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ADVANCEMENTS IN OXYGEN GENERATION AND HUMIDITY CONTROL BY WATER VAPOR ELECTROLYSIS

FINAL REPORT

by

D.B. Heppner, M. Sudar
and M.C. Lee

June, 1988

Prepared Under Contract NAS9-17558

by

Life Systems, Inc.

Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract NAS9-17558, during the period of May, 1986 through June, 1988. The Program Manager was Dr. Dennis B. Heppner. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Charles T. Bunnell	Single cell testing, water vapor electrolysis module assembly, module and test stand integration and testing
Dennis B. Heppner, Ph.D.	Program Manager, system design and analysis
John O. Jessup	Test stand design and fabrication and electronic device assembly
M.C. (Gene) Lee, Ph.D.	Water vapor electrolysis cell water balance and flux models, reaction mechanisms
Marty Sudar	Single cell testing, epoxy testing, matrix bubble pressure tests, water vapor electrolysis module total equivalent weight calculations
Dan C. Walter	Water vapor electrolysis cell, module and associated parts design and drawing preparation

The contract's Technical Manager was Ms. Cinda Chullen, Crew and Thermal Systems Division, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, TX.

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LIST OF ACRONYMS

ARS	Atmosphere Revitalization System
ECLSS	Environmental Control and Life Support System
IR	Internal Resistance
OGS	Oxygen Generation Subsystem
ORUs	Orbit Replaceable Units
RH	Relative Humidity
WES	Water Electrolysis Subsystem
WVE	Water Vapor Electrolysis
WVEM	Water Vapor Electrolysis Module

LIST OF SCHEMATIC SYMBOLS

Sensors

D	Dew Point Temperature
E	Cell Voltage
F	Flow
I	Current
P	Pressure
RH	Relative Humidity
S	Speed
T	Temperature
W	Valve Position Indicator
Y	Level Sensor

Actuators

H	Heater
M	Motor
PU	Pump
V	Valve (Electric)

Components

AF	Air Filter
B	Blower
CC	Coolant Control Assembly
CV	Check Valve
EM	Electrochemical Module
F	Filter
FC	Fluids Control Assembly
FV	Filter/Isolation Valve
HX	Heat Exchanger
MV	Manual Valve
PR	Pressure Regulator
SG	Sight Guage
TK	Tank
WA	Water Accumulator

SUMMARY

Regenerative processes for the revitalization of manned spacecraft atmospheres or other manned habitats are essential for realization of long-term space missions. These processes include oxygen generation through water electrolysis. One promising technique of water electrolysis is the direct conversion of the water vapor contained in the cabin air to oxygen. This technique is the subject of the present program on water vapor electrolysis development. The objectives of this program were to (1) incorporate technology improvements developed under other similar electrochemical programs and add new ones, (2) design and fabricate a multi-cell electrochemical module and a testing facility and (3) demonstrate through testing the improvements.

Each aspect of the water vapor electrolysis cell was reviewed. The materials of construction and sizing of each element were investigated analytically and sometimes experimentally. The elements included the electrodes, electrolyte, electrolyte retention matrix, metallic components, cell frames, bonding agents and module construction. In addition, operational considerations such as temperature control in response to inlet conditions were investigated.

Three specific quantitative goals were established. First, the end product water vapor electrolysis cell had to operate for indefinite periods of time over the Space Station cabin air relative humidity range of 25 to 75%. Secondly, a 55 kPa (8 psid) minimum and 69 kPa (10 psid) nominal pressure differential capability across the cell matrix (hydrogen to air cavity) was required. Lastly, cell voltage was to be minimized with a goal of 1.70 V at a current density of 54 mA/cm^2 (50 ASF).

These three totals were established in order of importance to (1) ensure safety of operation, (2) provide operational flexibility and (3) minimize power. The first two goals were completely achieved; the last under limited conditions. Wide-range tolerance to cabin humidity is directly attributable to liquid cooling of the water vapor electrolysis and an algorithm for selecting the optimum coolant temperature. Unitized cell core construction permitted achieving the pressure differential capability. These two demonstrated achievements were the principal results of the program.

PROGRAM ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Achieved sustained one-person level oxygen (O_2) generation performance with state-of-the-art module hardware.
- Incorporated advancements of prior cell technology developments into state-of-the-art water vapor electrolysis (WVE) cell hardware, specifically liquid cooling and unitized core construction.

- Conducted over 1,000 hours of single cell testing, evaluating effects of electrolyte, relative humidity (RH), operating pressure and electrode construction on cell performance.
- Designed, developed and tested an advanced WVE module which utilized advanced components in cell hardware, end plates and operation.

INTRODUCTION

The WVE concept consists of electrochemical cell hardware to generate O_2 from water vapor contained in the cabin air. The removal of water vapor from cabin air results in partial humidity control, but more importantly, it provides the source for O_2 for crew consumption. Figure 1 shows the overall concept and potential uses for the hydrogen (H_2) which is a byproduct of the process.

Background

Environmental Control and Life Support System (ECLSS) technology is required to reduce the operational cost of a Space Station, especially one with projected indefinite operating life, e.g., greater than ten years. A major system of the regenerative ECLSS is the Atmosphere Revitalization System (ARS). Current concepts for revitalizing a Space Station module's atmosphere employ the electrolysis of water for generating O_2. Although years of development have resulted in safe, reliable and efficient subsystems for the primary production of metabolic O_2, these subsystems do not lend themselves to providing metabolic O_2 under certain situations which must be accommodated on the Space Station.

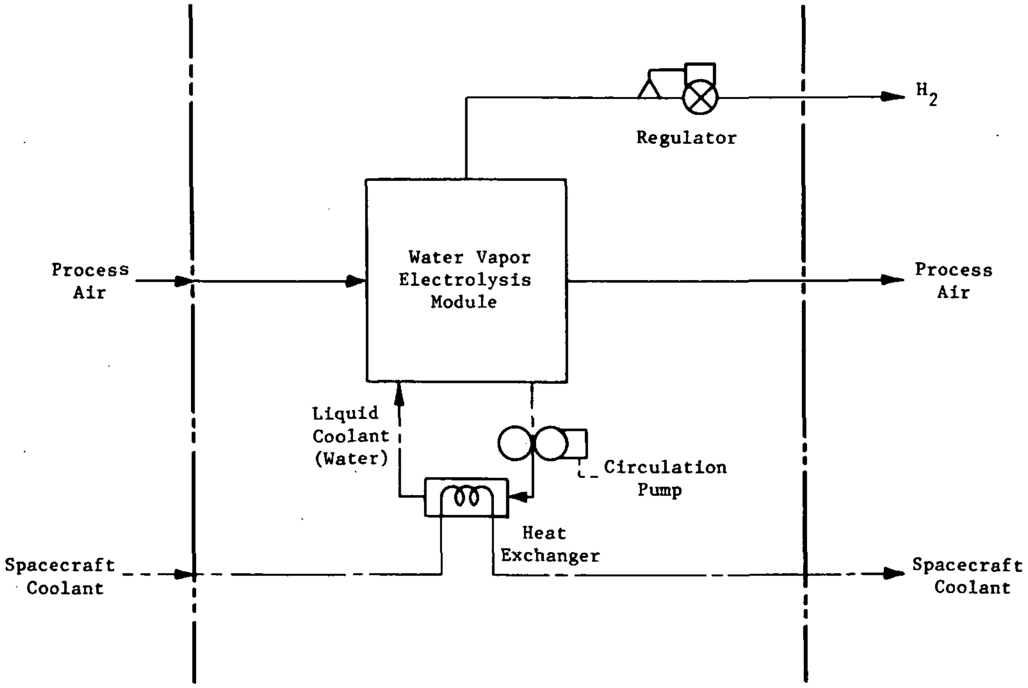
One such circumstance occurs when the crew's life support requirements are not evenly distributed throughout the Station, as in the case where the crew may gather for significant periods of time in any one Space Station module. To size the module's central air distribution and humidity control subsystems to handle these extreme conditions may not be efficient from both the cost and operational point of view. The WVE-based ARS, on the other hand, more effectively meets this need by employing the WVE as a "high activity area" ARS.

Since the WVE has few interfaces, it also lends itself to being "portable" and thus a potential candidate for providing a safe haven ARS. It was the intent of this program to therefore develop the "heart" of the WVE process, the WVE module or electrochemical plant, to the point where it can accomplish a potential mission objectives identified for the ARS.

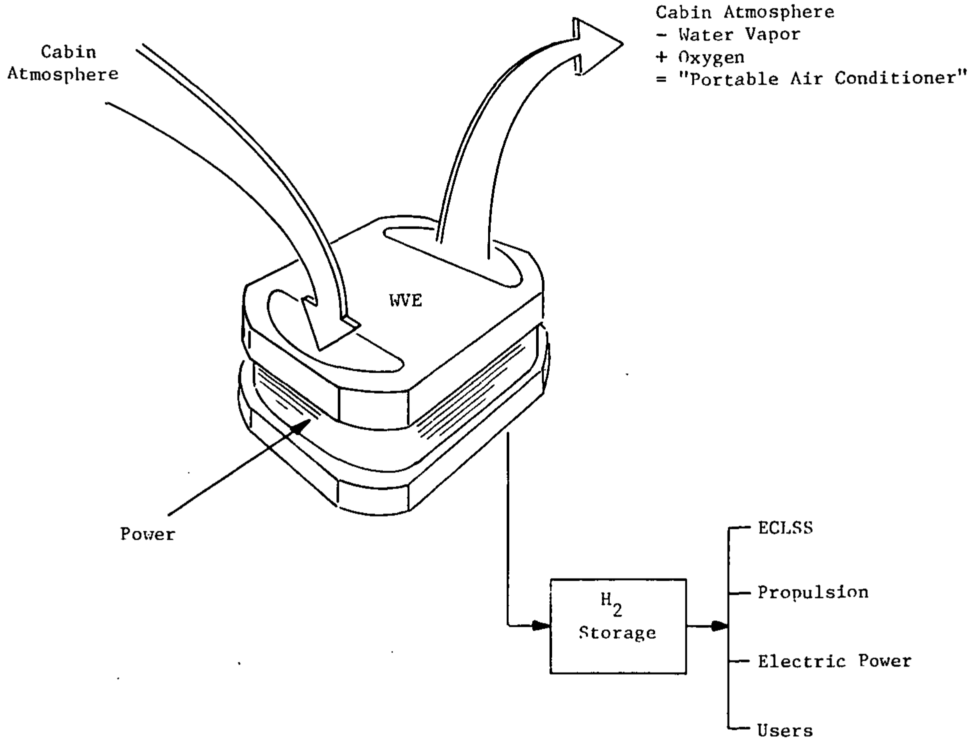
Program Objectives

The major objectives of this WVE program were multiple and included the following:

1. Upgrade the current baseline WVE cell hardware to allow higher pressure differential levels (H_2 to atmosphere) of at least 55 kPa (8 psid), resulting in greater safety margins.



A. Functional Schematic



B. Spacecraft Application

FIGURE 1 WATER VAPOR ELECTROLYSIS CONCEPT

2. Upgrade the WVE module (WVEM) construction for lower volume, lower cost of fabrication and lower weight. This activity also incorporated design improvements generated from other ongoing electrochemical technology programs.

3. Improve the WVE operating voltage to reduce the power needed for dehumidification and O_2 supply.

4. Improve the WVE tolerance to extremes in Space Station module (cabin) dry bulb and dew point temperature (i.e., RH). The ability to operate longer times under very dry or very humid conditions along with the capability of remaining in an overload operational mode (higher water removal and O_2 generation rates) was considered a key objective.

5. Eliminate the need to oversize the central atmosphere control system by using a portable, localized humidity and O_2 partial pressure control.

Program Organization

The program was organized into five major tasks. The specific tasks were:

1. Perform an assessment of the WVE elements and design modifications needed to meet or exceed the WVE performance goals while giving primary consideration to improving operation and performance and enhancing life.

2. Implement a WVE single-cell characterization test program to verify performance goals, expose deficiencies and incorporate recommended improvements into cell design.

3. Design and fabricate a multi-cell WVEM incorporating the new technological features. Also develop a test stand for testing this module.

4. Implement a WVEM test program to verify design and performance.

5. Establish, implement and maintain a mini-Product Assurance program throughout the contractual period to search out quality weaknesses and incorporate appropriate, effective measures.

These primary tasks of the program, along with data and program management requirements, were successfully completed. This Final Report discusses the results of the program. The following sections present the WVE concept and application aspects, a discussion of WVE technology improvements, the testing facilities employed, results of the testing, the conclusions reached and recommendations made.

WATER VAPOR ELECTROLYSIS CONCEPT

The function of the WVE is to generate a quantity of O_2 for metabolic consumption and provide partial humidity control by removing water vapor from the crew atmosphere. Oxygen and H_2 are generated from the water vapor contained in an air stream flowing through an electrochemical module consisting of a series of individual water vapor electrolysis electrochemical cells. Each cell consists of two electrodes separated by a matrix containing an acidic electrolyte. The specific electrochemical reactions are detailed in Figure 2.

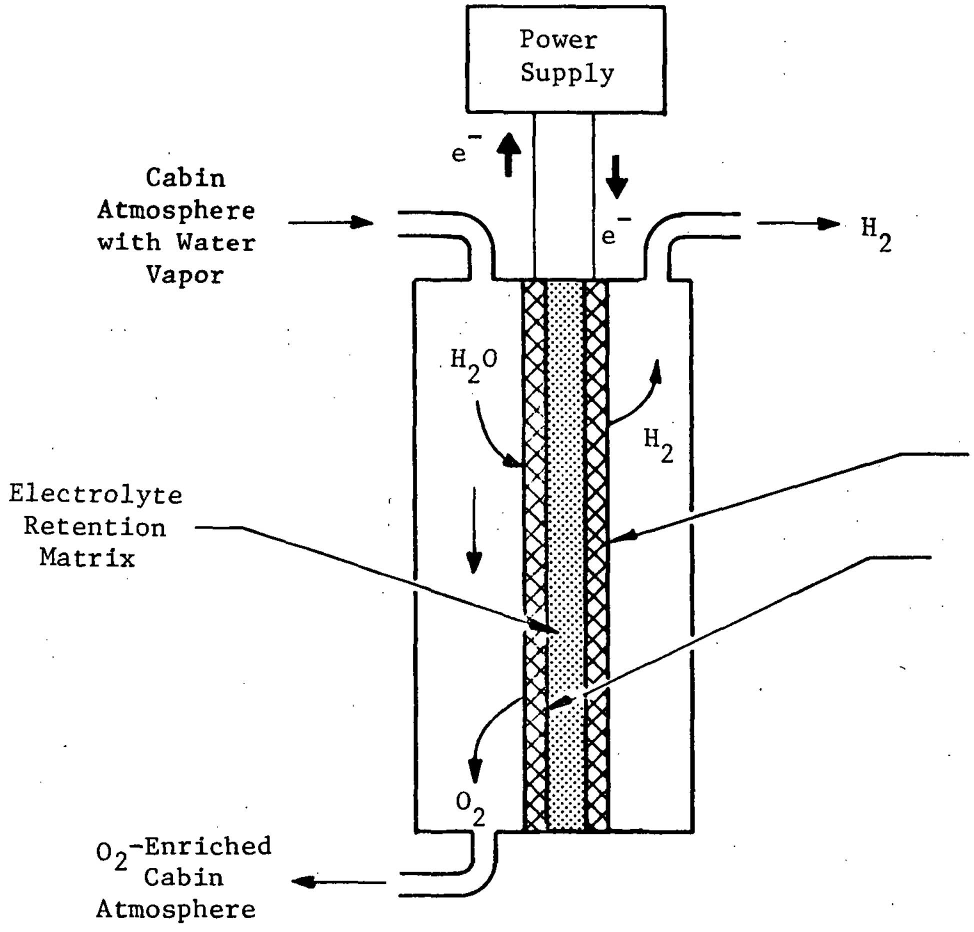
Moist air is fed to the anode compartment where water vapor is first condensed into the electrolyte and then electrochemically dissociated into O_2 and hydrogen ions (H^+) while releasing electrons. The output of the anode compartment is air which has been reduced in humidity and enriched in O_2 content. On the cathode side, H^+ acquire electrons to form gaseous H_2. The overall reaction requires electrical energy, and at practical voltage levels some waste heat is generated.

The performance of a WVE is reflected by voltage which is a direct measure of the power required by the WVE cell or module. Electrical energy consumed by the electrochemical reaction occurring in the WVE is a function of the current and cell voltage. The theoretical voltage required for water electrolysis is 1.23 V. In actual operation, however, higher voltages must be provided to overcome the effects of internal cell resistance (including that of the electrolyte and the electrical contacts) and the chemical activation overpotential. Sufficient energy must be provided to overcome the required activation energy before chemical reaction can proceed. Internal cell resistance is minimized by using highly conductive electrolyte, by providing good contact between cell components and by operating at low current densities. Activation energy and thus, activation overpotential is reduced by using highly active electrocatalysts for the specific reations involved. The use of large catalytic surface areas also contribute to reducing the activation overpotential losses.

High WVE electrical efficiency is reflected by low cell voltages and, therefore, low power consumption to perform the electrochemical process of O_2 and H_2 generation. The acid electrolyte is used in the process because of the presence of carbon dioxide (CO_2) in the process air, which is in direct contact with the anode and electrolyte. If a basic solution were to be used, the CO_2 in the air would combine with the hydroxide (OH^-) ions of the electrolyte to neutralize the electrolyte by creating a carbonate solution. The conductivity of the electrolyte would be reduced and higher theoretical voltages would result.

Design Requirements

A series of design specifications and design guidelines were established at the beginning of the program effort. These also were established with respect to the end-application of a WVE in a Space Station-like environment. This was done to focus the contractual effort on producing the best WVE for eventual Space Station or advanced mission applications.



Cathode: $4H^+ + 4e^- = 2H_2$

Anode: $2H_2O = O_2 + 4H^+ + 4e^-$

Overall: $2H_2O$ + Electrical Energy
$\rightarrow 2H_2 + O_2$ + Heat

FIGURE 2 WATER VAPOR ELECTROLYSIS SCHEMATIC AND REACTIONS

Water Vapor Electrolysis Performance Goals

The WVE design objectives and performance goals are listed in the order of importance as shown in Table 1. Of particular importance is the RH range of 25 to 75% and minimum cabin dew point temperature of 277 K (40 F). The performance goal of operating the WVE at low humidities and at full current densities over indefinite periods of time and still being able to maintain the H_2-to-air differential pressure was considered a key requirement. The module construction of the unitized core and composite cell draws upon prior Life Systems' experience in the electrochemical CO_2 concentrator system where these concepts have proven to be very successful.

Additional design guidelines are listed in Table 2. Some of these are more general and point to an end application.

Water Vapor Electrolysis End-Applications

As part of this program the end-application WVE was projected. The WVE development goals for a subsystem are summarized in Table 3. Given are the performance and operational goals and operational feature goals. These were projected for long-term operation and, while not having direct effect on the technology development program, allowed focus on the end-application.

Shown in Table 4 are the design specifications for a three-person subsystem for Space Station. A schematic for this projected system is shown in Figure 3. Indicated are the orbit replaceable units (ORUs) (eight in number), including the module and its supporting hardware. A projected mechanical component characteristic summary is given in Table 5 for this three-person subsystem.

WATER VAPOR ELECTROLYSIS TECHNOLOGY IMPROVEMENTS

The heart of the WVE is the electrochemical cell where O_2 is evolved on the anode (air side) and H_2 on the cathode. Much of the effort of this program was directed toward performing analyses or experiments which led to selecting the individual components of the electrochemical cell for the anticipated conditions. This section discusses key elements of the electrochemical cell and the results of the studies made for each. The following subsections discuss (a) electrode sizing, (b) electrolyte retention matrix selection and sizing, (c) bonding agents, (d) electrolyte selection, (e) metallics, (f) cell and module construction and (g) module sizing methods.

Electrode Sizing

Figure 4 shows a cross-section of the WVE cell illustrating the electrolyte/gas interface at the anode which, because it is exposed to air which varies in RH, is the principal electrode involved in the water balance. Shown also in Figure 4 is the governing equation for the transport of water vapor from the air to the electrolyte/gas interface. It is the balance of water vapor pressures in (a) the air (determined by air temperature and RH) and (b) the anode (determined by electrolyte temperature and concentration) along with

TABLE 1 ADVANCED WVE DESIGN OBJECTIVES

1. Develop a Unitized Core Which:

	Demonstrated
a. Provides high H_2-to-air pressure differential tolerance	69 kPa (10 psid) at 30% RH
b. Broadens RH tolerance range	25 to 75% RH 278 to 289 K (40 to 60 F) dew point 292 to 300 K (65 to 80 F) dry bulb
c. Provides for reproducible fabrication	Using unitized core
d. Simplifies handling and assembly	--

2. Demonstrate WVE Performance Goals:

No.	Parameter	Value	Conditions	Results
1	Cell Voltage (max), V	1.70	54 mA/cm^2 (50 ASF) 40-75% air RH	Met with H_2SO_4 at DP >284 K (52 F)
2	Inlet Air Relative, Humidity Range, %	25 to 75		Met
3	Minimum Cabin Dew Point, K (F)	278 (40)		Met
4	H_2-to-Air Side Delta Pressure, kPa (psid)			69 (10) demonstrated over RH range
	Nominal	55 (8)		
	Maximum	69 (10)		
5	Cooling Medium	Water		Water
6	Module Construction	Unitized Core Composite Cell		Incorporated

TABLE 2 END APPLICATION WVE DESIGN GUIDELINES LIST

1. Minimize weight, volume and power:

   a. Incorporate where economically practical
   b. Defer where not economically realistic, but establish steps to be taken to attain projected flight size (weight, volume and power).

2. Minimize or eliminate expendables -- within minimum allowable reservice time of 90 day. None identified so far.

3. Avoid toxic or corrosive chemicals except as cell electrolyte, then ensure containment.

4. Prevent leakage of hazardous gases (e.g., H_2) -- (1) incorporate fail-safe valving design and (2) resolve how H_2 venting will be handled (e.g., vent to catalytic oxidizer or overboard or storage).

5. Use standard commercial materials and parts to fullest extent possible -- to save development time, cost and the need for extensive testing to prove "new design" reliability.

6. Incorporate techniques which will result in a WVEM whose performance is characterized by:

   a. Low cell voltage and power consumption
   b. Tolerance to process air RH
   c. Compatible with low earth orbit cycle times or continuous operation
   d. Tolerance to variable O_2 generation rate by changing current
   e. Reliable performance
   f. Fast, easy startup in keeping with a "portable" ARS

   -- to accomplish the purpose of O_2 generation, without excessive restrictions concerning applicability and to carry out its function continuously for long unattended periods of time.

7. Incorporate straight-forward maintenance features -- preferably those that minimize disconnection of liquid lines. (Repair by replacement of subsystem components shall be permitted.)

TABLE 3 WVE DEVELOPMENT GOALS

Performance Goals

1.	Cell Voltage (max), V	1.70
2.	Inlet Air Relative Humidity Range, %	25 to 75
3.	Minimum Cabin Dew Point, K (F)	278 (40)
4.	H_2-to-Air Side Delta P, kPa (psid)	
	Nominal	55 (8)
	Maximum	69 (10)
5.	Cooling Medium	Water
6.	Module Construction	Unitized Core, Composite Cell

Operation Goals

1.	Unattended Operation, day	90
2.	Expendables	None
3.	Leakage	None
4.	Startup Time, hr	Less than 10 minutes
5.	Compatible With	CO_2 Removal Subsystem (Electrochemical CO_2 Removal) and CO_2 Reduction Subsystems
6.	Operating Environment	Space Station temperature, pressure, relative humidity
7.	Materials of Construction	Per NHB 8060.1B and SE-R-0006A
8.	Gravity Tolerance	0 - 1 G plus launch conditions (JSC-07700)
9.	Calibration	Needed infrequently and readily done
10.	Sensor Signal Outputs	
	VDC	0 - 0.5
	mA	5 maximum
11.	Noise	Noise Criterion (NC) -55
12.	Vibration	None
13.	Operation	Continuous and Cyclic (for earth orbit power compatibility)
14.	Safety	Per NHB 1700.7A and MIL-STD-1522

Operating Feature Goals

1.	Fail-Safe	Automatic Shutdown
2.	Automated Startup, Shutdown(a)	Manually or electronically initiated
3.	Accept Command Inputs(a)	External initiation of operating mode transitions and selection of measurement parameters
4.	Transmittal of Status Indicators(a)	Parameters measured, operating mode and operating mode transition underway
5.	Autoprotection(a)	Reject incorrect commands and detect failure in major components - initiate automatic shutdown

continued-

(a) A benefit of being microcomputer-based.

Table 3 - continued

6.	Fault Isolation	Display codes identifying incorrect commands and component causing shutdown
7.	Phase Change Design	Minimize gas/liquid separations
8.	Proprietary Features	None
9.	Proprietary Materials	None

Packaging Goals

1.	Configuration	Self-contained
2.	Maintainability	Orbit Replaceable Units (ORUs)
3.	Weight, kg (lb)	45 (100)
4.	Volume, m^3 (ft^3)	0.11 (4.0)
5.	Number of Interface Connections	6
6.	Power, W	600 W
7.	Shelf Life, yr	8
8.	Operating Life, yr	10 with maintenance
9.	Structural	Shock and vibration resistant

TABLE 4 WVE SUBSYSTEM DESIGN SPECIFICATION

Crew Size	3
O_2 Generation Rate, kg/day (lb/day)	
Nominal	2.51 (5.52)
Minimum	2.41 (5.31)
Maximum	3.00 (6.60)
Cabin pO_2, kPa (psia)	19.6 to 23.1 (2.85 to 3.35)
Cabin Temperature, K (F)	291 to 297 (65 to 75)
Cabin Dew Point, K (F)	278 to 289 (40 to 60)
Cabin Relative Humidity, %	25 to 75
Cabin Pressure, kPa (psia)	101 ± 1.4 (14.7 ± 0.2)
Purge Gas	N_2
Purge Gas Pressure, kPa (psia)	310 (45)
Electrical Power	
VAC	115/200, 400 Hz, 30
VDC	28
Gravity	0 to 1

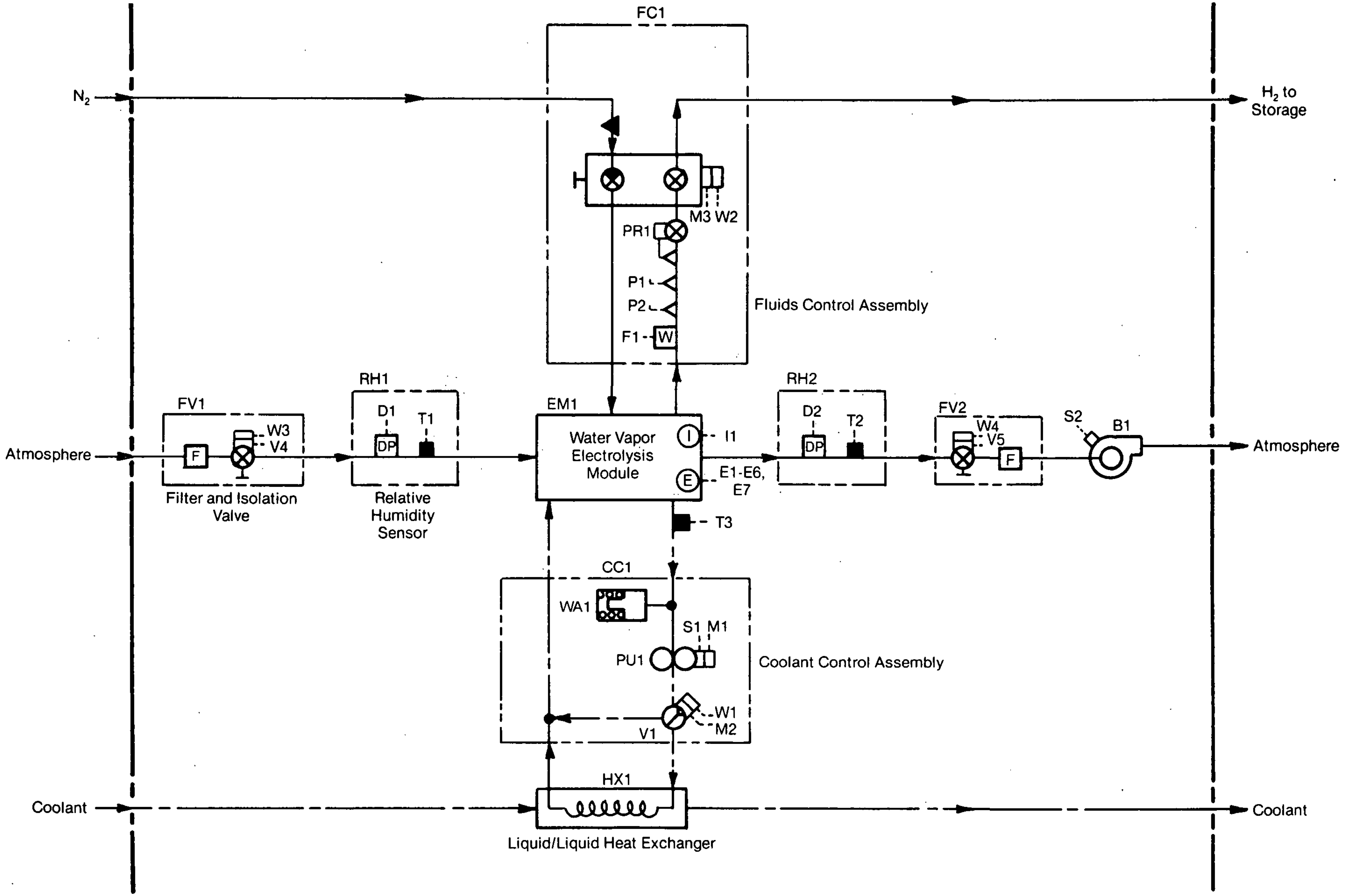


FIGURE 3 WVE MECHANICAL SCHEMATIC WITH SENSORS

TABLE 5 WVE MECHANICAL COMPONENT CHARACTERISTIC SUMMARY

Item No.	Unit or Component Name	Qty.[a]	Weight, kg (lb)	Dimensions, cm (in) Height	Width	Length	Diameter	Volume, dm^3 (in^3)	Power, W AC	DC	Total	Heat Rej., W
1	WVE Module	1	28.3 (62.2)	33.0 (13.0)	39.4 (15.5)	34.3 (13.5)	-	44.50 (2,720)	-	590	590	158
2	Fluids Control Assembly	1	1.7 (3.8)	8.9 (3.5)	7.6 (3.0)	24.1 (9.5)	-	1.64 (100)	-	1.9	1.9	1.9
3	Coolant Control Assembly	1	2.7 (6.0)	15.2 (6.0)	10.9 (4.3)	18.8 (7.4)	-	3.11 (190)	48	-	48	48
4	Heat Exchanger, Liquid/Liquid	1	0.9 (2.0)	-	-	15.2 (6.0)	6.4 (2.5)	0.49 (30)	-	-	-	-
5	Valve, Filter/Isolation	2	1.4 (3.0)	-	-	10.9 (4.3)	11.4 (4.5)	2.29 (140)	-	-	-	-
6	Sensor, Relative Humidity	2	0.4 (0.9)	-	-	5.8 (2.3)	3.6 (1.4)	0.11 (7)	-	2	2	2
7	Duct. Inlet Air With Heat Exchanger	1	2.3 (5.0)	15.2 (6.0)	11.4 (4.5)	34.3 (13.5)	-	5.90 (360)	-	-	-	-
8	Duct. Outlet Air	1	0.4 (1.0)	11.9 (4.7)	11.4 (4.5)	34.3 (13.5)	-	4.59 (280)	-	-	-	-
9	Blower	1	2.3 (5.0)	-	-	10.2 (4.0)	12.7 (5.0)	1.30 (80)	60	-	60	60
	Total	11	40.4 (88.9)	43.4 (17.1)	39.4 (15.5)	34.3 (13.5)		58.7 (3,580)	108	594	702	270
					(Envelope)			(Envelope)				

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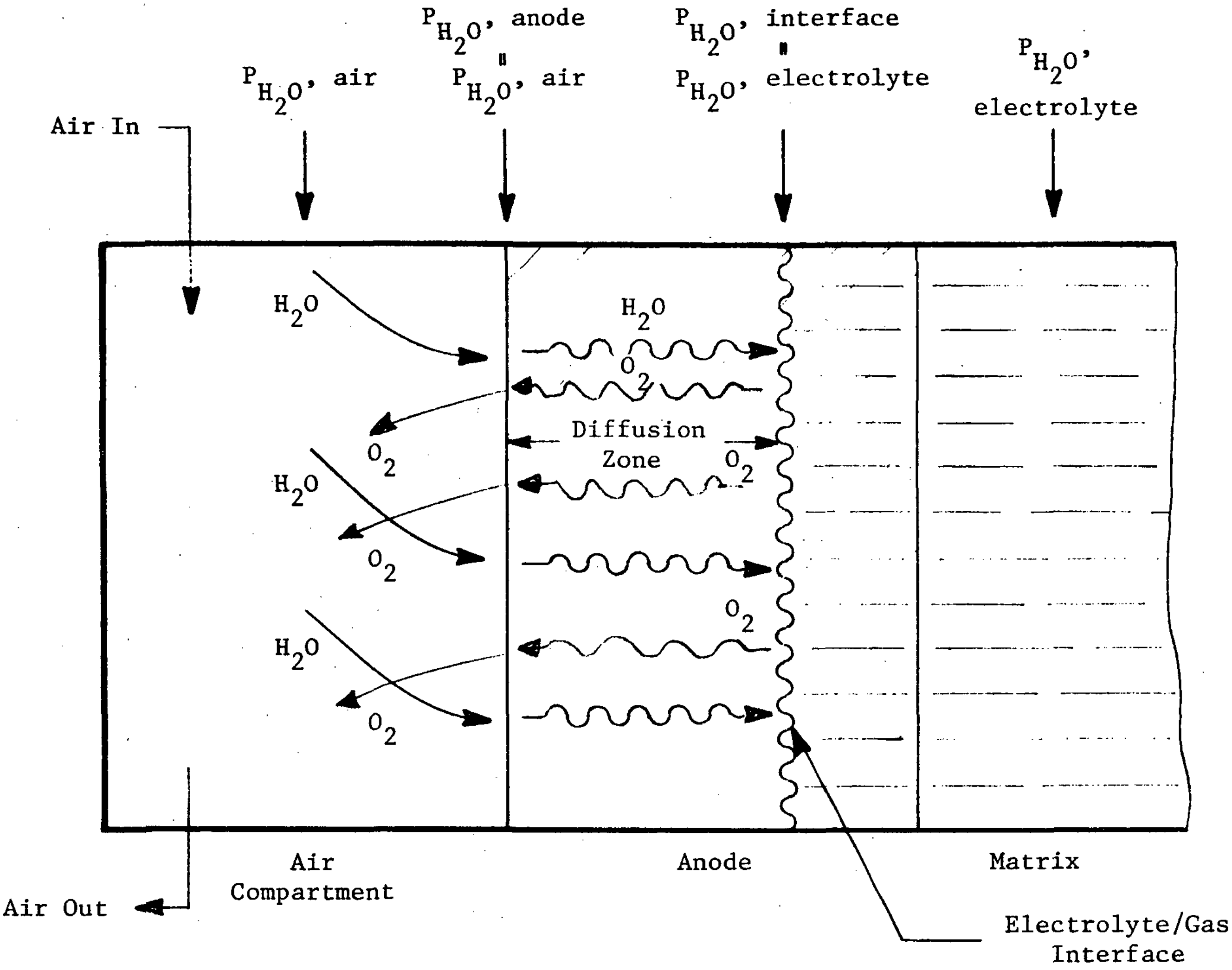
[a] Sizes given are for total number cited. If quantity is one, size is that of one unit, if two then combined for two units.



Water Balance Equation:

$$P_{H_2O}, \text{ anode} = P_{H_2O}, \text{ interface} + \frac{n_{H_2O}RTL}{D_e A}$$

Where: n_{H_2O} = water transport rate, $\frac{\text{g mole}}{\text{sec}}$

P_{H_2O} = water vapor pressure, mm Hg

R = gas constant, $\frac{(\text{cm}^3)\ (\text{mm Hg})}{(\text{g mole})\ (\text{K})}$

T = temperature, K

L = diffusion thickness, cm

D_e = effective diffusivity, $\frac{\text{cm}^2}{\text{sec}}$

A = electrode area, cm^2

FIGURE 4 WVE WATER BALANCE SCHEMATIC

electrode properties which determine water transport mechanisms at the location of the interface. It is desired that the interface be located near the center of the anode at nominal conditions so that changing air RH does not move it too close to either the air compartment, which may result in flooding, or to the matrix, resulting in dryout.

An analysis was performed to determine the makeup of the WVE cells, specifically the composition of the unitized core. A computer model was generated to further investigate the moisture balance in the electrode/matrix/electrode as a function of inlet air conditions. The WVE cell must be capable of operating within the required range of inlet air dew point temperature as specified to be 278 to 289 K (40 to 60 F). As the higher end of the dew point range is approached, the electrolyte/gas interface migrates out to the edge of the electrode. The electrolyte concentration must be such that its water vapor partial pressure creates a driving force for water vapor diffusion from the inlet air so that only the amount of water needed for electrolysis is transferred from the air to the liquid. If the electrolyte water vapor partial pressure is much lower than that of the inlet air (due to a high electrolyte concentration), excessive water transfer and subsequent electrode flooding will occur. Thus, the maximum inlet air dew point temperature (i.e., 289 K (60 F)) is one of the major factors that determine the electrolyte charge concentration, that is, what the cell is initially charged with. This initial charge concentration determines the initial electrolyte volume and, more importantly, the mass of the electrolyte solute.

A major factor in electrolyte volume expansion is the vapor pressure characteristics of the electrolyte. This depends on concentration and temperature. Characteristics for two principal candidate electrolytes, sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4), are shown in Appendix 1. Lines indicating 25% and 75% RH vapor pressure of the incoming air at 294 K (70 F) are also indicated. These figures help determine whether air enters or leaves the electrolyte for given incoming air conditions and initial electrolyte charge concentrations.

At the low end of the inlet air dew point range, the electrolyte/gas interface recedes back into the electrode toward the matrix as the electrolyte becomes more concentrated. A volume reduction must occur as the electrolyte becomes more concentrated since the initial electrolyte solute mass remains unchanged. The electrolyte concentration, in this case, is that which gives a water partial pressure sufficiently below that of the inlet air to overcome the diffusional resistance to water vapor transport provided by the porous electrode. The electrolyte reduction which occurs at the low inlet air dew point temperatures must not be so great as to cause the electrolyte/gas interface to recede out of the electrodes and into the matrix, at which point gas crossover could occur. Thus, for a given matrix thickness, the electrodes must be thick enough to allow the necessary amount of electrolyte volume reduction (due to increased concentration) without permitting the electrolyte/gas interface to recede into the matrix.

The electrode sizing was performed using a computer calculation. The program algorithm is described as follows:

1. Input cell temperature, current density, dew point temperature range, matrix thickness (initial).
2. Calculate initial charge electrolyte concentration based on the maximum dew point temperature.
3. Pick a trial electrode thickness.
4. Calculate initial electrolyte volume based on open volume of anode/matrix/cathode cell core.
5. Calculate final electrolyte concentration based on minimum dew point temperature, current and cell temperature.
6. Calculate final electrolyte volume.
7. Check to insure that electrolyte/gas interface remains within the electrode.
8. If not, repeat for new electrode thickness.

The results of the above calculations are shown in Figures 5 and 6. In Figure 5 the required electrode thickness is plotted against cell temperature for various matrix thicknesses. Note that the matrix thickness is dependent on the H_2-to-air differential pressure requirement. The plot was prepared for the case of 54 mA/cm^2 (50 ASF), 278 to 289 K (40 to 60 F) dew point temperature range and sulfuric acid (H_2SO_4) electrolyte. It is seen that the electrode thickness increases with increasing matrix thickness and with decreasing electrolyte temperature. In Figure 6, similar data is presented for a wider dew point temperature range of 275 to 291 K (35 to 65 F). It is seen that thicker electrodes are required to accommodate the wider dew point temperature operating range. Plots for H_3PO_4 would show similar trends and values differing only slightly.

Electrolyte Retention Matrix Sizing

A review of potential electrolyte retaining matrix materials was performed. The matrix material that has been used in the past was still found to have the desired property of inertness in an acid medium. To determine the proper thickness of this matrix, bubble pressure testing of candidate matrices was performed. Matrices of six different thicknesses were prepared. These ranged from 0.13 to 0.76 mm (0.005 to 0.030 in) in 0.13 mm (0.005 in) increments. At least two different matrix densities for each thickness were also prepared. The matrix density relates to pore open area and hence to differential pressure tolerance.

A fixture was prepared to hold the matrices for testing. The matrices were wetted with water (or electrolyte), placed in the fixture and a differential pressure applied. Clear plastic end plates permitted visual detection of bubble formation indicating breakthrough as pressure increased. The goal was

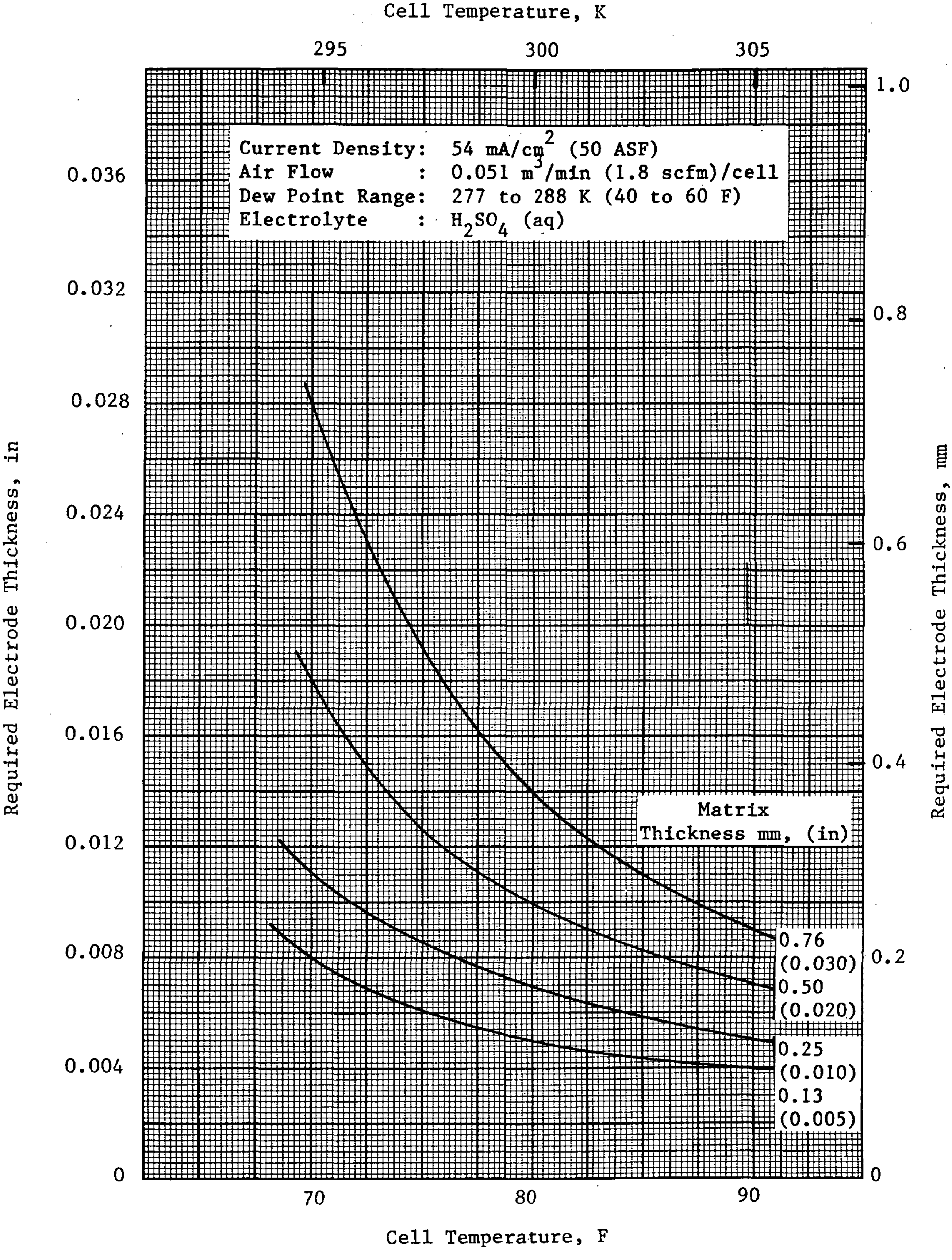


FIGURE 5 REQUIRED ELECTRODE THICKNESS VERSUS CELL TEMPERATURE (NOMINAL DEW POINT RANGE)

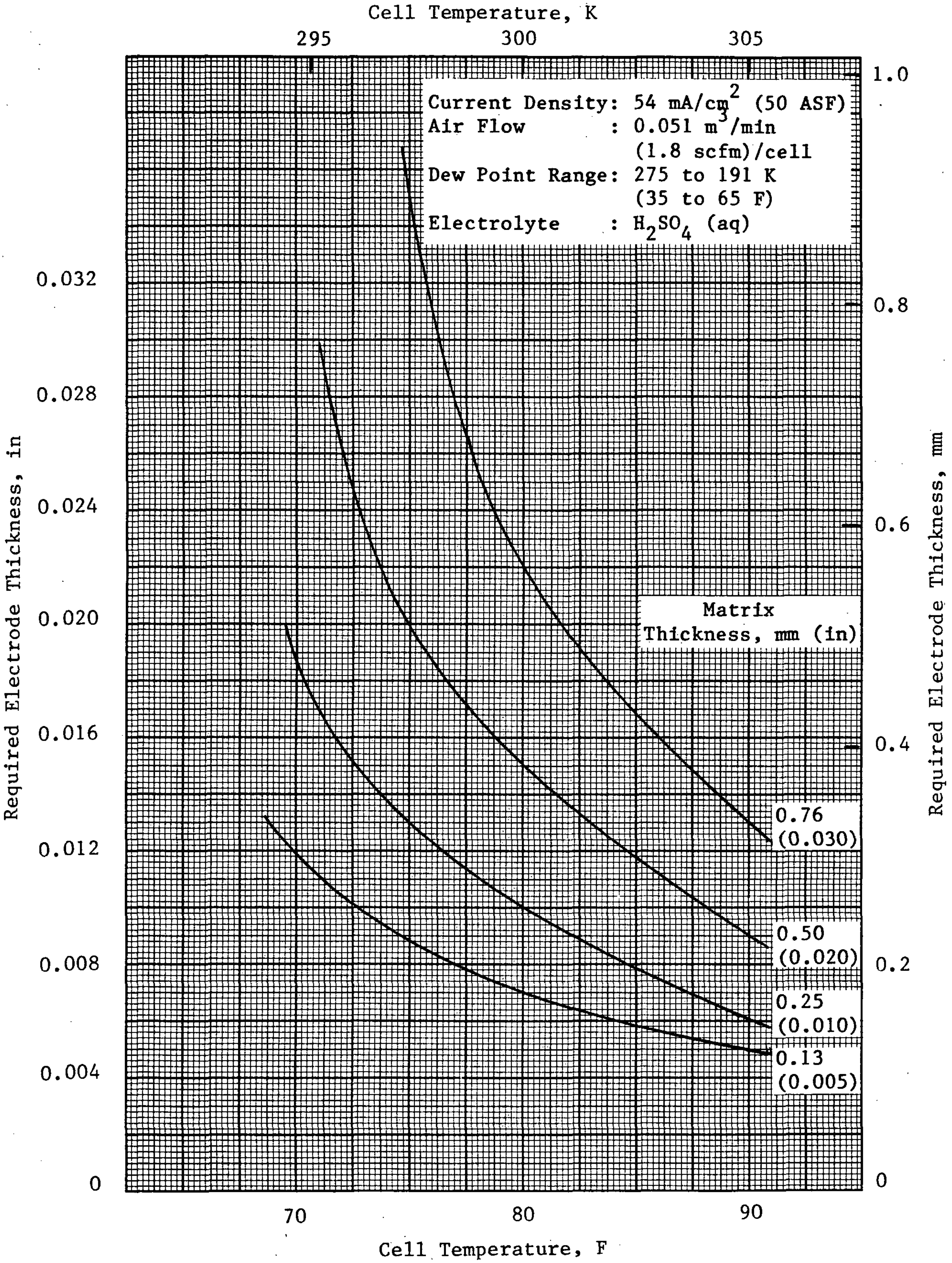


FIGURE 6 REQUIRED ELECTRODE THICKNESS VERSUS CELL TEMPERATURE (EXTENDED DEW POINT RANGE)

to select a matrix with breakthrough pressure that was at least two to three times that of the specification of 55 kPa (8 psid) nominal and 69 kPa (10 psid) maximum. This was done to provide an operational safety margin.

The results of the bubble pressure testing are given in Figures 7 through 9. Test matrices were prepared in the six thicknesses indicated above and two densities of 0.48 (30) and 0.72 (45) g/cm^3 (lb/ft^3). The lower density is the typical matrix density produced by Life Systems' normal manufacturing process. The higher density represents the highest compaction that could be achieved with the matrix material and facilities available. The two data points at each thickness are for two different samples. The actual thicknesses that are measured are not always right at the desired value due to variations in press load, water content, stackup heights (using shim stock) and other factors.

Tests were conducted as follows. A dry matrix was placed in the test fixture. It was then thoroughly wetted with water, although H_2SO_4 was used in one case. This procedure is referred to as "atmospheric charge." An increasing differential pressure was then applied step-wise across the matrix. The pressure was noted when the first bubble appeared on the low side pressure. This is the value that is plotted. Vacuum charging was also done in a couple of cases to ensure complete and uniform wetting.

As can be seen in Figure 7, good pressure capability of 207 kPa (30 psid) is obtained for 0.38 mm (0.015 in) matrices. This compares with the requirement of 55 kPa (8 psid). Increasing thickness above 0.38 mm (0.015 in) has little effect, as presumably a pathway (pore) is established which is independent of thickness.

Increasing density actually showed poorer pressure capability as shown in Figure 8. It was believed that the compaction to the higher density may have damaged the matrix (fractured fibers) and actually decreased the bubble pressure. It should be noted that at the higher density, most of the initial bubbles appeared near the edge where clamping forces were high and may have damaged the fibers. Within the limitations of the matrix preparation equipment 0.38 mm (0.015 in) matrices at other densities were prepared and tested. The results are given in Figure 9 and show an optimum at the baseline density of 0.48 g/cm^3 (30 lb/ft^3). Therefore, the selected baseline WVE matrix was 0.38 mm (0.015 in) at 0.48 g/cm^3 (30 lb/ft^3).

Bonding Agent Evaluation

Bonding agent compatibility and selection was assessed by testing. Candidate adhesives were identified as shown in Table 6. Several of these were procured and samples prepared and immersed in 60% H_2SO_4. This value of concentration was selected to be a "worst case" electrolyte condition. Periodically at 241, 1,442 and 2,496 hours these samples were visually inspected. The results are presented in Table 7. Shown is the sample, time in solution, percent weight change and visual observation. Weight change, if any, was always positive, indicating absorption of electrolyte into the material.

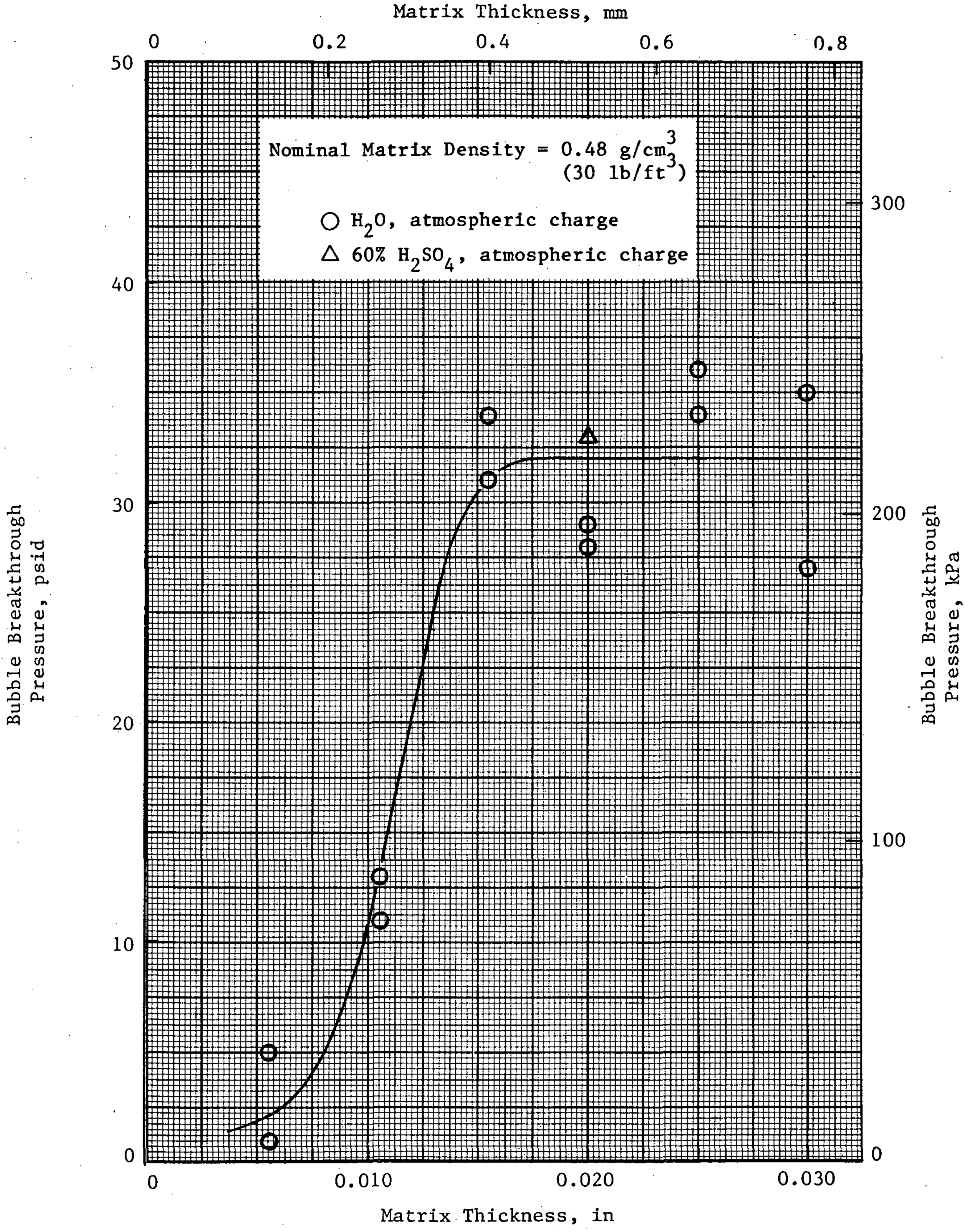


FIGURE 7 BUBBLE BREAKTHROUGH PRESSURE VERSUS MATRIX THICKNESS AT BASELINE MATRIX DENSITY

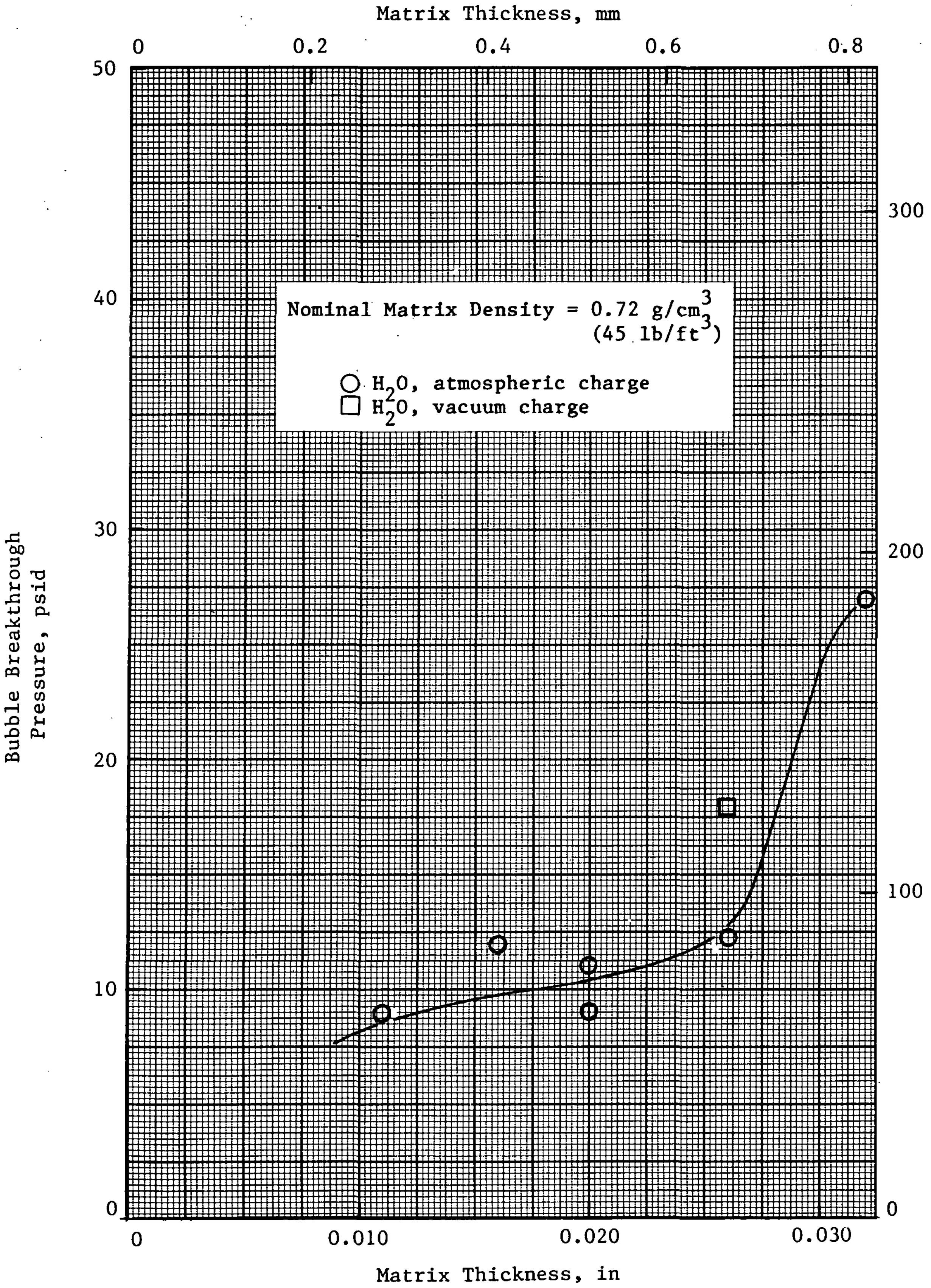


FIGURE 8 BUBBLE BREAKTHROUGH PRESSURE VERSUS MATRIX THICKNESS AT HIGH MATRIX DENSITY

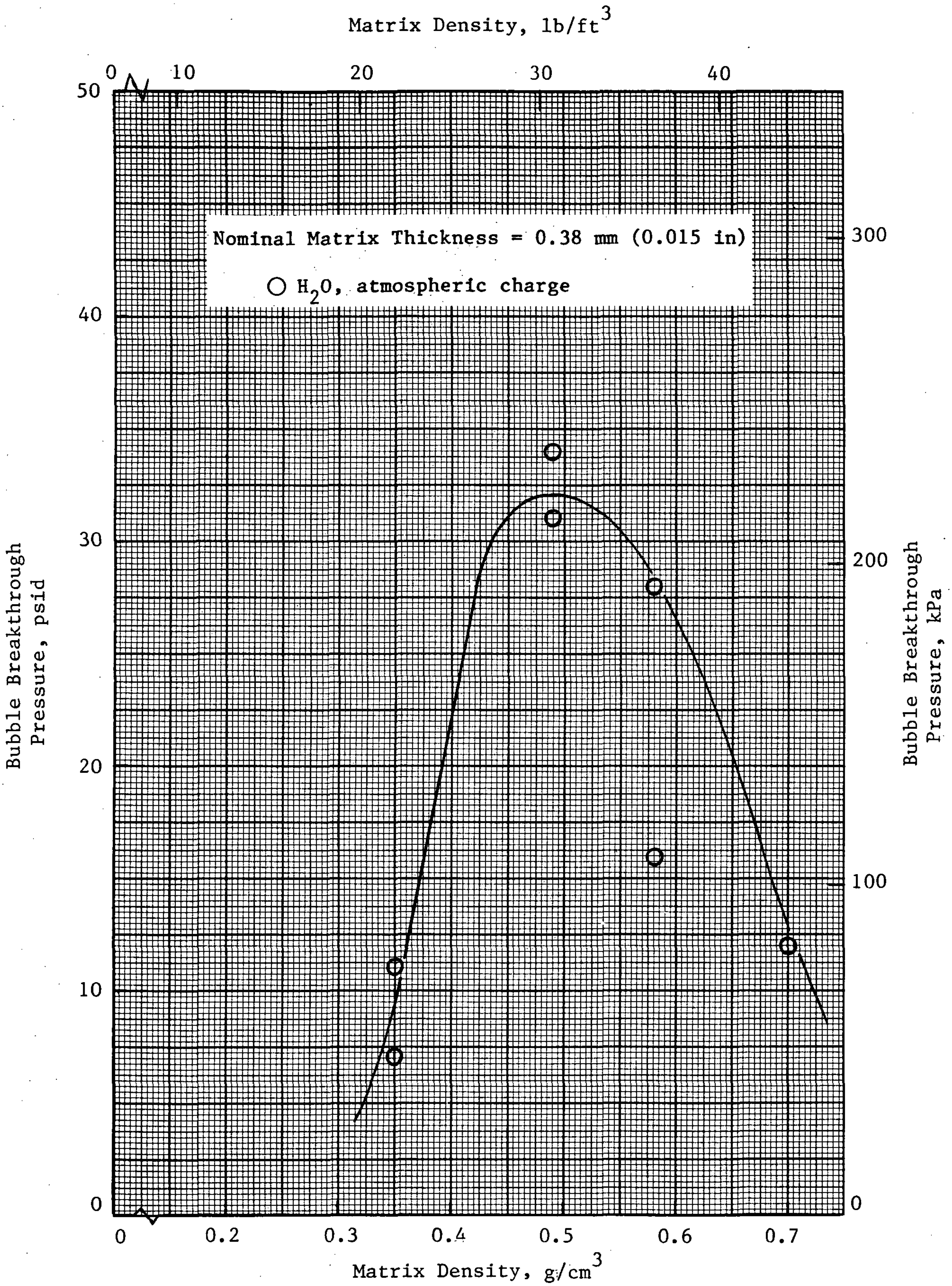


FIGURE 9 BUBBLE BREAKTHROUGH PRESSURE VERSUS MATRIX DENSITY AT FIXED MATRIX THICKNESS

TABLE 6 ADHESIVES FOR WVE UNITIZED CELL CORE

No.	Name	Type	Preparation/Use
1	Emerson and Cumming 104	Epoxy	Two parts, room temperature cure
2	Masterbond EP-21-AR	Epoxy	Two parts, room temperature cure
3	Tracon 2216	Epoxy	Two parts, room temperature cure
4	Tracon 2248	Epoxy	Two parts, high temperature cure
5	Thermoset DC 80	Epoxy	Two parts, room temperature cure (semi-rigid or rigid depending on ratio)
6	Armstrong A-701	Epoxy	Two parts, high temperature cure
7	Ryton Pre-preg	Epoxy	Impregnated epoxy, high temperature cure
8	3M 4060	Thermoplastic Adhesive Film	Hot melt film. Heat to 422 K (300 F)

TABLE 7 BONDING AGENT COMPATIBILITY TESTING RESULTS - H_2SO_4

Epoxy Sample	Time on Test, hr	Weight Change, %[a]	Comments
Emerson and Cumming 104	241	+0.05	No effect
	1,442	+0.11	No effect
	2,496	+0.11	No effect
Masterbond EP-21-AR	241	+2.00	Surface etching/pitting
	1,442	+3.28	Increased surface effects--remove from test
Tracon 2116	241	+1.75	Surface etching
	1,442	+3.40	Darkening, discoloration at edges--remove from test
Tracon 2248	241	+0.20	Very slight surface etching
	1,442	+0.81	Same as above
	2,496	+1.23	Same as above; solution has slight pink tint
Thermoset DC 80 (Semi-rigid)	241	+4.00	Significant discoloration, surface effects--remove from test
Thermoset DC 80 (Rigid)	241	+0.50	Slight darkening and surface etching
	1,442	+1.29	Increased darkening, surface effects--remove from test
Armstrong A-701	241	+0.10	No effect
	1,442	+0.27	No effect
	2,496	+0.32	No effect
Ryton Pre-preg	914	+5.9	Surface clouding.

---

[a] Test solution is 60% H_2SO_4 at room temperature (assumed to be worst case electrolyte condition).

Two epoxy samples performed well throughout the approximately 2,500 hours of compatibility testing at 60% H_2SO_4. These were (a) the Emerson and Cumming 104, which indicated a weight change of 0.11% and no visual effects. This is a two-part epoxy, one part of which is solid powder. The mixed epoxy is thick and fairly difficult to handle. It requires a high curing temperature, 450 K (350 F) for 2.5 hours, and (b) the Armstrong A-701, which indicated a weight change of 0.32% and no visual effects. This is a one-part epoxy. The epoxy is thick, also fairly difficult to handle and requires a high cure temperature--two hours at 450 K (350 F) or one hour at 478 K (400 F).

Additional testing of adhesive samples was performed using H_3PO_4 at 85% concentration. The results are shown in Table 8. The 3M 4060 adhesive film performed very well.

Quarter-scale sample unitized cores were made from the two candidate epoxies: Emerson and Cumming 104 and Armstrong A-701 and the 3M 4060 adhesive film. It was concluded that the 3M 4060 film permitted better ease in manufacturing and gave a better product. This included the characteristic surface finish which is important when it comes to sealing the H_2 cavity with O-rings. The Armstrong A-701 epoxy was used for cell frame bonding.

Electrolyte Selection

Electrolyte selection consisted of establishing criteria to be used in evaluating what had been used in the past as cited in the literature for WVE and other similar applications. Important properties of electrolytes were deemed to be the following:

a. Nonvolatility--solute that does not vaporize at operating conditions.

b. Water soluble--solute remains in solution over air humidity range.

c. Stability--does not decompose at operating conditions nor cause corrosion.

d. Ionic conductivity--has a low resistance to current flows at the operating concentration.

Quantification of these properties is given in Table 9. Note that data are missing in several areas: the data either were not found, or in the case of hydrochloric acid (HCl) and nitric acid (HNO_3), were not supplied after the volatility was determined to be high. Ionic conductivity can be used as a discriminator for selecting the electrolyte. This parameter, of course, varies with electrolyte temperature and concentration as shown in Appendix 1. A calculation was made to show that an anticipated 30 mV higher internal resistance (IR) drop would occur using H_3PO_4 rather than H_2SO_4 with each at their optimum concentration for the application. With no other discriminators, sulfuric acid would be the preferred electrolyte; however, as is discussed later, other factors such as secondary reactions can occur which produce undesirable byproducts. Phosphoric acid was the end-use selected electrolyte.

TABLE 8 BONDING AGENT COMPATIBILITY TESTING RESULTS – H_3PO_4

Sample	Time on Test, hr	Weight Change, %[a]	Comments
Emerson and Cumming 104	5,496	-0.1	No effect
Tracon 2248	5,496	+1.4	Surface etching
Armstrong A-701	5,496	+2.8	No effect
Ryton Pre-preg	1,920	+5.1	Some darkening
3M 4060	2,064	None	No effect

(a) Test solution is 85% H_3PO_4 at room temperature (assumed to be worst case electrolyte condition).

TABLE 9 WVE CANDIDATE ELECTROLYTE COMPARISON BY CATEGORY

Property	Electrolyte				
	HCl	HNO_3	H_2SO_4	H_3PO_4	TFMSA[a]
1. Solubility (at 294 K)	45%	Infinite	Infinite	85%	(b)
2. Volatility (at 293 K)					
pH_2O, mm Hg	13.1	13.2	13.1	12.5	(b)
p(Solute), mm Hg	0.0196	0.02	7.8×10^{-15}		
Other			4.7×10^{-22} (pSO_3)	$<10^{-16}$ (pP_2O_5)	
3. Ionic Conductivity					
Max Cond., mho/cm	(c)	(c)	0.82	0.23	0.41
At Concentration, %			30	50	40
4. Corrosivity					
Concentration, %	(c)	(c)	40	85	Monohydrate
At temperature, K			363	398	398
Corrosion Rate, $mg/cm^2/yr$					
Incoloy			-	25	23
Nickel			>1,100 at 298 K	1,100	30
Titanium			-	57 at 298 K	5,200
Platinum			131	-	5
Tantalum			<10	-	10
304 SS			-	420	210
316 SS			1,000 at 298 K	400 at 373 K	-

(a) Trifluoromethane sulfonic acid.
(b) Data not found.
(c) Data not supplied after electrolyte eliminated due to volatility reasons.

Trifluoromethane sulfonic acid (TFMSA) has been proposed for H_2/O_2 fuel cells but not for water vapor electrolysis. However, TFMSA has been found to wet teflon at high concentrations in a fuel cell application making the electrode less effective. Since WVE electrodes and matrices contain teflon this behavior made TFMSA an undesirable electrolyte choice.

Metallic Selection

Metallic surfaces are required at various places within the WVE cell. They are needed for (1) current conduction into the cell--current tabs, (2) sensors--voltage tabs, (3) current conduction within the cell--current collector foils, and (4) current and H_2 and air flow to the electrodes--expanded metal separators. Several metals have been evaluated and used in the past. Tantalum (Ta) was the selected metal of choice and represents a compromise between cost, availability in the forms needed and compatibility with the electrolyte. Table 10 shows properties of candidate metals.

Tantalum does have one slight drawback. Its electrical conductivity is about one fourth (i.e., 0.08 versus 0.31 micromho/cm) that of titanium (Ti), the material used on previous WVE hardware. The lower conductivity or high resistivity will show up as increased voltage drop across current carrying metallic sheets. For instance, a sheet of Ta 23 x 23 x 0.013 cm (9 x 9 x 0.005 in) will develop a voltage drop of 27 mV for 25 A current flow through the 23 cm (9 in) direction. Thicker sheets will reduce the voltage drop by lowering resistance to current flow.

Cell and Module Construction

A unique feature of this WVE program is the use of the unitized core assembly. The unitized core is the fabrication of electrodes, matrices and gas spacers into a single unit to be installed within the cell frames. Figure 10 shows the unitized core concept for the WVE composite cell. Individual pieces are bonded together using the thermoplastic film adhesive indicated in the above section. The final assembly is trimmed to size after forming. Table 11 shows the cell construction dimensions as used and the advantages achieved. The principal advantage is reproducibility of components from one unitized core to another.

The unitized core then becomes one element of the composite WVE cell. Steps of the composite cell assembly are shown in Figure 11 and include laser welding of the current foils to the cell frames and then bonding together the cell frames. Several cells are then stacked together to form a module. Figure 12 shows the actual cell hardware while Figure 13 illustrates an assembled module.

Module Sizing

The sizing of a WVE module is dependent on several factors: the surface area, the person-size selected (i.e., O_2 generation rate), current density, weight, etc. A computer program was written to allow optimization of the WVE module sizing based on a total equivalent weight calculation. Table 12 shows the factors involved in the total equivalent weight determination. A cost factor

TABLE 10 PROPERTIES OF SELECTED METALS

Characteristics	Metal						
	Ag	Au	Cu	Ni	316SS	Ta	Ti
Density, g/cm^3 (lb/in^3)	10.5 (0.379)	19.4 (0.698)	8.99 (0.324)	8.93 (0.322)	8.04 (0.290)	16.6 (0.600)	4.52 (0.163)
Coeff. of Expansion, microin/in-K	19.7	14.2	16.5	13.3	10.5	6.5	8.41
Thermal Conductivity, cal/cm^2-sec-K	1.0	0.71	0.94	0.22	0.11	0.13	0.04
Electrical Resistivity, microohm-cm	1.59	2.35	1.67	6.8	70.0	12.45	3.2
Acid Environment(a) Compatibility	F	VG	P	F	F	VG	G
Acceptability for WVE Use	No	Yes	No	No	No	Yes	Yes

(a) P = Poor, F = Fair, G = Good and VG = Very Good.

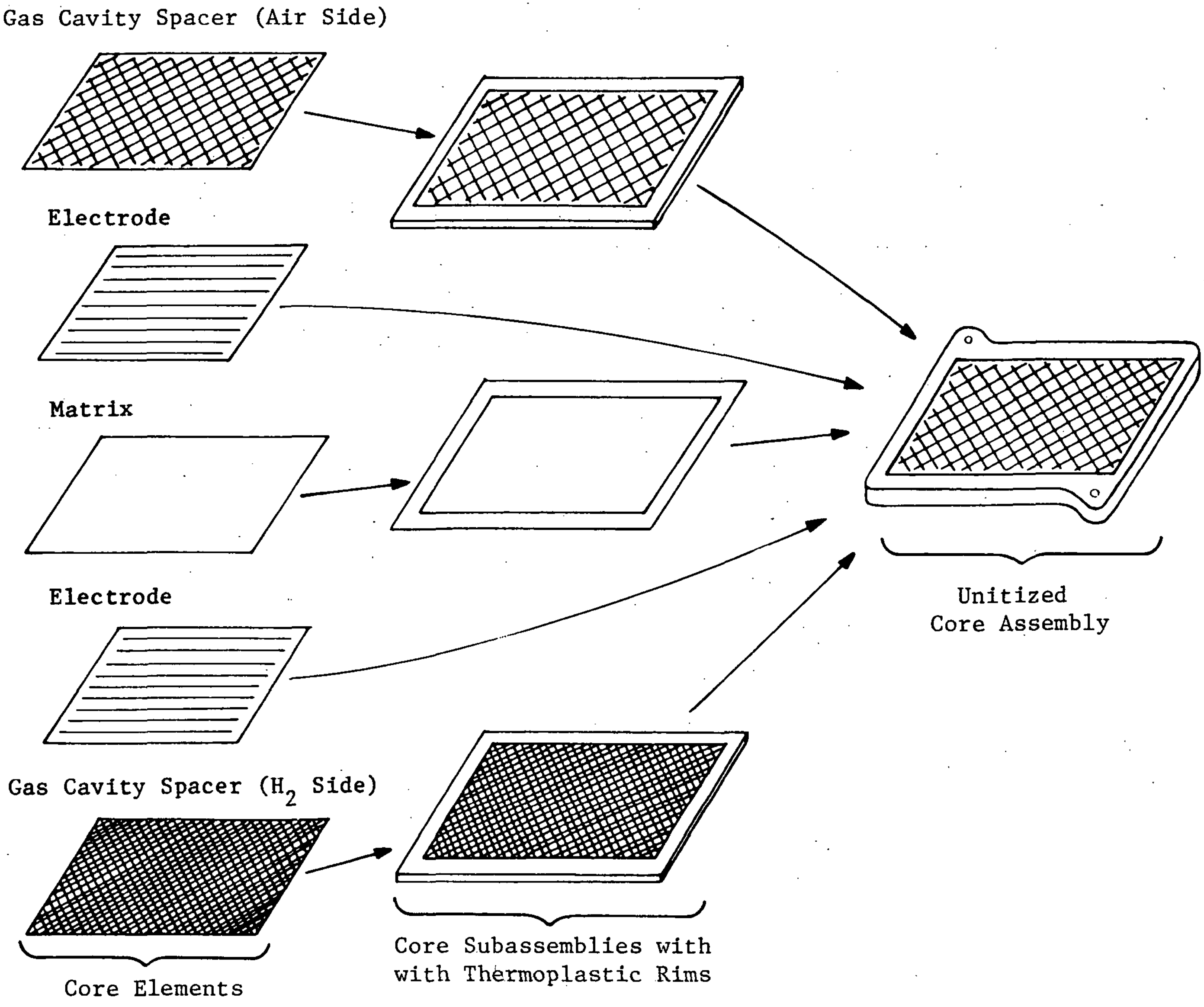


FIGURE 10 UNITIZED CORE CONCEPT FOR WVE COMPOSITE CELL

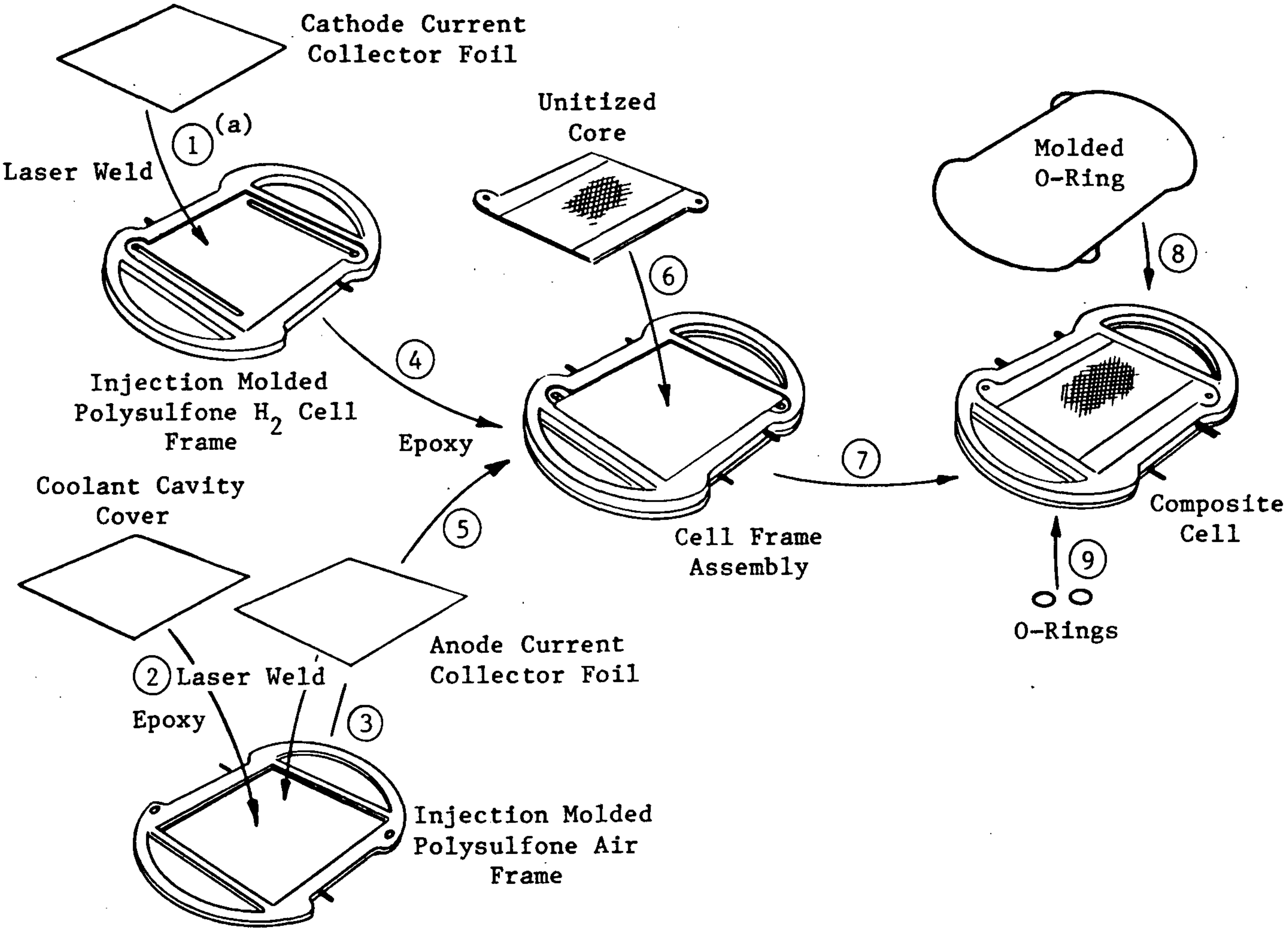
TABLE 11 ADVANTAGES OF WVE UNITIZED CORE

Unitized Core - Working elements of a WVE electrochemical cell including matrix, electrodes (anode and cathode) and H_2 and air gas spacers bonded together to form a single unit.

Construction -	0.76 mm	(0.030 in)	porous plaque anode
	0.25 mm	(0.010 in)	screen cathode
	0.38 mm	(0.015 in)	matrix
	1.27 mm	(0.050 in)	H_2 gas spacer
	2.54 mm	(0.100 in)	air spacer
Total	5.20 mm	(0.205 in)	construction bonded together with thermoplastic adhesive

Advantages:

1. Manufacturing Reproducibility - Dies and fixtures eliminate human error in manual startup of subelements.
2. Simplicity in Cell Construction - Single element installation versus buildup of several individual pieces.
3. Increased Pressure Tolerance - Fewer potential leakage pathways of H_2 into air stream.
4. Increased Quality Control - Smoothness of finished surfaces can be verified before assembly.
5. Time Savings - Final module assembly is done quickly with fewer parts to assemble.



(a) Assembly step order.

FIGURE 11 COMPOSITE WVE CELL FABRICATION

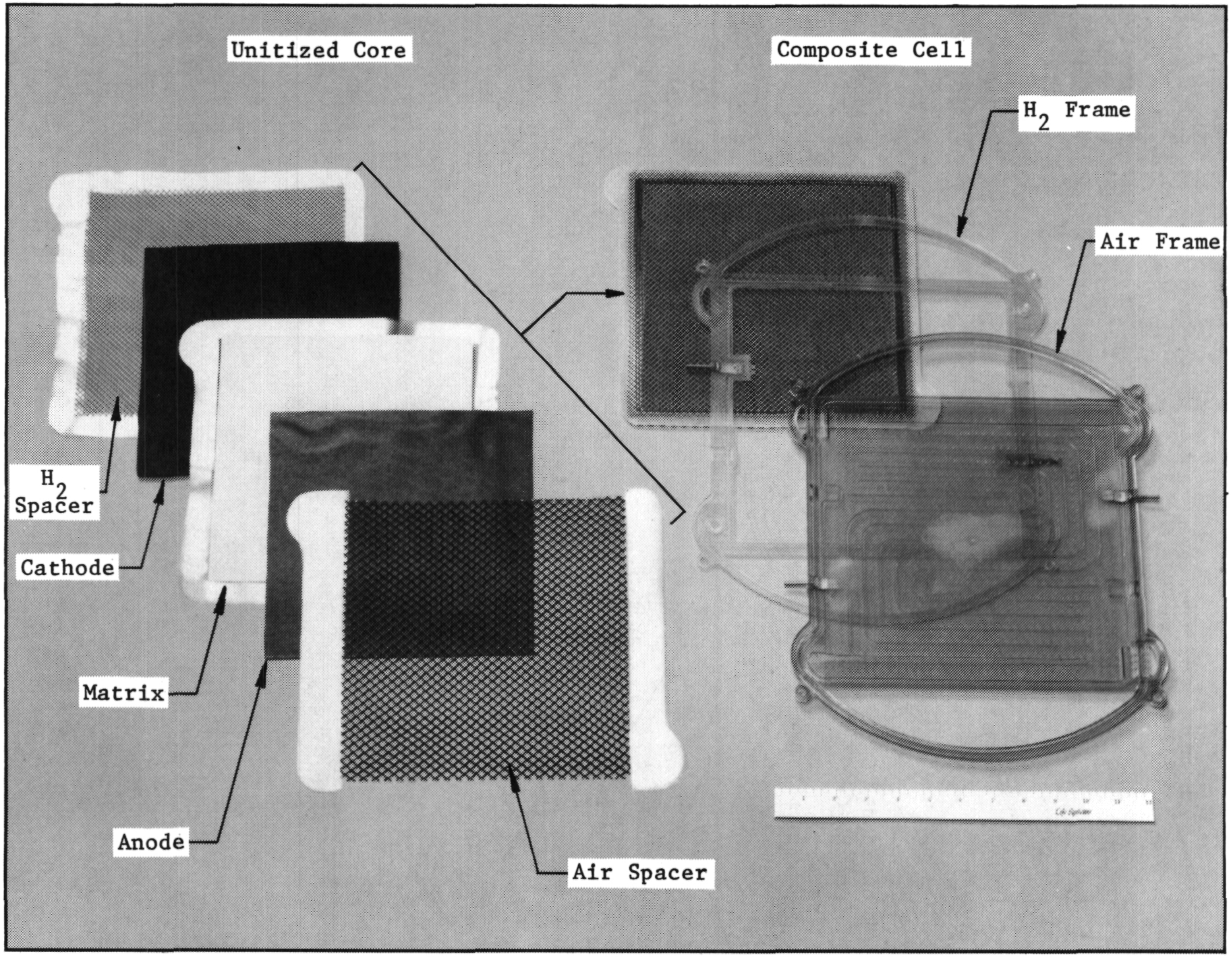


FIGURE 12 WVE UNITIZED CORE AND COMPOSITE CELL

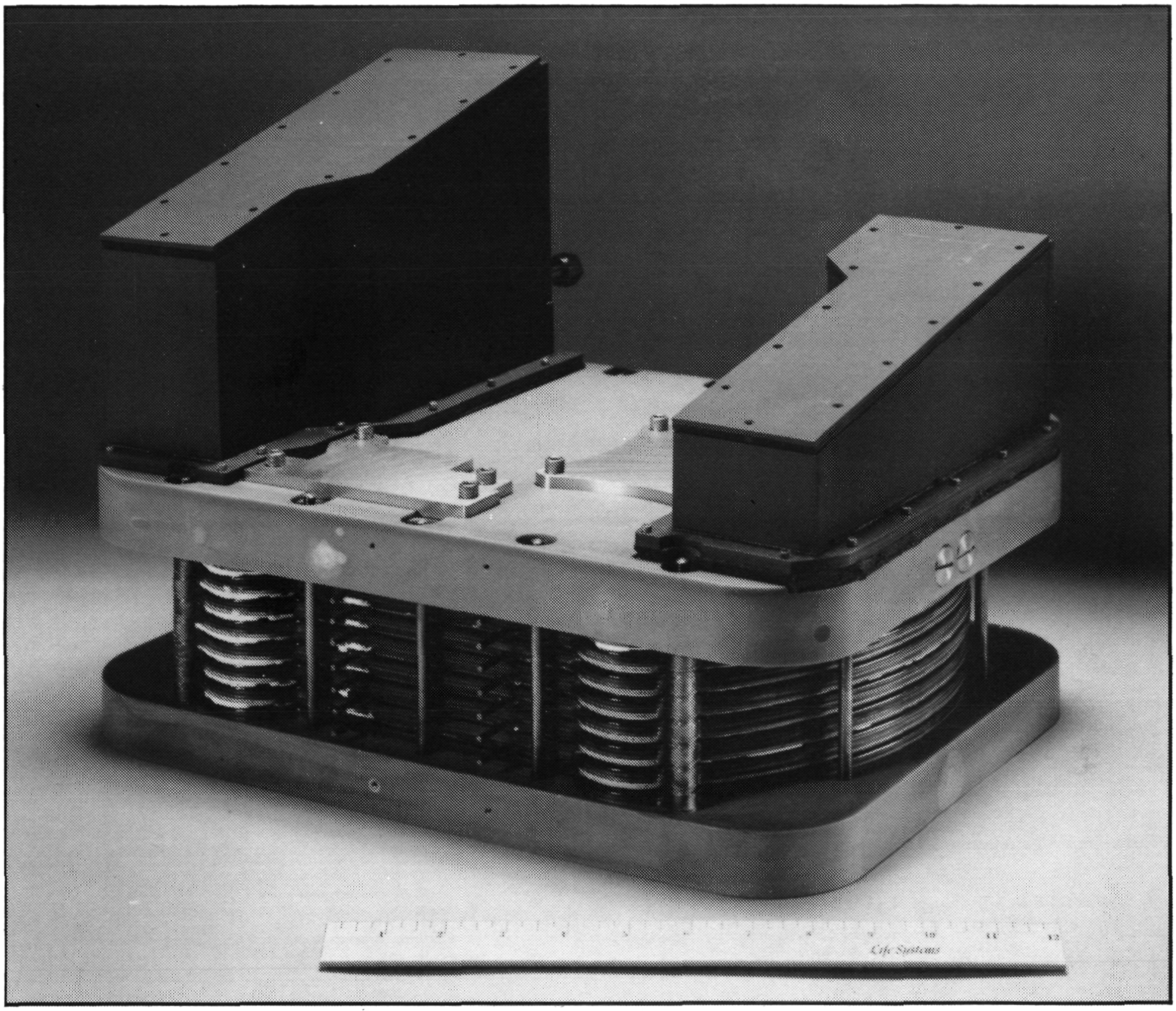


FIGURE 13 WVE ELECTROCHEMICAL MODULE ASSEMBLY

TABLE 12 WVE MODULE TOTAL EQUIVALENT WEIGHT (TEW) CALCULATION EQUATIONS

TEW = Module Weight (MW) + Power Penalty (PP) + Heat Rejection Penalty (HRP) + Cost Penalty (CP) (1)

MW = Number of Cells (N) x Cell Weight (CW) + End Plates Weight (EPW) (2)

PP = 0.59 x Total Watts (W) (3)

HRP = 0.18 x Heat Loss Watts (HLW) (4)

CP = 0.001 x N x Cell Cost (CC) (5)

$CW = (CA + 0.27\ CA^2 + 0.017) \times$ Cell Density (6)

$EPW = 68 \times CA^{3/2}$ (7)

W = Cell Voltage (CV) x Cell-Amps (8)

HLW = (CV - 1.48) x Cell-Amps (9)

$CV = 0.0053 \times CD + 1.583$ (10)

CC = Material Cost x CA + Man Hour Cost (6.5 + 5.5 x CA) (11)

N = Cell Amps/(CD x CA) (12)

Cell Amps = Oxygen Production (O_2) lb/hr x 1,520 cell-Amp-hr/lb (13)

O_2 = 6.05 lb/day/24 (14)

Cell Area Density = 3.35 lb/ft^2 (15)

Material Cost = 6,000 \$/ft^2 (16)

Man Hour Cost = 50 \$/hr (17)

Current (I) = CD x CA = Cell Amps/N (18)

$N \geq 1$, Integer (19)

$I \geq 10$ (20)

$CD \leq 100$ (21)

was also introduced and values for optimal module configuration with and without cost were used. The total equivalent weight versus current density and number of cells for a three-person capacity module are shown in Figures 14 and 15, respectively. The three-person capacity was selected as the end-application for the WVE although the results would tend to be fairly insensitive to person size. It is seen that an optimum of approximately 35 mA/cm^2 (33 ASF) is desirable for an optimal module configuration and an optimum cell area of 280 cm^2 (0.3 ft^2). However, constraining ourselves to an existing hardware configuration of 460 cm^2 (0.5 ft^2), an optimum current density of approximately 46 mA/cm^2 (43 ASF) and 18 cells for the three-person module results. These results are summarized in Table 13. The operating baseline for the WVE module selected in this program is six cells operating at 46 mA/cm^2 (43 ASF).

TESTING FACILITIES

In addition to the small scale test setups described above, two major facilities were used for testing in this program: a single cell test facility for testing individual WVE cell stackups and a WVEM module test stand. These facilities are described in this section.

Single Cell Test Facility

A single cell test facility was developed for single cell testing of electrochemical cells. This facility was modified to provide a power source of up to 30 A at 2.0 V. Electrode and cell frame materials were found from previous programs and were used in the testing. These included electrodes, Ti gas spacers, Ti current collectors and polysulfone cell frames. The latter were modified to permit use of liquid cooling versus air cooling. Figure 16 shows the test setup as originally designed. The H_2 supply and CO_2 supply were not used in this test. The gas humidifier (TK2) permitted alterations of air dew point temperature but only over a limited range of values. Similarly, the coolant tank (TK3) permitted use of coolant flow through the system. Even though the coolant temperature of TK3 was controlled, its value was set manually (nonfeedback control) using the heater (H2) control and the heat exchanger coolant bypass valve (MV10). This test facility performed very satisfactorily for the testing.

Water Vapor Electrolysis Module Test Stand

A WVEM test stand was designed and fabricated. Included were all the controls and monitoring to enable unattended operation of the testing. The test stand is shown in Figures 17 and 18, and the schematic of the test stand is given in Figure 19. A key element of the test stand is the gas humidifier which is shown in Figure 20. This device provides process air temperature and humidity within the desired Space Station range. These values are shown in Figure 21. The various controls and monitors are given in Table 14. There is an active feedback control of module temperature with the diverter valve (V2) controller maintaining module temperature by altering V2 in response to T3 and a setpoint. This feature is necessary for the module temperature control which permits the humidity tolerance that liquid cooling gives to the WVE.

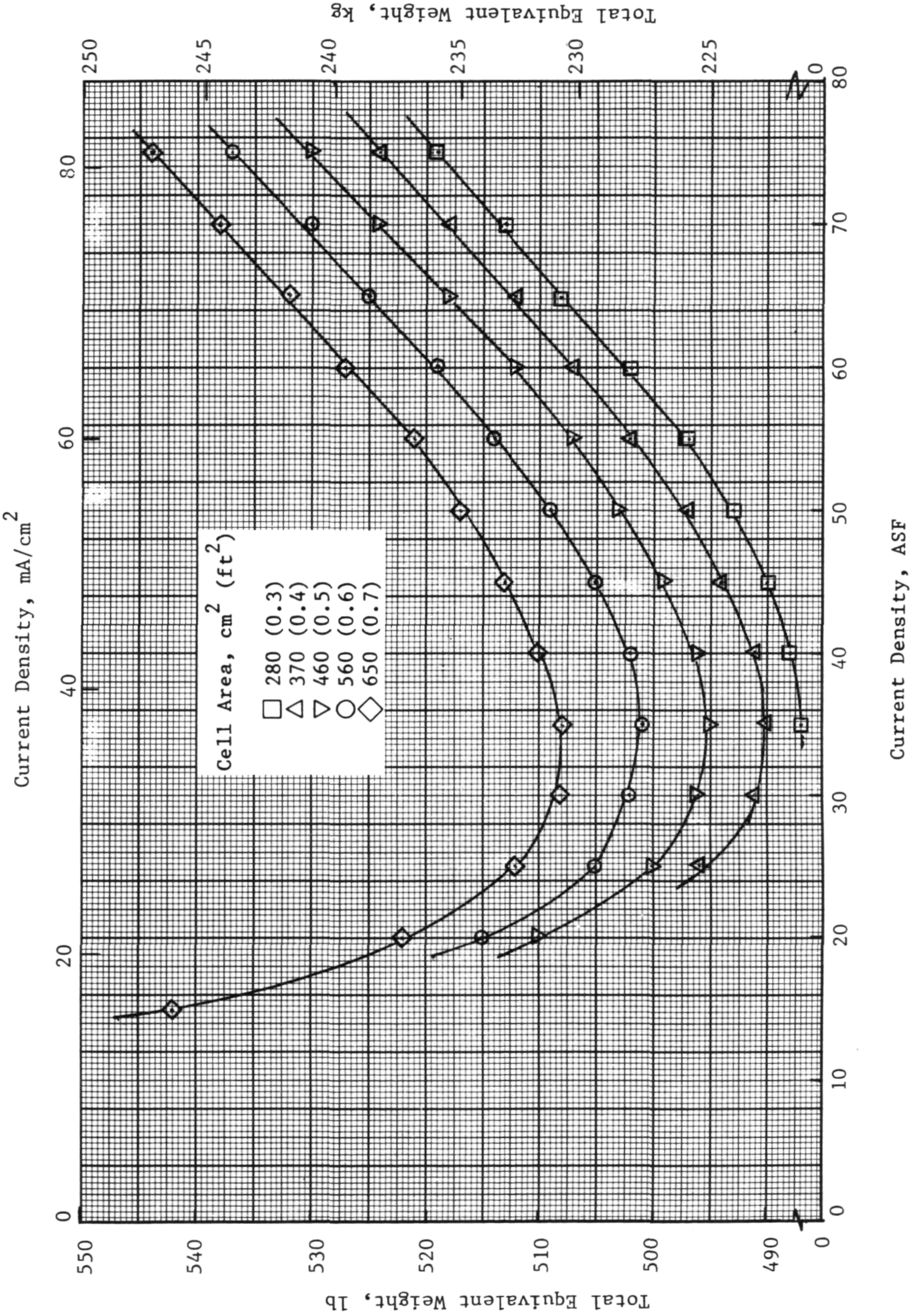


FIGURE 14 WEIGHT VERSUS CURRENT DENSITY FOR THREE-PERSON CAPACITY WVE MODULE

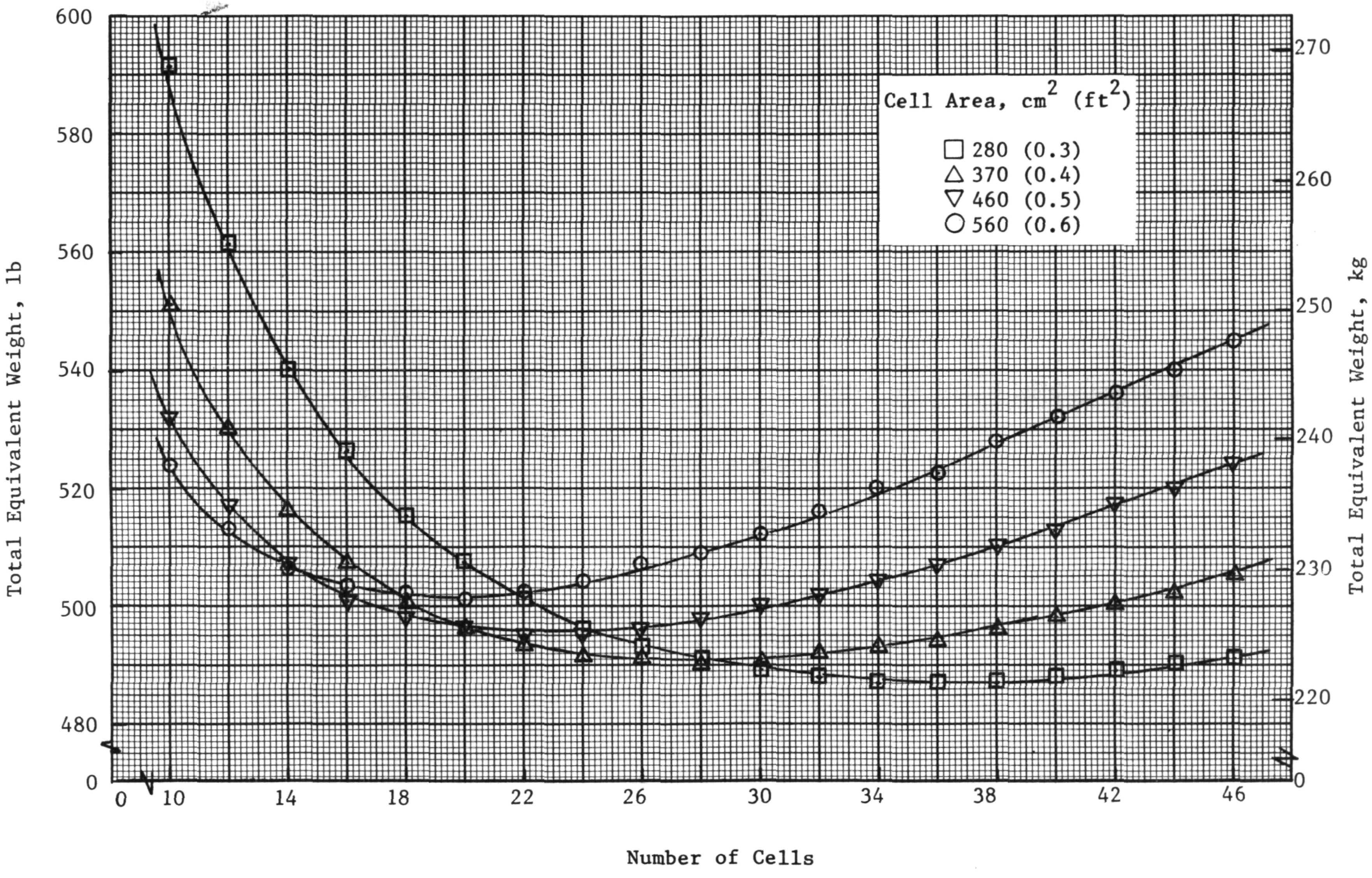


FIGURE 15 WEIGHT VERSUS NUMBER OF CELLS FOR THREE-PERSON CAPACITY WVE MODULE

TABLE 13 WVE MODULE CHARACTERISTICS OPTIMAL AND CHOSEN CONFIGURATIONS

WVE Module Characteristics	Optimal Module Configuration (w/o Cost)	Optimal Module Configuration (w/Cost)	Developed Hardware Configuration
Current Density, mA/cm^2 (ASF)	36.2 (33.6)	59.7 (55.5)	45.9 (42.6)
Cell Area, cm^2 (ft^2)	280 (0.30)	280 (0.30)	460 (0.50)
Number of Cells	36	23	18
Current, A	10.1	16.7	21.3
Cell Voltage, V	1.77	1.88	1.81
Power Consumption, W	678	720	693
Module Weight, kg (lb)	30.5 (67.2)	21.4 (47.0)	30.3 (66.7)
Total Equiv. Weight w/o Cost, kg (lb)	221 (487)	226 (498)	226 (498)
Total Equivalent Cost, $K	567	549	560

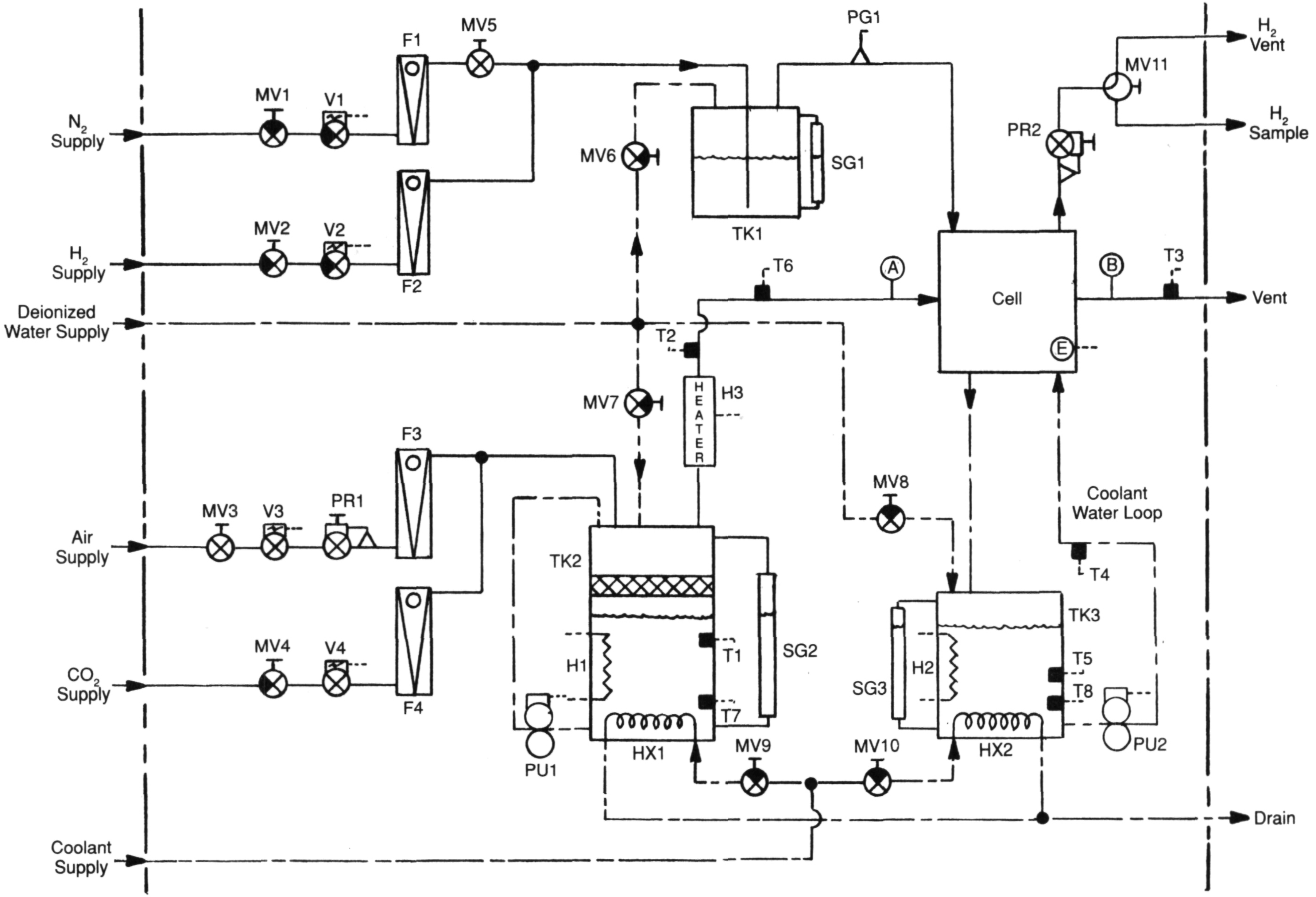


FIGURE 16 WVE SINGLE CELL TEST FACILITY

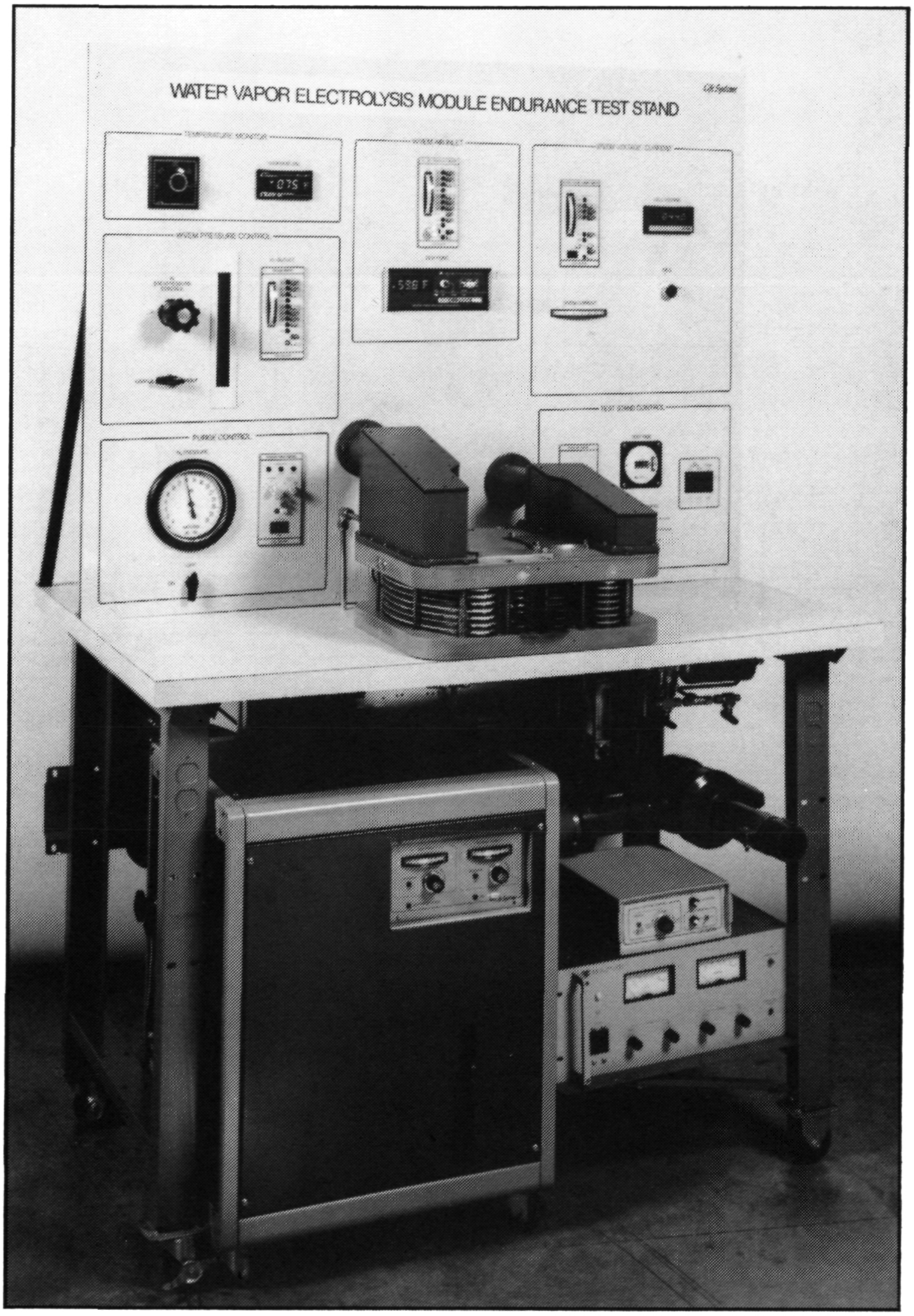


FIGURE 17 WVE MODULE TEST STAND

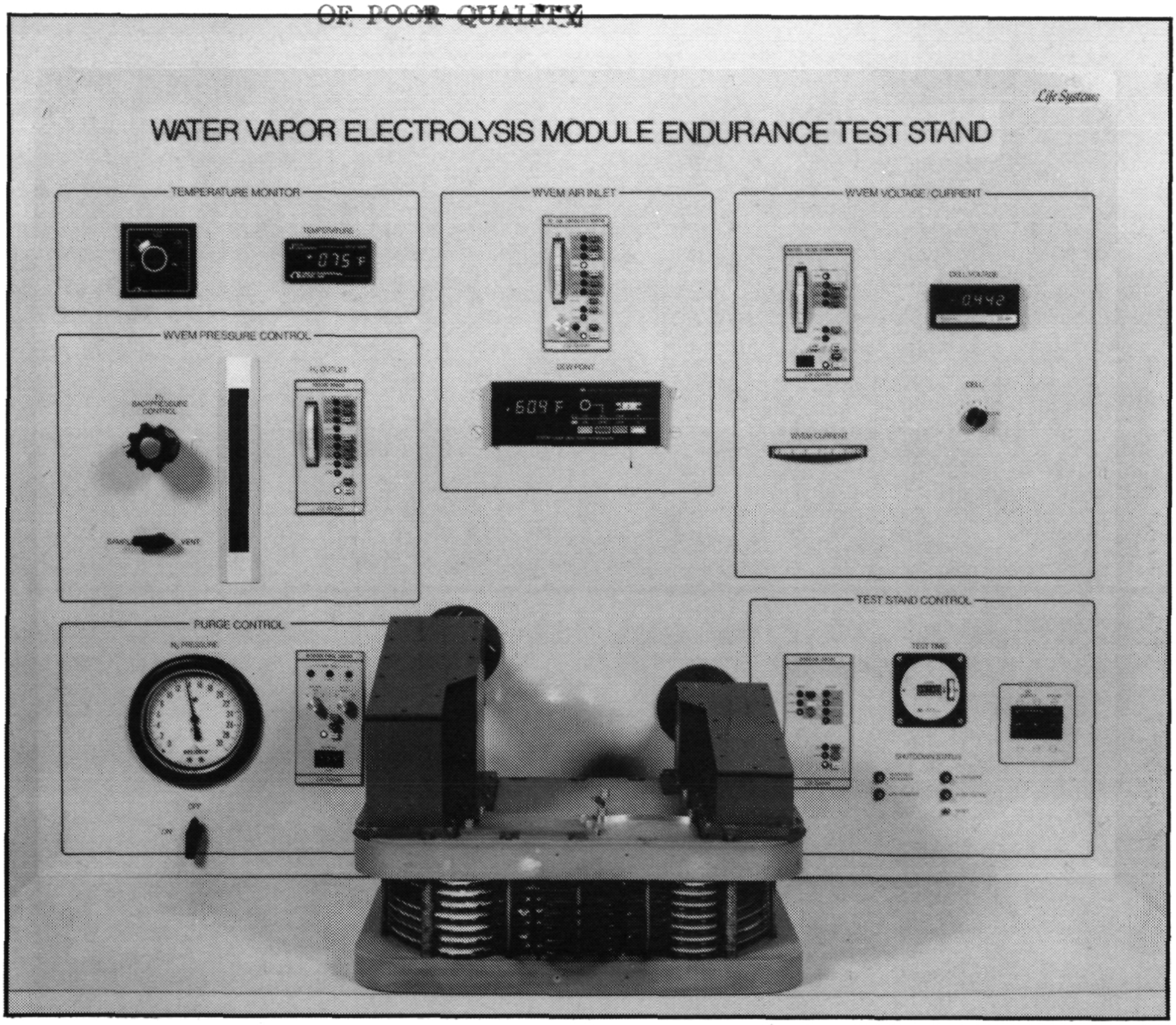


FIGURE 18 WVEM TEST STAND SHOWING MODULE

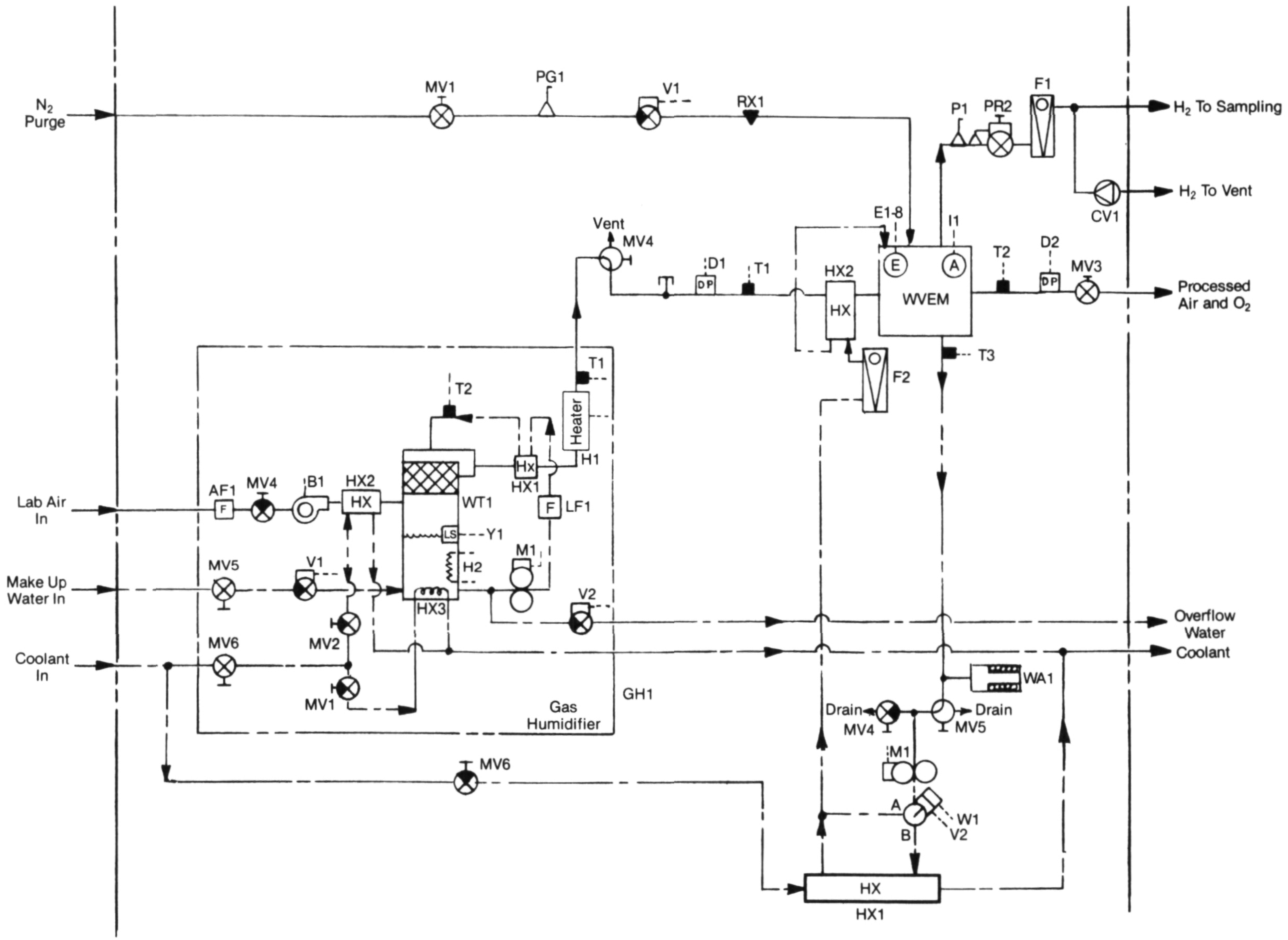


FIGURE 19 LIQUID-COOLED WVEM TEST STAND MECHANICAL SCHEMATIC WITH SENSORS

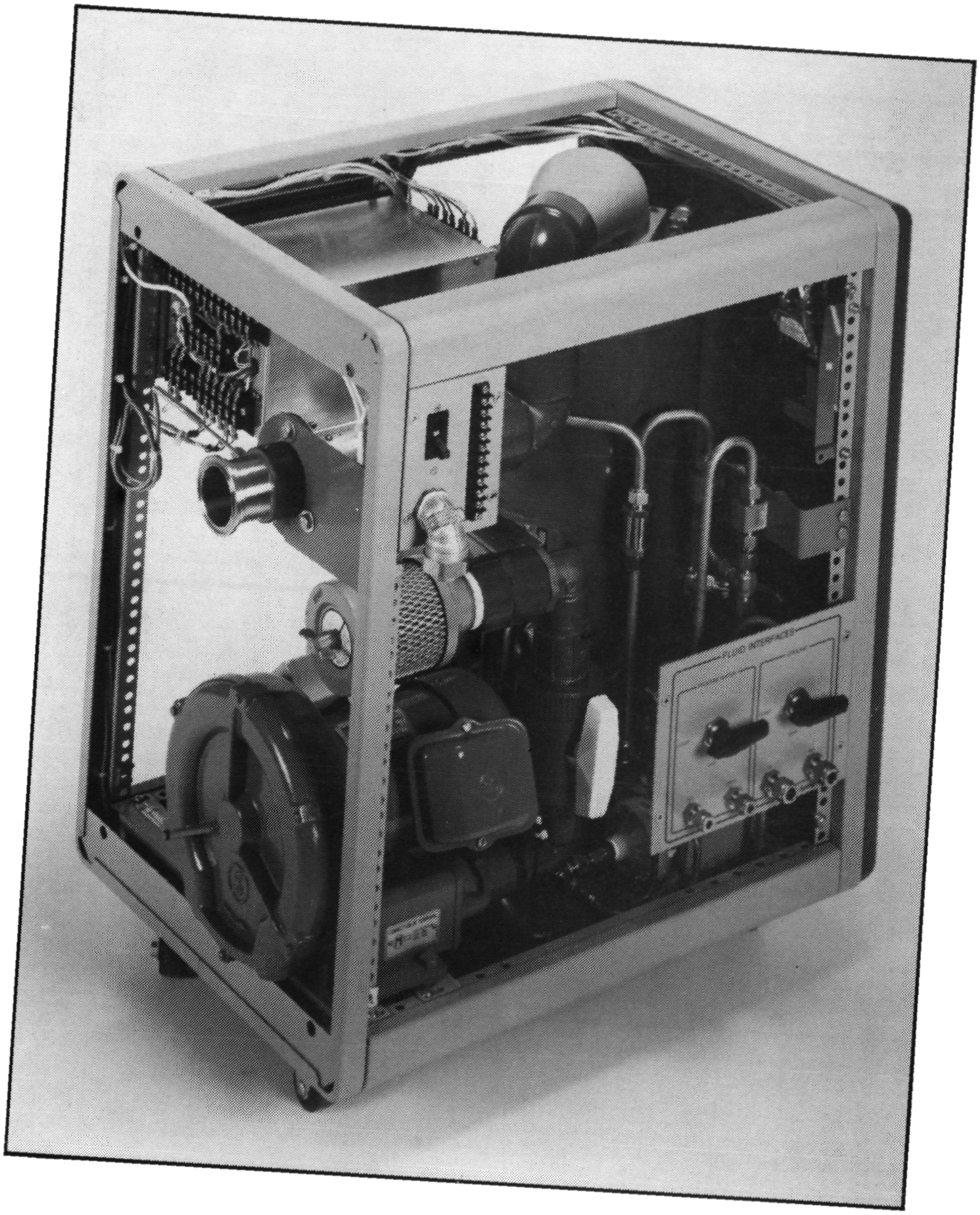
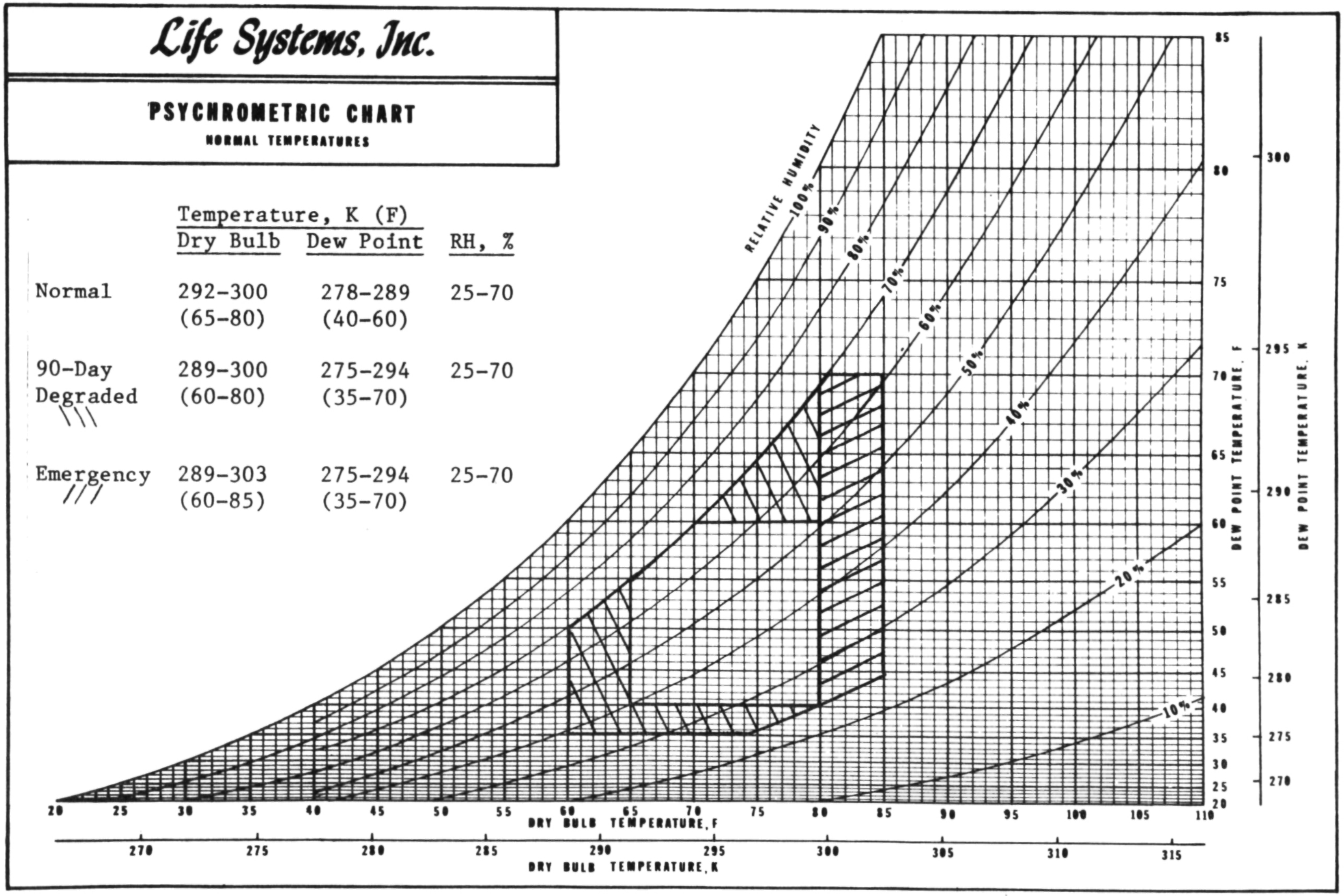


FIGURE 20 GAS HUMIDIFIER (WITHOUT SIDE PANELS)



	Temperature, K (F)		
	Dry Bulb	Dew Point	RH, %
Normal	292-300 (65-80)	278-289 (40-60)	25-70
90-Day Degraded \\\	289-300 (60-80)	275-294 (35-70)	25-70
Emergency ///	289-303 (60-85)	275-294 (35-70)	25-70

FIGURE 21 SPACE STATION TEMPERATURE AND HUMIDITY RANGES

TABLE 14 WVEM TEST STAND ELECTRICAL CONTROLS AND MONITORS

Controls

- Operation Control (OpC) - oversees overall test stand operation and the mode transitions (i.e., Normal, Shutdown, Standby and Unpowered).
- WVEM Current Controller - regulates the current passing through the WVEM, which is monitored with a current shunt and meter. The latest technology current controller will be used.
- Relative Humidity Controller and Monitor (RHCM) - monitors the inlet process air temperature and dew point, calculates and displays RH and controls module temperature via the diverter valve/controller.
- Nitrogen Purge Control (NPC) - activates valves during startup and shutdown to supply N_2 for purging the WVEM for selectable durations.
- Diverter Valve Controller - directs the diverter valve (V2) to appropriately regulate the coolant flow through or around a liquid/liquid heat exchanger (HX1).

Monitors

- Multicell Voltage Scanning Monitor (MVSM) - sequentially monitors cell voltages of WVEM.
- Pressure Monitor (PM) - initiate shutdown if WVEM downstream H_2 pressure exceeds limits.

TEST PROGRAM

The following test results are presented in two sections: single cell testing and module testing. The single cell testing consisted of evaluations of different anode, matrix and electrolyte constructions, while the module testing focussed in on the one-person module testing.

Single Cell Test Results

The results of single cell testing are shown in the following figures. Figure 22 shows the cell voltage versus current (E versus I) curve for catalyzed screen anode and a 50% H_3PO_4 electrolyte. This is to be compared with results using the same anode and matrix but charged with 32% H_2SO_4. These latter data are shown in Figure 23. The eletrolyte charge concentration of either acid is chosen to be compatible with the maximum anticipated dew point temperature. In all cases the H_3PO_4 values are higher than the corresponding ones for H_2SO_4, except at low current density and high humidity, i.e., at the "least stressful" operating conditions. Also shown is the internal resistance (IR) voltage drop measured using a Kordesch-Marko bridge. Results for the H_3PO_4 are generally three to four times larger at all current values. Figure 24 shows the results with the two electrolytes plotted together for the 70% RH inlet condition.

In order to investigate the effect of anode construction another style of anode was employed. This was a porous metal plaque. An electrode thickness of 0.081 cm (0.032 in) was used. The thicker porous plaque electrode provides increased electrolyte retention and improved differential pressure capability. This electrode was fabricated and installed in the test facilities. Results with H_3PO_4 electrolyte are shown in Figure 25. Significantly higher cell voltage was experienced; however, the IR drops were less. These data are summarized in Table 15.

Over 780 hours of testing was accumulated with a single WVE cell consisting of the porous plaque and H_2SO_4 electrolyte. Cell voltages were stabilized and remain in the range of 1.7 V to 1.85 V over the range of 278 to 289 K (40 to 60 F) dew point temperatures and 43 mA/cm^2 (40 ASF) current density. Hydrogen backpressure ranged from 21 to 69 kPa (3 to 10 psid). Terminal voltage values depend on cell temperatures which in turn depend on inlet conditions. This is because of the coolant control which was adjusted to the proper temperature in response to inlet dew point variations. Typically the coolant was adjusted to give a 5.5 K (10 F) difference between outlet dry bulb and inlet dew point temperatures (e.g., 294 K (70 F) outlet dry bulb for 289 K (60 F) dew point).

Figure 26 shows the results of the testing at 32 mA/cm^2 (30 ASF). At approximately the 170-hour mark the coolant pump of the test facility failed, and coolant temperatures could not be maintained. Consequently, cell voltages rose. After finding and fixing the problem, testing was continued at 43 mA/cm^2 (40 ASF). Results are shown in Figure 27. Note, that as before, inlet conditions are generally on the severe side of the Space Station dew point temperature range (i.e., near 278 K (40 F)).

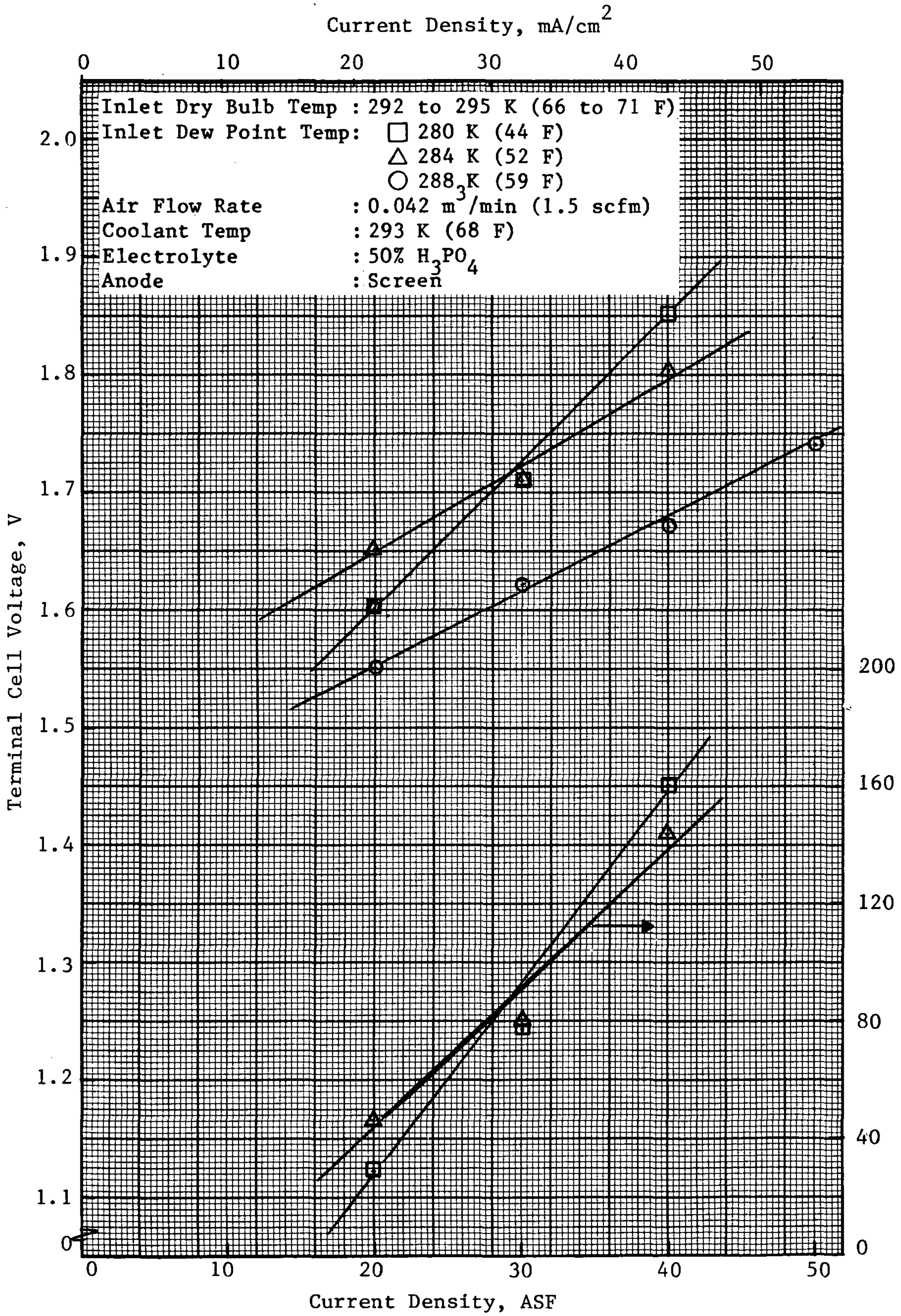


FIGURE 22 WVE SINGLE CELL PERFORMANCE - H_3PO_4 ELECTROLYTE AND SCREEN ANODE

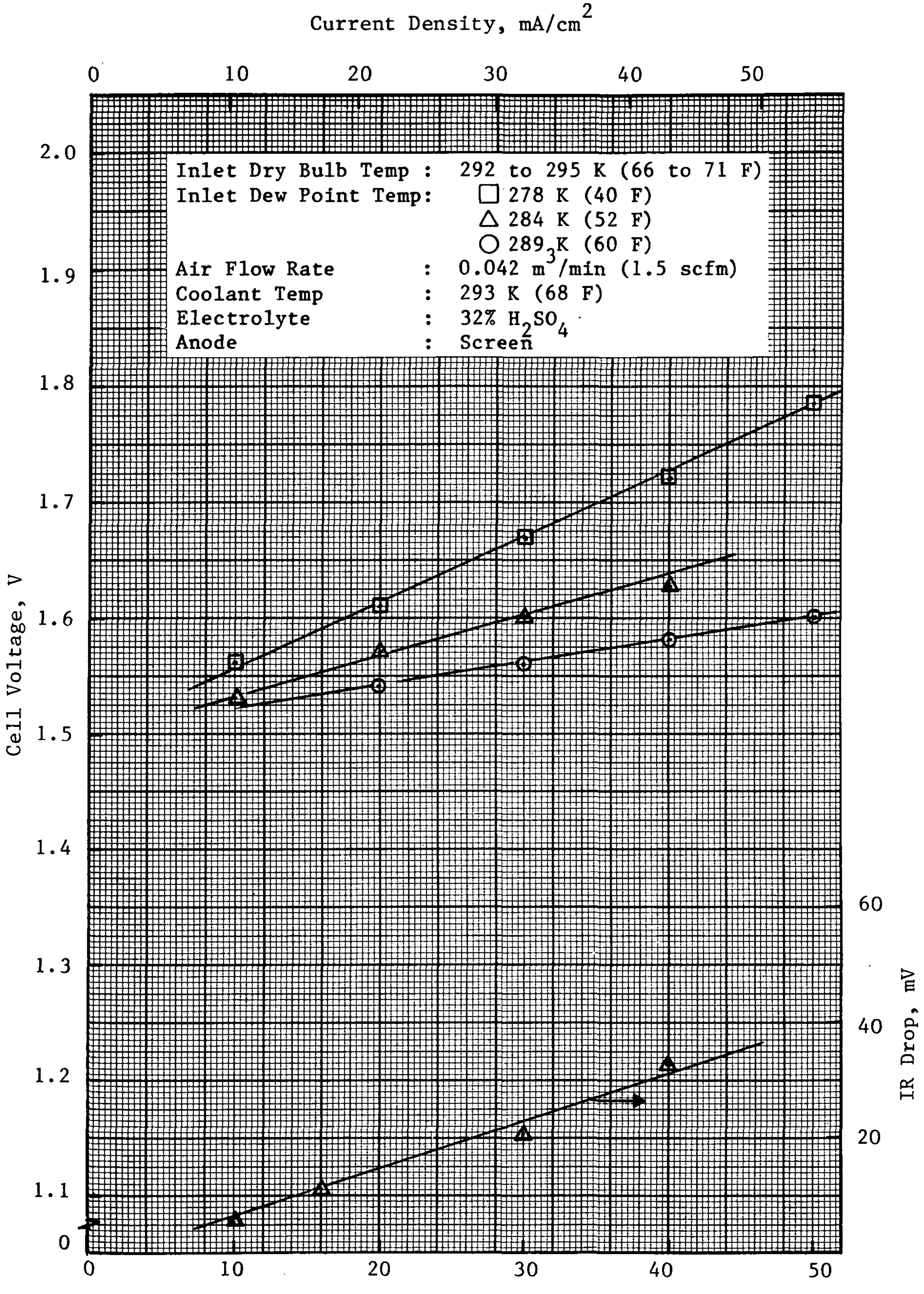


FIGURE 23 WVE SINGLE CELL PERFORMANCE - H_2SO_4 ELECTROLYTE AND SCREEN ANODE

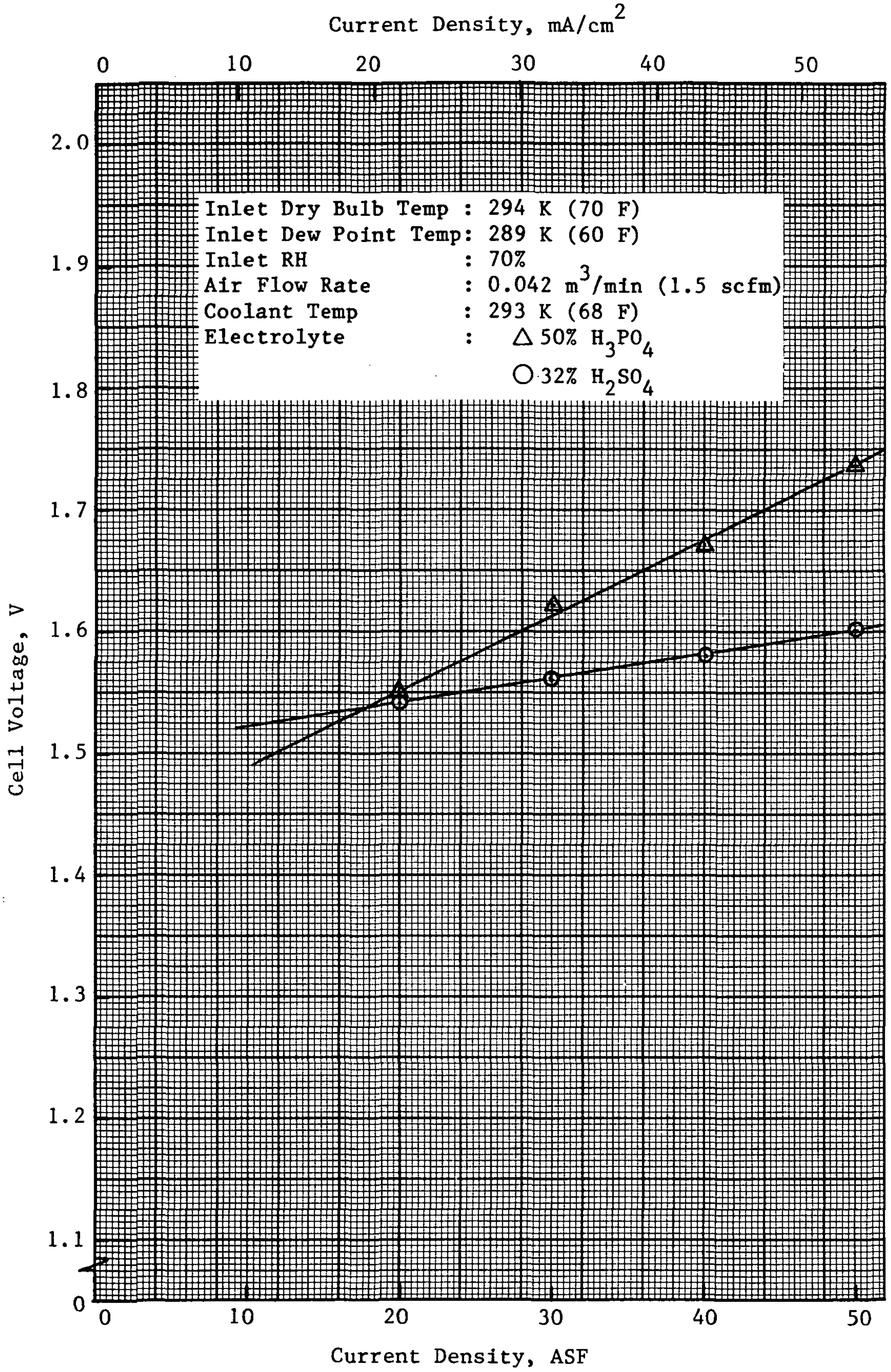


FIGURE 24 WVE SINGLE CELL PERFORMANCE AS FUNCTION OF ELECTROLYTE

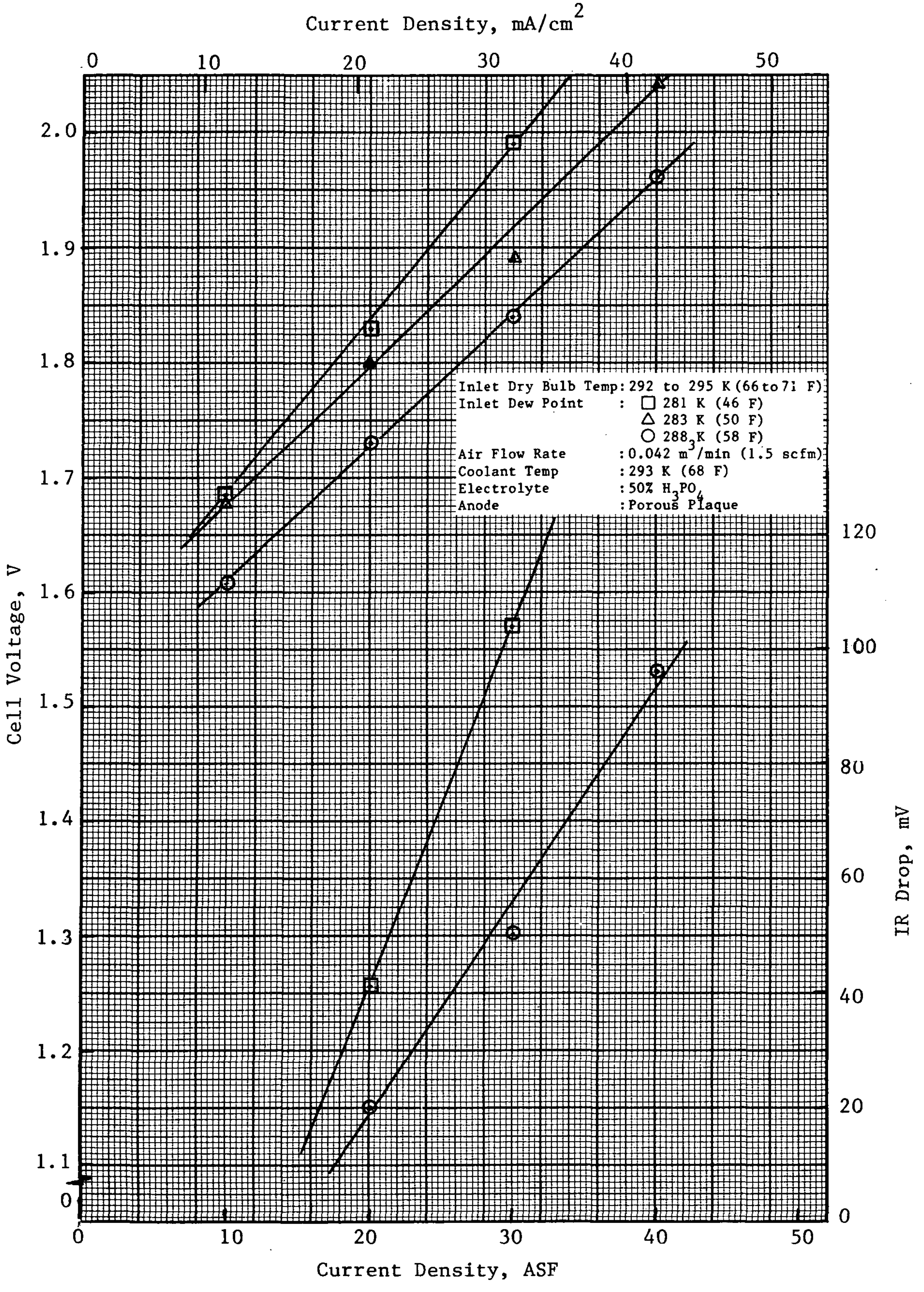


FIGURE 25 WVE SINGLE CELL PERFORMANCE - H_3PO_4 ELECTROLYTE AND POROUS PLAQUE ANODE

TABLE 15 WVE SINGLE CELL TESTS

A. Cell Voltage, V

No.	Anode	Electrolyte	Current Density, mA/cm^2 (ASF)[a] 10.8 (10)	21.5 (20)	32.3 (30)	43.0 (40)
1	Screen	H_2SO_4	1.55	1.57	1.60	1.63
2	Screen	H_3PO_4	-	1.65	1.72	1.81
3	Porous Plaque	H_2SO_4	-	1.67	1.71	1.75
4	Porous Plaque	H_3PO_4	1.65	1.80	1.89	2.04

B. IR Voltage Drop, mV

No.	Anode	Electrolyte	Current Density, mA/cm^2 (ASF)[a] 10.8 (10)	21.5 (20)	32.3 (30)	43.0 (40)
1	Screen	H_2SO_4	5	14	21	33
2	Screen	H_3PO_4	-	46	79	144
3	Porous Plaque	H_2SO_4	-	2	4	6
4	Porous Plaque	H_3PO_4	-	20	50	95

---

[a] Test Conditions:
Inlet Dry Bulb Temp : 292 to 295 K (66 to 71 F)
Inlet Dew Point Temp: 284 K (52 F)
Air Flow Rate : 0.042 m^3/min (1.5 scfm)
Coolant Temp : 293 K (68 F)

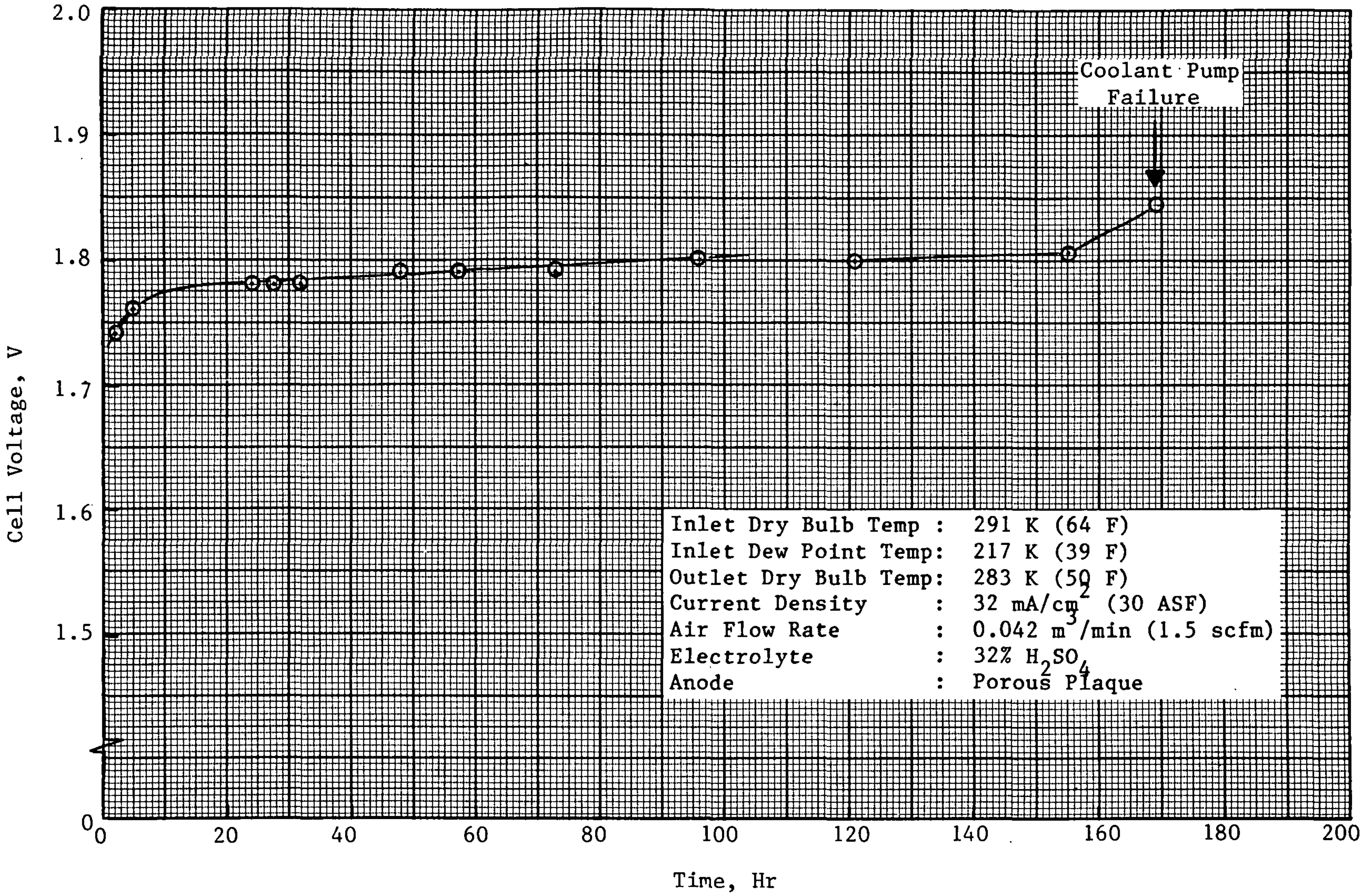


FIGURE 26 WVE SINGLE CELL PERFORMANCE OVER TIME 32 mA/cm^2 (30 ASF))

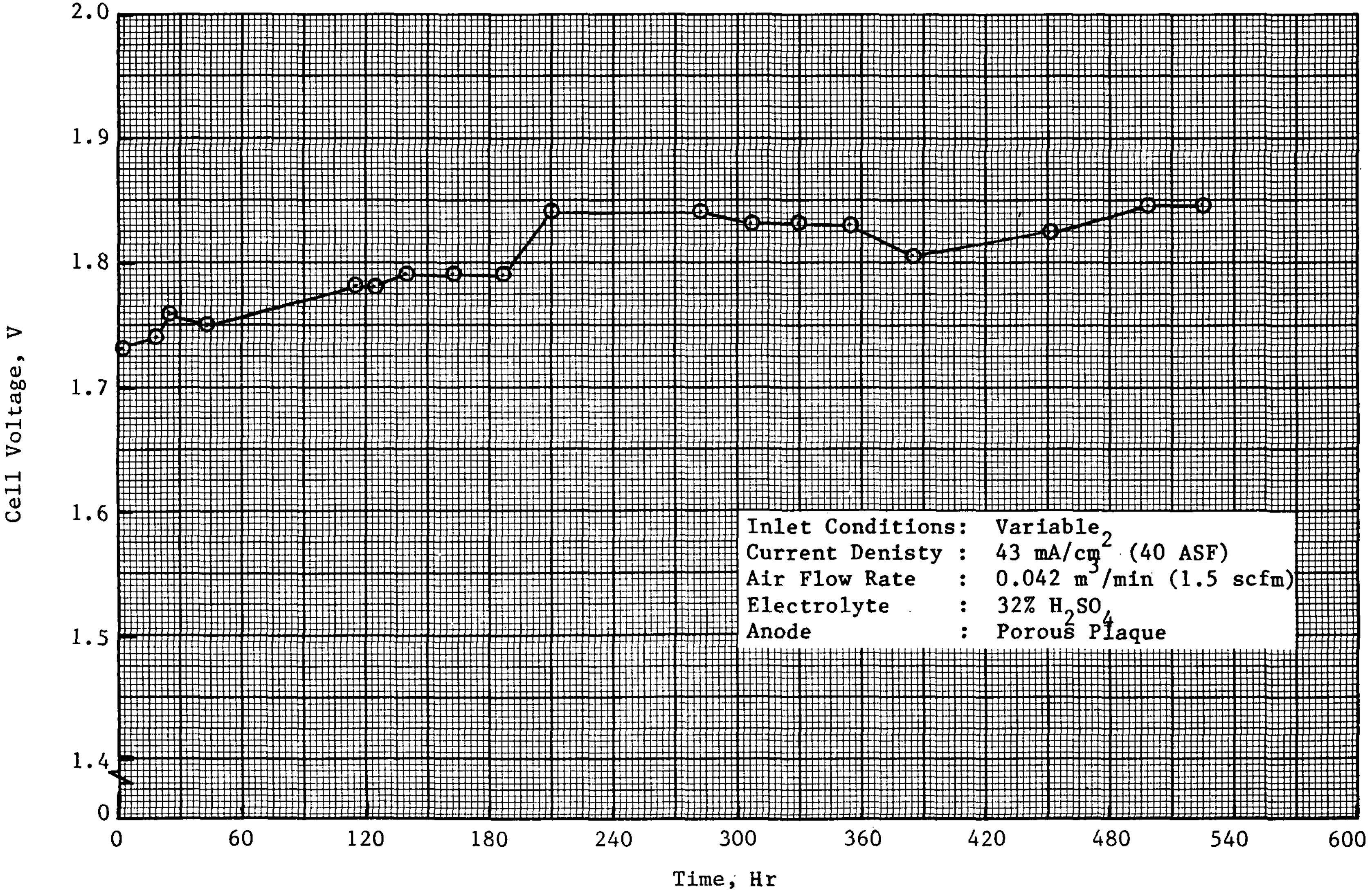


FIGURE 27 WVE SINGLE CELL PERFORMANCE OVER TIME (43 mA/cm^2 (40 ASF))

A total of 1,000 hours of testing, including parametric and endurance, were accumulated in the single cell test facilities. The principal variables were the two different electrolytes H_2SO_4 and H_3PO_4 and the two different anode materials--screen and porous plaque. The catalyzed screen electrode is similar to previously used electrodes for WVE, while porous plaque was tested because of its greater thickness and improved electrolyte retention/ differential pressure capabilities. Figure 28 shows the ranges of air inlet conditions experienced in the testing.

The results of the testing led to the following conclusions. The porous plaque anode gave good differential pressure (69 kPa (10 psid) or greater) results, but gave slightly a higher cell voltage. Phosphoric acid gave higher cell voltage but does not introduce a potential problem (see below). Therefore, the recommended unitized core configuration will utilize 0.076 cm (0.030 in) porous plaque electrode (anode) with 50% H_3PO_4 as the recommended electrolyte.

Problems with H_2SO_4 Electrolyte

A test was conducted to determine the susceptibility of the H_2SO_4 electrolyte to produce hydrogen sulfide (H_2S) under certain conditions. Evolution of H_2S from the cathode can poison the catalytic electrode surfaces. The single cell was operated at low dew point inlet conditions. The outlet air temperature was controlled by adjusting the coolant temperature. Hydrogen sulfide concentration in the hydrogen stream was measured with a gas analyzer tube with a range of up to 60 ppm and sensitivity of 0.1 ppm.

Figure 29 shows the results of one test. As long as the module delta T (outlet dry bulb minus inlet dew point temperature) is less than about 6 K (10 F), there was no H_2S production. For extremely low outlet RH (less than 25%), significant H_2S can occur. For this reason H_3PO_4 was selected for the final WVE module electrolyte.

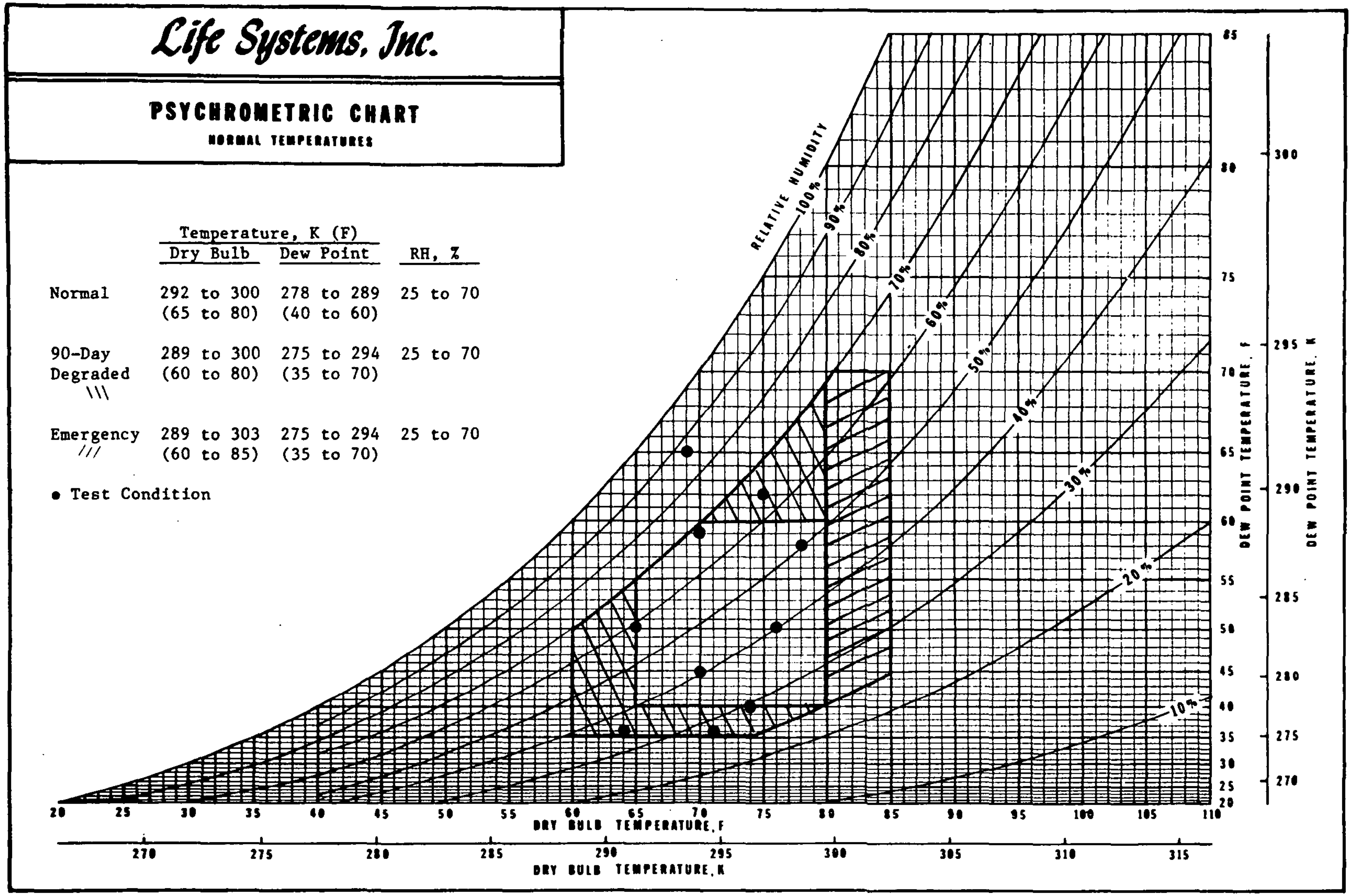
The above reported data on H_2S generation was reviewed for a possible correlation between H_2S generation and cell voltage. The two data points cited (12 and 40 ppm) exhibited cell voltages of 2.04 V and 2.09 V, respectively. Voltages less than 2.0 V do not generate H_2S. There appears to be some correlation between cell voltage and H_2S generation. However, the data presently are insufficient to prove that cell voltage alone and not dry conditions give rise to H_2S.

Module Testing

The six-cell WVEM module was assembled, charged with electrolyte and tested. The module was installed in the test stand previously discussed. Following checkout, performance testing was conducted according to a test plan and consisted of parametric and baseline tests.

Parametric Tests

The parametric tests consisted of current density spans at various levels of process air inlet RH. The latter was accomplished by altering the dew point temperature of the gas humidifier. Figure 30 shows the results of these tests. The average cell voltage is the total module voltage divided by six, the number of cells.



	Temperature, K (F) Dry Bulb	Temperature, K (F) Dew Point	RH, %
Normal	292 to 300 (65 to 80)	278 to 289 (40 to 60)	25 to 70
90-Day Degraded \\\	289 to 300 (60 to 80)	275 to 294 (35 to 70)	25 to 70
Emergency ///	289 to 303 (60 to 85)	275 to 294 (35 to 70)	25 to 70

● Test Condition

FIGURE 28 RANGE OF WVE AIR INLET CONDITIONS

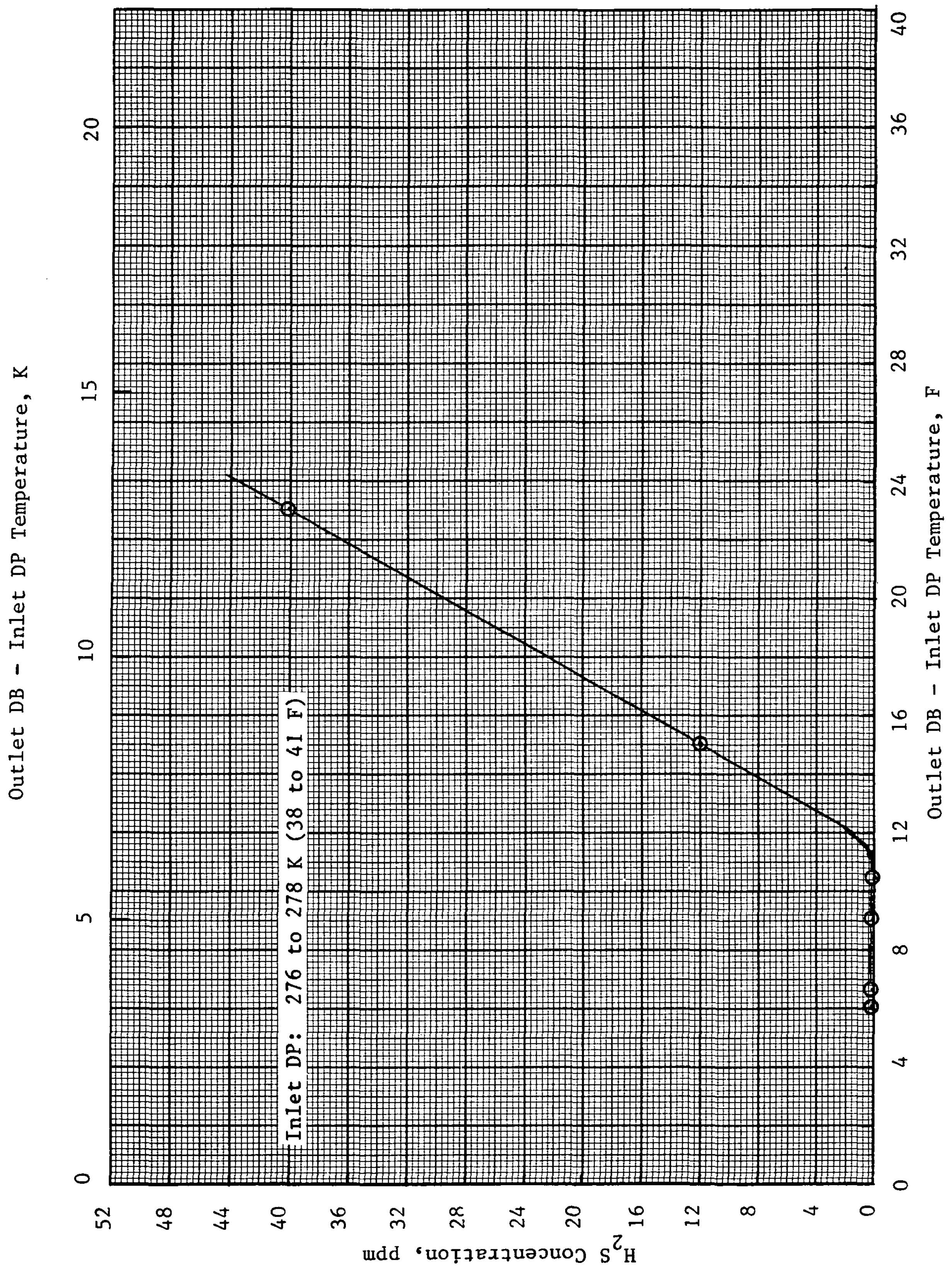


FIGURE 29 WVE SINGLE CELL H_2S PRODUCTION

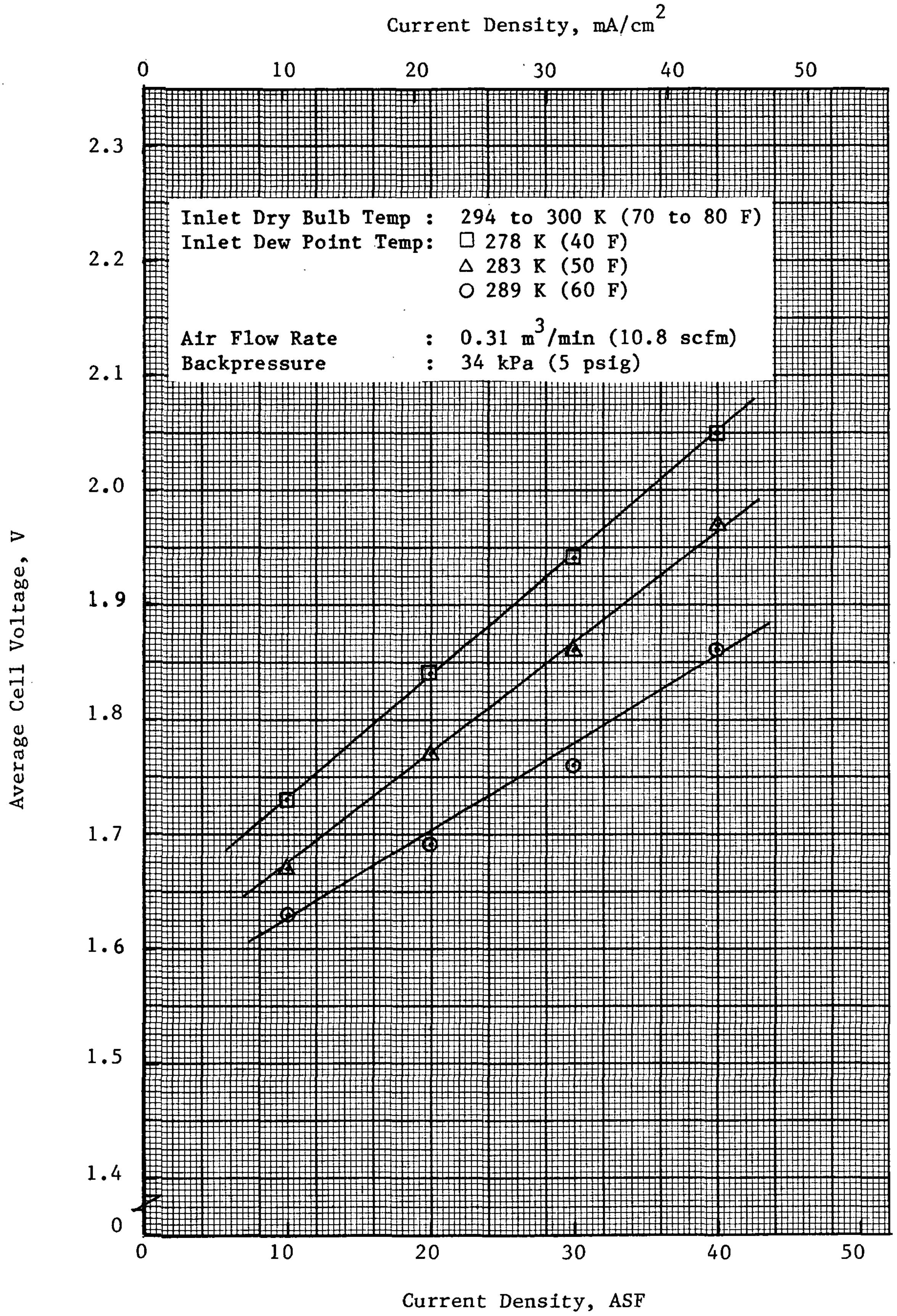


FIGURE 30 WVEM PARAMETRIC PERFORMANCE

Baseline Test

A 195-hour baseline test was conducted by operating the WVEM at essentially constant humidity conditions. Figure 31 shows the results of this test with the test conditions indicated.

PRODUCT ASSURANCE

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractural performance, including design, purchasing, fabrication and testing. The product assurance program included Quality Assurance, Reliability, Maintainability and Safety functions. Quality Assurance was necessary to ensure reproducibility of designs and configurations during subsequent developments. Reliability was included to ensure that test equipment and test data gathering and recording were basic factors in the development of WVE subsystem reliability and long life. Maintainability was included to identify parameters for routine and nonroutine maintenance requirements. Safety was included to ensure that no system or system component characteristic would be dangerous to personnel or equipment during testing.

Quality Assurance

The activities performed during this effort were included to ensure that no defective components or parts were incorporated into the test hardware. These activities consisted of performing receiving inspection of all vendor supplied parts, including preparation of required documentation; ensuring that assembly techniques specified in design drawings were complied with and were consistent with the developmental nature and scope of the program; and ensuring that configuration control was provided by monitoring the drawing and change control procedures. Quality assurance was active in monitoring all test activities.

Reliability

Reliability personnel participated in the program to ensure (1) proper calibration of test equipment instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. Calibration and test requirements for each subsystem and component were determined. Appropriate components were calibrated during assembly and after installation. A test procedure was established to ensure that all parameters would be properly monitored and that the testing would conform to the program's Quality Assurance and Safety procedures. All major testing required that a test plan be completed and reviewed.

Maintainability

A Maintainability function was carried out during the design and testing phases of the program. During design phases, the emphasis was placed on configuring the hardware and test stand components for accessibility with

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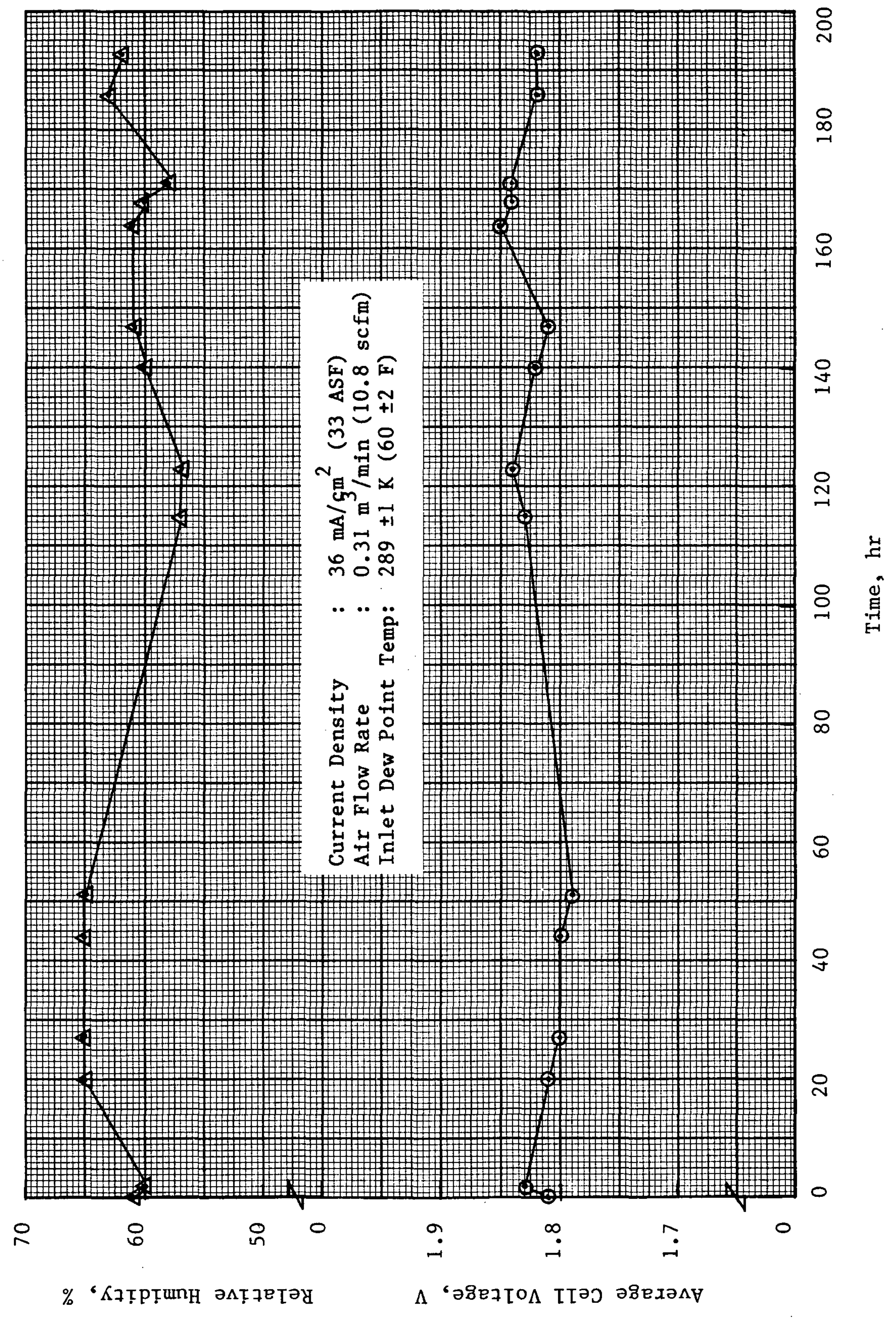

FIGURE 31 WVEM BASELINE TEST DATA

respect to maintenance activities. During the testing phases, logs of scheduled and unscheduled maintenance were maintained. Logs were prepared which detailed operational problems and their sources, the corrective actions taken and the operations and time required to implement the corrective actions.

During the design phases, shutdown avoidance analyses were performed. The objective was to identify preventive shutdown measures to increase the amount of test data obtained per test dollar and ensure that a shutdown caused by an out-of-tolerance condition would not damage components. The results of the analysis included the following:

1. All hardware was checked out prior to installation into the test facility.
2. All parameter level setpoints were checked out to ensure that the level warning lights operated by simulating inputs at the sensors and verifying these inputs.
3. All sensors were calibrated as required.
4. Where applicable, operational transitions were automated in order to avoid human error caused by manual operation.

Safety

A safety program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse component or subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing the National Aeronautics and Space Administration's (NASA's) Alerts for safety information and incorporating the equipment's protective features. The safety program included the following activities:

1. Although metallic material control was not required contractually, all materials were subjected to informal evaluation during design and manufacturing phases. Nonmetallics were evaluated for their compatibility with atmospheres and corrosive media to which the nonmetallic might be exposed. Nonmetallic materials lists were compiled. Metallic materials were evaluated with regard to corrosion resistance and strength criteria.
2. Human Engineering considerations were given to both operation and maintenance. All known possibilities of human error were eliminated, with primary emphasis being given to possible accidental activation of components or subsystems. Where feasible, fluid line end fittings or connections were used with dimensions or configurations which would not permit incorrect installation of a fluid line.
3. Electrical design considerations included prevention of electrical equipment shock hazard, protection against inadvertent actuation of

switches, use of current limiting devices on electrical equipment which could contact personnel or other conductive equipment, use of warning labels on all access panels leading to high voltages, and design of wire bundles to have the ability to withstand anticipated handling and operating deformations without wire damage.

4. Sharp edges and corners were eliminated or were adequately covered with a protective cushion in order to prevent injuries.

5. Items exhibiting elevated surface temperatures and which might be leaned on, brushed against or held for up to 10 seconds were insulated so that surface temperatures would not fall outside the range of 289 to 322 K (60 to 120 F).

CONCLUSIONS

Based upon the work completed, the following conclusions are drawn:

1. A WVE cell and module can be made that will operate over indefinite time periods within the Space Station atmospheric range of 278 to 289 K (40 to 60 F) dew point temperature and 292 to 300 K (65 to 80 F) dry bulb temperature. Control of the process air humidity is not required.

2. Differential pressure capability from the H_2 side cathode to the O_2/air side anode was demonstrated to be in excess of 69 kPa (10 psid). This adds an additional margin of safety for a process which interfaces directly with cabin air.

3. Phosphoric acid electrolyte provides a margin of safety in terms of operational flexibility since dry cabin conditions do not give rise to objectionable secondary reactions and products.

4. The liquid cooling approach to thermal control and the control algorithm developed under the program provides the mechanisms for achieving humidity tolerance. Similar results could not be achieved with air cooling.

5. The unitized core concept demonstrated excellent operational capabilities at both the single-cell and module levels. Single-cell endurance testing for over 1,000 hours demonstrated the capability of the unitized core to operate at differential pressures over 69 kPa (10 psid). Testing at the six-cell module level verified the performance and reliability of the unitized core. Based upon the results of the testing, overall WVE cell complexity can be reduced and cell operational capabilities and reliability can be improved by use of the unitized core concept.

6. Specific goals were established for the WVE improvements program. These are listed in Table 16. Increased humidity tolerance was one of the more important goals of this program.

TABLE 16 PAST AND PRESENT WVE CHARACTERISTICS

	WVE Technology Level Indicators	Prior Technology	Improved WVE Technology	Benefits of Technology Improvement
1.	Cell Voltage (Max.), V at 54 mA/cm^2 (50 ASF)			
	RH of 40%	1.80	1.70	Reduces power and heat rejection penalties, i.e., lower Air Revitalization System equivalent weight.
	RH of 50%	1.75	1.65	
	RH of 60%	1.73	1.60	
	RH of 75%	1.70	1.60	
2.	Relative Humidity Operating Range, %			
	Lower Limit	32	25	Meets all Space Station cabin dew point and dry bulb temperatures.
	Upper limit	70	75	
3.	Minimum Cabin Dew Point K, (F)	280 (45)	278 (40)	Meets Space Station ECLSS performance requirements.
4.	H_2-to-Air Side Delta P, kPa (psid)			
	Nominal	34 (5)	55 (8)	Provides safe and reliable operation under all ECLSS dry blub/dew point conditions.
	Maximum	41 (6)	69 (10)	
5.	Cooling Medium	Air	Water	Less heat rejection penality, lower hardware volume, improved reliability, decreased noise.
6.	Module Construction	Individual Parts	Unitized Core Composite Cell	Reduces weight, volume, fab. costs and improves reliability, safety and maintainability.
7.	Conductive Fluids Contact with Electrically Conductive Surfaces			
	Internal	Minimize	Eliminate	Eliminates the only source of electrical current efficiency loss.
	External	Eliminated	Eliminate	
8.	Atmosphere (Air) Manifold	Customized(a) Manifold	Integral with Cell Frame	Simplifies manufacturing cost and tolerates changes in requirements during development.
9.	Ratio Electrodes Electrolyte Volume to that in Matrix	1:1:1	1:1:2	Improves tolerance to low relative humidity.
10.	Technology Maturity, Operating Time, hr			
	Cells	>7,000	More Endurance Testing Needed	Improves technology maturity.
	Modules	>5,000		
	Subsystem	>5,000		
	Increase Tech. Data Base	Extensive		

continued-

(a) Needing new manifolds for each change in number of electrochemical cells in the module.

Table 16 - continued

WVE Technology Level Indicators	Prior Technology	Improved WVE Technology	Benefits of Technology Improvement
11. Decrease Size (Three-Person)			
Weight, lb	30.5 (67.2) w/o Manifold	28.2 (62.2) w/Manifold	Improves user acceptability.
Volume, ft^3	0.82 (1.8) w/o Manifold	0.73 (1.6) w/Manifold	
12. Increase Reliability	Not Available	Improve[(a)]	Improves user acceptability.
13. Increase Maintainability	Not Available	Increase	Improves user acceptability.
14. Reduce Manufacturing Costs	Not Available	Decrease[(b)]	Improves user acceptability.

(a) Using performance derating, operational simplification and greater tolerance to environmental changes.

(b) Using injection molding and unitized core construction.

RECOMMENDATIONS

Based on the work completed the following recommendations are made.

1. Perform analyses, studies and developments to advance the technology level of water vapor electrolysis-related hardware components, including instrumentation, with a goal of improving overall performance and Space Station applicability of the subsystem. This would involve building a three- or four-person size subsystem for further characterization studies. This hardware would pass into the Space Station ECLSS technology demonstration presently underway for evaluation.

2. Perform endurance testing on the water vapor electrolysis module, and characterize it for start, stop and standby operating modes and temperature ranges over which it can operate successfully. This would simulate a more operational situation of its use.

3. Perform studies, analyses and designs necessary to incorporate the water vapor electrolysis O_2 generation function into an integrated air revitalization system. This activity would focus on ground and potential flight verification testing.

4. Perform analytical and small-scale experimental studies necessary to incorporate the water vapor electrolysis technology into an advanced mission scenario. It would be used, along with other electrochemical technologies, to balance requirements of O_2 generation and CO_2 removal between human crews and biological (e.g., plants) support systems. It would form an important element of a closed ecological life support system.

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APPENDIX 1

SUPPLEMENTARY DATA CURVES

FIGURE		PAGE
A1-1	Water Vapor Pressure for Aqueous H_2SO_4	A1-2
A1-2	Water Vapor Pressure for Aqueous H_3PO_4	A1-3
A1-3	Conductivity of Aqueous H_2SO_4 AND H_3PO_4	A1-4

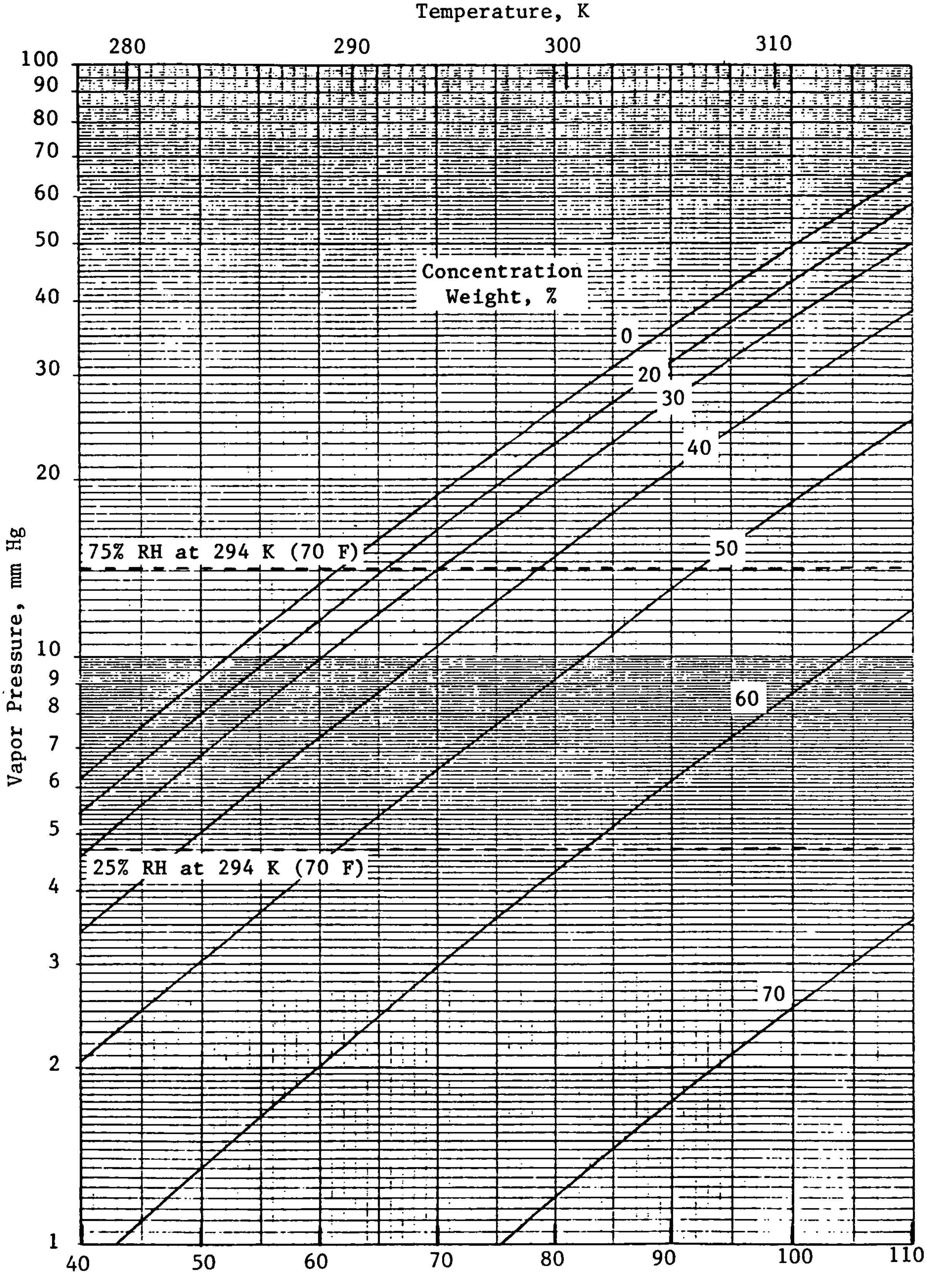

FIGURE A1-1 WATER VAPOR PRESSURE FOR AQUEOUS H_2SO_4

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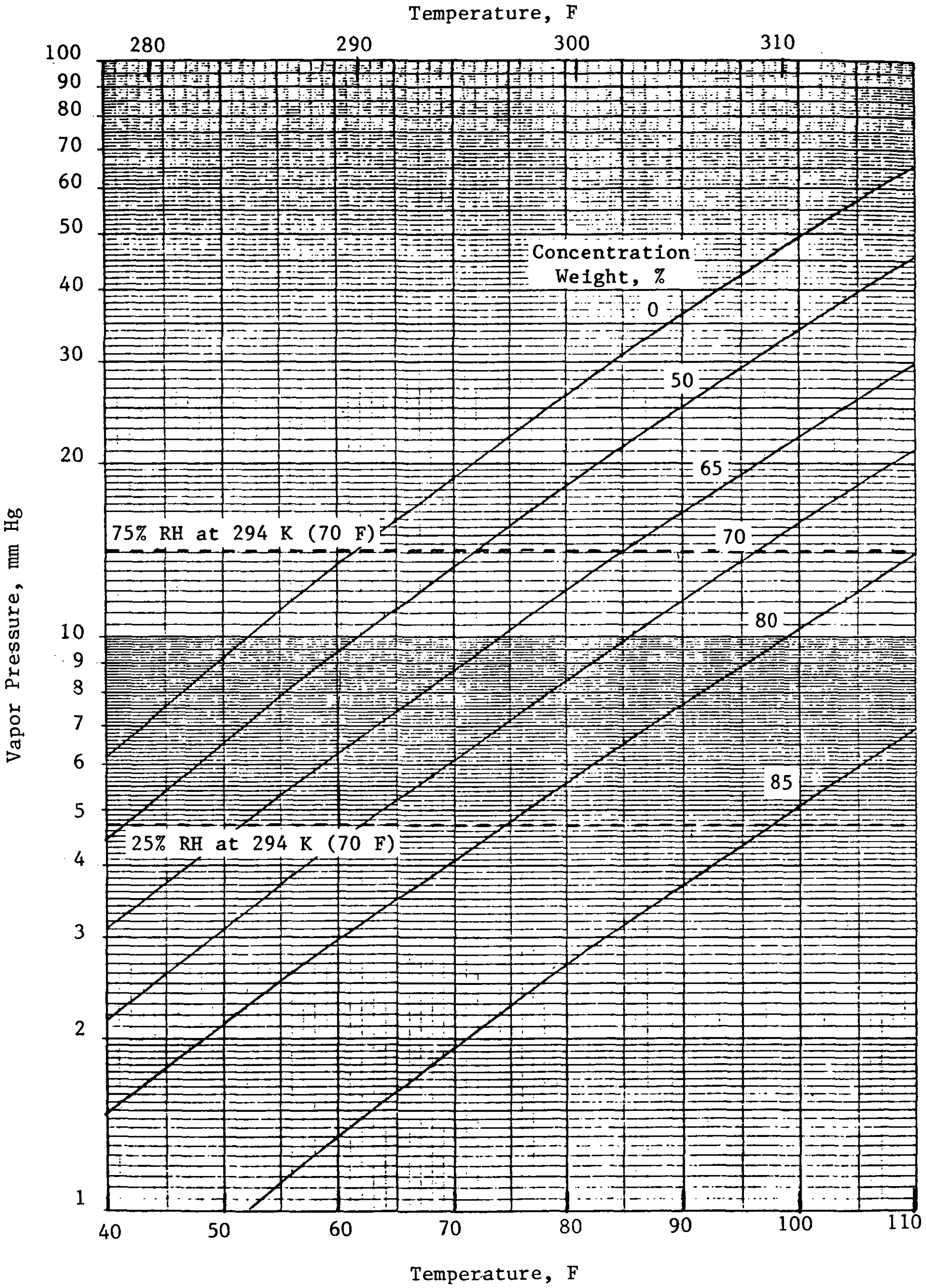

FIGURE A1-2 WATER VAPOR PRESSURE FOR AQUEOUS H_3PO_4

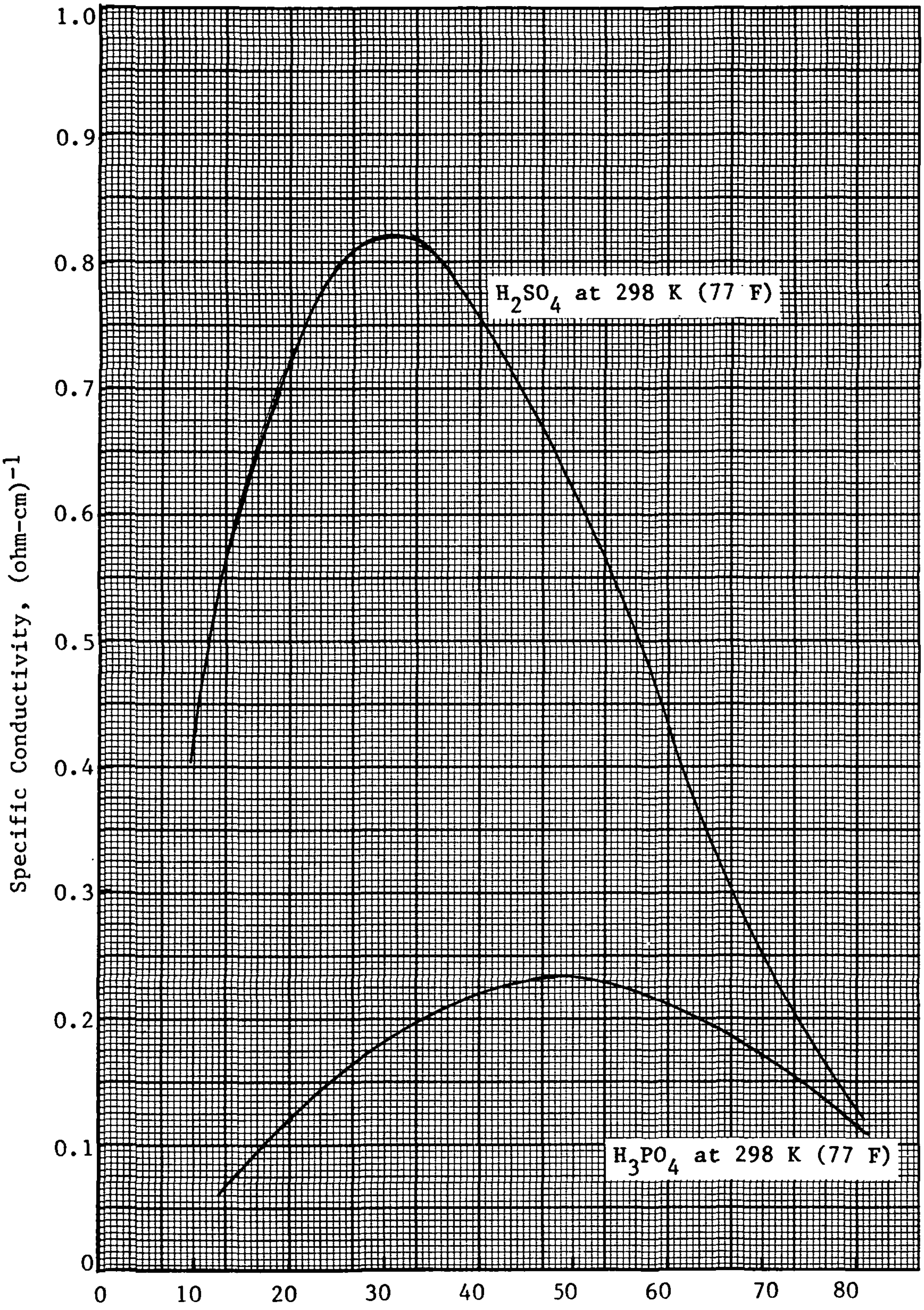

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FIGURE A1-3 CONDUCTIVITY OF AQUEOUS H_2SO_4 AND H_3PO_4