UNITED TECHNOLOGIES
HAMILTON STANDARD

IPTA-007-91

SPE® PROPULSION ELECTROLYZER

for

NASA'S INTEGRATED PROPULSION TEST ARTICLE

FINAL REPORT

November 1988 — August 1991

Contract No. NAS 9-18030

DRD MA-467T

Data Requirement List Item No. 3

prepared for

NATIONAL AERONAUTICS and SPACE ADMINISTRATION

JOHNSON SPACE CENTER

by

HAMILTON STANDARD DIVISION

SPACE & SEA SYSTEMS DEPARTMENT

ELECTRO-CHEM PROGRAMS

August 1991

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Contract No. NAS 9-18030 • DRD MA-467T, Line Item 3

ABSTRACT

Hamilton Standard has delivered a 3000 PSI SPE® Propulsion Electrolyzer Stack and Special Test Fixture to the NASA Lyndon B. Johnson Space Center (JSC) Integrated Propulsion Test Article (IPTA) program in June 1990, per contract NAS9-18030. This prototype unit demonstrates the feasibility of SPE-high pressure water electrolysis for future space applications such as Space Station propulsion and Lunar/Mars energy storage. The SPE-Propulsion Electrolyzer has met or exceeded all IPTA program goals. It continues to function as the primary hydrogen and oxygen source for the IPTA test bed at the NASA/JSC Propulsion and Power Division Thermochemical Test Branch.

Recognized potential benefits of an SPE-Electrolysis based Hydrogen-Oxygen (H-O) propulsion system include a high thruster specific impulse (I_{sp}>400 SEC), high propellant mass fraction to orbit (>0.8), a safe-to-handle fluid (H_2O), and the ability to utilize waste water to produce high performance propellant. The combined effect of these benefits could produce a significant reduction in the life cycle cost of large space platforms such as the NASA Space Station Freedom. While offering these benefits, only limited testing of an integrated electrolysis based H-O propulsion system had been conducted prior to the initiation of the NASA/JSC IPTA program. The IPTA ground test bed includes the water electrolysis system, H-O thrusters, and 3000 PSI gas storage.

The delivered SPE-Propulsion Electrolyzer is a full size Space Station prototype stack, shown to deliver 3000 PSIA hydrogen and oxygen at any rate from zero (a standby mode) to the Space Station projected emergency rate of four pounds H-O propellant per hour. Generation rate may be changed in seconds; start-up from ambient to 3000 PSIA requires less than 20 minutes. More than 850 hours have been demonstrated to date (August 1991) on the cell stack at full 3000 PSI pressure.

Hamilton Standard has delivered a conceptual flight SPE-Propellant Generator system design to NASA/JSC in February 1991, per contract NAS9-18030. The Conceptual System Design outlined requirements and system configurations for a highly reliable 3000 PSIA hydrogen-oxygen generator. The study identified critical technologies and components requiring development. Trade study emphasis was best reliability for a five-year system life, based on technology to be available by 1995. New concepts presented include a separate feed water supply ORU, a low pressure, low consumption nitrogen reference system, and a high differential (3000 PSID) pressure cell stack. Enabling technologies requiring priority development include 3000 PSIA microgravity-functional gas-water phase separators, high pressure accumulators and a power supply capable of using excess unused power from the main power bus.

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KEY WORDS

3000 PSI
Cell Stack
Electrolysis
Electrolyzer
Energy Storage
Hamilton Standard
Hydrogen
Ion-Exchange Membrane
Lunar/Mars
Membrane
NASA
NASA/JSC
Oxygen
Propulsion
Solid Polymer Electrolyte
Space Station
SPE-Propellant Generator
SPE-Propulsion Electrolyzer
SPE-Water Electrolysis
Water
Water Electrolysis

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1.0 PROGRAM DESCRIPTION

NASA-Johnson Space Center awarded contract NAS 9-18030 on October 31, 1988 to Hamilton Standard to develop an SPE® Propellant Generator, a prototype high pressure water electrolysis system for propulsion applications. The target application was Space Station Freedom reboost and attitude control, using hydrogen and oxygen gaseous propellants generated from excess water. High pressure water electrolysis has also been identified as an enabling technology for future Lunar/Mars initiatives. The contract award work was divided into two consecutive development phases. Phase 1 effort consisted of development and delivery to NASA-JSC of a full-size 3000 PSIA water electrolysis stack and the preliminary design of a flight prototype system. The optional Phase 2 consists of final design, prototype development, delivery and test. This report relates the activity, results and conclusions of Phase 1.

1.1 Phase 1 WBS and Task Descriptions

The contract statement of work (SOW) for Phase 1 has been amended and revised since the initial contract award. The final SOW elements (through Amendment 20) for Phase 1 are:

- Design, fabricate and test a 3000 PSIA prototype water electrolysis cell stack sized to produce 99.5% pure propellants at the rates of 0.6 (minimum), 2.0 (nominal) or 4.0 PPH (emergency) with a nominal efficiency better than 70%. The stack must have a minimum of 15 full-size cells. Preliminary and critical designs are to be presented to NASA in formal reviews (PDR and CDR).

- Fabricate an automated special test fixture for the electrolysis stack and demonstrate a minimum of 100 hours of 3000 PSIA electrolysis. Provide for standby, minimum, nominal, emergency and cyclic operating modes.

- Conduct a conceptual system design of a flight prototype 3000 PSI hydrogen/ oxygen propellant generator. A flight prototype conceptual design is necessary to define reference requirements for an SPE-Propellant Generator / 3000 PSI water electrolysis system prior to proceeding with a technology development program. The results are to be presented to NASA in a formal System Design Review (SDR).

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These SOW elements were established as separate Work Breakdown Structure (WBS) elements. Separate WBS elements were also created for program control and for reliability studies. The final Phase 1 WBS diagram is shown in Figure 1.1.

The Cell Stack task (WBS 100) resulted in delivery to NASA of a 16 cell SPE-Propulsion Electrolyzer prototype stack meeting all SOW requirements. Preliminary and critical design reviews were conducted. The cell stack was mounted in the Special Test Fixture, which was developed under a separate task (WBS 200). The combined electrolyzer and test fixture demonstrated more than 110 hours of 3000 PSIA operation before shipment and in excess of 740 hours at NASA–JSC. Figure 1.2 shows the SPE-Propulsion Electrolyzer and special test fixture. *{ Refer to section 2.0 for further discussion }*

The amended Preliminary Design task (WBS 300) resulted in delivery of a Conceptual System Design focused on high reliability. A direction for future development was identified. *{ Refer to section 3.0 for further discussion }*

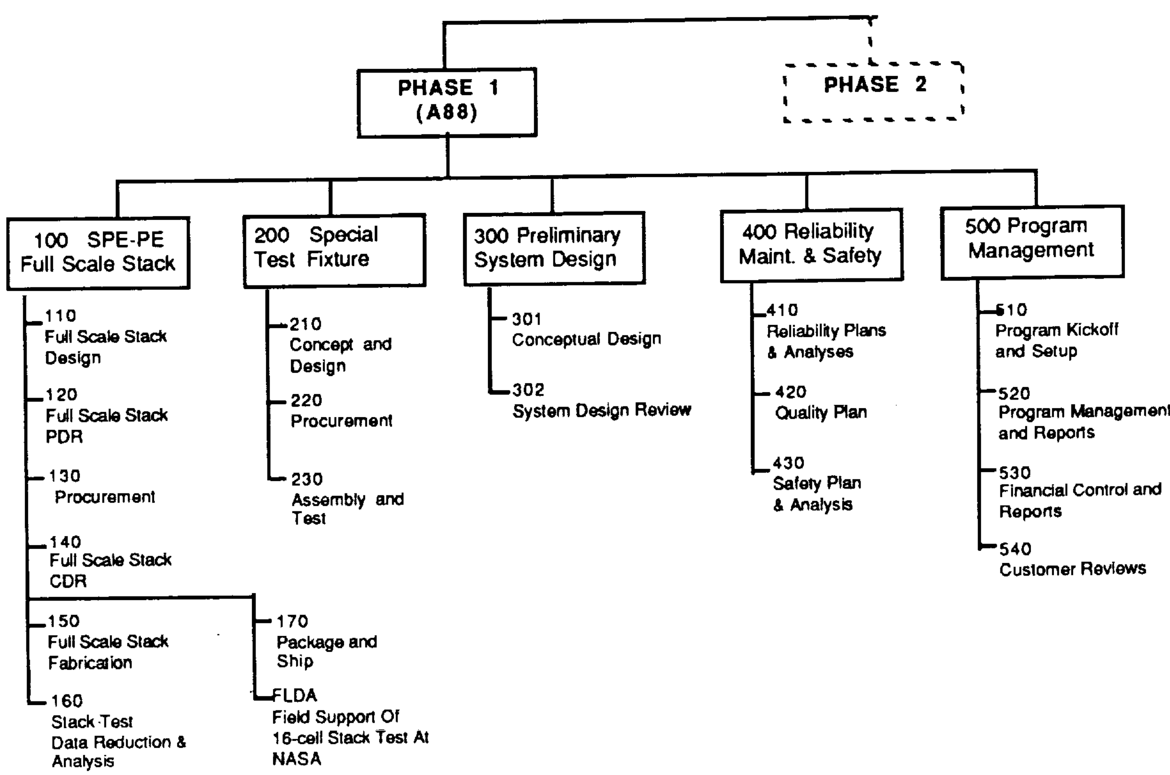

Figure 1.1 Final Phase 1 Work Breakdown Structure

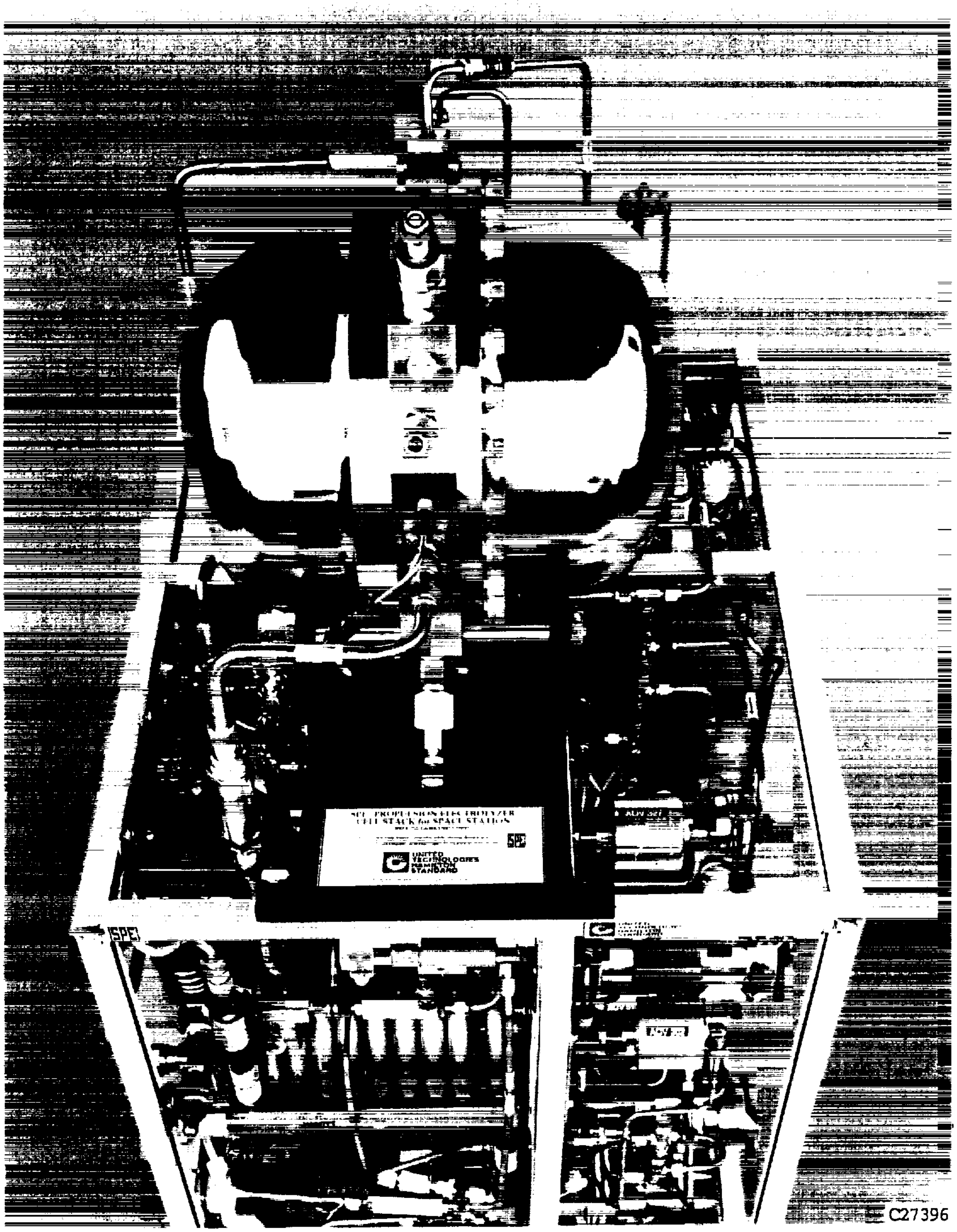

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Figure 1.2 Delivered SPE-Propulsion Electrolyzer and Test Fixture

The amended Reliability task (WBS 400) supported development of a System Hazard Analysis and Software Requirement Specification for the Special Test Fixture.

The Program Management task (WBS 500) supported technical and financial management and control aspects of the effort, including preparation and submission of all documentation as required by the contract Data Requirements List (DRL). *{ ref section 1.3}*

1.2 Major Contract Modifications

Contract Modification 1 exercised the option to construct a Special Test Fixture. Coincident with Mod. 1, a Stop Work order was issued on the Prototype System Preliminary Design task (WBS 300). Emphasis was directed to the cell stack and special test fixture tasks.

Modifications 15 and 18 directed a down-scope of the original Preliminary System design task to the present Conceptual System Design task.

1.3 Deliverable Items and Documentation

Deliverable items and major documentation delivered under this contract are listed in Table 1-1. Those items required by the DRL are listed with respective Data Requirement Description (DRD) numbers. Monthly technical reports were issued on the fifteenth day of each month from program start until July 1990. Monthly financial reporting was discontinued in February 1991.

TABLE 1-1
DELIVERED ITEMS AND DOCUMENTATION

HARDWARE

TITLE	PLANNED DATE	DELIVERY DATE
Cell Stack and Special test Fixture	2/90	5/90

DRL T-2183 REQUIRED DOCUMENTS

DRL	DRD#	TITLE	PLANNED DATE	DELIVERY DATE
1	MA-464T	Program Operating Plan	December 1988	12/15/88
2	MA-466T	Monthly Progress Reports	15 days after month end	12/88 through 7/90
3	MA-467T	Final Report	Draft 45 days prior to final	2/91 outline —8/91 final
4	MA-030T	Monthly Financial Reports	20 days after month end	12/88 through 2/91
5	OM-084T	Operations and Maintenance Manual	50 days before hardware	6/89 draft — 10/90 final
6	SE-1186	Engineering Drawings	With Hardware	
9	SE-1198	Materials in contact with O2 and H2	January 1989	2/89
11	TM-388T	Non-Metallic Materials	With Formal Design Reviews	2/89
12	SE-1167T	Materials Usage Report	With Formal Design Reviews	12/22/90
13	MA-1238T	Field Service Report	As required	7/90, 10/90
17	SE-1150T	Preliminary Design Review Package	Feb. 1989 (Stack)	1/23/89
		Preliminary Design Review Presentation	Two weeks after package	2/24/89
		Preliminary Design Review Minutes	Two days after presentation	3/3/89
18	SE-1151T	Critical Design Review Package	May 1989 (Cell stack)	6/24/89
		Critical Design Review Presentation	Two weeks after package	7/6/89
		Critical Design review Minutes	Two days after presentation	7/14/89
19	RA-432TA	Quality Plan	December 1988	12/15/88
20	RA-142TB	Acceptance Data Report	With hardware	5/10/90
21	SA-054TD	Mishap and Corrective Action Report	As required	
23	SE–1478T	System Design Review	12/90	2/91
		System Design Review Presentation	12/90	2/91

NON-DRL REQUIRED DOCUMENTS

TITLE	PLANNED DATE	DELIVERY DATE
Safety Plan	December 1988	12/15/88
Hazard Analysis	3/89 draft — 10/89 final	3/89 draft — 8/89 final
Test Fixture Reviews	2/89 — 7/89	2/89 — 7/89
Test Report	30 days after completion	4/90

2.0 PROTOTYPE SPE-PROPULSION ELECTROLYZER STACK

This section summarizes the configuration and test results of the cell stack and special test fixture delivered to NASA/JSC for the Integrated Propulsion Test Article (IPTA) Program. An SPE-Propulsion Electrolyzer Stack and Special Test Fixture have been provided by Hamilton Standard to demonstrate production of propulsion-grade hydrogen and oxygen by high pressure water electrolysis.

The cell stack is a full size prototype stack, capable of producing 3000 PSIA hydrogen and oxygen at the Space Station projected emergency electrolysis rate of four pounds of water per hour. The SPE-Propulsion Electrolyzer Stack is installed in a special test fixture designed to provide all control and support required to operate the cell stack in the IPTA test bed. The stack and test fixture are shown in Figure 1.2. The SPE-Propulsion Electrolyzer system delivered to NASA/JSC consists of a 16-cell, 3000 PSI water electrolysis cell stack and a special test fixture. The special test fixture is comprised of a fluids system package, a control/monitor cabinet which provides electrical/electronic support and monitors the process output, a high pressure water pump package, a process control computer and operator console, and the electrolysis module power supplies.

2.1 Cell Stack

Water electrolysis dissociates water into hydrogen and oxygen ions using direct current power applied across an electrolyte. Ions form gas molecules at the anode (O_2 generating) and cathode (H_2 generating) electrodes. A cell stack is a series of electrochemical water electrolysis cells where the current passes though all cells in series.

The IPTA SPE-electrolysis cell differs from a conventional cell in that it uses no liquid electrolyte. Instead it uses a tough, plastic sheet of perfluorosulfonic acid polymer approximately 0.010 inch thick, manufactured by DuPont under the trade name Nafion® . This gives the cell stack the capabilities to withstand large cross cell differentials (up to 700 PSID). Product gases and water effluent are

® **Nafion** is a trademark of E.I. Dupont de Nemoirs free of electrolyte. Figure 2.1 is a diagram of SPE-electrolysis cell reactions.

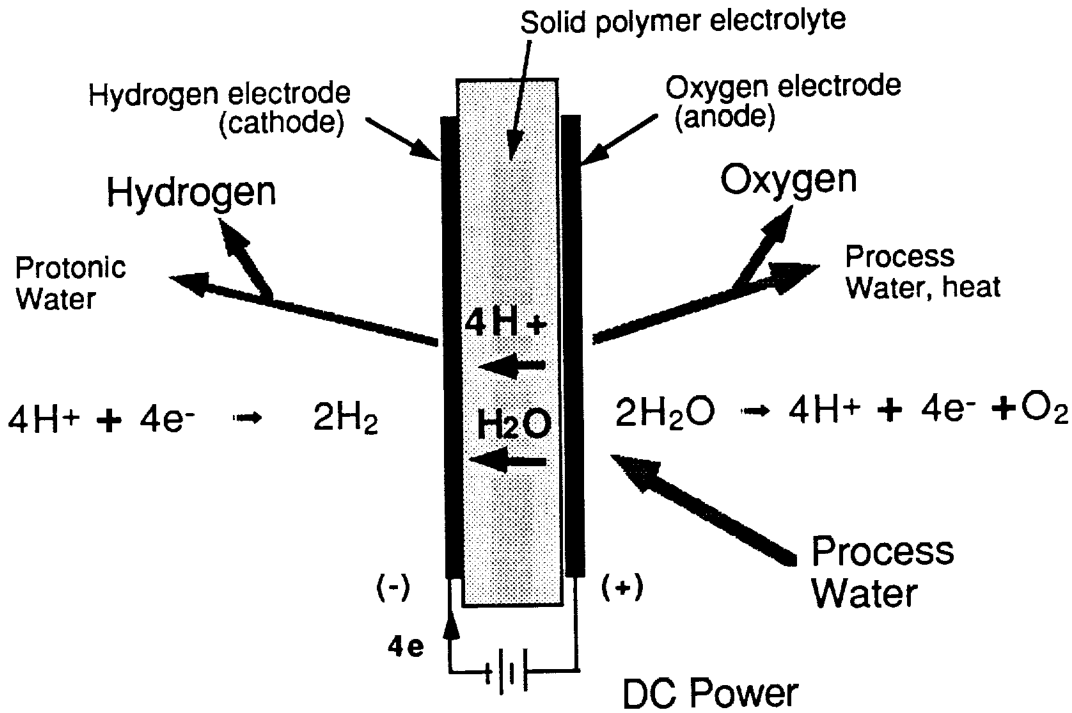

Figure 2.1 SPE-Electrolysis Cell Reactions

The SPE-electrolysis cell design that is the basis of the IPTA cell design has been proven reliable in over 8 million cell hours in US Navy oxygen generating equipment development hardware and Royal Navy submarines. Demonstration cells continue to run after more than 12 years continuous operation.

2.1.1 Cell Stack Design

The 16–cell stack shown in Figure 2.2 has a 9.50″ diameter and is approximately 7.25″ thick. The electrolysis cells are compressed and held between a solid end plate and fluid plate that is cored and drilled to distribute process water and remove product gases and excess water. Pneumatic end domes enclosing the stack extend its operating pressure to 3000 PSIA. The cell stack assembly with domes weighs 193 LBS and is 13″ by 13″ diameter. A summary chart of stack design features is presented in Figure 2.3 (*see page 12*).

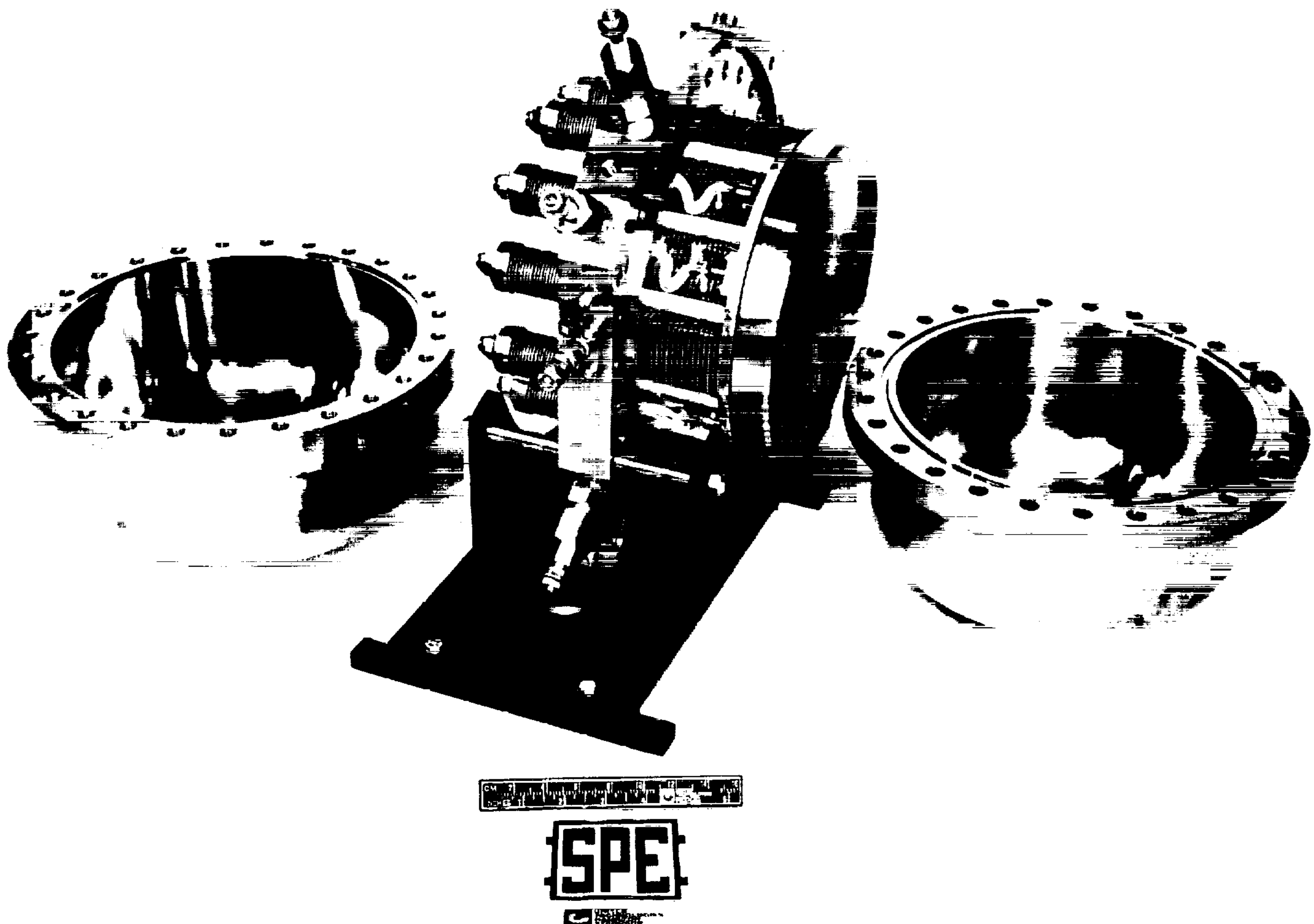

Figure 2.2 IPTA 16-Cell Stack and Domes

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2.1.1.1 *The Individual Cell* Components used in each of the 16 cell assemblies are shown in Figures 2.4a and 2.4b. Each cell assembly includes an O_2 and H_2 frame, screen package, and separator plate; a membrane/electrode assembly, a pressure pad, and gaskets. As seen in Figure 2.4a, the process water enters the cell through the O_2 inlet port and is distributed by the oxygen screen package across the membrane electrode surface Electrolysis takes place at the anode electrode surface bonded to the membrane and oxygen gas is formed. The excess process water stream carries oxygen and heat away to O_2 outlet ports on the opposite side of the oxygen compartment. Hydrogen ions (H^+) transport across the solid polymer electrolyte membrane to react and form hydrogen gas at the cathode electrode. Water is also transported across the membrane by ionic association with the H^+ ions. Hydrogen and water collect in the hydrogen side screen package and exit through the hydrogen outlet port.

2.1.1.2 *Cell Stack Assembly* Individual cell assemblies are stacked one on top of the other to form a stack. This arrangement is very compact; each cell assembly is little more that 0.12 inches thick. As a general description, the cells in the stack are configured in series electrically and in parallel for fluid transport. Current to drive the electrolysis reaction is passed in series from one cell to the next so that each cell is operating at the same current density. The electrically conductive rubber and metal strip pressure pad assembly is inserted between each cell assembly to provide even cell compression in each individual cell active area. This, in consort with selective platinum plating of current conducting surfaces, minimizes cell contact resistance. Sheet metal dividers separate cell compartments from the pressure pad. Screen packages serve several functions: as mechanical supports to the relatively soft membrane; as electrical conductors; and as fluid distribution and collection effectors. As cell assemblies are stacked one on top of the other, respective hydrogen and oxygen ports punched in the individual cell components align to form the cell stack H_2 and O_2 parallel manifolds. Tetrafluoroethylene (TFE) gaskets and the membrane itself work with molded ridges in the cell frames to promote gas-tight seals on manifolds and on the cell periphery.

2.1.1.3 *Stack Compression* The cells, fluid plate and end plate are compressed together by belleville springs acting on twelve tie rods. The spring washers collectively exert the 34 TONS (approximate) of force necessary to make the cell gasket seals and load the cell pressure pads. The assembly is then encapsulated by two high pressure domes which are fastened together by twenty-seven high strength bolts (See Figures 2.2, 2.3 and 2.5). Use of pressure domes extends the operating pressure range of the cell stack hardware, normally rated at 300 PSID in standard versions and 1000 PSID with reinforced frames. The domes are designed for 3150 PSIA nitrogen pressure during operation and have been proof tested at 4600 PSIG. The tie rods pass through the fluid plate and as such do not exert any deflective forces on it. The arrangement of two pressure-equalized domes opposed about the fluid plate also eliminates pneumatic forces acting on the plate. These design features allow the weight saving use of a thin section (1" thick) fluid plate. The arrangement of the spring stacks opposite the cell stack makes good use of the opposing dome volume and permits use of smaller profile domes.

2.1.1.4 *Fluid and Electrical Connections* The fluid plate is ported from the outside edges to the cell stack face to admit inlet water and to discharge oxygen/water and hydrogen/water streams. The fluid plate is also ported in two places to admit nitrogen into the dome space. The fluid plate accepts flanged line connections to these ports. The flanges are fastened with bolts and have face O-ring seals.

The fluid plate functions as the negative terminal to the cell stack, and is tapped to permit negative power cable bonding. The positive terminal is a flat niobium plate on the opposite end of the stack. Flexible current conductors are attached at four locations on the periphery of the positive terminal plate. These flexible conductors connect in turn to four insulated copper posts that pass through high pressure insulated gland seals mounted in the fluid plate. Four small current feed-throughs were used instead of one large current feed through to save cost, size and weight. Cell voltage leads from cells 4, 8 and 12 are conducted through a three-conductor high pressure gland. Cell voltage instrumentation was minimized by measuring groups of four cells instead of each individual cell. The fluid plate is bored to accept two temperature probes.

2.1.1.5 *Stack Size Analysis* The cell stack was designed to meet the requirements of the SOW. These requirements are listed in Table 2-1. The design basis was the 0.23FT^2 electrolysis cell operating at the requisite 3000 PSIA. The number of cells for the cell stack was optimized based on exceeding the efficiency requirement of 70%, using best cell performance data. Heat rejection was based on an oxygen compartment water flow of 300 CC/CELL•MIN. Diffusion current losses were based on theoretical and experimental data.

It was determined that a stack of 16 cells operating at a nominal current density of 812 ASF (187 amps) would operate at >77% electric efficiency. Operation at minimum or maximum currents would result in modest efficiency losses. The diffusion current (current to overcome gas cross-diffusion) at pressure and temperature would be in the range of 12—16 amps. Operating temperature would be in the range of 110—120°F. System power penalties were estimated; operation at Standby (no net gas production) was projected to require a minimum of 305 watts. A summary of the results is presented in Table 2-1.

TABLE 2-1
DESIGN ANALYSIS SUMMARY FOR THE CELL STACK

SOW DESIGN POINTS : 3000 PSIA operation, STANDBY, 0.6, 2.0, 4.0 PPH electrolysis rates ; Goal of >70% efficiency.

DESIGN BASIS: NAFION® 120 (10-12 MIL) MEMBRANE, LIQUID WATER ANODE FEED 0.23 FT2 CELL AREA, 300 CC/CELL-MIN

	0.6 PPH	2.0 PPH	4.0 PPH	STANDBY
TEMPERATURE (oF)	100	120	120	90
STACK EFFICIENCY (%)	74	77	72	-
SYSTEM EFFICIENCY (%)	70	75	70	-
CURRENT DENSITY (ASF)	280	812	1550	52
CURRENT (AMPS)	65	187	357	12
STACK VOLTS (16 CELLS)	26.9	29.9	33.7	25.4
POWER (WATTS)	1750	5600	12030	305

2.1.1.6 *Cell Stack Materials.* The cell design has already been proven in US Navy 3000 PSIG applications to be fully compatible with oxygen and hydrogen. The oxygen side is primarily water (98%) by volume, which allows the use of materials not normally used for high pressure dry oxygen but perfectly safe for high pressure oxygenated water. The oxygen side cell materials are Nafion®, niobium metal, TFE, and a proprietary anode catalyst. The hydrogen side cell materials are Nafion®, TFE, zirconium and a proprietary cathode catalyst. Zirconium was selected in part for resistance to hydrogen embrittlement.

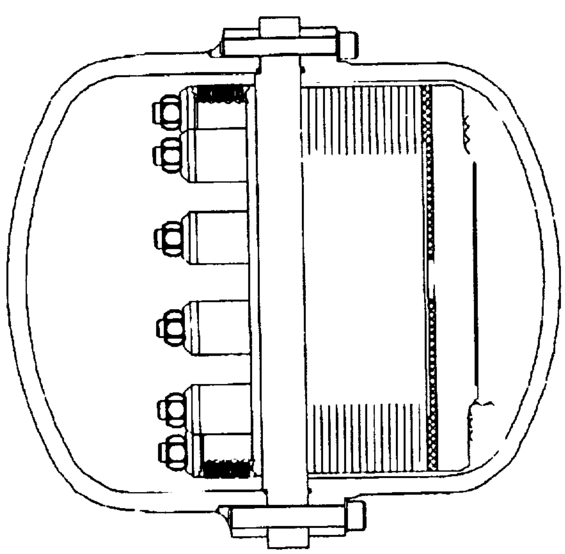
The central fluid plate material is passivated 316L stainless steel, selected for good compatibility with water, excellent hydrogen embrittlement resistance, good machineability and availability. Alternate materials (NP35-N) or composites were considered for future development.

The nitrogen-filled end domes were machined of Inconel 718, a high strength corrosion resistant alloy common to high pressure vessels. O-rings used to seal against the fluid plate are Viton.

2.1.1.7 *Design Reviews* This design passed Preliminary and Critical Design reviews conducted conducted by NASA/JSC in February and July of 1989. Copies of the design review presentations are available under separate cover.

2.1.2 Stack Fabrication and Assembly

The cell stack was fabricated at Hamilton Standard facilities in East Granby, Connecticut during the fall of 1989. Modified proprietary operations sheets were used to guide final assembly and check-out. A list of drawings and components is included in the Source Document section of this report. Performance verification test results are related in Section 2.3 of this report



- SIXTEEN CELLS, 0.23 FT2 ACTIVE AREA
- LIGHTWEIGHT PACKAGING OF PROVEN OGP CELL HARDWARE
- OPPOSED TORISPHERICAL DOMES ALLOW THIN SECTION FLUID PLATE
- LIGHTWEIGHT SPRING STACKS
- SPRINGS OPPOSITE CELL STACK FOR LOWEST PROFILE, WEIGHT
- CELL VOLTAGE MONITORING WITH 4-CELL GROUPS
- SIZE: 13" LONG BY 13" DIAMETER
- WEIGHT: 193 LBS

Figure 2.3 IPTA 16-Cell Stack Design Summary

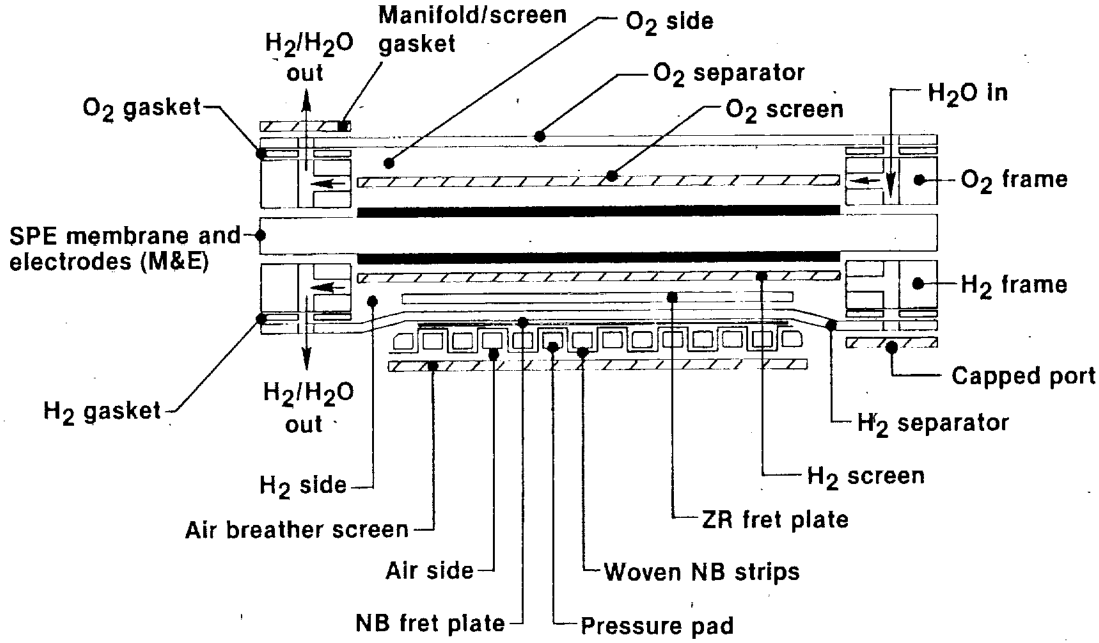


Figure 2.4a SPE - Electrolysis Cell Structure

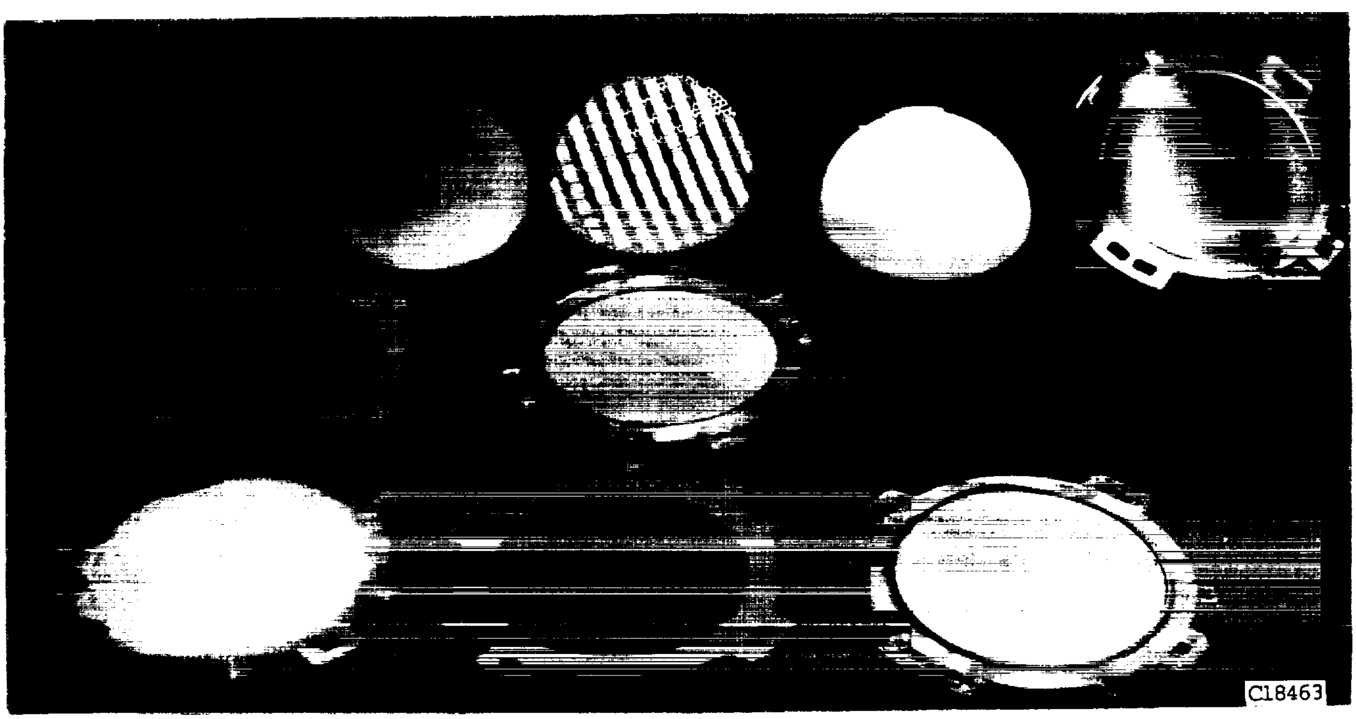


Figure 2.4b SPE-Electrolysis Cell Components

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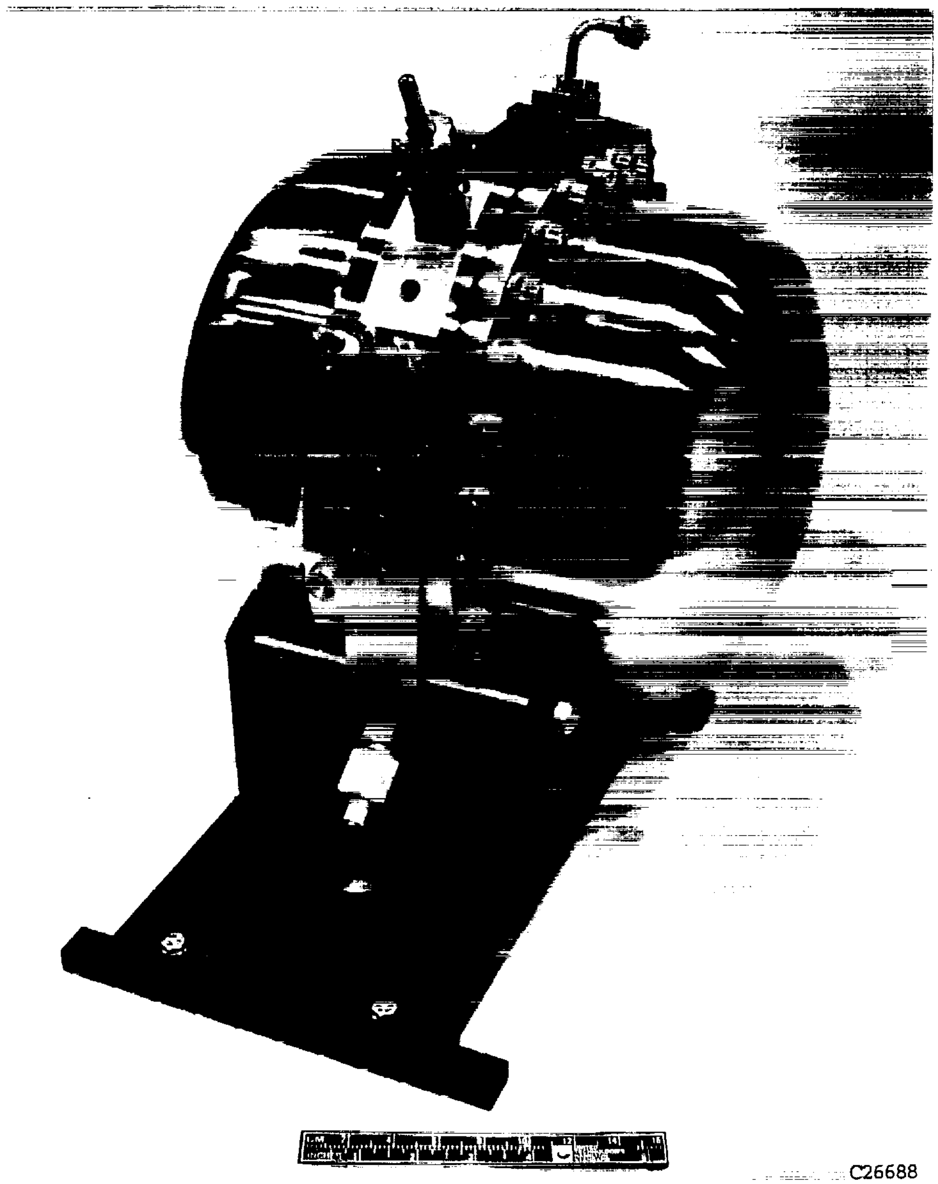


Figure 2.5 IPTA 16-Cell Stack Assembled

2.2 Special Test Fixture

The SPE-Propulsion Electrolyzer Stack is installed in a special test fixture designed to provide all control and support required to operate the cell stack in the IPTA test bed. Diagrams of the stack and test fixture components are shown in Figures 2.6a and b. The special test fixture is comprised of a fluids system package, a control/monitor cabinet which provides electrical/electronic support and monitors the process output, a high pressure water pump package, a process control computer and operator console, and the electrolysis module power supplies. The test fixture is designed for one-gravity ground test conditions only.

Electronic control allows the operator to control and monitor selected parametric functions in the gas generating process from a remote location in a manual or fully automatic mode. The test fixture control program has built-in alarms and thirty-nine automatic shutdowns. From the control console, the operator can change power to the cell stack and alter the gas production rate in either a steady or a cyclic mode.

2.2.1 Basic Test Fixture Design

A simplified version of the test fixture fluid schematic is given in Figure 2.7, showing major fluid components and streams.

The test fixture fluid section provides the means to circulate water, separate gas/water mixtures, recover water, discharge heat, control water level and control pressures. The system fluid schematic SVSK116070 is provided in the Source Document section. The following is a brief discussion of the test fixture fluid section.

Process water is circulated on the oxygen side by the circ pump. It is introduced into the cell stack [*A*] at a rate approximately 200 times the electrolysis rate. Oxygen and water exit the stack [*B*] and enter the O_2/H_2O phase separator. Water exiting the oxygen separator [*F*] gives up heat removed from the cell stack to a heat exchanger. Oxygen gas [*D*] exiting the separator is back pressured to 3100 PSIA by a regulator referenced to nitrogen [*L*] at 3141 PSIA. Oxygen relieved through the regulator is available for storage or use down stream of the regulator.

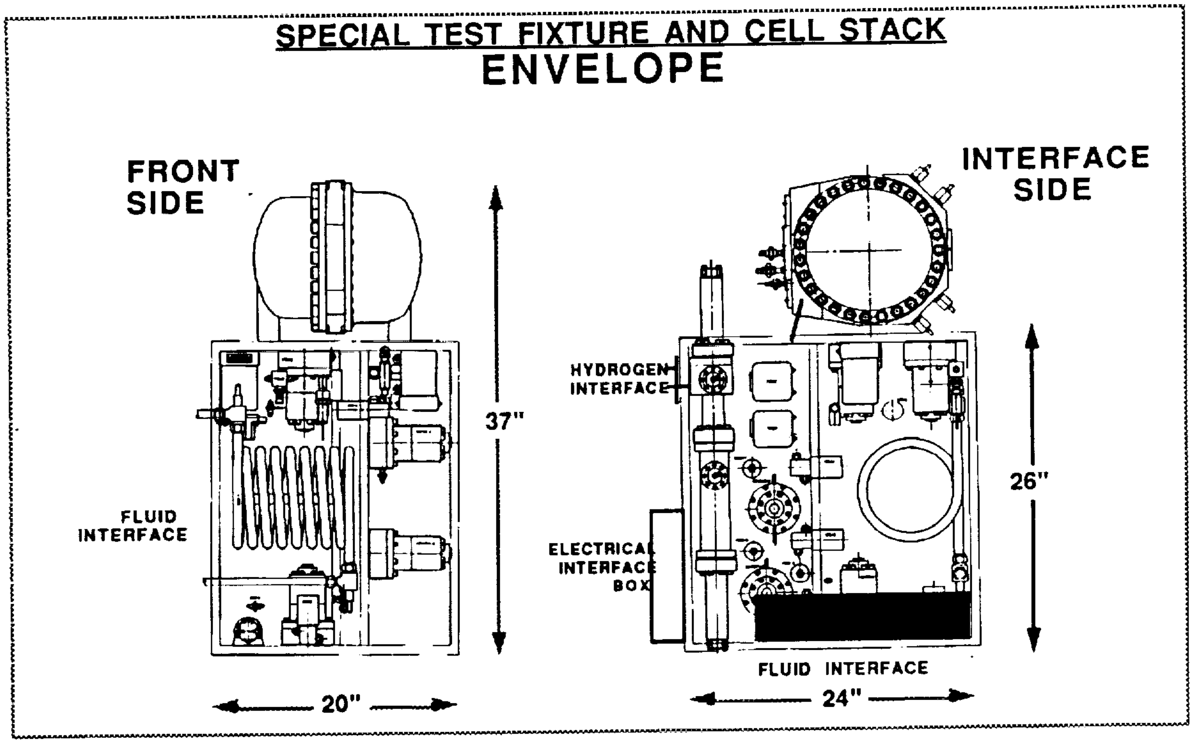


Figure 2.6a. Test Fixture Dimensions

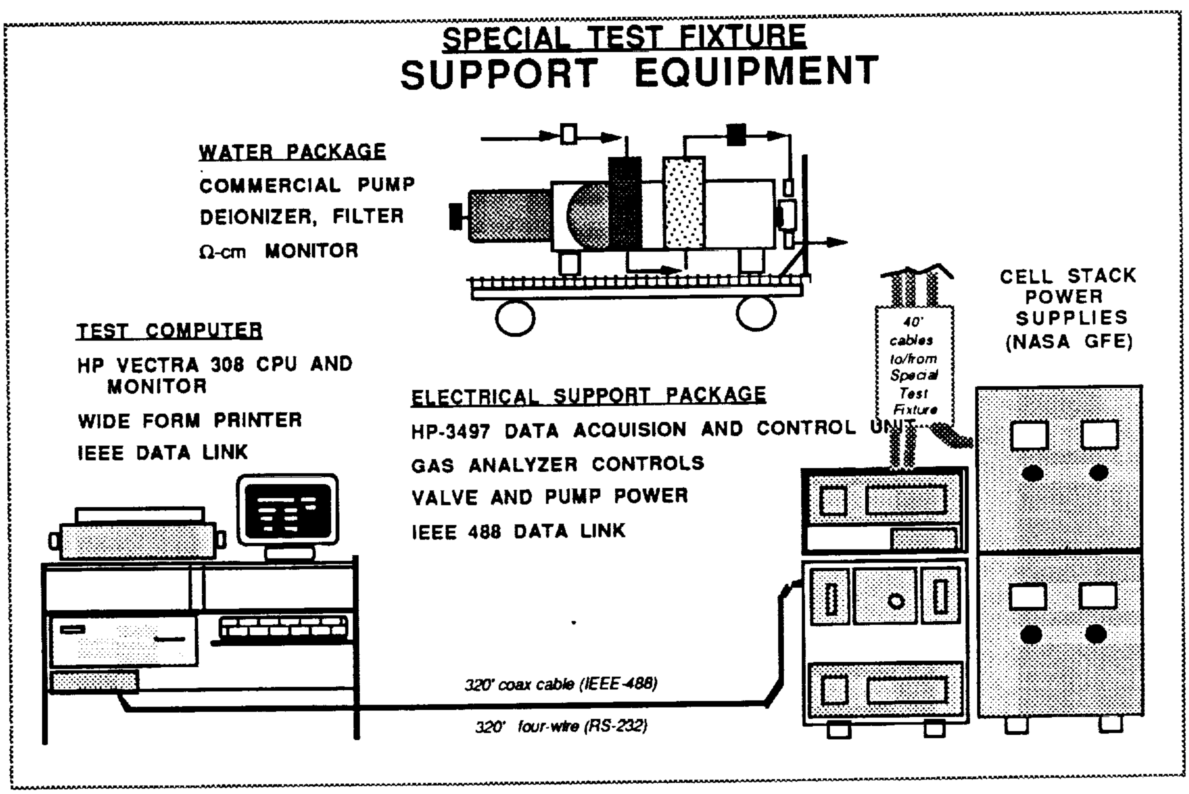
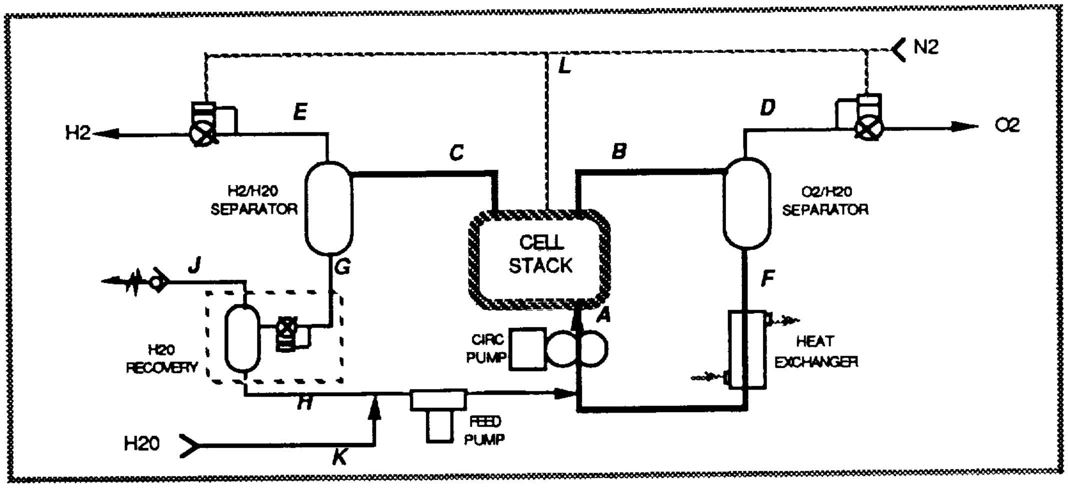


Figure 2.6b Test Fixture Support Equipment



A	3115 PSI CIRC H 20 IN	*E*	3000 PSI HYDROGEN OUT	*J*	DE-GAS / PURGE VENT
B	OXYGEN / CIRC H 20 OUT	*F*	3100 PSI RECIRC H 20	*K*	25 PSI FEED H 20
C	H2 / CATHODE H 20 OUT	*G*	H 20 W/ DISSOLVED H 2	*L*	3141 PSI REFERENCE / DOME NITROGEN
D	3100 PSI OXYGEN OUT	*H*	RECOVERED H 20		

Figure 2.7 Simplified Fluid Schematic

Hydrogen and water exit the cell stack [*C*] and enter the high pressure H_2/H_2O phase separator. Hydrogen gas [*E*] exiting the separator is back pressured to 3000 PSIA by a regulator referenced to nitrogen [*L*] at 3141 PSIA. Hydrogen relieved through the regulator is available for storage or use down stream of the regulator. Water removed from the hydrogen [*G*] is recovered and stripped of any dissolved gas [*J*] prior to recycling the water [*H*] back to the feed pump inlet. Level sensors and process conditions determine the rate that new feed [*K*] and recovered water is injected into the process water circulation loop to maintain a water balance.

2.2.2 Safety Features

System safety is based on pressure hierarchy of nitrogen being higher than oxygen, which in turn is higher than that of hydrogen. This hierarchy is maintained during operation through a system of cross-referenced gas pressure regulators. N_2 inlet and relief regulators are referenced to O_2 so that any increase or decrease in O_2 is followed by a corresponding change in N_2 pressure. H_2 and O_2 back pressure regulators are both referenced to N_2 so that they will follow N_2 pressure trends. In this way, during the initial pressurization, normal operation and during the rapid depressurization of a shut down, the regulators will maintain the pressure hierarchy of $N_2>O_2>H_2$. In-line precision flow restrictor orifices keep the fluid flow in check to predetermined safe levels. Redundant relief valves are installed in designated fluid lines to ensure controlled pressure venting in the event of overpressure conditions. In the event of H_2 loss, N_2 will back-fill the H_2 side to preserve O_2 to H_2 differential pressure to within mechanical limits of the cell.

The cell stack is encapsulated in a vessel pressurized with nitrogen. In the event of external cell stack leakage, inert nitrogen will leak inboard by virtue of the $N_2>O_2>H_2$ pressure profile.

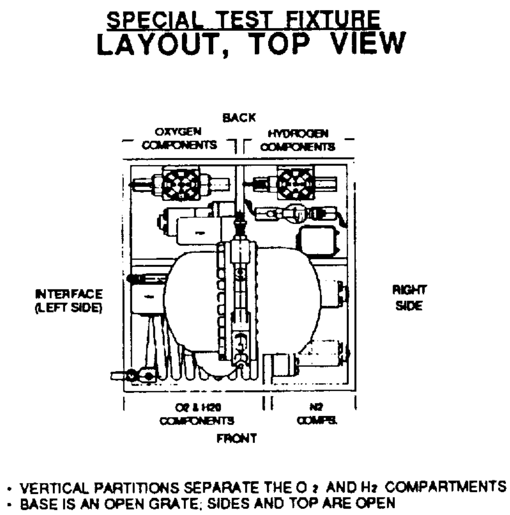


Figure 2.8
Test Fixture Compartments

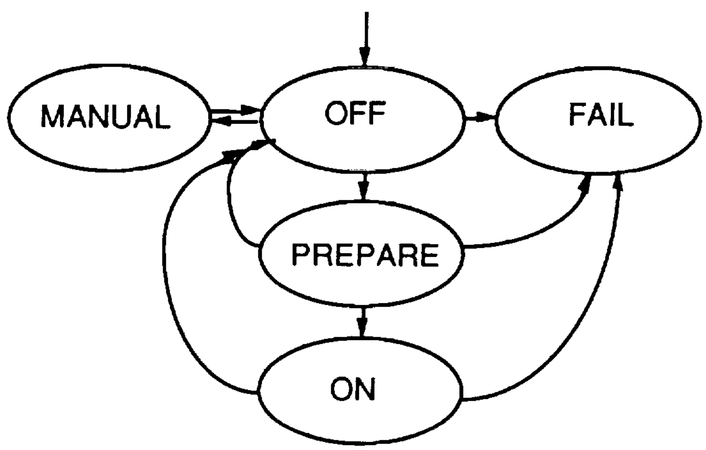
On the test fixture, oxygen and hydrogen components are segregated by vertical partitions. A top view diagram is given in Figure 2.8. With the exception of low power instrumentation, electrical operation is confined to the nitrogen management section. The test fixture open structure allows for any gas leakage to be diluted and dissipated in a vented test facility. H_2 sensors located above the test fixture will initiate a system shut down should the hydrogen exceed a safe level.

Internal unsafe levels of hydrogen-in-oxygen and oxygen-in-hydrogen are monitored with sensors in the gas vent lines. A guarded switch on the electrical console can be used for emergency shut down, shutting off all AC power and initiating a pneumatic controlled system depressurization and shut down.

2.2.3 System Control

The special test fixture provides for automatic operation and control of the production of product oxygen and hydrogen at the minimum, nominal and maximum rates of 0.6, 2 and 4 PPH. Manual control of devices can be achieved for pre-operational checkouts. Other controls include process and system pressure loading, process water circulating pump speed, cooling water regulation and fluid components heat tracing.

2.2.3.1 *Software Control* The software control consists of four modes and seven states. A State Transition diagram shown in Figure 2.9 illustrates the possible mode and state transitions. The four modes are OFF, PREPARE, ON and MANUAL. The seven possible states are *Off, Fail, Fill, Purge, Pressurize, Process-Vent* and *Process*. The OFF mode can be reached from any mode and state. In the OFF mode, the system is depressurized to ambient conditions. The PREPARE mode can only be entered from the OFF mode and the Off state. During PREPARE, the H_2 phase separators are filled to the correct water level and the H_2 volume is purged with N_2. ON follows PREPARE and can only be entered from the Purge state. Electrolysis occurs only in the ON mode. MANUAL mode is used to check system communications or hardware operation. Like PREPARE, this mode can only be reached through the OFF mode and the *Off* state.



MODE TRANSITIONS

MODE	STATES
A) MANUAL	OFF FAIL
B) OFF	OFF FAIL
C) PREPARE	FILL PURGE FAIL
D) ON	PRESSURIZE PROC-VNT PROCESS FAIL

NOTE - If system fails, the system can only be restarted by recycling power. The mode is reset to OFF.

Figure 2.9 Mode and State Transitions

The subsystem is in the *Off* state at the beginning and end of operation. In this state, all valves are in their unpowered positions unless the depressurization from *Process* has not occurred normally and a powered shutdown was necessary. If a powered shutdown was engaged, the valves are configured to their unpowered positions once ambient pressure has been reached.

A failure can occur in any state whereupon the state changes to the *Fail* state. Failures are signaled by satisfying anomaly conditions. To restart the system from *Fail* state, system power must be cycled (or the software reinitialized). The system is automatically reset to the *Off* state in the OFF mode.

2.2.3.2 *Operating Mode/State sequences.* Figure 2.10 presents the process control flow chart. To begin operation, the PREPARE mode is entered and the first state reached is *Fill.* Here, the operator is prompted to manually fill the H_2 phase separators through fill ports. When the levels are between 1100 and 1110 on each separator and the operator is satisfied, the subsystem progresses to the *Purge* state. (The level sensor configuration 1100 means that the first and second level sensors are on and the third and fourth are not--indicating that the water level is somewhere in between Sensor 2 and 3.) In the *Purge* state, the O_2 phase separator is filled to 1100 using the feed pump. When the O_2 phase separator has been filled, the N_2 pressure is raised to 50 PSIA. When the N_2 pressure reaches 50 PSIA, the N_2-H_2 solenoid valve is opened and the H_2 volume is purged with N_2.

When the N_2 pressure has fallen to ambient pressure from 50 PSIA, the operator may initiate transition to the ON mode. The initial state in ON mode is the *Pressurize* state. The N_2 pressure is raised to 200 PSIA and then the N_2-H_2 solenoid valve is opened briefly to bring the N_2-H_2 pressure differential within operating pressure bands. Then the system transitions to the *Process-Vent* state where current is applied to the cell stack to begin electrolysis gas generation. In this state, the current is ramped up to the nominal production rate and gas is vented for two minutes at approximately 200 PSIA. The two minute VENTTIME is of sufficient time to allow the subsystem to produce gases with 99.5% purity. Then, the N_2 inlet valve is opened and the system is allowed to increase in pressure until the N_2 volume can be maintained at approximately 3141 PSIA. At this pressure, the oxygen generated will be at 3100 PSIA and the hydrogen will be at 3000 PSIA.

The state transitions to *Process* state when pressure exceeds 3000 PSIA. In *Process*, the gases are no longer vented. Instead, they are directed to storage tanks.

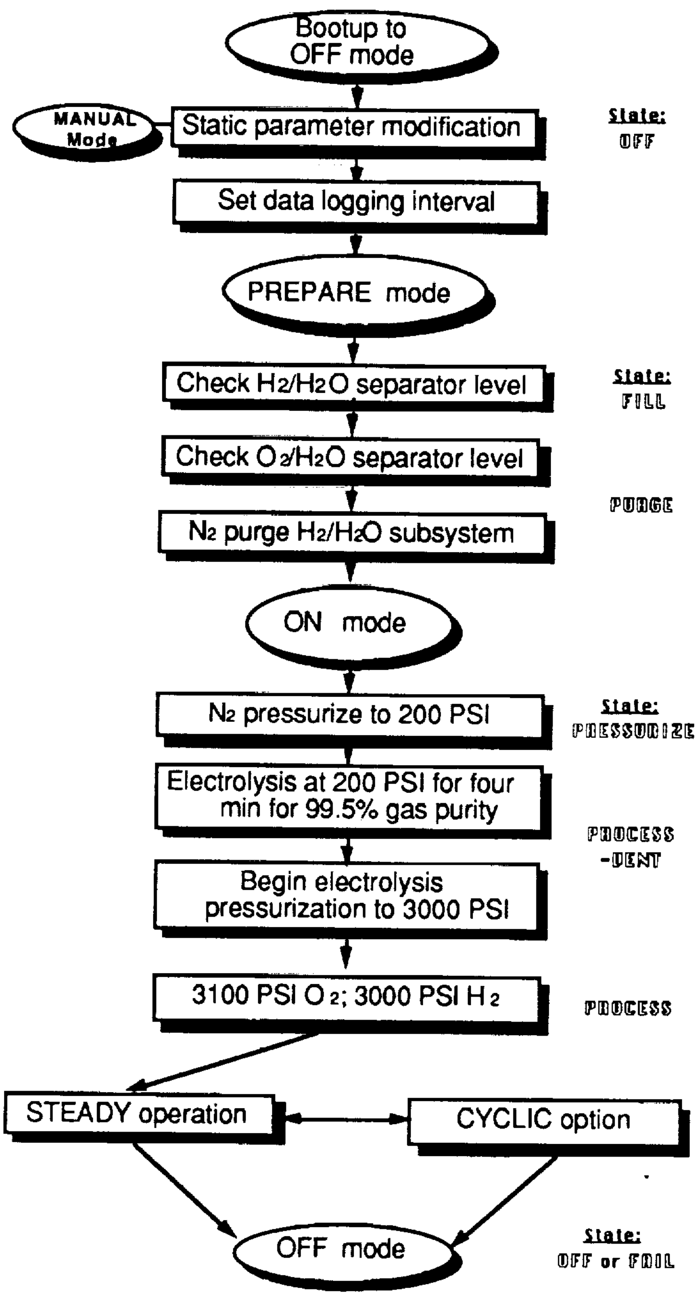


Figure 2.10 Process Control Flow Chart

The system operator has two different choices in *Process* state; **Cyclic** or **Steady** (default). Steady operation is simply continuous operation at a fixed generation rate. The operator may select one of three gas generation rates : maximum, nominal (default), and minimum generation rates (4.0, 2.0, and 0.6 pounds H_20 electrolyzed per hour respectively). The generation rate is selected by toggling a software defined key (*soft-key*) labeled **GENRATE**. The operating current can be incremented or decremented from the selected GENRATE value by ±1 amp increments using the **+AMPS** and **-AMPS** soft-keys.

During Cyclic operation, the system operates at a fixed generation rate for 54 minutes and then operates at standby conditions for 36 minutes. A low standby cell stack current (theoretically equivalent to the cross-cell gas diffusion rate) is estimated from system temperature and pressure. The standby current is then controlled to maintain operating pressure in the system. This type of operation is designed to simulate a Space Station low earth orbit dark side/light side power cycle.

2.2.3.3 *Additional software controls.* In addition to the features described beforehand, the system software has five defined controls. The first control (Control 1) is for the O_2 phase separator, feed pump, and N_2 purge. Basically, this control specifies the sequence of events in the Purge state and regulates the feed pump in Process-Vent and Process to maintain the water level in the O_2 phase separator. Control 2 maintains the water levels in the high and low pressure H_2 phase separators. Timers are included in these controls to insure proper drainage or filling. If these timers exceed calculated values, then a failure occurs.

Control 3 operates the N_2 valves in the Pressurized and Process-Vent states to bring the H_2 pressure within control bands and to raise system pressure. Control 4 is designed to lessen the impact of valve failure (either open or closed) during depressurization. The system should detect abnormal depressurization and respond by closing the appropriate solenoid valve. This action should minimize the increasing pressure differentials caused by the failure. The last control, Control 5, defines the operation of the power supply. This operation is dependant on the configuration options previously described.

2.2.3.3 *Other Controls.* Process and system pressure loading, process water circulating pump speed, cooling water regulation and fluid components heat tracing are other controls that are not managed by the main controller. The system of cross referenced gas regulators, vent valves and flow restrictors controls pressurization and depressurization without power. Circ pump speed is manually set by changing supply voltage to the circ pump motor. Cooling water regulation is controlled by a freon-actuated coolant regulator valve set to operate in the range of 100—120°F. Electric heaters on oxygen regulators and other components are managed by individual heater controllers mounted in the base of the test fixture fluid section.

2.2.4 Data Monitoring and Recording

Remote monitoring of the control functions allows the operator to view operation progress in the hydrogen/oxygen manufacture and anticipate trends in flow, pressure, water level and electrical power outputs. Twenty-one data points are printed out from a selected interval of one to nine minutes and with any automatic shut down. Data is also displayed on the process monitor and can be recorded on the controller's 160 meg hard disk drive at the maximum frequency of one update per control cycle (approximately 2 seconds). These data points printed out are as follows:

Date : D/M/Y
Time : H/M/S
Mode : Man/Off/Prep/On
State: Off/Fill/Fall/Purge/Press/Proc-Vnt/Proc
Cycle : On/Off
Press H_2 : (2) - PSIA
Press O_2 : (2) - PSIA
Press N_2 : (2) - PSIA
Press H_2 : - PSIA
Press H_2 : - PSIA

Cell Voltage - groups (4)
Cell Current - AMPS
Temp H_2O In (module) - deg F
Temp H_2O/O_2 out (module) - deg F
Temp Cell Stack - deg F
Flow, Cell Stack - CC/MIN.
Resistivity, Water - M-Ω
Rate water consumed - CC/MIN.
Temp Heat Ex In/out - deg F
O_2 Separator - Level
H_2 Separator - Level
H_2 Separator - Level

2.2.5 Component Descriptions

The system as supplied to NASA-JSC is comprised of a 16-cell, 3000 PSI water electrolysis cell stack, a fluids system package, a control/monitor cabinet, a high pressure water pump package, a process control computer and operator console, and the electrolysis module power supplies. Descriptions of each of the test fixture major components follow in this section. Details of major fluid components, schematics and component lists are provided in the Source Document section.

2.2.5.1 *Special Test Fixture Fluid Package* The test fixture package (shown in Figures 2.11 a, b, c, and d) provides the fluid processing components and lines which are required to activate and control the cell stack in a controlled and safe manner. It also serves as a support stand for the domed cell stack assembly. The open structure of the test fixture allows for ventilation, dilution and dissipation of product gases in the event of leakage. The test fixture is partitioned with vertical panels that separate the hydrogen, oxygen, nitrogen/water/electrical components in a compact grouping designed to minimize line length and gas volume. Instrumentation such as level sensors, gas analyzers, temperature, flow and pressure transducers are included in the fluid loops. Gas/water separators allow the gases to be collected and return the process water to the recirculating loop through pumps. Regulators maintain the product gases in the pressure hierarchy of nitrogen over oxygen over hydrogen. Orifices in the fluid lines control the flow during shutdown. Finally, line filters are installed prior to critical flow control components to insure functionality.

Metals wetted with oxygen or oxygenated water are primarily Inconel, whereas metals wetted with hydrogen, hydrogen saturated water or nitrogen are 316 stainless steel. TFE or Viton were the elastomers used throughout.

2.2.5.2 *Operator Console* The operation of the system is controlled at the Operator Console, Figure 2.12, where all data are received and control commands are issued to the cell stack support components. The Console includes a Hewlett-Packard HP 308C computer with an HP basic control extender card, an EGA monitor for visual display and a printer to record key data from twenty two channels. The monitor also displays a map of keyboard function keys for the different programmed modes of operation.

2.2.5.3 *Electrical Support Console* Processed operational data at the Operator Console is received from the Electrical Support Console, Figure 2.13, through a 320-foot coax cable. The console includes a Hewlett-Packard Data Acquisition Control Unit (DACU) HP 3497A which receives instrumentation data from the Special Test Fixture and operates process components. These include hydrogen monitors, cell stack operation elapse timer, power supplies for the circulation pump, level sensors, pressure and flow transducers, and valve actuators. The control block diagram in Figure 2.14 shows the input/output of the HP 3497A DACU.

2.2.5.4 *Cell Stack Power Supplies* Two Sorensen DCR 40-250 Power Supplies provide the electrical power to the cell stack. The power supplies are connected in parallel and are remote controlled from the HP 3497A DACU through a current loop. This remote control allows for output current level variations to the cell stack including programmed cycling and ramping. The current level is measured across a shunt (SH102) mounted in back of the power supplies along with the power contactor (K103).

2.2.5.5 *Water Pump Package* A commercial high pressure water pump and water conditioning equipment are packaged together (Figure 2.15). Electrolysis make-up water and degassed hydrogen-side water are injected into the 3100 PSI oxygen side process water loop using a high pressure piston pump (FP500). At the low pressure inlet, the water flows through a resin bed deionizer (DI506) and a replaceable cartridge filter (F501). A resistivity monitor (RS505) checks the incoming process water. On initial system start, feed water is diverted to drain until a minimum resistivity of 1 MΩ is achieved. During operation, a detected water quality of less than 1 MΩ will initiate a warning, followed by a shut down of the system. The pump outlet has a pulse damper plumbed installed to remove 90% of the pressure pulses from the pump outlet stream, making pressure control of the system much more even at full operating pressure. A relief valve (RV510) on the high pressure pump outlet relieves at pressures exceeding 3200 PSIG.

Materials in contact with the water include ceramic (piston, ball checks), TFE (supply plumbing, piston seals) and 316 stainless steel (pressure plumbing, pump and check valve housings).

2.2.6 Fabrication and Assembly

The test fixture was fabricated and programmed at Hamilton Standard facilities in East Granby, Connecticut during 1989, with final modifications during 1990. A Software Requirement Specification (SRS) was kept up to date to control system software configuration. The test fixture was pressure checked at 3500 PSIG, the limit of the actuated valves. A list of drawings and components and other applicable documentation is included in the Source Document section of this report. Performance verification test results are related in Section 2.3 of this report.

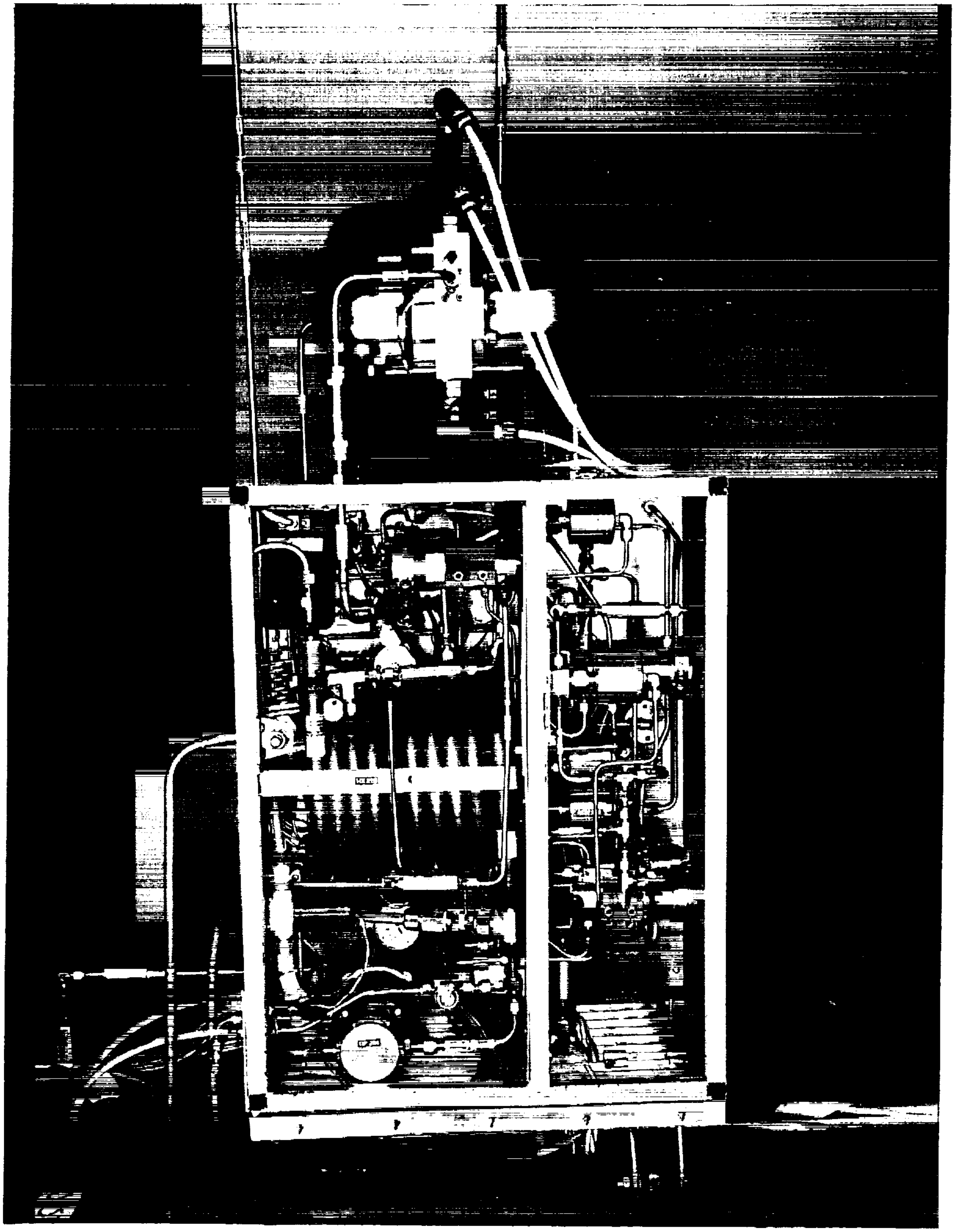


Figure 2.11a Stack and Test Fixture, Front

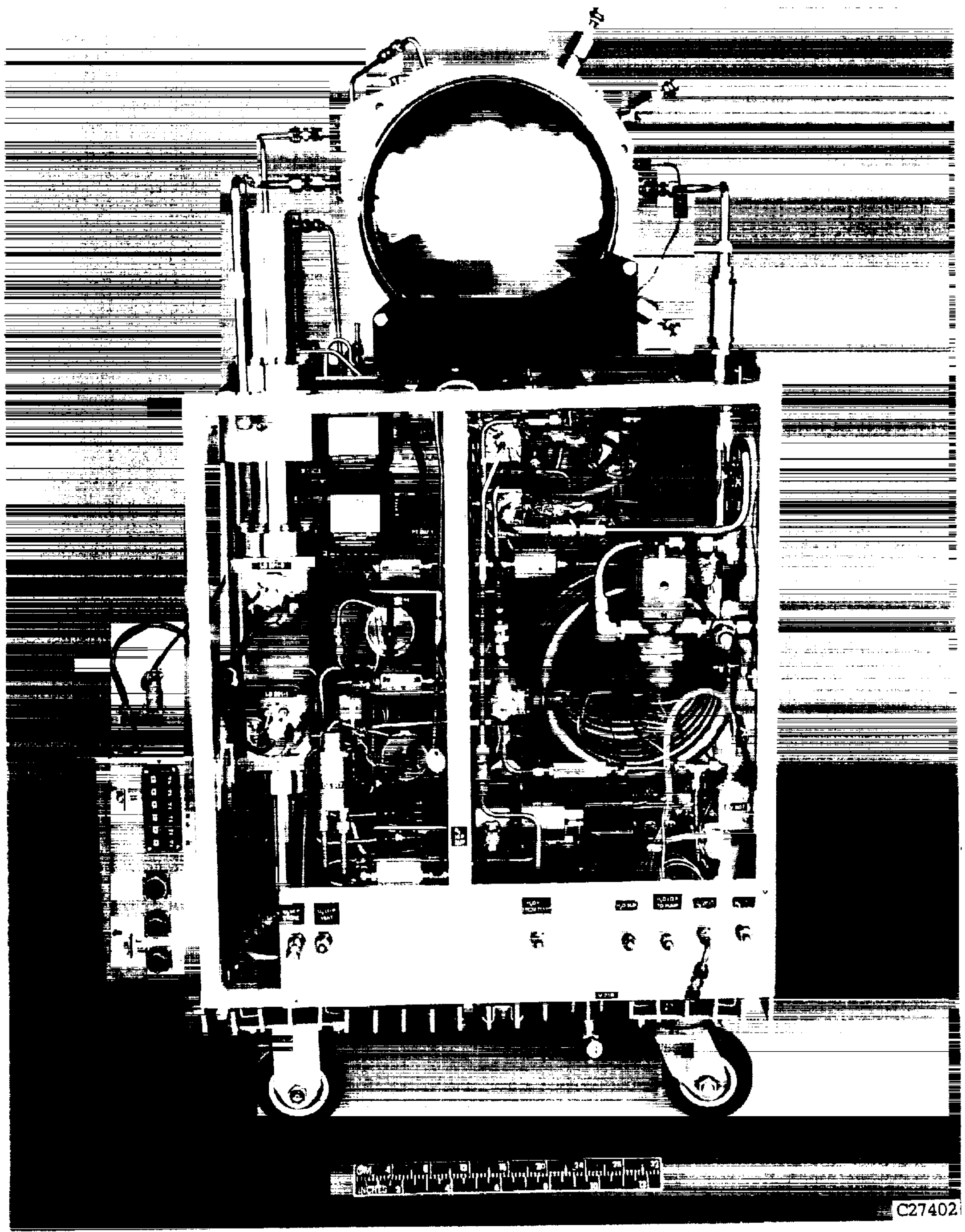


Figure 2.11b Stack and Test Fixture, Right

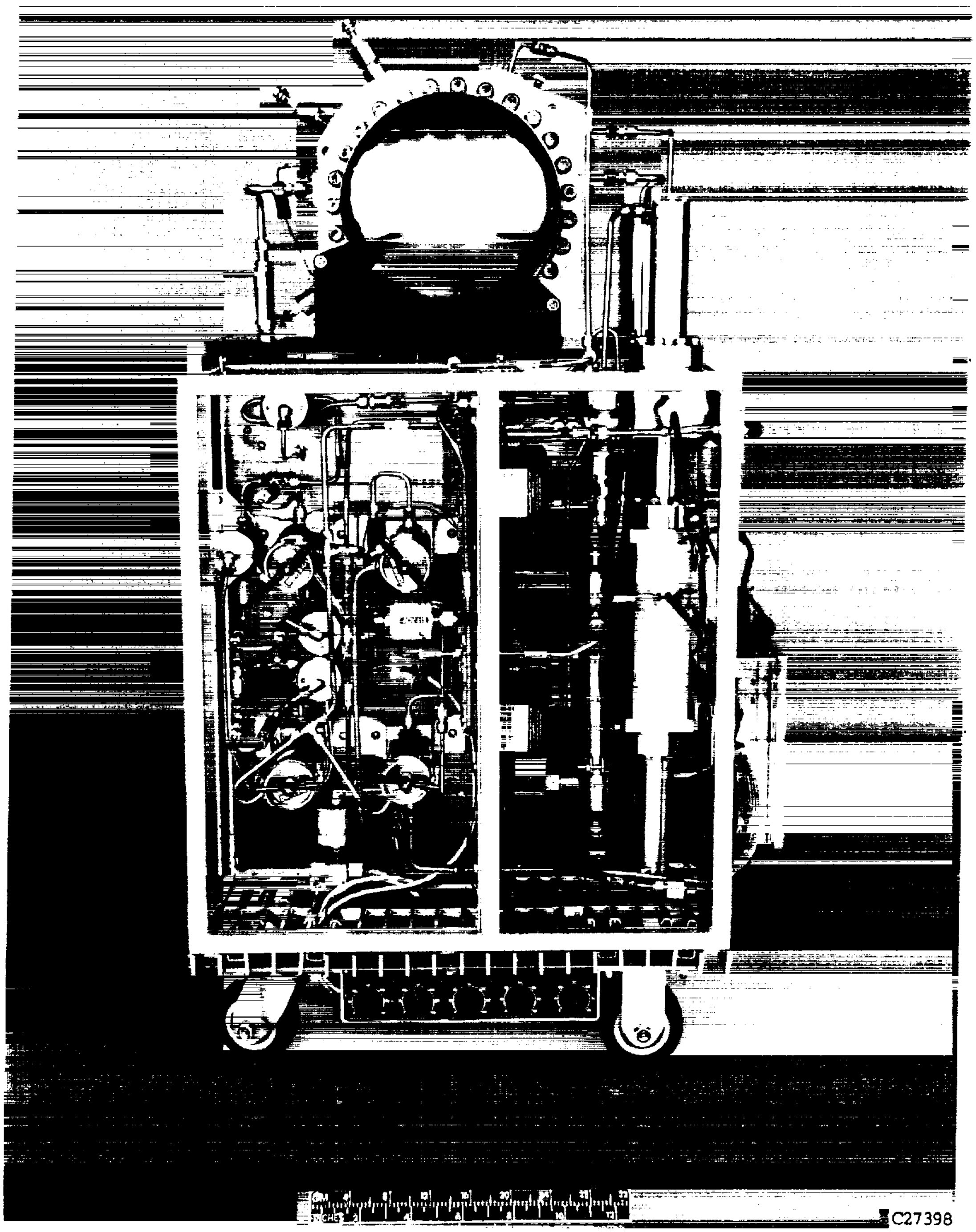


Figure 2.11c Stack and Test Fixture, Left

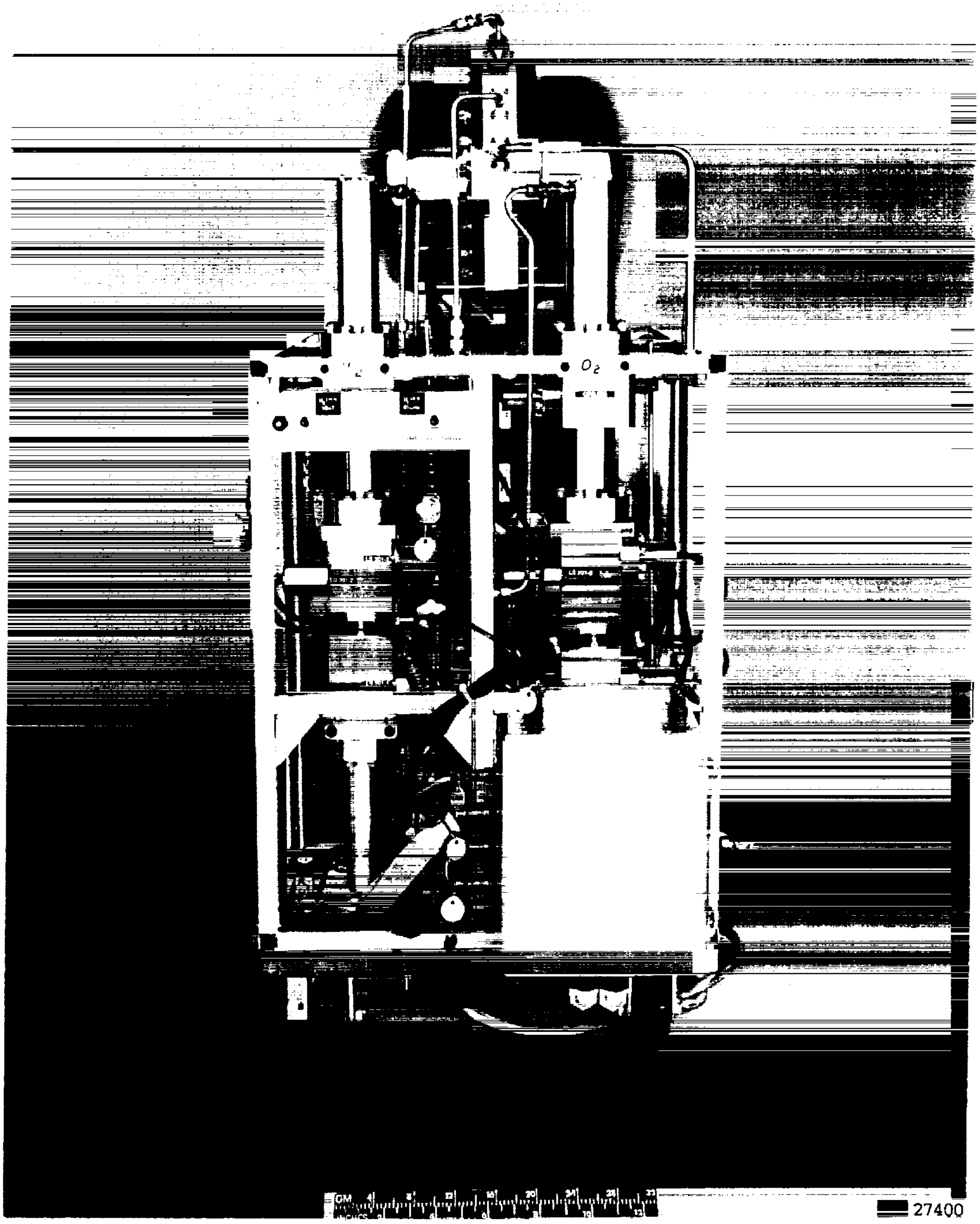


Figure 2.11d Stack and Test Fixture, Rear

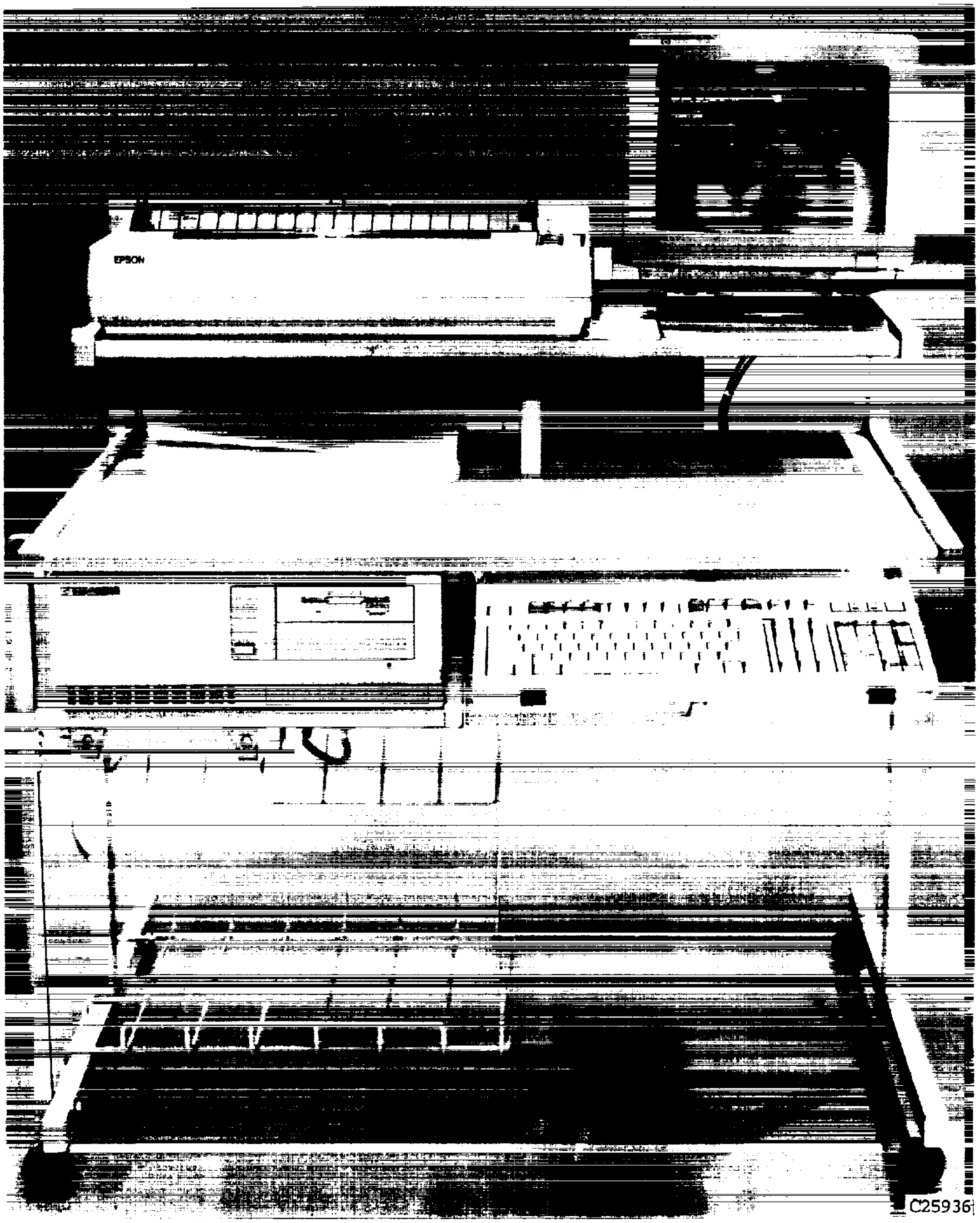


Figure 2.12 Operator Console

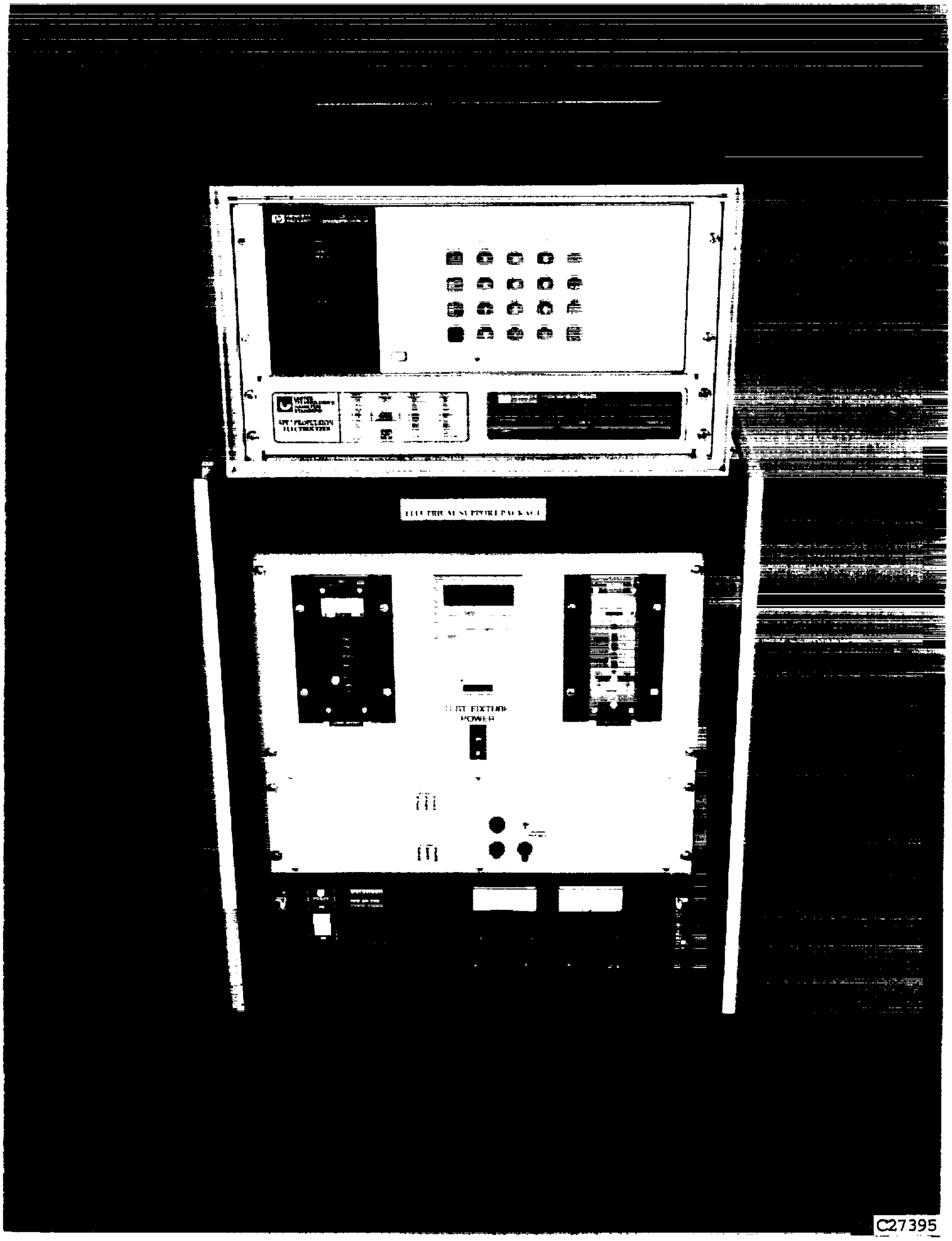


Figure 2.13 Electrical Support Console

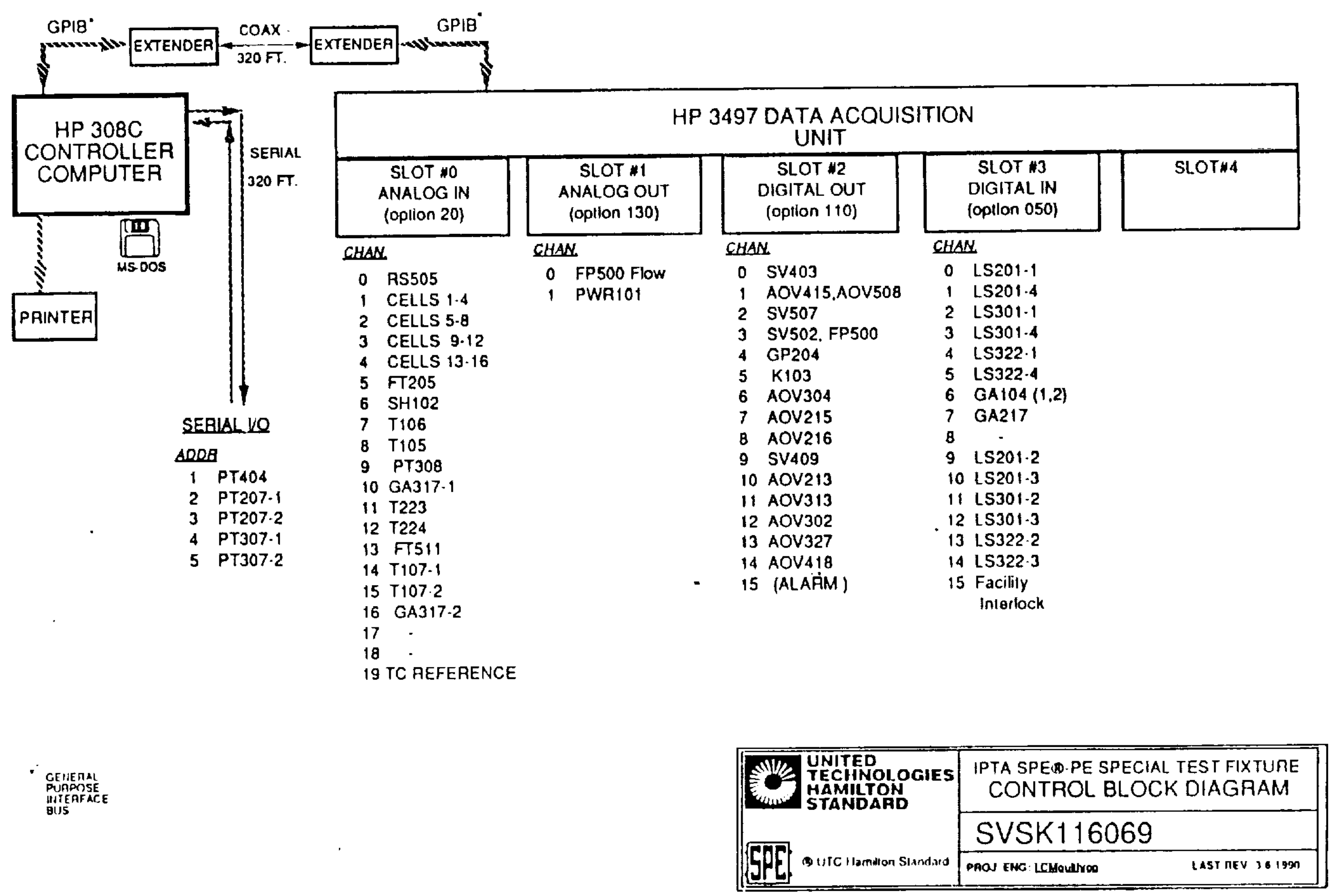


Figure 2.14 Control Block Diagram

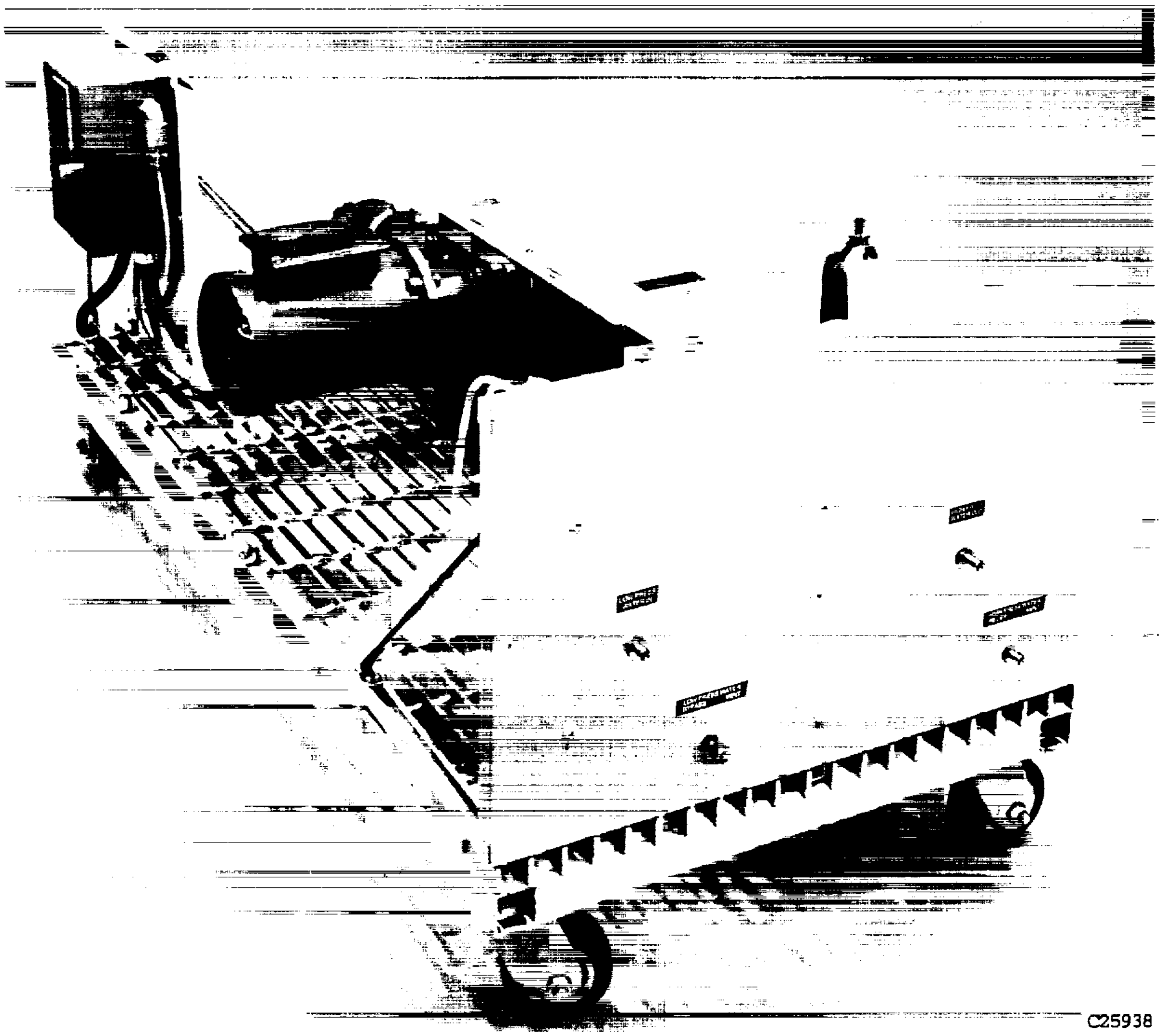


Figure 2.15 Water Feed Pump Package

2.3 Contractor Verification Test

The contract SOW required a performance verification of the SPE-Propulsion Electrolyzer prototype cell stack and test fixture, to be conducted by Hamilton Standard prior to shipment to NASA/JSC. The performance requirements to be met at 3000 PSIA during testing were:

- Operation for a minimum of 100 hours at >3000 PSIA
- Operate at 0.6, 2.0 and 4.0 PPH gas generation rates
- Operate in a Standby mode with no net gas production
- Operate in a 54 min. Generate / 36 min. Standby cyclic mode
- Operate at greater than 70% efficiency at nominal rate
- Produce 99.9% pure hydrogen and oxygen

Verification of all operating modes of the Special Test Fixture, including start-up, normal and emergency shut downs was also required.

All of these performance verification requirements were met by April 1990 and documented in a verification test report issued to NASA/JSC (IPTA-018-90, June 1990).

2.3.1 Test Plan Matrix

The test plan matrix for the SPE-Propulsion Electrolyzer (SPE-PE) verification tests conducted at Hamilton Standard is shown in Figure 2.16. All but initial stack leakage and short (*Health*) checks and the low pressure initial operation (**Green Run**) were conducted using the Special Test Fixture.

Following assembly of the cell stack, cell stack *Health* checks were conducted. The **Green Run** was performed to condition the cell stack and to obtain parametric performance data on all 16 cells. Witness filters were used to document final stack cleanliness.

As a final check-out of the operating system, the Special Test Fixture was operated using a substitute 6-cell stack. Low pressure check-out tests (**LoP Check Out**) with the 16-cell stack installed in the Special Test Fixture confirmed good system operation in all modes prior to operating the cell stack at high pressure. Pressure domes were then installed on the cell stack. High Pressure operation (**HiP Check Out**) to 3100 PSIA oxygen, 3000 PSIA hydrogen followed to demonstrate basic high pressure functionality of the combined system. An extended **100 Hour Run** followed at high pressure, at the nominal (2 PPH), (2 PPH), minimum (0.6 PPH) and maximum (4.0 PPH) electrolysis rates. During this run, the product gas rates was measured and sampled. Testing concluded with a demonstration of Cyclic operation and parametric testing.

	GENERATION RATE			SYSTEM PRESSURE		
	❶ Min.Nom.Max	❷ Standby	❸ Cyclic	200 PSIA	3100 PSIA	❹ Health
Health						✖
Green Run	✖			✖		✖
Test Fix. (6-cell)		✖	✖	✖		
LoP Check Out	✖	✖	✖	✖		✖
HiP Check Out	✖				✖	
100 Hour Run	✖	✖	✖		✖	✖

❶ Min., Nom, Max rates: 0.6 PPH H_2O, 2.0 PPH H_2O, 4.0 PPH H_2O
❷ Standby : maintain system pressures with no net gas output
❸ Cyclic : 54 min. of Nom. gas generation followed by 36 min at Standby
❹ Health checks include cell resistance and cross cell diffusion tests

Figure 2.16 Verification Test Matrix

For all high pressure, integrated (cell stack and test fixture) testing, test logs were maintained as written operator notes and as automatic data record sheets printed periodically by the test fixture system controller.

2.3.2 Test Set-up

Testing was conducted on the cell stack and test fixture during the period of November 1989 through May 1990 at Hamilton Standard Space and Sea department, Electro-Chem program facilities in East Granby, CT. All cell stack and special test fixture tests were conducted in a steel-walled test chamber (*12' x 12' x 10' H*) equipped with high volume air exhaust, hydrogen detection, external venting of product gases, high purity water supply, high pressure nitrogen supply, electrical power and provision for remote control.

2.3.3 Test Results

The test matrix was completed by April 1990. The cell stack performance met all SOW criteria as stated above, eventually completing 110 hours of 3100 PSIA operation at Hamilton Standard. The Special Test Fixture performance was good with the exception of the high pressure separator level sensors. This problem was resolved during the NASA/JSC test phase.

2.3.3.1 *Cell Stack Performance.* All data taken from the original green run through to the completion of the test matrix shows cell stack performance as typical of previous high pressure cell stacks. Efficiency criteria are met for nominal operating currents.

TABLE 2-2

Resistance values		
	Post test	As built
	12/22/89	12/16/89
cell #	mΩ	mΩ
1	3.1	2.9
2	3.5	2.8
3	2.6	2.7
4	2.8	2.4
5	2.7	2.7
6	2.7	2.6
7	3.2	2.6
8	2.6	2.5
9	3.0	2.6
10	2.8	2.5
11	3.4	2.6
12	2.6	2.5
13	2.5	2.5
14	2.5	2.6
15	2.6	2.6
16	2.5	2.6
Σ cells	45.1	41.7
avg. cell	2.8	2.6
	Post test	As built

The cell resistance data indicates typical cell resistances for cells of this type. Low cell resistance in the range of 0.6 mΩ/FT^2, or 2.5 mΩ per cell is desirable. The cell stack experienced a slight growth in cell resistance from when it was first assembled to completion of the low pressure **Green Run**. Resistance values remained constant through the remaining high pressure tests. A test anomaly and shut down, loss of water circulation, experienced during the first hours of the **Green Run** is suspected to have caused the resistance growth. Operation without proper water recirculation, even for a few minutes, will result in some water loss from the cell membranes. Performance loss is estimated to be ~0.040 mV per cell. As-built and post test cell resistances are listed in Table 2-2.

Figures 2.17, 2.18 and 2.19 present performance data at 3100 PSIA oxygen pressure, 3000 PSIA hydrogen pressure and temperatures averaging 115°F (±15°). Data is taken over the minimum to emergency gas generation range, or 273 to 1500 ASF.

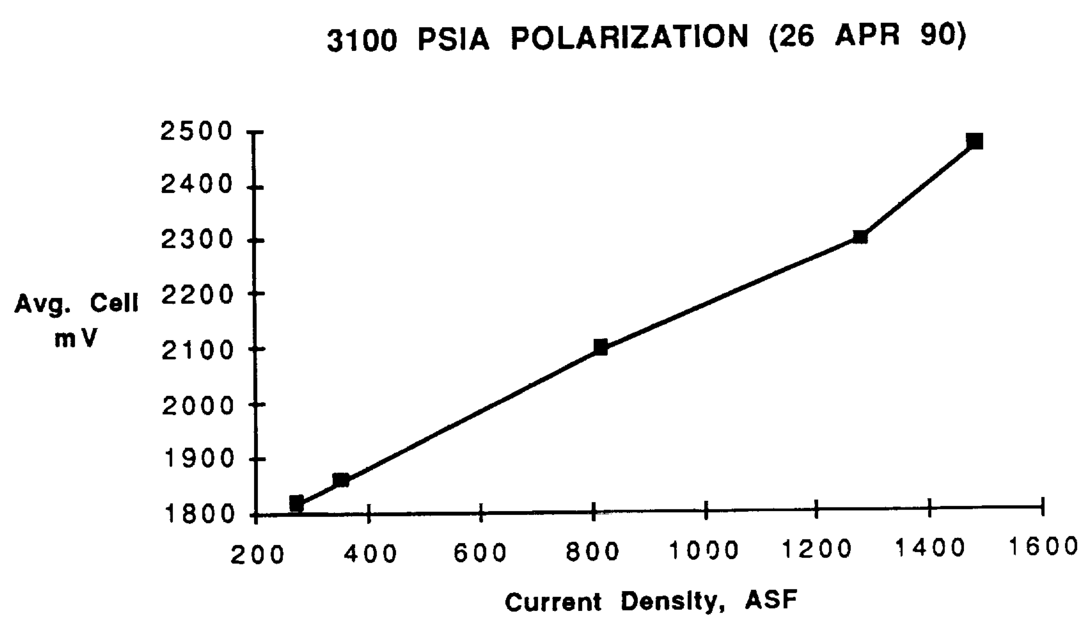


Figure 2.17 Average Voltage per Cell Performance

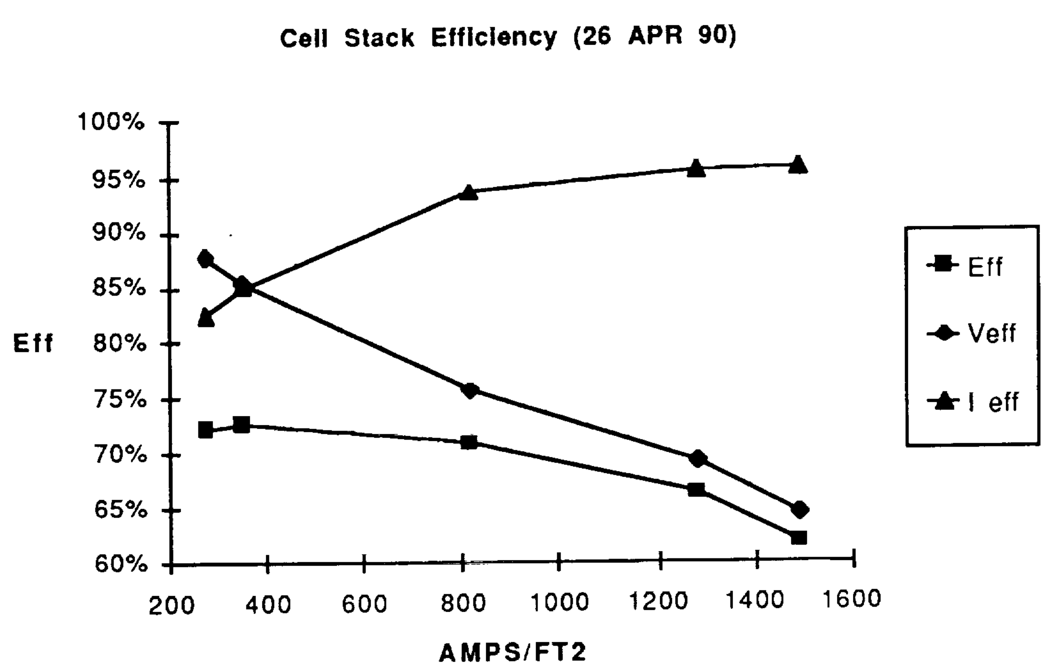


Figure 2.18 Stack Efficiencies

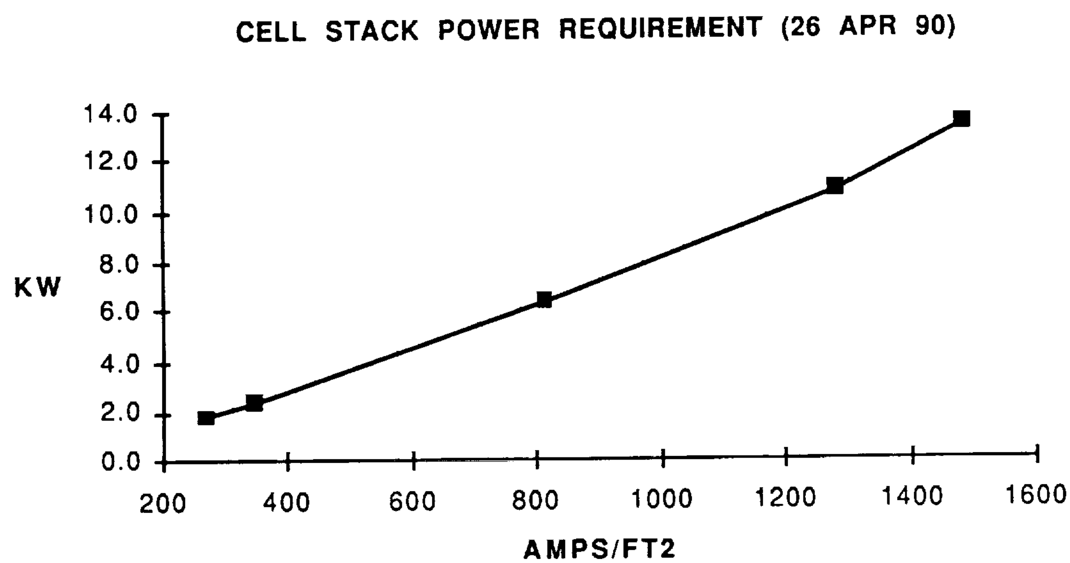


Figure 2.19 Stack Power Requirement

Voltage is averaged over the four group readings of four cells each to produce Figure 2.17. The polarization curve is fairly linear through to 1300 ASF, the established operating range of the US Navy oxygen generator cell stacks. Average cell voltage at minimum (273 ASF) generation rate is 1.82 volts; average cell voltage at nominal (817 ASF) generation rate is 2.10 volts. The maximum voltage reached at the emergency current density of 1500 ASF is 2.46 volts per cell. These points agree with typical data for previous new US Navy cell stacks.

Cell stack efficiency, the product of current and voltage efficiency, is shown in Figure 2.18. The cell stack is shown to exceed the SOW requirement of 70% at the minimum and nominal gas generation rates. Stack efficiency reduces to 62% at the emergency rate of 1500 ASF. The dominant driver in overall efficiency is voltage efficiency, which ranges from a high of 88% at 273 ASF to a low of 66% at the emergency 1500 ASF. The voltage efficiency is calculated by dividing the ideal thermal neutral voltage (V_{tnv}) by the actual cell voltage. V_{tnv} is adjusted from 1.48 V at STP to 1.590 V at 3000 PSIA and 110° F conditions using Nernst' s equations. Current efficiency is only slightly affected by trend in temperature and it's effect on diffusion losses.

Expressed as current loss, calculated diffusion ranged from 11 amps at 274 ASF and 100° F to 16 amps at 1500 ASF, 130° F (83%—95% current efficiency). Operation at standby conditions required balancing diffusion with current. The controller was programmed to increment or decrement current within range to maintain system pressure and cell stack charge. Agreement with calculated diffusion values were achieved within ±2 amps.

Power required to drive the electrolysis reaction is given in Figure 2.19. Calculated as the product of current and total stack voltage, the power ranged from 1.8 kW at minimum, 6.3 kW at nominal to 13.4 kW at emergency gas generation rate.

Gas purity, measured 20 minutes after start-up when 3100 PSIA pressures are reached, was better than 99.5% for both hydrogen and oxygen.

The cell stack maintained full integrity during all phases of testing, proving the design adaptation from the US Navy hardware to prototype propulsion electrolyzer to be successful. The cell stack maintained all internal and external seals from assembly through completion of testing. Current and cell voltage feed-throughs functioned well with no overheating, shorting or leak failures. No internal shorts or leaks developed between cells or between a cell and ground.

Test logs, data disks and records are available separately. A summary of test runs is given in the Source Documents section.

2.3.3.2 *Test Fixture Performance.* The Special Test Fixture accommodated all cell stack and test system goals outlined in the SOW. At the time of delivery to NASA/JSC, the total system had accumulated in excess of 110 operating hours at full pressure. Problems with the process water filter and high pressure liquid level sensing would be resolved by NASA/JSC and Hamilton Standard after installation at JSC Thermochemical Test Area.

A summary of test runs, including commentary as to the development of the test fixture is given in the Source Documents section. The Operation and Maintenance Manual (IPTA-033-90) includes description of the system and the level sensor solution.

2.3.4 Delivery to JSC

A total of seven packages were prepared for shipment to NASA-JSC via government bill of lading. The shipment consisted of the cell stack, the test fixture fluids package, the test fixture electrical support console, the test fixture high pressure pump, the test fixture control console and computer, cell stack power supplies, control cables, power cables, low pressure water line, spare regulator soft goods, manuals and documentation. All items were crated on May 5th. The shipment left the dock on May 8th and was received in good condition at the PPD-TTA.

2.4 IPTA Installation and Operation

NASA/JSC completed installation of the system in the IPTA test facility and initiated test in June 1990. Hamilton Standard provided field support to the subsequent tests. As of this writing NASA has logged in excess of 740 hours on the SPE-Propulsion Electrolyzer and plans to continue operations in support of H-O thruster testing.

2.4.1 Installation

NASA personnel uncrated the shipment and located the system components in the Building 356 facility. The cell stack and test fixture fluids package were placed in the 356E test cell with the existing IPTA test equipment. The high pressure water feed pump, cell stack power supplies and the test fixture electrical support console were located in the compatibility cell adjacent to the test cell. The control console and computer were located in the Building 356 control room approximately 300 feet away. This system component layout is shown schematically in Figure 2.20.

On-site contractor support was initiated on May 23rd to assist NASA in final system installation. By May 31st the cell stack was installed and water had been circulated through the oxygen side of the system using the test fixture circ pump and water loop. All control lines were installed and checked out, and the control computer was verified operational with all sensors operating. Cell stack resistances were measured and shown to correlate to the readings taken prior to shipment, thereby indicating no drying or mechanical damage to the cell stack due to shipment or storage.

A test fixture AC power relay box was built and installed to provide the NASA test operator with a manual power shut down of the system in the event of a controller failure. This replicated a similar device in place at the contractor's test facility during the 100 hour test.

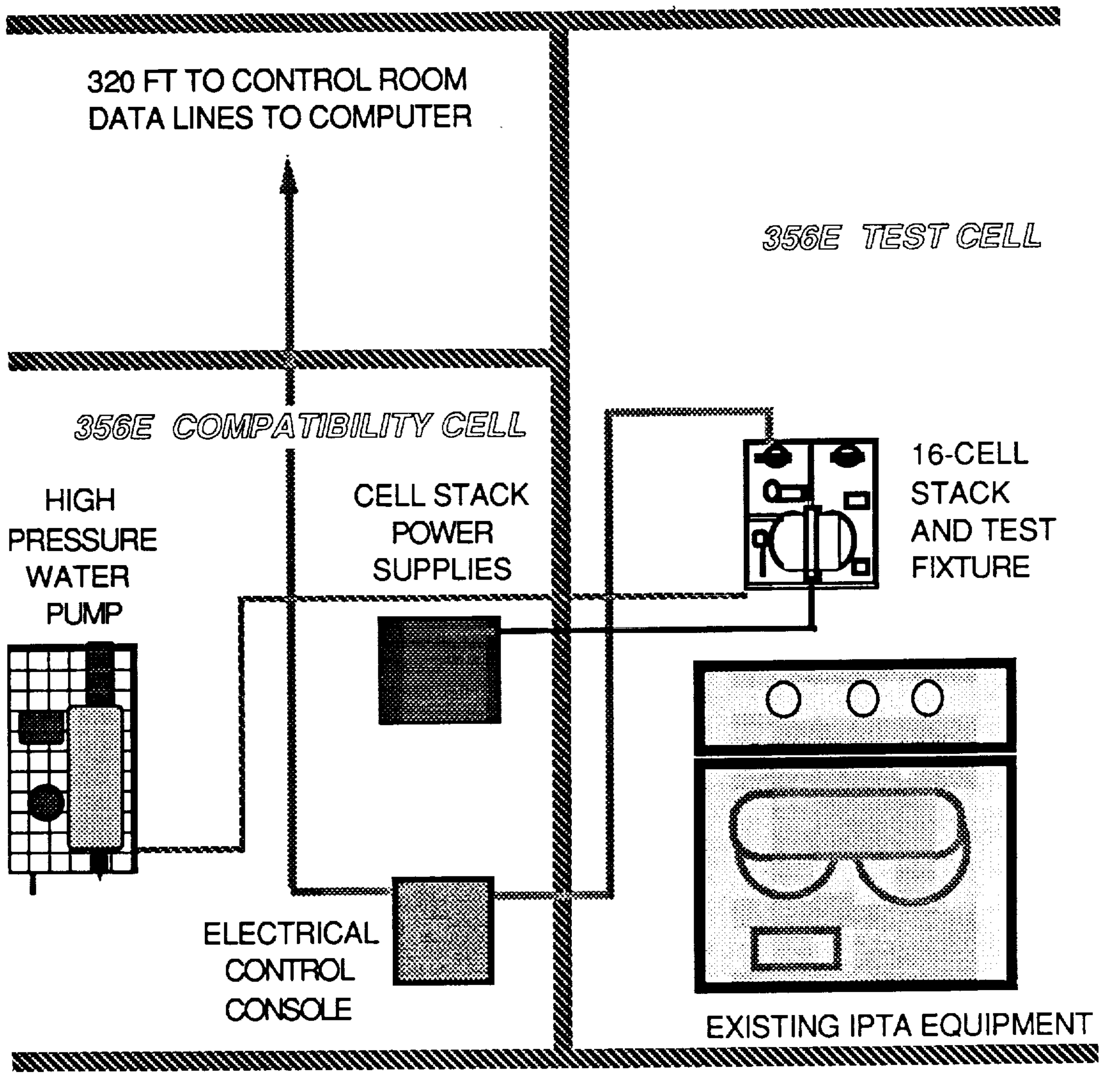


Figure 2.20 Installation Schematic, NASA/JSC Bldg 356E

NASA completed final plumbing installation of vent lines. A Test Readiness Review (TRR) was called by NASA . Prior to the TRR the completed NASA installation was inspected by Hamilton Standard. The cell stack power supplies were phased and calibrated. The oxygen in hydrogen sensors were found to be malfunctioning due to a corroded electrical connector at the sensor. The hydrogen /

nitrogen vent gas line was recommended to be increased from 3/8" to 1/2" diameter to alleviate back pressure during system depressurization.

The TRR was held on June 19th as scheduled. NASA Safety questioned the absence of dedicated relief valves in the oxygen side of the test fixture. Hamilton Standard was able to satisfy the review board that adequate relief capability existed with the redundant back pressure regulator DBPR210-2 and the bypass vent valve AOV-213. The review board approved initiation of system testing and accepted the NASA test plan. The test plan included a leak test at 200 PSI following operation at 3000 PSI, all to verify system integrity.

2.4.2 NASA Operation

The first NASA start-up at full pressure of >3000 PSI was achieved on June 21. Operations during June resulted in at least twelve hours of full pressure operation of the cell stack, the longest run lasting four hours. Additional run time was curtailed due to facility problems. In subsequent months, a series of test fixture and NASA test facility anomalies limited operation of the system to several hours at a time. Major events and problems were

- High Pressure optical sense liquid level sensor malfunctions
- Gas mixture sensor failures and moisture problems
- Recirculation water filter (F501) fouling
- Lightning strikes on the facility
- Limited data storage for long term operation

Resolution of these problems eventually led to a reliable system capable of unattended operation. NASA proceeded toward their goal of 500 hours continuous operation. The longest run to date is 383 hours, ended by yet another lightning strike. NASA has logged over 740 hours at full pressure as of this writing.

2.4.2.1 *Start-up* The first attempts to start up the system on June 20th and 21st were hampered by a failed seal on the water drain valve V218. The valve was capped off until a repair could be made. Full pressure of >3000 PSI was achieved on the next attempt. Operations during June resulted in at least twelve hours of full pressure operation of the cell stack, the longest run lasting four hours. Additional run time was curtailed due to facility problems.

On June 22nd, the system was operated for two hours at 3000 PSI, shut down, and the nitrogen supply regulator turned back to 2000 PSI. The system was then operated at the reduced pressure while personnel examined the system for leaks. This satisfied the proof and leak test called for in the NASA test plan.

2.4.2.2 *Level sensor resolution.* The liquid level sensor problems were resolved through a cooperative NASA-HS development of an electrical conductivity probe to replace all high pressure liquid level sensors. As shown in Figure 2.21, the principal of operation is a measurement of water conductivity using a low level alternating current. A single insulated electrical probe is used as one conductor; the wall of the phase separator is the other. When the probe is dry, no current passes. When the probe is wetted, the AC current flow is detected. The design is such that a retrofit of the existing optical-sense level sensor was easily accomplished. Probe and flange materials provided by HS for O2 level sensing were Inconel, ceramic and Viton. Stainless steel (316SS) was recommended for hydrogen side use.

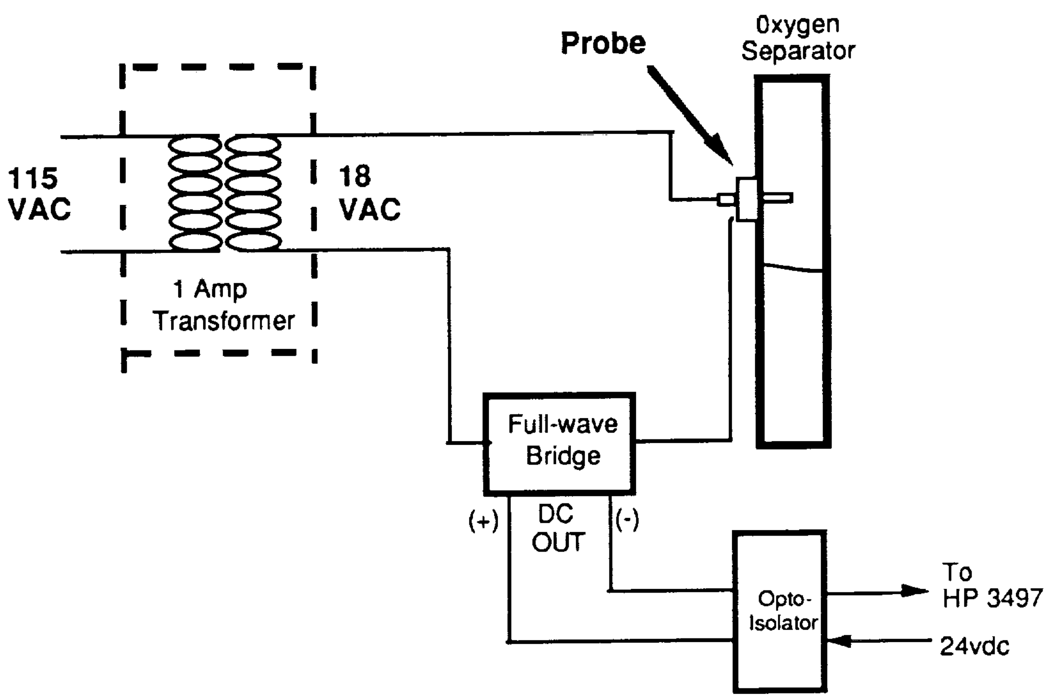


Figure 2.21 Replacement Liquid Level Sensor

2.4.2.3 *Gas mixture sensor problems.* Gas mixture sensors have caused some problems. Both H_2 in O_2 and O_2 in H_2 type sensors have experienced water droplet fouling leading to false mixture sensing. TFE hydrophobic membrane (effective at HS) has been supplied by along with installation and calibration instructions to minimize the problems. NASA has procured replacement sensors. One of the O_2 in H_2 sensors (GA317-x) showed cracks in the plastic housing, indicating pressures in excess of the 50 PSI design. NASA resized the hydrogen vent line with a larger diameter to prevent overpressurization. As of this writing, resolution of moisture problems has not occured and NASA has elected to remove the sensors for closed test cell operation.

2.4.2.4 *Reconfiguration of the data storage* NASA/JSC has experienced some difficulty with the data retrieval procedures and have expressed an interest in alternatives to storage on the computer hard disk, which limits total storage to approximately eight hours at a rate of thirty records per minute. NASA and HS cooperated on a solution which included installation of a 160 Mbyte hard disk and upgrade of the system controller software and BASIC operating system. The controller now can log data for seven days continuous at the rate of one record every 10 seconds. Data retrieval and backup is accomplished via simple MS-DOS file commands. Hamilton Standard provided software revision and field support for installation and check-out.

2.4.2.5 *Lightning Strikes* NASA/JSC-TTA facilities have been hit with several electrical storms which have adversely affected the intelligent pressure transmitters installed on the test fixture. NASA has twice repaired electronics in the Paroscientific absolute pressure transmitters, resulting in delays. To date, no isolation method to prevent future occurrences has been identified.

2.4.2.6 *Revised documentation* Hamilton Standard has issued a revised operations manual (IPTA-033-90) and revised software listing and requirement specification (IPTA-054-90) to document changes and updates to the test fixture.

3.0 SPE-Propellant Generator Conceptual Design

This section summarizes the the Conceptual System Design (CSD) study conducted by Hamilton Standard in 1990. The System Design Review (SDR) was delivered to NASA/JSC in early 1991. Concepts were developed for a flight-type high pressure H_2/O_2 SPE-Propellant Generator system for Space Station propulsion. The study emphasis was best reliability for 5-year life based on projected 1995 available technology (1990 start). Key trades and key technology areas for development were identified and a baseline system was concepted.

3.1 Trade Studies

The technology baseline was IPTA demonstrator system delivered under this contract. The trade studies built upon previous trade studies conducted for NASA, MDAC and for Hamilton Standard internal use.

As a guideline for the trade studies, absolute, primary and secondary criteria for trade study selection were established based on Statement of Work definition and current knowledge of the Space Station architecture.

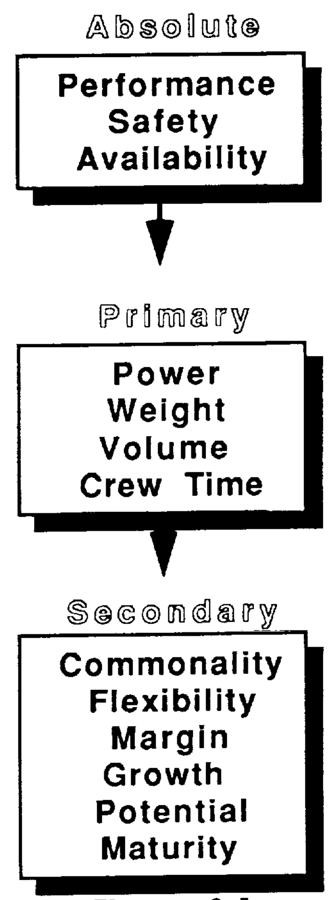


Figure 3.1
Trade Study Criteria

Absolute criteria are defined by the SOW. Gas production requirements are 2 PPH nominal with a 0.6 to 4.0 PPH range. Product gas is to have less than 2500 PPM impurities with a dew point at point of use of -100° F. The system must deliver 3000 PSI gas to storage. The operating environment will be zero-G, space vacuum, with a temperature range of from +150 to -20° F. System life is to be 30 years - stack, major components, 5 years to replacement. The basic duty cycle is 54 min on / 36 min standby, with 3 minutes to reach full power. Electrical Efficiency is to be better than 70% at B.O.L. The environmental goal is to be non-venting. Finally, no two independent failures can harm crew or other systems.

Figure 3.2 illustrates the basic SPE-Propellant Generator (SPE-PG) interface as derived from the absolute criteria and 1990 Space Station PDR information. The two-phase ammonia coolant loop temperature had not been decided on, so the higher temperature (62±5°F) was used for these trade studies. Also, the nitrogen utility pressure available to the system is likely to be in the range of 600—800 PSIA, much lower than that used in previous systems.

PARAMETER	COMMENTS
Power	120VDC
Feed Water	Hygiene Grade TBD Press 30±2 PSIA Temp 70±5 °F
Nitrogen	Press 600-800 PSIA
Coolant	2-Ø NH_3 Hfg = 500 Btu/lb Temp = 62±5 °F or 35°F
Oxygen	3000 PSIA -100°F dew point <2500 ppm impurity
Hydrogen	3000 PSIA -100°F dew point <2500 ppm impurity

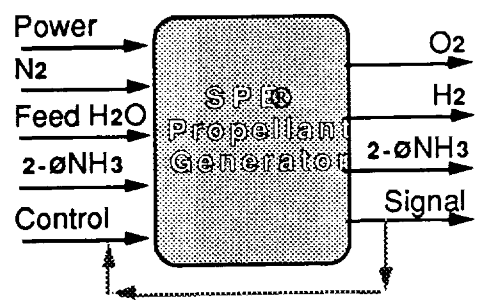


Figure 3.2 Interface Definition

Primary study criteria considered a maintenance EVA period of 5 years, requiring system reliability to be 5 years. Resupply periods were assumed to be every 90 days. Secondary criteria considered component commonality, growth potential and maturity.

The following major trades were considered during the conceptual study:

3000 PSID (One-way) DOMED STACK vs Present Design

600 PSI GN_2 SAVE SYSTEM vs High Pressure Supply *

NON-REGENERATIVE vs Regenerative Driers*

"Non- Active" TEMP CONTROL vs 120°F Active Control

PASSIVE FREEZE PROTECTION vs Active Freeze Control

DOME LOADED REGULATORS vs Electronic Regulators *

WATER FEED PUMP Location

Combined WATER FEED, TEMPERATURE, DRIER $ Study

Mean Time Between Failure (MTBF) configurations

Several of these trade studies (marked with an *) were conducted as part of an independent study conducted by Hamilton Standard as an evaluation of QFD product development methodology. The HS sponsored "QFD – High Reliability SPE-PG" study occurred prior to award of the CSDR study contract modification. The results of the QFD studies were reviewed and adopted or revised for the present CSDR.

A modular system schematic that incorporates the major study recommendations and meets the study criteria is given in Figure 3.3. The following sections provide an overview of the CSDR trade study results as they relate to this schematic. The CSDR trades are discussed in greater detail in the System Design Review Presentation (IPTA-055-90).

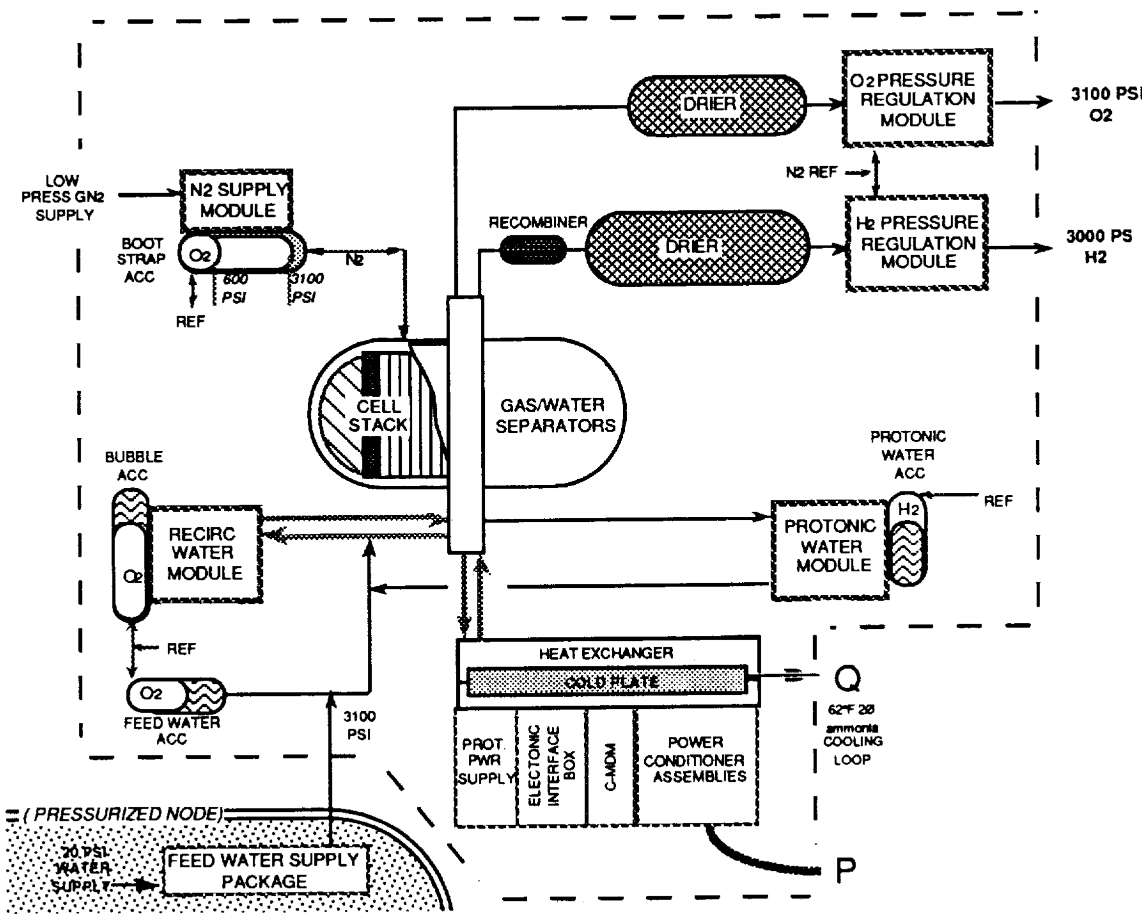


Figure 3.3 SPE-Propellant Generator Modular Schematic

3.1.1 3000 PSID (One-way) DOMED STACK vs Other Designs

The cell stack is the primary component in the gas generator system. It's configuration determines the requirements for the remaining components. The cell stack trade study considered three options:

1. Phase 1 IPTA design, requiring 3150 PSI nitrogen dome pressure and a pressure hierarchy system to control membrane ΔP to within 700 PSID
2. Enhanced domed cell stack capable of full 3000 PSID oxygen over hydrogen membrane differential pressure ("$O_2 > H_2$ ΔP")
3. Enhanced cell stack , undomed, capable of full 3000 PSID in either direction and overboard ("full ΔP")

Option 2 was selected based on maturity, projected 1995 availability, reduced nitrogen consumption, and system reliability enhancement criteria. The cell stack basic cell design, with the exception of an enhanced hydrogen side membrane support, would retain the same proven components of the existing design. High ΔP designs are already under development for other products. (Differentials as high as 3000 PSID have already been demonstrated in similar hardware and 5000 PSID in specialized electrochemical gas compressor hardware) The ability of the cell stack to withstand the total loss of hydrogen pressure without damage allows the electrolysis pneumatic system to be simplified. Previous systems, including the recently delivered Special Test Fixture, have a cross-referenced system of oxygen, hydrogen and nitrogen pressure regulators and relief valves that are designed to maintain the proper pressure profile in any event. The "$O_2 > H_2$ ΔP" stack allows elimination of this elaborate system in favor of a fixed oxygen regulator, an O_2 referenced nitrogen system and a N_2 referenced hydrogen regulator. The simpler system with fewer functions and components enhances reliability.

A qualified "full ΔP" domeless cell stack (Option 3) was not estimated to meet the 1995 readiness criteria. It would be an attractive choice for a future, simpler system as it would require no nitrogen or nitrogen-referenced pressure controls.

3.1.2 600 PSI GN2 SAVE SYSTEM vs High Pressure Supply

Nitrogen is required for cell stack dome pressurant and for pneumatic reference to the H2 regulator; previous requirements for N2 purge/backfill of the H2 side during system shut down were eliminated by the "$O_2 > H_2$ ΔP" cell stack trade study selection. Information from the 1990 Space Station PDR indicated that nitrogen would be available for other equipment in the pressure range of 600—800 PSIA; higher pressure would require a special gas source.

The HS QFD-High Reliability team studied an accumulator system whereby low pressure GN_2 would be compressed by generated O_2 to the required 3100 PSIA pressure. On system depressurization, the nitrogen is "saved" as it is allowed to expand back into the accumulator. The required nitrogen volume would be minimized by filling voids in the cell stack pressure dome with an inert, lightweight material. The concept is depicted in Figure 3.4.

The present CSDR study estimated that the total GN_2 pressure volume could be reduced to 120 IN^3 and that a suitable "boot-strap" accumulator would require 0.8 FT^3 of space in the SPE-PG package. On the negative side, up to 6 hours are required (2 PPH H_2O rate) to pressurize the accumulator. Also, a large high pressure accumulator has to be qualified; previous assemblies of this size are commercial devices for hydraulic service.

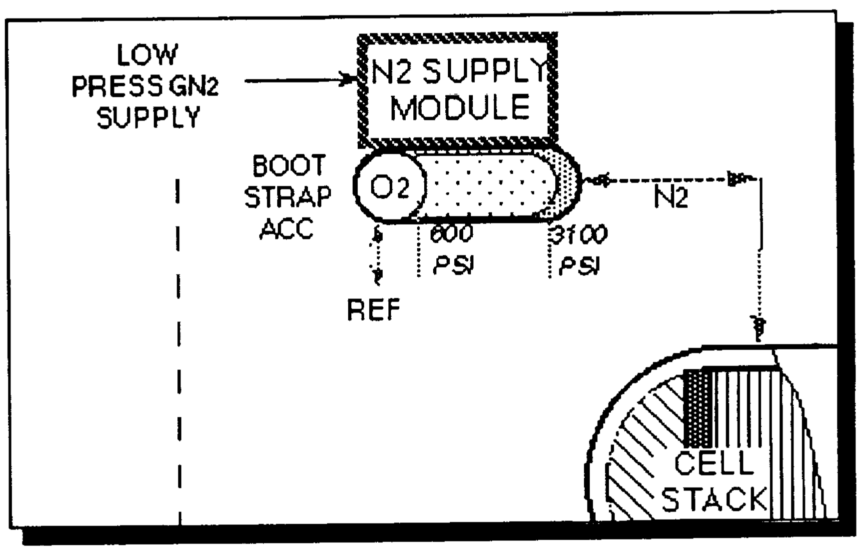


Figure 3.4 Nitrogen Save System

An alternative 5-year high pressure supply was compared on a tank volume basis. Assuming that the high pressure gas was not recoverable (vented) and that the SPE-PG experienced a complete depressurization and restart every 90 days, a 6000 PSI GN_2 supply tank volume of 2.1 FT^3 would be needed. 16.5 LBS of nitrogen would be vented in 5 years. System start-up pressurization to 3100 PSIA without a boot-strap accumulator would be comparable to the Phase1 Special Test Fixture (<15 minutes).

With the criteria of low supply pressure and a goal of no venting, the 600 PSI GN_2 Save System is selected. It requires no significant resupply, requires no venting, is smaller in volume than a special supply and is compatible with the planned GN_2 utility. If venting were allowed, however, a simple special high pressure tank may be more reliable than an accumulator.

3.1.3 NON-REGENERATIVE vs Regenerative Driers

Gas drier beds for the removal of water vapor from product gas streams would make use of a molecular sieve material (Linde 13X). The product gas is dried to a low dew point (-100° F) so that moisture does not condense in gas storage tankage, gas transmission lines or in the thruster.

The previous drier concept (1988 IPTA proposal HSPC 88T14) was a pressure swing regenerable drier system. One drier would be valved on-line while the second one would be purged using a vent stream expanded to low pressure (200—300 PSI). The drier system could be made small, based on the frequency of cycling. The wet purge stream, representing 3—5% of the gas produced, had to be disposed of in some fashion.

The present study examined the use of a simple non-regenerative drier sized for 5 years before replacement. A non-regenerable drier would eliminate the switching valves, pressure swing stress and purge gas waste features of the regenerable system.

Non-regenerable drier size is directly related to water content of the product gas streams, which is determined by system gas generation temperature and pressure. Water load imposed on the driers is five times less at 70° F than at 120° F. Conversely, if system pressure is allowed to vary from 300 to 3000 PSI, the water load is increased 250% over constant 3000 PSI operation.

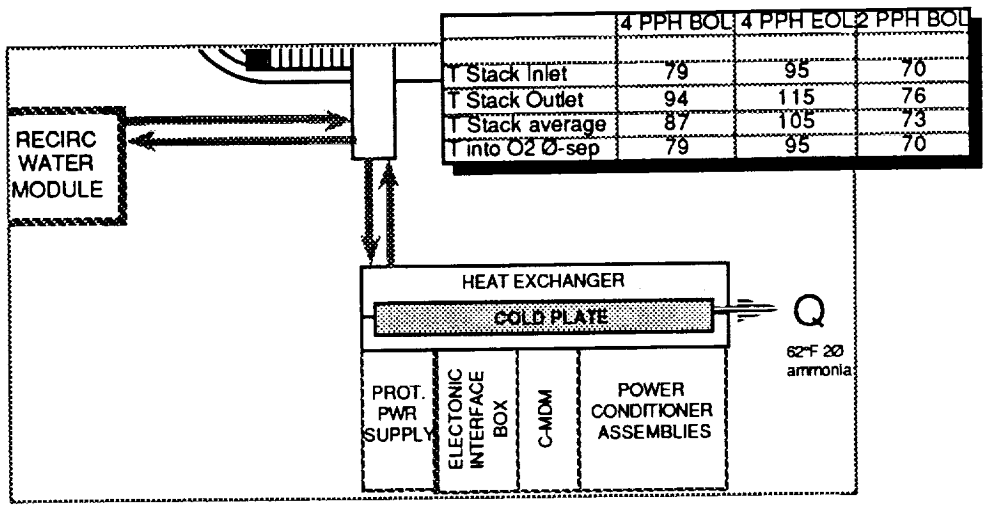
The non-regenerative approach was selected in the current study for reasons of simplicity (higher reliability) and elimination of a purge stream. An effort to reduce gas generation temperature is required so as to minimize drier size.

If the no venting criteria can be relaxed and if size becomes more important, regenerable driers should be reconsidered for their size advantage. Regeneration studies at NASA/JSC showed temperature and vacuum to be most effective in regenerating molecular sieve beds.

3.1.4 "Non- Active" TEMP CONTROL vs 120°F Active Control

Previous concepts (1988 IPTA proposal HSPC 88T14) showed the most efficient cell stack temperatures for gas generation to be 110—120° F. Alternatives were considered for the present CSDR trade because of the non-regenerable drier trade study results and because of the goal of greater system reliability and simplicity.

The heat sink for rejecting waste heat is the two-phase ammonia coolant loop. As of the 1990 Space Station PDR the operating temperature of the heat sink was expected to be 62±5 ° F. A non-invasive means of transferring heat to the 2-Ø NH_3 loop is required by Space Station PDR guidelines; this mandates use of a cold plate.



	4 PPH BOL	4 PPH EOL	2 PPH BOL
T Stack Inlet	79	95	70
T Stack Outlet	94	115	76
T Stack average	87	105	73
T into O2 Ø-sep	79	95	70

Figure 3.5 "Non-Active" Thermal Control

A "non-active" thermal control system was concepted to meet the study criteria. A heat exchanger is positioned within the O_2 side water recirculation loop between the cell stack outlet and the O_2/H_2O phase separator inlet. Gas exiting the phase separator is saturated with water vapor at the bulk water temperature, so by cooling the two-phase stream prior to phase separation, the lowest dew point is achieved. The heat exchanger is configured as a flat plate to interface with a Space Station mounted ammonia cold plate. A specific cold plate configuration had not been specified by Space

Station PDR, so a multi-layer plate 2.5′ by 4′ was concepted. Figure 3.5 shows the concept schematic and the expected operating temperatures at beginning of life (BOL) and end of life (EOL). The average operating temperature and oxygen gas dew point is 85° F. The minimum temperature possible approaches the NH_3 loop temperature of 62° F. This low temperature during Standby operation reduces diffusion losses to less than half of the diffusion loss at 120° F.

3.1.5 PASSIVE FREEZE PROTECTION vs Active Freeze Control

Passive and active methods of preventing water freezing of inactive SPE-PG systems stored on Space Station were examined. The simplest, most efficient method requires only a thin space suit type insulation sheath with selective use of a coating to adsorb solar energy.

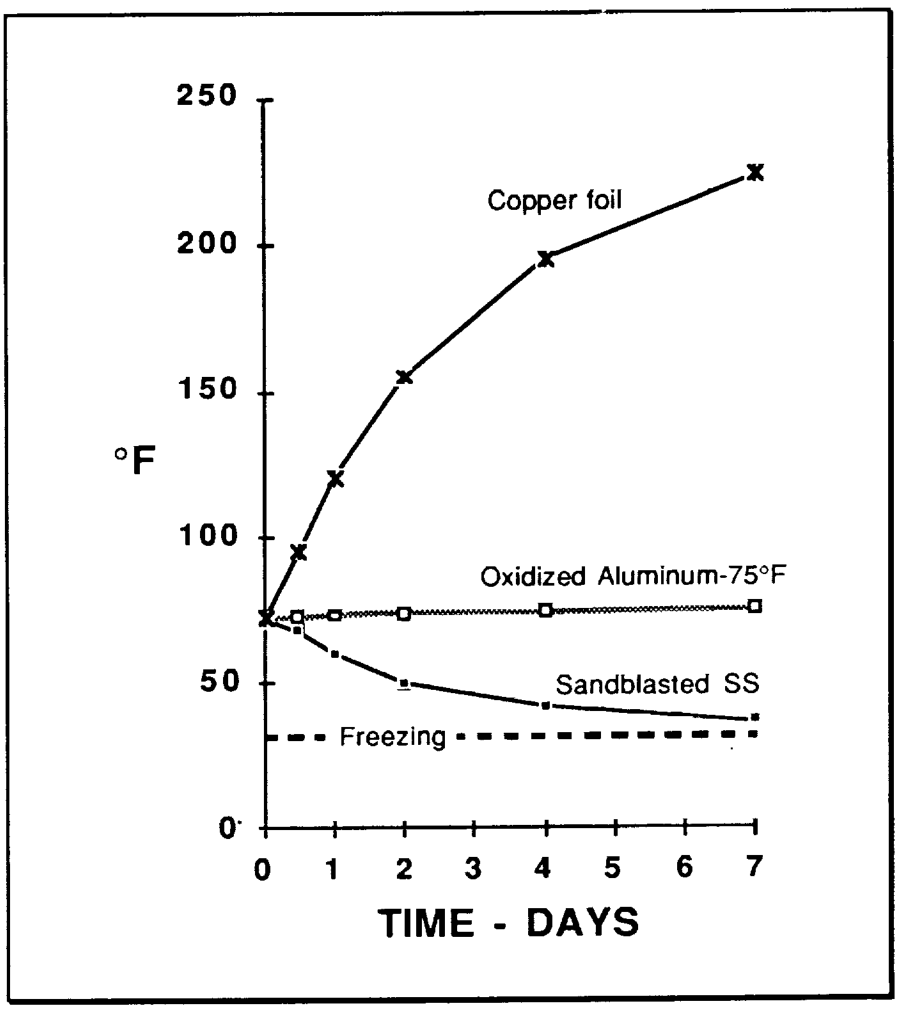


Figure 3.6 Performance of Thermal Coatings

A transient thermal model was written for study of electrolysis system freeze protection. The system transient model assumes high internal thermal conductance (a uniform internal temp), a 90 minute low earth orbit (54 min sunlight), and the conceptual design system rectangular geometry (absorbtion to radiation view factor = $^1/_4$). Results show that a selective outside surface coating is sufficient to prevent electrolyzer system freezing when deactivated . The outer coating should have the proper radiation absorbtivity/emmissivity (a/e) ratio for system orbit, weight, shape and attitude to sun and earth. Figure 3.6 shows the estimated performance of three different surface coatings. Oxidized aluminum (a/e = 2.7) proved to be the correct choice, maintaining an internal temperature close to 75° F for days (or years, if required). To retain absorbed heat during solar occlusion, the use of space suit type thin insulation (0.06 BTU/FT^2-°F) is needed under the aluminum coating.

3.1.6 DOME LOADED REGULATORS vs Electronic Regulators

Pressure control of the generated hydrogen and oxygen and maintenance of the pressure dome nitrogen blanket was evaluated. The standard method of pressure control in high pressure SPE-water electrolysis systems is a system of cross-referenced dome-loaded pressure regulators. Nitrogen is the common reference gas. Electronic-variable pressure regulators (EVPR) are a new class of control devices that have been demonstrated for propellant gas pressure reduction from 300 to 3 PSI. They eliminate the need for nitrogen reference gas.

Dome-loaded regulators were retained for the CSDR study because

- Dome-loaded regulators have higher maturity for water electrolysis than EVPR
- GN2 dome reference gas is already available from cell stack trade
- Pneumatic system controls even in loss of power
- 1995 development status criteria
- High pressure materials compatibility with present EVPR magnetics designs

The selection of the "High O_2>H_2 ΔP" cell stack allows use of a simple back-pressure regulator for oxygen. Referenced regulators are still needed for hydrogen and nitrogen pressure control.

For a post-1995 SPE-PG that would use a domeless cell stack, the EVPR would have to be developed.

3.1.7 WATER FEED PUMP Location

Studies of oxygen-pressurized batch water feed (non-venting and venting approaches) and integral continuous feed pumps were conducted by the HS QFD-High Reliability team. The studies concluded that, while batch feed could be made to operate at a lower power penalty than continuous feed (3.5 vs. 21 kW), the size and complexity (690 LBS — 17 components vs. 41 LBS — 5 components) of batch feed did not trade well. The team selected continuous feed but expressed concern that the continuous feed pump would require a high level of maintenance. A reliable, low maintenance high pressure feed pump was identified as a critical development item.

The present CSDR study team considered an option: remote location of the feed pump off the external package to inside the pressurized Space Station habitat. Internal location of the feed pump eliminates any need for EVA on this item, minimizing concerns over reliability and maintenance. The CSDR team surveyed the Work Package II contractor (McDonnell-Douglas Aerospace) and NASA/JSC and received concurrence as to the acceptability of 3000 PSI water generated in a pressurized node. This concept was then incorporated into the SPE-PG conceptual design.

3.1.8 Combined WATER FEED, TEMPERATURE, DRIER $ Study

Cost sensitivity trades were conducted on the interrelated water feed, system temperature and drier trades. Five cases, four with non-regenerable (5-year) and one with a regenerable drier system, were considered:

① Constant Water Feed / 100°F stack exit / 80°F O_2 phase separator inlet

② Batch Water Feed / 100°F stack exit / 80°F O_2 phase separator inlet

③ Constant Water Feed / 120°F stack exit and O_2 phase separator inlet

④ Batch Water Feed / 120°F stack exit and O_2 phase separator inlet

⑤ 90 day Regenerable Driers; vent to vacuum, heat to 350° F for 8 hours to regenerate/ Case ① conditions

Relative weight, power penalties for launch and resupply were compared using primary criteria cost penalties derived from the 1990 Space Station PDR. Table 3-1 presents a case summary of weight, energy and cost associated with launch and 30-year maintenance or resupply for the five cases.

Results show Case ① is the lowest weight, largest power, and lowest power+weight penalty case of the four non-regenerable drier systems. Regenerable driers (Case ⑤) have a lower weight penalty (40% lighter) and only slightly lower power+weight cost (5%) in contrast to the best non-regenerable system, Case ①.

TABLE 3-1
CASE SUMMARY

30-YR WEIGHT, POWER, COST PENALTY FOR DRIERS, TEMPERATURE AND WATER FEED

CASE	30 YR WEIGHT (LBS) LAUNCH	RESUPPLY	TOTAL WT	ELECTRICAL ENERGY (KW-HR)	30YR POWER PENALTY ($M)	30YR WEIGHT PENALTY ($M)	30YR PWR+WT PENALTY ($M)
①	445	3575	4020	38894	8.87	27.50	36.37
②	1527	3670	5197	28908	6.59	34.10	40.69
③	780	5248	6028	9986	2.28	41.00	43.28
④	2245	7256	9501	0	0.00	63.10	63.10
⑤	149	2093	2242	83440	19.00	15.50	34.50

Launch weight = driers, feed pumps or batch bladder tanks, structural support
Resupply weight=driers (life=5-years), associated valves, feed pump (life=1 year)
A power penalty of 110 watts was assessed the 80°F cases for stack voltage inefficiency
A power penalty of 38 watts was assessed the constant feed cases for the feed pump
Power is required to heat the regenerable driers every 90 days, 500°F for 8 hours

The CSDR team had previously selected the Case ① system based on reliability and non-venting criteria. For future trades where weight, volume are of greater concern and venting to space vacuum for regeneration is allowable, then Case ⑤ should be reconsidered.

3.1.9 Mean Time Between Failure (MTBF) configurations

Using established aerospace criteria, the functional SPE-Propellant Generator system schematic has an MTBF of 8 months (see Source Document section for schematic). The SPE-PG MTBF may be improved to 2-1/2 years by implementing the following measures:

- Redundant control instrumentation
- Bifilar windings on solenoid valve coils
- Redundant circulation and protonic water pumps
- Redundant H_2, O_2 pressure regulation modules
- Triple redundant cell stack power converter controller section, one additional power converter stage (5+1)
- Redundant system relief valves
- Redundant control units

To achieve the goal of a 5-year MTBF, a single propellant generator unit must include two parallel fluid operating systems, less the cold plate / heat exchanger assembly. The feed pump is not included in the MTBF calculations as it is a separate unit serviced without EVA.

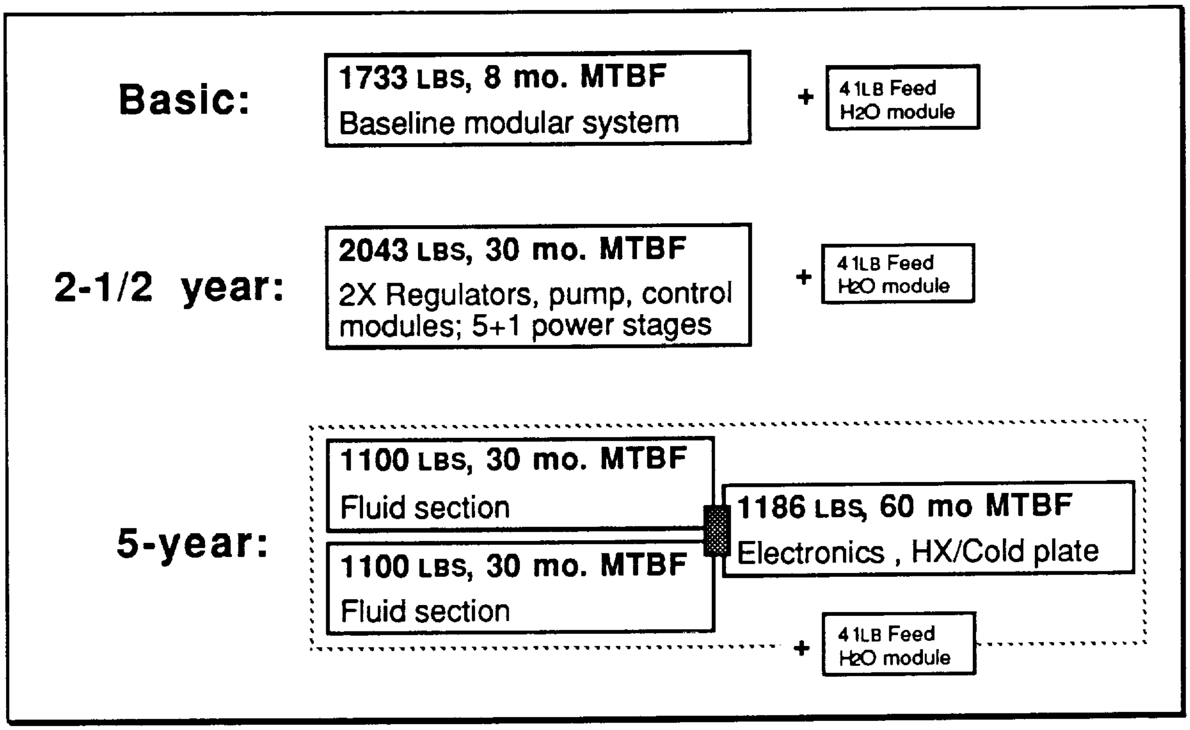


Figure 3.7 MBTF Configurations

Figure 3.7 is a diagram of the 8 month, 2.5 and 5-year configurations. The 2.5-year configuration was the subject of a conceptual mechanical design packaging effort described in Section 3.2.

3.2 Conceptual Design and Layout

The SPE-Propellant Generator primary function is to produce 3000 PSIA dry (-100° F) hydrogen and oxygen for Space Station propulsion. To accomplish this, it must perform these internal functions:

- Electrolyze water to produce hydrogen and oxygen
- Deliver feed and cooling water to the electrolysis stack
- Separate gas and liquid water
- Dry the product gases
- Reject stack and system waste heat

- Maintain pressure control
- Manage protonic water
- Conserve pressurant nitrogen
- Maintain pressure hierarchy and system limits for safety

The Modular Concept SPE-PG shown in Figure 3.3 is designed to perform these functions. Component modules and major components have been selected to perform the internal functions required.

A mechanical and electrical design package was concepted for the SPE-PG in consort with the results of the system trade studies. The total system package consists of two ORU's (Orbital Replacement Units): the external mount Generator package and the internal mount Feed Water package. The Generator ORU consists of a cell stack / gas separator module, recirculation and protonic water modules, pressure regulation modules, H_2 and O_2 driers, four accumulators, electrolysis power conditioner, control electronics, and a heat exchanger / cold plate assembly. The Feed Water ORU consists of a 3100 PSI water feed pump, a valve and sensor module, a feed water cleanup bed, and control electronics.

3.2.1 System Attributes

The SPE-Propellant Generator conceptual design features the following attributes as a result of the trade studies:

- 600 PSI N_2 BOOTSTRAP SYSTEM
- LIQUID ANODE FEED
- DOMED STACK FILLED WITH N_2
- STACK OPERATES COLD ~ 85°F INLET TEMPERATURE
- "Non-Active" TEMPERATURE CONTROL
- DOME LOADED PRESSURE REGULATORS
- OPERATING PRESSURE 3100 PSIA WITH O_2 MAINTAINED ABOVE H_2
- NODE-MOUNT FEED PUMP CAPABLE OF 3100 PSI HEAD RISE
- PROTONICALLY PUMPED WATER IS STRIPPED OF H_2 AND RECIRCULATED INTO THE RECYCLE LOOP
- NON-REGENERABLE DRIERS ARE USED (OPTION CONSIDERED)
- CELL STACK CAPABLE OF 3000 PSID O_2 >H_2

3.2.2 System Packaging

One Feed Water ORU and two variations of the Generator ORU were packaged using mainframe CAD for 2-D and a personal computer modeling program for 3-D representations. The Generator ORU representations include electronics and power modules as they reject heat to the cold plate.

3.2.2.1 *Baseline Concept* Figure 3.8 is a perspective view of the Generator ORU baseline package concept. The non-regenerable driers are the largest volume pressure vessels. The N_2 boot-strap accumulator, feed water and protonic water recovery accumulators, and the cell stack/phase separator module are adjacent to the driers. Mounted on the heat exchanger/cold plate is the stack power supply, the control electronics, and component modules for pressure regulation and water management. The Generator ORU dimensions are 21 by 30 by 104 inches. The estimated mass of the ORU is 2043 LBS based on a two and one-half year MTBF configuration. Figures 3.9 a—f orthographic views of the Generator ORU baseline package.

A mass summary of the baseline concept subassemblies, including mass multiplying factors to achieve 2.5 and 5 year MTBF levels, is presented as Table 3-2. The factors derive from the level of component redundancy.

TABLE 3-2

Baseline and Regenerable Concept Mass Summary (Units in LB-M)

	8 Month		2.5 Year		5 Year		Regen Drier Concept
CELL STACK/ SEPARATOR ASSEMBLY	247	x 1.00	247	x 2.00	494	(2.5 yr) x 1.00	247
GAS DRIERS	337	1.00	337	2.00	674	0.10	34
ACCUMULATORS	218	1.00	218	2.00	436	1.20	262
PRESSURE REGULATION MODULES	77	2.00	154	2.00	308	1.00	154
RECIRC/PROTONIC WATER MODULES	63	2.00	126	2.00	252	1.00	126
RECO IER	18	1.00	18	2.00	36	1.00	18
HX/COLD PLATE	240	1.00	240	1.00	240	1.00	240
FRAMEWORK/PLUMBING/MISC	193	1.15	222	1.87	415	1.00	222
POWER SUPPLY (CELL STACK)	250	1.20	300	1.00	300	1.00	300
EIB / MDM / PROTONIC WATER P.S.	90	2.00	180	1.00	180	1.00	180
FEED WATER SUBSYSTEM	41	1.00	41	1.00	41	1.00	41
Total Wts:	1774		2083		3376		1823

3.2.2.2 *Regenerative Concept* The baseline Generator ORU concept adheres to the non-venting criteria through the use of non-regenerable driers and the N_2 save system. An alternative package was assembled to show the mass and volume reduction realized through incorporation of regenerable driers and rearrangement. The 2.5 year MTBF baseline Generator ORU was modified with 90-day size regenerable driers and repackaged bootstrap and bubble accumulators. This regenerable drier package concept for the Generator ORU is shown in Figure 3.10. The alternate ORU package is 21 by 30 by 65 inches and has an estimated mass of 1782 LBS. Orthographic views of the regenerable drier Generator ORU concept are given in Figures 3.11 a—c.

A mass summary comparing the optional concept to the baseline at the 2.5 MTBF level is included in Table 3-2. A 14 FT^3 volume reduction is effected by the changes (37.9 FT^3. reduced to 23.7 FT^3).

3.2.2.3 *Feed Water ORU* The Feed Water ORU is the same for both the baseline and the optional regenerative drier concepts. This unit is to be located inside the habitable Space Station for ease of maintenance without the need for EVA. The unit is concepted to operate for 90 days at the 2 PPH rate before change-out of the cleanup bed. The clean-up bed is a polishing demineralizer and organics removal bed. Weight of the Feed Water ORU is estimated to be 41 LBS . Power requirement during operation is 38 watts. Dimensions are 8 x 11 x 28 inches.

Description of Generator ORU components and subassemblies can be found in the CSDR presentation (IPTA-055-90) documentation and in the Source Document section of this report.

3.2.3 Electrical Design

The SPE-Propellant Generator electrical system requirements are divided into functional blocks representing control processing, instrumentation, sensor signal conditioning, effectors and drivers, the electrolysis power converter (EPC), and H_2 electrochemical "stripper" power processing. The SPE-Propellant Generator electrical system must also interface with a Space Station Controller multiplexer/demultiplexer (C-MDM). The C-MDM interfaces with the Space Station Data Management System (DMS). The C-MDM is customer furnished.

A conceptual electrical block diagram of the Generator ORU control architecture is given in Figure 3.13. Control of the Feed Water ORU is not represented.

ORIGINAL PAGE
COLOR PHOTOGRAPH

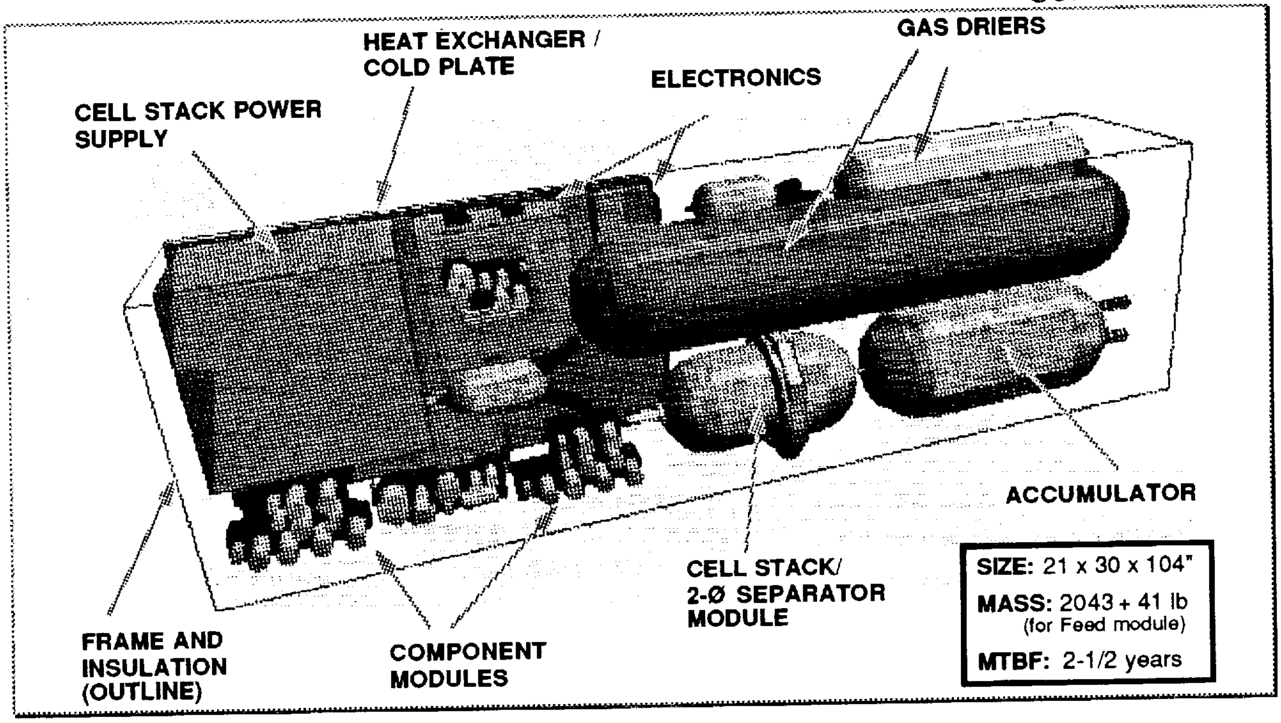


Figure 3.8 Generator ORU Package

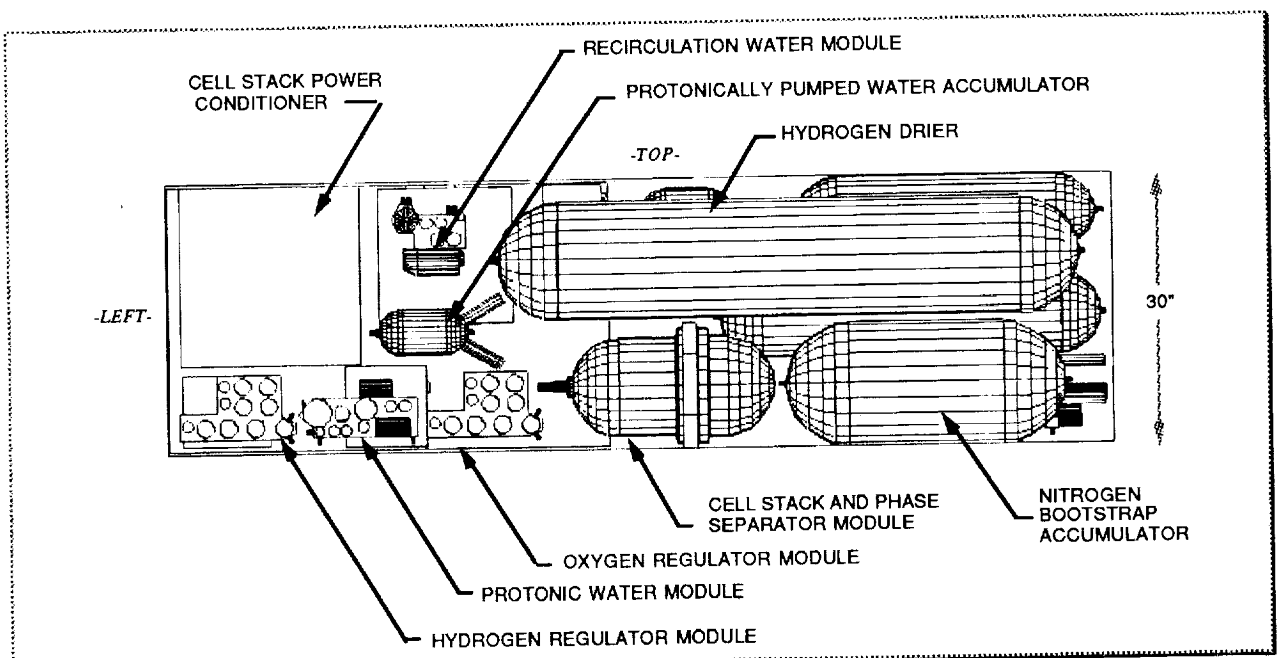


Figure 3.9a Generator ORU, Front

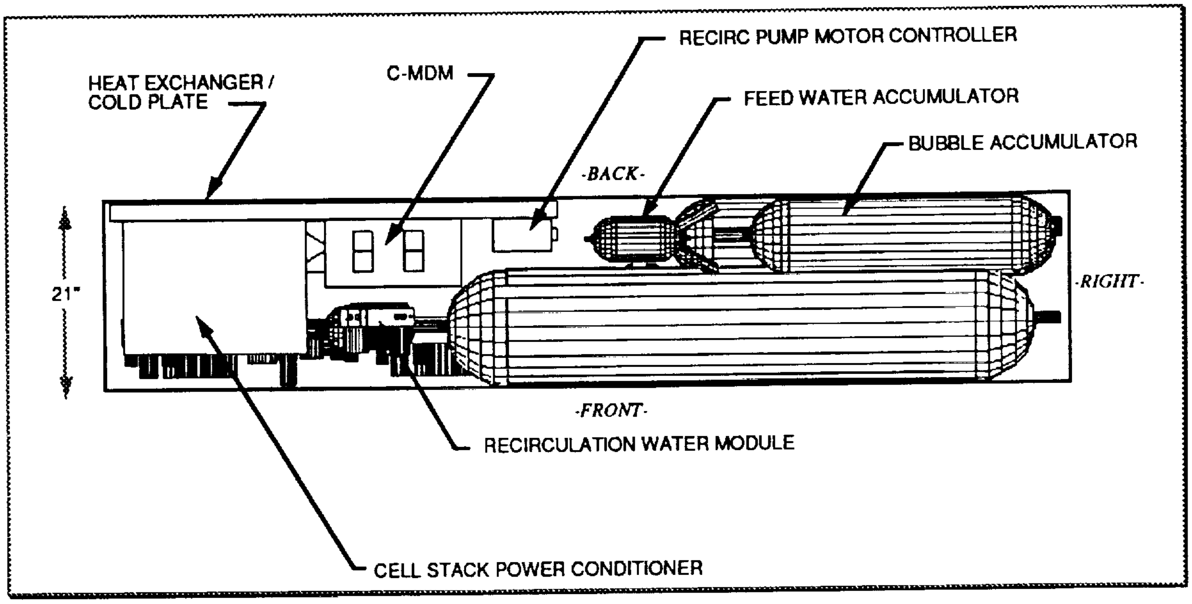


Figure 3.9b Generator ORU, Top

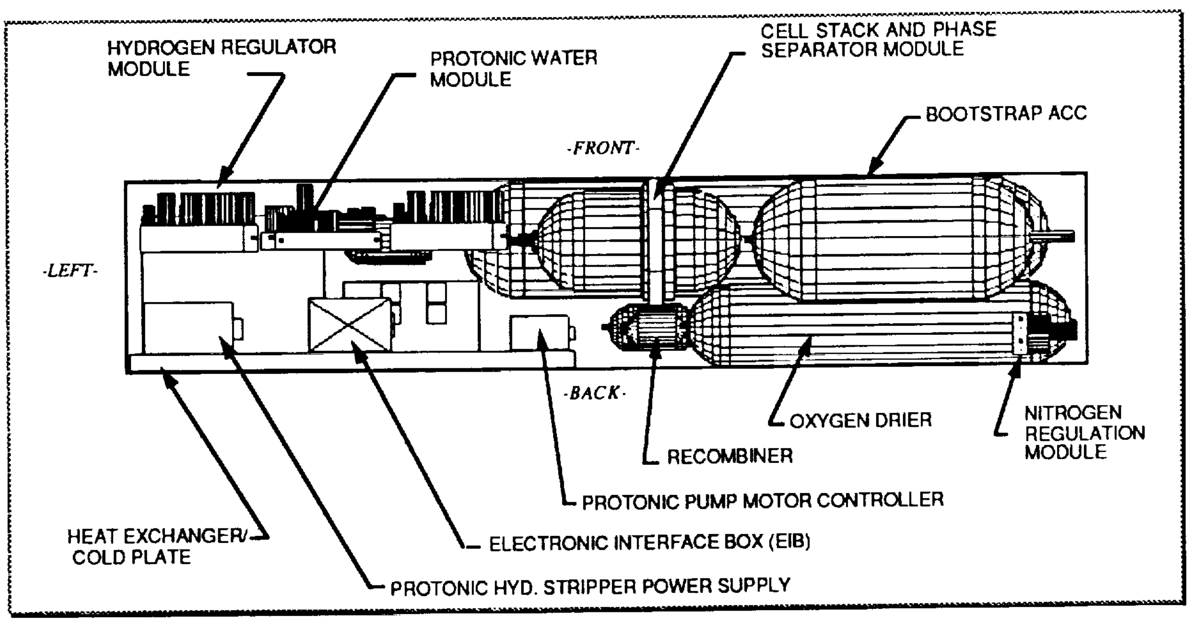


Figure 3.9c Generator ORU, Bottom

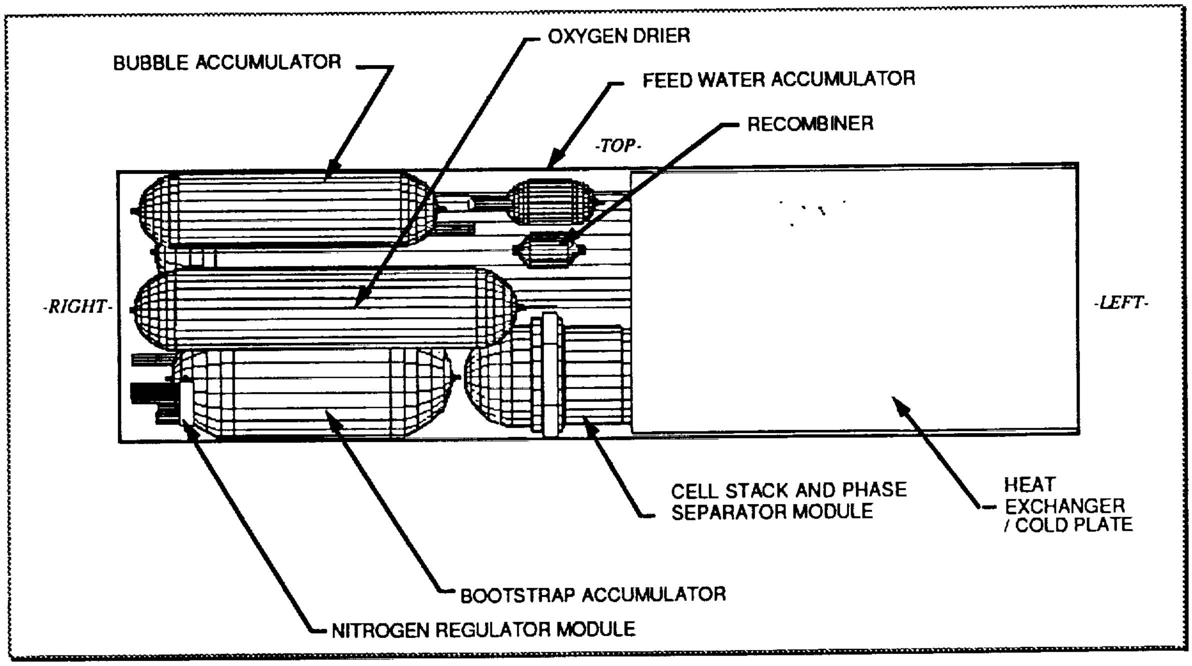


Figure 3.9d Generator ORU, Back

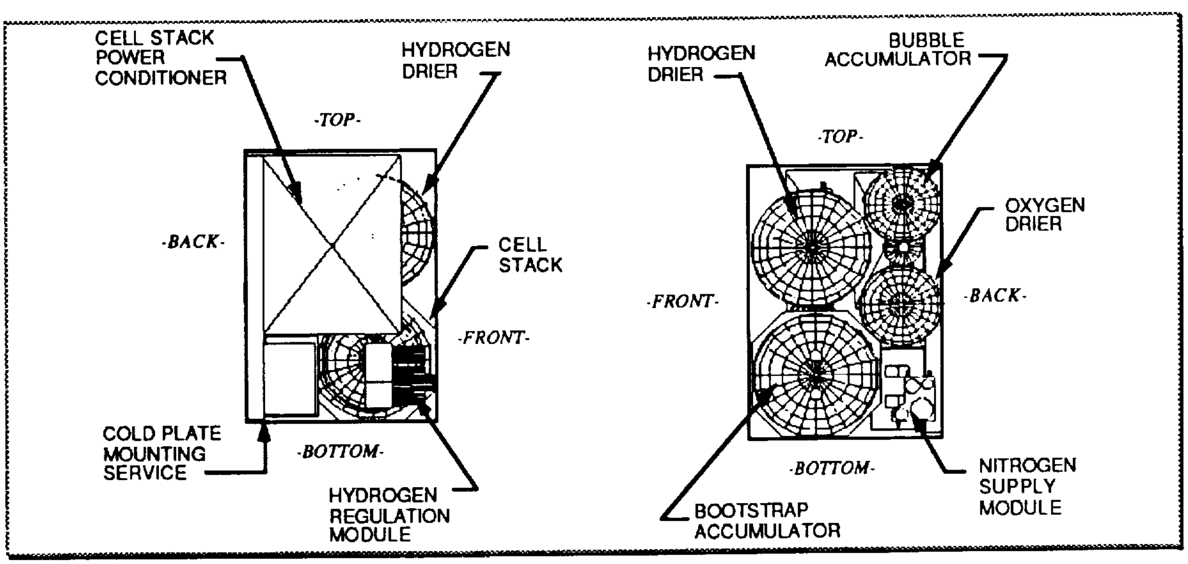


Figure 3.9e Generator ORU, Left and Right

ORIGINAL PAGE
COLOR PHOTOGRAPH

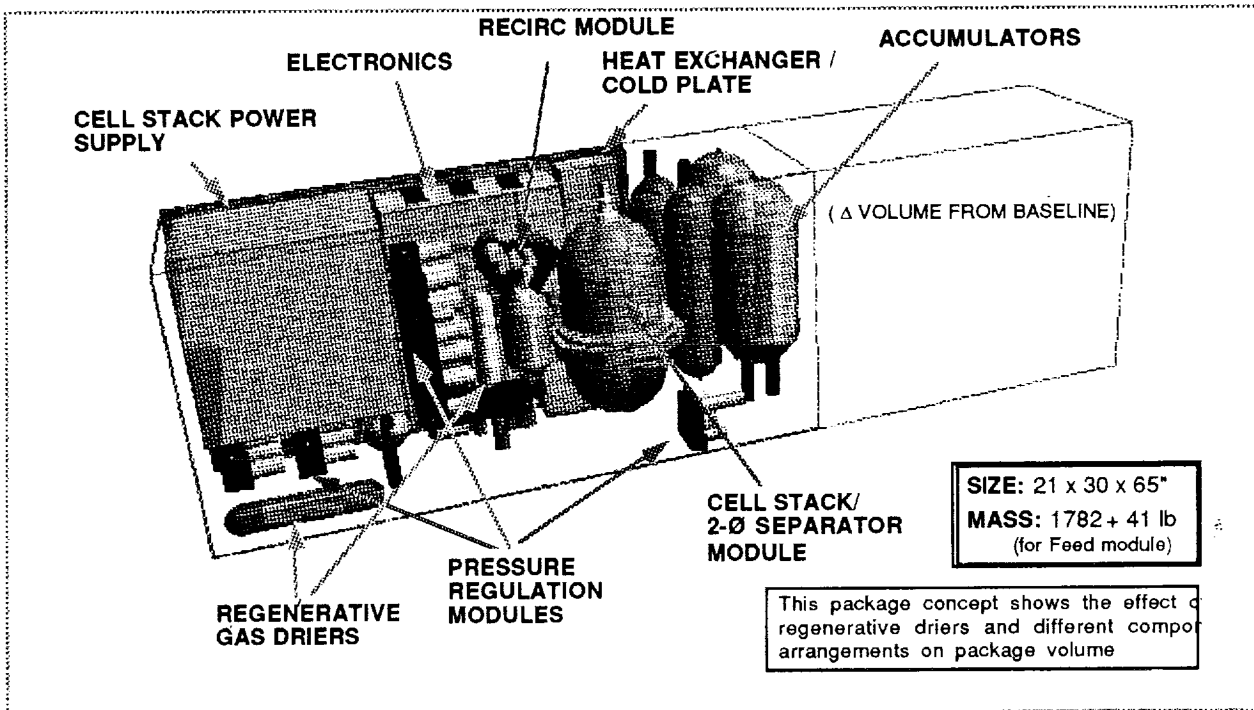


Figure 3.10 Regenerable Drier Generator ORU Concept

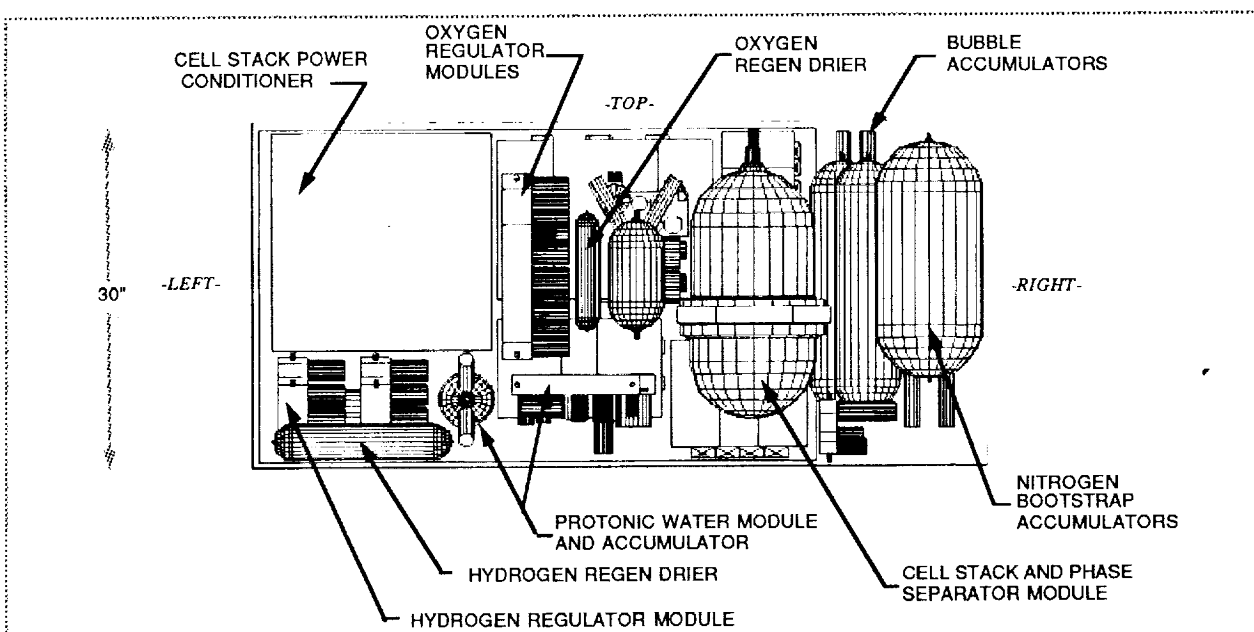


Figure 3.11a Regen. Drier Generator ORU, Front

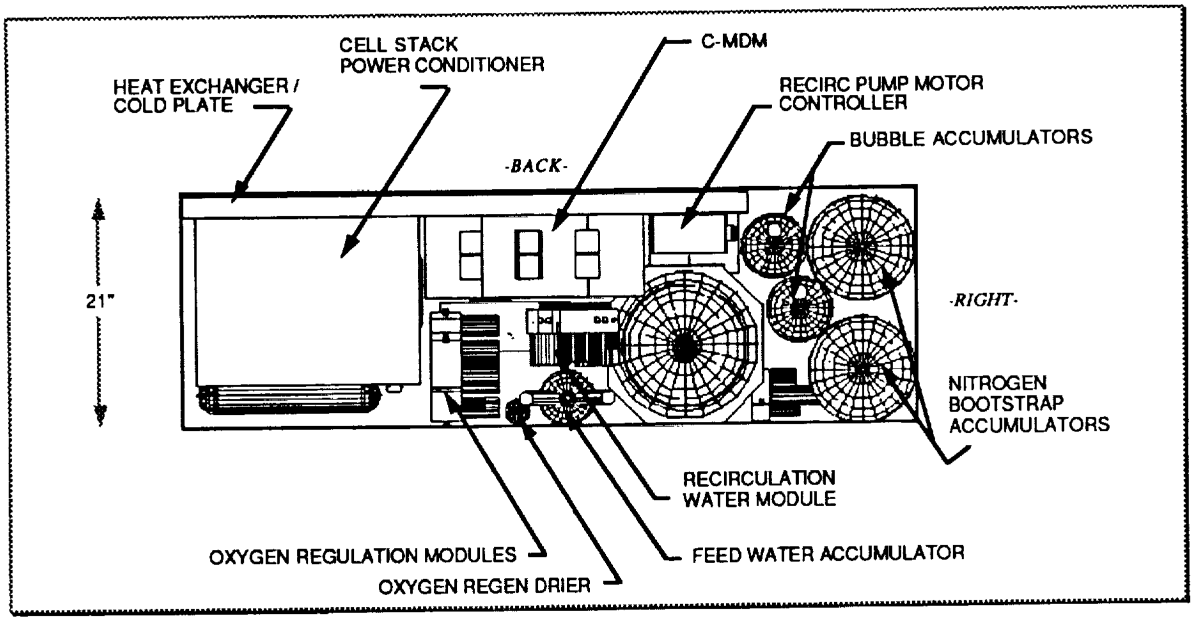


Figure 3.11b Regen. Drier Generator ORU, Top

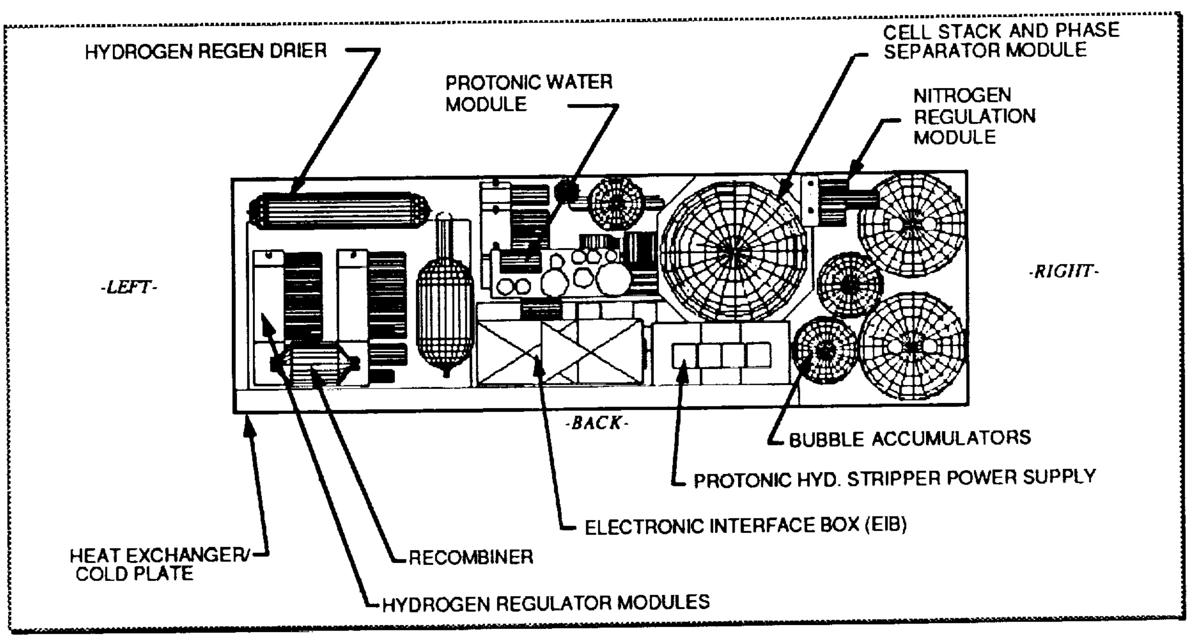


Figure 3.11c Regen. Drier Generator ORU, Bottom

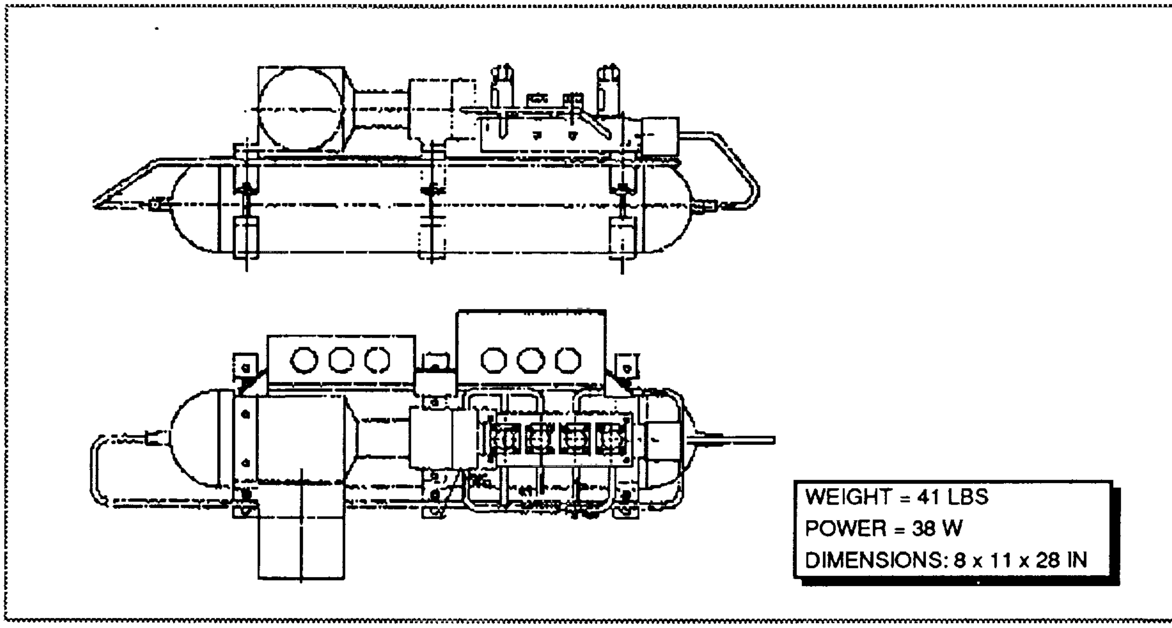


Figure 3.12 Feed Water ORU Concept

3.2.3.1 *Control and Signal Conditioning* The C-MDM provides standard signal conditioning for RTD temperature sensors, pressure transducers, solenoid/relay driver outputs, discrete input/output (I/O), high and low level analog interfaces, and serial data I/O. An Electrical Interface Box (EIB) is the Propellant Generator interface to the C-MDM. Custom sensor signal conditioning is provided in the EIB where C-MDM standard interfaces are not available. Feed Water ORU control is managed by a separate, local C-MDM.

Redundant controls are needed to achieve multi-year reliability. The second C-MDM has a full redundant set of instrumentation and effector drivers. The primary and secondary C-MDM's communicate sensor and status information via a serial data link. The primary C-MDM has access to equivalent secondary redundant sensor data in event of a failure in the primary instrumentation set.

3.2.3.2 *Electrical Power* Two power services are required to the Generator ORU. A dedicated 120VDC, 16.3 kW service is provided to the EPC. A second 120VDC, 360W service is provided to the EIB for an internal logic supply, pump motor controllers, solenoid drivers, and H_2 stripper power supply. The Feed Water ORU requires a 75W power service in the pressurized node.

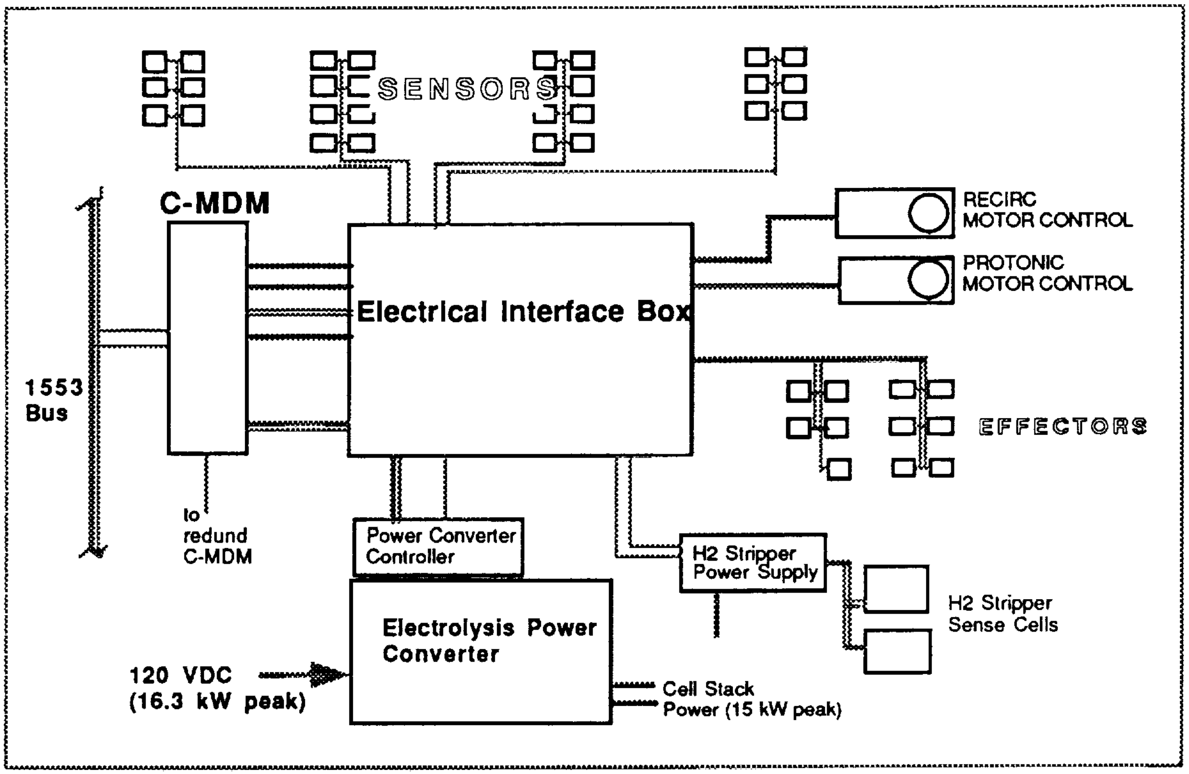


Figure 3.13 Generator ORU Electrical System Architecture

3.2.3.3 *Electrolysis Power Converter* A modular power stage architecture concept for the EPC was developed in response to unique requirements:

- RAPID RESPONSE TURN ON/OFF
- 2 to 15 kW OUTPUT RANGE (Basis: 5-year EOL)
- MAXIMUM RELIABILITY
- 200 W STANDBY POWER OUTPUT (STACK DIFFUSION)
- CONTROLLED OUTPUT POWER RAMPING RATE
- DROP POWER WITHOUT USE OF BREAKERS OR FUSES
- MINIMUM WEIGHT AND VOLUME
- 92% PEAK EFFICIENCY, GOOD LOW POWER EFFICIENCY
- EMI COMPLIANCE

The EPC concept shown in Figure 3.14 features six 3.0 kW power modules in parallel: five modules to meet the 15 kW output range requirement and one redundant module for reliability. Individual contactors and control lines are employed for flexible power module selection. A single module is used to support the 200 watt standby requirement; additional modules can be brought on-line to support up to the maximum 15 kW.

A resident EPC controller (EPCC) with built-in diagnostics and it's own resident programming allows the EPC to respond rapidly to commands from the C-MDM. An auto-protective "down-program" drops power output to the electrolysis stack without the use of breakers or fuses. Critical EPCC circuitry is redundant.

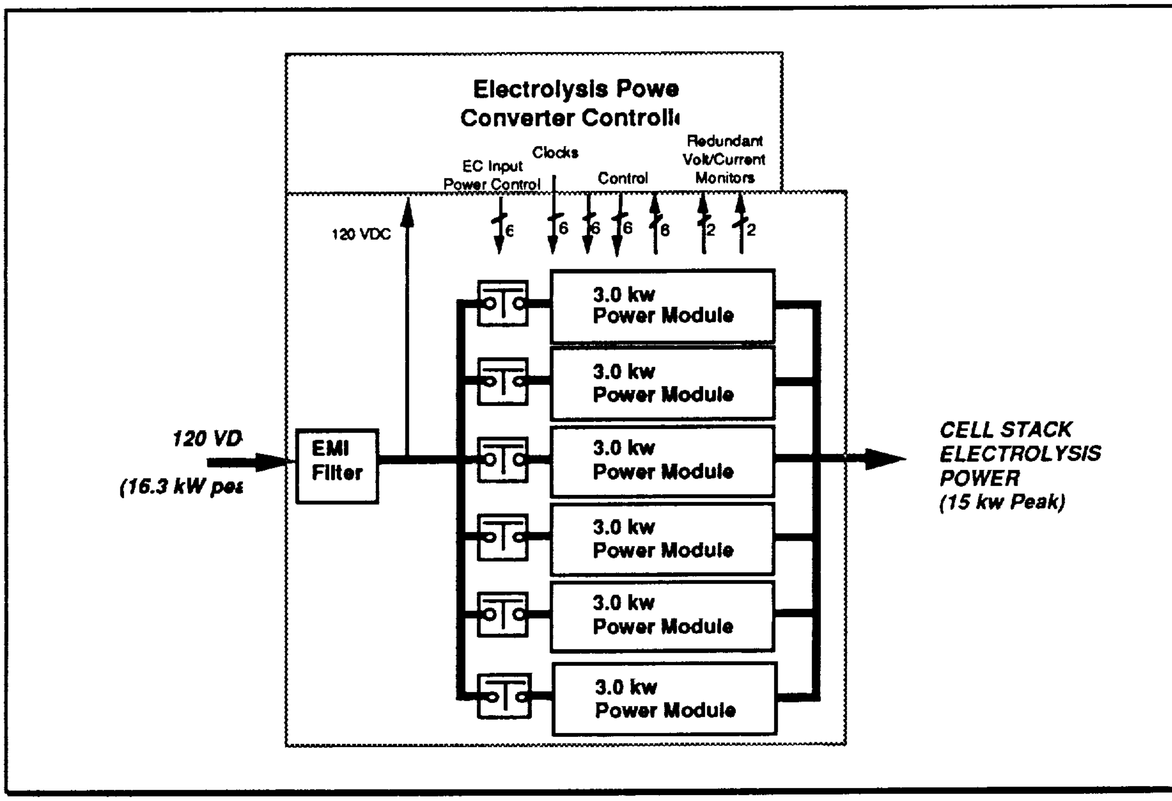


Figure 3.14 EPC Concept

The EPCC enables the power supply to respond to rapid changes in the Space Station power bus, so that the SPE-PG can function off of so-called "unscheduled" power that cannot be utilized to charge the Space Station energy storage batteries or operate other loads. SPE-Water Electrolyzer cell stacks has demonstrated the ability to accommodate power surges and transients within seconds.

3.2.3.4 *Software Items* There are two software configuration items: the UAS (User Application Software) for the C-MDM and control software for the EPCC. The redundant C-MDMs communicate via an RS-449 link. Each will have the capability to assume primary control. One will be commanded "ON" while the other will be on standby.

Prototype development programs will be written in "C". Commercial hardware would be used during development to emulate the MDM interface. Software specifications will have commonality with the flight design. Flight unit UAS will comply with the Data Management System (DMS) standards and defined support environments.

3.2.4 Cell Stack / Phase Separator Module

The key module in the SPE-PG is the cell stack and phase separator module. The cell stack and phase separators are co-located within the same pressure vessel to reduce size and weight and to take advantage of the cell-like static phase separator technology currently under development. A combined cell stack and phase separator module has been demonstrated at low pressure.

Figure 3.15 is a functional diagram of the cell stack/phase separator module. The oxygen phase separator removes O_2 gas from the water recirculation stream. The hydrogen phase separator separates gaseous H_2 from H_2O. The H_2 stripper electrochemically removes any dissolved H_2 remaining, and the hydrogen sensor detects any H_2 that was not stripped.

A conceptual cross-section of the module is given in Figure 3.16. Features determined in the cell stack trade study are seen.

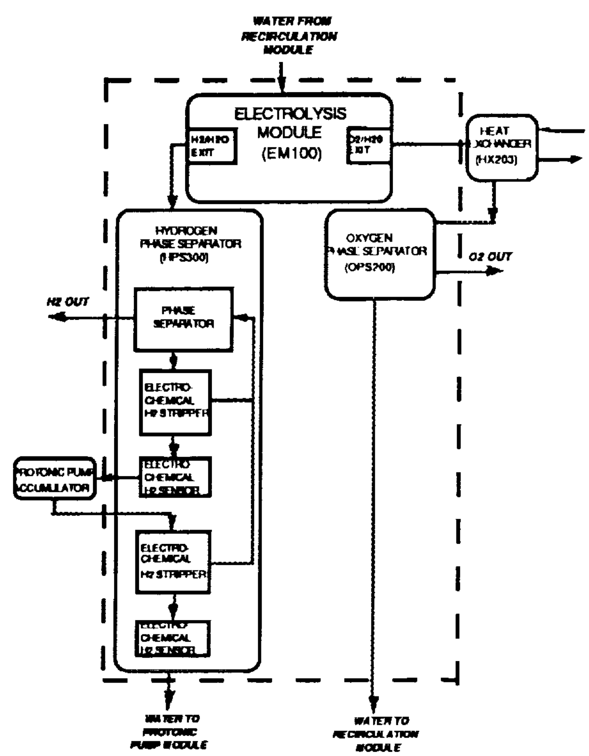
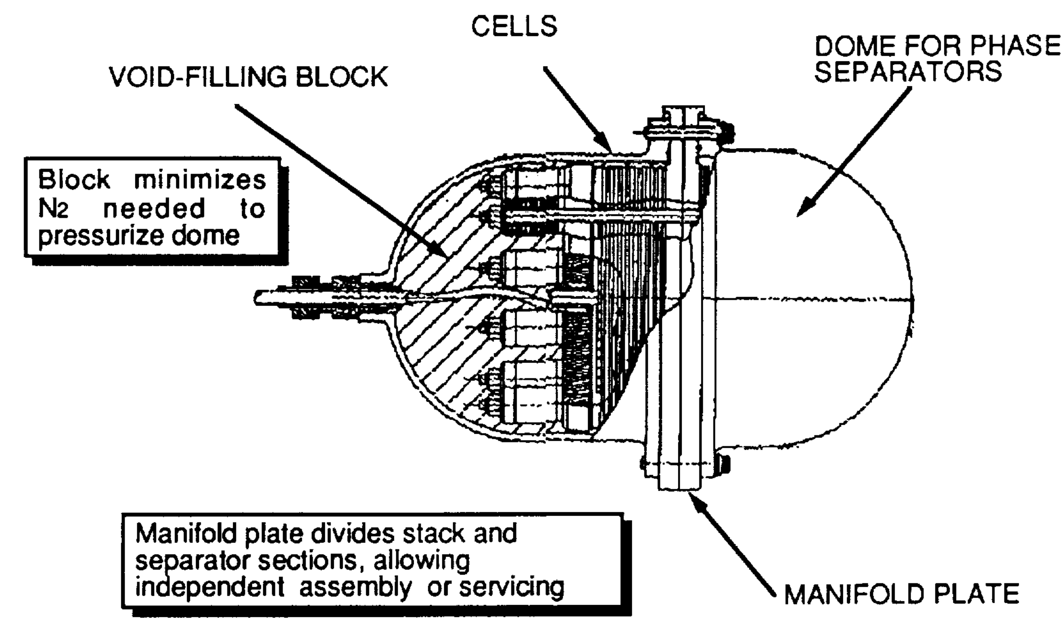


Figure 3.15
Cell Stack / Ø-Separator Diagram



SIZING CRITERIA - 16 CELLS AS IN IPTA PROTOTYPE CELL STACK

TECHNOLOGY - LIQUID ANODE FEED IN A NITROGEN DOME (SAME AS IPTA)
<u>SLIGHT MODIFICATIONS ASSUMED AS FOLLOWS</u>:

- UTILIZE MANIFOLDING AT FLUID PLATE TO COOL H_2/H_2O EXIT DOWN TO STACK INLET TEMP. (REDUCES LOAD ON DRYERS)
- INCREASE FRAME SIZE TO REDUCE FREE VOLUME IN THE STACK AND TO REDUCE GAS DIFFUSION THROUGH THE FRAME
- USE TEFLON AT THE EDGE OF THE MEMBRANE TO REDUCE H_2O, H_2 AND O_2 DIFFUSION
- DOME VOLUME IS MINIMIZED BY ADDITION OF POLYSULFONE PLUGS
- THERE IS A SMALL AMOUNT OF CATALYST IN THE DOME TO RECOMBINE DIFFUSED H_2 AND O_2
- WATER FORMED BY RECOMBINATION OF DIFFUSED H_2 AND O_2 IS ABSORBED BY A DESICCANT
- $O_2 > H_2$ CROSS-PRESSURE CAPABILITY INCREASED TO 3000 PSID

Figure 3.16 Cell Stack / Ø-Separator Module

Additional details of cell stack / phase separator functionality can be found in the CSDR documentation.

3.3 Operating Approach

The SPE-PG is required to operate in a prescribed manner to accomplish it's mission. Upon installation it may reside in a dormant state. When commanded to activate, the SPE-PG would proceed through various operations:

- ACTIVATE FROM A "DORMANT" STATE
- PREPARE FOR GAS GENERATION
- PRESSURIZE TO 3000 PSI OPERATING PRESSURE
- GENERATE 3000 PSI H2 AND O2 AT DEMANDED RATES
- ENTER INTO 36 MINUTE "HOLD" STATE DURING L.E.O. ECLIPSE
- PERFORM WATER, PRESSURE MANAGEMENT
- DEPRESSURIZE AND RETURN TO "DORMANT" STATE
- PERFORM FAULT DETECTION AND SYSTEM SAFING

System operations can be defined in terms of modes and states. The modes used for the SPE-Propellant Generator are MANUAL, OFF, ON, and STANDBY. System states of operation exist within each system mode. Transitions from state to state within each mode and between modes are predetermined by control code.

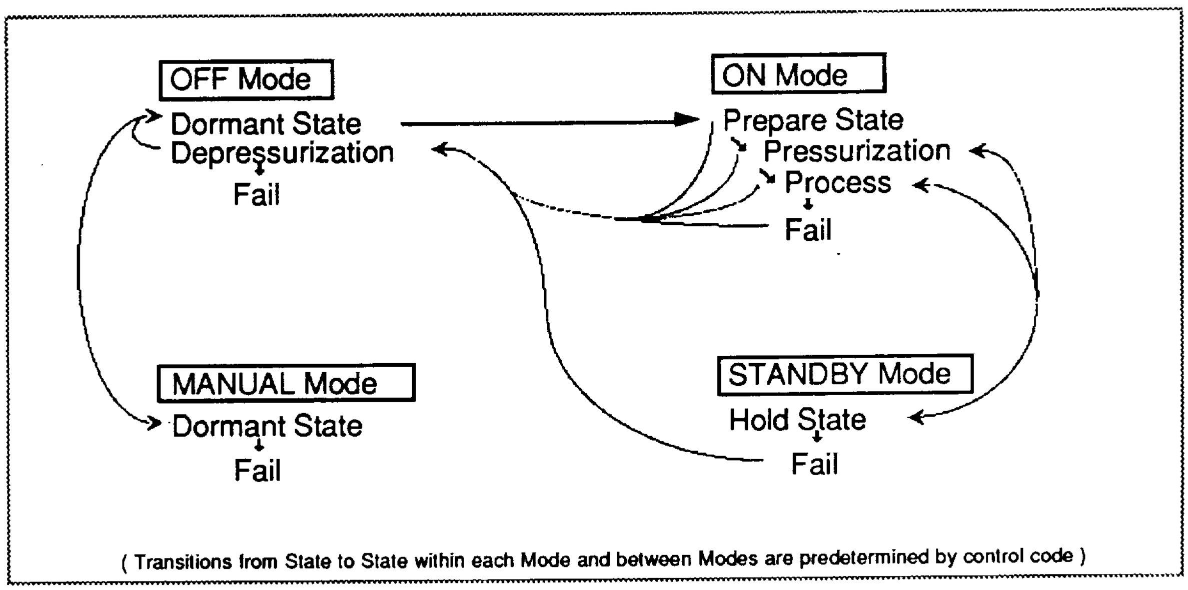


Figure 3.17 SPE-PG Control Mode and State Transitions

The mode and state control approach conceived for the SPE-PG is diagrammed in Figure 3.17. The initial state is the Dormant state in the OFF mode. It is an inactive state where the propellant generator components are unpowered and depressurized. The controller is active and the cell stack is in a benign "O_2 takeover" situation. System pressure is ~30 PSI, set by vent relief valves. Freeze protection is expected to be totally passive, requiring no power or control.

On activation, control transitions to the ON / Prepare mode/state. Here, devices are selectively activated to adjust accumulators, activate pumps, and check system readiness. The water feed control is activated, governed by water accumulator quantities. Cyclic operation logic is activated to initiate transfer between STANDBY and ON modes to accommodate to solar array power cycles as the Station orbits through light and dark. The nitrogen bootstrap accumulator is topped off at 600 PSI, if required. Recirculation of water on the O_2 side is started and tested. Some anomaly checking is initiated.

On completion of Prepare state, control transitions to the ON / Pressurization mode/state. The electrolysis system is activated to pressurize up to 3100 PSI delivery pressure. First, the O_2 stack takeover is reversed electro-chemically using low voltage and current. Then, gas evolution begins at 2 PPH rate (~180 amps). The protonic water management logic control activated to work with the water feed control. As product gas is generated, O_2 pressure will slowly rise to 3100 PSI. O_2 pressure bootstraps the N_2 in the bootstrap accumulator up to O_2 + 6 PSI (set by accumulator spring). Most of the fault conditions are being continually checked at this point. H_2 excess pressure may need to vent to maintain pressure control.

On completion of Pressurization state, control transitions to the ON / Process mode/state. This is the normal operating mode/state where the SPE-PG supplies dry 3000 PSI gases to storage. Generation rate will vary to follow power profile. The supply valves to tanks are open, process anomalies detection is fully enabled, and load control logic initiates transfer between STANDBY and ON and varies production rate according to available power.

STANDBY is a system ready mode, an energy conservation state used during dark side operation or on command. While in this mode, no net gas production occurs as cell stack current is controlled to offset and oppose the diffusion current (~8 amp). All other system logic controls are active. The expected time distribution in Low Earth Orbit (LEO) is 54 minutes ON, 36 minutes STANDBY, but other power profiles such as unscheduled power can be accommodated.

The OFF / Depressuration mode/state is a controlled depressurization of system in the event of full tanks or OFF mode selection. Electrolysis continues at the STANDBY rate. The propellant storage tanks are isolated. The O_2 vent valve is controlled to limit the depressurization rate. N_2 expands into the bootstrap accumulator as O_2 vents; H_2 vents to follow the N_2 reference gas depressurization. When O_2 pressure is less than 30 PSI, power is removed from the cell stack and pumps. Water management and cyclic logic control is discontinued. Anomaly detection is selectively disabled thoughout Depressuration. The system control reverts to Dormant state or Fail state at completion. Eventually, residual oxygen within the cell stack module will diffuse to both sides of the membranes, completing an oxygen takeover of the cell stack.

In the event a critical fault is detected, the OFF / Fail mode/state is entered. The SPE-PG control is configured such that upon loss of power or a failure, the oxygen outlet solenoid valve is unpowered open to allow system depressurization. The cell stack module and water pumps will be unpowered. The oxygen in the recirculation loop water will expand into a bubble accumulator designed for that purpose.

3.4 System Development

Certain enabling technologies require further study and earnest development to bring the SPE-Propellant Generator to the flight prototype stage. These enabling technologies are listed in order of importance in Table 3-3. A parallel development effort beginning in 1991 could produce a flight prototype by 1995 at an estimated cost of $25M (1990 dollars). Additional background information on the specific items can be found in the CSDR documentation.

TABLE 3-3

ENABLING TECHNOLOGY DEVELOPMENT ITEMS

ZERO-G GAS/WATER PHASE SEPARATORS
DEVELOP AND DEMONSTRATE ZERO-G, 3000 PSI OPERATING PHASE SEPARATORS FOR THE OXYGEN AND HYDROGEN SUBSYSTEMS. USE EXISTING 200 PSI ZERO-G SEPARATORS AND TRADE STUDIES AS POINT OF DEPARTURE.

HIGH " ONE -WAY" ΔP CELL STACK MODIFICATION
DEMONSTRATE 3000 PSID OXYGEN > HYDROGEN CELL STACK. POINT OF DEPARTURE IS EXISTING 700 TO 1000 PSID STACK. ELIMINATES NEED FOR GN2 PURGE, SIMPLIFYING SYSTEM. (HAVE DEMONSTRATED UP TO 5000 PSID IN GAS CONCENTRATOR CELLS)
CONFIRM BEST CELL STACK SIZE IN STUDY OF SSF POWER PROFILE
(FUTURE DEVELOPMENT WILL RESULT IN DOMELESS STACK)

POWER SUPPLIES
DEMONSTRATE MULTI-STAGE DESIGN. DEMONSTRATE CELL STACK POWER SUPPLY CAPABLE OF FOLLOWING RAPID CHANGES IN AVAILABLE POWER. ASSESS H2 STRIPPER POWER SUPPLY REQUIREMENT AND DESIGN. ESTABLISH SSF POWER PROFILE FOR DESIGN

GAS DRIERS
TRADE OFF HIGHER MTBF, NON-REGEN DESIGN AGAINST LOW WEIGHT VACUUM+HEAT DESORBED REGEN DESIGN. ESTABLISH VENTING SCENARIO FOR REGEN DRIERS. DEMONSTRATE RELIABLE HUMIDITY SENSORS.

LONG LIFE PUMPS
DEVELOP CIRC WATER PUMP BASED ON UP(GRADE OF EXISTING SHUTTLE PUMP. DEVELOP 100 PSID PROTONIC WATER PUMP, NON-LEAK 3100 PSI FEED PUMP

ACCUMULATORS
DEMONSTRATE RELIABILITY AND LIFE FOR BELLOWS AND POSITION SENSORS. REVIEW TECHNOLOGIES FOR REDUCED SIZE AND WEIGHT.

HEAT EXCHANGER/COLD PLATE
PROVE MANUFACTURING TECHNIQUES FOR LARGE PLATES. REVIEW TECHNOLOGY FOR GREATER COMPACTNESS, LOWER WEIGHT. ADAPT TO FINAL SSF COOLANT SYSTEM.

4.0 Conclusions and Recommendations

Recognized potential benefits of an SPE-Water Electrolysis based hydrogen-oxygen propulsion system include a high thruster specific impulse (I_{sp} >400 SEC), high propellant mass fraction to orbit (>0.8), a safe-to-handle fluid (H_2O), and the ability to utilize waste water to produce high performance propellant. The combined effect of these benefits could produce a significant reduction in the life cycle cost of large space platforms such as the NASA Space Station Freedom. While offering these benefits, only limited testing of an integrated electrolysis based H-O propulsion system had been conducted prior to the initiation of the NASA/JSC IPTA program. The ongoing IPTA testing is enhancing the SPE-Water Electrolysis knowledge and experience base for future high pressure H-O propulsion and energy storage applications.

SPE-Water Electrolysis for the production of hydrogen and oxygen propellants is a developing technology. The heart of the process, the high pressure SPE-cell stack, is highly developed. The IPTA Phase 1 test program has demonstrated the robustness of the SPE-Propulsion Electrolyzer through nearly 900 hours of accumulated test time, including test system problems and several environmental "act of God" events. The basic cell stack design was and can again be readily adapted to meet the Space Station or other mission goals.

The SPE-Propellant Generator system concepts show promise. Several key technologies, most notably zero-G gas and water phase separation, require development from low pressure or experimental prototypes to fully reliable 3100 PSIA components. As future mission goals are clearly identified, the development path for the accessory package can be directed to meet those goals.

A development program to pursue the enabling technologies is highly recommended. A development plan that identifies all applicable missions, their goals and probability, and establishes a logical, evolutionary development path for the SPE-Propellant Generator technology is needed.

SOURCE DOCUMENTS

SPE-Propulsion Electrolyzer for NASA's Integrated Propulsion Test Article, Volume 1, (contract proposal)
HSPC88T14

Statement of Work, Contract **NAS 9-18030** (through Mod. 19)

SPE-Propulsion Electrolyzer Critical Design Review package,
IPTA-036-89

100 Hour Test Completion Summary Report,
IPTA-018-90

Operations and Maintenance Manual,
IPTA-033-90

SPE-Propellant Generator Conceptual System Design Review package,
IPTA 055-90

SOURCE DOCUMENT APPENDIX

PARTS LISTS AND DRAWINGS
COMPONENT DESCRIPTIONS
TEST DATA
COMPONENT CONCEPT DESCRIPTIONS

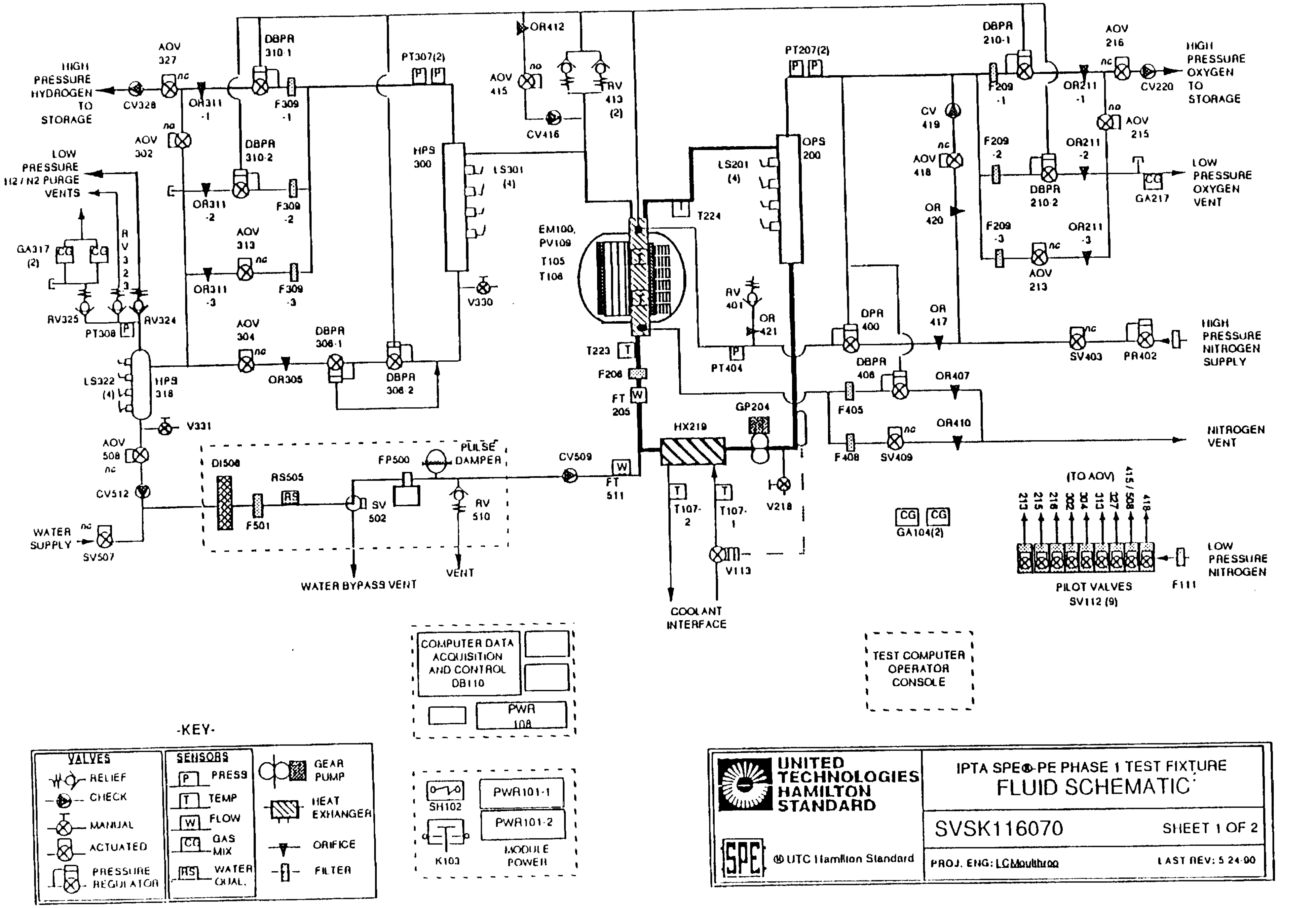
SOURCE DOCUMENT APPENDIX

CELL STACK DRAWINGS LIST

TEST FIXTURE PARTS LISTS AND DRAWINGS

IPTA CELL STACK DRAWINGS — CONTRACT NAS 9-18030

CELL SUBASSEMBLIES & PARTS	*IPTA SVSK#*
Divider, Oxygen Assembly	**SVSK117701-1**
VOLTAGE TAB	*SVSK117703-1*
OXYGEN DIVIDER	*SVSK117702-1*
GASKET, O2	**SVSK117704-1**
DIVIDER, OXYGEN	**SVSK117702-1**
O2 Frame and Screen Assembly	**SVSK117705-1**
OXYGEN FRAME	*SVSK117706-1*
PROTECTOR RING (Niobium)	*SVSK117707-1*
OXYGEN SCREEN	*SVSK117708-1*
H2 Frame and Screen Assembly	**SVSK117711-1**
HYDROGEN FRAME	*SVSK117713-2*
PROTECTOR RING (Polysulfone)	*SVSK117707-2*
Screen and Fret Sheet Assembly	*SVSK117712-1*
FRET SHEET	*SVSK117714-1*
H2 SCREEN	*SVSK117715-1*
GASKET, H2	**SVSK117716-1**
Hydrogen Divider and Rings	**SVSK117717-1**
HYDROGEN DIVIDER	*SVSK117718-1*
Fret Sheet and Ring Assembly	*SVSK117719-1*
FRET SHEET	*SVSK117722-1*
PROTECTOR RING (Mylar)	*SVSK117707-3*
Pressure Pad Assembly	*SVSK117720-1*
PRESSURE PAD	*SVSK117724-1*
PRESSURE PAD STRIP	*SVSK117725-1*
PRESSURE PAD STRIP	*SVSK117725-2*
Screen and Ring Pad	*SVSK117721-1*
PROTECTOR RING (Mylar)	*SVSK117707-3*
PAD SCREEN	*SVSK117726-1*
M & E ASSEMBLY	**SVSK117709-1**
GASKET, MANIFOLD	SVSK115596-1
GASKET, MANIFOLD	SVSK115596-2


HIGH PRESSURE HYDROGEN TO STORAGE
LOW PRESSURE H2 / N2 PURGE VENTS
GA317 (2)
RV 3 2 3
RV325
PT308
RV324
LS322 (4)
HPS 318
V331
AOV 508 nc
CV512
WATER SUPPLY
SV507
AOV 327
CV328
AOV 302
OR311 -1
OR311 -2
OR311 -3
DBPR 310-1
DBPR 310-2
AOV 313
AOV 304
OR305
F309 -1
F309 -2
F309 -3
DBPR 308-1
DBPR 308-2
PT307(2)
HPS 300
LS301 (4)
V330
OR412
AOV 415
CV416
RV 413 (2)
EM100, PV109
T105
T108
T223
F206
FT 205
DI506
RS505
F501
FP500
PULSE DAMPER
SV 502
RV 510
VENT
WATER BYPASS VENT
CV509
FT 511
HX219
T107-2
T107-1
V113
COOLANT INTERFACE
GP204
V218
T224
LS201 (4)
RV 401
OR 421
PT404
OPS 200
PT207(2)
DPR 400
DBPR 406
F405
F408
SV409
OR407
OR410
NITROGEN VENT
OR 417
OR 420
CV 419
AOV 418
SV403
PR402
HIGH PRESSURE NITROGEN SUPPLY
DBPR 210-1
F209 -1
F209 -2
F209 -3
DBPR 210-2
AOV 213
OR211 -1
OR211 -2
OR211 -3
AOV 216
CV220
HIGH PRESSURE OXYGEN TO STORAGE
AOV 215
GA217
LOW PRESSURE OXYGEN VENT
(TO AOV)
213 215 216 302 304 313 327 415 / 508 418
PILOT VALVES SV112 (9)
F111
LOW PRESSURE NITROGEN
GA104(2)
COMPUTER DATA ACQUISITION AND CONTROL DB110
PWR 108
TEST COMPUTER OPERATOR CONSOLE
SH102
K103
PWR101-1
PWR101-2
MODULE POWER
-KEY-
VALVES
RELIEF
CHECK
MANUAL
ACTUATED
PRESSURE REGULATOR
SENSORS
PRESS
TEMP
FLOW
GAS MIX
WATER QUAL.
GEAR PUMP
HEAT EXHANGER
ORIFICE
FILTER
UNITED TECHNOLOGIES HAMILTON STANDARD
UTC Hamilton Standard
IPTA SPE-PE PHASE 1 TEST FIXTURE
FLUID SCHEMATIC
SVSK116070
SHEET 1 OF 2
PROJ. ENG: LCMoulthrop
LAST REV: 5 24 00

ITEM	NUM.	QN.	ITEM NAME
EM	100	1	ELECTROLYSIS CELL STACK
PWR	101	2	POWER SUPPLY
SH	102	1	CURRENT SENSOR
K	103	1	CONTACTOR
GA	104	2	COMB. GAS SENSOR
T	105	1	TEMPERATURE SENSOR
T	106	1	TEMPERATURE SENSOR
T	107	2	TEMPERATURE SENSOR
PWR	108	1	POWER SUPPLY, GP204
PV	109	1	CELL STACK PRESSURE VESSEL
DB	110	1	DATA AQ. AND CONTROL
F	111	1	FILTER
SV	112	9	3-WAY SOL. FOR AOV VALVES
V	113	1	THERMAL CONTROL VALVE
OPS	200	1	OXY. PHASE SEPARATOR
LS	201	4	LEVEL SENSOR
GP	204	1	CIRC PUMP
FT	205	1	FLOW TRANSDUCER
F	206	1	FILTER
PT	207	2	PRESSURE TRANSMITTER
F	209	3	FILTER
DBPR	210	2	DIFF. BACK PRESS. REG.
OR	211	3	ORIFICE
AOV	213	1	PNEU. VALVE, N.C.
AOV	215	1	PNEU. VALVE, N.O.
AOV	216	1	PNEU. VALVE, N.C.
GA	217	1	COMB. GAS SENSOR
V	218	1	MANUAL VALVE
HX	219	1	HEAT EXCHANGER
CV	220	1	CHECK VALVE
T	223	1	TEMPERATURE SENSOR
T	224	1	TEMPERATURE SENSOR
HPS	300	1	HYD. PHASE SEP., HI. PRESS.
LS	301	4	LEVEL SENSOR
AOV	302	1	PNEU. VALVE, N.O.
AOV	304	1	PNEU. VALVE, N.C.
OR	305	1	ORIFICE
DBPR	306	2	DIFF. BACK PRESS. REG.
PT	307	2	PRESSURE TRANSMITTER
PT	308	1	PRESSURE TRANSDUCER
F	309	3	FILTER
DBPR	310	2	DIFF. BACK PRESS. REG.
OR	311	3	ORIFICE
AOV	313	1	PNEU. VALVE, N.C.
GA	317	2	COMB. GAS SENSOR
HPS	318	1	HYD. PHASE SEP., LOW PRESS.
LS	322	4	LEVEL SWITCH
RV	323	2	RELIEF VALVE
RV	324	1	RELIEF VALVE
RV	325	1	RELIEF VALVE
AOV	327	1	PNEU. VALVE, N.C.
CV	328	1	CHECK VALVE
V	330	1	MANUAL VALVE
V	331	1	MANUAL VALVE

ITEM. NUM.	QN	ITEM NAME
DPR 400	1	DIFF. PRESS. REDUCER
RV 401	1	RELIEF VALVE
PR 402	1	PRESSURE REDUCER
SV 403	1	SOL. VALVE, N.C.
PT 404	1	PRESS. TRANSMITTER
F 405	1	FILTER
DBP 406	1	DIFF. BACK. PRESS.
R 407	1	REGULATOR
OR 408	1	ORIFICE
F 409	1	FILTER
SV 410	1	SOL. VALVE, N.C.
OR 412	1	ORIFICE
RV 413	1	RELIEF VALVE
AOV 415	1	PNEU. VALVE, N.O.
CV 416	1	CHECK VALVE
OR 417	1	ORIFICE
AOV 418	1	PNEU. VALVE, N.C.
CV 420	1	CHECK VALVE
OR 421	1	ORIFICE
FP 500	1	WATER FEED PUMP
F 501	1	CARTRIDGE FILTER
SV 502	1	THREE-WAY SOL. VALVE
RS 505	1	WATER RESISTIVITY SENSOR
DI 506	1	DEIONIZER COLUMN
SV 507	1	SOL. VALVE, N.C.
AOV 508	1	PNEU. VALVE, N.C.
CV 509	1	CHECK VALVE
RV 510	1	RELIEF VALVE
FT 511	1	FLOW TRANSDUCER
CV 512	1	CHECK VALVE

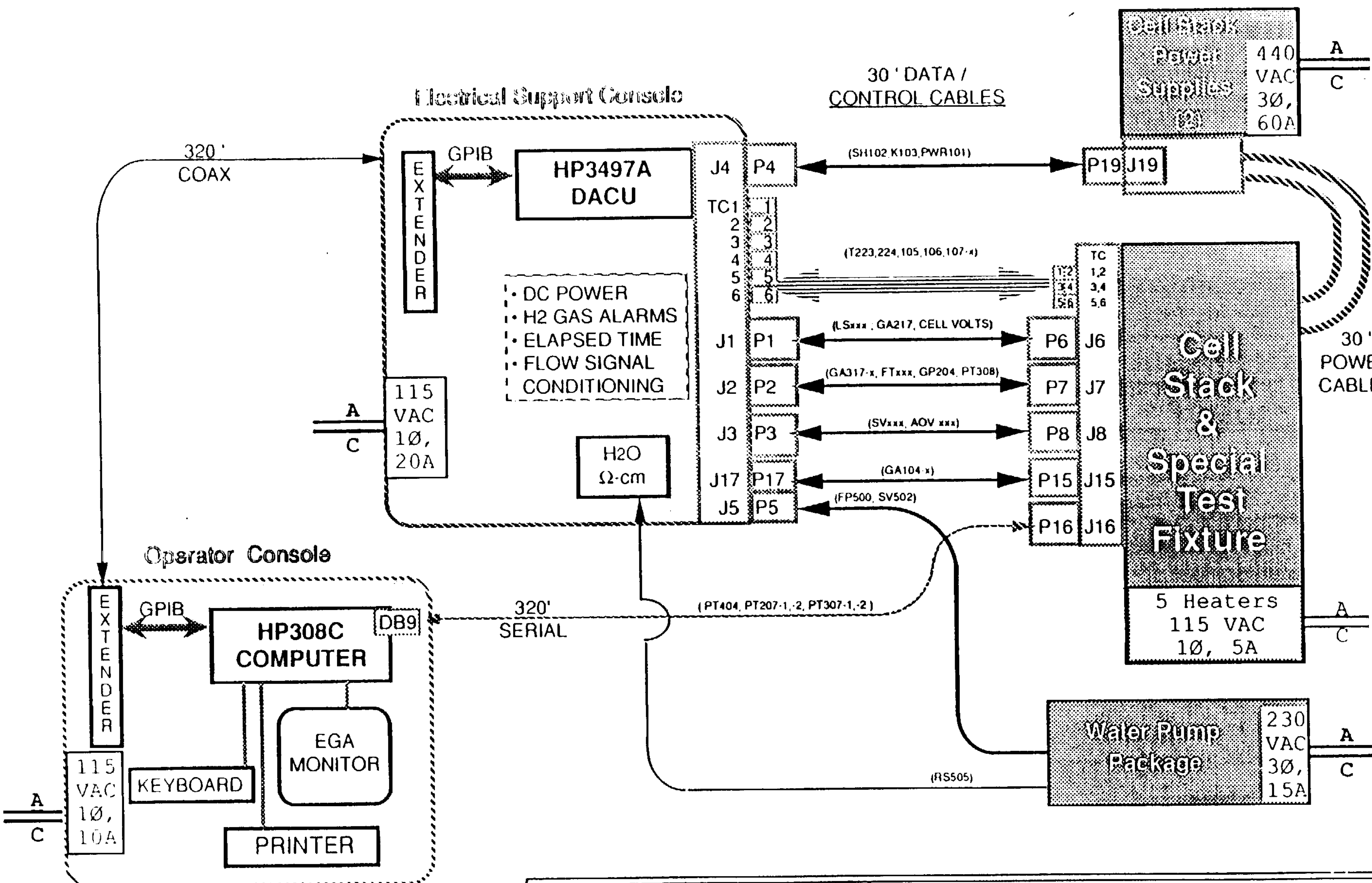
PARTS LIST	IPTA SPE®-PE PHASE 1 TEST FIXTURE FLUID SCHEMATIC	
	SVSK116070	SHEET 2 OF 2
	PROJ. ENG: LCMoulthrop	LAST REV: 5-24-90

MAJOR PARTS LIST — TEST FIXTURE SCHEMATIC SVSK 116070

MAJOR PARTS LIST — TEST FIXTURE SCHEMATIC SVSK 116070

ITEM	NO.	QN.	ITEM NAME	P/N	SUPPLIER	WETTED MATERIAL	PRESSURE
EM	100	1	ELECTROLYSIS MODULE	SVSK117505	HAMILTON STANDARD	REF DWG	3100 O2
PWR	101	2	POWER SUPPLY	DCA250-40A	SORENSEN	-	-
SH	102	1	CURRENT SENSOR	HA-400-40	EMPRO	-	-
K	103	1	CONTACTOR	6041H217	CUTLER-HAMMER	-	-
GA	104	2	COMB. GAS SENSOR	MODEL 580	MSA	-	-
T	105	1	TEMPERATURE SENSOR	C01-T	OMEGA	-	-
T	106	1	TEMPERATURE SENSOR	1/8" TYPE T	OMEGA	-	-
T	107	2	TEMPERATURE SENSOR	C01-T	OMEGA	-	-
PWR	108	1	POWER SUPPLY, GP204	DCR 40-25B	SORENSEN	-	-
PV	109	1	CELL STACK PRESSURE VESSEL	SVSK117505	HAMILTON STANDARD	INCONEL 718	3150 N2
DB	110	1	DATA AQ. AND CONTROL	82319D	HEWLETT PACKARD	-	-
SV	111	10	PNEU. ACTUATOR VALVE	8380A2	ASCO	ALUMINUM, VITON	80 N2
TV	113	1	COOLANT CONTROL VALVE	V47-AB-2	PENN	BRASS	20 COOLANT
OPS	200	1	OXY. PHASE SEPARATOR	SVSK117764	HAMILTON STANDARD	INC 718, VITON A	3100
LS	201	4	LEVEL SENSOR	4G2536	TEDECO	INC 718, VITON A, GLASS	3100
GP	204	1	CIRC PUMP	MODEL 220	MICROPUMP	INC 718, VITON A, RYTON	3100
FT	205	1	FLOW TRANSDUCER	SP711-110-L(1)	SPONSLER	INC718, TFE	3100
F	206	1	FILTER	29058	MECTRON	INC718, HAST B, VITON A	3100
PT	207	2	PRESSURE TRANSDUCER	1006-K-INC	PAROSCIENTIFIC	INCONEL 718	3100
F	209	3	FILTER	SK-1277	NEWARK WIRE	INC 718, HASTELLOY	3100
DBPR	210	2	DIFF. BACK PRESS. REG.	269-476G	TESCOM	INC 718, VESPEL SP21	3100
OR	211	3	ORIFICE	JETX0524050B, RevA	LEE	316SS IN MONEL HOUSING	3100
AOV	213	1	PNEU. VALVE, N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	3100
AOV	215	1	PNEU. VALVE, N.O.	SS-HBVS4-O	WHITEY	316SS, VESPEL	3100
AOV	216	1	PNEU. VALVE, N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	3100
GA	217	1	COMB. GAS SENSOR	MODEL 480	MSA	316SS, VITON	5
V	218	1	MANUAL VALVE	INC-4P-4T	NUPRO	INC, VITON A	3100
HX	219	1	HEAT EXCHANGER	DHTC-IN-6	PARKER	INCONEL 600	3100
CV	220	1	CHECK VALVE	M-4C-1/3	NUPRO	MONEL, VITON A	3100
T	223	1	TEMPERATURE SENSOR	CO1-T	OMEGA	-	-
T	224	1	TEMPERATURE SENSOR	CO1-T	OMEGA	-	-
HPS	300	1	HYD. PHASE SEP., HI. PRESS.	SVSK117750	HAMILTON STANDARD	316L, 316, VITON A	3000
LS	301	4	LEVEL SENSOR	4G2535	TEDECO	316SS, VITON A, GLASS	3000
AOV	302	1	PNEU. VALVE, N.O.	SS-HBVS4-O	WHITEY	316SS, VESPEL	3000
AOV	304	1	PNEU. VALVE, N.C.	SS-HBS4-C	WHITEY	316SS, KEL-F	3000
OR	305	1	ORIFICE	JETX0524100B, RevA	LEE CO	316SS	3000
DBPR	306	2	DIFF. BACK PRESS. REG.	269-474G	TESCOM	316SS, KEL-F	3000
PT	307	2	PRESSURE TRANSDUCER	1006-K-A286	PAROSCIENTIFIC	A-286	3000
PT	308	1	PRESSURE TRANSDUCER	IPT	AMETEK	316SS	15
F	309	3	FILTER	SS-4FW-15	NUPRO	316SS	3000
DBPR	310	2	DIFF. BACK PRESS. REG.	269-475G	TESCOM	316SS, KEL-F	3000
OR	311	3	ORIFICE	JETX0524000B, RevA	LEE CO	316SS	3000
AOV	313	1	PNEU. VALVE,N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	3000
GA	317	2	COMB. GAS SENSOR	474106 (Modified)	MSA	POLYCARBONATE, TFE	10
HPS	318	1	HYD. PHASE SEP., LOW PRESS.	SVSK117736	HAMILTON STANDARD	316L, 316, VITON A	3000
LS	322	4	LEVEL SWITCH	4G2535	TEDECO	316SS, VITON A, GLASS	3000
RV	323	1	RELIEF VALVE	SS-4CA-50	NUPRO	316SS, VITON A	10
RV	324	1	RELIEF VALVE	SS-6C-3	NUPRO	316SS, VITON A	3
RV	325	1	RELIEF VALVE	SS-4C-1	NUPRO	316SS, VITON A	1
AOV	327	1	PNEU. VALVE, N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	10
CV	328	1	CHECK VALVE	SS-4C-1/3	NUPRO	316SS, VITON A	10
V	330	1	MANUAL VALVE	SS-4P4T	NUPRO	316SS, VITON A	3000
V	331	1	MANUAL VALVE	SS-4P4T	NUPRO	316SS, VITON A	10

MAJOR PARTS LIST				TEST FIXTURE SCHEMATIC SVSK 116070			
						WETTED	
ITEM	NO.	QN.	ITEM NAME	P/N	SUPPLIER	MATERIAL	PRESSURE
DPR	400	1	DIFF. PRESS. REDUCER	269-477G	TESCOM	316SS, KEL-F	3250
RV	401	1	RELIEF VALVE	SS-4RCA-350	NUPRO	316SS, VITON A	3250
PR	402	1	PRESSURE REDUCER	44-1125-24	TESCOM	316SS, KEL-F	5000
SV	403	1	SOL. VALVE, N.C.	MV100	MAROTTA	CRES300, VESPEL, VITON A	3200
PT	404	1	PRESS. TRANSDUCER	1006-K-INC	PAROSCIENTIFIC	INCONEL 718	3150
F	405	1	FILTER	SS-4FW-15	NUPRO	316SS	3150
DBPR	406	1	DIFF. BACK. PRESS. REGULATOR	269-478G	TESCOM	316SS, KEL-F	3150
OR	407	1	ORIFICE	JEHA1875350L	LEE CO	304L SS	3150
F	408	1	FILTER	SS-4FW-15	NUPRO	316SS	3150
SV	409	1	SOL. VALVE, N.C.	MV100	MAROTTA	CRES300, VESPEL, VITON A	3150
OR	410	1	ORIFICE	JEHA1875350L	LEE CO	304L SS	3150
OR	412	1	ORIFICE	JEHA1875350L	LEE CO	304L SS	3150
RV	413	1	RELIEF VALVE	SS-4CA-350	NUPRO	316SS, VITON A	3150
AOV	415	1	PNEU. VALVE, N.O.	SS-HBVS4-O	WHITEY	316SS, VESPEL	3150
CV	416	1	CHECK VALVE	SS-4C-1/3	NUPRO	316SS, VITON A	3150
OR	417	1	ORIFICE	JETA1875170D	LEE CO	304L SS	3150
AOV	418	1	PNEU. VALVE, N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	3150
CV	419	1	CHECK VALVE	SS-4C-1/3	NUPRO	316SS, VITON A	3150
OR	420	1	ORIFICE	VDCX0513600B, RevA	LEE CO	304L SS	3150
OR	421	1	ORIFICE	JEHA1875350L	LEE CO	316SS	3150
FP	500	1	WATER FEED PUMP	MB1-A13-PO71	MILTON ROY	316SS, TFE, CERAMIC	3100
F	501	1	FILTER	MCY4463H025	PALL	POLYPROPYLENE	10
SV	502	1	THREE-WAY SOL. VALVE	203-3414-21-5	GALTEK	PFA (TFE)	10
RS	505	1	WATER RESISTIVITY SENSOR	874RS-AT	FOXBORO	TITANIUM, 316SS	10
DI	506	1	DEIONIZER COLUMN		HAMILTON STANDARD	RESIN, POLYCARBONATE	10
SV	507	1	SOL. VALVE, N.C.	203-1414-21-5	GALTEK	PFA (TFE)	10
SV	508	1	PNEU. VALVE, N.C.	SS-HBVS4-C	WHITEY	316SS, VESPEL	10
CV	509	1	CHECK VALVE	H-4C-1/3	NUPRO	HASTELLOY C	3100
RV	510	1	RELIEF VALVE	SS-4RCA-350	NUPRO	316SS, VITON A	3200
FT	511	1	FLOW TRANSDUCER	MF-30	SPONSLER	INC718, TFE	3100



UNITED TECHNOLOGIES HAMILTON STANDARD

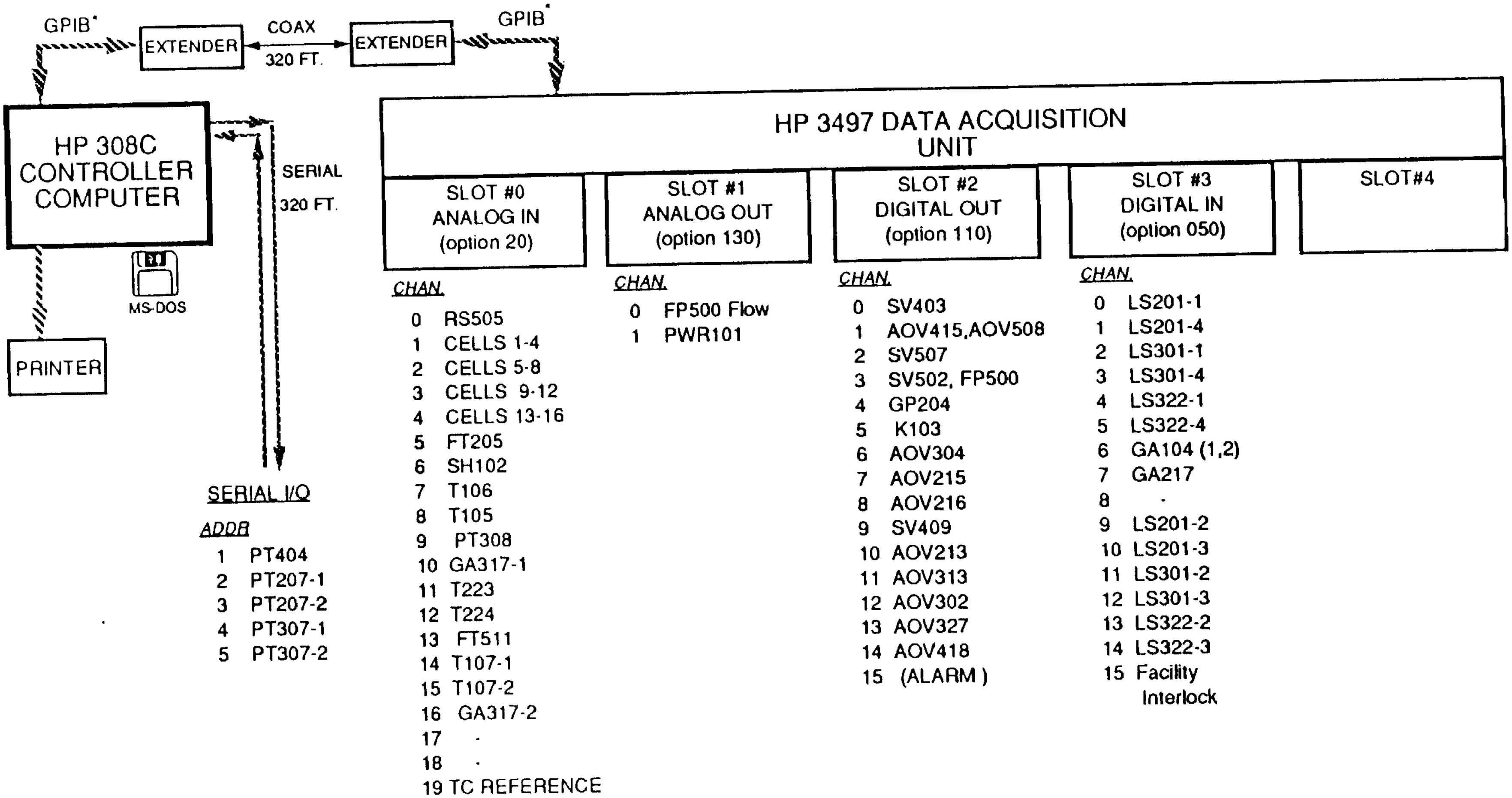
SPE ® UTC Hamilton Standard

IPTA SPE®-PE SPECIAL TEST FIXTURE
ELECTRICAL BLOCK DIAGRAM

SVSK119332

PROJ. ENG: LCMoulthrop

LAST REV: 3-6-1990



* GENERAL PURPOSE INTERFACE BUS

UNITED TECHNOLOGIES HAMILTON STANDARD

SPE ® UTC Hamilton Standard

IPTA SPE®-PE SPECIAL TEST FIXTURE
CONTROL BLOCK DIAGRAM

SVSK116069

PROJ. ENG: LCMoulthrop   LAST REV: 3-6-1990

SOURCE DOCUMENT APPENDIX

COMPONENT DESCRIPTIONS

Major Components Descriptions, Special Test Fixture

Major fluid components in the system are described by class in the following sections.

Pressure Transducers/ Transmitters

Pressures of the oxygen and hydrogen produced, the nitrogen reference gas and the differential pressure between nitrogen and each product gas are needed for process control and fault detection. For 3000+ PSI measurements, a high accuracy absolute pressure transmitter with a range capability of 0 to 6000 PSIA, an accuracy of ±0.01% and a 5×10^{-8} resolution was selected (Paroscientific model 1006-K). These devices are temperature compensated and communicate with the process controller via a RS-232 bi-directional "daisy-chain" two-wire loop. The test fixture pressure transmitters are designated PT207-x (two required) for oxygen; PT307-x (two required) for hydrogen; and PT404 for nitrogen. The process controller computes differential pressures using the respective absolute pressure transmitter readings. Material wetted by the gases are Inconel for oxygen and A286 and 316 stainless steel for hydrogen. The standard Inconel material is used on nitrogen service. Excitation voltage to the transmitters is 15 VDC.

A 60 PSIG strain gauge type pressure transducer is used to measure hydrogen pressure in the low pressure hydrogen water recovery circuit. Protonic water is reduced in pressure in a phase separator to release dissolved hydrogen. This sensor, designated PT308, is located on the vent output of the low pressure phase separator HPS318. Wetted materials are 316SS. (Ametek p/n IPT)

Pressure Regulators

The role of back pressure regulators DBPR 210, 310 and 406 is to maintain a pressure differential between the gases at any operating pressure within minimum hardware.

Safe operation requires that nitrogen pressure dominates that of oxygen, which in turn exceeds that of hydrogen. This scheme will always allow for a total system nitrogen flush-down.

To keep a balance between inside and outside cell stack pressure, a dome sensed reducing regulator, DPR 400, will control the nitrogen pressure to the cell stack dome as referenced by the oxygen produced. A manually set positive bias insures the pressures to be nitrogen over oxygen.

In a similar way, when the cell stack is depressurized, oxygen sensed dome regulator DBPR 406 will vent the cell stack external pressure so that the nitrogen pressure is favored over the oxygen as set by a positive bias. Although the oxygen production is the control factor in the cell stack operating pressures, hydrogen pressure is also controlled by negative bias, back pressure regulator DBPR 310. The dome pressure of this regulator is nitrogen sensed instead of oxygen for safety reasons. The differential between nitrogen and hydrogen will be sufficiently larger throughout the working range so that oxygen pressure will be maintained over that of hydrogen. Control bands for the regulators require regulation to ±9 PSI at any pressure. Refer to **Operations Manual, Appendix D** for the pressure set on each regulator.

In addition, two regulators, DBPR 306-1 and -2, reduce the water/hydrogen pressure for the low pressure separator. The upstream regulator, -2, is referenced to the system nitrogen to reduce pressure downstream. The downstream regulator, -1, maintains a constant pressure for the -2 regulator, assisting in the control of pressure reduction from 3000 PSIA to 20 - 50 PSIA.

Wetted materials in contact with oxygen include Inconel 600/X750, Elgiloy, Haynes 188 and Vespel SP21, Teflon soft goods. Wetted materials in contact with hydrogen and nitrogen include 316 stainless steel and Kel-F, Teflon soft goods.

Regulator setting records are included in **Operations Manual, Appendix D**.

Feed Water Pump (FP 500)

Electrolysis feed water and pressure-reduced protonic water at near-ambient pressure is pressurized to 3100 PSIA and injected into the oxygen side water recirculation loop with a positive displacement pump, part of a pump package (Figure 2-9a). The pump is a Milton Roy Model MB1-A13-P071, packed plunger liquid end, totally enclosed self-lubricating, controlled volume, with double ball checks. The stroke length is adjustable from 0-100% capacity while the pump is in operation. Capacity adjustment is done through an electronically controlled actuator. The plunger is 7/16 ceramic and at 113 SPM delivers 4.8 GPH at 3200 PSIG. The plunger is sealed with replaceable Teflon rope packing. The ball checks are ceramic with carbide seats.

Power rating of the pump motor is 1 HP; the electric power supply is three phase 240 VDC . A pulsation damper (LDI Model PH 4.5 - 5000P - D 4.5) is connected immediately after the pump discharge and removes 90% of the pulses in the pressure range of 2500 to 3200 PSIG. The damper is made of 316 stainless steel and has a Viton diaphragm. The diaphragm is inflated with gaseous nitrogen through a valve adapter to 80% of the operating pressure.

Water Circulating Pump (GP 204)

Water is circulated through the oxygen side (anode) compartments of the electrolysis cell stack in order to provide electrolysis feed water and to remove product oxygen and heat. This oxygen side water is circulated by a high case pressure gear pump. A special version of the Micropump Model 220 gear pump was made so that the case will withstand 3000 operating pressure with an input/output differential pressure of 30 PSI. Materials in contact with feed water and entrained/dissolved oxygen include Ryton gears, Inconel pump case, and a tantalum shroud around the drive magnet sealed by a Viton "O"-ring. The Ryton gears are replaceable.

The pump motor is operated and controlled from a 24 VDC power supply which provides delivery of feed water from 2500 to 6200 ml/min, depending on the voltage and current selected. The process controller turns the power supply on or off as required.

Flow Transducers (FT 205, FT 511)
The water circulation flow rate through the cell stack is measured with an in-line Sponsler turbine flowmeter, Model MF 175. The flowmeter has a range of 300 to 11,355 cc/min at 3000 PSIA pressure. Flow reading is obtained from the magnetic rotor by a modulating coil. The output signal of the transducer is then fed into a signal conditioner, where it is amplified and linearized. The output of the signal conditioner is a 0-5 VDC signal that is proportional to flow rate. Due to the dissolved oxygen in the water, the wetted components of the transducer are Inconel and TFE.

At the time of shipment, FT 511 sensor was not active. (The signal has been tied to ground.)

Valves
A mixture of electric solenoid (SV) and air-operated (AOV) actuated valves are used in the test fixture. The following table lists all process valves in the system according to valve type, unpowered position, system operating pressure, working fluid and major materials of construction.

PROCESS VALVES

VALVE #	POS	OP PRESS	FLUID	MATERIALS
AOV 213	nc	3100 PSIA	OXYGEN	316SS, Vespel
AOV 215	no	3100 PSIA	OXYGEN	316SS, Vespel
AOV 216	nc	3100 PSIA	OXYGEN	316SS, Vespel
AOV 302	no	3000 PSIA	HYDROGEN	316SS, Vespel
AOV 304	nc	3000 PSIA	HYD./WATER	316SS, KEL-F
AOV 313	nc	3000 PSIA	HYDROGEN	316SS, Vespel
AOV 327	nc	3000 PSIA	HYDROGEN	316SS, Vespel
SV 403	nc	3200 PSIA	NITROGEN	ALUM, SS, Nylon
SV 409	nc	3150 PSIA	NITROGEN	ALUM, SS, Nylon
AOV 415	no	3150 PSIA	NIT./HYD.	316SS, Vespel
AOV 418	nc	3150 PSIA	NIT./OXYGEN	316SS, Vespel
SV 502	3-WAY	25 PSIA	WATER	PFA, Kalrez
SV 507	nc	25 PSIA	WATER	PFA, Kalrez
AOV 508	nc	25 PSIA	WATER	316SS, Kalrez

Pneumatic Valves (AOV-xxx)
The pneumatically-actuated process valves used for all H_2 and O_2 service (Nupro p/n HBVS4-x) consist of a valve body coupled to a pneumatic actuator which is isolated from the wetted area of the valve by a high pressure design bellows and diaphragm assembly. The pneumatic actuator has a spring to return the valve to its normal open or close configuration (Normally open is designated by a "-O" suffix to the part number; normally closed by a "-C" suffix). A vent hole between the valve body and the valve operator prevents pressure build-up should a leak occur in the bellows/diaphragm assembly. The valve body, seat and stem are rated at 3500 PSI. Material in contact with process

fluids is 316 stainless steel; the valve stem has a soft seat insert made of Vespel (A0V304 has a Kel-F insert, p/n HBS4-C).

The pneumatic valves are actuated using 75 PSI nitrogen applied by remote, dedicated pilot valves (designated as SV112-x, manufactured by Asco as p/n 8380A2) These 3-way valves vent the AOV actuator pressure when deactivated, returning the AOV to its normal open or closed position. Respective pilot valve/AOV pairs are indicated on the system fluid schematic SVSK116070

Solenoid Valves (SV403, SV409)
The Marotta solenoid valves, Model MV100A, are 2-way, 2-position electric valves requiring 24 VDC, 1.0 amps. The valve operates at pressures from 0 to 3200 PSIG by actuating a poppet connected to the armature through a seal; poppet return is by a spring. The valve features a balanced pressure poppet design, assuring positive shutoff at full pressure. Wetted material includes a forged CRES body, 304SS poppet, and Vespel seat.

Solenoid Operated Diaphragm Valve (SV 507)
This valve admits low pressure feed water to the system, making up for that water which is converted to product gases. Wetted parts in this solenoid-actuated valve are PFA/Teflon except for the Kalrez poppet seal. The valve operating pressure range is limited from atmospheric to 70 PSIG; operating fluid temperature range is 0 to 100 °F. The valve is actuated by 24 VDC and draws 0.5 amperes. The wetted area and electrical components are isolated from each other by a PFA diaphragm.

Three-way Valve (SV 502)
A three-way valve in the pump package is used to divert low resistance process water (<1 MΩ) away from the feed pump inlet to a waste drain during PREPARE mode. Normal unpowered position of the valve rejects water via a drain port in the pump package. When the water is at or above 1 MΩ, the three-way valve is actuated, admitting the water to the high pressure pump inlet. Materials used in the valve are similar to diaphragm valve SV507.

Separators, H2 (HPS 300, HPS 318)
Gas/water separators were designed and built to separate hydrogen gas and protonically pumped water in the cell stack hydrogen outlet stream. The high pressure separator (HPS300) receives hydrogen and water directly from the cell stack at 3000 PSI and separates the hydrogen from the water through impingement of the incoming two-phase stream on a baffle and by swirling action inside the separator body. Water collects in the bottom half of the separator due to gravity. High pressure hydrogen exits the top of the separator, passing through a screen to trap fine aerosol mist. Water exits through a screen in the base of the separator; the screen holds back most entrained gas bubbles.

Water from the high pressure separator is saturated with dissolved hydrogen gas at the operating pressure of 3000 PSIA. This dissolved gas must be removed prior to injecting the water into the oxygen side water recirculation loop via the feed pump . "De-gassing" of the protonic water is accomplished by pressure reduction and a second gravity phase separation stage. The water/dissolved gas stream passes through a pressure reduction stage consisting of two back-pressure regulators, a flow restrictor and a shut-off valve. The valve is controlled by level sensors in the primary phase separator HPS300, preventing this separator from draining completely and passing gas into the second stage. In the second separator (HPS 318), hydrogen escapes from the water due to reduced pressure (0 to 15 PSIA) and is vented to the low pressure outlet of the test rig. The water is collected at the bottom of the low pressure separator. Protonic water is recycled until a need for make-up feed water is sensed. Level sensors mounted in HPS318 detect the quantity of accumulated protonic water available and direct the controller to keep water supply valve SV507 closed until a low level is reached, indicating the need for make-up water.

<u>Separator, O2 (OPS 200)</u>
The high pressure oxygen/water separator receives oxygen and water directly from the cell stack outlet at 3100 PSI and separates them by impingement and by a swirling action induced by the tangential inlet. The high pressure oxygen escapes through the separator top, passing through a de-mister screen. Most entrained gas bubbles in the water are removed by a screen as the water flows through the bottom of the separator and exits to the circulation pump (GP204) downstream.

<u>Water Level Sensors (LS201-x, LS301-x, LS322-x)</u>
Four sensors are mounted vertically in each phase separator column to detect and control water level. The top level sensor (designated LSxxx-4) provides a high water level alarm. The water level is controlled between the middle two level sensors (designated LSxxx-3 and LSxxx-2). A low level alarm is provided by the bottom level sensor (designated LSxxx-1).

<u>As-shipped level sensors</u>. The sensors supplied at the time of shipment sense the presence of water by optical means. An arrangement consisting of a borosilicate glass prism, a photodiode and a photosensor detect the change in refraction at the exposed conical end of the prism when wetted by water. On board sensor circuitry provides a digital signal to the controller. The sensor housings are made of Inconel 718 for oxygen; 316SS for hydrogen. The sensors are model 4G2536 for oxygen service and 4G2535 for hydrogen service , manufactured by Vickers/TEDECO.

<u>Alternate level sensors.</u> In response to operational instability of the high level optical level sensors in the oxygen phase separator (LS201-4 and LS201-3 positions) , an alternate level sensor based on sensing low voltage AC electrical conductivity was developed by Hamilton Standard. Subsequent modifications by NASA led to replacement of all high pressure sensors with low voltage AC conductivity sensors. Diagrams and description of the sensor are included in **Operations Manual, Appendix E**.

Heat Exchanger (HX 219)

Heat generated as a byproduct of the water electrolysis reaction is removed from the cell stack by the process water recirculation flow. This heat is subsequently removed from the process water stream through a dual heat transfer coil type heat exchanger (Parker DHTC-IN-6). The Inconel center tube conducts the process water through the heat exchanger while the surrounding copper tube allows the coolant to counter flow. A flow control valve (TV113) on the coolant inlet meters the coolant flow required to maintain a controlled process water temperature between 100 and 130°F. The valve is actuated by a freon sensor bulb in thermal contact with the water outlet tube from the oxygen separator. Inlet and outlet thermocouples monitor coolant temperature.

SOURCE DOCUMENT APPENDIX

CELL STACK, TEST FIXTURE TEST DATA

SPE® PROPULSION ELECTROLYZER
FOR NASA'S INTEGRATED PROPULSION TEST ARTICLE

NASA-JSC CONTRACT NAS 9-18030

100 hour Test Completion

16-Cell Stack

Review and Discussion

- Stack Performance
- Test Log

[redacted]

- Anomalies
- Option Matrix

Design : 16 cells, 0.23 ft_2 , 200 psi (3100 psi in domes) Capacity : 4.0 pph product gas at 1500 ASF

Stack Performance

MET ALL CELL STACK REQUIREMENTS:

- **Demonstrated 0.6, 2.0, 4.0 pph water electrolysis rates at 3100 psia.**
- **Demonstrated 54 min on /36 min standby cyclic operation at 3100 psia**
- **Produced 99.9% pure H2 and O2 as soon as system reached 3100 psia**
- **Operated at >70% efficiency at nominal electrolysis rate**

UNITED TECHNOLOGIES
HAMILTON STANDARD

SPE-PE TEST MATRIX

	GENERATION RATE			SYSTEM PRESSURE			
	❶ Min,Nom,Max	❷ Standby	❸ Cyclic	200 psi	3100 psi	❹ Health	100 Hrs
Health						✖	
Green Run	✖			✖		✖	
Test Fix. (6-cell)		✖	✖	✖			
LoP Check Out	✖	✖	✖	✖		✖	
HiP Check Out	✖				✖		
100 Hour Run	✖	✖	✖		✖	✖	✖

❶ Min., Nom, Max rates: 0.6 pph H20, 2.0 pph H20, 4.0 pph H20

❷ Standby : maintain system pressures with no net gas output

❸ Cyclic : 54 min. of Nom. gas generation followed by 36 min at Standby

❹ Health checks include cell resistance and cross cell diffusion tests

100 HOUR TEST LOG
SIGNIFICANT EVENTS

2-17-90	Installed 16-cell stack in Special Test Fixture. Started 200 psi check-out of SPE-PE combined system.
2-20-90	Began 3000 psi checkout of SPE-PE system.
2-28-90	Started 100 hour endurance run, 4 hours at 2pph rate **(Run #1)**
3-06-90	Longest single run,10.7 hours at 2.0 pph rate **(Run #9)**
3-15-90	Error-free run demonstrating 0.6, 2.0 and 4.0 pph rates for durations of 30, 90 and 30 minutes, respectively **(Run #20)**
3-19-90	Completed 2 consecutive 90 minute cycles demonstrating Standby control for first time. **(Run #23)**
3-23-90	Resolved system water balance **(Run #24)**
4-06-90	Completed 104 hours with 7 hour run **(Run #35)**

100 HOUR TEST LOG
ANOMALIES

NO ANOMALIES WITH THE 16-CELL STACK

SEVERAL ANOMALIES WITH TEST FIXTURE:

- Level Sensors
- F206 Circ Filter
- GA317 Gas Sensors
- PWR101 Power Supplies
- DBPR210-1 O_2 Regulator
- AOV304 Drain Valve
- Water Balance

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100 HOUR TEST LOG
ANOMALIES EXPERIENCED

Level Sensors - Optical-type water level sensors in high pressure phase separators are not fully reliable, are direct cause of 18 forced shut downs in 100 hours. Best operation at out-of spec supply voltage. Vendor has not offered a resolution of problems yet.

F206 Circ Filter - Final 25μ filter before cell stack required ultrasonic cleaning 4 times so far. (10 hrs, 25 hrs,28 hrs,26 hrs) Filter has 1 sq.in. filter area of Hastelloy screen mesh. Spalled-off catalyst particles expected to diminish with time. Circ flow pump GP204 can be speeded up to compensate during a run.

GA317 Gas Sensors - Succeptable to moisture in gas line, are repositioned above separator water line, some wetting due to level sensor problems.

100 HOUR TEST LOG
ANOMALIES EXPERIENCED

PWR101 Power Supplies - Frequent excursions off calibration handled with feed-back control loop, but not always able to make max current or standby current. (357, 18 amps)

DBPR210-1 O_2 Regulator - Worn poppet after 51 hours of high pressure operation, may be aggravated by water due to level sensor failures. Backup reg finished run, rebuilt reg installed.

AOV304 Drain Valve - Worn Vespel poppet after 80 high pressure hours. Only valve in system cycled frequently (4 to 20 x / min). Replaced with Kel-F version.

Water Balance - Determined that water shutoff valve SV507 required low supply pressure <12 psi; also adjusted software parameters to reach proper water pump rates.

ANOMALIES
OPTIONS MATRIX

Level Sensors	Fix optical sensors, with vendor support *or* Replace (some) with conductivitiy sensors
F206 Circ Filter	Clean as needed (25 hour intervals?) *or* Source larger replacement filter
GA317 Gas Sensors	Replumb / configure to minimize moisture (trap?) *and \ or* Gortex membrane moisture shield
PWR101 Power Supplies	Establish recalibration schedule (50 hours?) *or* Automatic recalibration software routine
DBPR210-1 O_2 Regulator	Change poppet and seat materials as needed *or* Use OGP materials (Monel/SP-1 or 316ss/Kel-F)
AOV304 Drain Valve	Change valve as required
Water Balance	Maintain feed water pressure at 5 - 10 psi

RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
c/o	2-8	0.1	6-cell, 200 psi	Test fixture check-out, 6-cell stack installed temporarily	Erratic current control No soft-key action	Software edit
c/o	2-9	0.2	200 psi O_2	Test fixture checkout	•LS201-3 erratic •Time out H2 sep drain •Flood out O2 sep	•Fitted spash shield to -3 •Lengthened time out •Modified pump control
c/o	2-12	0.2	200 psi	Test fixture c/o	•hi lev LS201-3 timeout •Illegal LS301-1,3	•Lengthen time out •Change to warning
c/o	2-13	0.4	200 psi	Test fixture c/o	•Hi voltage shutdown	•Cyclic software bug fixed
c/o	2-14	0.7	200 psi	Test fixture c/o	•Bad LS301-3, no change	•Replaced sensor, add deflector
c/o	2-17	0.1	16-cell, 200 psi	**Install 16-cell stack** Low pressure c/o of 16cell stack installation	•Hi lev timeout LS301 •LS301-1 dry, -2 wet	•Software bug fixed •Gas hangup after shut down, requires time to clear
c/o	2-19	0.5	370 psi O_2	Stack/ fixture c/o. Allow slightly higher pressure on system (370 psia)	•Hi ΔP N2-O2 start up •Illegal LS322 -1,-3 •Hi lev timeout, LS201-3 •Hi alarm LS322-4	•Ramp current 4 A/6 sec •Gas bubble, sense adj. •(no action) •(Water balance problem)
c/o	2-19	0.5	2500 psi O_2	First hi pressure attempt	•Hi alarm LS322-4	•(Water balance problem)
c/o	2-20	0.5	3000 psi O_2	Hi pressure check out	•Hi alarm LS322-4	•(Water balance problem)
c/o	2-21	0.2	1500 psi O_2	Hi press c/o	•Hi alarm LS322-4	•Increased DELFLOW parameter to 25%
c/o	2-21	0.3	3000 psi O_2	Hi press c/o	Hi pressure shutdown @ 3100	Correct erroneous limit
c/o	2-21	0.1	1500 psi O_2	Hi press c/o	Illegal LS201-1,3	Incr. sensitivity LS201-2
c/o	2-23	1.2	3100 psi O_2	Hi press. c/o	Hi alarm LS322-4	Reduced OSFAC to 0.03 from 0.0448 to change water balance
c/o	2-23	1.1	3100 psi O_2	Hi press. c/o	•Hi level LS201-4 •Reduced circ flow	•Erroneous high level •Cleaned F206 circ water filter of catalyst debris
c/o	2-27	0.4	1500 psi	Hi press. c/o	•Illegal LS201-1,3 at 1500 psi •Hi lev LS301-4	•LS201-2 replaced •Shorted LS301-4 harness Nicked wire fixed.
c/o	2-28	0.3	2900 psi	Hi press. c/o	•Lo level LS301-1 •Illegal LS201 -1,-3 readings	•False reading LS301-3 caused excessive drain •Increased LS201-3 sensitivity
c/o	2-28 (total c/o)	0.6 (7.4)	3100 psi	Hi press. c/o	•N_2/H_2 DP > 175 psi limit upon entering PROCESS state	•Increased limit to 200 psi •No illegal level sensor indications

RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
1	2-28	4.0	3100 psi	**Start of 100 hour endurance run**	LS201-4 false indication, interrupt driven shut down	Changed level -4 interrupts to regular anomaly status
2	3-1	0.9	3100 psi	100 hr Endurance run, NOMINAL rate	•Shut down due to low flow and high Δ T •Warnings, LS201-1,-3	•Checked GP204, F206 •Shortened deflector hood on LS 201-3
3	3-2	1.1	3100 psi	NOM rate	Hi lev LS201-4 warning, S/D	
4	3-3	5.9	3100 psi	NOM rate	Hi lev LS201-4 warning, S/D	Installed water deflector on phase separator baffle and set sensor voltage to 24V
5	3-5	0.6	3100 psi	NOM rate	Hi lev LS201-4 warning, S/D	Found bubble in Viton coating of LS201-4 anti-reflection guard; popped bubble and reinstalled sensor 90° from previous
6	3-5	1.9	3100 psi	NOM rate	Hi level LS201-4 warning, S/D	Increased sensor voltage to 25 volts
7	3-5	0.5	3100 psi	NOM rate	•Lo level LS301-1 interrupt	•LS301-2 off illegally, caused drain valve to stay open per software instruction
8	3-5	1.5	3100 psi	NOM rate	• Manual shut down. Operator noticed flow rate reduction.	•Cleaned F206
9	3-6	10.7	3100 psi	NOM rate, 1st attempt at MIN rate. Work with LS201-4 problem, shut down changed to warning.	• Six hours until first problem with illegal LS201 (1,2,4 on), then three more indications •Feed pump leakage > 15cc/min •Flooded LS301 in MIN rate. Manual shut down	•Determined LS201-4 malfunction reversed by setting supply to 28 V. •Tightened feed pump gland •(Water balance problem)
10	3-7	0.3	3100 psi	NOM rate Set LS power supply to 26V	•Lo level LS301-1 interrupt due to false -3 on •Noted 12 amp power supply offset	•Increased LS301-3 sensitivity
11	3-7	0.1	3100 psi	NOM rate	•Lo level LS301-1 interrupt due to false -3 on •Noted 9 amp power supply offset	•Change software to keep AOV304 closed in event of illegal LS configuration
12	3-7	7.0	3100 psi	NOM rate, measure O_2 production rate	•False LS201-4 indication •Almost timed out on LS201-3 drain time limit •Manual shut down, LS301 flood	•Set LS supply to 28 V to eliminate false LS201-4 •Loosened feed pump gland to get 10cc/min leak rate

RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
13	3-7	0.8	3100 psi	NOM rate, sample product gas Set LS power supply to 28 V Set OSFAC to .03	•Illegal LS301-1,-3 •Manual shut down to examine level sensors	• Found anti-reflection Viton rubber coating on LS301-3 guard severely bubbled and touching sensor prism
14	3-7	2.3	3100 psi	Exersize MIN, NOM, MAX controls Attempt cyclic	•Nearly flooded during cyclic offtime, Shut down during manual drain attempt •Continued LS301 problems	•(Water Balance problem) •Found LS301 sensors to be faulty with shorts to case. Fitted sensors with connectors to minimize wire twisting.
15	3-12	1.1	3100 psi	NOM rate Test refurbished level sensors	•False LS301-4 on, eventually floods separator per software control to keep AOV304 closed	•Manual shut down
16	3-12	1.3	3100 psi	NOM, MIN rate Test newly installed thermal control valve V113	•Almost timed out on LS201-3 drain time limit, Shut down during manual drain attempt $N_2 > O_2$	•Reduce OSFAC parameter to .029 •V113 works well to control approx 110°F temperature
17	3-13	1.5	3100 psi	MIN, NOM, MAX rates	•H_2 >3030 shut down •Frequent LS322-4 high level warnings •LS201-1,-3 warnings •Low circ flow	•Heating up at MAX caused N_2 ref overpressure. •Frequent manual drain via remote line off V331 •Set LS voltage to 28 •Clean F206 ultrasonically
18	3-14	4.3	3100 psi	NOM, MIN rate, H_2 sample Set OSFAC =.031	•Frequent LS322-4 high level warnings, 5 min frequency •High level timeout, LS201-3	•Frequent manual drain via remote line off V331 • OSFAC not effectiv e change for time out. •Tried wetproofing GA317 with Gortex
19	3-14	4.6	3100 psi	NOM, MIN, MAX Replaced SV507 to address overfilling problem in HPS318	•GA317-2 >2 volt shut down at start, due to wetting from HPS318 flooding •Feed pump stepper motor shaft pin vibrated loose •Required HPS318 manual drain only in MIN rate •Shut down $N_2 > O_2$ by 100 psi	•Gortex not good, disconnect GA317 sensors temporarily •Replaced pin while running and held in place with electric tape. •Water balance improved at NOM •Low pressure in MIN ; possible leaky regulator 210-1

RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
20	3-15	2.5	3100 psi	MIN,NOM, MAX rates (ran 30,90,30 mins)	•Required HPS318 drain only during startup •Manual shut down by operator	•Runs water rich at MIN, lean at MAX.
21	3-15	0.2	3170 psi	Test new feedback current control to compensate for power supply variable offset	•H_2 >3030 shut down	•Too high setting on PR402 nitrogen inlet regulator •Current control works well
22	3-16	2.5	3100 psi	MIN, NOM, MAX rates Try Cyclic Standby Removed DBPR210-1 oxy . reg. Set DBPR210-2 to run at 40Δpsi	•DBPR210-1 valve poppet found to be pitted or eroded, causing leakage, poor regulation •Required periodic HPS318 drain in NOM •Shut down in Cyclic off due to low current < diffusion current	•Back up regulator works well, -1 lines capped off temporarily •Water balance still off, new SV507 not the answer •Software fix to limit current control in Cyclic
23	3-19	3.5	3065psi	MIN,NOM,MAX,Cyclic test Test Standby current control software modification Process state now P>3000 psia	•Needed 30 V to avoid false LS201-4 and LS322-4 indications •Unable to reach full MAX current	•Completed 2 consecutive cycles. Current control increases current to maintain pressure during Standby. •Manual shut down via OFF mode
24	3-23	10.2	3100 psi	MIN,NOM,Cyclic	•Initial HPS318 flooding •Warning LS201-1,-3 on every 3 to 4 minutes •Flow diminishing, had to increase circ pump voltage	•Replaced pressurized water supply with carboy, resolved water balance problem •Completed 3 full cycles •Manual OFF mode selected •Cleaned F206 filter
25	3-26	3.3	3100 psi	MIN, Cyclic Test of 0 psig feed water supply on water balance	•Start up problem with LS322-1 •Overfilled to LS322-4 at 2000 psi •Facility coolant problem •Shut down during repeated reversion to cyclic standby, shut down N_2>O_2 by 100 psi	•Restore25psi feed for startup •Revert to 0psi feed for operation, raised carboy 2 ft. •Fix facility coolant system

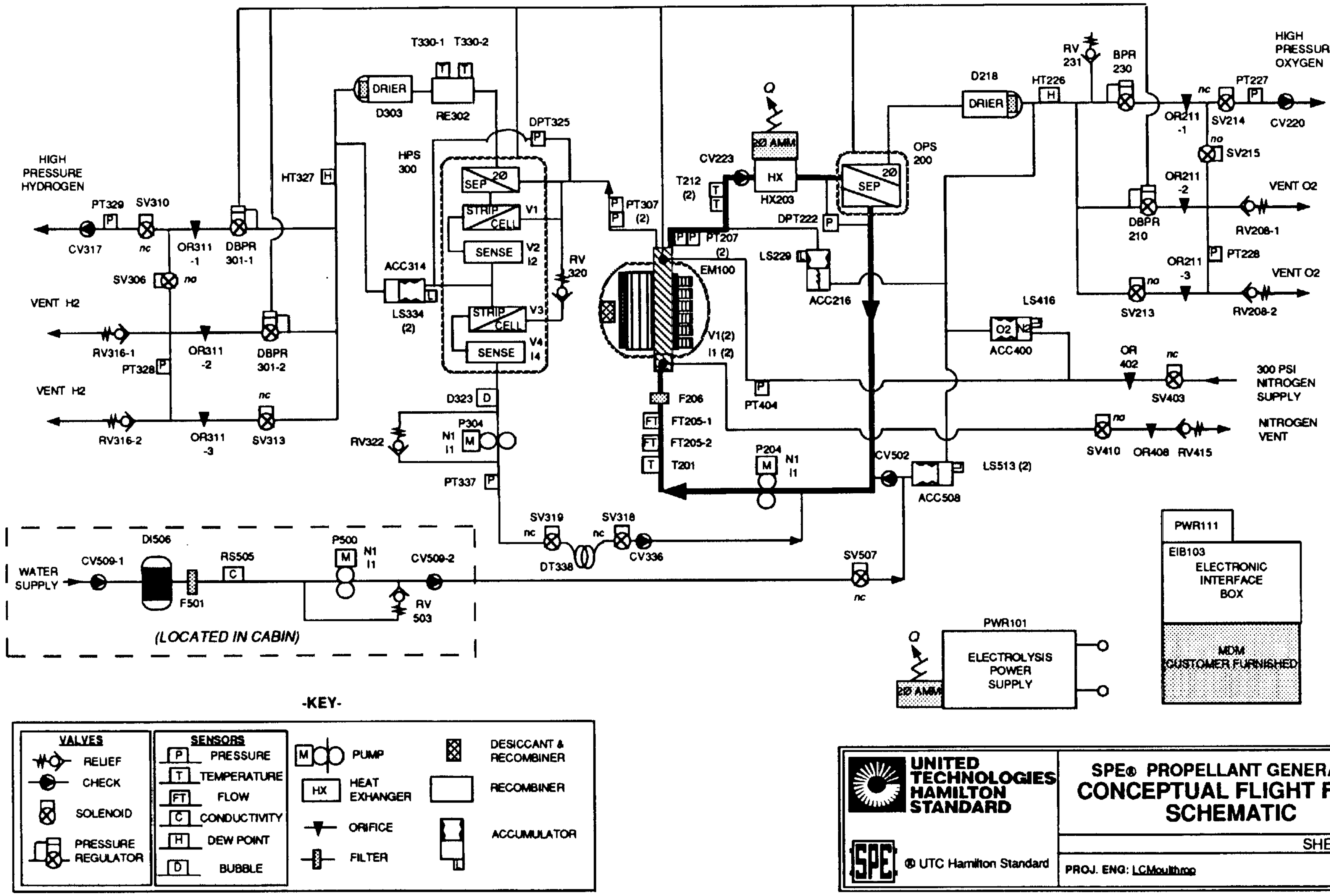
RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
26	3-28	1.2	3100 psi	MIN,NOM,MAX,Cyclic Test 10 psi water supply modification on water balance	•Frequent Warning LS201-1,3 on	•Reduced LS201-2 sensitivity, diminished freq. •Manual OFF mode selected
27	3-29	0	3100 psi	Continue run Evaluate turning level sensor LS201-2	•Difficulty in startup LS201-2, even at ambient •Shut down GA317-2	•Rotated sensor and reinstalled per vendor •Gas sensor very wet, removed gas sensors pending replumb above HPS318 and fix of water problem
28	3-29	2.4	3100 psi	MAX rate	•Noticed louder drain noise, takes several drain cycles to get from LS301-3 to -2	• Drains Ok at NOM, MIN •Manual OFF mod selected
29	3-30	6.7	3100 psi	MIN rate	•Shut down N_2>O_2 by 102psi	•Possible high feed pump leakage
30	4-2	3.0	3100 psi	MAX rate	•Unable to get 357 amps (344) •Warning LS201-1,3 persist •LS301-1,2,4 on . Manual shut down	•Possibly voltage limited at power supplies, got more current as cell stack warmed •Levels ok during depress.
31	4-2	2.6	3100 psi	MAX rate	•LS301-1,2,4 on •LS301-1 off, -2 on interrupt shut down	•Manual drain reset -4. Apparent failure of -3 sensor to indicate •LS301 set ok after depress •Got to 358 amps
32	4-3	0.2	3100 psi	NOM, MIN rate	•LS301-1 off interrupt •Noticed reduction of flow	• No recorded occurance, must have been momentary •Swapped LS301-1 and -2 sensors •Increased pump voltage to 18
33	4-3	6.4	3100 psi	NOM rate	•LS301-1,2,4 on, required drain via V330 to reset (several times) •Drain frequency of HPS300 and HPS322 slower •Noticed reduction of circulation flow	•Possible LS301-3 intermittant problem •Confirmed AOV304 drain valve leaks-will replace •Saw CV512 does not check to prevent water flow back into HPS322 •Intentional shut down test of H_2 sensors •Clean F206, replace AOV304

RUN #	DATE 1990	Δ hrs.	CONDITIONS	PURPOSE OF RUN	PROBLEMS ENCOUNTERED	OBSERVATION/ ACTION TAKEN
34	4-5	1.7	3100 psi	MIN rate Test replaced AOV304 w/ Kel-F seal (original failed Vespel seal)	•LS301-1,2,4 on, required drain via V330 to reset •Facility shut down	•Lack of low pressure N_2 (<60) •Inspected LS301-3, could see no problem.
35	4-6	7.0	3050 psi	MIN, NOM, MAX, Cyclic	•LS301-1,2,4 on, required drain via V330 to reset (several times) •Unable to go below 33 amps in Standby mode •Shut down while draining HPS300, low PT308 pressure (12psia)	•Still problem with LS301-3. Sensitivity, voltage adjust do no clear up, only drain and 10 minute wait do. •Low PT308 during drain because of feed pump suction
Total Runs 1 - 35	2-28 thru 4-6	103.8 hrs				

SOURCE DOCUMENT APPENDIX

SPE-PG CONCEPT SCHEMATICS, PARTS LISTS

SPE-PG COMPONENT CONCEPT DESCRIPTIONS



UNITED TECHNOLOGIES HAMILTON STANDARD

SPE® UTC Hamilton Standard

SPE® PROPELLANT GENERATOR CONCEPTUAL FLIGHT FLUID SCHEMATIC

SHEET 1 OF 2

PROJ. ENG: LCMoulthrop

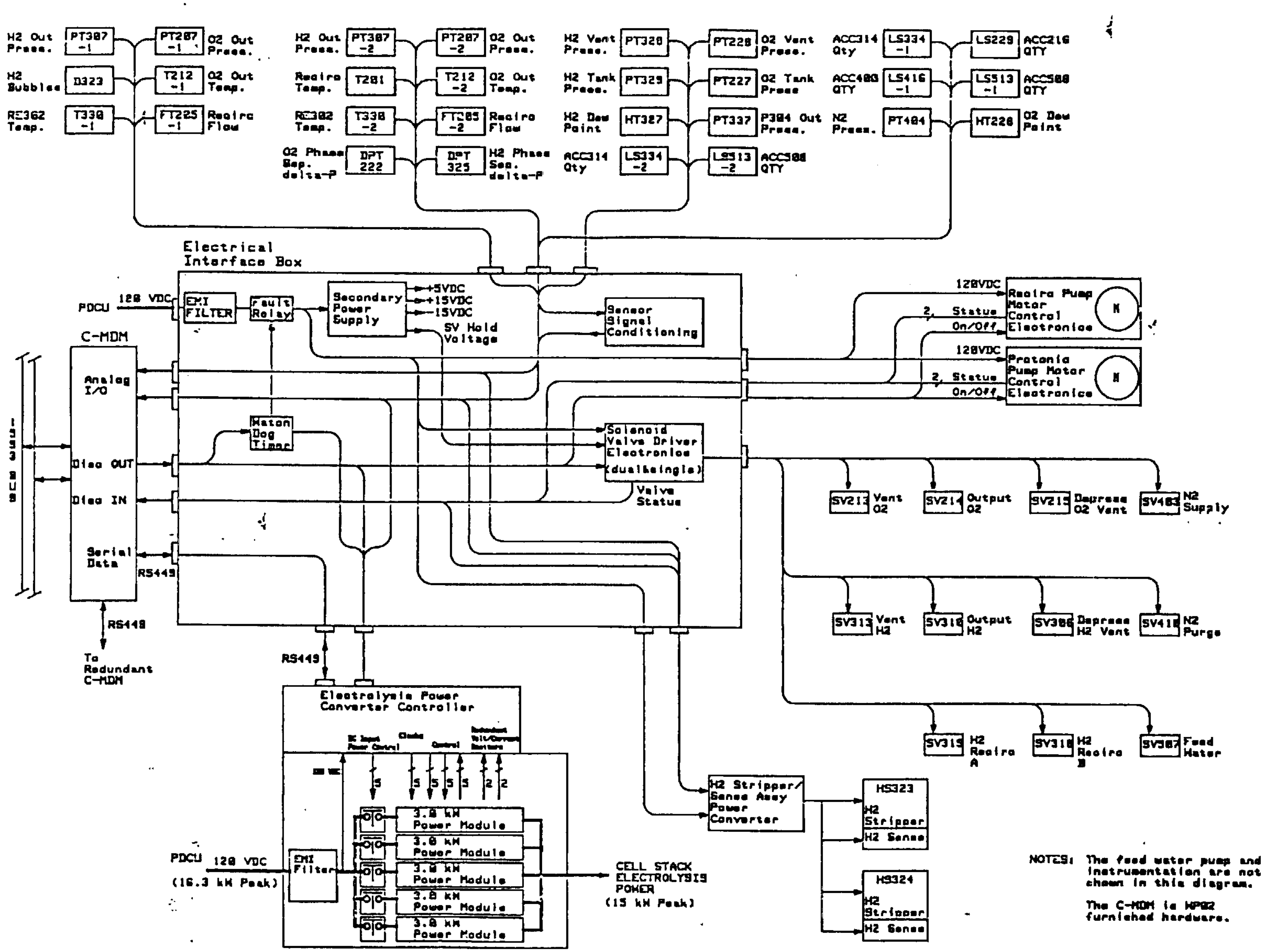
LAST REV: 11-28-90

REV F

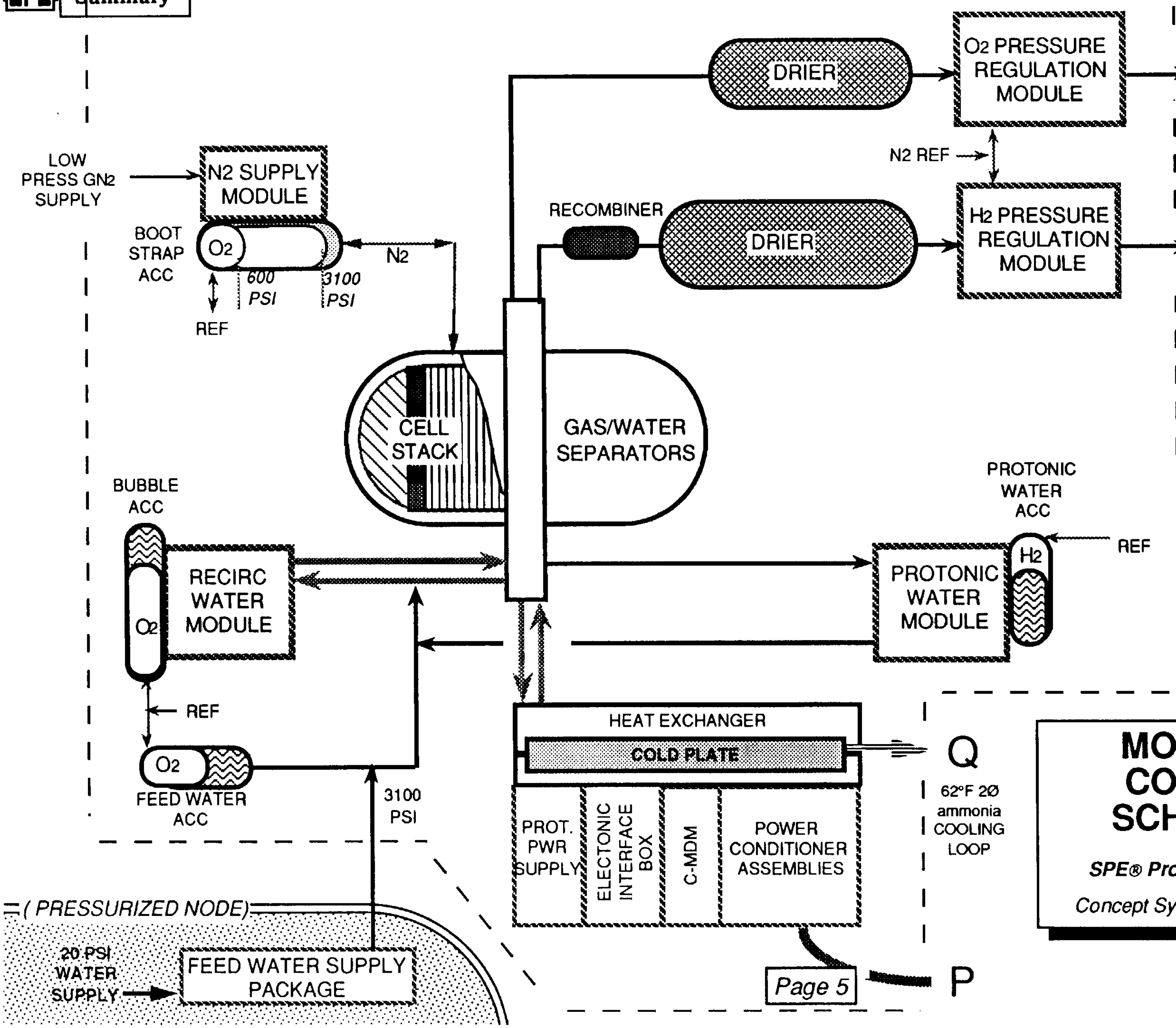
SPE® PROPELLANT GENERATOR
CONCEPTUAL FLIGHT FLUID SCHEMATIC PARTS LIST

REV F
11/28/90

ITEM	NO.	QN.	ITEM NAME	MAJOR STRUCTURAL MATERIAL	OPERATING PRESSURE
EM	100	1	CELL STACK, ELECTROLYSIS	VARIOUS	3100psi
PWR	101	1	POWER SUPPLY, STACK	VARIOUS	N\A
EIB	103	1	INTERFACE BOX, ELECTRONIC	VARIOUS	N\A
PWR	111	1	POWER SUPPLY, H2 STRIPPER	VARIOUS	N\A
OPS	200	1	PHASE SEPARATOR, OXYGEN	TBD	3100psi
T	201	1	TEMP. SENSOR, STACK INLET	INCONEL718	3100psi
HX	203	1	HEAT EX., HEAT REJECTION	INCONEL718	3100psi
P	204	1	PUMP, RECIRCULATION	INCONEL718	3100psi
FT	205	2	FLOW TRANSDUCER, RECIRCULATION	INCONEL718	3100psi
F	206	1	FILTER, RECIRCULATION WATER	TBD	3100psi
PT	207	2	PRESSURE TRANS., STACK O2 EXIT	INCONEL718	3100psi
RV	208	2	RELIEF VALVE, 02 VENT	INCONEL718	3100psi
DBPR	210	1	DIFFERENTIAL BACK PRESSURE REG., O2 EXIT	INCONEL718	3100psi
OR	211	3	ORIFICE, O2 EXIT	INCONEL718	3100psi
T	212	2	TEMP. SENSOR, STACK EXIT	INCONEL718	3100psi
SV	213	1	SOLENOID VALVE, O2 VENT	INCONEL718	3100psi
SV	214	1	ISOLATION VALVE, 02 EXIT	INCONEL718	3100psi
SV	215	1	SOLENOID VALVE, O2 VENT	INCONEL718	3100psi
ACC	216	1	ACCUMULATOR, BUBBLE	INCONEL718	3100psi
D	218	1	DRIER, OXYGEN	INCONEL718	3100psi
CV	220	1	CHECK VALVE, O2 EXIT	INCONEL718	3100psi
DPT	222	1	DIFF. PRESSURE TRANS., O2 PHASE SEPARATOR	INCONEL718	3100psi
CV	223	1	CHECK VALVE, HEAT EX. INLET	INCONEL718	3100psi
HT	226	1	HUMIDITY DETECTOR, O2 DRIER EXIT	TBD	3100psi
PT	227	1	PRESSURE TRANSDUCER, 02 TANK	INCONEL718	3100psi
PT	228	1	PRESSURE TRANS., O2 RELIEF VALVE INLET	INCONEL718	3100psi
LS	229	1	LEVEL SENSOR, BUBBLE ACCUMULATOR	TBD	3100psi
BPR	230	1	PRESSURE REGULATOR, OXYGEN	INCONEL718	3100psi
RV	231	1	RELIEF VALVE, OXYGEN OVERPRESSURE	INCONEL718	3100psi
HPS	300	1	PHASE SEP/STRIPPER/SENSOR ASSY, H2	TBD	3000psi
DPBR	301	2	PRESSURE REGULATORS, HYDROGEN	316L	3000psi
RE	302	1	RECOMBINER	A286	3000psi
D	303	1	DRIER, HYDROGEN	CRYOFORMED S.S.	3000psi
P	304	1	PUMP, PROTONIC H2O	316L	3000psi
SV	306	1	SOLENOID VALVE, H2 VENT	316L	3000psi
PT	307	2	PRESSURE TRANS., STACK EXIT H2	316L	3000psi
SV	310	1	ISOLATION VALVE, H2 EXIT	316L	3000psi
OR	311	3	ORIFICE, H2 EXIT	316L	3000psi
SV	313	1	SOLENOID VALVE, H2 VENT	316L	3000psi
ACC	314	1	ACCUMULATOR, PROTONIC PUMP	316L	3000psi
RV	316	2	RELIEF VALVE, H2 VENT	316L	3000psi
CV	317	1	CHECK VALVE, H2 EXIT	316L	3000psi
SV	318	1	ISOLATION VALVE, PROTONIC H2O INLET	TBD	3000psi
SV	319	1	ISOLATION VALVE, PROTONIC H20 PUMP EXIT	TBD	3000psi
RV	320	1	RELIEF VALVE, PROTONIC H2O RCYCLE	316L	3000psi
RV	322	1	KICKBACK RELIEF VALVE, PROTONIC PUMP	316L	3000psi
DS	323	1	DOPPLER BUBBLE SENSOR, H2	316L	3000psi
DPT	325	1	DIFF. PRESSURE TRANSMITTER, H2 PHASE SEPARATOR	316L	3000psi
HT	327	1	HUMIDITY DETECTOR, H2 DRIER EXIT	TBD	3000psi
PT	328	1	PRESS. TRANS.,H2 RELIEF VALVE INLET	316L	3000psi
PT	329	1	PRESSURE TRANS.,H2 TANK	316L	3000psi
T	330	2	TEMPERATURE SENS., RECOMBINER	316L	3000psi
LS	334	2	LEVEL SENSOR, PROTONIC WATER ACCUMULATOR	TBD	3000psi
CV	336	1	CHECK VALVE, PROT. WATER MIX POINT	316L	3000psi
PT	337	1	PRESSURE TRANS, PROTONIC PUMP EXIT	316L	3000psi
DT	338	1	TUBE, DWELL TIME	316L	3000psi
ACC	400	1	ACCUMULATOR, BOOT STRAP	INCONEL718	3150
OR	402	1	ORIFICE, N2 IINLET	316L	3150
SV	403	1	SOLENOID VALVE, N2 INLET	316L	3150
PT	404	1	PRESSURE TRANSDUCER, N2	316L	3150
OR	408	1	ORIFICE, N2 EXIT	316L	3150
SV	410	1	SHUTOFF VALVE, N2 VENT	316L	3150
RV	415	1	RELIEF VALVE, N2 VENT	316L	3150
LS	416	1	POSITION SENSORS, O2/N2 ACCUMULATOR	TBD	3150
P	500	1	PUMP, FEED WATER	316L	3100
F	501	1	CARTRIDGE FILTER, FEEDWATER	TBD	15
CV	502	1	CHECK VALVE, FEEDWATER ACCUMULATOR EXIT	TBD	3100
RV	503	1	KICKBACK RELIEF VALVE, FEEDPUMP	TBD	3100
RS	505	1	RESISTIVITY SENSOR, FEEDWATER	TBD	15
DI	506	1	CLEAN UP BED, FEEDWATER	TBD	15
SV	507	1	SHUTOFF VALVE, INLET WATER	TBD	15
ACC	508	1	ACCUMULATOR, FEED WATER	INCONEL718	3100
CV	509	2	CHECK VALVES, FEEDWATER	TBD	3100
LS	513	2	LEVEL SENSORS, FEED WATER ACCUMULATOR	TBD	3100



SPE® Propellant Generator Electrical System Architecture



MODULAR CONCEPT SCHEMATIC

SPE® Propellant Generator

Concept System Design Review

UNITED TECHNOLOGIES HAMILTON STANDARD

New Concepts

NEW CONCEPTS DEVELOPED FOR 3000 PSIA SPE® PROPELLANT GENERATOR DIFFERENTIATE IT FROM PREVIOUS CONCEPTS

- **Modular component assemblies** are better match to current development program ('88 mockup: common system manifold, discrete components)

- **Nitrogen save system** conserves N_2; needs 600 psi N_2 supply only on start up; filler blocks in domes reduce volume 90%; O_2 driven accumulator conserves N_2
- **No N_2 purge** of hydrogen side also conserves N_2, eliminates venting.

- **Feed water pump in pressurized node** (reduced EVA)
- **Cold plate** interface to 2-Ø NH_3 coolant loop
- **No active thermal controller** needed in any SSF deployed mode
- **Lower system temperature** (85° vs 120°F) reduces drier humidity load by 2/3
- **Five-year non-regenerable driers** offer best reliability; thermal vacuum desorb regenerable driers are an alternative design
- **Power Supply and controls packaged into system**; cooled by cold plate

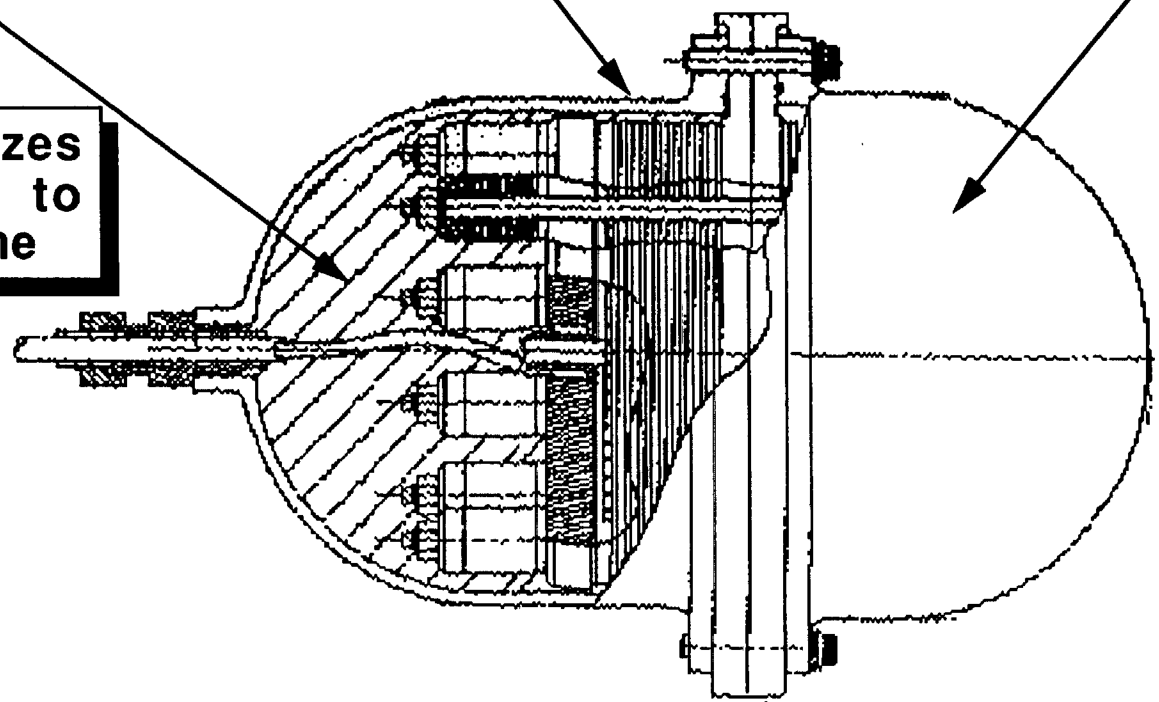
UNITED TECHNOLOGIES HAMILTON STANDARD

Descriptions
Assemblies / Modules

System components are packaged into functional modules or assemblies:

ELECTROLYSIS / PHASE SEPARATORS MODULE
PRESSURE CONTROL MODULES
RECIRCULATION MODULE
BUBBLE ACCUMULATOR
PROTONIC WATER MODULE
PROTONIC WATER ACCUMULATOR
FEED WATER ACCUMULATOR
BOOTSTRAP ACCUMULATOR
NITROGEN SUPPLYAND VENT MODULE
GAS DRIERS
HEAT EXCHANGER / COLD PLATE
CONTROL MULTIPLEXER/DEMULTIPLEXER (C-MDM)
ELECTRONIC INTERFACE BOX (EIB)
PUMP CONTROLLERS
POWER CONVERTERS
FEED WATER ORU

Electrolysis/ Separator Module



Block minimizes N_2 needed to pressurize dome

Manifold plate divides stack and separator sections, allowing independent assembly or servicing

Electrolysis Cell Stack Design

SIZING CRITERIA - 16 CELLS AS IN IPTA PROTOTYPE CELL STACK

TECHNOLOGY - LIQUID ANODE FEED IN A NITROGEN DOME (SAME AS IPTA)
SLIGHT MODIFICATIONS ASSUMED AS FOLLOWS:

- UTILIZE MANIFOLDING AT FLUID PLATE TO COOL H_2/H_2O EXIT DOWN TO STACK INLET TEMP. (REDUCES LOAD ON DRYERS)
- INCREASE FRAME SIZE TO REDUCE FREE VOLUME IN THE STACK AND TO REDUCE GAS DIFFUSION THROUGH THE FRAME
- USE TEFLON AT THE EDGE OF THE MEMBRANE TO REDUCE H_2O, H_2 AND O_2 DIFFUSION
- DOME VOLUME IS MINIMIZED BY ADDITION OF POLYSULFONE PLUGS
- THERE IS A SMALL AMOUNT OF CATALYST IN THE DOME TO RECOMBINE DIFFUSED H_2 AND O_2
- WATER FORMED BY RECOMBINATION OF DIFFUSED H_2 AND O_2 IS ABSORBED IN A DESICCANT BED
- $O_2>H_2$ X-PRESSURE CAPABILITY INCREASED TO 3000 PSID

JUSTIFICATION

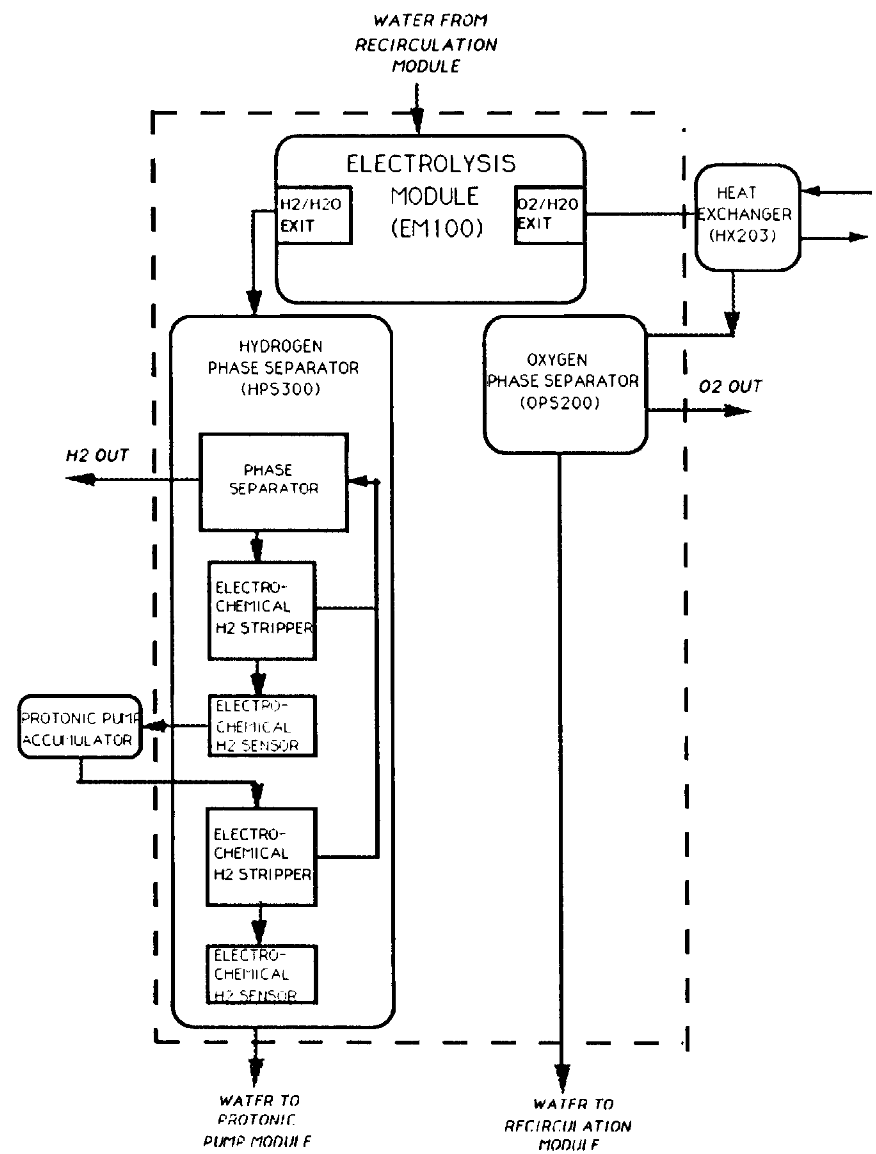
- KEEP THE RELIABLE "HEART" OF THE ELECTROLYZER SYSTEM AS CLOSE AS POSSIBLE TO PROVEN DESIGN

TECHNOLOGY DEVELOPMENT

- CONTINUE EFFORT ON DOMELESS STACK WITH 3000 PSI X-PRESSURE CAPABILITY

Electrolysis/Phase Separator Module DIAGRAM

- The cell stack and phase separators are co-located within the same pressure vessel
- The oxygen phase separator removes O2 gas from the water recirculation stream
- The hydrogen phase separator separates gaseous H2 from H2O
- The H2 stripper electrochemically removes dissolved H2 remaining
- The hydrogen sensor detects any H2 that was not stripped



UNITED TECHNOLOGIES HAMILTON STANDARD

Electrolysis/Phase Separator Module

Operating Media, Temperatures and Mass Rates
(Maximum electrolysis rate)

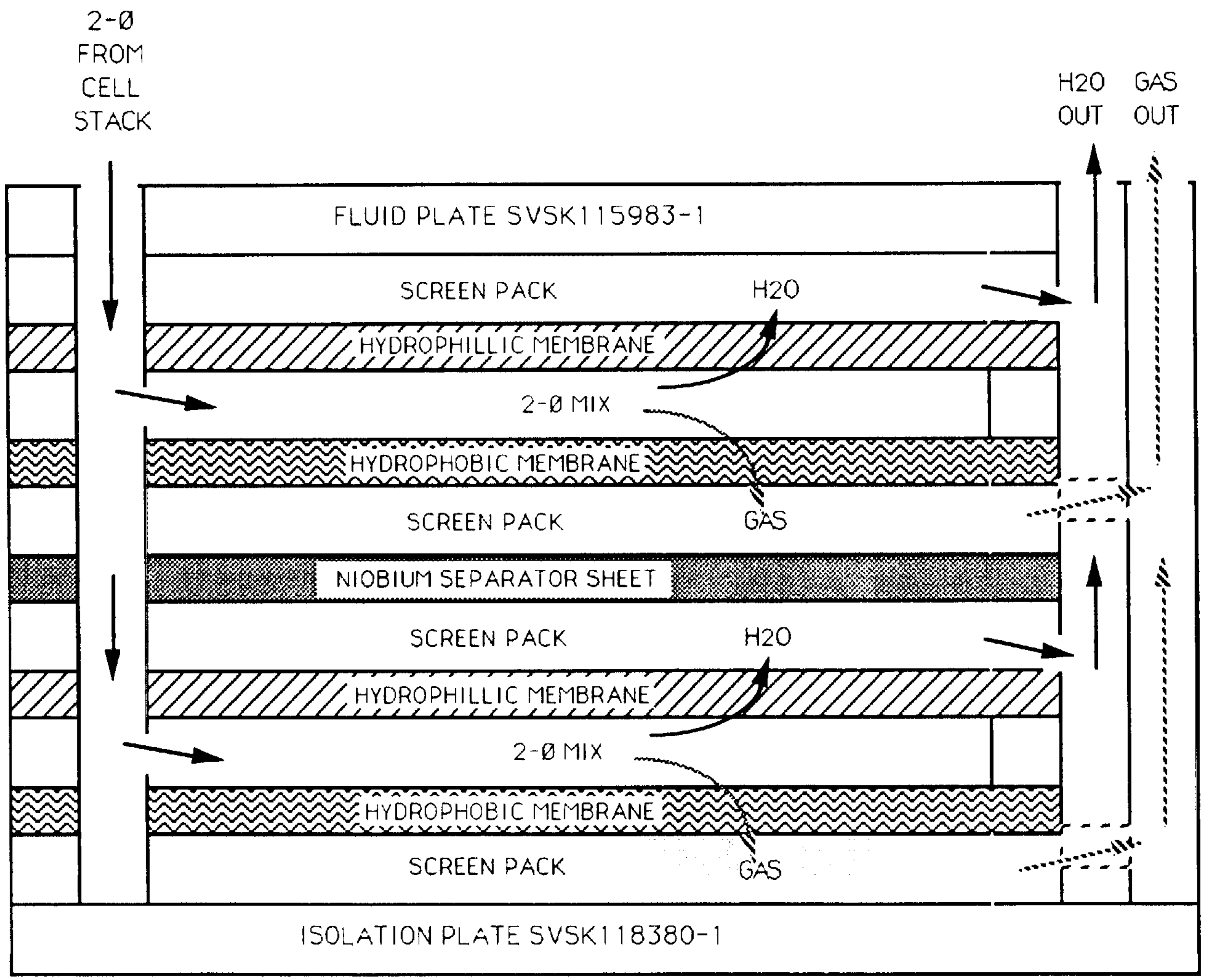
Electrolysis Stack	**Inlet**	**Outlet1**	**Outlet2**
Flow rate lb/hr			
H_2O liquid	1000	960	36
O_2 gas @ 3100 psi		3.6	
H_2 gas @ 3000 psi			0.4
Operating Temp. Range	62-115oF		

Oxygen Phase Sep.	**Inlet**	**Outlet1**	**Outlet2**
H_2O Liquid	960	960	saturated with dissolved O_2
O_2 gas	3.6	3.6 sat. w/water vapor	
Operating Temp Range	62-92oF		

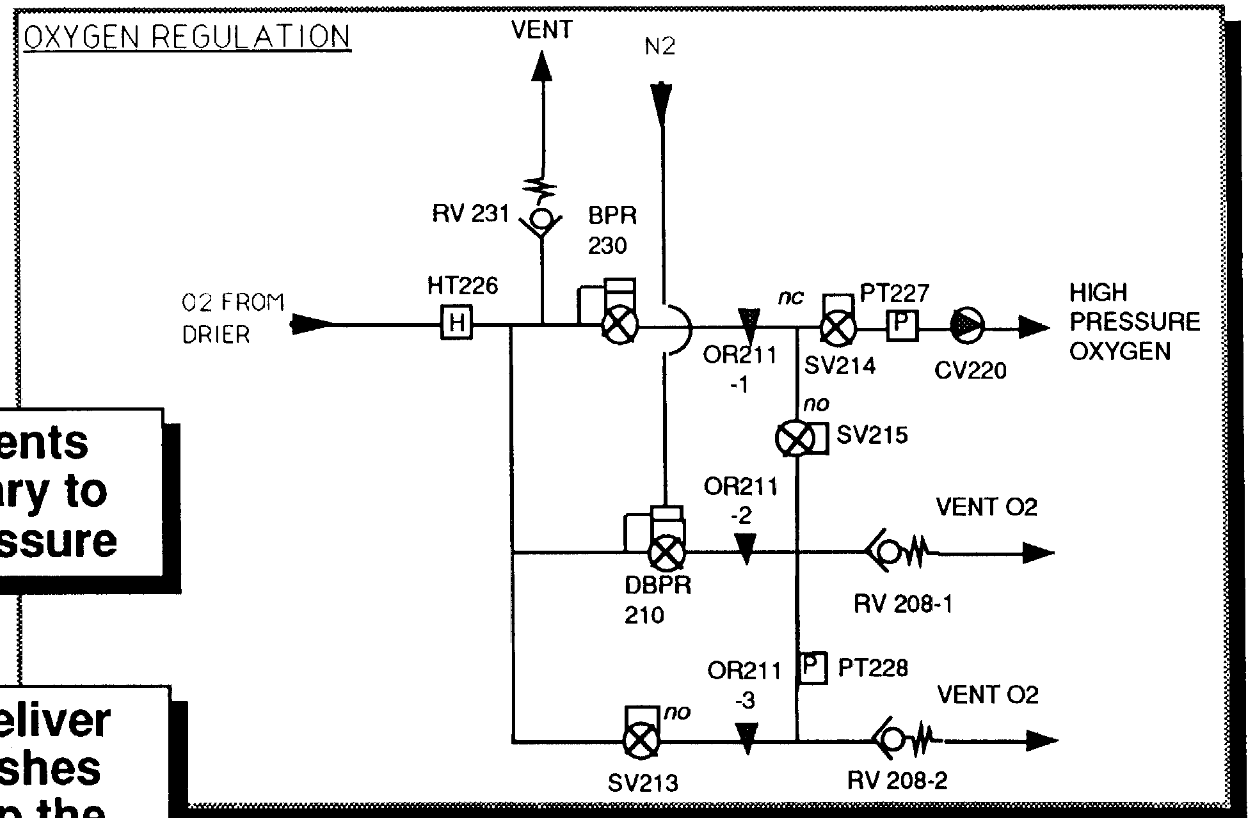
Hydrogen Phase Sep.	**Inlet**	**Outlet1**	**Outlet2**
H_2O Liquid	3.6	3.6	no dissolved H_2
H_2 gas	0.4	0.4 sat. with water vapor	
Operating Temp Range	62-115oF		

Electrolysis/Phase Separator Module

Static Phase Separator (Baseline)



O_2 Pressure Control Module

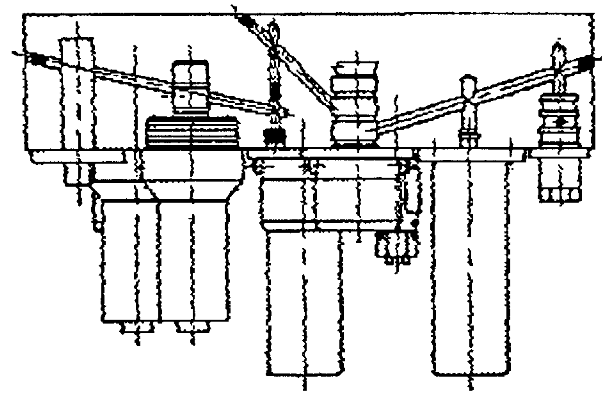


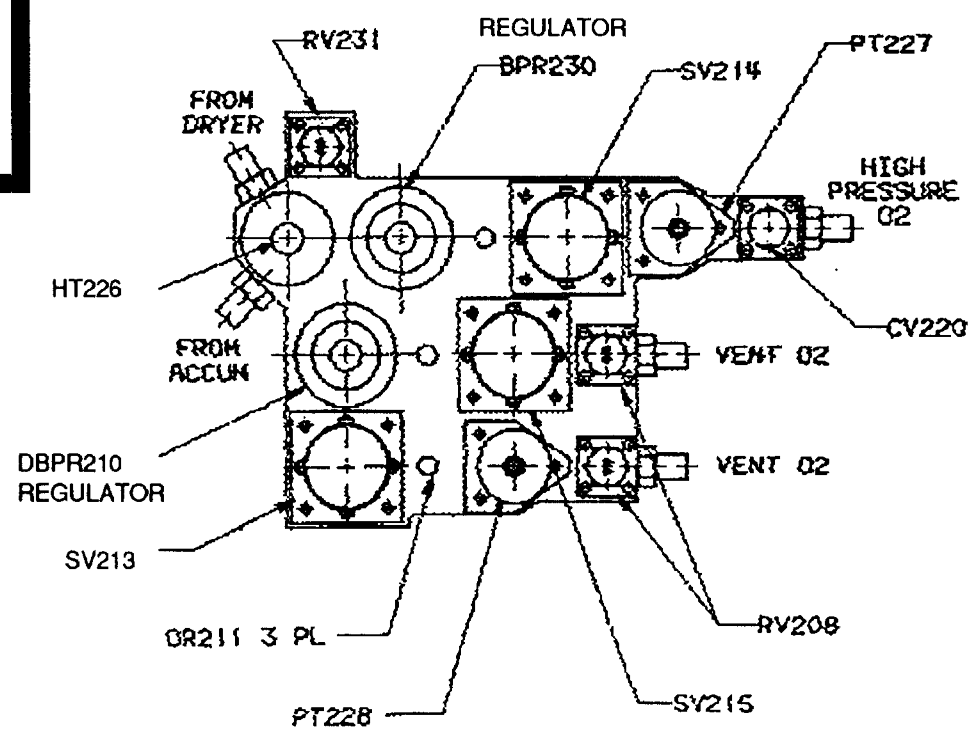
Contains all components and sensors necessary to safely control O_2 pressure

BPR230 is fixed to deliver at 3100 psi. It establishes pressure to bootstrap the N_2 reference gas.

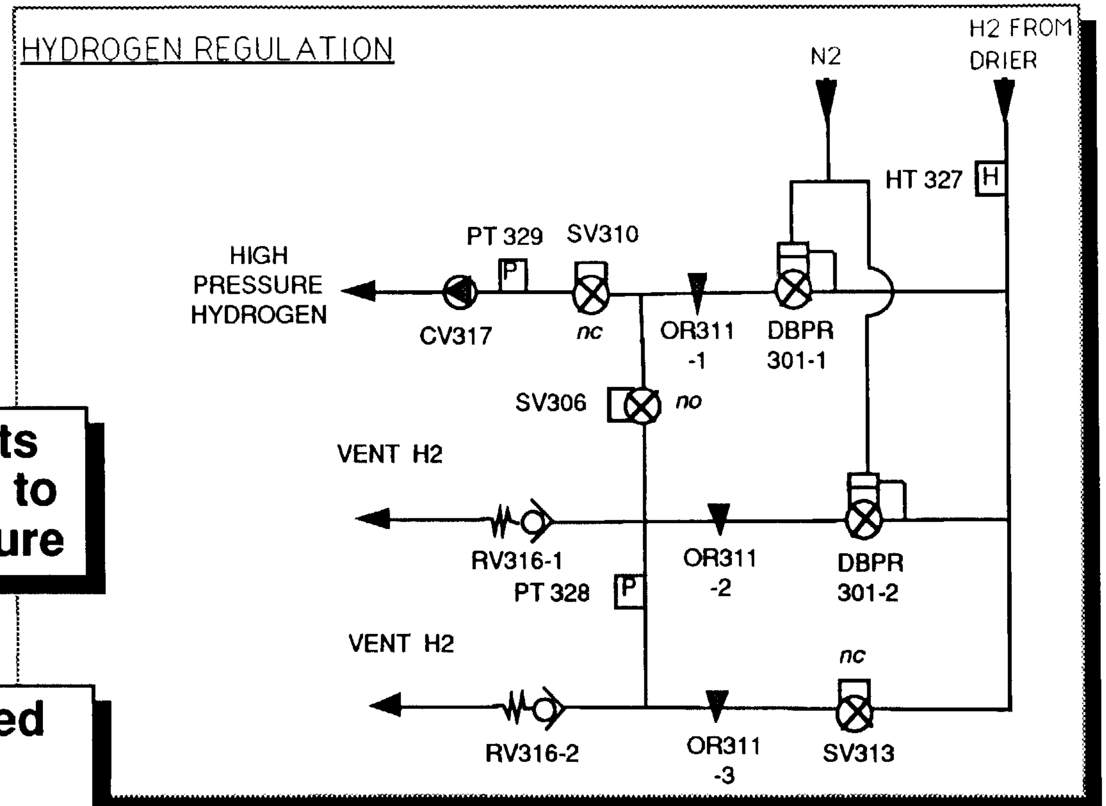
Components plug into a machined manifold block of O_2 compatible material. Electrical leads are wired into a module wire harness and single module connector.

O_2 Pressure Control Module: Conceptual Layout





H_2 Pressure Control Module



Contains all components and sensors necessary to safely control H_2 pressure

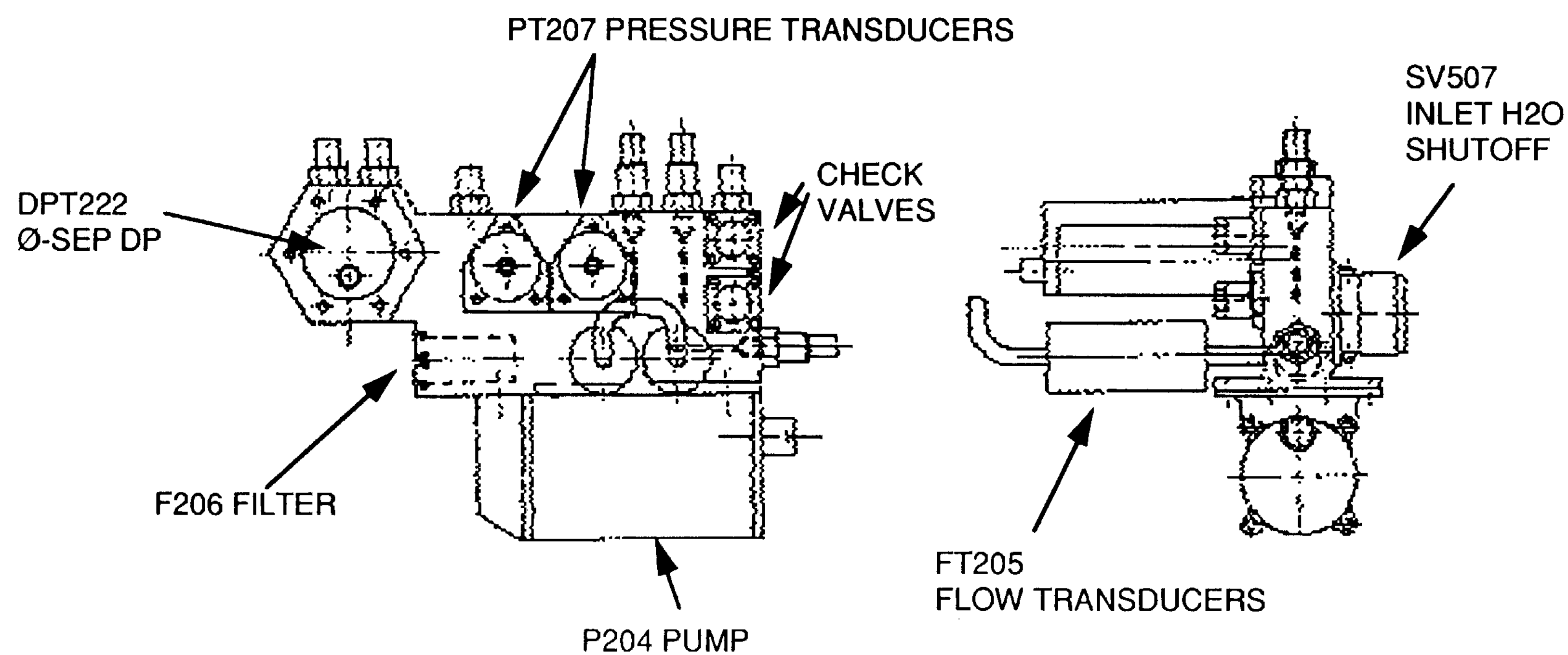
DBPR301-1 is referenced to N_2 pressure so as to control at O_2 -100 psi

Concept layout is similar to O_2 pressure control module

Components plug into machined manifold block of 316L SS. Electrical leads are wired into a module wire harness and single module connector.

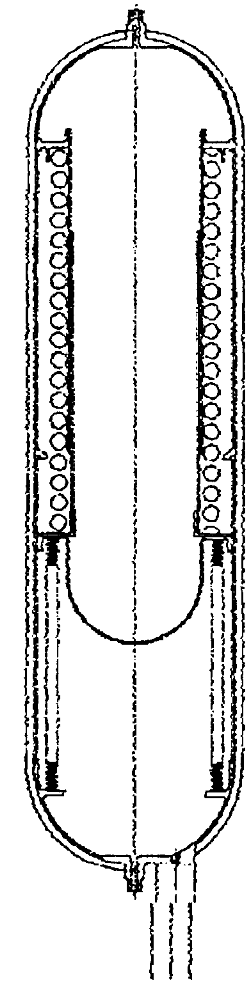
Recirculation Module

- Contains all components in the oxygen/water recirculation loop except the stack and heat exchanger.
- All components mount to a machined manifold
- Electrical connections are wired into a common module wire harness and connector.



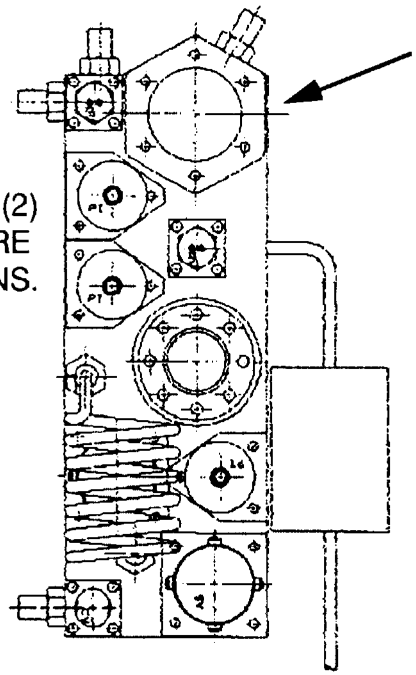
Bubble Accumulator

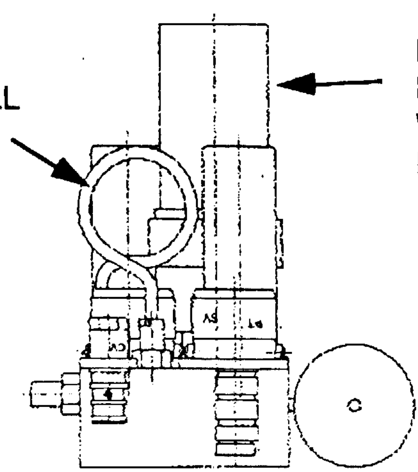
The bubble accumulator provides expansion volume for H_2O-evolved O_2 during depressurization, especially loss of power depressurization



- **O_2 side spring (15-30 PSID) keeps bellows collapsed during normal operation**
- **Inconel bellows has 6.5" mean diameter and 11.25" stroke**
- **Composite pressure vessel with Inconel liner**
- **External-mount bellows position sensor**
- **32" overall length**

Protonic Water Module

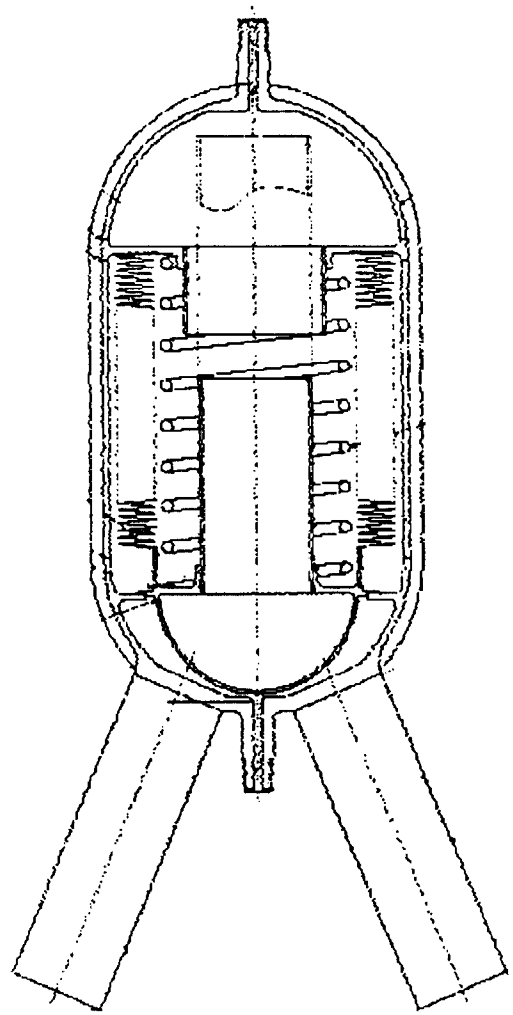




Handles protonically pumped water from separators/strippers, recovering it into the O_2 side water recirculation loop

- **Contains all components in the protonically pumped water recirculation loop except the stack/separator and protonic accumulator**
- All components mount to a machined manifold; electrical connections are wired into a common module wire harness and connector.
- **Fluid interfaces are to & from stack and separator and protonic water accumulator**
- Dwell tube affords required residence time for analysis of protonic water

Protonic Water Accumulator

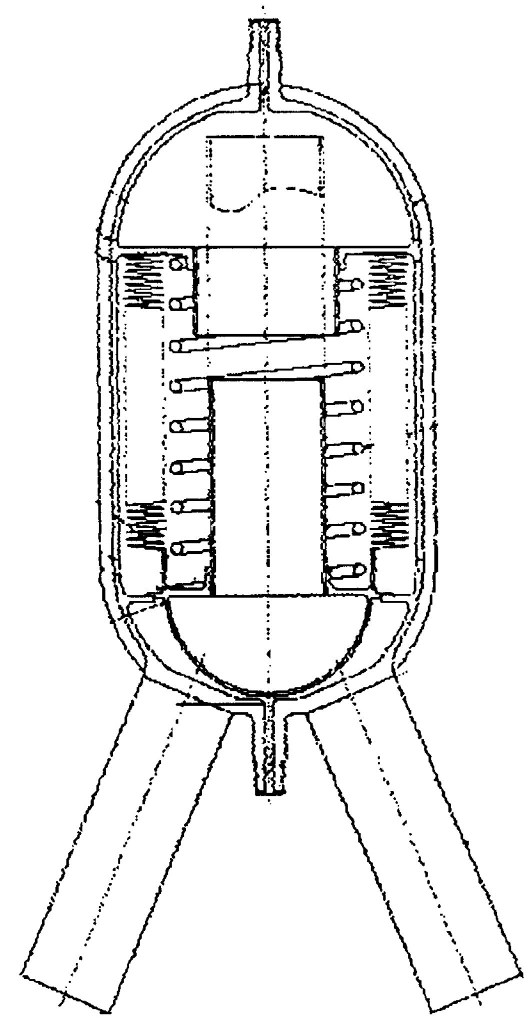


The protonic water accumulator primes the protonic water pump, prevents short cycling of the protonic pump, and provides stability during water/gas slugging through the separator

- **Water side spring assists in filling the bellows with water**
- **Stainless steel bellows has 3.8" stroke**
- **Composite pressure vessel with stainless liner**
- **External-mount bellows position sensors provide analog signal to cycle pump**
- **15" overall length; 5.25" outside diameter**

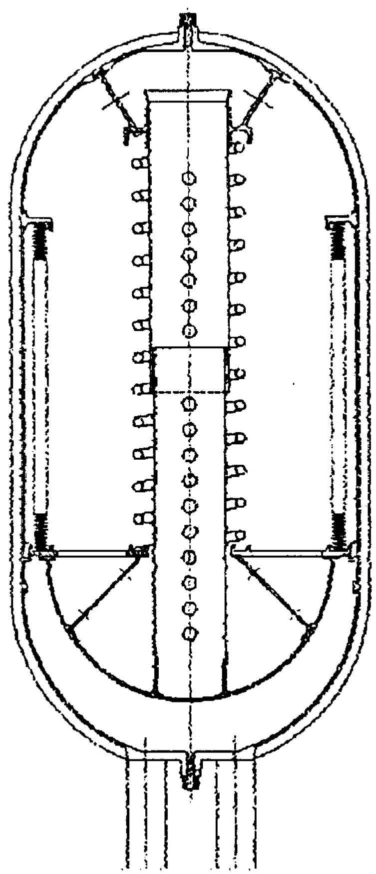
Feed Water Accumulator

The feed water accumulator prevents short cycling of the feed water pump and dampens pressure pulses



- O_2 side spring assists in expelling water
- Inconel bellows has 3.8" dia. ; 5.5" stroke
- Composite pressure vessel with metal liner
- External-mount bellows position sensors provide analog signal to cycle feed water pump
- 15" overall length; 5.25" outside diameter

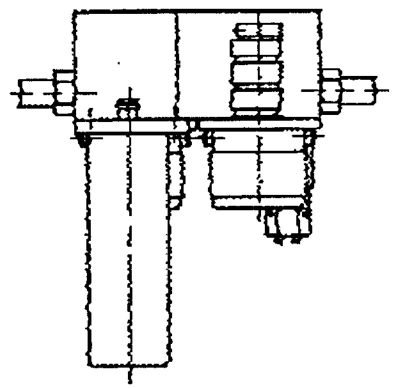
N_2 Bootstrap Accumulator



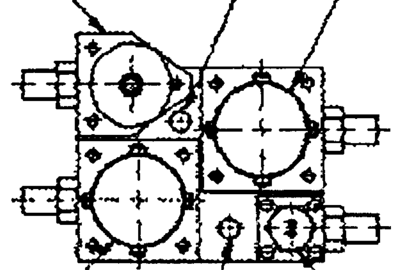
The bootstrap accumulator pressurizes 600 psi N_2 to >3100 psi through compression of the bellows with generated O_2. During depressurization, N_2 expands back into the bellows, saving N_2.

- **O_2 side spring (2-6 PSID) keeps N_2 pressure slightly above O_2**
- **Inconel bellows has 12.5" mean diameter and 11.25" stroke**
- **Composite pressure vessel with Inconel liner**
- **External-mount bellows position sensors**
- **34" overall length; 14" outside diameter**

Nitrogen Supply Module

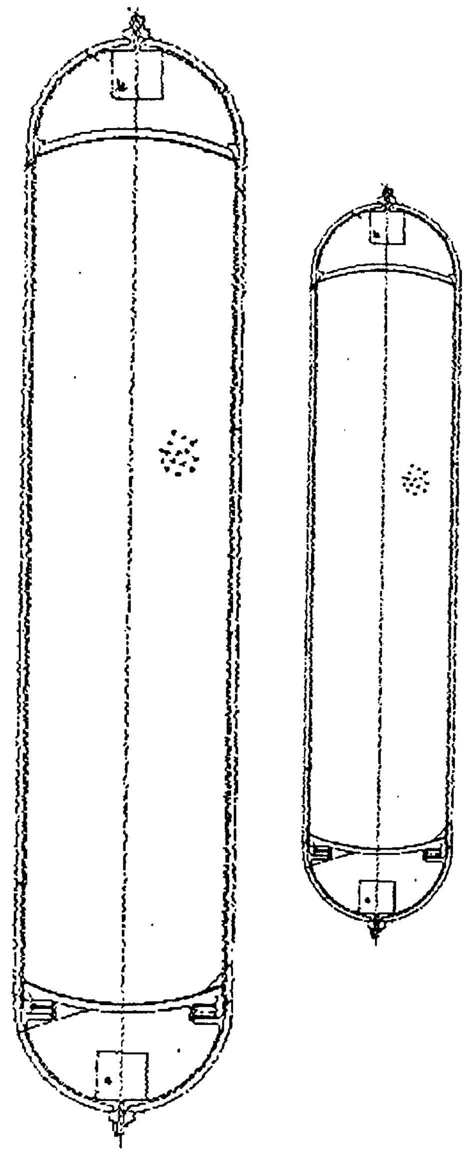


The Nitrogen Supply module regulates the initial fill of the Bootstrap Accumulator with 600 psi nitrogen and can provide overpressure relief if necessary



Components plug into a machined manifold block. Electrical leads are wired into a module wire harness and single module connector.

Non-Regenerable Driers



The driers are 3100 psi pressure vessels filled with molecular sieve material so as to dry the product gases to -100°F dew point

- **Depth filters on outlets and inlets**
- **Spring-loaded inlet mol sieve retaining plate**
- **Kevlar P-V overwrap for lightness**

Characteristics:	**O2**	**H2**
Liner	Inconel	2219 Al
Bed Volume	0.9ft3	3.4ft3
Length	43.5"	65.5"
Diameter	8.3"	13.3"
Avg. inlet gas d.p.	85°F	100°F

Electronic Packaging

All electronics packages mount and conduct heat to a heat exchanger / cold plate surface

- **Six packages on Propellant Generator ORU:**

  EPS • EIB • C-MDM
  Pump motor controllers (2)
  H2 Stripper Power Supply

- **H-S designed packages will have dip-brazed aluminum housings with internal aluminum component mount/heat sinks**

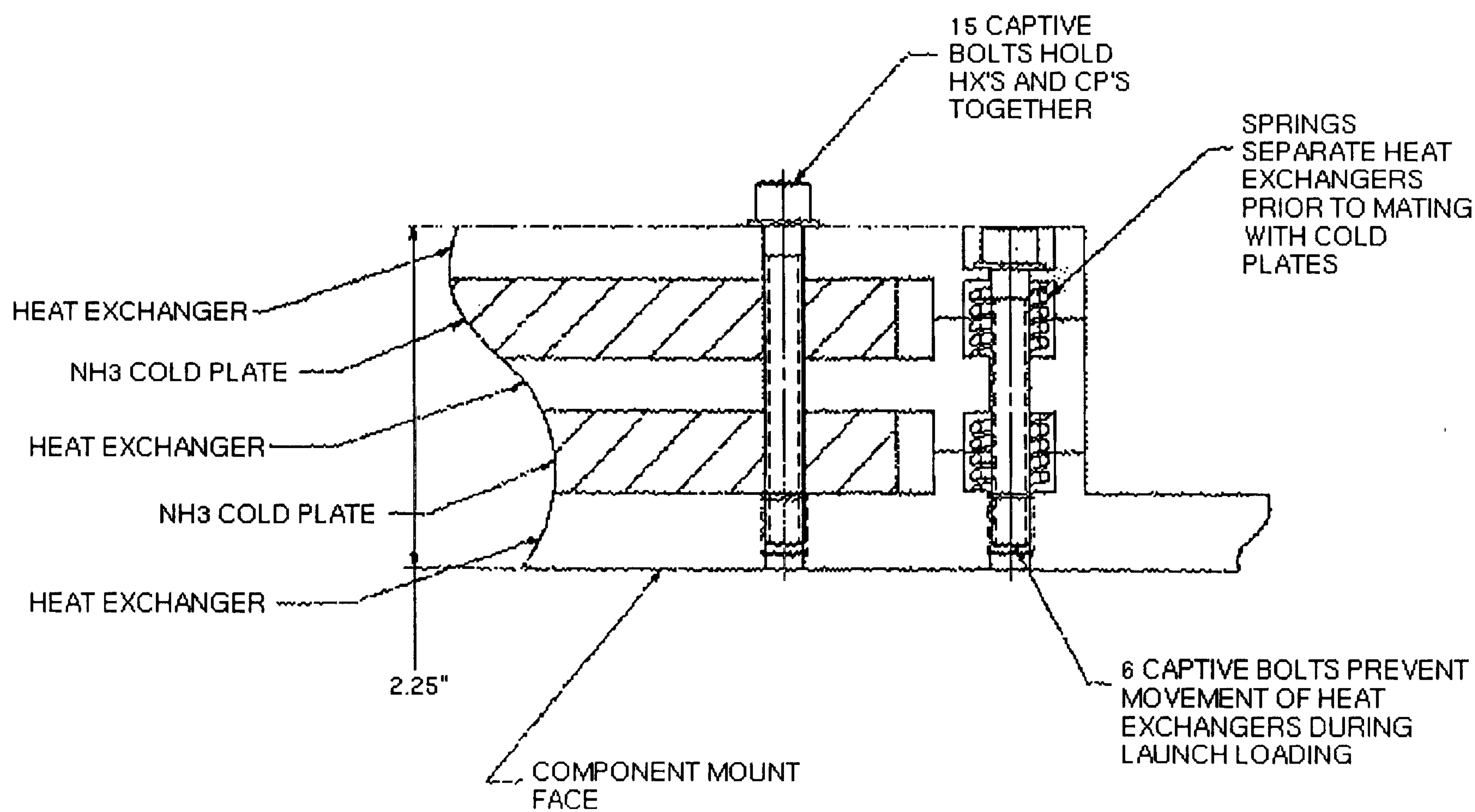
- **The Feed Water ORU has one motor controller**

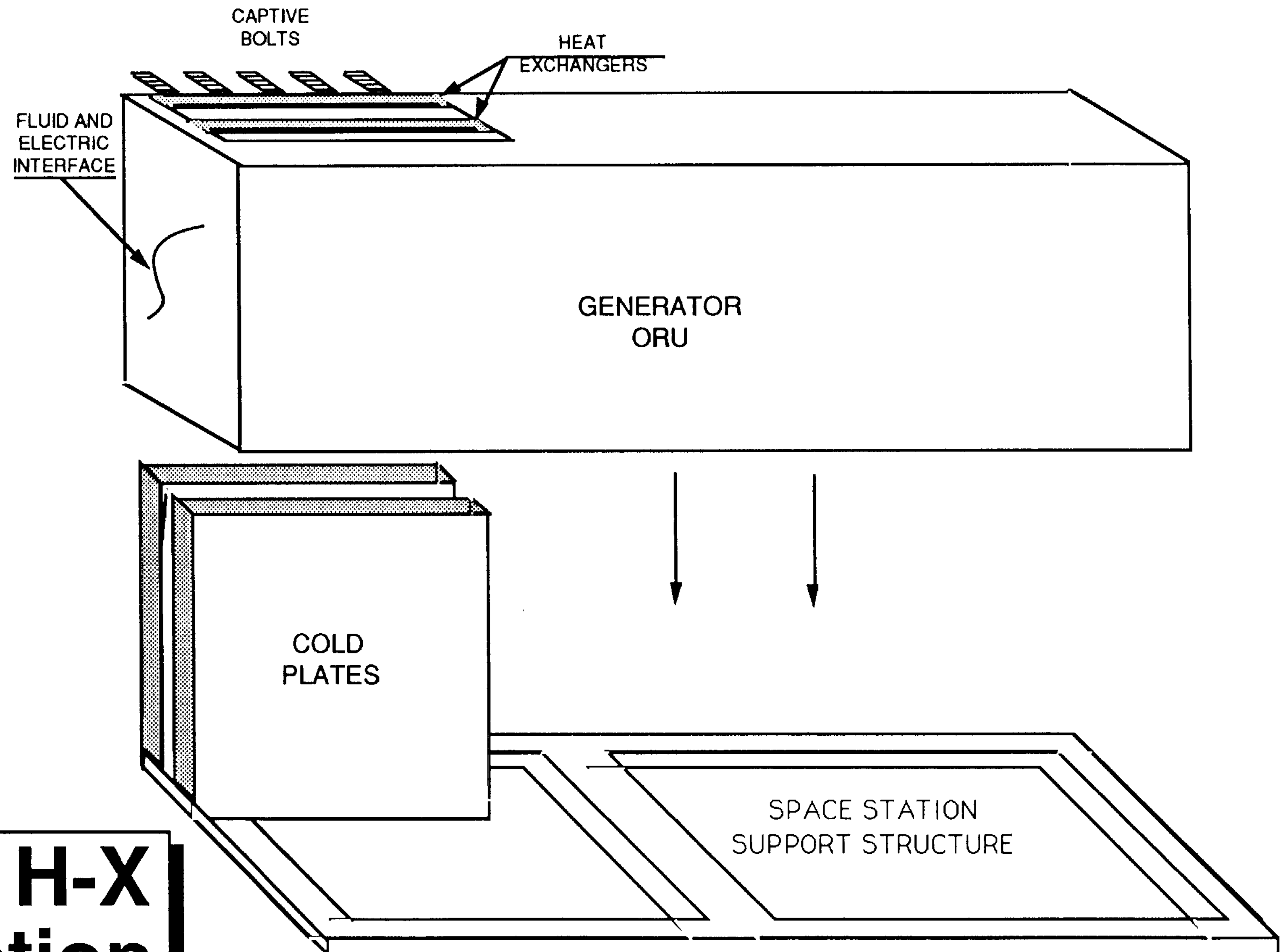
Heat Exchanger / Cold Plate Design Concept

The heat exchanger (part of Propellant Generator) and the mating NH_3 cold plate (part of Space Station interface) are interdependent designs. Electrolysis waste heat and electronic waste heat are removed to the two-phase ammonia loop, assumed to be operating at 62°F

- **Two Heat Exchanger plates, each with sixty 1/4" O_2-side water flow tubes cast into aluminum**
- **Plate dimensions are 30" x 50" (40ft2 total area)**
- **Captive screws hold HX plates together until deployment, when loose captive screws , internal springs spread HX plates apart , allow SSF-mount NH_3 loop cold plates to be inserted**
- **Electrical components bolt to one HX surface**

Heat Exchanger / Cold Plate Cross Section





ORU & H-X Installation

SYSTEM INSTALLATION

- **Fluid and electrical connections on generator ORU are on left hand face**
- ORU is installed by lowering onto support plate over cold plates and fastening captive screws to sandwich cold plates between HX plates. ORU is also fastened to support plate
- **Feed water ORU is mounted in a pressurized node equipment rack**

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