

## Analysis and Test of a Proton Exchange Membrane Fuel Cell Power System for Space Power Applications

Arturo Vasquez

National Aeronautics and Space Administration  
Johnson Space Center  
2101 NASA Road 1  
Houston, Texas 77058

Donald Varanauski Robert Clark, Jr.

The Boeing Company  
Space and Communications Group  
13100 Space Center Blvd.  
Houston, Texas 77059

**Abstract:** An effort is underway to develop a prototype Proton Exchange Membrane (PEM) Fuel Cell breadboard system for future space applications. This prototype will be used to develop a comprehensive design basis for a space-rated PEM fuel cell powerplant. The prototype system includes reactant pressure regulators, ejector-based reactant pumps, a 4-kW fuel cell stack and cooling system, and a passive, membrane-based oxygen / water separator. A computer model is being developed concurrently to analytically predict fluid flow in the oxidant reactant system.

Fuel cells have historically played an important role in human-rated spacecraft. The Gemini and Apollo spacecraft used fuel cells for vehicle electrical power. The Space Shuttle currently uses three Alkaline Fuel Cell Powerplants (AFCP) to generate all of the vehicle's 15-20kW electrical power. Engineers at the Johnson Space Center have leveraged off the development effort ongoing in the commercial arena to develop PEM fuel cells for terrestrial uses.

The prototype design originated from efforts to develop a PEM fuel cell replacement for the current Space Shuttle AFCP's. In order to improve on the life and an already excellent historical record of reliability and safety, three subsystems were focused on. These were the fuel cell stack itself, the reactant circulation devices, and reactant / product water separator. PEM fuel cell stack performance is already demonstrating the potential for greater than four times the useful life of the current Shuttle's AFCP. Reactant pumping for product water

removal has historically been accomplished with mechanical pumps. Ejectors offer an effective means of reactant pumping as well as the potential for weight reduction, control simplification, and long life. Centrifugal water separation is used on the current AFCP. A passive, membrane-based water separator offers compatibility with the micro-gravity environment of space, and the potential for control simplification, elimination of moving parts in an oxygen environment, and long life. The prototype system has been assembled from components that have previously been tested and evaluated at the component level.

Preliminary data obtained from tests performed with the prototype system, as well as other published data, has been used to validate the analytical component models. These components have been incorporated into an integrated oxidant fluid system model. Results obtained from both the performance tests and the analytical model are presented.

### NOMENCLATURE

$\Delta P$  - Delta pressure (kPa)  
 $\dot{m}$  - Mass Flow Rate (kg/sec)  
 $\rho$  - Density ( $\text{kg/m}^3$ )  
 $\gamma$  - Ratio of Specific Heats  
 $a$  - Velocity of Sound (m/sec)  
 $ccm$  - Cubic centimeters per minute  
 $d$  - Diameter (cm)  
 $k$  - Spring Stiffness (N/m)  
 $x$  - Regulator Poppet Displacement (m)

- $A$  - Area ( $m^2$ )
- $F$  - Force (N)
- $L$  - Length (m)
- $M$  - Mach Number
- $P$  - Pressure (kPa)
- $R$  - Gas Constant (N-m/kg-°K)
- $SLPM$  - Standard liters per minute
- $T$  - Temperature (°K)
- $V$  - Velocity (m/sec)

## SUBSCRIPTS

- 1 - Upstream
- 2 - Downstream
- $H$  - Ejector High Pressure Supply
- $R$  - Ejector Secondary Return Loop
- $O$  - Ejector Exit
- crit* - Critical sonic condition across a nozzle

## I. INTRODUCTION

Efforts in the recent past at the Johnson Space Center have concentrated on developing a PEM fuel cell as a long life, lower operating cost upgrade to the current orbiter alkaline fuel cell powerplant. The performance and packaging requirements for the upgraded Shuttle PEM fuel cell are similar to requirements for other proposed space vehicles, such as for 2<sup>nd</sup> generation Reusable Launch Vehicles, Lunar/ Planetary Surface Rovers, and Planetary Transit Vehicle Power Systems. Engineers developing these fuel cell systems for space power applications are leveraging from the research and development that is being completed for terrestrial based PEM Fuel Cell Powerplants (FCPs). However, because of the differences in the operating environments (space vs. terrestrial), several important design parameters must be addressed during the design and development of fuel cell powerplants for space applications (Reference 1). Of course, many different system configurations might be arrived at using basic PEM fuel cell stack and accessory section building-block elements. The following design parameters from Reference 1 have specifically been addressed in the development of this design.

1. Stack humidification. The system design provides for reactant prehumidification by mixing humid gas from the fuel cell oxidant water outlet through a passive water separator with dry oxidant gas from the

supply. The level of prehumidification is dependent on stoichiometric flow ratios developed between the circulation and consumption flow streams.

2. Product water removal. This design incorporates an external water removal scheme whereby excess oxidant flow entrains the product water in the vicinity of the internal cell reaction sites and sweeps it out to a common cell manifold. From there, the circulating oxidant stream continues to sweep the product water out of the stack.
3. Product water separation. The circulating oxidant stream continues to move the product water into a passive water separator. This device consists of an assembly of membranes, flow passages, and manifolds that provide for the two-phase oxidant gas and product water stream to be separated.
4. Reactant pumping. Oxidant gas circulation is accomplished with the use of ejectors and external sense regulators.

## II. JSC PASSIVE, SELF-REGULATING PEM FUEL CELL POWERPLANT

The breadboard at JSC is currently demonstrating operation of a set of PEM fuel cell components in an integrated, self-regulating, passive system configuration. This system is similar to a previously patented configuration (Reference 2) that performs reactant circulation with a regulated vacuum ejector. The particular configuration under development at JSC is shown in Fig. 1 in schematic form and pictorially in Fig. 6.

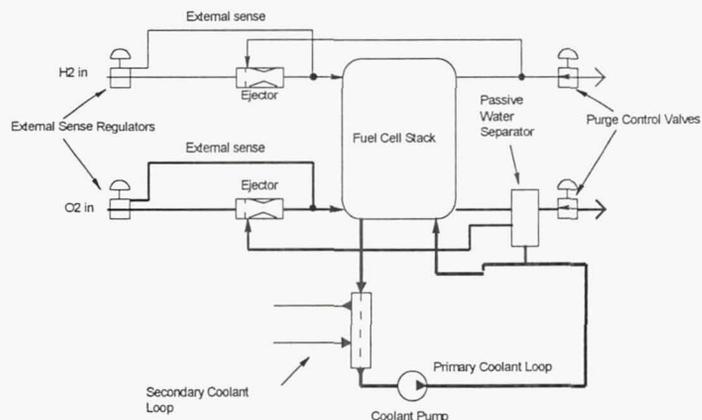


Figure 1 - PEM Fuel Cell Powerplant Schematic

The PEM fuel cell stack is a 15-cell, 4-kW PEM fuel cell stack manufactured by Energy Partners, Inc. The stack incorporates an internal pre-humidification assembly. The use of a gas ejector to circulate fuel cell reactants provides a passive, reliable device offering potentially long service life. An ejector uses a high velocity gas from a high pressure source to entrain and pump gas from its suction port to its exhaust port. For the fuel cell, the high pressure supply gas is the same as the consumption gas stream in the fuel cell. The system uses two types of ejector-based reactant pumps to accomplish both fuel and oxidant gas circulation. The first type was designed and fabricated at the NASA-JSC. The second type is a commercially available Mini-Ejector from Fox Valve Development Company. One Fox Mini-Ejectors is used to provide hydrogen reactant circulation and the NASA-JSC ejector is used to provide oxygen reactant circulation. Water separation from the circulating oxygen stream will be accomplished using a passive, membrane based separator manufactured by Hamilton Standard.

### III. EJECTOR / REGULATOR AND WATER SEPARATOR PERFORMANCE IN THE JSC SPACE PEM FCP DESIGN

As stated in Reference 2, there are several ways to accomplish regulation of the ejector. One method is with the use of a pneumatic pressure transducer feeding back to an electrically operated control valve, which opens or closes as required to maintain pressure downstream of the ejector. Another is to use a mechanical connection between a pneumatically operated positioner and a mechanically operated control valve. This latter method was the avenue chosen for this development effort. A simplified schematic of the external sense regulator and ejector is shown in Fig. 5. This control configuration allows for the ejector supply pressure to vary as the requirement for reactant mass flow through the ejector jet varies. This mass flow requirement is dependent on the consumption flow required by the fuel cell. One of the constraints placed on the ejector performance as it relates to fuel cell performance was that the ratio of fuel cell input flow to consumption flow be greater than 1.5 to facilitate sufficient excess reactant flow through the cells to remove product water from the cell stack. Conversely, one of the requirements for the flow resistance of the fuel cell system (fuel cell stack, water separator, and interconnecting tubing) be that delta pressures developed

at stack inlet flow rates of 1.5 times or greater the consumption flow rate be less than the delta pressure that an ejector could produce at the given consumption flow rate. The ejector dimensions were  $d_{\text{orifice}}=0.05$  cm (0.02 inch) and  $d_{\text{mixer}} = 0.31$  cm (0.122 inch).

Water separation from the circulating oxygen stream is accomplished using a passive, membrane based separator manufactured by Hamilton Standard. The water separator consists of 12 circular sets of hydrophobic and hydrophilic membranes stacked between two large stainless steel endplates. The separator also incorporates a dome loaded back pressure regulator (BPR) which controls the water pressure inside the separator to approximately 20.7 kPa (3 psi) less than the gas outlet pressure. A simplified, exploded view of the water separator is shown in Fig. 2.

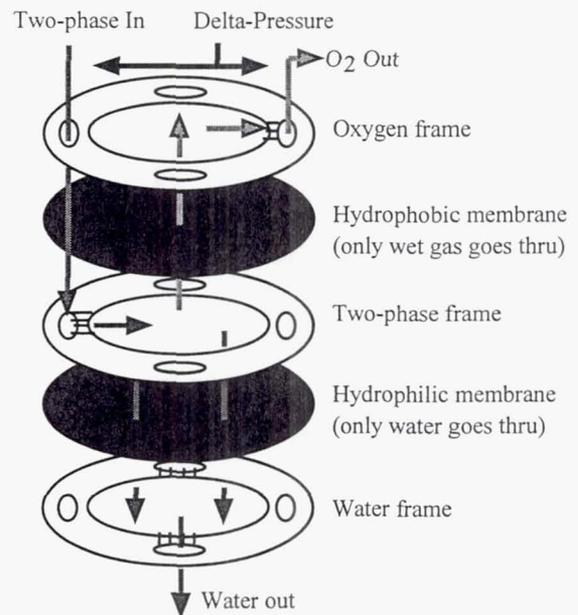


Figure 2 - Passive Water Separator Internal Flow Schematic

The water separator was designed to separate up to 100 SLPM of gas and 125 ccm of water at operating pressures of 0-517 kPa (0-75 psia) and temperatures between 4.4-93.3°C (40-200°F). In addition, the water separator was designed to perform this function with a pressure drop across the gas membrane of < 20.7 kPa (3 psi). The water separator is shown installed in the PEM fuel cell test system in Fig. 6. Approximately 140 hours of time have been accumulated on the water separator with acceptable performance.

#### IV. FUEL CELL OXIDANT FLOW ANALYTICAL MODEL

The computational analysis focused on the oxidant portion of the fuel cell system. The goal of this modeling effort was to provide first-order transient predictions of the fluid flow within the oxygen system. This first-order degree of freedom was chosen in order to simplify the initial modeling task. A more complex effort may be applied in future efforts if the initial modeling attempt does not provide sufficient accuracy.

EASY5, a software package developed by Boeing Computer Services (Reference 3), was used for modeling the fuel cell system. This software is a general engineering tool that provides time and frequency-domain analyses. Fluid macro components utilizing a one-dimensional node-flow method, developed by Boeing's Orbiter Systems Dynamics Group (Reference 4), were used to denote the fuel cell system components. These macro components were the building blocks of the computational analysis of the fuel cell system.

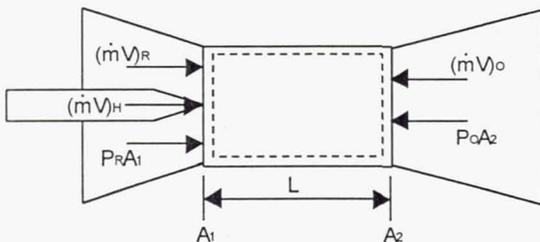
#### V. SYSTEM COMPONENT MODELING

##### A. Ejector

The NASA-JSC gas ejector system was the most important component developed for this modeling effort. References 5 and 6 detail the performance of the ejector; however, they rely solely upon steady state relationships. Transient flow equations were then derived from these relationships. The equations are necessary to accurately model the entrainment flow of the ejector's secondary supply line.

As mentioned before, the ejector relies on a small quantity of high-pressure gas fed through a nozzle to entrain a comparatively larger amount of gas through a mixer and diffuser. A control volume (CV) is drawn around the Mixer Section of the ejector, refer to Fig. 3.

Figure 3 - Forces acting upon the ejector control volume



There is a constant cross sectional area across this CV. The gas within the CV is assumed to be an ideal gas with isentropic flow characteristics. Constant pressure is also assumed within the CV. The  $P_R A_1$  term, the secondary return pressure force, acts upon the entire entrance of the mixer section. This is a valid assumption when the CV is positioned just beyond the end of the nozzle.

Summing the forces on the gas in the CV yields,

$$\sum_{\rightarrow} F = (\dot{m}V)_R + (\dot{m}V)_H - (\dot{m}V)_O + P_R A_1 - P_O A_2 = \rho L A \frac{dV_O}{dt} \quad (1)$$

where  $\dot{m}_H$  can be represented by the calculated mass flow through a nozzle, as seen below.

$$\dot{m}_{orifice} = ACdP_1 \sqrt{\frac{2\gamma \left[ \left( \frac{P_2}{P_1} \right)^{\frac{2}{\gamma}} - \left( \frac{P_2}{P_1} \right)^{\frac{\gamma+1}{\gamma}} \right]}{(\gamma-1)RT_1}} \quad (2)$$

$$\dot{m}_H + \dot{m}_R = \dot{m}_O \quad (3)$$

The change in flow through the ejector, EQ. (4), can be derived by substituting EQ. (2) for  $\dot{m}_H$  and solving for  $\dot{m}_R$  from the continuity relationship, EQ. (3).

$$\frac{d\dot{m}_O}{dt} = \left\{ P_R A_1 - P_O A_2 - f(\dot{m}_O) \right\} \frac{1}{L} + \left\{ \left( \frac{\dot{m}^2 RT}{PA} \right)_R + \left( ACdP_1 \frac{2\gamma}{(\gamma-1)} \sqrt{\left( \frac{2}{R\gamma^{\frac{2}{\gamma}} - R1^{\frac{\gamma+1}{\gamma}} \right) \left( 1 - R1^{\frac{\gamma-1}{\gamma}} \right)} \right) - \left( \frac{\dot{m}^2 RT}{PA} \right)_O \right\} \frac{1}{L} \quad (4)$$

where  $f(\dot{m}_O)$  represents the viscous drag force and  $R1$  is defined by EQ. (5).  $R1$  has a minimum value limit  $R1_{crit}$ , as defined by EQ. (6).

$$R1 = \frac{P_R}{P_H} \quad (5)$$

$$R1_{crit} = \left( 1 + \frac{\gamma-1}{2} \right)^{\frac{\gamma}{1-\gamma}} \quad (6)$$

The ejector model component was validated using both analysis results from Reference 6 and actual fuel cell test stand results. A test case from Reference 6 was used to

validate the transient equations derived by the authors of this report. The preset data from this test case was entered into the model. Table 1 shows that the model results were actually more accurate than the predicted results from that analysis.

	Jet Pr. kPa	Jet Flow kg/hr	Sec. Loop Pr. kPa	Sec. Loop ΔP kPa	Sec. Flow kg/hr	Mass Ratio
Predicted	358.53*	1.303	126.86*	1.234*	12.02	9.23
Experimental	358.53*	1.293	126.86*	1.244*	12.473	9.65
Model	358.53*	1.293	126.86*	1.241*	12.469	9.64

\* these values are initial conditions for experiment, prediction and model results

Table 1 - Predicted and Experimental (Reference 6) vs. Model Ejector Values

### B. Regulator

The dome regulator was modeled using data provided by the manufacturer. This is a modified regulator that uses an external sense line to regulate the pressure of the system downstream of the ejector, refer to FIG 5. The inclusion of this sense line creates four separate chambers within the regulator, all with distinct pressure forces, refer to FIG 4. Equation (7) shows the forces acting on the regulator poppet.

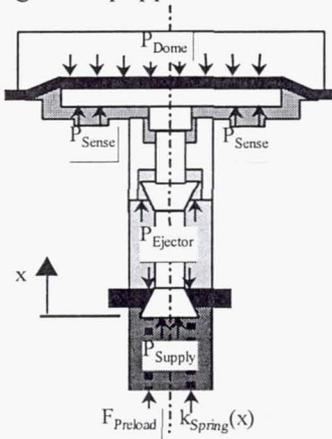


Figure 4 - Forces acting upon the regulator poppet

$$\sum \downarrow F = (PA)_{Dome} - (PA)_{Sense} - (PA)_{Supply} - (PA)_{Ejector} - F_{Preload} - k_{Spring}(x) = Mass_{poppet} \ddot{x} \quad (7)$$

The regulator orifice opening area with respect to poppet position and the spring and preloaded forces were estimated from test data. The single degree-of-freedom regulator model was verified using test data.

The regulator model also includes a Proportional-Integral-Derivative (PID) controller. The PID controller simulates the electronic control software being used to regulate the dome pressure on the fuel cell test stand.

### C. Fuel Cell Stack and Water Separator

Due to the complex internal dynamics associated with the fuel cell stack and the water separator, the current modeling efforts focus only on the effective pressure losses associated with the flow through both of these components. This simplification still provides acceptable first order predictions of flow characteristics.

During certain tests, the fuel cell system experienced excessively humid, and in some cases, two-phase flow (gas and water), between the fuel cell stack and the water separator. One disadvantage to the current modeling approach is the inability to handle the more complex interaction of two phase, or humid, fluid flow in the breadboard.

## VI. CORRELATION OF OXIDANT FLOW ANALYTICAL MODEL TO TEST RESULTS

The correlation between the ejector model predictions and the actual Fuel Cell test data is shown in Table 2.

Data From	Equivalent Power Level Amps	$m_r$ kg/sec	$m_H$ kg/sec	$m_r/m_H$	$P_H$ kPa	$P_R$ kPa	$\Delta P$ kPa	$P_o$ kPa
PEMFCP	140.7	1.810E-04	1.754E-04	1.03	580.74	438.944	8.813	447.757
Model		1.790E-04	1.752E-04	1.02	579.90	438.28	9.47	447.75
PEMFCP	241.1	4.496E-04	3.102E-04	1.45	765.32	430.175	14.67	444.845
Model		4.560E-04	3.100E-04	1.47	764.90	429.77	15.07	444.84
PEMFCP	340.5	7.051E-04	4.379E-04	1.61	1001.99	414.835	21.244	436.079
Model		7.140E-04	4.380E-04	1.63	1001.60	414.46	21.62	436.08

Table 2 – Fuel Cell Data vs. Model Predictions

## VII. CONCLUSIONS

The results of preliminary breadboard system tests and analyses have been presented. The breadboard system continues to be refined and evaluated, especially with respect to improving and understanding the thermal interdependencies of the breadboard system components. The effort to produce a first order fluid model of the system has been successful. Including thermal aspects of the system in the analytical model is currently the next planned step in the development of the system model. A PEM fuel cell system based on the design presented here continues to offer the potential to meet the long-duration,

low-cost, low-maintenance, and high safety and reliability requirements for future space power applications.

### VIII. REFERENCES

1. "Development of a Space-Rated Proton Exchange Membrane Fuel Cell Powerplant", AES-Vol. 39, Proceedings of the ASME Advanced Energy Systems Division, 1999, ASME 1999, pp. 317-325.
2. Merritt, Robert D., Gorbell, Brian N. of Ballard Power Systems, Inc. (North Vancouver, CA). U.S. Patent #5,441,821, "Electrochemical fuel cell system with a regulated vacuum ejector for recirculation of the fluid fuel stream.", Aug. 15, 1995
3. EASY5x, Analysis Software, Boeing Computer Services, The Boeing Company, Seattle WA.
4. Clark, R. W., Arndt, S. D., Hurlbert, E. A. "Analysis of Fluid/Mechanical Systems using EASY5", Fourth Annual Thermal and Fluids Analysis Workshop, 1992, pp. 155-167, NASA Conf. Pub. 10106.
5. Jalali, S. A., Andrea, S. J. "Ejector Design for the Advanced Technology Spacesuit", Society of Automotive Engineers 28<sup>th</sup> International Conference on Environmental Systems, 1998, SAE Technical Paper 981669.
6. Jalali, S. A., Andrea, S. J. "Advanced Technology Spacesuit Ejector Testing and Analysis", Society of Automotive Engineers 28<sup>th</sup> International Conference on Environmental Systems, 1998, SAE Technical Paper 981670.

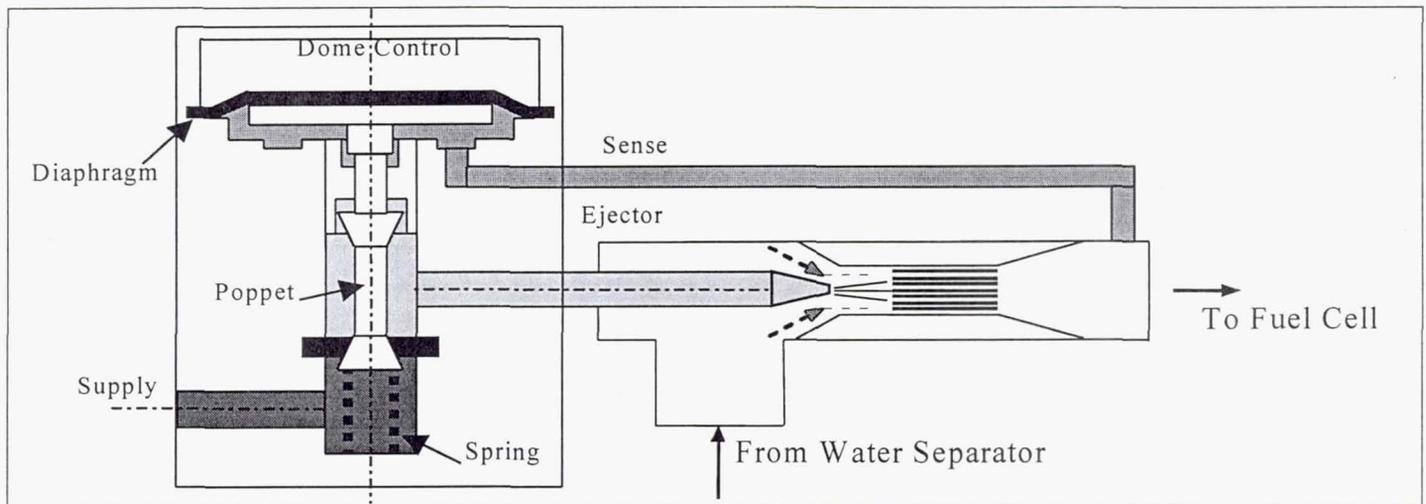


Figure 5 - Regulator Reference Zones and Ejector Layout

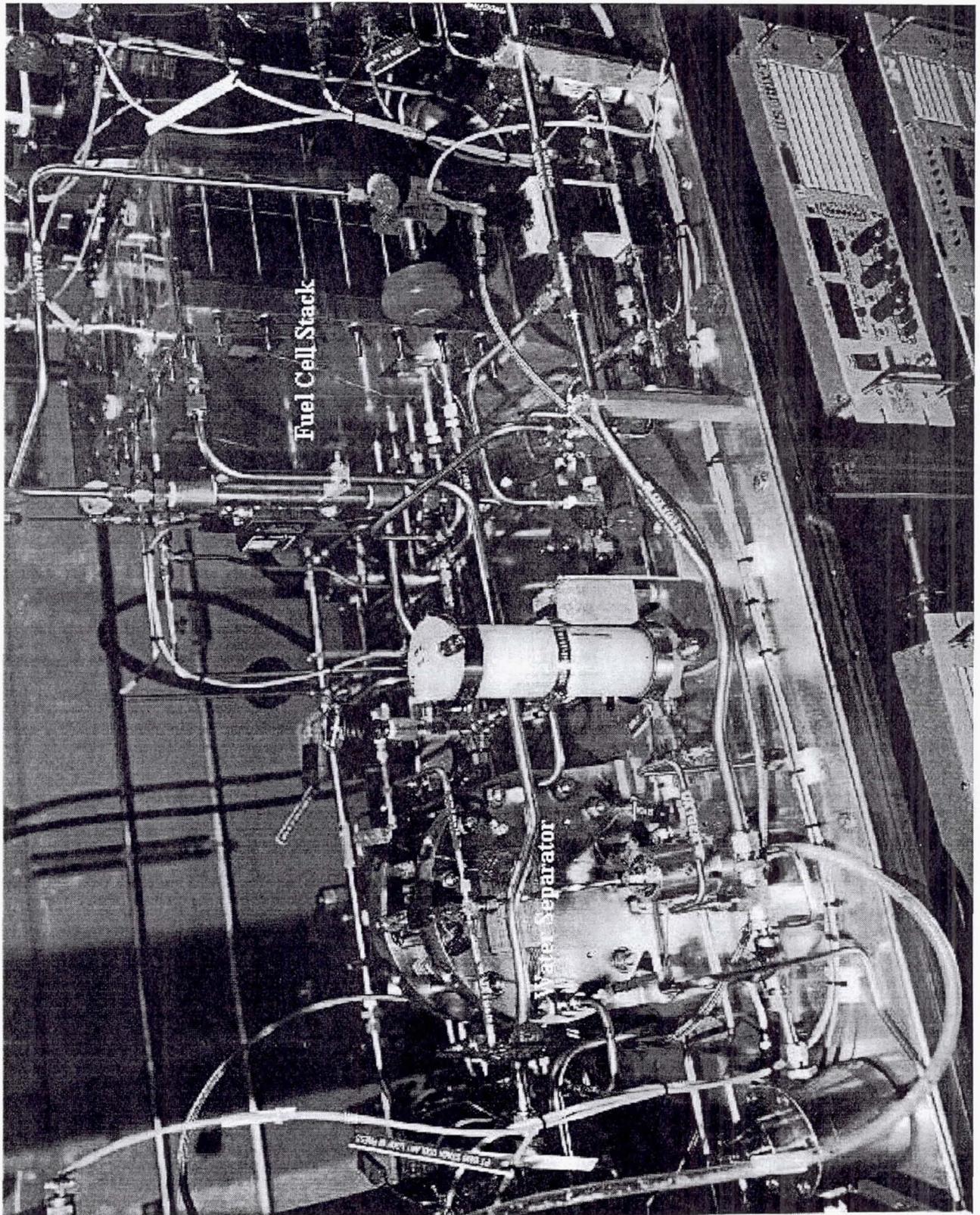


Figure 6 - Integrated PEM Fuel Cell Test System