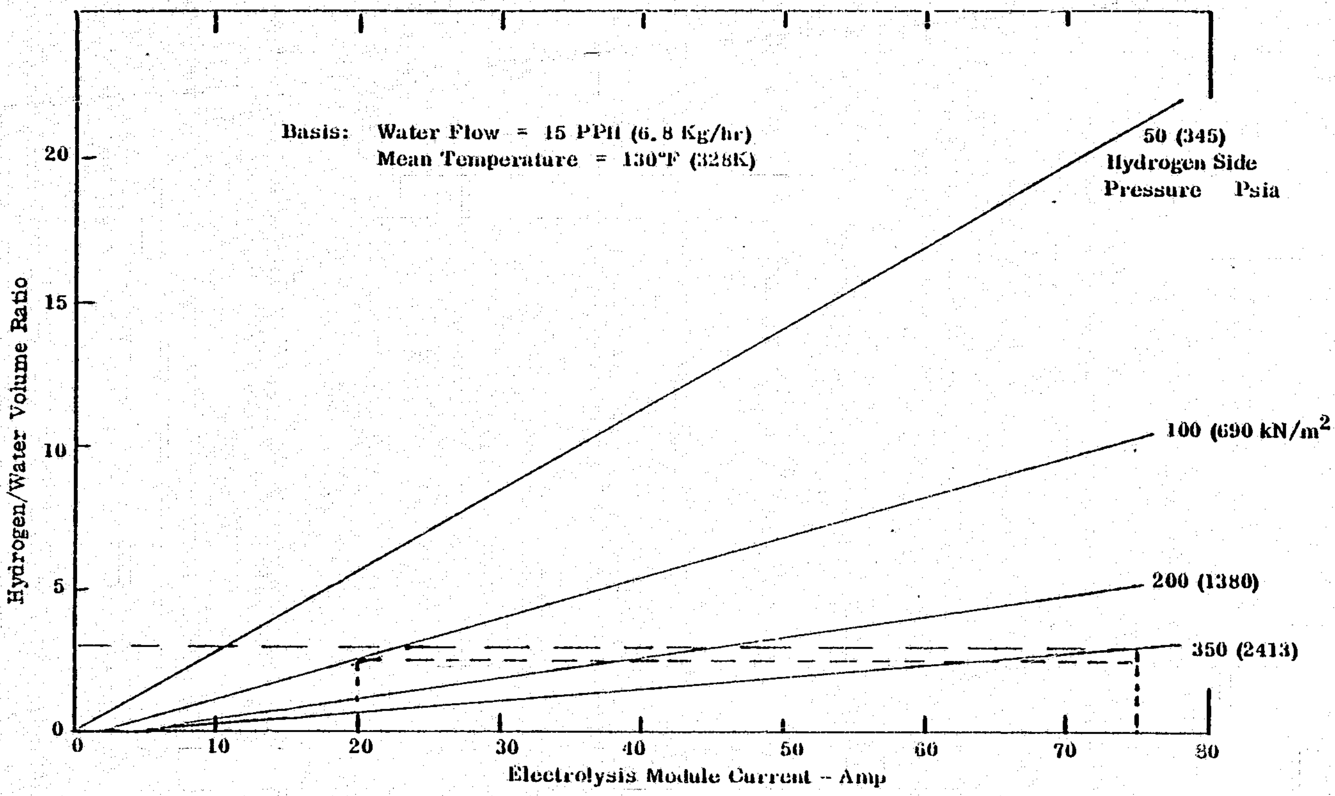


Figure 43. Calculated Hydrogen/Water Volume Ratio Versus Electrolysis Module Current at Different H_2 Side Pressures

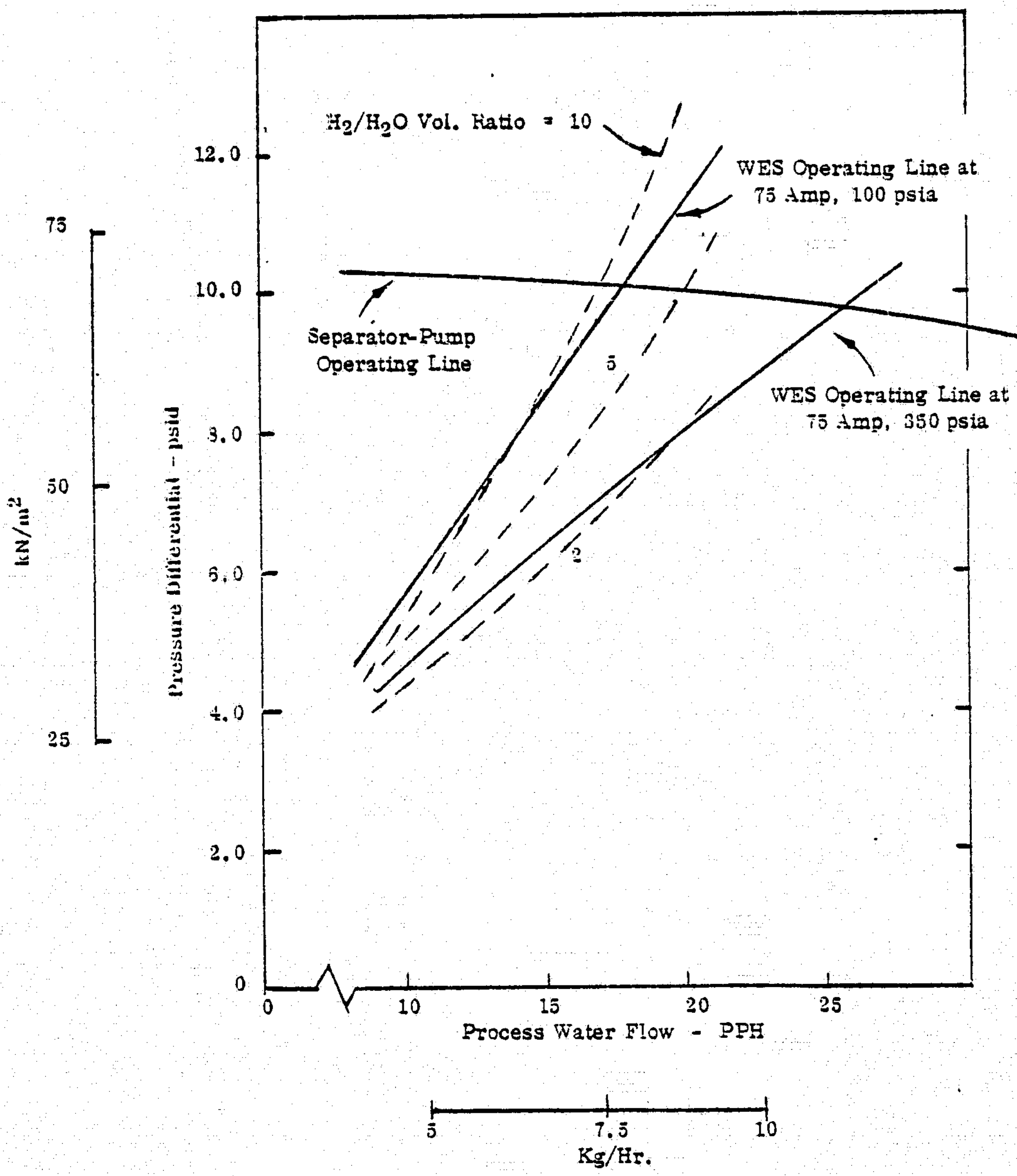


Figure 44. Dynamic Phase Separator-Pump Calculated Pressure - Flow Characteristics

pressure, and a mean cell temperature of 355k (180°F). At high pressure, and temperature parasitic losses are increased. This is particularly due to diffusion of gases across the solid polymer electrolyte (SPE) membrane. A parasitic current of about 5 amps was expected at the cited conditions, requiring process water flow of about 20 lb/hr. to limit the cell temperature gradient to 22k (40°F). A higher process water flow could reduce module temperature gradients, but increase system pressure drop and pump requirements.

A volume study of the proposed system was also performed to predict water content retention on the two-phase side especially during oxygen generation rate changes of cyclic operation, startup and shutdown. Since the volume ratio of water to gas varies as a function of O_2 generation rate (process water rate is essentially constant), it becomes necessary to provide a water accumulator of adequate storage capacity within the process water loop of the system.

Definition of the advanced system configuration resulted in the requirement of those major components listed in Table IV on Page 37 installed as shown in the functional schematic in Figure 16 which was described earlier. Some small but no basic revisions were made in the course of development. A safety study and a failure mode and effect analysis (FMEA) were performed to establish single point failures. A fault detection and isolation analysis (FDIA) was also made to establish fault sensors and monitoring equipment requirements of the WES installation. The FMEA is included in Table IX accompanied by the guideline criteria used in conducting the analysis. A summary of the fault conditions, derived from the FDIA, which result in an automatic safe emergency shutdown (ESD) of the system is provided in Table X. The limit values and hold periods shown are those set for high pressure operation at the WES design point. Most of the limit values and hold periods were established in advance from design criteria which defined emergency controller logic and shutdown requirements. Potentiometer adjustments for setting all pressure limits provide for system operation and automatic ESD at any selected pressure level and allowed for component and system variations experienced during development.

Table IX

Failure Mode and Effects Analysis

Guideline Criteria

a) For the purpose of the Failure Mode and Effect Analysis, the term "failure" is defined as a structural break, a change in dimension or a change in functional characteristics to the extent that the part or component no longer performs within specification limits.

b) In the interest of cost effectiveness, monitoring and recording is performed manually by an operator.

c) In the interest of cost effectiveness, isolation is indicated by lights. When two or more lights are indicating, further investigation will be necessary to isolate the failure and cause.

d) In the interest of cost effectiveness, redundancy of instrumentation to provide a voting validation of a fault at the same location is not included in this pre-prototype WES.

e) Only the major components of the WES (Table IV, Figure 16) will be considered in the FMEA.

f) Although the NASA/JSC WES components are considered "non-flyable" breadboard hardware, the FMEA will be evaluated for severity of consequences, with failures categorized in accordance with space station classes as:

Class	Description
I	A single failure which could cause loss of personnel.
IIA	A single failure whereby the next associated failure could loss of personnel.
IIB	A single failure that could cause return of one or more personnel to earth, or loss of subsystem function(s) essential to continuation of space operations and scientific investigation.
III	A single failure which could not result in loss of primary or secondary mission objectives or adversely affect crew safety.

Table IX

WES FAILURE MODE AND EFFECT ANALYSIS

6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
1.	Water Electrolysis Module	To generate oxygen and hydrogen by electrolysis of water proportional to input current.	a) Mixture (O_2 to H_2/H_2O side), internal cross leakage.	Cell assembly gasket displacement, deterioration or rupture; solid polymer electrolyte (SPE) membrane preforation or rupture.	WES will automatically shutdown by oxygen sensing in H_2 outlet or by hydrogen sensing in O_2 outlet.	III	Temperature rise of catalytic O_2/H_2 mixture sensor. Temperature rise of H_2/H_2O fluid at module outlet (Items 32-1, 32-2, 21).	Red "O_2 in H_2" or "H_2 in O_2" or "Mod Temp High" light on.	
			b) Internal cross leakage, N_2 in dome to O_2 or H_2/H_2O sides.	Cell assembly gasket displacement, deterioration or rupture.	Pressure decay of trapped N_2 in module dome, dilute output gases with N_2. WES will ESD (i.e., automatic emergency shutdown).	III	Dome pressure on Press Trans (Item 17-4) drops below low limit.	Red "N_2 Dome Low" light on.	
			c) External leakage of N_2.	Loss of gland or O-ring seals by permanent set or deterioration. Fracture of dome.	Pressure decay of trapped N_2 in module dome. N_2 to cabin. WES will ESD.	III	Same as (b).	Same as (b).	
			d) External leakage of O_2.	Loss of O-ring seal at module end plate tube connections.	Gross leak will drop O_2 pressure below O_2 regulated pressure. WES will ESD. Small leak has no effect.	III	O_2 pressure on Press Trans (Item 17-2) falls below low limit.	Red "O_2 Low" light on.	
			e) External leakage of H_2 or H_2O.	Same as (d)	a) Gross leak will drop H_2/H_2O pressure below H_2 regulated pressure. WES will ESD. H_2 and/or H_2O will vent to cabin. WES will ESD.	III	a) Two-phase pressure on Press Trans (Item 17-3) falls below low limit.	Red "2Ø Low" light on.	
					b) H_2 small leak to cabin. WES will ESD.		b) Combustible Gas Detector (Item 22) exceeds high limit.	b) Red light on CGD, Item 22.	
					c) H_2O small leak to cabin. No ESD.		c) Visual inspection by crew.	c) Location of H_2O drop formation.	
			f) Performance decay (i.e., higher input voltage required at current setting to generate desired O_2 and H_2 rate).	Increased cell(s) impedance due to (1) water starvation, (2) SPE ion contamination, (3) low contact pressure (4) corrosion of current collector.	Module terminal voltage will increase until WES will ESD.	III	Output voltage sensing on Power Conditioner (Item 11) exceeds high limit.	Red "Mod Volt High" light on.	
			g) H_2/H_2O side restriction.	Contamination clogging cell(s) H_2/H_2O side flow passages.	Water starvation of one or more cells. WES will ESD on module high voltage.	III	Same as (f).	Same as (f).	
2-1 2-2	Redundant N_2 Input Check Valves to H_2 Side	To prevent H_2 feed back to N_2 supply line.	Valve(s) stuck closed.	Contamination.	a) Unable to pressurize H_2 side with N_2 during system pressurization prior to start-up	III	a) Pressure Trans. (Items 17-1, 17-3) show no increase on display meters when $P_{N_2} > P_{H_2}$. Visual readout.	a) Remove both check valves and separately bench test.	
					b) H_2 pressure falls below N_2 base pressure during normal, cyclic (WES will ESD) or emergency shutdown.		b) Items 17-1 and 17-3 fall below low limit setting for cyclic operation.	b) Red "2Ø Low" light on, perform (a).	
			One valve stuck open.	a) Contamination and/or spring rupture.	No effect with redundant units.	III	None.	Remove both check valves and separately bench test.	

Table IX

Sheet 2 of 11
Date: 9-20-74

GENERAL ELECTRIC

WES FAILURE MODE AND EFFECT ANALYSIS

6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
2-1 2-2	Continued		Two valves stuck open.	Same as (a), both valves.	H_2 admission into N_2 supply line, gradual mixture admission to O_2 side after normal, cyclic or emergency shutdown. WES will ESD on restart.	III	Temperature rise of catalytic O_2/H_2 mixture sensor (Item 32-2).	Red "H_2 in O_2" light on.	
			External leakage	Seal material set or loose connection.	a) N_2 side, eventual exhaustion of N_2 supply to cabin. WES will ESD.	III	a) N_2 pressure on Press Trans (Item 17-5) falls below low limit.	Red "N_2 Base Low" light on.	
					b) H_2 side, H_2 leakage to cabin. WES will ESD.		b) Comb. Gas Detector exceeds high limit.	Red light on CGD, Item 22.	
2-3 2-4	Redundant N_2 Input Check Valves to O_2 Side	To prevent O_2 feed back to N_2 supply line.	Valve(s) stuck closed.	Contamination.	a) Unable to pressurize O_2 side with N_2 during system pressurization prior to start-up.	III	a) Press Trans (Item 17-2) shows no increase on display meter when $P_{N_2} > P_{O_2}$. Visual readout.	a) Remove both check valves and separately bench test.	
					b) O_2 pressure falls below N_2 base pressure during normal, cyclic (WES will ESD) or emergency shutdown.		b) Item 17-2 falls below limit setting for cyclic operation.	b) Red "O_2 Low" light on. Perform (a).	
			One valve stuck open.	a) Contamination and/or spring rupture	No effect with redundant units.	III	None	Remove both check valves and separately bench test.	
			Two valves stuck open.	Same as (a), both valves.	O_2 admission into N_2 supply line. Mixture admission into H_2/H_2O side after normal, cyclic or emergency shutdown. WES will ESD on restart.	III	Temperature rise of catalytic O_2/H_2 mixture sensor (Item 32-1).	Red "O_2 in H_2" light on.	
			External leakage.	Seal material set or loose connection.	a) N_2 side, eventual exhaustion of N_2 supply to cabin. WES will ESD.	III	a) N_2 pressure on Press Trans (Item 17-5) falls below low limit.	a) Red "N_2 Base Low" light on.	
					b) O_2 side, O_2 leakage to cabin. No effect unless gross leakage (see Item 1, Failure Mode d).		b) None.	b) None.	
2-5	Makeup Water Check Valve	To prevent drain back of high pressure process water (and H_2) to low pressure makeup water supply.	Valve stuck closed.	Contamination.	Unable to resupply process water loop with makeup water. WES will ESD.	III	Water Accumulator (Item 16) "Empty" position switch remains actuated beyond 20 sec. limit.	Red "Accum Empty" light on.	Makeup Pump Ass'y. (Item 4) has outlet check valve, so Item 2-5 is redundant.
			Valve stuck open.	Contamination and/or spring rupture.	a) No effect if outlet check valve on makeup pump (Item 4) checks properly.	III	a) None.	a) Remove and bench test.	
					b) If outlet check valve on makeup pump fails open, WES will ESD.		b) H_2/H_2O pressure on Press Trans (Item 17-3) falls below low limit.	b) Red "2Ø Low" light on.	
			External leakage.	Seal material set or loose connection.	a) Gross leak on high pressure side will drop H_2/H_2O pressure to cause ESD.	III	a) H_2/H_2O pressure on Press Trans (Item 17-3) falls below low limit.	a) Red "2Ø Low" light on.	
					b) H_2O small leak to cabin. No ESD.		b) Visual inspection by crew.	b) Location of H_2O drop formation.	

Table IX

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Date: 9-20-74

WES FAILURE MODE AND EFFECT ANALYSIS

6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

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Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
2-6	Water Accumulator Check Valve	Allows quick fill of water accumulator from 2Ø loop during start-up or load change transients. Prevents reverse surge during this transient and when makeup water pump (Item 4) is operating.	Valve stuck closed.	Contamination.	H_2/H_2O pressure will suddenly increase during start-up or increase in load. WES will ESD.	III	H_2/H_2O pressure on P. T. (Item 17-3) will exceed high limit.	Red "2Ø High" light on.	
			Valve stuck open.	Contamination and/or spring rupture.	Reverse surge of water from accumulator to 2Ø loop could cause ΔP cycling in loop and spitting of separator/pump to H_2 outlet. Probable ESD.	III	H_2/H_2O pressure on P. T. (Item 17-3) will exceed high limit during pressure surge.	Red "2Ø High" light on.	Pressure measurements and transient behavior of 2Ø loop to be investigated with Item 2-6 removed during WES development tests.
			External leakage.	Seal material set or loose connection.	a) Gross leak will drop H_2/H_2O pressure to cause ESD.	III	a) H_2/H_2O pressure on P. T. (Item 17-3) falls below low limit.	a) Red "2Ø Low" light on.	
					b) H_2O small leak to cabin. No ESD.		b) Visual inspection by crew.	b) Location of H_2O drop formation.	
3	Makeup Water Filter	To remove particulate material from water supplied to makeup pump (Item 4).	High filter ΔP or no water flow.	Partial or complete clogging by contamination. Loss of makeup water supply pressure.	Makeup pump suction pressure is low when operating. WES will ESD.	III	Pressure at pressure switch (Item 19) falls to actuation point.	Red "Makeup H_2O Low" light on.	
			External leakage.	Seal material set or loose connection.	H_2O leakage to cabin. No ESD.	III	Visual inspection by crew.	Location of H_2O drop formation.	
4	Makeup Water Pump	To supply makeup water to high pressure process water loop.	No water delivery to water accumulator.	Failure of motor, drive mechanism, plunger seal leak, or stuck inlet or outlet check valves	a) Unable to supply process water loop with makeup water. WES will ESD.	III	Water accumulator (Item 16) "Empty" position switch remains actuated beyond 20 sec. limit.	Red "Accum Empty" light on.	
			External leakage.	Seal material set or loose connection.	H_2O leakage to cabin. No ESD unless leak exceeds output as in (a).	III	Visual inspection by crew.	Location of H_2O drop formation.	
5	Coolant Water Filter	To remove particulate material from cooling water supplied to WES.	Low or no water flow.	Partial or complete clogging by contamination.	WES will ESD at coolant flow under 0.2 gpm.	III	Coolant flow under 0.2 gpm will actuate flow switch, (Item 25).	Red "Cool Flow Low" light on.	
			External leakage.	Seal material set or loose connection.	H_2O leakage to cabin. No. ESD.	III	Visual inspection by crew.	Location of H_2O drop formation.	
6	Electronic Controller for Phase Separator/Pump (Item 8)	Provides manual switches and electronic control for energizing separator/pump motor and solenoid valve.	Loss of power input to pump motor.	Open circuit from poor solder connections, or component failure.	Loss of separator/pump ΔP and process water flow. WES will ESD.	III	ΔP press. trans. (Item 18-1) will fall below low limit setting.	Red "Sep. ΔP Low" light on.	
			Loss of power to energize N.C. solenoid valve open.	Open circuit from poor solder connections, or component failure.	Two-phase loop pressure will increase until solenoid valve relieves and/or relief valve (Item 26-3) opens. WES will ESD.	III	2Ø pressure will exceed high limit setting of P. T. (Item 17-3).	Red "2Ø High" light on.	
7	Deionizer Resin Bed	To remove ionic impurities from process water.	High conductivity effluent water from deionizer.	Resin monobed channeling, high conductivity makeup H_2O, ionic contamination of process water by WES components.	WES will ESD by high conductivity H_2O. Ion exchange of impurities with hydrogen proton in SPE of module cell will cause some permanent degradation of electrolysis module (Item 1) performance.	III	Process water conductivity will exceed high limit setting of conductivity sensor (Item 24).	Red "Cond. High" light on.	

Table IX

WES FAILURE MODE AND EFFECT ANALYSIS

6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
7	Continued		Low process water flow rate.	Resin bed has become partially clogged with particulate contamination.	Reduced process water flow rate will increase electrolysis module H_2/H_2O outlet temperature. WES will ESD.	III	Module outlet temperature sensor will exceed high limit.	Red "Mod Temp High" light on.	
			No process water flow.	Resin bed has become completely clogged with particulate contamination.	Water starvation of one or more electrolysis module cells increases module terminal voltage. WES will ESD.	III	Output voltage sensing on power conditioner (Item 11) exceeds high limit.	Red "Mod Volt High" light on.	
			External leakage.	Seal material set or loose connection.	H_2O leak to cabin.	III	Visual inspection by crew.	Location of H_2O drop formation.	
	Two-Phase Dynamic Separator/Pump	To separate process water and H_2 from 2Ø mixture and provide ΔP for process water circulation.	Loss of pumping ΔP and water circulation.	Motor failure, decoupling of magnet drive, excessive torque due to bearing or component failure, lack of adequate H_2O in 2Ø mixture.	Inadequate or loss of process water flow would overheat and/or starve electrolysis module (Item 1). WES will ESD.	III	ΔP on press. trans. (Item 18-1) will fall below low limit.	Red "Sep ΔP Low" light on.	
			Normally closed solenoid fails to open.	Open circuit due to poor solder joint or broken wire, jammed plunger, contamination.	2Ø mixture will increase in pressure at module gas generation rate until vented by relief valve (Item 26-3). WES will ESD.	III	2Ø pressure on P. T. (Item 17-3) will exceed high limit.	Red "2Ø High" light on.	
			N. C. solenoid stuck open or leaks internally.	Spring fracture, seal material set, jammed plunger, contamination.	Water discharge to downstream hydrogen.	III	Visual inspection of H_2 flowmeter by crew.	H_2O droplets in glass H_2 flowmeter, downstream H_2O discharge in H_2 stream.	
			External leakage.	Seal material set or loose connection.	a) H_2 leakage to cabin detected by comb. gas detector. WES will ESD.	III	Comb. gas detector (Item 22) exceeds high limit.	Red light on CGD, Item 22.	
					b) H_2O leakage to cabin.		Visual inspection by crew	Location of H_2O drop formation.	
9	Cooling Water Flowmeter	To provide visual display of coolant flow.	High float reading.	Contamination of gas in flowmeter.	None.	III	Visual inspection by crew	If no ESD on 25 at low flow, check 29 calibration.	
			Low float reading.	Same.	None.	III	Same as above.		
			External leakage.	Seal material set, loose connection, glass fracture.	H_2O leakage to cabin. No ESD.	III	Same as above.	Location of H_2O drop formation.	
10	Temperature Regulating Valve	To control the inlet water temperature to the electrolysis module (Item 1).	High outlet H_2O temperature.	Wax actuating valve binding due to contamination or corrosion limiting cold-water in flow or poor heat transfer to wax actuator due to excessive gas in H_2O.	Electrolysis module inlet and outlet temperatures increase improving module performance. WES will ESD.	III	Temperature of 2Ø mixture at module outlet rises above high limit.	Red "Mod Temp High" light on.	
			Low outlet H_2O temperature.	Wax actuating valve binding due to contamination or corrosion limiting hot-water in flow.	Electrolysis module inlet and outlet temperatures decrease reducing performance. Terminal voltage may exceed high limit at high loads resulting in ESD of WES.	III	Output voltage sensing on power conditioner (Item 11) will exceed high limit.	Red "Mod Volt High" light on.	

WES FAILURE MODE AND EFFECT ANALYSIS

6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
10	Continued		External leakage.	Seal material set or loose connection.	H_2O leak to cabin.	III	Visual inspection by crew.	Location of H_2O drop formation.	
11	Power Conditioner/ Cold Plate Assembly	To provide manually pre-set regulated current to electrolysis module below a maximum voltage limit.	Zero or low current output to module below setting.	Loss of amplifier gain, broken wire, overheated or shorted electronic elements, poor solder joints.	Possible burned out electronic elements or insulation in P.C. Zero or reduced WES gas output.	III	Visual inspection of module current meter and O_2 and H_2 gas flowmeters by crew.	Low meter readings.	
			High current output to module, above manual setting.	Same as above.	Possible burned out electronic elements. Excessive current drawn by P.C. may activate circuit breaker (Item 33) or increase module voltage resulting in ESD of WES.	III	a) Input P.C. current may exceed circuit breaker limit. b) Output voltage may exceed high limit.	a) Red "Current High" light on. b) Red "Mod Volt High" light on.	
			Overheating.	Contamination in coolant tubes of cold plate.	Zero or reduced coolant flow. WES will ESD.	III	Coolant flow will fall below actuation point of flow switch.	Red "Cool Flow Low" light on.	
			External coolant leakage from cold plate.	Corroded tubing, loose connection.	H_2O coolant leak to cabin.	III	Visual inspection by crew.	Location of H_2O drop formation.	
12	Regenerative Heat Exchanger	Recovery of waste heat from electrolysis to preheat process water to module for elevated temperature operation.	Inadequate heat transfer from hot side to cold side.	Partial or complete clogging of tubes with contamination.	a) Module operating temperature will reduce which may cause excessive terminal voltage at high loads. WES will ESD. b) WES will ESD if low process water flow causes water starvation of one or more cells, increasing terminal voltage.	III	Output voltage sensing on power conditioner (Item 11) would exceed high limit.	Red "Mod Volt High" light on.	
			External leakage.	Seal material set or loose connection.	H_2 leakage to cabin detected by GCD.	III	Combust. gas detector (Item 22) exceeds high limit.	Red light on CGD is on.	
					H_2O leakage to cabin.		Visual inspection by crew.	Location of H_2O drop formation.	
13	Primary Heat Exchanger	To transfer WES waste heat (elec. module and power cond.) to coolant water.	Inadequate heat transfer from hot (process water) to cold (coolant water) side.	Partial or complete clogging of tubes with contamination.	a) Reduced process water flow or surface fouling will cause module temp. to increase. b) Blocked process water flow same as Item 12 b. c) Reduced or blocked coolant flow. All will cause ESD of WES.	III	a) Module outlet temp. sensor will exceed high limit. b) Output voltage on power cond. would exceed high limit. c) Coolant flow will fall below actuation point of flow switch.	Red "Mod Temp High" light on. Red "Mod Volt High" light on. Red "Cool Flow Low" light on.	
14	Absolute O_2 Back Pressure Regulator	Regulates pressure level on O_2 side of electrolysis module.	Valve elements stuck closed.	a) Contamination binding movable parts in closed position.	O_2 side pressure increases until vented by O_2 relief valve (Item 26-2). WES will ESD.	III	O_2 pressure on P.T. (Item 17-2) exceeds high limit.	Red "O_2 High" light on.	
			Valve elements stuck open.	b) Spring fracture, soft seat rupture, contamination binding movable parts in an open position.	O_2 side pressure falls to N_2 base pressure where N_2 is admitted. WES will ESD.	III	O_2 pressure on P.T. (Item 17-2) falls below low limit.	Red "O_2 Low" light on.	

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6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
14	Continued		External leakage.	c) Seal material set or rupture.	O_2 leakage to cabin. No ESD unless O_2 pressure falls to low limit.	III	None unless audible hiss heard by crew.	Location of leakage point by bubble check.	
15	Absolute H_2 Back Pressure Regulator	Regulates pressure level at H_2 discharge of phase separator/pump (Item 8) and H_2 side of H_2O accumulator (Item 16).	Valve elements stuck closed.	Same as Item 14 a.	H_2 regulator inlet pressure increases until vented by H_2 relief valve (Item 26-1). WES will ESD.	III	H_2 pressure on P.T. (Item 17-1) exceeds high limit.	Red "H_2 High" light on.	
			Valve elements stuck open.	Same as Item 14 b.	H_2 regulator inlet pressure falls to N_2 base pressure where N_2 is admitted. WES will ESD.	III	H_2 pressure on P.T. (Item 17-1) falls below low limit.	Red "H_2 Low" light on.	
			External leakage.	Same as Item 14 c.	H_2 leakage to cabin. WES will ESD.	III	Combust. gas detector (Item 22) exceeds high limit.	Red light on CGD is on.	
16	Water Accumulator	Provides high pressure reservoir for makeup water and absorbs changes in H_2O quantity in 2Ø loop during startup and load changes.	Piston stuck in "Empty" position.	Contamination, corrosion or seal wear binding piston or Rod. "Empty" position switch fails closed.	WES will ESD after 4 minute delay if "Empty" position signal held continuously.	III	"Empty" position switch actuated by piston Rod. electronic timer.	Red "Accum Empty" light on.	
			Piston stuck in intermediate position.	Contamination binding as above.	Lack of H_2O in 2Ø loop will reduce separator/pump ΔP and WES will ESD.	III	ΔP on P.T. (Item 18-1) will fall below low limit.	Red "Sep ΔP Low" light on.	
			Piston stuck in "Overfill" position.	Contamination binding as above. "Overfill" switch fails closed.	WES will ESD after 4 minute delay if "Overfill" position signal held continuously.	III	"Overfill" position switch actuated by piston Rod. electronic timer.	Red "Accum Overfill" light on.	
			Internal leakage.	Piston seal wear, set, scored cylinder from contamination.	H_2O will leak across piston to H_2 chamber and H_2 discharge line. Excessive makeup water "consumption".	III	Visual inspection of H_2 flowmeter by crew.	H_2O droplets visible in glass H_2 flowmeter.	
			External leakage.	Seal material set, loose connection.	H_2 leakage to cabin. WES will ESD.	III	Combust. gas detector (Item 22) exceeds high limit.	Red light on CGD is on.	
					H_2O leakage to cabin. No ESD.		Visual inspection by crew.	Location of H_2O drop formation.	
			"Empty" position switch fails open.	Fatigue, lever fracture.	Makeup pump will not come on. Lack of H_2O quantity in 2Ø loop will reduce separator/pump ΔP and WES will ESD.	III	ΔP on P.T. (Item 18-1) will fall below low limit.	Red "Sep ΔP Low" light on.	
			"Overfill" position switch fails open.	Fatigue.	"Overfill" accumulator condition can only occur at start-up, load change or secondary failure. Excessive 2Ø pressure buildup as a result would vent 2Ø relief valve (Item 26-3). WES will ESD.	III	2Ø pressure on P.T. (Item 17-3) will exceed high limit.	Red "2Ø High" light on.	
17-1	Pressure Transducer, 0-500 psig, H_2 Press.	To monitor regulator H_2 pressure and provide high and low ESD signals.	High signal output.	Failure of internal electronic component.	a) False "High" pressure signal can cause ESD.	III	"H_2" meter display, red "H_2 High" light on.	Compare P.T. 17-1 readout with P.T.s 17-3 and 17-5.	
			Low signal output.	Same as above.	b) False "Low" pressure signal can cause ESD.	III	"H_2" meter display, red "H_2 Low" light on.	Same as above.	
			Zero signal output.	Same as above.	c) WES will ESD.	III	Same as above.	Same as above.	

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WES FAILURE MODE AND EFFECT ANALYSIS

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Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
17-2	Pressure Transducer, 0-500 psig, O_2 Press.	To monitor regulator O_2 pressure and provide high and low ESD signals.	High signal output.	Same as 17-1.	Same as 17-1 a).	III	"O_2" meter display, red "O_2 High" light on.	Compare P.T. 17-2 readout with 17-5.	
			Low signal output.	Same as 17-1.	Same as 17-1 b).	III	"O_2" meter display, red "O_2 Low" light on.	Same as above.	
			Zero signal output.	Same as 17-1.	WES will ESD.	III	Same as above.	Same as above.	
17-3	Pressure Transducer, 0-500 psig, H_2/H_2O Press.	To monitor H_2/H_2O pressure at module outlet and provide high and low ESD signals.	High signal output.	Same as 17-1.	Same as 17-1 a).	III	"2Ø" meter display, red "2Ø High" light on.	Compare P.T. 17-3 readout with P.T.'s 17-1 and 17-5.	
			Low signal output.	Same as 17-1.	Same as 17-1 b).	III	"2 phase" meter display, "2Ø Low" light on.	Same as above.	
			Zero signal output.	Same as 17-1.	WES will ESD.	III	Same as above.	Same as above.	
17-4	Pressure Transducer, 0-500 psig, N_2 Dome Press.	To monitor N_2 pressure in module dome and provide low ESD signal.	High signal output.	Same as 17-1.	None.	III	"N_2 Dome" meter display.	Compare P.T. 17-4 readout with 17-5 with 27-1, 27-2 and 28-7 full open at low N_2 pressure.	
			Low signal output.	Same as 17-1.	Same as 17-1 b).	III	"N_2 Dome" meter display, red "N_2 Dome Low" light on.	Same as above.	
			Zero signal output.	Same as 17-1.	WES will ESD.	III	Same as above.	Same as above.	
17-5	Pressure Transducer, 0-500 psig, N_2 Base Press.	To monitor N_2 base pressure and provide low ESD signal.	High signal output.	Same as 17-1.	None.	III	"N_2 Base" meter display.	Compare P.T. 17-5 readout with 17-1 and 17-3.	
			Low signal output.	Same as 17-1.	Same as 17-1 b).	III	"N_2 Base" meter display, red "N_2 Base Low" light on.	Same as above.	
			Zero signal output.	Same as 17-1.	WES will ESD.	III	Same as above.	Same as above.	
18-1	Differential Pressure Transducer, ± 15 psid Separator/Pump ΔP	To monitor separator/pump ΔP and provide a low ESD signal.	High signal output.	Failure of internal Electronic component.	None.	III	"Separator" meter display.	Check P.T. 18-1 readout when separator 8 is switched on and off. Compare P.T. 18-1 with P.T. 20.	
			Low signal output.	Same as above.	False "Low" signal can cause ESD.	III	Same as above.	Same as above.	
			Zero signal output.	Same as above.	WES will ESD.	III	Same as above.	Same as above.	
18-2	Differential Pressure Transducer, ± 15 psid, H_2O Flow Orifice ΔP	To monitor process water flow rate.	High signal output.	Same as 18-1.	None.	III	"Orifice" meter display.	Check P.T. 18-2 readout when separator (8) is switched on and off.	
			Low signal output.	Same as 18-1.	None.	III	Same as above.	Same as above.	
			Zero signal output.	Same as 18-1.	None.	III	Same as above.	Same as above.	

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6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A490-868 Rev. A

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
19	Pressure Switch (N.O.)	To monitor makeup pump suction pressure and provide low (switch closes) ESD signal.	Switch fails closed.	Failure of internal component or contamination.	False "low" pressure signal will cause ESD.	III	Red "Makeup H_2O Low" light is on.	Verify makeup H_2O supply pressure and check with makeup water pump (4) switched on and off.	
			Switch fails open.	Same as above.	Low makeup H_2O supply pressure or clogged makeup H_2O filter (Item 3) will not be detected.	III	None.	No ESD will result with shut-off makeup H_2O supply line and makeup water pump (Item 4) on.	
			External leak.	Seal material set or rupture, loose connection.	No ESD. H_2O leak to cabin.	III	Visual inspection by crew.	Location of H_2O drop formation.	
20	Differential Pressure Transducer ± 100 psid H_2O Accumulator ΔP	To monitor water accumulator (P_{H_2O} - P_{H_2}).	High signal output	Same as 18-1.	None.	III	"Accumulator" meter display.	Check P. T. 20 readout when separator (8) is off and P. T.'s 17-1, 17-3 and 17-5 are at same pressure.	
			Low signal output.	Same as 18-1.	None.	III	Same as above.	Compare P. T. 20 readout with 18-1 with separator (8) on.	
			Zero signal output.	Same as 18-1.	None.	III	Same as above.	Same as above.	
21	Module Outlet Temp. Sensor	To monitor module H_2/H_2O outlet temp. and provide high ESD signal.	High signal output.		False "High" temperature signal can cause ESD.	III	"Mod. Out" meter display.	Check Item 20 readout at low module current.	
			Low or zero signal output.	Broken or burned out resistance element.	High module outlet temperature will not be detected.	III	Same as above.	Check Item 20 readout at high module current.	
22	Combustible Gas Detector	To monitor H_2 leakage from WES to cabin and provide high ESD signal.	High signal output.	Electrical component failure as breakage, overheating, shorts, poor connections.	False "High" H_2 level signal can cause ESD.	III	Red light on CGD meter display is on.	Check other cabin CGD monitors. Recalibrate CGD.	
			Low or zero signal output.	Same as above.	H_2 leakage if present would not be detected.	III	CGD meter display.	"Malfunction" light on CGD display.	
23	Dual O_2 and H_2 Flowmeter Assembly	To provide visual display of O_2 and H_2 output flow rate.	High float reading.	Contamination or H_2O in flowmeter.	None.	III	Visual inspection by crew.	Check module current and WES pressures. Tap flowmeter.	
			Low float reading.	Same as above.	Possible gas leak upstream of flowmeter.	III	Same as above.	Same as above. Check for gas leakage.	
			External leakage.	Seal material set, loose connection, glass fracture.	Same as above.	III	Same as above.	Same as above.	
24	Conductivity Sensor	To monitor the ionic impurity level of process water effluent from deionizer (Item 7) and provide high ESD signal.	High output signal.	Same as 22. Contamination or rupture of sensor cell.	False "High" H_2O conductivity signal can cause ESD.	III	Conductivity sensor (24) meter display.	Take H_2O sample thru valve 28-6 and check conductivity. Check module (1) voltage.	
			Zero or low output signal.	Same as above.	Possible damage to module (1) cells if makeup H_2O has high ionic content or if deionizer not serviced regularly.	III	Same as above.	Same as above.	

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Refer Drawing 73A490-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
25	Coolant H_2O Flow Switch (N.O.)	To monitor cooling H_2O flow rate and provide low (switch closes) ESD signal.	Switch fails closed.	Switch actuator stuck by contamination, failure of internal component.	False "Low Flow" signal will cause ESD.	III	Red "Cool Flow Low" light on. Coolant flowmeter (24) display.	Verify coolant H_2O supply pressure and check with supply on and off.	
			Switch fails open.	Same as above.	Low coolant flow would not be detected by Item 25, but overheating of module would cause ESD by Item 21	III	None without secondary failure.	Verify Item 25 failure by no ESD with shut-off coolant supply.	
26-1	In-Line Relief Valve, H_2 Relief	To provide over-press. relief in the event of a failed-closed H_2 regulator (Item 15).	a) Valve elements stuck closed.	a) Contamination binding elements.	Dual failure of Items 15 and 26-1 will increase H_2 pressure. WES will ESD.	III	H_2 pressure on P.T. 17-1 exceeds high limit.	Red "H_2 High" light on. Bench test 15 and 26-1.	
			b) Valve elements stuck open or internal leakage.	b) Same as above. Seat material set or damage.	None if H_2 leakage is less than H_2 generation rate. WES will ESD at higher leakage as H_2 pressure falls to N_2 base pressure.	III	H_2 pressure on P.T. 17-1 falls below low limit.	Red "H_2 Low" light on. Bench test to verify failure of 26-1, 15, or 28-1.	
26-2	In-Line Relief Valve, O_2 Relief	To provide over-press. relief in the event of a failed-closed O_2 regulator (Item 14).	Same as 26-1 a).	Same as 26-1 a).	Dual failure of Items 14 and 26-2 will increase O_2 pressure. WES will ESD.	III	O_2 pressure on P.T. 17-2 exceeds high limit.	Red "O_2 High" light on. Bench test 14 and 26-2.	
			Same as 26-1 b).	Same as 26-1 b).	None if O_2 leakage is less than O_2 generation rate. WES will ESD at higher leakage as O_2 pressure falls to N_2 base pressure.	III	O_2 pressure on P.T. 17-2 falls below low limit.	Red "O_2 Low" light on. Bench test to verify failure of 14 or 26-2.	
26-3	In-Line Relief Valve, Two-Phase Relief	To provide over-press. relief in the event of a failed-closed and stuck solenoid valve on phase separator/pump (Item 8).	Same as 26-1 a).	Same as 26-1 a).	Dual failure of Items 8 and 26-3 will increase H_2/H_2O pressure. WES will ESD.	III	2Ø pressure on P.T. 17-3 exceeds high limit.	Red "2Ø High" light on. Check for H_2/H_2O dump.	
			Same as 26-1 b).	Same as 26-1 b).	H_2/H_2O discharge thru dump if leakage less than H_2 generation rate. Excess makeup H_2O "consumption" and low H_2 output. WES will ESD at higher leakage as 2Ø pressure falls to H_2 regulator pressure.	III	H_2 flowmeter (23) display. 2Ø pressure on P.T. 17-3 falls below low limit.	Low H_2 flow indicates 2Ø leakage to dump. Red "2Ø Low" light on. Bench test 26-3.	
26-4	In-Line Relief Valve, N_2 Input to 2Ø	To provide check when ($P_{2Ø} > P_{H_2}$) and input ΔP ($P_{N_2} > P_{2Ø}$) during pressurization and shutdown.	Same as 26-1 a).	Same as 26-1 a).	Unable to pressurize 2Ø loop with N_2 for start-up. 2Ø pressure will decay below N_2 base pressure during WES shutdown. No effect during WES continuous operation.	III	2Ø pressure on P.T. 17-3 below pressure on P.T. 17-1 by greater difference than 26-9 ΔP relief setting.	Red "2Ø Low" light on. Compare 17-3 and 17-1 difference during N_2 pressurization.	
			Same as 26-1 b).	Same as 26-1 b).	H_2O present in H_2 output. High leakage can cause ESD.	III	H_2 flowmeter (23) display. 2Ø pressure on P.T. 17-3 can fall below low limit.	Closure of valve 28-4 halts H_2O discharge. "2Ø Low" light on.	
27-1	Manual N_2 Pressure Regulator, N_2 Dome Input.	Manual setting provides N_2 dome pressure on module (1).	a) Regul. valve elements fail open.	a) Contamination, valve elements stuck open, spring rupture.	No effect during WES operation with valve 28-7 normally closed.	III	"N_2 Dome" meter display.	Pressure on P.T. 17-4 will increase with 27-1 backed off and valve 28-7 open.	
			b) Regul. valve elements failed closed.	b) Contamination, valve elements stuck closed.	Same as above.	III	Same as above.	Unable to pressurize dome with 28-7 open.	

Table IX

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6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

Refer Drawing 73A190-868 Rev. A

GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
27-2	Manual N_2 Pressure Regulater, N_2 Base Input	Manual setting provides N_2 base pressure to O_2 and H_2 lines.	Same as 27-1 a).	Same as 27-1 a).	Blow down of N_2 supply pressure to H_2 regulator pressure setting. High "O_2" and "H_2" flow readings on Item 23. H_2 2Ø and O_2 pressure will increase and may cause high pressure ESD.	III	"N_2 Base" meter and O_2 and H_2 flowmeter display. Possible red "H_2 High" light on.	Pressure on P. T. 17-5 will increase with 27-2 backed off. Low N_2 supply pressure.	
			Same as 27-1 b).	Same as 27-1 b).	WES will ESD during normal or cyclic shutdown as N_2 base pressure decays.	III	Pressure on P. T. 17-5 will fall below low limit.	Red "N_2 Base Low" light on. Unable to re-pressurize.	
28-1	Manual Shut-Off Valve H_2 Regulator Bypass (N. C.)	To provide means for by passing H_2 regulator to vent H_2 and depressurize WES.	a) Internal leak.	a) Seat material set or damage.	WES will ESD if H_2 leak exceeds H_2 generation rate or during normal or cyclic shutdown.	III	H_2 pressure on P. T. 17-1 falls below low limit.	Red "H_2 Low" light on. Bench test to verify failure of 28-1, 15, or 26-1.	
			b) External leak.	Gland material set or damage. Loose connection.	Same as above. H_2 leakage to cabin. WES will ESD.	III	Same as above or combustible gas detector (22) exceeds high H_2 limit.	Same as above or red light on CGD is on.	
28-2	Manual Shut-Off Valve O_2 Regulator Bypass (N. C.)	To provide means for bypassing O_2 regulator to vent O_2 and de-pressurize WES.	Same as 28-1 a).	Same as 28-1 a).	WES will ESD if O_2 leak exceeds O_2 generation rate or during normal or cyclic shutdown.	III	O_2 pressure on P. T. 17-2 falls below low limit.	Red "O_2 Low" light on. Bench test to verify failure of 28-2, 14 or 26-2.	
			Same as 28-1 b).	Same as 28-1 b).	Same as above.	III	Same as above.	Same as above.	
28-3	Manual Shut-Off Valve 2Ø Relief Valve By-pass (N. C.)	To provide means for bypassing 2Ø relief to vent H_2/H_2O and de-pressurize WES.	Same as 28-1 a).	Same as 28-1 a).	WES will ESD if H_2 leak exceeds H_2 generation rate. High makeup H_2O "consumption".	III	2Ø pressure on P. T. 17- falls below low limit.	Red "2Ø Low" light on. Bench test to verify failure of 28-3 or 26-3.	
			Same as 28-1 b).	Same as 28-1 b).	H_2 and H_2O will leak to cabin. WES will ESD.	III	Same as above. CGD (22) may exceed high limit.	Same as above or red light on CGD.	
28-4	Manual Shut-Off Valve, N_2 Input to 2Ø Shut-Off (N. O.)	To provide means of separately pressurizing O_2 side during maintenance only.	External leak.	Gland material set or damage, loose connection.	H_2 leakage to cabin. WES will ESD.	III	Same as 28-1 b).	Red light on CGD (22) is on.	
28-5	Manual Shut-Off Valve, H_2O Orifice Shut-Off (N. O.)	To provide means of adjusting H_2O flow on metering valve (30-2).	Same as above.	Same as above.	H_2O leakage to cabin. No ESD.	III	Visual inspection by crew	Location of H_2O drop formation.	
28-6	Manual Shut-Off Valve, H_2O Sample Point (N. C.)	To provide means of extracting process H_2O sample.	Same as above.	Same as above, or seat material set or damage.	Same as above.	III	Same as above.	Same as above.	
28-7	Manual Shut-Off Valve, Module Dome Shut-Off (N. C.)	To provide means for locking H_2 in dome.	Same as 28-1 a).	Same as 28-1 a).	N_2 pressure decay on module dome. WES will ESD.	III	Pressure on P. T. 17-4 will fall below low limit.	Red "N_2 Dome Low" light on.	
			Same as 28-1 b).	Same as 28-1 b).	Same as above. N_2 leakage to cabin.	III	Same as above.	Same as above.	
28-8	Manual Shut-Off Valve, Module Dome Drain Valve (N. C.)	To provide means for venting or draining module dome.	Same as 28-6.	Same as 28-6.	Same as above.	III	Same as above	Same as above.	
30-1	Needle Valve, Accumulator H_2O Metering (N. O.)	To provide means of restricting H_2O flow from accumulator.	Same as 28-5.	Same as 28-5.	Same as 28-5.	III	Same as 28-5.	Same as 28-5.	
			Clogged valve.	Contamination.	No makeup H_2O to process H_2O loop. WES will ESD.	III	Separator ΔP on P. T. 18-1 will fall below low limit.	Red "Sep ΔP Low" light on.	

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6-MAN ADVANCED BREADBOARD WATER ELECTROLYSIS SYSTEM (WES)

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GENERAL ELECTRIC

Item No.	Component Title	Component Function	Failure Mode	Hypothetical Failure Mechanism	Effect of Failure	Failure Class	Fault Detection	Fault Isolation	Comments
30-2	Needle Valve, Process H_2O Metering (N.C.)	To provide means of adjusting H_2O flow.	Same as 28-1 a).	Same as 28-1 a).	None. Module (1) ΔT may be lower.	III	Orifice meter display for ΔP on P.T. 18-2 may be lower.	Bench check.	
31	Process Water Flow Orifice	To provide means of monitoring process water flow rate.	Partially clogged orifice or screen.	Contamination.	Inadequate process water flow rate will increase module (1) outlet temperature. WES will ESD.	III	Module outlet temperature sensor will exceed high limit.	Red "Mod Temp High" light on.	
			Completely clogged orifice or screen.	Contamination.	Loss of process water flow will reduce separator/pump (8) ΔP.	III	Separator ΔP on P.T. 18-1 will fall below low limit.	Red "Sep ΔP Low" light on.	
32-1	Catalytic O_2/H_2 Mixture Sensor (O_2 in H_2)	To monitor presence of O_2 in H_2 output gas.	a) High output signal.	Internal electrical failure.	False O_2 signal would cause ESD of WES.	III	"O_2 in H_2" meter display.	Red "O_2 in H_2" light on. Check output signal with N_2 gas in H_2 output line.	
			b) Zero or low output signal.	Same as above. Shorted resistive element.	O_2 in H_2 output possibly caused by module (1) internal leak would go undetected.	III	Same as above. Visual inspection by crew.	Meter readout is constant H_2 output temp., unless 32-1 has failed.	
			c) External leakage.	Seal damage. Loose connection.	H_2 leakage to cabin. WES will ESD.	III	Combustible gas detector (22) will exceed high limit.	Red light on CGD is on.	
32-2	Catalytic O_2/H_2 Mixture Sensor (H_2 in O_2)	To monitor presence of H_2 in O_2 output gas.	Same as 32-1 a).	Same as 32-1 a).	False H_2 signal would cause ESD of WES.	III	"H_2 in O_2" meter display.	Red "H_2 in O_2" light on. Check output signal with N_2 gas in O_2 output line.	
			Same as 32-1 b).	Same as 32-1 b).	H_2, if present in O_2 discharged to cabin, would result in ESD of WES.	III	"H_2 in O_2" meter display. Combustible gas detector (22) would exceed high limit if H_2 in cabin.	Meter readout is O_2 output temperature unless 32-2 has failed. Red light on CGD is on.	
			Same as 32-1 c).	Same as 32-1 c).	None.	III	None.	Bubble check by crew.	
33	Circuit Breaker (N.C.) 50 amp DC	To prevent excess input current to power conditioner (11).	Contacts stuck closed.	Welded contacts or spring rupture.	Unable to manually open 28 VDC input switch. Secondary failure in power conditioner, if causing high current, would probably result in burned out transistor in P.C., and loss of input power to module (11). WES would ESD during O_2 pressure decay at open circuit.	III	Green "28 VDC" light remains on. Red "O_2 Low" light on.	Unable to remove 28 VDC input to WES by manual switching of (33).	
			Contacts stuck open.	Contamination. Open relay coil.	Unable to apply 28 VDC to WES.	III	Green "28 VDC" light remains off.	Unable to apply 28 VDC input to WES by manual switching of (33).	

For Sensor and Display Device Item No. Identification and Location Refer Table I and Figure 1

TABLE X

6-MAN WATER ELECTROLYSIS SYSTEM (WES) FDIA EMERGENCY SHUTDOWN SUMMARY

	Fault Condition	Fault Sensor	Sensor Item No.	Limit Setting*	Limit Hold Period	Inhibit Required	Display Device	Disp. Devel. Item No.	Fault Visual Signal
1.	High Module Voltage	Voltage Meter Relay	None	$>$ 24 VDC	Instant	None	0-50 VDC Meter	40	Red Light "On"
2.	High Module (P.C. Out) Curr.	Current Shunt	None	$>$ 80 amp	Instant	None	0-100 A Meter	41	Red Light "On"
3.	High Power Cond. Input Curr.	100 A Circuit Breaker	33	$>$ 80 Amp	Instant	None	None	-	Red Light "On"
4.	Loss 28 VDC Supply Voltage	Voltage Divider	None	$<$ 26 VDC	Instant	Reset	None	-	Green Light "Off"
5.	Loss 115 VAC Supply Voltage	Voltage Divider	None	$<$ 100 VAC	Instant	Reset	None	-	Green Light "Off"
6.	High Module Outlet Temp.	Temperature Sensor	21	$>$ 220°F	10 Sec.	None	0-250°F Elec. Meter	44	Red Light "On"
7.	Low Sep./Pump Press. Rise	ΔP Press. Trans.	18	$<$ 3.5 psid	1 Sec.	Start-up	0-5 VDC Elec. Meter/Sel. Sw.	50	Red Light "On"
8.	High Module 2 O Outlet Press.	Press. Trans. 0-500 psig	17-3	*$>$390 psig	1/4 Sec.	None	0-500 psig Elec. Meter	50	Red Light "On"
9.	Low Module 2 O Outlet Press.	Press. Trans. 0-500 psig	17-3	*$<$350 psig	1 Sec.	Start-up + 5 min timer	0-500 psig Elec. Meter	50	Red Light "On"
10.	High O_2 Outlet Press.	Press. Trans. 0-500 psig	17-2	*$>$412 psig	1/4 Sec.	None	0-500 psig Elec. Meter	48-2	Red Light "On"
11.	Low O_2 Outlet Press.	Press. Trans., 0-500 psig	17-2	*$<$380 psig	1 Sec.	Start-up + 5 min timer	0-500 psig Elec. Meter	48-2	Red Light "On"
12.	High H_2 Outlet Press.	Press. Trans. 0-500 psig	17-1	*$>$380 psig	1/4 Sec.	None	0-500 psig Elec. Meter	48-1	Red Light "On"
13.	Low H_2 Outlet Press.	Press. Trans. 0-500 psig	17-1	*$<$330 psig	1 Sec.	Start-up + 5 min timer	0-500 psig Elec. Meter	48-1	Red Light "On"
14.	Empty Water Accumulator	"Empty" Position Switch On	16	Closed Sw.	9 Min.	Start-up	None	-	Red Light "On"
15.	Overfilled Water Accum.	"Max Stroke" Posn. Sw. On	16	Closed Sw.	20 Sec.	None	None	-	Red Light "On"
16.	Low Coolant Water Flow	Flow Switch	25	$<$ .1 GPM	1 Sec.	None	None	-	Red Light "On"
17.	High H_2 Conc. In O_2 Line	Catalytic Temp. Sensor	32-2	$>$187°F	1 Sec.	None	0-250°F Elec. Meter	44	Red Light "On"
18.	Low Makeup H_2O Inlet Press.	Pressure Switch	19	$<$ .5 psig	30 Sec.	None	None	-	Red Light "On"
19.	High Process H_2O Conductivity	Conductivity Sensor	24	$>$ 5μ MHO	1 Min.	Start-up	Meter	On (47)	Red Light "On"
20.	High H_2 Concentration	Combustible Gas Detector	22	$>$ .5%	Inst.	None	Meter	On (46)	Red Light "On"
21.	High O_2 Conc. In H_2 Line	Catalytic Temp. Sensor	32-1	$>$140°F	1 Sec.	None	0-250°F Elec. Meter	44	Red Light "On"
22.	Low Module Dome N_2 Press.	Press. Trans., 0-500 psig	17-4 Pot. Adj.	$<$400 psig	1 Sec.	None	0-5 VDC Elec. Meter/Sel. Sw.	50	Red Light "On"
23.	Low N_2 Base Press.	Press. Trans., 0-500 psig	17-5	$<$320 psig	15 Sec.	None	0-5 VDC Elec. Meter/Sel. Sw.	50	Red Light "On"

* Limit Setting With Potentiometer Adjustment

3.4.2 System Assembly and Check Out

The pre-prototype assembly for the system consisted of a fluid package and control package or cabinet (photographed in Figure 15). The fluid package was made of "Unistrut" aluminum frame with a vertical aluminum panel for mounting the larger fluid components. A commercially available cabinet was selected of a size for mounting all the display components on the front face resulting in a generous interior for mounting electrical control components and circuit boards.

Prior to installation in the fluid package, fluid components were bench tested for proof pressure, leakage, regulated settings, etc. and instruments were checked out as calibrated by vendors or by in-house verification. Some of this component testing is described in Section 3.3. Sections of fluid lines with components were also proof pressure and leak checked as sub-assemblies prior to installation wherever possible.

Initial system testing was conducted at pressures under 345kN/m^2 (50 psig) to check out major functional components such as the power-conditioner/electrolysis module, phase separator/pump, water accumulator and make-up pump. These conditions were also used to verify sensor outputs, automatic startup and shutdown sequence functions and automatic emergency shutdowns.

All major components performed satisfactorily so that most of check out period was occupied with troubleshooting of automatic controls.

3.4.3 System Evaluation

The following discussion summarizes in chronological order the conditions experienced and observations made during extensive testing of the advanced WES which commenced in June, 1974. Operating results and test data relating to a specific component have been presented in Section 3.3 and a functional description of components as part of overall system operation is provided in Section 3.2.

Operation of the system at regulated system pressure and temperature was initially performed on June 13, 1974. A load profile versus time showing the temperature transients during warmup is provided in Figure 25. Operation of all pressure regulators, nominally set for a 690kN/m^2 (100 psig) level, and the water temperature regulator was very satisfactory.

Electrical checkout of automatic startup and emergency shutdown functions was sufficiently complete to allow unattended system operation around the clock. Erratic automatic shutdowns in the module overvoltage channel and later in the separator ΔP channel, however, interrupted sustained operation. The first was corrected by utilizing isolated voltage sensing with a meter relay in place of the previous electronic-comparator circuit approach. The cause of the latter erratic behavior was found to be sensitivity to 115 VAC noise and load switching on the power line which was subsequently corrected with a commercial noise filter on the input 115 VAC line.

The first week of endurance testing was hampered by false shutdowns as described. However, two weeks of continuous unattended operation was subsequently demonstrated at the nominal 690kN/m^2 (100 psig) system pressure level. Maximum gas generation rate at an electrolysis module load of 75 amperes was sustained for most of the 429 accumulated hours of endurance testing at this pressure.

As shown by Figure 25, a regulated process water temperature of 339K (150^{o}F) was achieved after warmup resulting in a H_2/H_2O module outlet temperature of 431K (190^{o}F). At 75 amp load, module surface temperatures reach about 344K (160^{o}F). The pressure of trapped nitrogen in the module dome is seen to increase and eventually stabilize with temperature.

Measurement of steady state temperatures at different loads was obtained subsequent to a sustained period at maximum load. This load/temperature profile is shown in Figure 26. Recorded temperatures were not continuous but readings were taken at least six hours after load changes to obtain essentially steady state values. Process water regulated temperature is maintained at about 339K (150^{o}F) at 50 amps or higher and with electrolysis module ΔT, i.e., module H_2/H_2O out minus module H_2O in, proportional to load. Heat generation rate below 50 amps was not sufficient to maintain a 339K (150^{o}F) process water temperature; the "hot" port of the temperature regulator is fully open, and system temperatures fall as shown.

The initial 429 hour endurance test period was established at system pressures tabulated in Figures 25 and 26, nominally 690kN/m^2 (100 psig). Subsequently the system was shutdown to adjust pressure regulators, relief valves and a the accumulator return spring for operation at nominally 1724kN/m^2 (250 psig). The load/temperature profile and tabulated pressures are shown in Figure 27. Because phase separator/pump pressure rise had dropped to under 41kN/m^2 (6.0 psid) and reduced process water flow rate, maximum load of 75 amp could not be sustained without module outlet temperature exceeding 441K (200°F). In addition, a water discharge was observed in the H_2 outlet flowmeter. Differential pressure gages were added to monitor separator/pump ΔP and water flow rate. Also, 1/4 inch diameter translucent nylon tubing was inserted at the separator/pump H_2 outlet to observe any water discharge.

The phase separator/pump was found to have a loss in ΔP with increasing system pressure and a leaky solenoid valve. With the concurrence of Fluid Dynamics Corporation, the manufacturer, it was decided to obtain system performance data at maximum system pressure of 2413 to 2760kN/m^2 (350 to 400 psig) before returning the separator/pump for vendors examination and correction. This would identify any other component difficulty at design pressure level before suffering the extended downtime expected for separator/pump repair.

The pressure regulators, relief valves and water accumulator spring load were adjusted for nominal 2760kN/m^2 (400 psig) system operation. Evaluation of system operation at gradually increasing pressure levels was accomplished by self-pressurization at a 10 amp load (with automatic ESD deactivated) and gradually "bootstrapping" the system with manual control of valves to the following operating pressures kN/m^2 (psig) at regulated conditions: N_2 dome, 2896 (420); O_2 regulator, 2723 (395), module two-phase 2586 (375); H_2 regulator, 2427 (352) and N_2 base 2289 (332). Phase separator-pump ΔP was found to fall off briskly from 66 to 31kN/m^2 (9.6 to 4.5 psid) with increased line pressure indicating possible deflection of internal components proportional to pressure. Sustained operation of the WES at high pressure was not possible because of sudden loss of pump output due to uncoupling of the magnetic drive. The unit was removed from the system on 9-11-74 and sent to the manufacturer, Fluid Dynamics Corporation, Chester, California for high pressure evaluation and corrective modifications. Further discussion of phase separator/pump performance is included in Para. 3.3.3.

Subsequent to installation of the repaired phase separator/pump on 10-30-74 high pressure system evaluation was resumed. Adjustment of the switch position on the water accumulator and a change in the timing cycle of the make-up pump was required to avoid false "empty" signals. After satisfactory component performance was verified and system automatic startup and shutdown sequences were tested, ESD pressure limits were readjusted for high pressure operation. The ESD limit settings are listed in the FDIA Table X. These limits were verified under actual test conditions where possible with the automatic ESD controls reactivated. "High" limit pressure values could not be demonstrated under actual system operation because the O_2 and H_2 pressure regulators relieved gas under the fault ESD valve.

System depressurization with ESD controls activated did not allow components such as the phase separator/pump to operate at system pressures below ESD limits. Therefore, expulsion of hydrogen gas (plus water) from the two-phase region was accomplished by venting the fluids through manual valve (Items 28-3, Figure 16) to atmosphere. Subsequent to rapid system depressurization on 11-9-74 because of a leaky seat on the H_2 vent valve (Item 28-1) the water line connecting the outlet of the phase separator/pump and inlet of the deionizer was found to contain resin beads dislodged from the deionizer by pulsating, reverse two-phase flow during depressurization. The deionizer was modified as discussed in Para. 3.3.7 and additional phase separator/pump repair was required because of damage by the resin particles. Also as a corrective measure, an enabling switch was added inside the control cabinet which could correct or interrupt all ESD signals to the controller. The switch enabled component and system operation outside of ESD limits. In particular, it allowed phase separator/pump operation during systems depressurization to vent essentially all entrapped and dissolved hydrogen gas from the two phase region to the hydrogen outlet and simultaneously prevented flow reversal in the process water loop. This switch also permitted low pressure system operation and self-pressurization as previously described up to regulated operating pressures although manual valve adjustments were required for pressure control. Normal system pressurization is accomplished by gradual pressurization with the N_2 manual regulators until all pressures are within design limits with all FDIA lights out. The system can then be activiated electrically using the desired push button panel controls.

System operation was resumed on 12-4-74 with development testing concentrated on performing cyclic (orbital) operation at high pressure conditions. System checkout and testing during the normal work day was concentrated on the setting and evaluation of automatic functions for cyclic operation. Overnight, the system was placed on unattended continuous operation to accumulate hours of endurance testing. Electrical trouble shooting during the cyclic evaluation tests revealed that a faulty transistor had caused erratic time functions for cyclic operation and was corrected. The electronic timer was subsequently set to provide a 54.7 minute system powered period and a 40.7 minute standby period. It is not possible at high pressure to hold a period of unpowered electrolysis module without the cyclic consumption of nitrogen to maintain a minimum allowable base pressure on both the oxygen and hydrogen sides. Also, it was learned that the phase separator could not be operated with the module unpowered since the separator would lose pressure differential and the impeller would become noisy (caused by enlargement of the gas core). For these reasons a minumum module load was to be determined by additional testing in the standby mode.

On December 31, 1974 the system was automatically shutdown due to high two-phase pressure which was caused by a faulty hydrogen regulator. Bench check and disassembly of the component revealed a leaky gas bellows apparently cracked from cyclic fatigue. The poppet of the component continuously cycles between an open and closed position as the solenoid valve on the phase separator is energized cyclically. The frequency, dependent upon gas generation rate, was about 10 cycles per minute at 30 amperes. It was estimated that 400,000 cycles were accumulated to this failure point. A spare bellows assembly and gland for the H_2 regulator was received from Ausco, Incorporated, bench checked, and installed on January 3, 1975. An electrical counter was also installed to measure the number of cycles of solenoid valve operation. Subsequent system operation was satisfactory and evaluation of the cyclic operating mode was resumed.

When the failed hydrogen regulator was disassembled some particles of catalyst material were found inside. Inspection of the upstream catalytic sensor revealed the catalyst material had been eroded away apparently from the impingement of water slugs on the catalyst in the line. A future modification would include a protective screen to reduce erosion and an enlarged fitting to reduce fluid velocity.

During the period of system evaluation from January 3 to January 9, 1975, accumulating 119 hours of module operation under load, 62,703 solenoid valve (on the phase separator) operating cycles were counted for an average rate of 525 cycles/hour. In order to prevent the potential cyclic fatigue of related components it was decided to add a hydrogen differential pressure regulating valve downstream of the solenoid valve. (Refer Figure 16, Item 20). The purpose of this regulating valve is to hold a pressure differential across the phase separator (water outlet pressure minus hydrogen outlet pressure) slightly less than its normal pressure rise when the gas core diameter is controlled by the magnetic pickup and solenoid valve. With this pressure regulator the gas core is slightly larger, such that the magnetic pickup impeller is not rotated by the water vortex and the solenoid valve is energized continuously open to let hydrogen out. An Ausco, Incorporated differential pressure regulator, P/N P321-50, previously used on this program as a water differential pressure regulator (refer to Figure 45 and to Para. 2.3.6) was tried for this purpose. It was necessary to add a small spring on the poppet side of the bellows to increase operating pressure differential to an initial adjusted value of 52.4kN/m^2 (7.6 psid).

The addition of the differential hydrogen regulator was very successful in almost eliminating solenoid valve cycling except during momentary transient periods of startup, load change, and at times during system pressurization and water priming. It was also found that the previously observed cyclic emission of water slugs out a cycling solenoid valve was essentially eliminated by the use of the differential regulator.

System evaluation continued on parametric testing in the cyclic mode consisting of a 54.7 minute high power period and a 40.7 low power or standby period. A minimum standby electrolysis module current of 6 amperes was established to maintain a small net gas output rate of about 330 SCCM H_2 and 165 SCCM O_2 such that the hydrogen and oxygen pressure regulators would hold minimum pressures above emergency shutdown limits. Pressure regulator settings and ESD limits were accordingly adjusted. A minimum current is required to overcome the relatively higher rate of

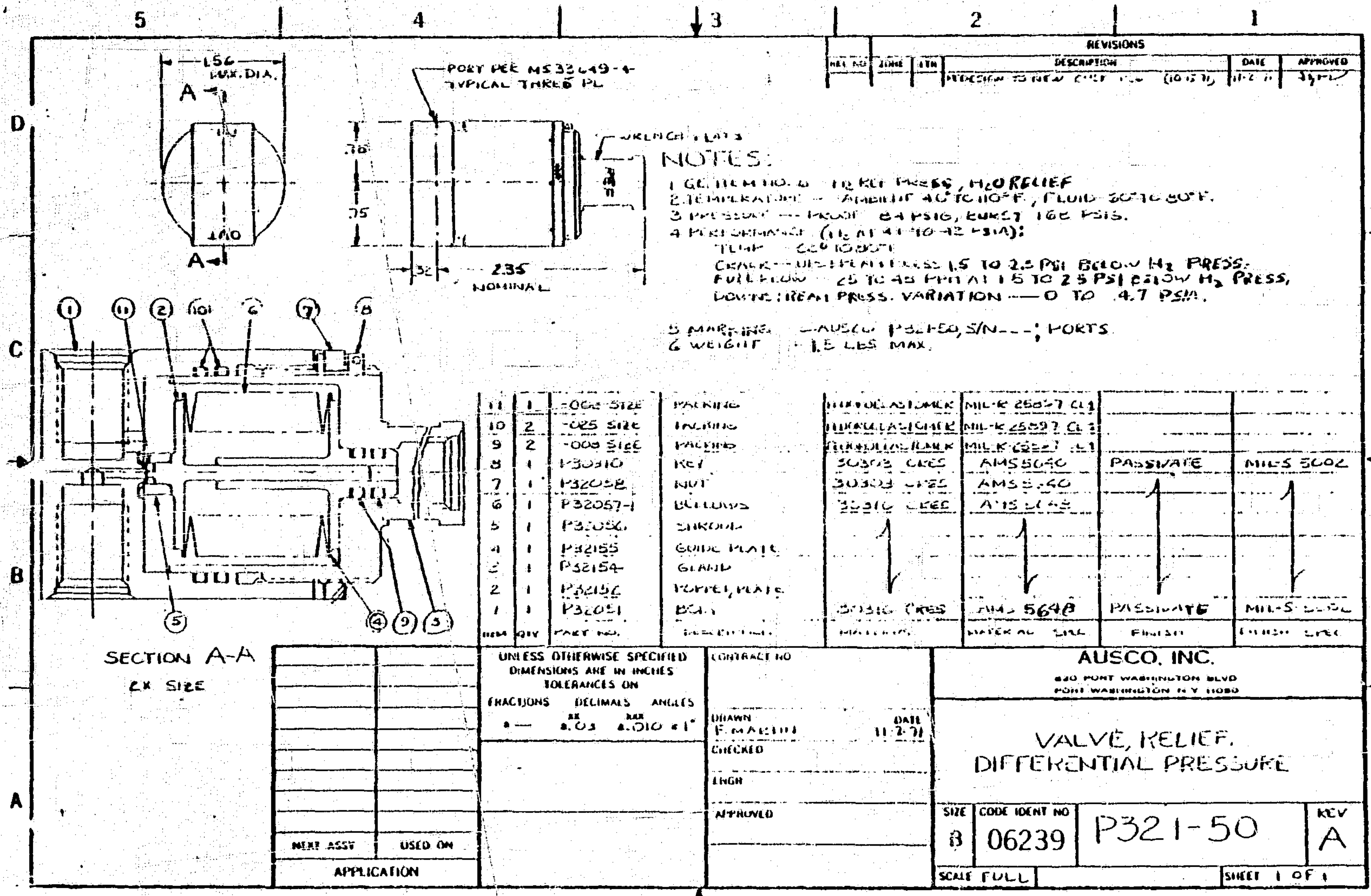
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Figure 45.

gas diffusion across the cell SPE membrane at 361 to 367K (190-200°F) as load is abruptly changed from a high power of 50 amperes or greater to the standby value. As the cells of the electrolysis module cool during the low power period a somewhat lower current would be sufficient for a net gas output to prevent pressure decay (when H_2 and O_2 back pressure regulators are closed). During an extended period of system operation of over 200 hours the pressure rise of phase separator/pump gradually diminished from 52.4 to 41.4kN/m^2 (7.6 to about 6.0 psid) which required readjustment of the differential pressure regulator to "hold" the solenoid valve open.

System accumulated gas generation time had now reached 995 hours. Sustained unattended operation at high pressure except for load changes and five differential regulator adjustments described above, was demonstrated for 190 hours from January 22 to January 30, 1975. After 20 hours of continuous operation the system was changed to the cyclic mode demonstrating cyclic load changes between 6 amperes standby current to high power values of 10, 20, 30, 40 and 50 amperes each for extended periods totalling 170 hours without shutdown. Because of the loss phase separator/pump speed and pumping differential it was decided to deactivate the system on January 30, 1975 until the phase separator problem could be investigated and resolved.

On February 10, 1975, functional aspects of the system were demonstrated at various loads and operating modes for a short period prior to system depressurization to remove and disassemble the phase separator/pump. Inspection of the pump revealed that a teflon washer shim between the impeller and housing had been worn and frayed. This was replaced by a 13 mm (.005 inch) thick niobium metallic washer. The separator/pump was then reassembled and bench tested with a pressurized water reservoir up to 2413kN/m^2 (350 psid) and circulated water flow (without two-phase input capability). A pump ΔP of about 62kN/m^2 (9.0 psid) was measured in this set-up. On February 11 the phase separator/pump was reinstalled in the system. Initial system operation at low pressure of approximately 172kN/m^2 (25 psig), revealed a low water flow rate at normal pump ΔP. After removal and bench flow testing of the deionizer the problem was corrected. The added flow impedance was attributed to gas blockage of the deionizer caused by the previous day's depressurization with a closed water metering valve. This dead-ended the inlet line to the deionizer and trapped the gas coming out of solution. Subsequent normal system operation at design pressure and at module load from 10 to 75 amperes was demonstrated at phase separator/pump ΔP of 52kN/m^2 (7.6 psid) and water flow of 90.2kg/hr. (22.5 PPH).

Additional system tests were conducted to determine the variation in phase separator/pump performance which is discussed in Para. 3.3.3.. Phase separator/pump ΔP output remained at 44.8 to 51.7kN/m^2 (6.5 to 7.5 psid) at high line pressure attributable to internal clearance changes. Except for maintaining module current under 50 amp during sustained operating periods to keep outlet temperature under 367K (200F), high pressure system operation was otherwise satisfactory.

In support of preliminary design work on a parallel program for a Life Science WES Demonstrator Unit, continued system testing was used to provide data for electrolysis module and system performance analysis. Also, design approaches for simplifying pressure control, priming and depressurizing techniques were also investigated. From this work a recommendation for the Demonstrator Unit included the use of O_2 and H_2 differential back pressure regulators which would be referenced to the base pressure nitrogen regulator. This modification would allow manual adjustment of a single regulating valve to establish control of both H_2 and O_2 pressures at any desired operating level rather than by pre-adjustment of absolute gas regulators in the current system. Additional tests also verified that the accumulator check valve (Item 2-6) was not a necessary system component and its removal was proposed for the Demonstrator Unit.

Because of a planned change in facility location, the six-man packaged WES was satisfactorily disconnected and transported to the new location. With the availability of services in the new facility on 6-2-75 the packaged system was reconnected and satisfactorily operated at design conditions within two-days time. Subsequently the electrolysis module was removed from the system, as planned, for disassembly, refurbishment, and installation of fluorosilicone cell gaskets to be evaluated. Total accumulated operating time under load was 1077 hours.

SECTION 4.0 HIGH PRESSURE OXYGEN GENERATION

4.1 System Analysis

As part of the subject program, design analyses were made for the electrolytic generation of oxygen at up to 17.24 MN/m^2 (2500 psia) with the basic SPE cell and module configuration for the purpose of providing oxygen for a waste process reaction.

Requirements for the oxygen generator would be that it provide oxygen at a temperature between 283 and 343K (50-140°F) and at a constant rate of 2.95 kg/day (6.5 lb/day) into a reactor in which pressure normally varies between 14.5 and 15.9 MN/m^2 (2100-2300 psia). The water utilized by the oxygen generator would be supplied at ambient pressure. The high pressure oxygen output control valve would be part of the waste process system. Two separate electrical signal pulses of 5 VDC from the waste process system would be utilized to start and stop the oxygen generator.

Electrolysis cell operating performance at high pressure was derived from development testing of SPE electrolysis cells for oxygen generation at 20.79 MN/m^2 (3015 psia) and conforming to requirements for a Navy oxygen generating plant under Contract N00024-72-C-5557, Project Serial No. SF0433-104, Task 16670 under Naval Ship Systems Command, Department of the Navy. At a mean cell operating condition of 393K (120°F), 17.24 MN/m^2 (2500 psia) and at a current density of 242 mA/cm^2, it was determined that 12 cells of 214.2 cm^2 area (same as in 13-cell module of advanced WES) would provide the required oxygen rate of 2.957 kg/day (6.52 lb/day). Process water circulation rate would be 26.1 kg/hr (57.5 lb/hr) for an electrolysis module water inlet temperature of 311K (100°F) and a H_2/H_2O outlet temperature of 333K (140°F).

This was the operating temperature and the current density demonstrated during most of the life tests on submarine cells operating in the cathode water feed mode. Higher operating temperatures were not found advantageous since higher parasitic losses due to gas diffusion through SPE cells at high pressures offset the reduction in cell operating voltage. Predicted input power to the power conditioner (90% efficiency) and electrolysis module would be 1425 watts whereas, heat rejection from both components would be 672 watts. Consistent input current would be 50.9 amps at a supply voltage of 28 VDC.

The electrolysis module design for 17.24 MN/m^2 (2500 psia) would be similar in concept to the 2.86 MN/m^2 (415 psia) design of the advanced WES. That is, the stack of 12 cells would be contained within a dome pressurized with nitrogen to reduce cell gasket differential pressures to about 690 kN/m^2 (100 psid).

The basic high pressure oxygen generation system schematic is shown in Figure 46. Redundant components for improved reliability and necessary instrumentation for performance monitoring and fault detection are not included for simplification. Functional components are similar to those of the six-man advanced WES (refer to Figure 16) except that differential rather than absolute back pressure regulators are employed for high pressure control and means of system pressurization and depressurization. The process water loop operating conditions of lower temperature and higher pressure have allowed for elimination of the regenerative heat exchanger. This requires operation of the phase separator/pump at about 333K (140°F) and the deionizer at about 311K (100°F) which is considered feasible for both components.

As shown in Figure 46, a hand-loading base pressure regulator is used for manually raising and lowering system operating pressure. O_2 and H_2 differential back pressure regulators and the module dome pressure regulator are referenced to regulated base pressure. It is proposed that the O_2 generator system would be started at low pressure and be self-pressurized by electrolysis at increasing pressure levels as base pressure is adjusted upward to design operating conditions at the following regulated values:

N_2 Base Regulated Pressure: $P_{N_2\ BASE} = 0\text{-}16.5\ MN/m^2$ (0-2400 psia)
(Manually adjusted)

Hydrogen Regulated Back Pressure: $P_{H_2} = P_{N_2\ BASE} + 345\ kN/m^2$
(50 psid)

Oxygen Regulated Back Pressure: $P_{O_2} = P_{N_2\ BASE} + 690\ kN/m^2$
(100 psid)

N_2 Dome Regulated Pressure: $P_{N_2\ DOME} = P_{N_2\ BASE} + 1135\ kN/m^2$
(150 psid)

Relief valves are provided for overpressure protection and would backup FDIA instrumentation with ESD controls. Several manual valves are shown for shut-off and venting capability to completely depressurize the system.

A water temperature regulator controls process water delivered to the deionizer and to the H_2 side of the module at a temperature of 311K (100°F). Two-phase H_2/H_2O flow leaves the module at a temperature of 333K (140°F) and is delivered to the phase separator. Because of the high pressure, only a small amount of water vapor is discharged with the hydrogen at this temperature. Water discharged from the phase separator is cooled by the heat exchanger with some by-pass directly to the temperature regulator. A water accumulator, as in the advanced six-man WES, has the dual function of providing logic for make-up water addition and a water storage capacity for load changes. A piston-type make-up pump delivers feed water from ambient supply pressure to the accumulator at a pressure of about 16.9 MN/m^2 (2450 psia). Coolant supplied to the system removes waste heat from the heat exchanger and power conditioner.

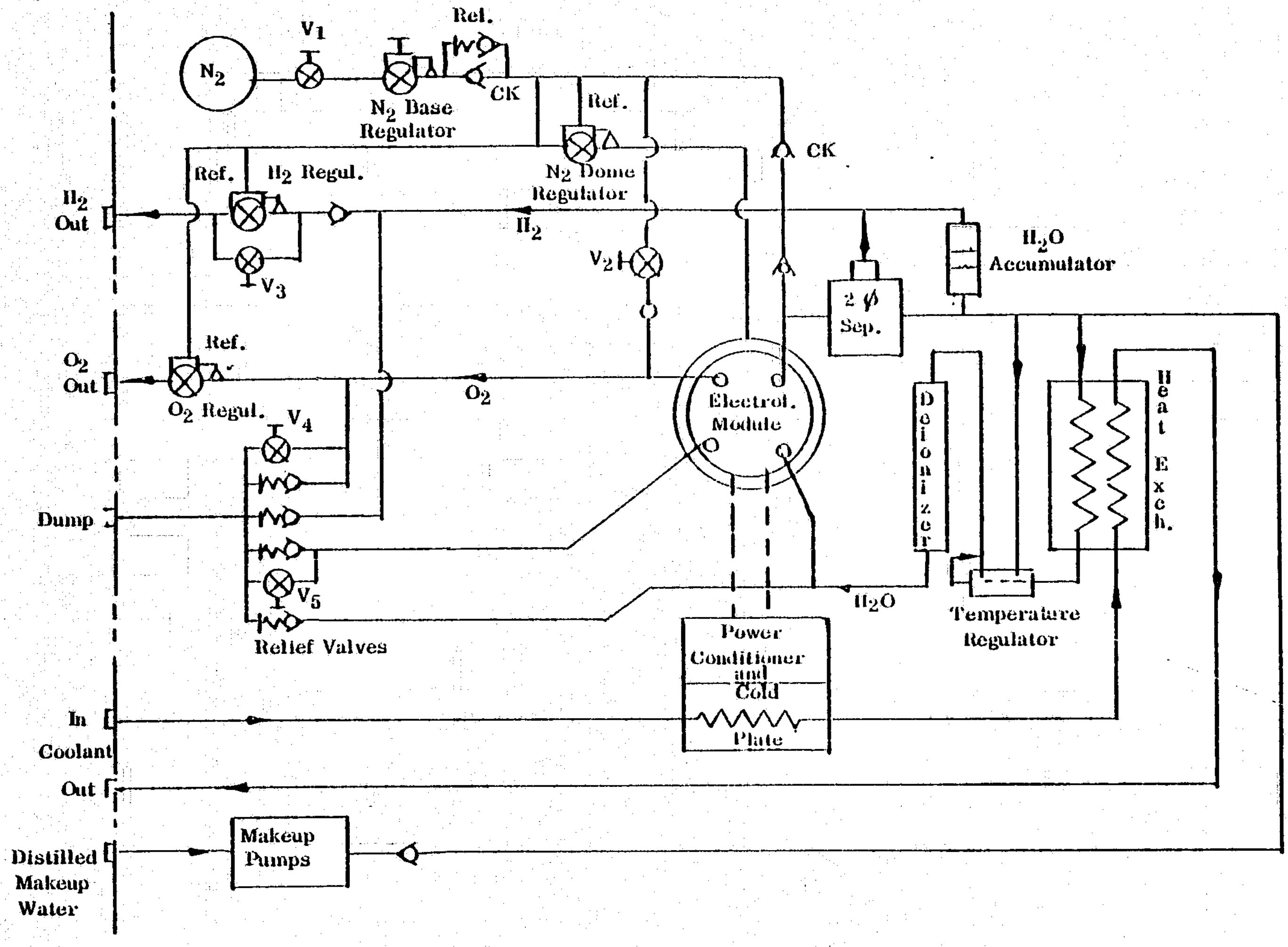


Figure 46.- High Pressure Oxygen Generation System

A trade-off study would be required to determine the most feasible means of meeting power, weight, start/stop requirements of a waste process system. Because of a high rate of O_2 and H_2 gas diffusion at high pressure or so-called "fuel celling", gas pressures would drop suddenly if load was removed from the electrolysis module. Either a standby current must be maintained such that a small net O_2 and H_2 gas production is discharged through the back pressure regulators, or as the pressures fall in the electrolysis module, nitrogen would be admitted through the check valves shown in Figure 46, to hold system pressure at regulated N_2 base pressure. For short, frequent down times of the waste process reaction, maintaining a standby load on the O_2 generator sounds feasible whereas for long, infrequent down times, the nitrogen back fill would conserve power with little addition weight for N_2 usage.

It was determined that a standby current of 16 amps would be required to overcome estimated diffusion losses at a module temperature and pressure of 316K 110°F) and 17.2 MN/m^2 (2500 psia). An input power of 386 watts and system heat rejection of 375 watts would be required to maintain this condition. Some O_2 output valve control would be necessary to dump or by-pass the small amount of oxygen discharged from the O_2 generator.

Complete removal of current from the electrolysis module would result in nitrogen at 16.5 MN/m^2 (2400 psia) replacing essentially all oxygen and the equivalent stoichiometric amount of hydrogen which are gradually combined to form water by diffusion at the electrodes in the SPE cells. It was calculated that a total quantity of 4.54 kg (10 lb) of nitrogen would be used for 100 system shutdowns. This nitrogen would necessarily be purged overboard with the generated O_2 and H_2 for a sufficient period of time after restarting to eliminate this diluent from oxygen delivered to the waste process reactor. Assuming three complete system changes which include N_2 pressurization of the module dome, the total nitrogen requirement would be 7.5 kg (16.5 lb). The gas bottle volume requirement for initial storage at 41.3 MN/m^2 (6000 psia) and use at 16.5 MN/m^2 (2400 psia) would be 26.4 liters (0.932 ft^3) equivalent to a sphere having an inside diameter of 36.9 cm (14.5 inch).

4.2 Component Design

Because cell design would be identical to and the stack assembly of 12 cells would closely approximate the 13-cell advanced module configuration, only the enclosure plate and domed enclosure would require redesign for higher pressure. Conditions of maximum operating pressure of 17.9 MN/m^2 (2600 psia), a proof pressure (1.5 X) of 26.9 MN/m^2 (3900 psia), and a burst pressure (2.5 X) 44.8 MN/m^2 (6500 psia) were applied for module design stress analysis. The following modifications would apply to the module design shown in Figure 22. The bottom enclosure plate would consist of 7075S-T6 aluminum, 5.08 cm (2.00 inch) thick utilizing type 316 stainless steel inserts for fluid porting and corrosion resistance. The lower module operating temperature permits the use of this design approach and use of this high strength aluminum to reduce weight. The elliptical dome of the module is made of 2024-T6 aluminum with a wall thickness of 1.42 cm (0.56 inch) and having a flange thickness of 3.8 cm (1.50 inch). The diameter of the flange and enclosure plate have been increased from 33 to 37.4 cm to accomodate these larger dimensions and larger flange bolts. Twenty-four flange bolts 9/16-18 thread are specified by MS9738 (17-4 Ph), precipitation hardened stainless steel. The estimated weight of this 12-cell 17.24 MN/m^2 (2500 psia) module design, is 41 kg (90.5 lb).

The water accumulator design shown in Figure 34, which incorporates an external actuating rod was found not feasible for much higher pressures because of imbalance forces. A modified design concept would include an internal stainless steel piston with encapsulated magnets and without a piston rod. Reed-type position switches would be contained in sealed tubes inserted in the end plates of the accumulator. Water capacity was reduced to 164 cc (10 $in.^3$) because of elimination of the regenerative heat exchanger in the water process loop and the high operating pressure. Cylinder size would be 7.62 cm (3.00 inch) O.D. x 20.6 cm (8.12 inch) long. Net additional weight over the six-man WES accumulator is 1.4 kg (3.1 lb) to a total new weight of 7.13 kg (15.74 lb).

The phase separator/pump would not change in concept, but would increase in size and weight to provide for a heavier housing to accomodate the higher internal pressure. Estimated weight would be 9.1 kg (20 lb).

Design of a nitrogen bottle for minimum weight considered an ARDEFORM sphere made from cryogenically formed 301 stainless steel shell with external glass filament reinforcing. As fabricated, the steel inner shell is under compression and approaches a zero stress condition at the design operating pressure of 41.3 MN/m^2 (6000 psia). Design burst pressure (2.5 X) would be 103 MN/m^2 (15,000 psia). The external fiber structure is of glass filament wound construction with resin cured at 422K (300F). Demonstrated tensile strength at room temperature is 2275 MN/m^2 (330,000 psi). Design configuration would be a stainless steel shell of 36.9 cm (14.5 inch) inside diameter and wall of 3.19 mm (0.125 inch) surrounded by a fiberglass shell with a wall thickness of 4.19 mm (0.165 inch). This configuration would weigh 19.5 kg (42.9 lb) and hold 12.5 kg (27.5 lb) of nitrogen having a standard volume of 13.4 std. liters (380 SCF).

Gas regulators for differential control at high pressure are commercially available as special equipment for the conditions cited. Contact was made with Tescom Corporation, Minneapolis, Minn., who provided information on the units listed in the following table.

Regulator Name	Tescom P/N	Weight kg	Max Inlet Pressure	Outlet Pressure	Max Reference Pressure	Positive Bias Differential kN/m^2 (psid)
			←	MN/m^2 (psia)	→	
N_2 Base Pressure Hand Loader	26-1024-34	2.5	41.4(6000)	.1- 17.2(15-2500)	-	-
N_2 Dome Pressure Reduced W1 Ref.	Similar to 26-1000	2.5	41.4(6000)	Max 17.6(2550)	16.5(2400)	103(150)
O_2 Back Pressure Regulator W1 Ref.	Similar to 26-1700	2.3	17.2(2500)	$<$ 15.8(2300)	16.5(2400)	69(100)
H_2 Back Pressure Regulator W1 Ref.	Similar to 26-1700	2.3	16.9(2450)	$<$ 15.8(2300)	16.5(2400)	34.5(50)

Because of the higher process water flow rate and higher operating pressure than the six-man rated WES, the deionizer would utilize a larger 1000 ml capacity sampling cylinder rated for 24.1 MN/m^2 (3500 psia) operation. Container size would be 8.9 cm (3.5 inch) outside diameter by 29.2 cm (11.5 inch) long, weighing 5.56 kg (12.25 lb).

Pressure rating of the dual heat transfer coil heat exchanger, P/N 3101-6, 4-8-6X, Parker Hannifin Corp., is 18.6 MN/m^2 (2700 psia). Similarly, most standard commercial tube fittings, hand valves, check valves, etc., have pressure ratings greater than 20.7 MN/m^2 (3000 psia) and would be suitable for service in this system.

Major components of a water electrolysis system which are weight sensitive to operating pressure are listed below. A comparison of component weight is provided between that of the six-man rated system at nominal 2.860 MN/m^2 (415 psia) and that of the high pressure O_2 generation system at nominal 17.2 MN/m^2 (2500 psia).

Component Name	Six-Man WES	High Pressure O_2 Gen.
	Weight kg (lb)	
Electrolysis Module	32.9 (72.5)	41.1 (90.5)
Water Accumulator	5.7 (12.7)	7.1 (15.7)
Phase Separator	7.2 (15.8)	9.1 (20.0)
Deionizer	1.5 (3.3)	5.6 (12.3)
N_2 Gas Bottle (Empty)	Not Included	19.5 (42.9)
N_2 Gas Bottle (Full)	-	32.0 (70.4)
N_2 Base Pressure Regulator	2.5 (5.5)	2.5 (5.5)
N_2 Dome Pressure Regulator	2.5 (5.5)	2.5 (5.5)
O_2 Back Pressure Regulator	0.7 (1.5)*	2.3 (5.0)
H_2 Back Pressure Regulator	0.7 (1.5)*	2.3 (5.0)

* Absolute Back Pressure Regulators designed to specification.

It should be noted that the component weights listed, excepting the N_2 gas bottle, are for commercial off-the-shelf hardware or for preprototype designs without a critical regard for weight and would not be, necessarily, respective of flight-weight designs.

SECTION 5.0 SPACE STATION PROTOTYPE SUPPORT WORK

The design of an Oxygen Generation Subsystem as a part of the overall Life Support System for the Space Station Prototype was conducted in parallel with Phase I of this program. As reported, testing of the four-man breadboard WES provided information on component and system characteristics in different operating modes and supplied test data in support of engineering design. After shipment of the packaged Oxygen Generation Subsystem to NASA/JSC in Houston, Texas, in September 1973, consultation by telephone was provided to NASA during its installation and checkout.

During subsystem testing at NASA/JSC on February 19, 1975, the electrolysis module exhibited evidence of internal leakage. The torque of the nuts on the module tie bolts was not checked before the system was tested and this was surmised initially to be the cause of the leakage. The 27-cell electrolysis module was returned to General Electric Co./DECP for failure analysis, refurbishment, and checkout. This work was accomplished and is summarized in a letter report included in the Appendix. The refurbished module, containing 15 of the original 27 cells, was returned to NASA/JSC on March 24, 1975. Satisfactory performance of the electrolysis module and Oxygen Generation Subsystem was subsequently demonstrated over a 100-hour checkout test period.

SECTION 6.0 CONCLUSIONS

1) A 13-cell, SPE advanced module design for operation at an average temperature of 355k (180°F), and 2860kN/m^2 (415 psia) conditions was successfully demonstrated in a six-man rated water electrolysis system (WES) over a total operation period of 1060 hours.

2) Safe, unattended operation of a six-man rated, advanced pre-prototype WES was demonstrated in continuous and cyclic operating modes at a nominal pressure of 2860kN/m^2 (415 psia). The packaged system included semi-automatic controls for pushbutton start, stop, FDIA instrumentation and emergency controller for a safe emergency shutdown at high pressure.

3) A combination water pump/centrifugal phase separator was developed which demonstrated positive separation of hydrogen and water and pumping capability in the six-man advanced WES over a wide range of operating pressures from 172 - 2758kN/m^2 (25 - 400 psia).

4) An improved, dual-beaded fluorosilicone rubber gasket system was installed in the cells of the electrolysis module and successfully tested at maximum design operating conditions of 367k (200°F) and 3000kN/m^2 (435 psia).

5) A high pressure, catalytic O_2/H_2 gas mixture sensing device was developed which demonstrated excellent sensitivity for both lean and rich mixtures below and above the flammability limits. This device was installed in both the O_2 and the H_2 output lines of the six-man rated, advanced WES as a fault detection sensor.

6) The results of a preliminary design study of a high pressure water electrolysis system are presented for an oxygen generator which would supply oxygen at a rate of 2.95kg/day (6.5 lb/day) and at a pressure of 17.2kN/m^2 (2500 psia) applicable to a waste process system.

SECTION 7.0 RECOMMENDATIONS

1) Redesign of the phase separator/pump developed under this program is recommended to provide a larger magnetic coupling and motor and modification of internal parts to eliminate impeller clearance changes caused by deflection at high pressure. Also, a design should be developed which would incorporate a proportionate control on the H_2 gas discharge to eliminate the cyclic pressure pulsations encountered in the initial design.

2) Electrolysis module design improvement resulting from incorporation of a beaded fluorosilicone gasket system should be life tested at maximum module outlet operating temperature of 361-367k (190-200°F). Also, the integrity of sealing capability should be evaluated by exercising the gasket system between 0 and 2860kN/m^2 (0-415 psia) reflecting anticipated WES shutdowns for servicing and maintenance.

3) Further unattended testing of the advanced pre-prototype system, derated to three-man oxygen output, should be performed in continuous, cyclic, standby and high pressure ESD modes. The purpose of this testing would be to further evaluate component performance, life capability and uncover anomalies requiring possible adjustment or modification in pressure regulator settings, automatic start-stop and ESD controls including setting of timing sequences and FDIA limits. Information from this testing would be applied to improvement in the performance and reliability of components and the system configuration for the Water Electrolysis Demonstrator Unit in the Life Sciences Payload Program.

APPENDIX

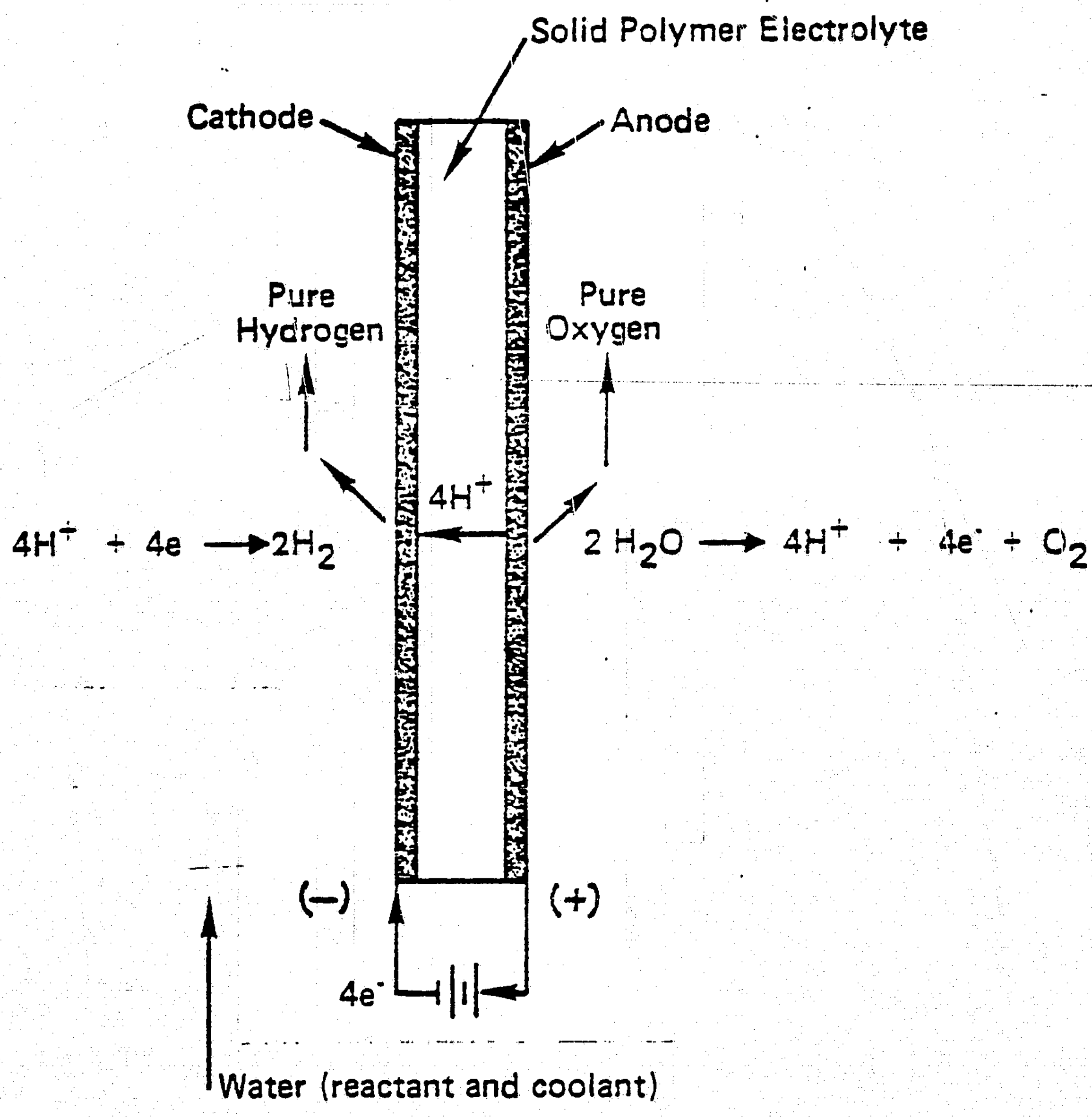
BASIC SPE WATER ELECTROLYSIS TECHNOLOGY

The electrolyte in the SPE electrolysis concept is a solid plastic sheet or membrane of perfluorinated sulfonic acid polymer about 0.030 cm (0.012 in.) thick, having many of the physical characteristics of Teflon. This polymer, when saturated with water, is an excellent ionic conductor ($\leq$ 15 ohm-cm resistivity) and is the only electrolyte required in the system. There are no free acid or alkaline liquids, with only water as the free liquid. A typical cell is shown in the following illustration. This is a cross-sectional view through the SPE and the attached catalyst structure (or electrodes) on either side of the membrane. Ionic conductivity is provided by the mobility of the hydrated hydrogen ions ($H^+ \cdot x\, H_2O$). These ions move through the SPE membrane by passing between the fixed sulfonic acid groups.

To reduce the complexity of the water/gas separation techniques, the process water (reactant and coolant) is fed to the hydrogen electrode known as the cathode feed mode. The SPE is sufficiently water permeable to allow water to diffuse from the hydrogen electrode to the oxygen electrode, where it is electrochemically decomposed to provide oxygen, hydrogen ions and electrons. The hydrogen ions move to the hydrogen evolving electrode (cathode) by migrating through the SPE. The electrons pass through the external electrical circuit to reach the hydrogen electrode. At the hydrogen electrode, the hydrogen ions and electrons recombine electrochemically to produce hydrogen gas.

The process water entering the cell is in excess of the amount required for the cell reaction. This excess water functions as the system coolant by transferring the electrolysis cell waste heat to an external system heat exchanger and is recirculated within the system water loop.

The gases are generated at a stoichiometric ratio of hydrogen and oxygen at any pressure required of the system by simply back pressurizing the corresponding gas side. For high pressure operation, e.i. greater than 790 kN/m^2 (115 psia), the cell is enclosed in a pressure vessel and the differential pressure across the SPE is controlled by the system gas regulators.



SPE Electrolysis Cell Schematic

*DYNAMIC PHASE SEPARATOR/PUMP ASSEMBLY SPECIFICATION

*1.0 Functional Purpose: During one GEE and zero GEE operation the dynamic phase separator/pump assembly, in any attitude, shall provide separation of a mixture of hydrogen and liquid water and also provide circulation capability of process water in an electrolysis system for a manned space station application.

1.1 End Items: Delivered dynamic phase separator/pump assembly hardware shall be:

a) One (1) dynamic phase separator/pump with integrally mounted solenoid valve and relief valve.

b) One (1) separator electronic controller.

*2.0 Mechanical Description: The dynamic phase separator/pump assembly shall consist of an electric motor magnetically coupled to provide rotation to a spin chamber in which centrifugal force will separate liquid and gas phases from a mixture of hydrogen and water and also to provide an impeller for pressure rise with subsequent water circulation. Rotating parts shall be fully self-contained in the event of failure.

In addition, the assembly shall include a speed sensor (i.e., magnetic pickup and impeller) driven by a fluid coupling with the rotating water mass and conditioning electronic logic to open or close a solenoid valve, which is located in the hydrogen outlet. An in-line relief valve shall be connected in parallel at the hydrogen outlet to bypass the normally-closed solenoid valve.

*3.0 Weight: Minimal weight shall be employed in the design of end items consistent with compliance with requirements of this specification. Weight estimates shall be identified on drawings.

*4.0 Port Configuration:

° Hydrogen/water inlet boss	MS33649-6
° Hydrogen outlet (one or two to be defined)	1/4 inch Swagelok
° Water out boss (size to be defined)	MS33649-4 or -6

Note: "NPT" pipe threads are not permitted.

*5.0 Electrical Interfaces and Requirements:

115 VAC ± 5%, 60 Hz, single phase	Available for motor
28 VDC ± 5%,	Available for control logic and solenoid valve operation

Note:

° Minimum power demand of end items shall be provided in the design consistent with requirements herein.

° Suitable Bendix bulkhead male connectors shall be provided on the end items including appropriate mating female connectors.

° The dynamic phase separator/pump assembly shall be designed to be ignition proof, i.e., the assembly or components thereof, shall not be capable of igniting any explosive mixture existing in or surrounding the assembly either functioning or at standstill in accordance with Procedure II, Method 511 of MIL-STD-810B dated 15 June 1967. The separator electronic controller is permitted to be "breadboarded" however, without potting compounds and need not be considered "explosion proof".

° The dynamic phase separator/pump assembly shall be designed with electromagnetic interference (EMI) characteristics (emission and susceptibility) in accordance with Class No. ID equipment of MIL-STD-461A dated 1 August 1968.

° Electrical wiring shall be properly supported and routed to prevent chafing, provide protection against sharp edges, mechanical strain, etc., and conform to MIL-W-16878. Color coding of conductors of the equivalent shall be provided for identification.

° Bonding requirements in accordance with MIL-B-5087 Class H, R and S as applicable.

° The motor and solenoid valve shall be capable of withstanding for one (1) minute a potential of 1000 volts RMS at 60 Hz gradually applied to each connector pin and the case without damage, arcing or breakdown and shall have a minimum insulation resistance of 2 megohms after this dielectric strength test.

*6.0 Mounting Provisions: Mounting of the dynamic phase separator/pump assembly shall have adequate structural integrity to assure compliance to this specification without mechanical failure or performance deterioration when subjected to:

- Acceleration "hard" environment of Procedure I, Method 513, paragraph 3.2.4 with "Manned Aerospace-Vehicle Category".

- Vibration "hard" environment of Procedure I, Method 514, paragraph 4.5.1, Part 1 (sinusoidal vibration curve "P" and time schedule I) and paragraph 4.5.2 Part 2 (random vibration curve AG), MIL-STD-810B dated 15 June 1967.

- Bench handling shock "hard" environment of Procedure V, Method 516, paragraph 3.7, MIL-STD-810B, dated 15 June 1967.

The mounting configuration of the separator electronic controller shall be designed for securement to a horizontal plate.

The mounting configuration of the dynamic phase separator/pump assembly shall be designed for securement to a cold plate which has cooling water flowing therein to remove heat. The dynamic separator/pump and cold plate will be secured to a vertical panel. The cold plate is not an end item of this specification.

*7.0 Permissible Materials: In configuration proximity with the water, permissible materials are 316 or 321 AISI stainless steels, Viton "A", Lexan or Teflon. Consideration of other materials will be given when presented to GE/DECP by the vendor. No copper, iron, silver, zinc, cadmium or processes of brazing soldering are allowed in the configuration proximity of the water. Corrosion reduction processes shall be introduced to those surfaces which are in configuration proximity with the water; such as annealing after welding plain 316 SST, passivation of stainless steel and thermoplastic coating surfaces; i.e., fluorinated ethylene polypropylene (FEP) coating a 316 SST spin chamber or similar plastic coating to nickel magnetic slugs of the speed sensor.

Redundant Viton "A" O-ring seals shall be introduced into the design in appropriate regions to assure no external leakage of hydrogen to ambient.

Rub wear materials which could contaminate the delivered water and/or hydrogen or compromise useful life shall be minimized.

Titanium is not permitted in the design.

Lubrication materials are not permitted in the design which could contaminate the water and hydrogen or leak to ambient.

Electroactivity contact of dissimilar metals per MS33586 shall be avoided.

Materials that could liberate toxic gases shall be avoided.

The use of metallic self-locking nuts is the preferred method to secure the assembly detail parts. Lockwire should be considered as an alternate approach. Star washers, jam nuts, lock washers, etc. shall not be used.

Assembly drawing copies with appropriate parts list, material identification and process specification definition shall be submitted to GE/DECP for review.

*8.0 Overall Envelope Dimensions and Spin Chamber Storage Capacity:

Minimum sizing for compatibility to requirements of this specification is required.

Outline-installation drawing copies delineating all pertinent details of the end items (e.g., port title and fitting identification, connector identification and pin designation electrical schematic, detail installation and outline dimensions, servicing and acceptance test notes as necessary, rated requirements, etc.) shall be submitted to GE/DECP for review.

*9.0 Performance Requirements

The dynamic phase separator/pump assembly shall be capable of continuous or cyclic operation in any attitude in a one GEE or zero GEE environment with a two (2) phase mixture of saturated hydrogen gas and "sluglet" water at 50 to 100°F (normally 75°F) delivered to the inlet.

Note: A cycle is equivalent to one (1) 94 minute orbit of 55 minutes "on" power and 39 minutes "off" power.

The dynamic phase separator/pump assembly shall reach a sufficient speed of rotation for positive centrifugal separation of gas and liquid delivered to the unit and/or contained therein within 15 seconds of motor energization. The unit shall also be capable of pumping water at the specified rate and pressures within one (1) minute of motor energization.

The dynamic phase separator/pump shall be capable of acceptable functional performance at standstill, startup transient, steady state operation and/or shutdown transient during any attitude within an environment of one GEE or zero GEE and in an environment of 40 to 110°F and 0 to 14.7 psia.

During transient periods of starting and stopping the unit as well as at standstill both gas and liquid may be transferred to or from the cavity between the two-phase inlet port to water outlet port depending on environmental gravity conditions, shifting and circulation of fluids in the two-phase circuit, and gradual consumption of hydrogen by the electrolysis system. The solenoid valve and relief valve must remain closed and unenergized during these periods to prevent any discharge of water through the hydrogen outlet. Also, the inlet passages of these components shall be designed for negligible hold up or transfer of water to the hydrogen outlet during startup.

The dynamic phase separator assembly shall be capable of delivering a water flow of 10 to 30 lb/hr with a pressure rise (from two-phase inlet port to water outlet port) design requirement of 10 psid at 20 lb/hr. Simultaneously it shall provide phase separation and delivery of hydrogen to the hydrogen outlet port at the following conditions:

- The hydrogen content of the two-phase mixture will be delivered to the two-phase inlet port of the unit at a flow rate of 0 to 0.10 lb/hr.

- The hydrogen outlet pressure will be maintained by a downstream back pressure regulator (which is not an end item of this specification) at a selected pressure level adjustable between 100 and 380 psia. The selected pressure level will be regulated from 0 to plus 20 psid respectively, from cracking pressure to full hydrogen flow and with a minimum reseat pressure of minus 20 psid from cracking pressure at zero hydrogen flow.

- The hydrogen/water volumetric mixture ratio can vary from zero to 15.0 coincident with maximum hydrogen flow, minimum water flow and minimum hydrogen outlet pressure.

The dynamic phase separator/pump shall be capable of no external leakage, structural damage or performance deterioration with a proof pressure of 549 psig or no structural damage with a burst pressure of 915 psig.

Acceptable functional performance is defined as:

- No liquid water (e.g., sluglet or mist) is permitted in the hydrogen discharge for any conditions. The hydrogen outlet gas however, will be saturated with water vapor.

- No hydrogen gas is permitted in the water discharge for any conditions.

- Pump pressure-rise capability and flow capacity as mentioned above.

- Minimal power demand (watts) shall be employed in the design consistent with compliance to the requirements of this specification.

- Pressure drop (two phase mixture inlet minus hydrogen outlet) of 2 psid maximum for all flows and pressures with solenoid valve open.

- Integrally mounted in-line relief valve shall have a nominal relieving pressure differential adjustable between 3 and 50 psid (between core pressure and H_2 outlet). Breaking of fluid connections and partial disassembly is permissible for manual adjustment.

- No external leakage of hydrogen or water.

10.0 Continuous Mission Rate Duty: Acceptable functional performance as defined in paragraph 9.0 during steady operation for six (6) months.

11.0 Cyclic Mission Rate Duty: Acceptable functional performance as defined in paragraph 9.0 during 5514 equivalent orbital cycles of paragraph 9.0.

12.0 Reliability: Useful life two (2) years.

WATER TEMPERATURE REGULATING VALVE SPECIFICATION

1.0 * Functional Purpose: During one GEE and zero GEE operation in any attitude the temperature regulating valve shall establish a constant controlled mixture-out temperature of hot and cold process water which is circulated to a solid polymer electrolyte module for a manned space station application.

2.0 Mechanical Description: The water temperature regulating valve consists of a sleeve mixing valve actuated by a sealed eutectic wax actuator which is sensitive to temperature by mixing hot and cold water. The valve shall provide forced flow of the water passed the waxed actuator for optimum heat transfer and sensing characteristics.

3.0 Weight: 1.6 lbs. maximum.

4.0 Port Configuration: Three ports (cold inlet, hot inlet and controlled mixture outlet) in accordance with MS 33649-6.

5.0 Electrical Interfaces: None.

6.0 Mounting Provisions: The water temperature regulating valve will be secured at three (3) mounting points.

7.0 Permissible Materials: 316, 321, 347, 17-4 PH AISI Stainless Steels; Viton "A" seal material; proprietary eutectic wax mixture.

8.0 * Maximum Overall Envelope Dimensions: 6.00" x 1.52" x 3.00".

9.0 Performance Requirements:

* With 170 to 200°F water admitted to the "hot-in" port and 50 to 100°F water admitted to the "cold-in" port, the controlled mixture out temperature of the total process water flow (10.0 to 15.0 lb/hr) shall be 160 ± 5°F. The valve shall be capable of external adjustment of the controlled mixture out temperature within a range of 150 to 170°F.

*	Pressure Loss:	At 15.0 PPH; less than 0.25 psid.
	Working Fluid:	Water with dissolved hydrogen and random gas "sluglets".
*	Upstream Pressure:	333 to 373 psig.
	Environment Requirements:	40 to 110°F and 0 to 14.7 psia.
	External Leakage:	None.
*	Proof Pressure:	560 psig.
*	Burst Pressure:	933 psig.

10.0 Continuous Mission Rate Duty: Steady state operation for six (6) months at 160±5°F controlled mixture outlet temperature.

11.0 Cyclic Mission Rate Duty: 5514 temperature cycles consisting of a transient rise to 160±5°F controlled mixture out temperature, steady state at 160±5°F 55 min., transient decrease to 75±5°F controlled mixture out temperature and then 75±5°F for 39 min.

12.0 Reliability: Useful life - two (2) years.

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*HYDROGEN ABSOLUTE BACK-PRESSURE REGULATOR SPECIFICATION

1.0 Functional Purpose: During one GEE and zero GEE operation in any attitude the regulator shall establish a controlled pressure level on the hydrogen discharge side of a dynamic phase separator/pump in a water electrolysis system for a manned space station application.

2.0 Mechanical Description: The hydrogen absolute back-pressure regulator consists of a soft-seated valve actuated by a differential force of "upstream" hydrogen pressure, bellows gradient, compression spring and "downstream" pressure.

3.0* Weight: 1.60 lb. maximum.

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

5.0 Electrical Interfaces: None.

6.0 Mounting Provisions: In-line tubing installed.

7.0* Permissable Materials: 17-7 PH, 316 AISI Stainless Steels; Viton "A" seal material.

8.0* Maximum Overall Envelope Dimensions: 1.56" dia x 4.40" long.

9.0 Performance Requirements:

* With 50 to 100°F mixture of hydrogen and water vapor supplied to the inlet, the regulator shall crack within and be capable of controlling the upstream pressure to 361 to 381 psia, when passing a 50 to 100°F saturated mixture of 0.0194 to 0.220 lb./hr. of hydrogen independent of the downstream pressure. The regulator shall reseat (shut off hydrogen flow) at 341 psia minimum. The regulator shall be capable of external adjustment of the upstream pressure within a range of 100 to 500 psia.

Working Fluid: Hydrogen and water vapor.

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

* Downstream Working Fluid Pressures: 0 psia minimum; 265 psia maximum for 500 psia upstream pressure; 53 psia maximum for 100 psia upstream pressure; 15.5 psia nominal.

* Upstream Working Fluid Temperatures: 50°F minimum; 100°F maximum; 75°F nominal.

* Proof Pressure: 572 psig maximum.

* Burst Pressure: 1000 psig maximum limited by bellows.

Environment Requirements: 40 to 110°F and 0 to 14.7 psia.

10.0 Continuous Mission Rate Duty: Steady-state flows for six (6) months varied within a hydrogen range of 0.0194 to 0.220 lb./hr. of 75°F saturated.

11.0 Cyclic Mission Rate Duty: 5514 cycles of hydrogen/water vapor flow "on and off", i.e., one cycle equals 55 minutes of 75°F saturated hydrogen "on" flow time at 0.220 lb./hr. and 39 minutes of no flow.

12.0 Reliability: Useful life - two (2) years.

* OXYGEN ABSOLUTE BACK-PRESSURE REGULATOR SPECIFICATION

1.0 Functional Purpose: During one GEE and zero GEE operation in any attitude the regulator shall establish a controlled pressure level on the oxygen discharge side of a solid polymer electrolyte module for a manned space station application.

2.0 Mechanical Description: The oxygen absolute back-pressure regulator consists of a soft-seated valve actuated by a differential force of "upstream" oxygen pressure, bellows gradient, compression spring and "downstream" pressure.

3.0 * Weight: 1.60 lb. maximum.

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

5.0 Electrical Interfaces: None.

6.0 Mounting Provisions: In-line tubing installed.

7.0 * Permissible Materials: 17-7 PH, 316 AISI Stainless Steel, Viton "A" seal material.

8.0 * Maximum Overall Envelope Dimensions: 1.56" dia x 4.40" long.

9.0 Performance Requirements:

* With 100 to 200°F mixture of oxygen and water vapor supplied to the inlet, the regulator shall crack within and be capable of controlling the upstream pressure to 415 to 435 psia, when passing a 100 to 200°F saturated mixture of 0.154 to 1.750 lb/hr of oxygen independent of the downstream pressure. The regulator shall reseat (shut off oxygen flow) at 395 psia minimum. The regulator shall be capable of external adjustment of the upstream pressure within a range of 100 to 500 psia.

Working Fluid: Oxygen and water vapor.

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

* Downstream Working Fluid Pressures: 0 psia minimum; 265 psia maximum for 500 psia upstream pressure; 53 psia maximum for 100 psia upstream pressure; 15.5 psia nominal.

* Upstream Working Fluid Temperatures: 50°F minimum; 250°F maximum; 150°F nominal.

* Proof Pressure: 653 psig maximum.

Table III (Cont'd.)

* Burst Pressure: 1000 psig maximum limited by bellows.

Environment Requirements: 40 to 110°F and 0 to 14.7 psia.

10.0 Continuous Mission Rate Duty: Steady-state flow for six (6) months varied within an oxygen range of 0.154 to 1.750 lb./hr. at 150°F saturated.

11.0 Cyclic Mission Rate Duty: 5514 cycles of oxygen/water vapor flow "on and off", i.e., one cycle equals 55 minutes of 150°F saturated oxygen "on" flow time at 1.75 lb./hr. and 39 minutes of no flow.

12.0 Reliability: Useful life - two (2) years.

WATER ACCUMULATOR SPECIFICATION

1.0 Functional Purpose

The water accumulator shall establish a water storage capacity during starting and operating transients in the water circuit of a water electrolysis system. It also shall provide three (3) position switches for identifying "empty" and "full" points of a smaller volume to be used for charging the system with make-up water, as well as the position for "maximum stroke".

2.0 Mechanical Description

The water accumulator shall consist of a pressurized cylindrical container having a spring-loaded piston or diaphragm separating the water storage chamber from a hydrogen chamber at a lower pressure. The quantity of water stored will be dependent upon the pressure differential ($pH_2O - pH_2$) as opposed by a return spring. The differential area gained by incorporating a piston rod may be utilized for balancing forces to reduce spring force and size. The position switches shall be integrally mounted and provided with a single electrical connector.

3.0 Weight

Minimal weight shall be employed in the design consistent with the requirements of this specification. A weight estimate of the assembly shall be identified on drawings.

4.0 Port Configuration

Hydrogen boss	MS33649-4
Water boss	MS33649-4

Note: "NPT" pipe threads are not permitted.

5.0 Electrical Interface and Requirements

Magnetic reed switches may be utilized as position switches which will be connected to a logic circuit (not an end item) for controlling a make-up water pump used for charging the water accumulator.

Switch Rating: 0.25 amps resistive, 28 VDC
Both normally closed and normally open contacts available.

Switch Location: Three position switches shall be installed to signal volume point of the water accumulator per Table I.

Electrical Connector: An integrally mounted Bendix-type bulkhead male connector shall be provided including the mating female connector.

The water accumulator assembly shall be designed to be ignition proof, i.e., the assembly or components thereof, shall not be capable of igniting any explosive mixture existing in or surrounding the assembly either functioning or at standstill in accordance with Procedure II, Method 511 of MIL-STD-810B dated 15 June 1967.

Electrical wiring shall be properly supported and routed to prevent chafing, provide protection against sharp edges, mechanical strain, etc., and conform to MIL-W-16878. Color coding of conductors of the equivalent shall be provided for identification.

Bonding requirements in accordance with MIL-B-5087 Class H, R and S as applicable.

6.0 Mounting Provisions

Mounting of the water accumulator shall have adequate structural integrity to assure compliance to this specification without mechanical failure or performance deterioration when subjected to:

- Acceleration "hard" environment of Procedure I, Method 513, paragraph 3.2.4 with "Manned Aerospace Vehicle Category".
- Vibration "hard" environment of Procedure I, Method 514, paragraph 4.5.1, Part 1 (sinusoidal vibration curve "P" and time schedule I) and paragraph 4.5.2, Part 2 (random vibration curve AG), MIL-STD-810B dated 15 June 1967.
- Bench handling shock "hard" environment of Procedure V, Method 516, paragraph 3.7, MIL-STD-810B, dated 15 June 1967.

The mounting configuration of the water accumulator shall be designed for securement to a vertical plate, water side up.

7.0 Permissible Materials

Wetted Areas (Both water and hydrogen chambers)

Type 316, 321 A1S1 stainless steel, passivated; 316L, 321, 347 A1S1 stainless steel for welded parts, or solution anneal 316.

Type 316 (preferred), 302, 17-4 pH in springs.

No copper, iron, silver, zinc, nickel, cadmium or processes of brazing or soldering is permissible in wetted regions.

Elastomers: Teflon TFE, FEP, Viton A preferred
Buna N acceptable.

Corrosion protection of large, exposed non-rubbing surfaces in the water chamber is desired by thermoplastic coating with FEP (fluorinated ethylene propylene).

Electroactivity contact of dissimilar metals per MS33586 shall be avoided.

Materials that could liberate toxic gases shall be avoided.

The use of metallic self-locking nuts is the preferred method to secure the assembly detail parts. Lockwire should be considered as an alternate approach. Star washers, jam nuts, lock washers, etc. shall not be used.

Assembly drawing copies with appropriate parts list, material identification and process specification definition shall be submitted to GE/DECP for review.

Redundant Viton "A" O-ring seals shall be introduced into the design in appropriate regions to assure no external leakage to ambient.

Rub wear materials which could contaminate the delivered water and/ or hydrogen or compromise useful life shall be minimized.

Titanium is not permitted in the design.

Lubrication materials are not permitted in the design which could contaminate the water and hydrogen or leak to ambient.

8.0 Maximum Overall Envelope Dimensions

5.00 inch dia. x 24 inch long (including stroke)

Cylinder diameter and piston stroke shall be selected to minimize unit volume and weight, yet maintain optimum L/D considerations for smooth stroking performance of the accumulator.

Outline-installation drawing copies delineating all pertinent details of the water accumulator assembly (e.g., port title and fitting identification, connector identification and pin designation electrical schematic, detail installation and outline dimensions, servicing and acceptance test notes as necessary, rated requirements, etc.) shall be submitted to GE/DECP for review.

9.0 Performance Requirements

The water accumulator shall be in any attitude under cyclic operation capable of providing water storage capacity as a function of water pressure minus hydrogen pressure differential (PH_2O - PH_2) according to Figure 1. The volume settings for switch positions are indicated with tolerances provided in Table I.

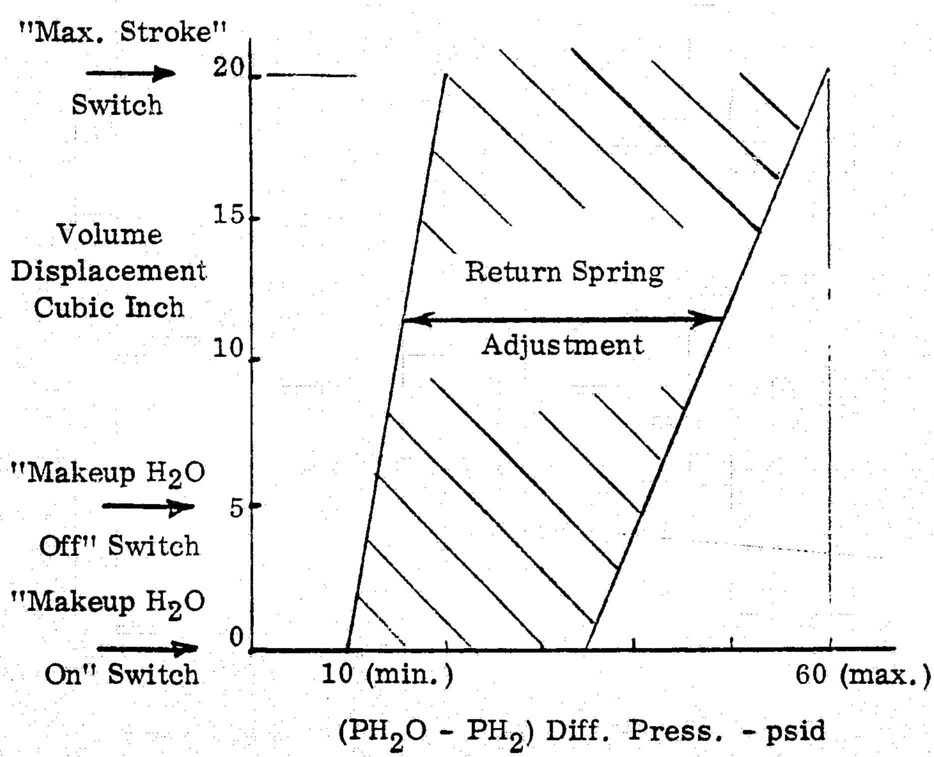

Figure 1

Table I

	Switch Position	Volume Point-in.^{3}	Percent Storage Capacity Nominal	Percent Storage Capacity Switch Location Tolerance
1.	"Make-up H_2O on"	0	0	0 - 10
2.	* "Make-up H_2O off"	5	25	22 - 28
3.	"Max. Stroke"	20	100	90 - 100

*Adjustable switch position is desirable, unit disassembly permissible.

Provision shall be made in the water accumulator design for adjustment of the return spring force as indicated by Figure 1. Unit disassembly for spring adjustment or for replacement with a spring of different size is permissible. Alteration of stroke length beyond 20 cubic inch capacity is permissible for spring adjustment.

Hysteresis due to friction shall be minimized to provide repeatable, smooth stroking within ± 10% of a mean linear pressure differential versus stroke characteristic.

Fluid Media:

Water Side: Distilled water
Hydrogen Side: Saturated hydrogen with possible water condensate.

Hydrogen Pressure:

Range: 100 to 365 psig
Design Point: 365 psig

Water Pressure:

Greater than hydrogen pressure per Figure 1.
Maximum Pressure: 425 psig

Case Proof Pressure: 637 psig

Case Burst Pressure: 1060 psig

Internal Seal or Diaphragm Differential Proof Pressure:
100 psid either direction

External Leakage: zero hydrogen or water at proof pressure

Internal Leakage: zero, water at proof pressure: $pH_2O > pH_2$
5 cc/hr hydrogen at proof pressure: $pH_2 > pH_2O$

Environmental Conditions:

Ambient Pressure: 0 to 15 psia
Ambient/Fluid Temperature: 40 to 110°F
Gravity: 0 to 1 g any direction

10.0 Duty Cycle

Acceptable functional performance as defined in paragraph 9.0 for the following inclusive duty cycles.

Percent "Maximum Stroke" Cycle	Rate	Total Cycles for 6 Months Mission
0 - 100 - 0	one per 94 minutes	5,514
0 - 25 - 0	three per hour	15,000
± 2 at any point	one per minute	262,000

11.0 Reliability: Useful life (2) years.

GENERAL ELECTRIC

AIRCRAFT EQUIPMENT DIVISION

GENERAL ELECTRIC COMPANY . . . . DIRECT ENERGY CONVERSION PROGRAMS
50 FORDHAM ROAD, WILMINGTON, MASS. 01887, Phone (617) 657-4610

April 3, 1975

National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas 77058

Attention: Mr. R. B. Martin
Mail Code EC 39

Subject: SSP 27-Cell Electrolysis Module Failure Analysis, Refurbishment, and Checkout by General Electric Company, Direct Energy Conversion Programs

Gentlemen:

The following is a chronology of the pertinent observations, measurements, and operations made by General Electric Company (GE) as part of the failure analysis, reburbishment and checkout of the SSP electrolysis module as received from NASA/JSC on March 3, 1975.

<u>March 3, 1975</u>

1. Removed module, delivered by R. Reysa, from carton - no apparent damage.

2. Checked all cells for electrical shorts using the capacitor charge technique with a Simpson Voltmeter. No shorts in all cells.

3. Measured 1000 Hz impedance of 27 cell stack (0. 054 ohms) and of each cell (0. 0016 to 0. 0021 ohm range) which compared closely with measurement (0. 00158 to 0. 00189 ohm range) made during original buildup by GE on September 12, 1973.

4. Pressurized oxygen side with nitrogen at 22 psig. Gross leakage out H_2 ports to atmosphere was observed. Closed both H_2 side MDV's and raised pressure to 50 psig. No overboard (gasket) leakage was apparent.

5. Set up module in a test hood with DC power supply, feed water pump at 5 to 7.0 psig, and H_2 and O_2 sides vented approximately to atmospheric pressure. During electrolysis operation at about one ampere, all cells exhibited expected voltage level (1.48 VDC).

6. Measured the outside distances of end plates and residual break away torque tension tie bolts. Values were essentially as measured at NASA/JSC prior to delivery to GE/DECP.

7. Removed module bellyband, tie rod nuts, belleville washers, and rear end plate. Cell No. 27 was removed and inspected. No gasket damage was evident and the imprint of the gasket dual bead rings on the cell solid polymer electrolyte (SPE) membrane was not severe enough to cause damage or leakage. Some corrosion of the anodized aluminum end plate was caused by water trapped in the pressure pad area during assembly. This corrosion cannot reach the cells or interfere with module performance or sealing capability.

March 4, 1975

1. Measured about 0.06 to 0.09 inch growth in stack height over night as evidence of gasket recovery without load, since the tie rods were not installed. Retorque tie bolts to 45 inch-pounds to revaluate gasket seal.

2. Pressurized oxygen side with nitrogen at low pressure showing gross leakage as before.

3. Supplied a mixture of 5% H_2/95% N_2 first to O_2 (dead ended) side and purged H_2 side with air. Fuel cell charging capability was under 0.2 VDC for most cells. Reversed the gas supplies to provide 5% H_2/95% N_2 to H_2 side, air to O_2 side. Cell Nos. 3, 6, 10, 12, 13, 14, 17, 18, 19, 20, 22, 23, 25, 26, 27 evidenced open circuit values under 0.4 VDC. Test was not considered conclusive in locating cells with cross membrane leakage because of blockage and masking effects of entrapped residual water in the cells from electrolysis operation.

4. Module disassembly was initiated and using a plexiglass clamping fixture cell assemblies (M&E plus screens and gaskets) from No. 27 down through Cell No. 22 were leak checked at about 1/2 psi air pressure with the active area submerged in water. Because the air pressure would distend the membrane and wrinkle the protector ring welded to the screens, allowable pressure was very limited to the 1/2 psi value. No bubbles as evidence of leakage were observed.

March 5, 1975

1. Continued leak checking. Cells 21 down through 17 showed no leakage.

2. The module with its 16 remaining cells was compressed using "C" clamps on the end plates and leak checked for cross membrane leakage. Gross leakage still existed.

3. Remaining cells with their associated screens were individually tested for leakage. Cell No. 4 was found to have a small pin hole in the membrane at the edge of the catalyst region near the H_2 outlet port. Pin hole was only detectable by holding cell against a fluorescent light background. The tongued portion of the H_2 side screen protruding into the H_2 outlet port showed evidence of slightly brown oxidized surface. The oxygen side of the membrane showed a fanned out region from the hole exhibiting cracked catalyst, whereas the H_2 side showed indentations or dimples (between screen openings) resulting from membrane heating and distortion from $H_2 > O_2$ pressure differential. The hole itself was fish-mouthed toward the H_2 side indicating O_2 over pressure. Inspection of adjacent screening did not reveal any barbs or broken strands which might have caused the membrane puncture.

4. Measurement of the screen and gasket thickness showed the molded gaskets averaged 0. 030 to 0. 031 (0. 025/0. 029 per drawing in the flat unbeaded region), whereas the screens were 0. 023 for a difference of 0. 007 to 0. 008. Bead height was about 0. 011 inches on each side. Assuming 100% impression of the beads and as confirmed by stack/component measurements during stack assembly and from component and overall stack dimensions an average 0. 008 inch rubber deflection per cell was calculated. This calculates to about 7. 5 percent compression of 0. 106 inch rubber per cell (2 x 0. 0305 cell gaskets plus 0. 045 manifold gasket) in the flat region. The torque region at the manifold ports has the lowest loading or gasket pressure and in view of the 0. 007 inch height difference was vulnerable to local unloading of the gasket due to rubber relaxation, O_2/H_2 mixing in the manifold region and high pressure differential and local heating which damaged the cells.

March 6, 1975

1. Measurements of cell gaskets revealed that the gaskets were molded 0. 001 inch thicker in the O_2 and H_2O port region than at the H_2 outlet port region. Since the stack assembly contains 54 cell gaskets, the 0. 054 inch total differential explained the apparent tendency toward non-parallelism of end plates during tightening of the bolts with uniform torque measurements. It also may explain the

1. Continued

tendency toward unloading and possible leakage of the gasket in the H_2 outlet port region.

2. Review of NASA/JSC data from testing on 2-19-75 showed evidence of module cross membrane (or manifold) leakage, i.e., fairly rapid increase of about 1 psi/min in oxygen pressure, during the period of holding H_2 side pressure at 30 to 35 psig for system pressurization and startup.

3. The test data on 2-19-75 at 1:57:36 DARS time showed an oxygen pressure decay rate of 1.6 psi/min during the shutdown period which sharply increased and resulted in severe manifold leakage and probably primary cell damage when the oxygen pressure suddenly dropped from 10.4 to 7.70 psig as the module voltage dropped from 26.16 to 7.41 volts in 7.3 seconds at about 2:00:00 DARS time. This abrupt loss of oxygen pressure and cell voltage occurs when rapid hydrogen admission to the O_2 side consumes most of the oxygen within the cell screen cavity and at the electrode with local temperatures which can soften and damage the SPE membrane. Further testing the same day revealed normal cell operation and lower oxygen pressure decay rates during subsequent shutdowns probably due to resealing of the gaskets due to rubber expansion at higher module operating temperature. At oxygen pressures under 20 psig or at $H_2 > O_2$ pressure differentials greater than 25 psid during shutdown further evidence of excessive leakage was revealed by an increasing oxygen pressure (3:05:14 DARS time) as hydrogen (and water) leaked into the oxygen side.

<u>March 7, 1975</u>

1. A repeat of individually leak checking of cells was performed with the screen assemblies removed in test fixture up to an air pressure of 31 inch water column. Found Cell No. 7 a leaker from a small pin hole in addition to Cell No. 4, and rejected Cell No. 8 because of overheated damaged area in the sealing region near the O_2 port. Cells No. 1, 2, 3, 5, 6, 9, 10, 11, 12 and 13 showed no evidence of leakage by air bubble formation inside the flooded catalyst area

<u>March 10, 1975</u>

1. Completed individual leak checking of cells and rejected Cell Nos. 17, 18, 19 and 26 because of leakage. Discovered air pressures as high as 18 and 26 inch W.C. in two cases which were required for air bubble break through because of water sealing of the small pin holes at lower pressures.

2. Pressed a sample cell assembly (using No. 4 M&E assembly) including pressure pads in Wabash hand press up to 12 ton load to measure gasket deflection and to visually inspect afterward for any signs of excessive embossing of separator sheets in the port area from 0.005 shim. Sample OK.

<u>March 11, 1975</u>

1. Visually inspected all cells under a microscope first using the rejected leaking cells as a reference. All cells showed some evidence of locally cracked catalyst from overheating, particularly on the O_2 side near the O_2 port or dimpling or cratering between screen openings on the H_2 side due to softening of the SPE membrane and $H_2 > O_2$ differential pressure. Cell Nos. 10, 13, 20 and 22 were rejected on the basis where opposite sides both showed local damage as described.

<u>March 13, 1975</u>

1. Reassembled module with 16 cells (1, 2, 3, 5, 6, 9, 11, 12, 14, 15, 16, 21, 23, 24, 25 and 27) having been refurbished as follows:

   a) The bolt holes in the 0.005 inch thick niobium separator sheets were elongated 0.03 to 0.06 inch, sheets were reflattened, solvent cleaned, vapor degreased and ultrasonically cleaned. Voltage tabs were spot welded to edge of separator sheets.

   b) Eyelets on the protector rings surrounding the manifold ports were trimmed off to increase gasket sealing area. Other electrolysis hardware has shown this eyelet to be ineffective in protecting the silicone rubber from the SPE and could interfere with sealing capability.

   c) Gasket and screen assemblies were cleaned in water and gaskets were re-attached to protector rings using silicone rubber adhesive as required.

   d) Niobium shims 0.005 inch thick were tack welded to screens in the tongued port region on the side facing the separator sheet to accommodate the unequal assembly thickness.

   e) Removed wrinkled and damaged teflon sleeving from tie bolts and applied heat shrinkable polyolefin HS-101 tubing (Original 0.280 O.D. x 0.12 inch wall, Manufacturer: Insultab, Inc., Waltham, Mass.). Original heat shrinkable teflon tubing was not in stock and would require seven to 10 days delivery time.

f) Made eighteen 1.30 inch long stainless steel spacer sleeves for tie bolts to compensate for reduced stack width of eleven cells left out.

g) Reduced width of sheet metal band surrounding module to 3.50 inches and removed harness for measurement of cell voltages 17 through 27.

h) Measured belleville washer stack height and module end plate distances at tie bolt torque values of 45 and 60 in-lb and let sit overnight.

<u>March 14, 1975</u>

1. Electrically checked all cells for shorts, and shorts to ground with Simpson meter. All cells OK.

2. Measured residual torques on tie bolts (46 in-lb average) and retorqued to 75 in-lb.

3. Pressurized H_2 side with N_2 at 50 psig and measured 41.2 cc/min out O_2 port. This was excessive. Reduced N_2 pressure to 50 inch H_2O and leak was hardly detectable by H_2O slug movement in 1/4 inch tygon line. Increased N_2 pressure and measured 6.4 cc/min leakage at 7.2 psig ($6.4 \times \frac{50}{7.2} = 45$ cc/min).

   <u>Conclusion:</u> Probable sealing of very fine pin hole with water at bubble points under 50 inch H_2O.

4. Disassembled module and individually leak checked each cell with air at 40 psig while clamped between the module end plates with four "C" clamps. Found original Cell No. 5 leaked and all others OK. Subsequent microscopic inspection of Cell No. 5 revealed an isolated region of cracked catalyst on the O_2 side about two inches from O_2 port. A small isolated dimple and hole was also visible on the opposite side.

<u>March 17, 1975</u>

1. Reassembled electrolysis module with 15 cells in following order 1, 2, 3, 6, 9, 11, 12, 14, 15, 16, 21, 23, 24, 25 and 27 in positions 1 through 15.

   NOTE: (With the removal of original Cell No. 5 from position No. 4, voltage tabs of positions 4 through 15 are labeled (under bellyband) 5 through 16 consecutively.)

   Measured belleville washer stack height and end plate distances at tie bolt torque values of 15, 30, 45, 60 and 75 inch-lbs. See data in Table I.

2. Leak checked module with H_2 side pressurized with N_2 at 50 psig and measured 3.5 cc/min out O_2 port. Calculated theoretical N_2 diffusion through 15 cells at 50 psid is 3.67 cc/min.

3. Discussed observations and conclusions of failure analysis to date and module refurbishment with R. Gillen, NASA/JSC during his brief visit to GE/DECP in late afternoon. Presented him with M&E of failed Cell No. 4 and additional cell parts for NASA inspection.

<u>March 18, 1975</u>

1. Measured washer and end plate distances, residual torques (average 63 inch-lbs) and retorqued to 75 inch/lb.

2. Pressurized H_2 and O_2 sides in common with air at 50 psig and module submerged in water tank. Observed no visible leakage.

3. Assembled module dolly base to front end plate, connected voltage leads to voltage tabs using teflon insulating tape, and attached sheet metal band with hose clamps.

4. Retorqued tie bolts to 90 inch-lb and recorded measurements.

5. Placed assembled module in air circulated oven at 120°F at 1600 hours.

6. Informed R. Reysa, B. Pond, NASA/JSC by telephone to reduce power supply input to 34 VDC and to reduce output power conditioner shutdown voltage to 29 to 30 VDC by altering resistors in emergency controller.

<u>March 19, 1975</u>

1. Removed module from oven at 122°F at 0815 hours and measured residual torques, belleville washer heights and end plate distances while still hot.

2. Installed module in low pressure test hood with compound gages at H_2 and O_2 ports and operated at 2 ampere load. Found Cell No. 1 partially shorted by voltage tab against negative terminal plate and with lead wires of cell position No. 14 and No. 15 reversed. Added additional electrical insulation and corrected reversed wires. Short test with Simpson meter showed all cells OK.

3. Operated electrolysis module at 5 to 7 psig water input pressure and approximately 0.5 psig O_2 and H_2 output pressure, with applied loads of 2, 10, 20, 30, 40, 50, and 60 amperes. Normal cell voltages (all under 1.66 VDC @ 60 amperes) were recorded on all cells.

4. Closed off valves at H_2O in, H_2 out, and O_2 outlet ports while monitoring pressure on H_2 and O_2 cavities with compound gages. After 54 minutes (lunch hour) H_2 pressure was 22.5 inch Hg vacuum and O_2 pressure was 10.9 inch Hg vacuum. Because some residual water is trapped in the H_2 side and two volumes of H_2 gas are consumed for each volume of O_2 gas to form water, in time all H_2 would be consumed and O_2 would occupy both sides at equal pressure. This is called an "oxygen takeover". Test was repeated after a few minutes of electrolysis operation monitoring module voltage and pressures for 25 minutes with values plotted in Figure 1.

5. After module operation at 10 amps and shutdown, the O_2 outlet valve was closed and H_2 side valves remained open allowing communication with the water supply at atmospheric pressure. The data plotted in Figure 2 was recorded over a 45 minute period of an eventual "hydrogen takeover". These tests demonstrated the behavior of the electrolysis module with regard to voltage and gas pressures after shutdown at atmospheric pressure. Decay rates would be affected by the gas pressures at shutdown and the trapped volumes on each side. The ability of the module in this test to support a vacuum condition and differential pressure over a one hour period of time verified the integrity of the cells and gasket seals.

March 20, 1975

1. Measured residual torques (68.8 in-lb average), module dimensions and retorqued tie bolts to 100 in-lb.

2. Purged H_2 side of residual water with nitrogen and conducted cross membrane leak check with H_2 side pressurized with N_2 at 50 psig. Measured 4.16 cc/min out O_2 port which was acceptable.

3. Purged and pressured H_2 side with helium gas to 50 psig and measured a rate of 20.2 cc/min out O_2 port at atmospheric pressure. Because of the high diffusion rate of helium gas through the SPE, nitrogen gas is normally used for multiple cell cross membrane leak checks to avoid masking of a pin hole leak.

4. Retorqued tie bolts to 100 in-lb and recorded dimensions in Table I. Checked cells for shorts. All OK.

5. Attached handles, brackets, and packed for shipment.

NOTE: Rear end plate was discovered rotated by one bolt hole such that rear handle is tilted 20°. It was left in this manner to avoid delay in shipment.

<u>March 24, 1975</u>

1. Electrolysis module delivered to NASA/JSC by A. C. Erickson, GE/DECP.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are provided to NASA/JSC which have resulted from the module failure analysis, refurbishment and subsequent oxygen generation system testing at NASA/JSC.

1. Electrolysis module failure is attributed to unloading of the cell gaskets in the fluid port area, over a 20 month period, which resulted in leakage from the hydrogen manifold into the oxygen screen cavity of one or more cells at a pressure differential greater than 20 psid. This was caused by inadequate local compression of the gasket for the reasons described herein (See chronology date March 5, 1975).

2. The refurbished module contains 15 of the 27 damaged original cells which exhibited normal performance and sealing capability as demonstrated by electrolysis operation at full load and from supportive leak checks. The integrity of the damaged SPE membranes is unknown, and cross membrane gas diffusion rates should be monitored during periods of high $H_2 > O_2$ pressure differential as during initial pressurization and after removal of electrical load. Based on observations made during system tests at NASA/JSC on March 27, 1975, an oxygen side pressure rise of about 3.0 psi/hr appears normal during system pressurization with the H_2 side at 30 to 35 psig. Also, an oxygen side pressure decay rate of 0.7 psi/min was measured after load removal at operating pressures. Abrupt or severe departure from these rates would indicate excessive cross membrane leakage and the module should be leak checked on the bench with nitrogen gas.

3. Detection of hydrogen in the oxygen output stream was provided in the oxygen generation subsystem, as designed, by two combustible gas detectors at the oxygen discharge to atmosphere. This capability was lost by the installation of an oxygen output line to a saturator, wet test meter and discharge outside the building at NASA/JSC. Some means of continuous detection of hydrogen in the

3. Continued

oxygen stream is recommended during electrolysis operation to stop system operation thus avoiding a mixture buildup in downstream components. A brief discussion of electrolysis module failure as experienced on February 19, 1975 at NASA/JSC and the potential safety hazard is offered. Internal cross membrane leakage as experienced, results in the mixing of hydrogen and oxygen within the screen cavity and combination at the electrode catalyst with the generation of heat. For the rates involved, the relatively high activity and surface area of the catalyst to the small cell volume occupied by multi-layered screening prevents the accumulation of a mixture in an explosive volume. During electrolysis operation, the continuous supply of water for heat removal and the self-quenching capability of water leakage along with any hydrogen admitted to the oxygen cavity results in relatively unaffected module operation as experienced on February 19, 1975. Depending on the size and location of the leakage point, some hydrogen may bypass the catalyst area and be carried out the oxygen manifold which is a small tube like volume formed by the alignment of holes in the stack of rubber gaskets. Because of the process and configuration described, the formation of a quantity of gas mixture and an amount of energy which could result in an internal pressure rise or rupture of the assembly or components is extremely remote as demonstrated by the 27-cell module failure. Rather, it has been found from pressure tests that a gasket-type assembly as used in the module design provides a self-venting feature by local separation or displacement of the gaskets.

4. The beaded gasket design was introduced for the first time into the SSP electrolysis module delivered to NASA/JSC. Since only short-term acceptance tests were employed before shipment, no continuous long-term evaluation of the design and ensuing rubber relaxation phenomena was possible. It is felt that the molded dual-bead sealing concept is a sound design and failure in the manifold region was due to inadequate control of tolerances and rubber deflection under load. Because it is difficult to maintain the tolerances in rubber fabrication as closely as desired, future compensation will be made by the adjustment in the pressed height of the cell screen package. That is, shims or stops will be used during manufacture of the multi-layered screen package to provide a difference of 0.002 to 0.004 inch between the measured face rubber thickness (flat region) and screen assembly as adjusted. Previous flat gasket design criteria employed a nominal 10 percent initial rubber deflection during assembly for sealing internal gas pressures up to 100 psig. Local rubber deflection in the beaded gasket during module assembly could be 50 percent in the beaded region and was calculated at 10 percent in the

4. Continued

flat region from end plate measurements. It is recommended that periodic measurements at 2 to 3 month intervals be made of belleville washer stack height (See Table I) and the tension tie bolts should be retorqued to 90-100 inch-lb when average washer height expands beyond 1.750 inches.

Very truly yours,

A. C. Erickson
Project Engineer - Electrolysis System
Building 1A
Tele. No.: (617) 657-4698

TABLE I

ELECTROLYSIS MODULE TIE BOLT TORQUE AND DIMENSIONAL MEASUREMENTS

BELLEVILLE WASHER STACK HEIGHT** AND MEASURED RESIDUAL BREAKAWAY TORQUE ON BOLT

** Includes 40 Washers (Theo. Solid Hgt. = 1.400"), Two .063" Flat Washers and .188" Head of Guide

DATE	3-17-75						3-18-75					3-19-75		3-20-75					3-24-75	
TIME	1010	1030	1112	1250	1340	1620	0815	0815	0900	1005	1550	0815	0815	0840	0840	0915	1130	1145	1100	1100
						Leak Check					Set in Oven			Electrolysis Operation			Leak Check			
BOLT POSITION*																				
1	2.010	1.975	1.926	1.894	1.816	1.816	1.814	65	1.800	1.740	1.736	1.738	100	1.752	66	1.733	90	1.732	1.736	72
2	1.991	1.952	1.907	1.861	1.791	1.775	1.786	62	1.766	1.737	1.734	1.735	90	1.751	65	1.724	95	1.728	1.731	66
3	1.992	1.956	1.915	1.864	1.801	1.794	1.800	63	1.776	1.733	1.732	1.735	85	1.751	65	1.726	100	1.727	1.735	68
4	2.015	1.979	1.938	1.899	1.851	1.849	1.859	59	1.858	1.793	1.737	1.737	85	1.757	64	1.738	95	1.736	1.741	68
5	1.988	1.951	1.906	1.859	1.792	1.776	1.782	65	1.767	1.737	1.733	1.734	90	1.752	66	1.728	95	1.729	1.734	65
6	2.005	1.976	1.935	1.893	1.846	1.842	1.846	62	1.844	1.761	1.742	1.742	95	1.760	66	1.739	95	1.736	1.740	60
7	2.010	1.973	1.943	1.898	1.840	1.826	1.834	63	1.817	1.742	1.742	1.742	93	1.760	68	1.732	100	1.731	1.735	68
8	1.991	1.961	1.923	1.875	1.825	1.821	1.828	63	1.818	1.755	1.746	1.749	90	1.768	68	1.735	100	1.735	1.740	68
9	1.994	1.961	1.915	1.864	1.805	1.799	1.804	66	1.792	1.742	1.731	1.733	95	1.750	65	1.725	97	1.729	1.735	55
10	1.999	1.976	1.930	1.889	1.823	1.820	1.824	64	1.816	1.772	1.762	1.766	95	1.782	75	1.764	90	1.750	1.750	64
11	2.012	1.985	1.946	1.904	1.872	1.869	1.873	60	1.870	1.833	1.741	1.742	98	1.757	70	1.747	90	1.743	1.749	72
12	1.990	1.950	1.906	1.857	1.790	1.790	1.795	74	1.797	1.749	1.750	1.750	90	1.768	65	1.740	94	1.736	1.739	65
13	2.010	1.959	1.907	1.844	1.776	1.763	1.767	70	1.760	1.732	1.731	1.733	96	1.747	65	1.738	95	1.729	1.732	58
14	2.013	1.975	1.911	1.858	1.766	1.754	1.757	55	1.754	1.732	1.726	1.732	85	1.747	60	1.728	93	1.732	1.734	54
15	2.002	1.964	1.921	1.868	1.814	1.807	1.813	62	1.807	1.749	1.750	1.749	90	1.766	70	1.741	94	1.737	1.744	62
16	2.013	1.979	1.937	1.900	1.836	1.820	1.827	62	1.817	1.747	1.743	1.739	95	1.751	60	1.732	90	1.732	1.734	68
17	1.985	1.936	1.888	1.827	1.773	1.768	1.772	59	1.767	1.732	1.741	1.736	95	1.748	65	1.726	100	1.727	1.731	74
18	2.000	1.948	1.903	1.844	1.777	1.763	1.769	59	1.762	1.733	1.733	1.732	85	1.746	58	1.725	100	1.727	1.732	66
Avg.	2.001	1.964	1.920	1.872	1.811	1.803	1.808	62.9	1.799	1.751	1.739	1.740	91.8	1.756	68.8	1.735	95.2	1.733	1.737	65.2
Δ		-.037	-.044	-.048	-.061	-.008	+.005		-.009	-.048	-.012	+.001		+.016		-.022		-.002	+.004	

*In clockwise order facing washer end of module. H_2 out port at 12:00 o'clock, H_2O in port at 6:00. No. 1 to right of H_2 port, No. 10 between O_2 and H_2O ports.

OVERALL DISTANCE OUTSIDE OF END PLATES, INCHES

CLOCK POSITION	BOLT	3-17-75 1010	1030	1112	1250	1340	1620	3-18-75 0815	0815	0900	1005	1550	3-19-75 0815	0815	3-20-75 0840	0840	0915	1130	1145	3-24-75 1100	1100
12	18/1	4.700	4.654	4.635	4.625	4.611	4.605	4.597		4.591	4.578	4.569	4.570		4.556		4.536		4.532	4.532	
2	3/4	4.741	4.693	4.678	4.660	4.646	4.641	4.633		4.624	4.614	4.607	4.602		4.586		4.566		4.565	4.563	
4	6/7	4.773	4.721	4.697	4.678	4.659	4.655	4.650		4.642	4.637	4.626	4.634		4.607		4.595		4.587	Not Meas.	
6	9/10	4.784	4.734	4.702	4.678	4.659	4.654	4.650		4.612	4.633	Not Measured			Not Measured		4.595		4.594	"	
8	12/13	4.746	4.679	4.646	4.633	4.615	4.608	4.607		4.598	4.593	4.589	4.575		4.556		4.560		4.558	"	
10	15/16	4.698	4.661	4.663	4.621	4.596	4.588	4.578		4.574	4.568	4.563	4.553		4.544		4.530		4.526	4.515	
	Avg.	4.740	4.690	4.665	4.649	4.631	4.625	4.619		4.612	4.604	4.591	4.587		4.570		4.564		4.560		
	Δ		-.050	-.025	-.016	-.018	-.006	-.006		-.007	-.008	-.013	-.004		-.017		-.006		-.004		
Applied Torque In-Lbs.		15	30	45	60	75	75			75	90	90					100		100		
Comment							Re-torque	Overnite set		Re torque		Re-torque	Hot check @ 120°F		Overnite set @ 70°F		Re-torque		Re-torque	Retorqued #9 and 10 to 75 in-lb at NASA/JSC	

4/3/75

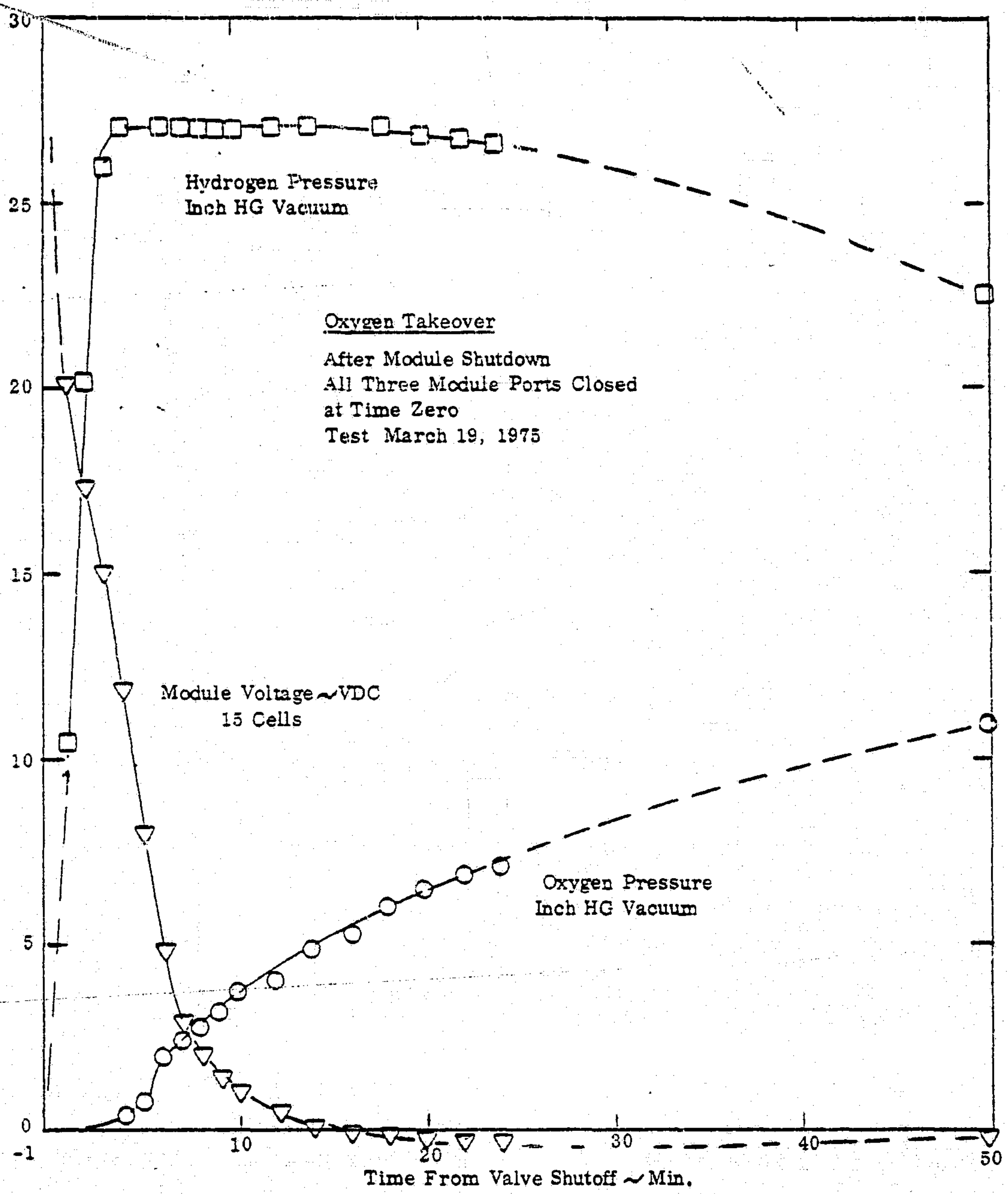
Hydrogen Pressure
Inch HG Vacuum
Oxygen Takeover
After Module Shutdown
All Three Module Ports Closed
at Time Zero
Test March 19, 1975
Module Voltage ~VDC
15 Cells
Oxygen Pressure
Inch HG Vacuum
30
25
20
15
10
5
0
-1
10
20
30
40
50
Time From Valve Shutoff ~ Min.

Figure 1.

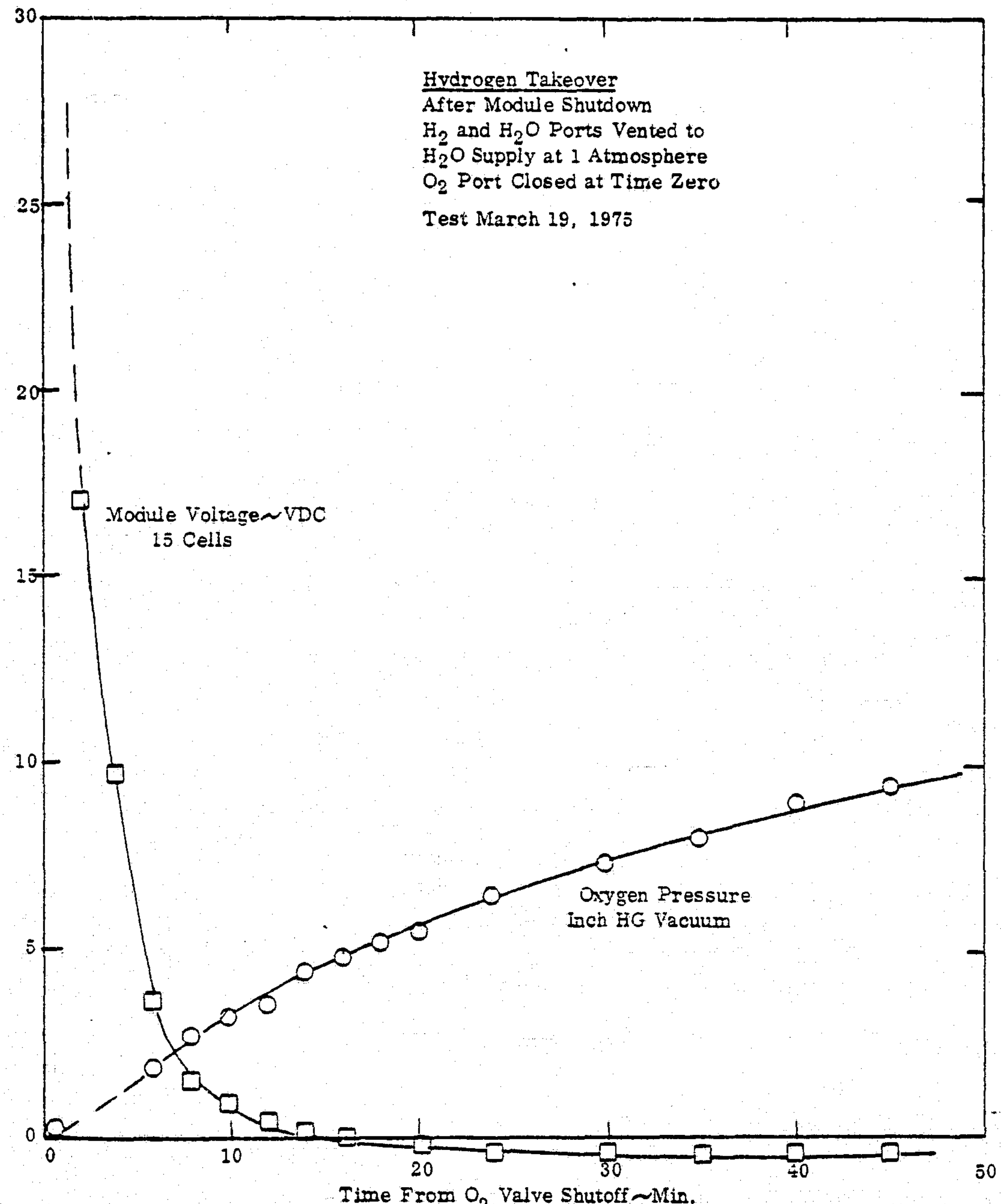
Hydrogen Takeover
After Module Shutdown
H_2 and H_2O Ports Vented to
H_2O Supply at 1 Atmosphere
O_2 Port Closed at Time Zero
Test March 19, 1975
Module Voltage~VDC
15 Cells
Oxygen Pressure
Inch HG Vacuum
30
25
20
15
10
5
0
0
10
20
30
40
50
Time From O_2 Valve Shutoff~Min.

Figure 2.