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NASA CR-
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ADVANCED WATER IODINATING SYSTEM

FINAL REPORT

by

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and R. A. Wynveen

February, 1975

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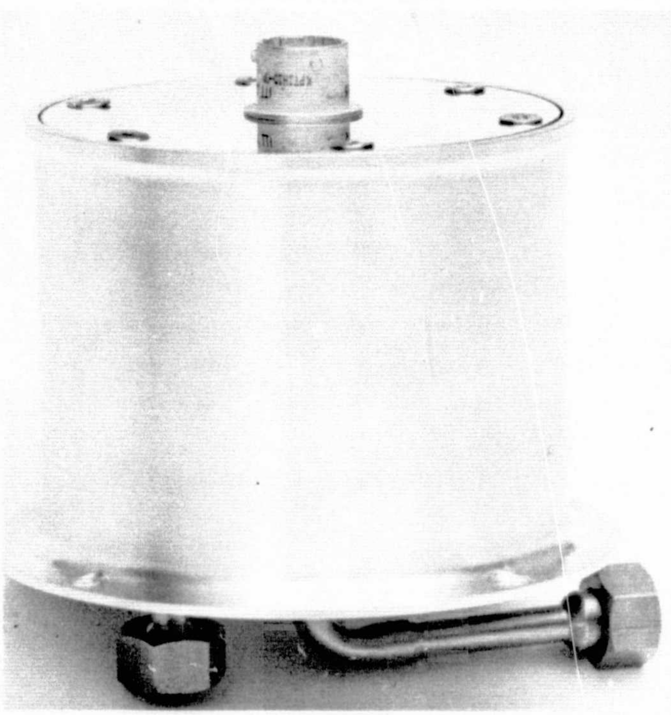

Weight:	890 g (1.96 Lb)
Dimensions:	8.89 Dia. x 7.21 cm (3.50 Dia. x 2.84 In)
Volume:	447 cm^3 (27.3 in^3)
Capacity:	Sized for 22 Space Shuttle Missions at 5 ppm I_2

Prepared Under Contract No. NAS 9-13931

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

JOHNSON SPACE CENTER

National Aeronautics & Space Administration

FOREWORD

The work described herein was conducted by Life Systems, Inc. during the period May 3, 1974 through February 28, 1975, under NASA Contract NAS9-13931. The Program Manager was F. H. Schubert. Life Systems, Inc. personnel contributing to the program include the following:

Personnel	Area(s) of Responsibility
Jan N. Carlson	Analytical model
Ron J. Davenport, PhD	Iodine chemistry, electrochemistry and ion exchange membrane technology
Fred C. Jensen	Iodine valve, accumulator, and dispenser design and system packaging
Mike L. Kruszynski	Test stand fabrication
Glenn A. Little	Ground Support Accessories layout and fabrication
Carol A. Lucas	Documentation
Sam Mazzola	Electronics fabrication
Nancy L. Post	Analytical model
J. David Powell	Control and monitor instrumentation design
Debbie M. Preske	Documentation
Mike Prokopcak	Engineering drawings
Franz H. Schubert	Mechanical design and system concept derivation
John W. Shumar	Product Assurance and materials evaluation
Tom S. Steenson	Analytical, parametric, and endurance testing
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The contract's Technical Monitor was O. Karl Houck, Crew Systems Division, NASA Johnson Space Center, Houston, Texas 77058.

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SUMMARY

Potable water stores aboard manned spacecraft must remain sterile. Suitable sterilization techniques are needed to prevent microbial growth. A program to develop these techniques has been underway at NASA and Life Systems, Inc. (LSI) for the past few years. The work reported herein, the development of an Advanced Water Iodinating System (AWIS) for possible application to the Shuttle Orbiter and other advanced spacecraft, is a portion of the overall program.

The AWIS provides a means of automatically dispensing iodine (I_2) (a biocide) and controlling iodination levels in potable water stores. Work that is described in this report consisted primarily of the design and construction of an electrochemical device to dispense I_2. The feasibility of combining this I_2 Source with an available I_2 concentration detector, the Automated I_2 Monitor System (AIMS), was also demonstrated as part of the required work. During tests, the AWIS (consisting of the combined automated I_2 Source and the AIMS) successfully iodinated simulated fuel cell water to nominally a 5 ppm I_2 concentration over the anticipated 22.7 to 172.5 cm^3/min (72 to 547 lb/day) fuel cell water flow regime of the Shuttle Orbiter.

In a recirculation mode test, simulating application of the AWIS to a water management system of a long term (180 day), six-man capacity space mission, noniodinated feed water flowing at 32.2 cm^3/min (102 lb/day) was iodinated to 5 ±1 ppm concentrations after it was mixed with previously iodinated (5 ±1 ppm) water recirculating through a potable water storage tank at a flow rate of 337 cm^3/min (44.5 lb/hour). Also, the AWIS was used to successfully demonstrate its capability to maintain potable water at a desired I_2 concentration level while circulating through the water storage tank, but without the addition of noniodinated water.

The I_2 Source, designated as Model IX-S, contains sufficient I_2 to iodinate the fuel cell water generated during 27 seven-day Orbiter missions before the Source must be repacked with I_2 crystals. In operation, the crystals undergo chemical changes at the electrodes of the electrochemical cell in the IX-S, such that I_2 is transferred across the cell and into the water to be iodinated, in proportion to the electrical current, automatically modulated by the AIMS, that is supplied to the cell. Operation is independent of water flow rate, temperature, and pressure.

Model IX-S, built as two identical items designated as IX-SA and IX-SB, requires only 5.75 watts of electrical power, is cylindrical, 8.89 cm (3.50 in) in diameter, 7.3 cm (2.84 in) in height, and weighs 890 g (1.96 lb) dry. Several product assurance activities were included as part of Model IX-S development so the final design represents a high level of hardware maturity. Additionally, several tests were made with the IX-S and AWIS such that little additional testing is necessary to verify the flight readiness of the design concepts used in the AWIS. Potential problems such as operation with "worst case" fuel cell water, steam sterilization during ground operations, membrane differential pressure capability, and IX-S/AIMS integration were successfully resolved during the selection of the final AWIS design concept.

It is concluded from the results of the work reported herein that the AWIS is a viable solution to the problem of providing desired quantities of a biocide to potable water stores of manned spacecraft. Furthermore, successful AWIS operation during testing, that was constrained by anticipated Shuttle Orbiter water management system operational parameters, indicates that the AWIS is a contender for use in the Orbiter water management system. Continued development of iodination techniques are recommended to further reduce AWIS weight, volume and power penalties. Successful completion of this development will provide a water biocide system very competitive with the baseline system for the Orbiter and will produce timely technology necessary to plan future advanced Environmental Control and Life Support System (ECLSS) programs and experiments.

INTRODUCTION

The potable water supply on future long-term manned spacecraft will use recycled water in the distribution system. Other short-term duration spacecraft, such as the Shuttle Orbiter, will use fuel cell generated water as the source for potable water. Water reclaimed with regenerative life support systems is inherently susceptible to microbial contamination because it originates from human sources (i.e., urine and humidity condensate). Water generated by fuel cells is very pure when delivered. However, it may become backcontaminated from crew and passenger use points. In either water generation or reclamation system, therefore, provisions must be made for microbial control, but the difficulty of maintaining the control is considered less severe for the Orbiter.

Pasteurization has been proven to be a reliable method for sterilization; however, other approaches offer distinct advantages in terms of weight, volume, cost, and power consumption for maintaining water quality. One such approach was investigated under NASA Contract NAS1-9917[(1)] which led to the development of a laboratory breadboard of an in situ chlorine (Cl_2) generating device called the Chlorogen which was an electrochemical valve that dispensed Cl_2 into water for disinfecting purposes.. Other biocides, silver ion (Ag^+) and I_2, for instance, have merit and have received attention in the manned space program. Iodine, because of its superior microorganism annihilation potential at low dosages and dose rates, among other advantages, is favored. The use of I_2 to maintain water quality on board manned spacecraft was demonstrated in the lunar excursion module of the Apollo and in the Skylab program. In these applications, I_2 was manually administered as a microbial control agent into the potable water systems.

Under Contract NAS1-11765, a program was successfully completed that demonstrated the feasibility of automatically dispensing I_2 into a flowing water stream using the electrochemical valve concept.[(2)] The electrochemical valve consists of an anion exchange membrane between two noble metal electrodes. The I_2 valve is one element of the I_2 Source shown in Figure 1. The I_2 accumulator on one side of the valve contains I_2 in the form of a slurry, contacting the cathode of the valve. When current flows between the electrodes, I_2 in the accumulator is reduced to iodide (I^-). The current is carried by the I^- through the membrane, and when the I^- reaches the anode in the I_2 dispenser, the I^- is oxidized to I_2

(1) References cited are on page 109.

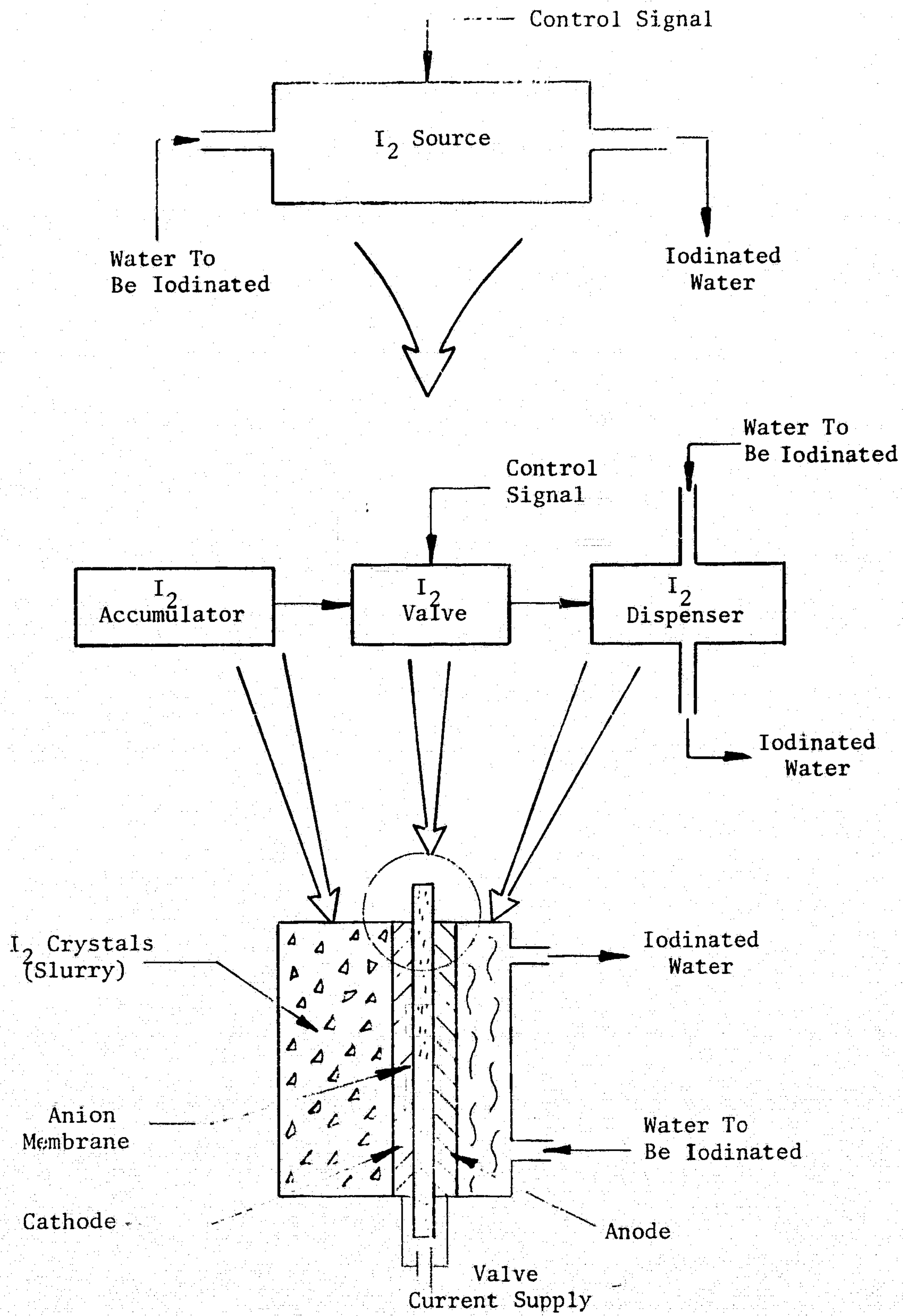


FIGURE 1 I_2 SOURCE SCHEMATIC

which dissolves in the water in the dispenser. Current applied to the I_2 valve controls the rate of I_2 transfer into the dispenser. Figure 2 depicts the I_2 valve reactions. The specific anion transferred determines the process efficiency. If 100% of the current flow is via I^-, the current efficiency will be 100%; via triiodide (I_3^-), the current efficiency will be 300%; and via hydroxyl ions (OH^-), the current efficiency will be 0%. Actual operation indicates a complex combination of all three.

An experimental I_2 Source, Model LSI-100, was fabricated and tested during NAS1-11765. The Source was a body constructed of Lucite as shown in Figure 3. The Model LSI-100 was sized to iodinate to 20 ppm of I_2 water nominally consumed by six men (selected in the range of 4.5 to 13.6 kg (10 to 30 lb) per man-day).

The test and electronics enclosure used to test the Model LSI-100 are shown in Figures 4 and 5, respectively. The electronics could be used to operate the source at constant current or with feedback control of the valve current by a remote I_2 sensor placed in the water system downstream of the Model LSI-100. Controls for a mechanical I_2 injection system were included in the electronics package, although mechanical I_2 injection was considered only as a backup method in the event the electrochemical concept was not feasible.

The Model LSI-100 and its associated electronics comprised the I_2 Generating and Dispensing System (IGDS). The IGDS did not include methods for controlling the I_2 concentration level nor was the hardware developed of a flight-like nature. The program reported herein that was conducted under Contract NAS9-13931 was, therefore, initiated for the development of an Advanced Water Iodinating System (AWIS) that would advance hardware maturity as well as demonstrate complete automation for a Shuttle Orbiter biocide addition system.

Program Objectives

The primary program objective was to develop an AWIS for microbial control in the potable water stores of the Shuttle Orbiter or other advanced spacecraft. The AWIS was to be a self-contained system consisting of a flight-like I_2 Source (IX-S), integrated with a Government-Furnished Automated I_2 Monitor System (AIMS) that, with minimum modification, would meet long duration manned mission as well as Shuttle Orbiter requirements. The AWIS was to have flight characteristics of low weight, low pressure drop, and be a simple, maintainable, and compact design that automatically dispensed I_2 at desired I_2 concentration levels into a stream of flowing water. The AWIS was to be designed, to the greatest extent possible, to Shuttle Orbiter specifications.

Program Organization

A seven-task program was undertaken to achieve the program objectives.

1. Design, develop, fabricate, and assemble two advanced prototypes of an automated I_2 Source (Model IX-SA and IX-SB).

2. Design, develop, fabricate, assemble, functionally check out, and calibrate the Ground Support Accessories (GSA) for testing the IX-S.

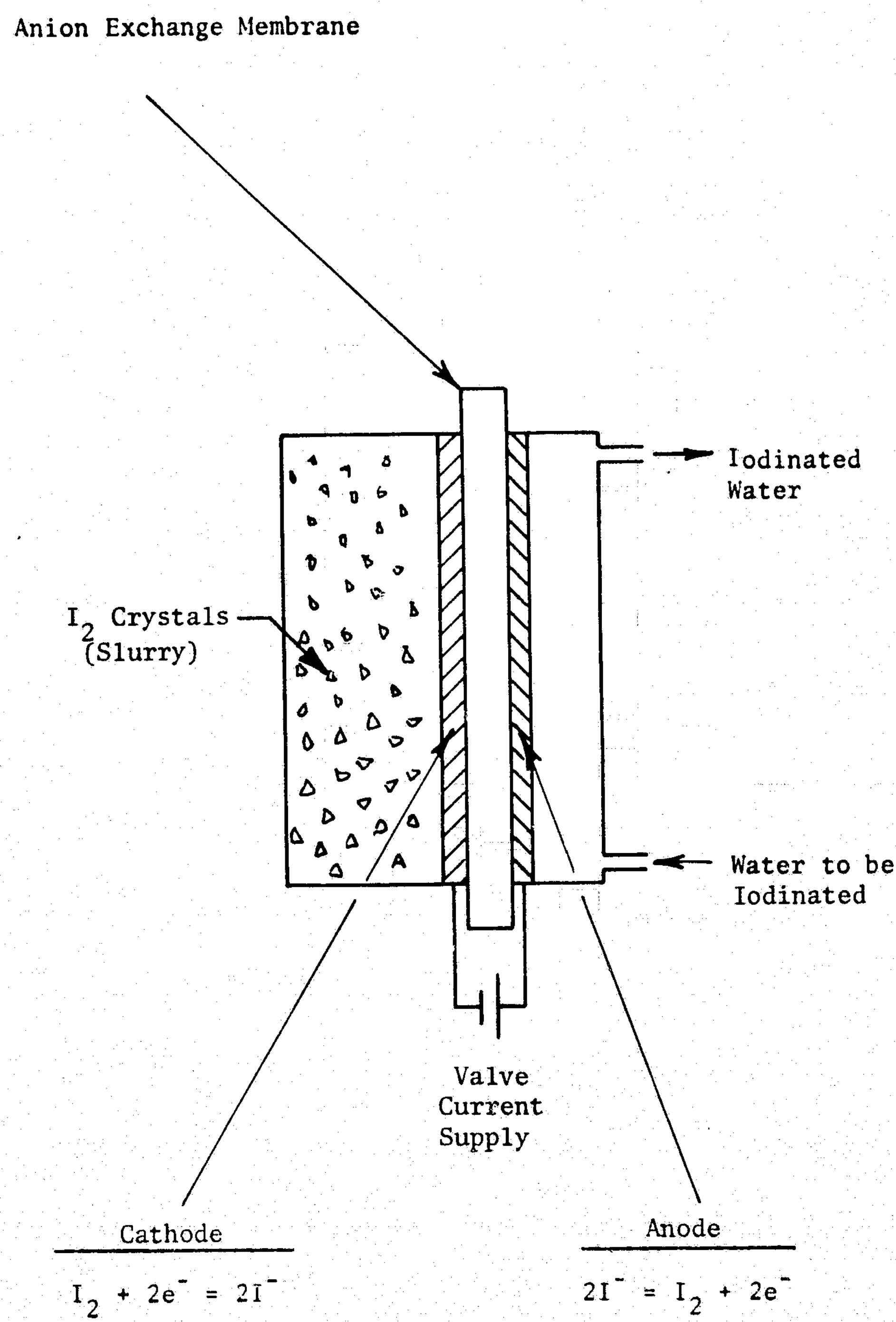


FIGURE 2 I_2 VALVE REACTIONS

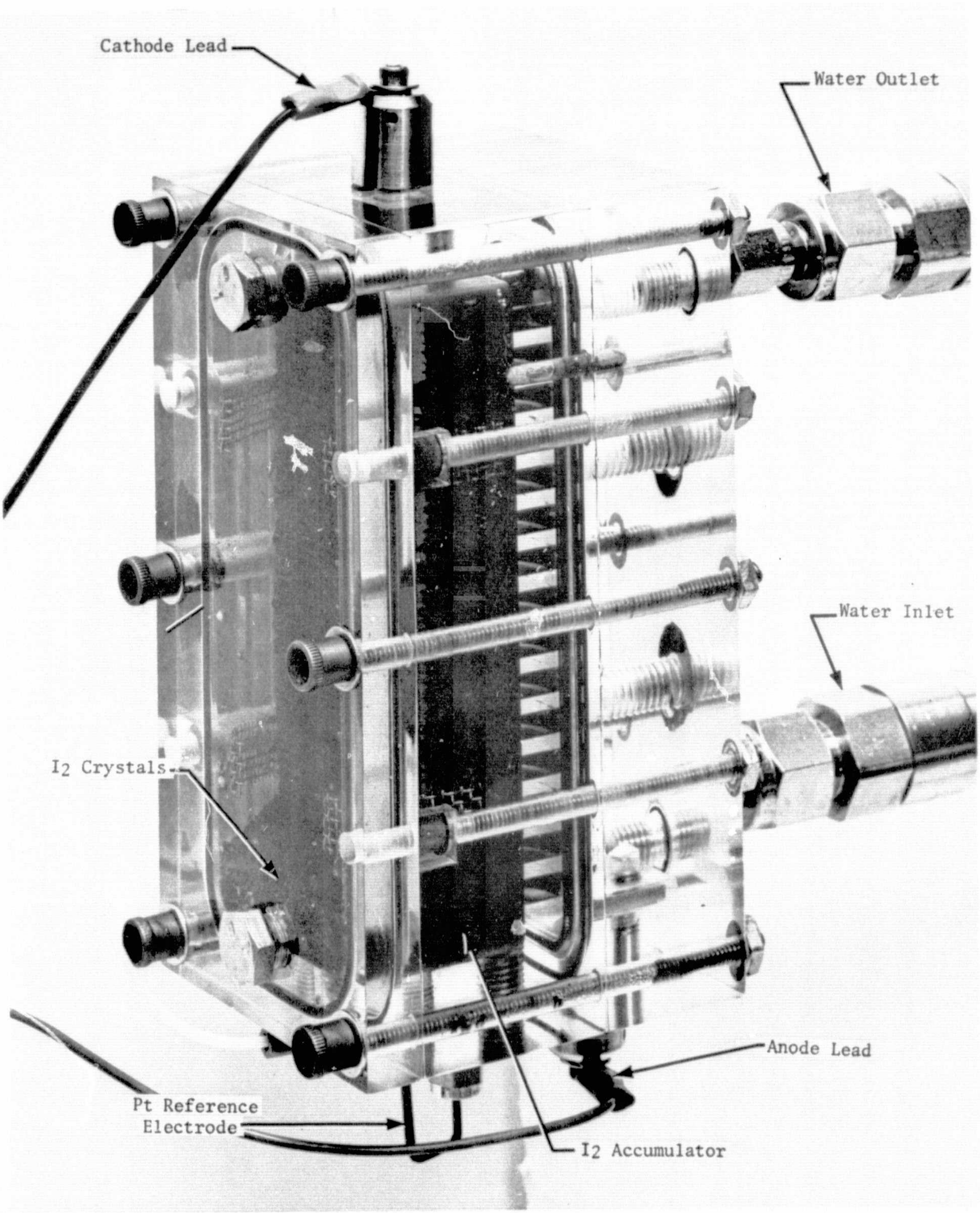


FIGURE 3 BREADBOARD I_2 SOURCE (MODEL LSI-100)

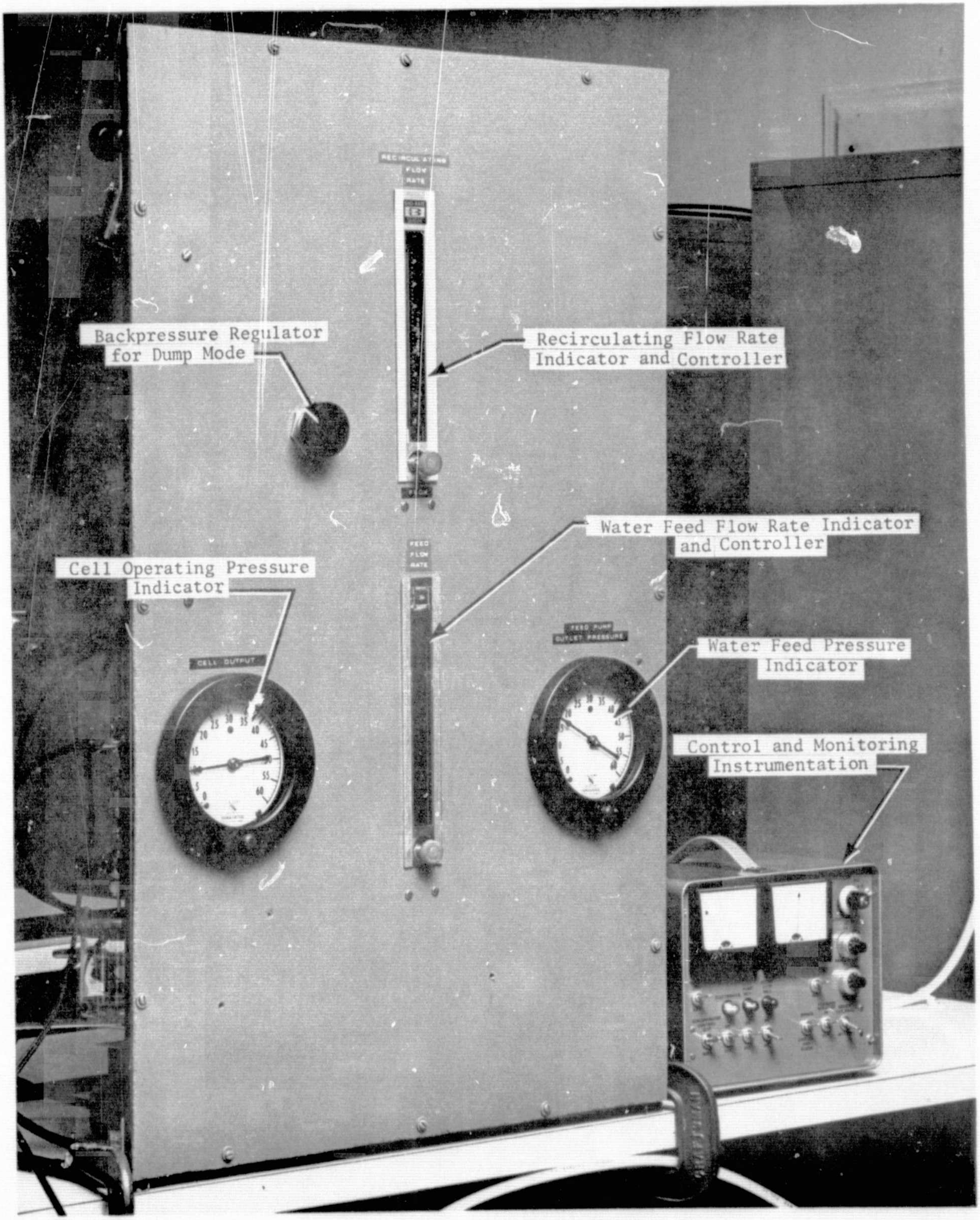


FIGURE 4 MODEL LSI-100 TEST STAND

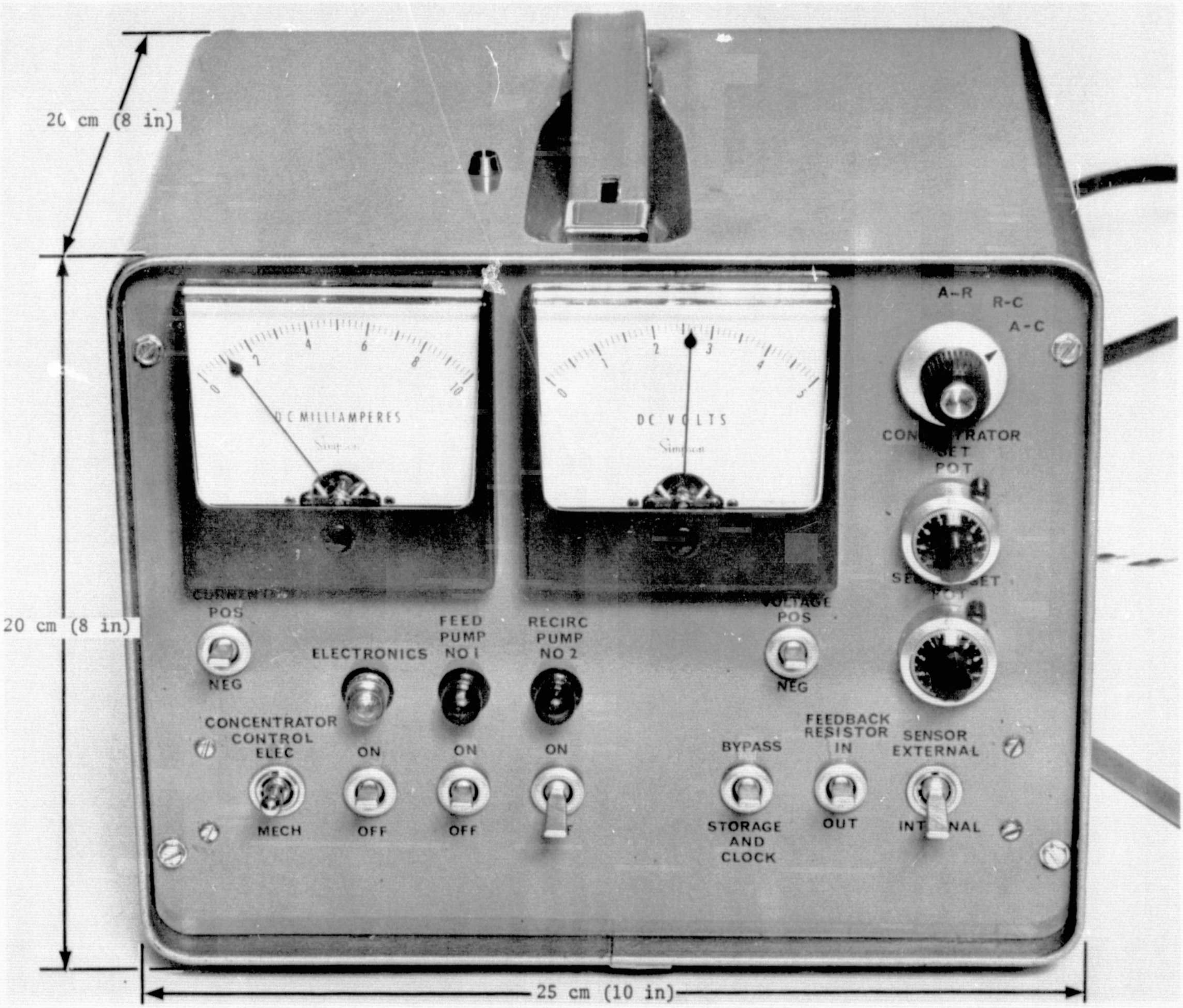


FIGURE 5 MODEL LSI-100 OPERATING PANEL AND ELECTRONICS ENCLOSURE

3. Establish, implement, and maintain a mini-Product Assurance Program throughout the contractual period to search out quality weaknesses and define appropriate corrective measures.

4. Perform tests to demonstrate the hardware maturity of the AWIS technology by extensively testing the IX-SA with qualification type rigor.

5. Conduct supporting technology studies to investigate optimization of the I_2 electrochemical valve and control technology.

6. Prepare and submit the program's documentation and data requirements and deliver the program's end item, the IX-SB.

7. Perform program management to successfully meet the program's Cost, Schedule, and technical Performance objectives and requirements to result in customer satisfaction.

Report Organization

The preceding program objectives were met. The following sections summarize the work completed. The remainder of this report is organized to first discuss design specifications and the considerations and experiments necessary to conceptually design and size the IX-S, followed by the hardware development, test results, and conclusions and recommendations.

AWIS DESIGN SPECIFICATIONS

The design specifications used for the AWIS were primarily governed by the requirements of the potable water system of the Shuttle Orbiter. Secondary emphasis was placed on design requirements of future long duration advanced spacecraft missions. While projected system schematics and quantitative design requirements were used as available for the Shuttle water system, only conceptual considerations were included for application of the AWIS concept to advanced spacecraft water reclamation systems.

Shuttle Potable Water System

The AWIS must be compatible with the projected potable water system of the Space Shuttle. Figure 6 presents a schematic of this system with proposed AWIS integration. Water produced from fuel cells must be treated with I_2 prior to storage in one of two water tanks. This water is used from the tanks without further treatment against microbial growths. Figure 6 shows that an installed redundancy concept is proposed for the AWIS. Both an operating and nonoperating unit is installed with a redundant I_2 sensor downstream of the two units.

Detailed Design Specifications

Table 1 presents the detailed design specifications used for the AWIS. The specifications are based on contractual requirements and on expanded requirements as were available from the Shuttle Orbiter potable water system specifi-

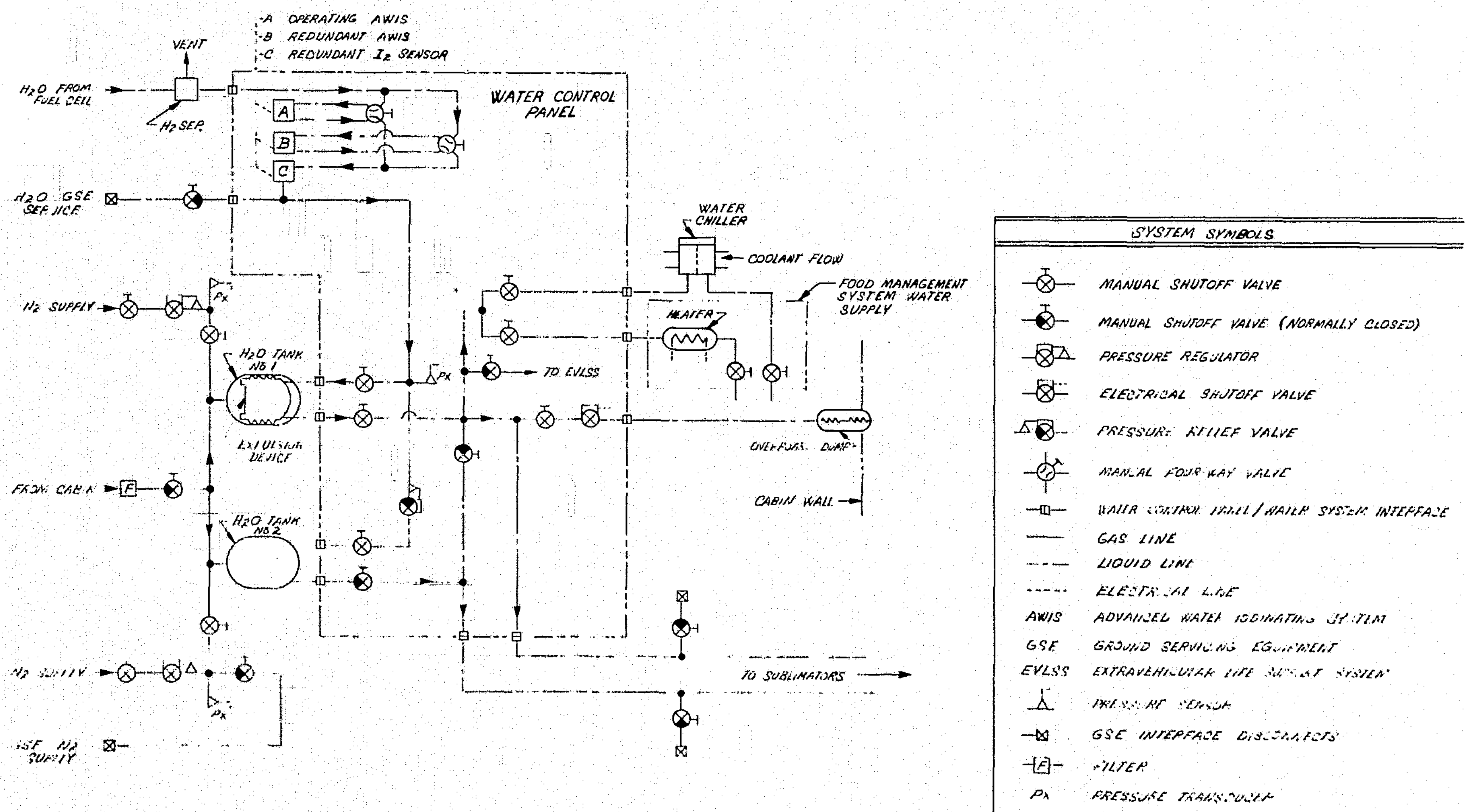


FIGURE 6 PROPOSED AWIS INTEGRATION INTO THE SHUTTLE ORBITER POTABLE WATER SYSTEM

TABLE 1 AWIS DESIGN SPECIFICATIONS

Water Supply	
Composition	See Table 3
Flow Rate, (a) cm^3/Min (Lb/Day)	
Nominal	83.3 (264)
Maximum	172.5 (547)
Minimum	22.7 (72)
pH at 298K (77F)	6 to 8
I_2 Concentration, Ppm	
Nominal(b)	5 (+1, -2)
Range	0 to 5
Temperature, K (F)	
Nominal	294 (70)
Maximum	297 (75)
Minimum	277 (40)
Pressure above Ambient, kN/m^2 (Psig)	
Nominal	
Low Range	83 ±7 (12 ±1)
High Range	117 ±14 (17 ±2)
Maximum	248 (36)
Minimum	55 (8)
Capacity (Shuttle)	
Mission Duration, Day	7
Water Processed/Mission, kg (Lb)	841 (1850)
I_2 Needed/Mission (Nominal 5 Ppm)	
Weight, g	4.19
Volume, cm^3 at 4.93 g/cm^3	0.851
Number of Shuttle Missions (Reusability)(c)	22
Cell Characteristics	
Cell Area, cm^2 (In^2)	22 (3.4)
Current, mA	
Nominal	15
Maximum	36

continued-

(a) Contractual requirements specify a water flow rate of 32.2 cm^3/min (102 lb/day).
(b) Goal at 172.5 cm^3/min water flow.
(c) For iodination level of 5 ppm of I_2 and I^-, each, and 25% of accumulator volume alloted for water to make slurry.

Table 1 - continued

Current Density, mA/cm^2	
Nominal	0.77
Maximum	1.85
Cell Voltage, V	
Nominal	2.0
Maximum	3.6
Cell Power, mA	
Nominal	30
Maximum	130
Weight (Goal) w/o AIMS,[a] kg (Lb)	$\leq$0.91 (2.0)
Pressure Drop, kN/m^2 (Psid) at 172.5 cm^3/Min	$\leq$6.89 (1.0)
Capacity (Long-Term Mission)	
Mission Duration, Day	180
Water Processed, kg/d (Lb/Day)	
CTHCS[b]	14.7 (32.4)
CRS[c]	3.3 (7.3)
Urine	15.7 (34.5)
Total:	33.7 (74.2)
Water Processed/Mission, kg (Lb)	6071 (13,356)
Recirculation Rate, cm^3/Min (Lb/Hr)	337 (44.5)
I_2 Needed/Mission (Nominal 5 Ppm)	
Weight, g	30.3
Volume, cm^3	6.15
Number of Missions (Overcapacity)	2.5
Vibration Level (Goal)	See Table 4
Electrical Power	
Type, Volt AC/Phase	115 Ø Single
Range in Cycles, Hz	50 to 440
Power w/o AIMS, W	6 ±2

(a) Automated I_2 Monitor System
(b) Cabin Temperature and Humidity Control Subsystem
(c) Carbon Dioxide Reduction Subsystem (Sabatier)

cations.[3] For example, the maximum water flow rate listed in the specifications is 172.5 cm^3/min (547 lb/day) compared to the contractual value of 32 cm^3/min (102 lb/day). Initial Shuttle specifications included a flow rate range of 6.8 to 93.8 cm^3/min (21 to 298 lb/day). The AWIS was sized using data obtained with the Model LSI-100 I_2 Source to iodinate to 5 ppm ±1 over this initial water flow rate range.

Recent Shuttle specifications have called for a flow rate range of 22.7 to 172.5 cm^3/min (72 to 547 lb/day) based on a range of Shuttle fuel cell power consumption of 4.0 to 24.0 kW as shown in Table 2.[3] It was anticipated, prior to testing the AWIS, that for this new flow rate range, the nominal iodination level would be 5 ppm +1, -2. This value is indicated in Table 1.

Similar specification adjustments have resulted in an increase in total water to be treated per Shuttle mission. This change was from 507 to 841 kg (1,116 to 1,850 lb) per mission.[3] A design goal of the IX-S was sufficient capacity for 18 Space Shuttle missions at the increased water generation rate.

Tables 3 and 4 are referenced in Table 1 and contain the "worst case" composition of the synthetic fuel cell water and the Shuttle Orbiter lift-off/boost random vibration levels, respectively. While the AWIS was designed for operation with this "worst case" fuel cell water, the vibration specifications were used for design considerations only.

System Interfaces

The AWIS must interface with the potable water system; the electrical system for power, onboard data managment, and signal input corresponding to the desired I_2 level for the iodinated water; and the structural system of the Shuttle or other advanced spacecraft. Figure 7 functionally depicts the water and electrical interfaces of the AWIS for Shuttle application.

Table 5 quantifies these interfaces. Figure 8 shows the relationship between the water inlet and outlet connections and the location and spacing of the mounting bolts projected for the baseline Shuttle potable water disinfecting system. This mounting arrangement was chosen for the AWIS to aid in integration of the AWIS in the existing Shuttle potable water system should such an integration become necessary.

AWIS PRE-DESIGN CONSIDERATIONS

Two major problems had been identified as a result of the previous program (NAS1-11765). The first was that I_2 was found to diffuse through the anion exchange membrane and into the water even when no current was applied to the I_2 valve. This was most noticeable at low water flow rates, where the rate of I_2 diffusion was approximately equal to the rate of electrochemical I_2 generation necessary to iodinate the water to 5 ppm.[2] The second problem was that the solution in the I_2 accumulator (the catholyte) became acidic during the operation

TABLE 2 SHUTTLE FUEL CELL POWER OUTPUT AND WATER FLOW RATE DESIGN CRITERIA

	Minimum	Nominal	Maximum	Contractual[a]
Fuel Cell Power, kW	4.0 (1.2)[b]	12.9 (7.8)	24 (13.0)	5.0
Fuel Cell Water Flow Rate,				
cm^3/Min	22.7 (6.8)[c]	83.3 (50.3)[d]	172.5 (93.8)[e]	32.2[d]
kg/h	1.4 (0.41)	5.0 (3.0)	10.4 (5.6)	1.9
Lb/Hr	3.0 (0.90)	11 (6.6)	22.8 (12.4)	4.3
kg/Day	32.7 (9.8)	120 (72.8)	249 (135)	46.0
Lb/Day	72 (21.6)	264 (159)	547 (298)	102
kg/7-Days[f]	-	841 (507)	-	325
Lb/7-Days	-	1850 (1116)	-	714

(a) Initial contract specifications written prior to adjustments to Shuttle fuel cell power requirements.
(b) Numbers in parenthesis indicate intermediate Shuttle fuel cell power and water flow rate specifications. Numbers preceding parenthesis represent latest available Shuttle specifications.
(c) Based on 340.2 g (0.75 Lb) water/kW-h.
(d) Based on 385.6 g (0.85 Lb) water/kW-h.
(e) Based on 430.9 g (0.95 Lb) water/kW-h.
(f) Mission

TABLE 3 COMPOSITION OF FUEL CELL WATER

Property	"Worst Case"	Water Used For Verification Testing
pH (at 298K (77F))	6 to 8	6 to 8 (adjusted with NaOH)
Total Solids	20 Ppm	100 Ppm (from silica)
Odor	None at Threshold (Odor Number of 3)	None
Turbidity	11 Units	1.3 NTU[c]
True Color	None Expected	None
Total Organics	10 Ppm	10 Ppm
Particulate Matter (Number of particles per 500 ml fluid)[a]		
0 - 10 microns	Unlimited	-
10 - 25 microns	1000	-
25 - 50 microns	200	-
50 - 100 microns	100	100 Ppm, 250 Mesh silica
100 - 250 microns	10	-
Cd^{+2}	0.01 Ppm	0.01 Ppm
Cl^{-}	2.8 Ppm	2.8 Ppm
Cr^{+6}	0.05 Ppm	0.05 Ppm
Cu^{+2}	1.0 Ppm	1.0 Ppm
Fe^{+3}	0.3 Ppm	0.3 Ppm
Pb^{+2}	0.05 Ppm	0.05 Ppm
Mn^{+2}	0.05 Ppm	0.05 Ppm
Hg^{+2}	0.005 Ppm	0.005 Ppm
Ni^{+2}	0.05 Ppm	0.05 Ppm
K^{+}	0.08 Ppm	0.08 Ppm
Se^{+4}	0.05 Ppm	0.05 Ppm
Silica	For reference only	100 Ppm
Ag^{+}	0.05 Ppm	0.05 Ppm
NH_4^{+}	0.5 Ppm	0.5 Ppm
Na^{+}	0.03 Ppm	0.43 Ppm[b]
NO_3^{-}	0.17 Ppm	0.17 Ppm

(a) Simulated with silica.
(b) Includes NaOH used for pH adjustments.
(c) NTU = Nephelometric Turbidity Unit

TABLE 4 LIFT OFF/BOOST RANDOM VIBRATION LEVELS[a]

20 to 80 cps at 3 db/octave increase
80 to 180 cps at 0.06 G^2/cps
180 to 200 cps at 12 db/octave increase
200 to 400 cps at 0.1 G^2/cps
400 to 450 cps at -12 db/octave decrease
450 to 2000 cps at 0.06 G^2/cps

(a) Used for design considerations only.

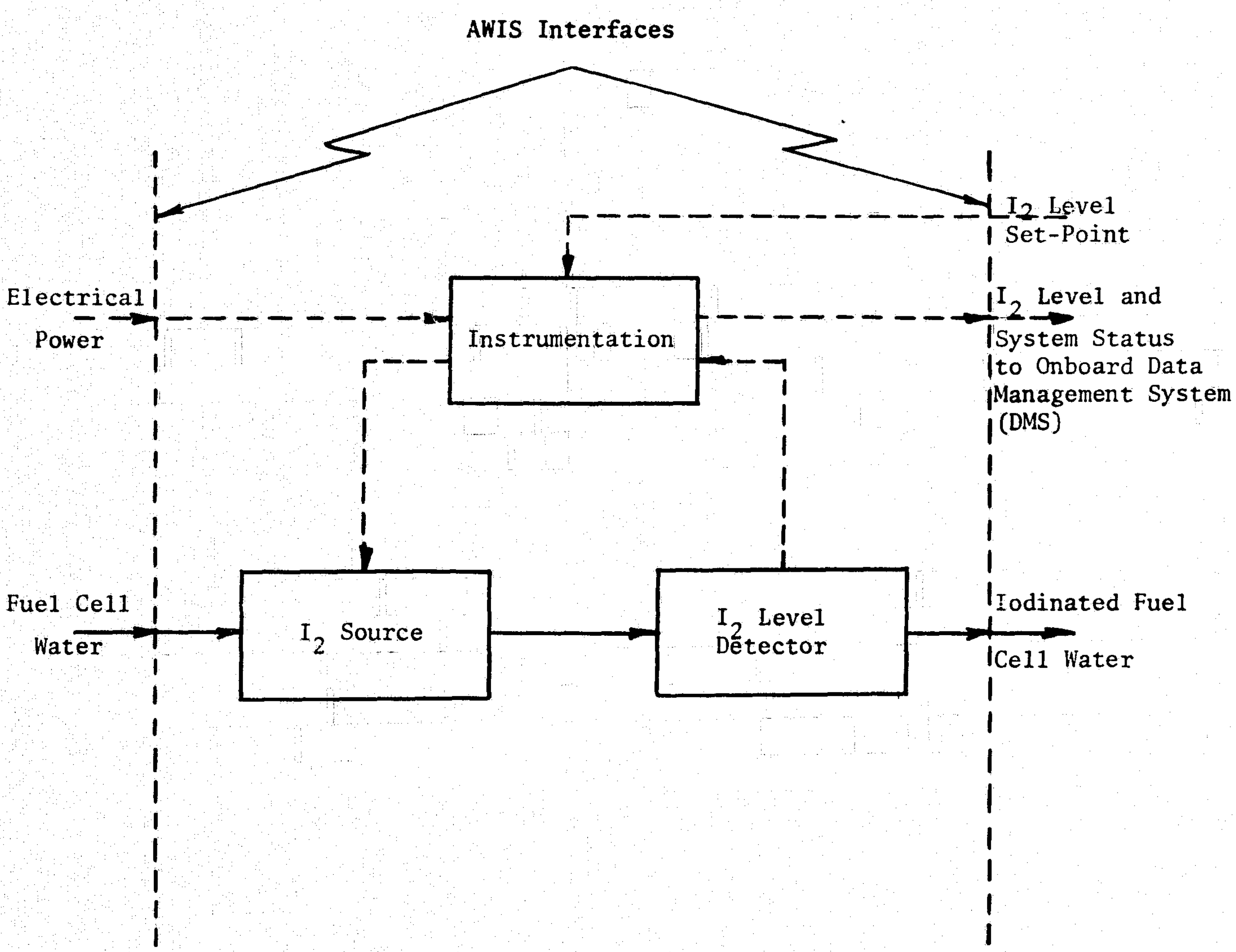
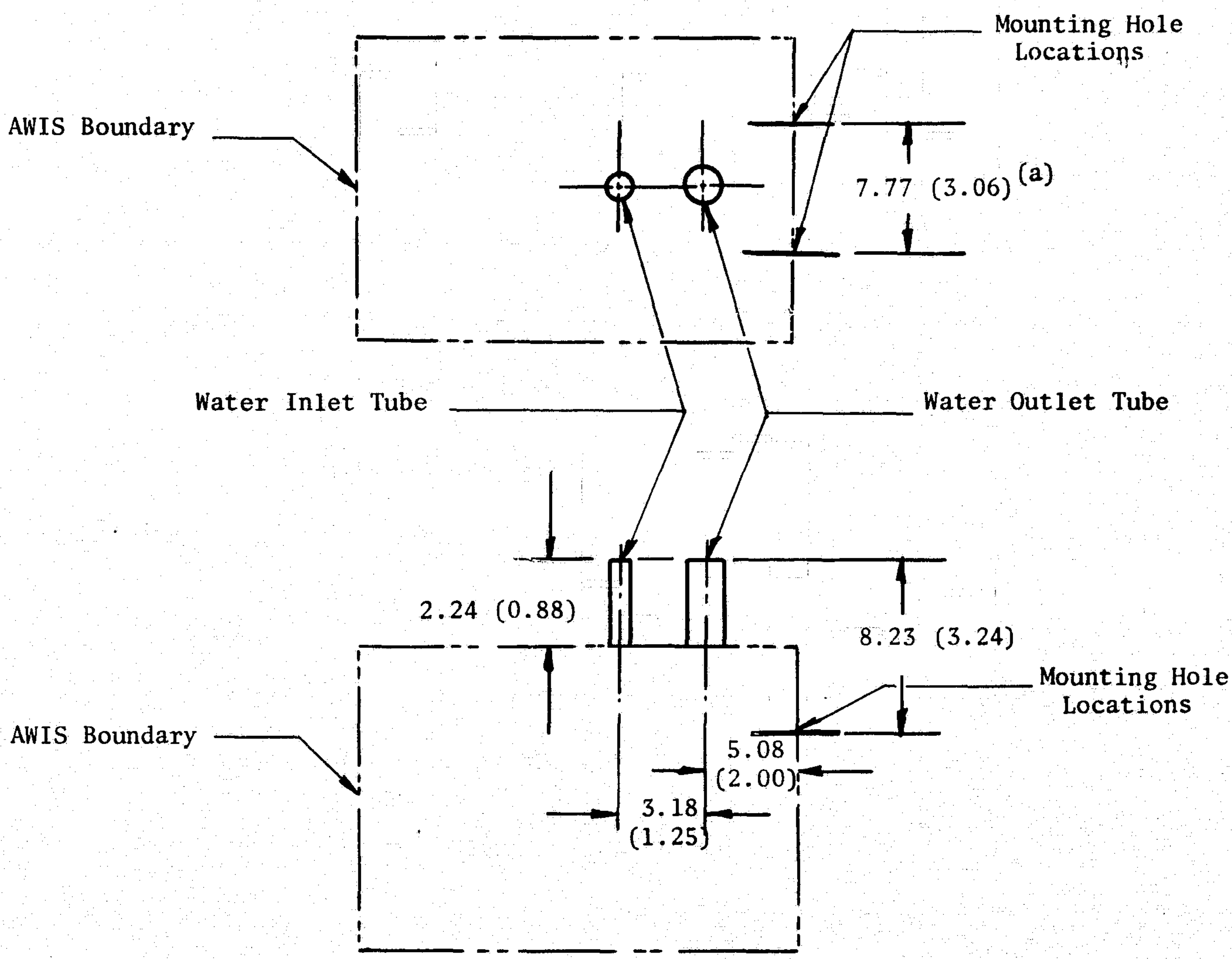


FIGURE 7 AWIS WATER AND ELECTRICAL INTERFACES

TABLE 5 AWIS INTERFACES

Electrical	
Power Input	
Voltage Level, VAC	115
Phase	Single
Frequency, Hz	50 to 440
Power Level, W	6 ±2
Signal Output	
I_2 Level, V/Ppm I_2	0-5/0-20
System Status, V Discrete	0/5
Signal Input, V/Ppm I_2	0-5/0-20
Water	
Input	
Type	See Table 3
Flow Rate, cm^3/Min (Lb/Day)	22.7 to 172.5 (72 to 547)
I_2 Level, Ppm	0
Tube Diameter (Outside), cm (In)	0.635 (0.25)
Output	
Flow Rate, cm^3/Min (Lb/Day)	22.7 to 172.5 (72 to 547)
I_2 Level, Ppm	5 (+1, -2)
Tube Diameter (Outside), cm (In)	0.953 (0.375)
Structural	
Mounting Bolts	1/4-28 NF Socket Head Cap Screws
Mounting Arrangement	See Figure 8



(a) Dimensions given in cm with inches in parenthesis

FIGURE 8 AWIS ENVELOPE AND MOUNTING ARRANGEMENT of the LSI-100. The hydrogen ion (H^+) buildup was considered to affect the choice of materials to be used for construction of the I_2 accumulator.

Also, new aspects, specifically related to the IX-S application to the Shuttle Orbiter potable water system had to be considered and resolved before the design and materials of construction could be finalized. These new aspects included (1) consideration of the anion exchange membrane to withstand the maximum pressure differentials possible in Shuttle application (including appropriate factors of safety), (2) operation of the I_2 Source with "worst case" simulated fuel cell water, (3) compatibility of the IX-S with steam sterilization at 394K (250F), (4) mechanical and electronic integration of the IX-S with the AIMS, and (5) identification of acceptable metallic and nonmetallic materials of construction consistent with the flight-like design approach to be used for the IX-S.

Specific program tasks were established to identify and test, as required, possible solutions to these problems. The results of these tests and considerations were analyzed and the most promising approaches were selected for incorporation into the final design of the AWIS.

Iodine Diffusion

Two approaches to reducing or controlling the rate of I_2 diffusion through the membrane were identified: (1) reduction of the membrane/water contact area and (2) bipolar control of the I_2 valve current.

Area Reduction

Based on results of the previous program, it was concluded that the rate of I_2 diffusion through the membrane is proportional to the area of the membrane exposed to the water flow. To verify and quantify the effect of area size, the working area of the valve of the LSI-100 I_2 Source was decreased from 21.9 cm^2 (3.40 in^2) to 10.6 cm^2 (1.64 in^2) and the diffusion of I_2 through the membrane into the I_2 dispenser was measured at various water flow rates without applying electrical current to the I_2 valve.

The rate of I_2 diffusion through the smaller membrane was 7.6 x 10^{-2} g/day (1.7 x 10^{-4} lb/day), compared to a rate of 1.9 x 10^{-2} g/day (4.2 x 10^{-5} lb/day) for the larger membrane. This higher diffusion rate through the smaller area membrane was unexpected and could only be attributed to small differences in assembly techniques such as using Teflon tape to mask part of the cell area, thus creating possible leakage paths at tape junctions. Additonal investigations into the phenomenon were not undertaken since diffusion can be controlled by reversing the direction of current flow, and the power required to maintain control is insignificant.

Bipolar Current Source

A power supply for the I_2 Source was designed to operate in a bipolar fashion. Current could be supplied either to transfer I_2 into the dispenser, or to return excess I_2 from the dispenser into the I_2 accumulator.

The bipolar current concept was operated with the Model LSI-100 source and showed the capability to maintain an I_2 concentration level of less than 0.2 ppm with water flowing at flow rates as low as 22 cm^3/min (70 lb/day).

The bipolar current supply concept was chosen for use in the AWIS design since it required only slightly more complex electronics than did a monopolar power supply.

Hydrogen Ion Buildup in Iodine Accumulator

Three possible methods of dealing with the H^+ ion buildup were identified: (1) addition of a base to the catholyte, (2) injection of oxygen (O_2) into the catholyte, and (3) construction of the I_2 accumulator from materials compatible with the acidic catholyte.

Base Addition

The simplest method for using a base would be a direct and one-time addition of a quantity of base sufficient to counteract the acidic buildup expected over a projected mission duration. This was found impossible, however, because of the reaction of I_2 in basic media that would deplete the I_2 crystal supply:

$$3I_2 + 6KOH = KIO_3 + 5KI + 3H_2O \qquad (1)$$

The addition of a base to the catholyte must therefore be done gradually, controlled by a monitor sensing the H^+ concentration. This would require a complex sensor and feedback system resulting in an I_2 Source complicated in concept and design.

Oxygen Injection

The H^+ concentration in the I_2 accumulator can be decreased by injection of O_2 into the accumulator, as shown below:

$$4I^- + O_2 + 4H^+ = 2I_2 + 2H_2O \qquad (2)$$

The injection of O_2 into the accumulator could be done electrochemically or by inclusion of an O_2-permeable membrane in one side of the I_2 accumulator chamber. The membrane would allow O_2 from the air to diffuse into the solution in the accumulator.

Electrochemical injection of O_2 into the catholyte would require a second power supply and additional electrodes. The use of a membrane in an exterior wall of the I_2 accumulator would present the hazard of the O_2 membrane rupture and possible spillage of I_2 crystals and solution.

Compatible Materials

The H^+ concentration in the I_2 accumulator was found to approach an equilibrium value of about 0.1M. The anions associated with the H^+ in the catholyte are I^-.

Therefore, materials that are compatible with 0.1M hydroiodic acid (HI) and aqueous I_2 are suitable for construction of the I_2 accumulator. Hastelloy C-276 was found to be compatible with 0.1M HI and aqueous I_2. The only other metallic material in contact with the catholyte would be the platinum anode. Platinum had previously been reported to be compatible with aqueous I_2.[2]

Hastelloy C-276 was experimentally determined to be compatible with 0.1M HI and aqueous I_2. A corrosion test sample of Hastelloy C-276, weighing 88.8094 g was immersed for 35 days in 0.1M HI. By the end of the test, the weight of the sample had decreased only 2.2 mg. Voltammetric studies of another sample of Hastelloy C-276 showed it to be compatible with aqueous solutions of I_2 and 0.1M HI.

Using Hastelloy C-276, the buildup of the H^+ concentration to its equilibrium value in the accumulator presents no problem to the durability and safety of the I_2 Source and does not increase the complexity of the I_2 Source design and operating procedures. An additional means of protection is to Teflon-coat the interior of the catholyte compartment. The final approach selected for the AWIS design included a partially Teflon-coated catholyte compartment to simultaneously evaluate plain Hastelloy C and Teflon-coated Hastelloy C.

Membrane Differential Pressure Capability

The nominal operating pressure range of the Shuttle Orbiter water system at the point of AWIS installation (see Figure 6) is from 83 to 117 kN/m^2 (12 to 17 psig) above ambient with a maximum pressure level of 248 kN/m^2 (36 psig). The anion exchange membrane that was used in the LSI-100 Source and selected for use in the IX-S has a reported burst strength of 1.4×10^3 kN/m^2 (200 psid).

To verify the pressure differential capability of the membrane as supported in an electrochemical valve, a test was conducted pressurizing the membrane to four times the expected nominal operating pressure. The test was conducted with the membrane mounted in the Model LSI-100 Source.

The membrane did withstand the pressure differential of 413 kN/m^2 (60 psid) without failure. The general membrane support concept and support dimensions (unsupported span) of the Model LSI-100 cell used to successfully demonstrate the membrane's pressure capability were selected for the Model IX-S design.

Fuel Cell Water Compatibility

The IX-S must be compatible with fuel cell water of the composition listed in Table 3. To demonstrate the compatibility of the I_2 Source concept a test with "worst case" simulated fuel cell water (see Table 3) was performed. Special emphasis was placed on cell or electrode clogging and interference of the simulated fuel cell water impurities with the iodination process. The Model LSI-100 Source was used to perform the testing.

After operation for seven days at an average water flow rate of 32 cm^3/min (102 lb/day), the Model LSI-100 source had successfully iodinated 322 liters (85 gallons) of simulated fuel cell water to a concentration of 5 ppm I_2. No interference with the iodination process was observed. Only 2.7 mg of particulate material had accumulated on the anode in the I_2 Source and this material did not affect its operation. While the I_2 Source was unaffected by the "worst case" simulated fuel cell water, the AIMS showed an unexpected response.

Operation with the simulated fuel cell water produced an erroneously high I_2 concentration indication. Recalibration using the simulated fuel cell water, however, alleviated this problem and was considered an acceptable solution. This is especially true since the simulated "worst case" fuel cell water was much more impure than water obtained from Pratt and Whitney fuel cells.

The Model IX-S source, therefore, was expected to iodinate fuel cell water without special design considerations or other precautions. The AIMS was also expected to operate normally and modulate the current in the I_2 Source as planned.

System Sterilization

The Shuttle baseline design requires steam sterilization of its water system prior to launch. Two approaches to sterilization of the AWIS were considered. The first approach was steam sterilization of the I_2 dispenser. Since, however, steam sterilization could be potentially harmful to the I_2 valve membrane and could result in excessive I_2 diffusion, a second approach was considered. This approach consisted of isolation of the I_2 dispenser from the steam using a four-way valve. The I_2 present in the I_2 dispenser during storage would be ample for sterilizing those portions of the I_2 Source not exposed to the steam.

The only component of the I_2 Source that could be degraded by steam sterilization is the membrane. The membranes projected for use in the IX-S are reported to be stable to 398K (257F). To demonstrate a steam sterilization concept, samples of the membrane were steam sterilized at 394K (250F) for 30 minutes. The membranes appeared as resilient after sterilization at 394K (250F) as before sterilization. The membrane withstood a pressure differential of 413 kN/m^2 (60 psi) and normal operation and performance was demonstrated in the Model LSI-100 Source. Figure 9 is a comparison of the performance of the sterilized and unsterilized membranes in the Model LSI-100. The I_2 generation rate is approximately identical at valve currents less than 40 mA. At higher currents the I_2 generation rate with the sterilized membrane is somewhat greater than with the unsterilized membrane. On the basis of this data it is concluded that sterilization of the membrane has little effect on its performance in the I_2 Source.

The solution in the I_2 dispenser (potable water side) was analyzed after storage for seven days to see if it contained sufficient aqueous I_2 to inhibit microbial growth during times that the potable water side of the AWIS would be isolated by the four-way valve. The I_2 dispenser was found to contain 25 ppm I_2 after

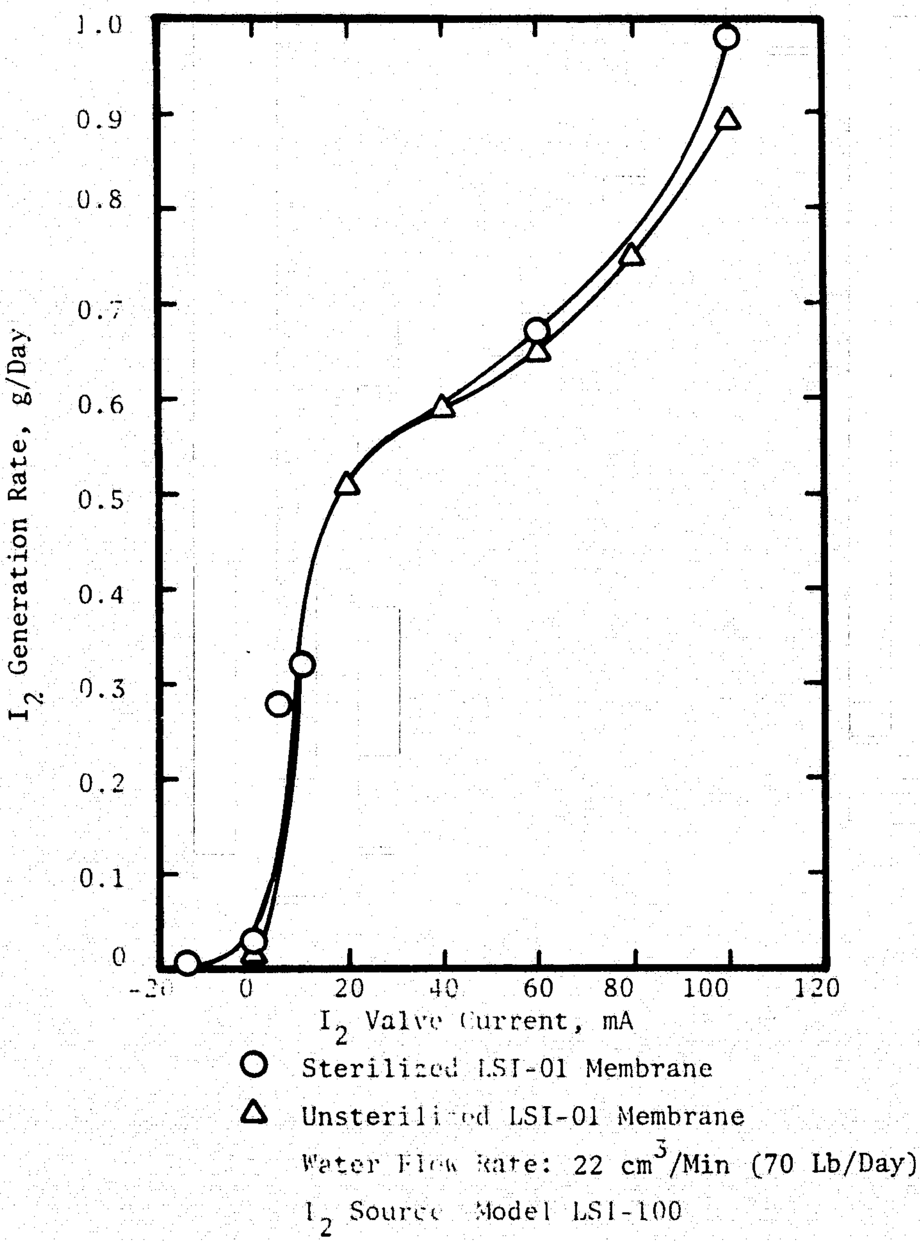


FIGURE 9 PERFORMANCE COMPARISON
OF STERILIZED AND UNSTERILIZED LSI-01 MEMBRANES

storage with no water flow for seven days. The entire I_2 Source should be sterile even if the steam is bypassed around the source through the four-way valve since less than 25 ppm I_2 is usually considered adequate for promoting sterility.

The use of the four-way valve was selected for use in the AWIS because long-term evaluation of the effects of sterilization of the membrane are costly. The addition of the four-way valve adds little weight and complexity to the AWIS and can be used effectively in a fail-operational/fail-safe system as shown in Figure 10.

IX-S and AIMS Integration

The I_2 valve feedback control circuitry has to respond rapidly to changes in the water flow rate at high flow rates, yet respond slowly to changes in the low flow rates. To prevent oscillation in the feedback network three approaches were derived and analyzed and/or tried: (1) mechanically minimizing time lag for transport of the iodinated water from the I_2 Source to the AIMS, (2) addition of a phase lead circuit for anticipatory control of the I_2 valve current, and (3) use of a RC integrator circuit for control of the I_2 valve current.

Minimizing Time Lag

To minimize the time lag between I_2 Source and detection of these changes at the AIMS, the length and diameter of the tubing connecting the source and the AIMS must be minimized. Based on the physical configuration of the AIMS, 10 cm (3.94 in) of tubing was considered the shortest length possible. The minimum size tubing considered practical was 0.3 cm (0.12 in) diameter tubing. The pressure drop through a 10 cm (3.94 in) length of 0.3 cm (0.12 in) OD tubing was calculated to be 193 kN/m^2 (28 psi) at a water flow rate of 100 cm^3/min (317 lb/day). Maximum allowable pressure drop for the AWIS was 6.89 kN/m^2 (1 psid) at 172.5 cm^3/min (547 lb/day).

Phase-Lead Circuit

A phase-lead circuit was evaluated for anticipatory control of the I_2 valve current to maximize the response of the I_2 Source to signals from the AIMS. The phase-lead network was rejected once the transportation lag time between the I_2 Source outlet and AIMS inlet was recognized as the limiting factor in the system response. Because the transportation lag time was the limiting factor, the phase-lead network had no advantage over a RC integrator circuit and was more complicated.

RC Circuit

A RC integrator circuit can be used to respond to signals from the AIMS without oscillations. The RC integrator required a time constant of 2000 seconds to prevent oscillations in the control loop at the water flow rate of 6.8 cm^3/min (21.5 lb/day).

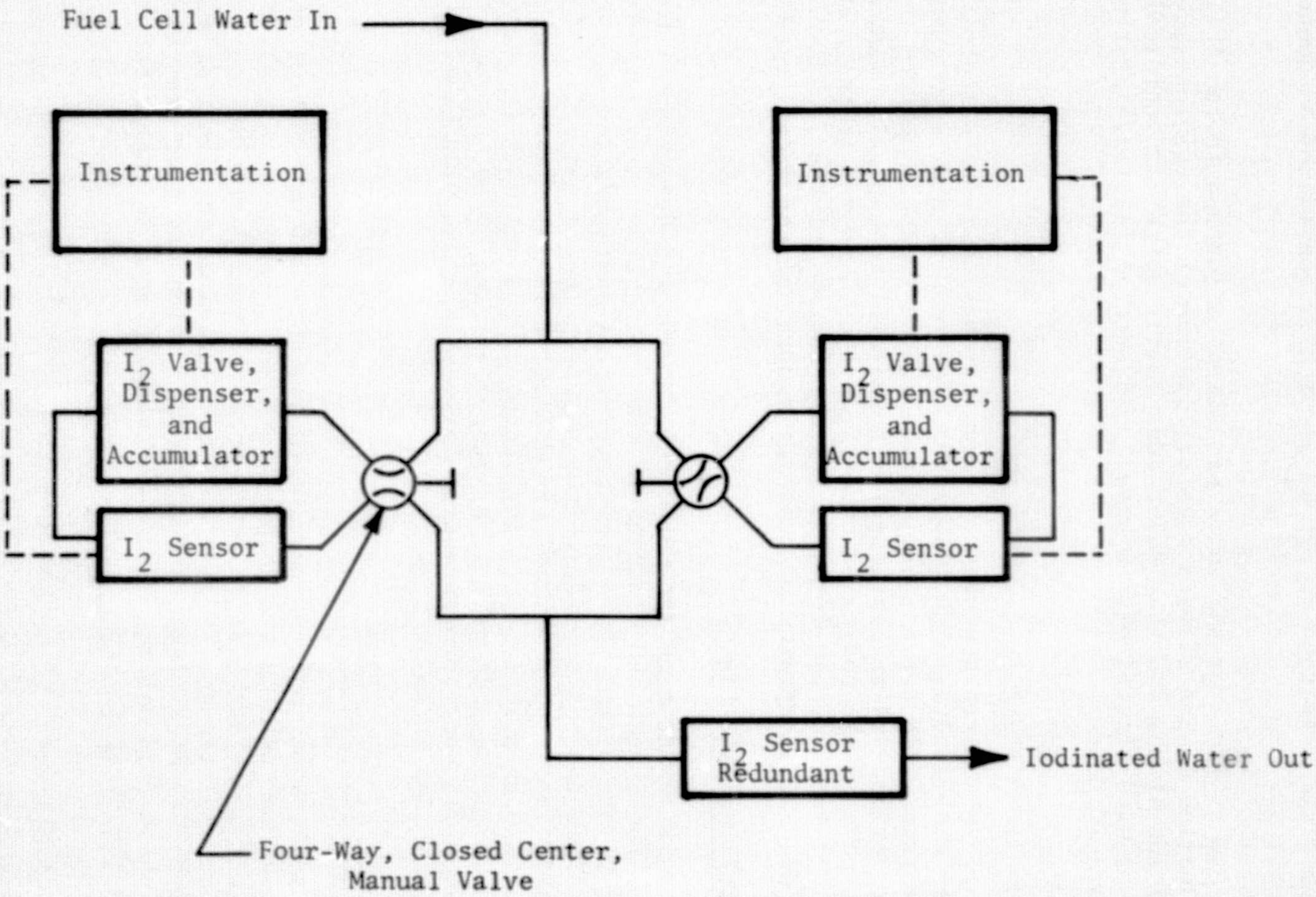


FIGURE 10 EQUIPMENT AND CONFIGURATION FOR FAIL-OPERATIONAL/FAIL-SAFE CONCEPT

The tubing connecting the I_2 Source and AIMS was 10 cm (3.94 in) long and 0.64 cm (0.25 in) in diameter. The IX-S/AIMS interface was designed to require a maximum of only 5 cm (2 in) of 0.64 cm (0.25 in) OD interconnecting tubing. The 0.3 cm (0.12 in) diameter tubing has been rejected because of the large pressure drop encountered. The shorter (5 cm (1.97 in) long) tubing will decrease the time constant from 2000 to 1000 seconds at the 6.8 cm^3/min (21.5 lb/day) flow rate. Since subsequent Shuttle specification had increased the lower flow rate from 6.8 to 22.7 cm^3/min (21.5 to 71.9 lb/day), the time constant decreased proportionately to 300 seconds.

Repackaging of the AIMS into a configuration more compatible with the IX-S was possible but beyond the program's scope. Advantages would be an even still shorter transportation lag time as well as smaller size and weight.

Nonmetallic Structural Materials

The I_2 and HI in the I_2 Source were known from previous testing to be corrosive to many nonmetallic materials. Because of the difficulty of identifying nonmetallic materials that are both compatible with aqueous I_2 and are acceptable based on outgassing and flammability, an I_2 Source which would contain no nonmetallics other than the membrane was considered. This membrane has been used extensively in the LSI-100 and is compatible with I_2 and HI and presents no flammability or outgassing problem since it is totally immersed in water.

The elimination of all nonmetallics other than the membrane in the I_2 Source, however, would result in the I_2 dispenser and accumulator being at the electrical potentials of the anode and cathode, respectively. The tubing leading to and from the I_2 Source would be at the potential of the anode. The membrane would have to extend to the edges of the I_2 Source to insulate the halves of the I_2 Source from one another. Leakage through the longitudinal pores of the membrane may occur in such a configuration. Thus, complete elimination of nonmetallics from the design is not practical.

Both polysulfone and Viton A had been previously identified to be acceptable for spacecraft application with respect to outgassing and flammability.[4] Polysulfone was reported to be compatible with aqueous I_2 solutions.[2] Additional testing showed that polysulfone is stable in saturated I_2 solutions even at 366K (200F) for three days and in saturated I_2 solutions at room temperature in a mechanically stressed condition for seven months.

Another piece of polysulfone was stressed with a stainless steel nut and bolt and was immersed in a solution of 20,500 ppm HI and 2,000 ppm I_2. This solution simulated the catholyte in the LSI-100 I_2 Source after long-term operation. The polysulfone, weighing 7.6341 g (0.0168 lb) initially, gained only 35.1 mg (7.73×10^{-5} lb) after 112 days.

Viton A O-rings have been used for more than 200 days in the I_2 Source, LSI-100. Some O-rings have been in contact with the catholyte in the I_2 accumulator continously during this time. The O-rings still seal well and are serviceable, although there is some roughness on the surface of the O-rings.

In view of the preceding factors, limited use of nonmetallics in the AWIS was considered necessary and acceptable. Polysulfone was selected to insulate the exterior of the I_2 dispenser from the I_2 valve anode. Thus, the tubing connected to the I_2 Source would be at the ground potential. Viton A O-rings were selected for seals in the I_2 Source.

ADVANCED WATER IODINATING SYSTEM PROTOTYPE

The design of the AWIS prototype combined the predesign selections, that are summarized below, with the requirements for a flight qualifiable I_2 Source.

Summary of Predesign Selections

1. Anion exchange membrane as used and supported in LSI-100 Source
2. Platinum screen anode and cathode
3. I_2 accumulator constructed of Hastelloy C-276
4. Polysulfone insulator in I_2 dispenser
5. Viton A O-rings for sealing purposes
6. Bipolar current control of I_2 valve
7. Feedback control of I_2 valve by the AIMS, with utilization of a RC integrator circuit
8. Use of a four-way valve to bypass the steam from the interior of the I_2 Source during steam sterilization

System Concept

The AWIS concept was a self-contained design capable of iodinating Shuttle Orbiter fuel cell water to 5 ppm +1, -2 of I_2. The AWIS concept included a Government-Furnished Equipment (GFE) AIMS with the LSI-designed I_2 accumulator, valve, and dispenser and its associated control and monitoring instrumentation (Figure 11). These components were designed using appropriate structural supports and required interconnecting plumbing to form the self-contained AWIS. A four-way valve was incorporated into the design for isolation during steam sterilization of the potable water lines and switchover to the redundant AWIS for fail-safe operation (see Figure 10).

The contractual design weight goal of less than 0.91 kg (2 lb) (see Table 1) applies only to the I_2 accumulator, valve, and dispenser and its associated control and monitoring instrumentation as designed for the maximum water flow rate of 93.8 cm^3/min (298 lb/day) at 5 ppm I_2 and 172.5 cm^3/min (547 lb/day) at 3 ppm I_2, minimum. Neither the AIMS nor the interconnecting plumbing, structural supports and four-way valve are included in the weight goal since it is expected that an AWIS for actual Shuttle Orbiter application would incorporate a redesigned and repackaged AIMS into one compact unit eliminating most of the structural and plumbing requirements. Also, all electronics, including those for the AIMS would be packaged together in a common housing.

The basic design concept of the Model IX-S included the I_2 accumulator, valve, and dispenser shown in Figure 1, and was not, therefore, functionally different

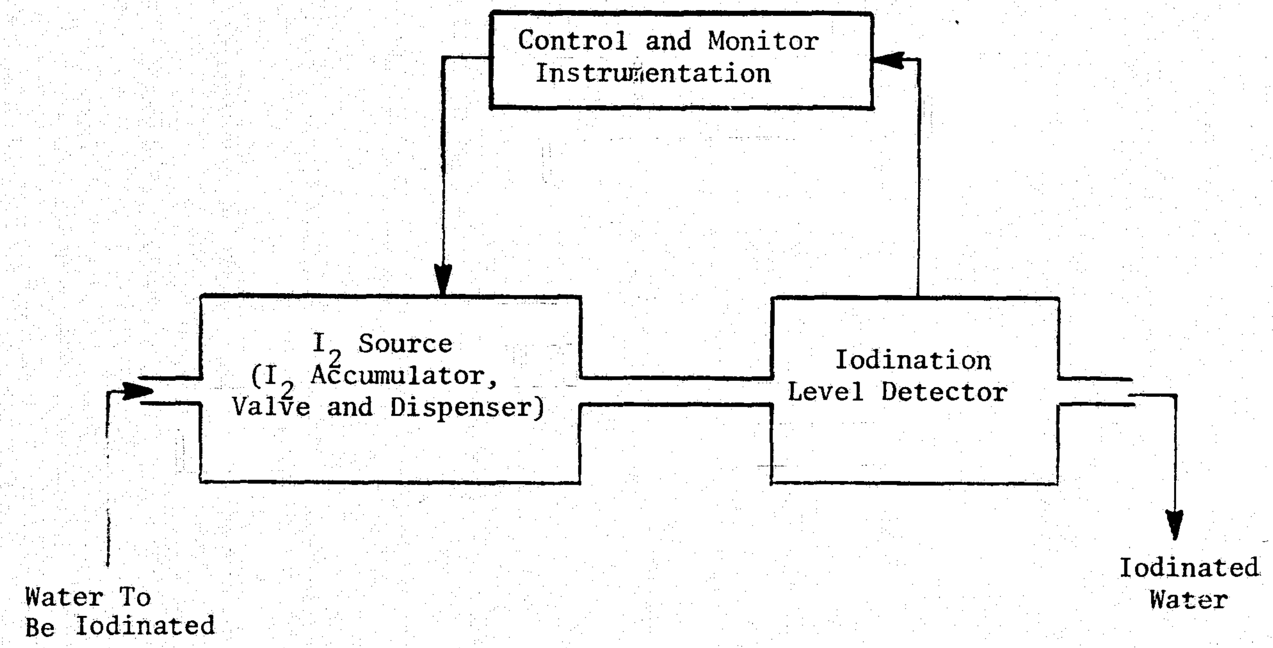


FIGURE 11 WATER IODINATING SYSTEM BLOCK DIAGRAM

from the concept of the Model LSI-100. The IX-S design adapted the I_2 Source to a lightweight, flight prototype, constructed of materials compatible with the solutions known to be present in the I_2 accumulator and dispenser. The IX-S design also included the I_2 valve control circuitry within the housing of the I_2 Source to produce a more compact package than that of the Model LSI-100 and its control instrumentation.

I_2 Accumulator, Valve, and Dispenser

The volume of the I_2 accumulator, the active area and shape of the I_2 valve electrodes, and the geometrical configuration of the I_2 dispenser were defined after further testing and evaluations using the Model LSI-100 unit.

Accumulator Size. The size of the accumulator is a direct function of the I_2 level required, amount of water to be iodinated, expected I^- concentrations in the potable water, and the amount of water that must be mixed with the solid I_2 crystals to provide the desired slurry. The accumulator for the AWIS was sized using the following criteria:

1. Equal concentrations of I_2 and I^- exist in the potable water when the water is iodinated to levels of 3 to 5 ppm I_2
2. Maximum I_2 level is 6 ppm (from 5 ppm +1)
3. Twenty-five percent by volume of water is required to make slurry
4. A minimum of 18 missions are desired with 841 kg (1850 lb) per seven-day mission of water to be iodinated

The resulting accumulator volume was 49.2 cm^3 (3.0 in^3). This volume would hold a maximum of 182 g (0.401 lb) I_2 and 12.3 g (0.027 lb) water. This quantity is sufficient for 18 seven-day Shuttle missions at 841 kg (1850 lb) of water per mission or 2.5 180-day missions at 6071 kg (13,356 lb) of water per mission iodinated to 6 ppm I_2.

Valve Active Electrode Area and Shape. The active area of the I_2 valve electrodes were determined by experimental analysis of the performance of the Model LSI-100, whereas the valve shape was determined after consideration of water flow distribution over the anode.

Valve Area. Data obtained with the Model LSI-100 I_2 Source were used to size the active area of the I_2 valve in the Model IX-S. The working area of the Model LSI-100 I_2 Source was 21.9 cm^2 (3.40 in^2) and the water flow rates used were from 7 to 100 cm^3/min (21 to 317 lb/day), which covered the range of flowrates in the initial Shuttle specifications. The I_2 concentration in the iodinated water was a nominal 5 ppm. These data are presented in Figures 12 through 17.

Figure 12 shows the calculated rates of I_2 generation necessary to iodinate water flowing at rates of 0 to 200 cm^3/min (0 to 634 lb/day) to 3 and to 5 ppm I_2. The actual I_2 valve current necessary to produce these I_2 generation rates in the Model LSI-100 is shown in Figure 13. From this curve, it is seen that

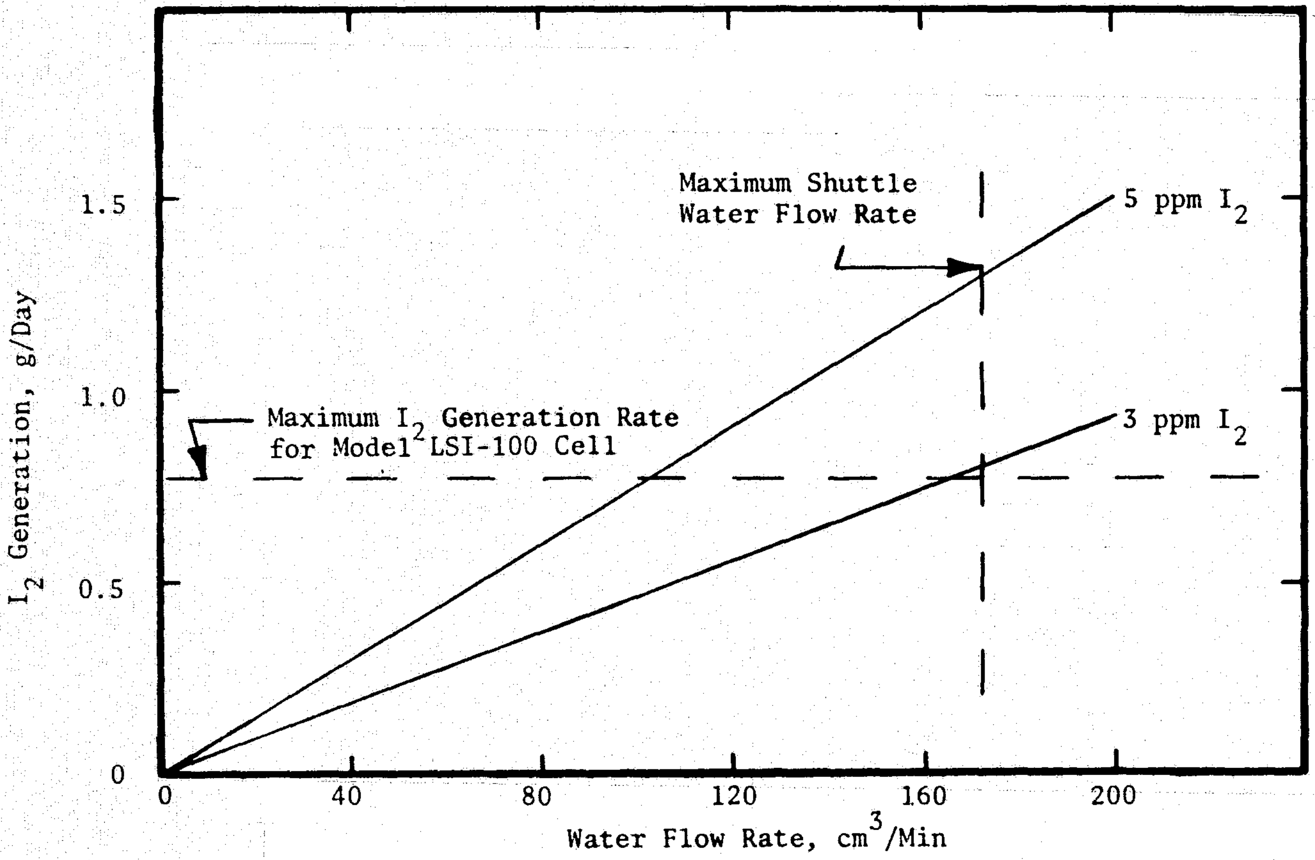


FIGURE 12 I_2 GENERATION IN TERMS OF I_2 CONCENTRATION AND WATER FLOW RATE

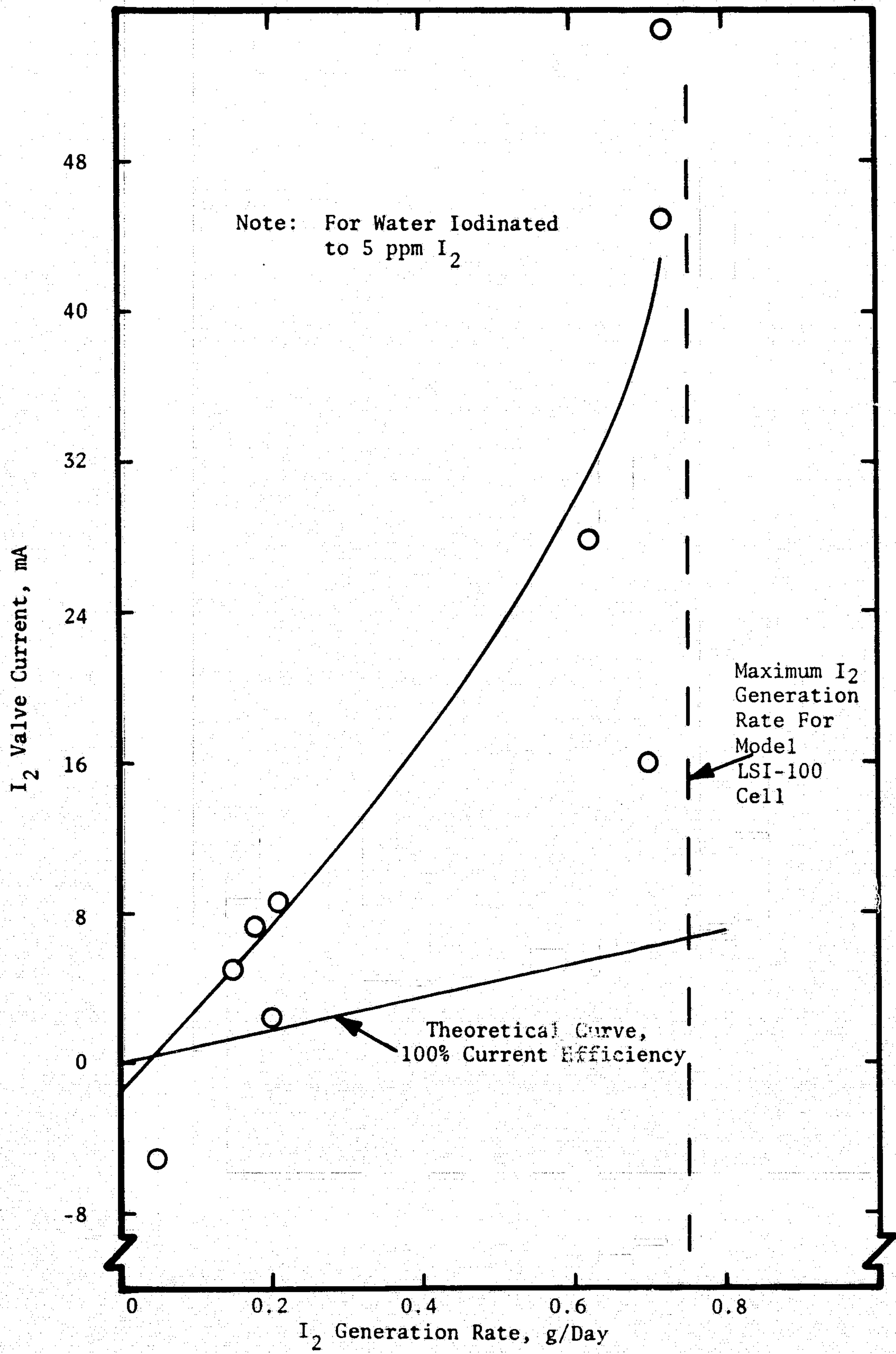


FIGURE 13 RELATIONSHIP BETWEEN I_2 VALVE CURRENT AND I_2 GENERATION RATE FOR MODEL LSI-100

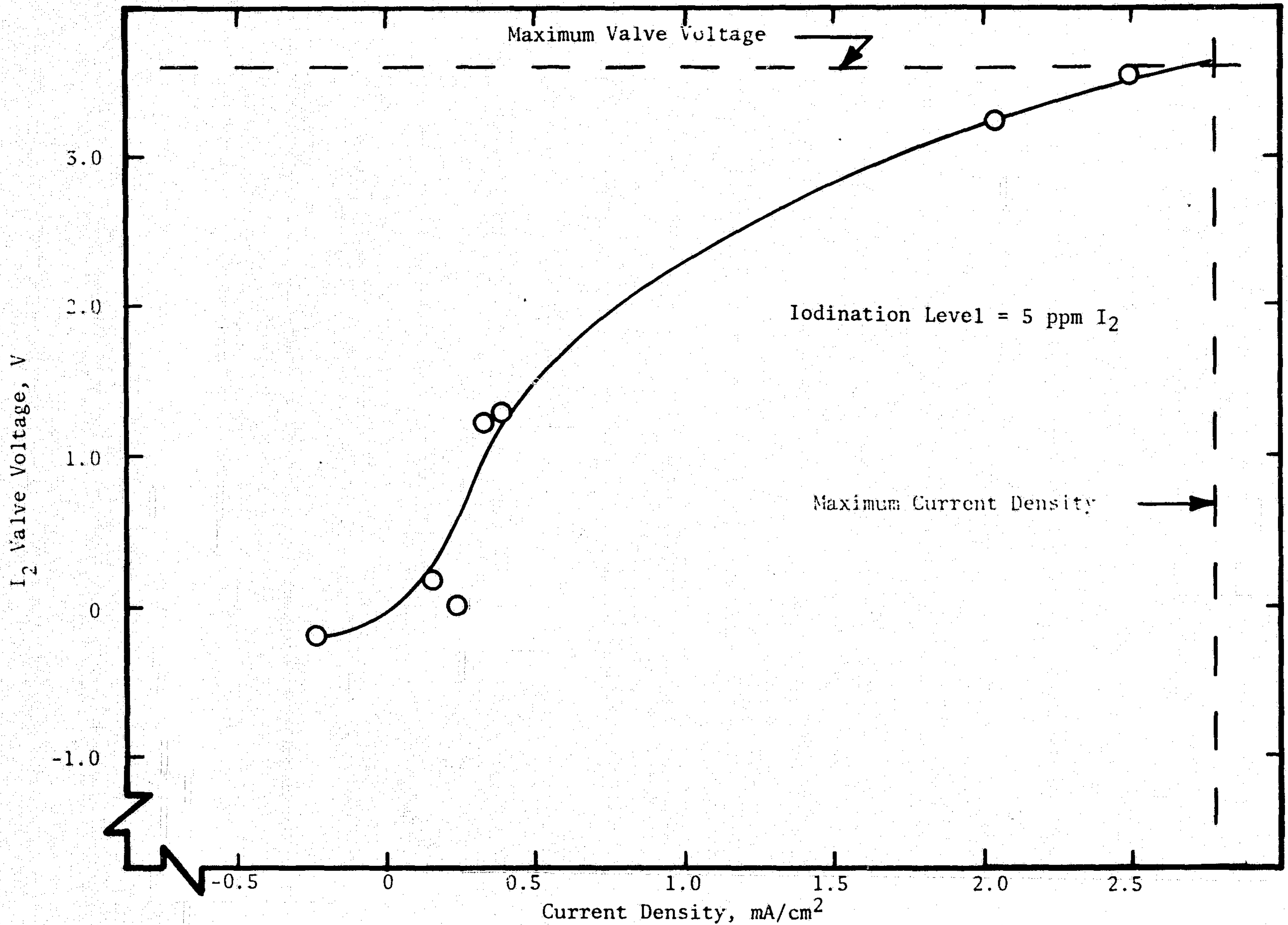


FIGURE 14 POLARIZATION PERFORMANCE FOR MODEL LSI-100

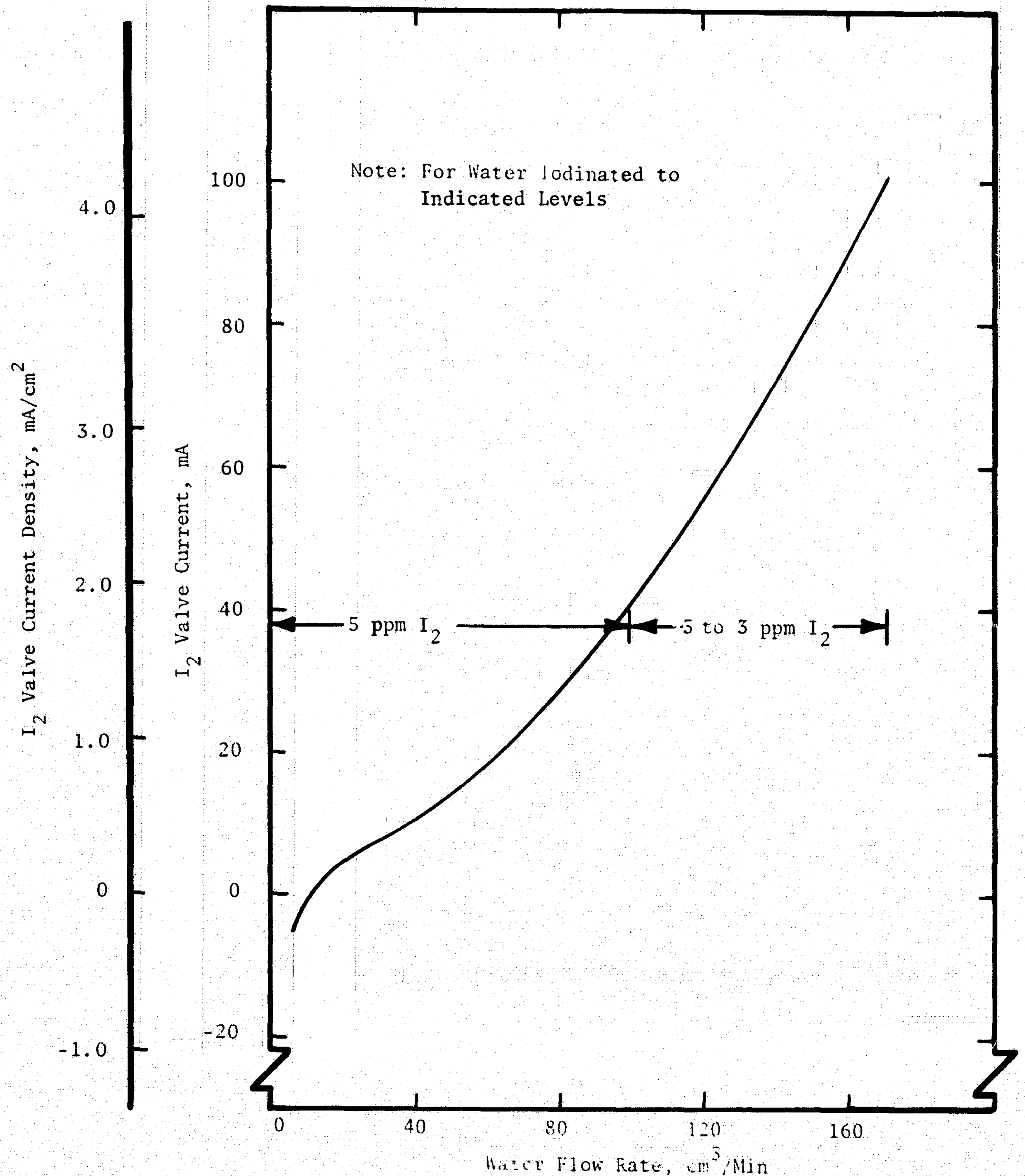


FIGURE 15 I_2 VALVE CURRENT VERSUS WATER FLOW RATE FOR LSI-100 CELL

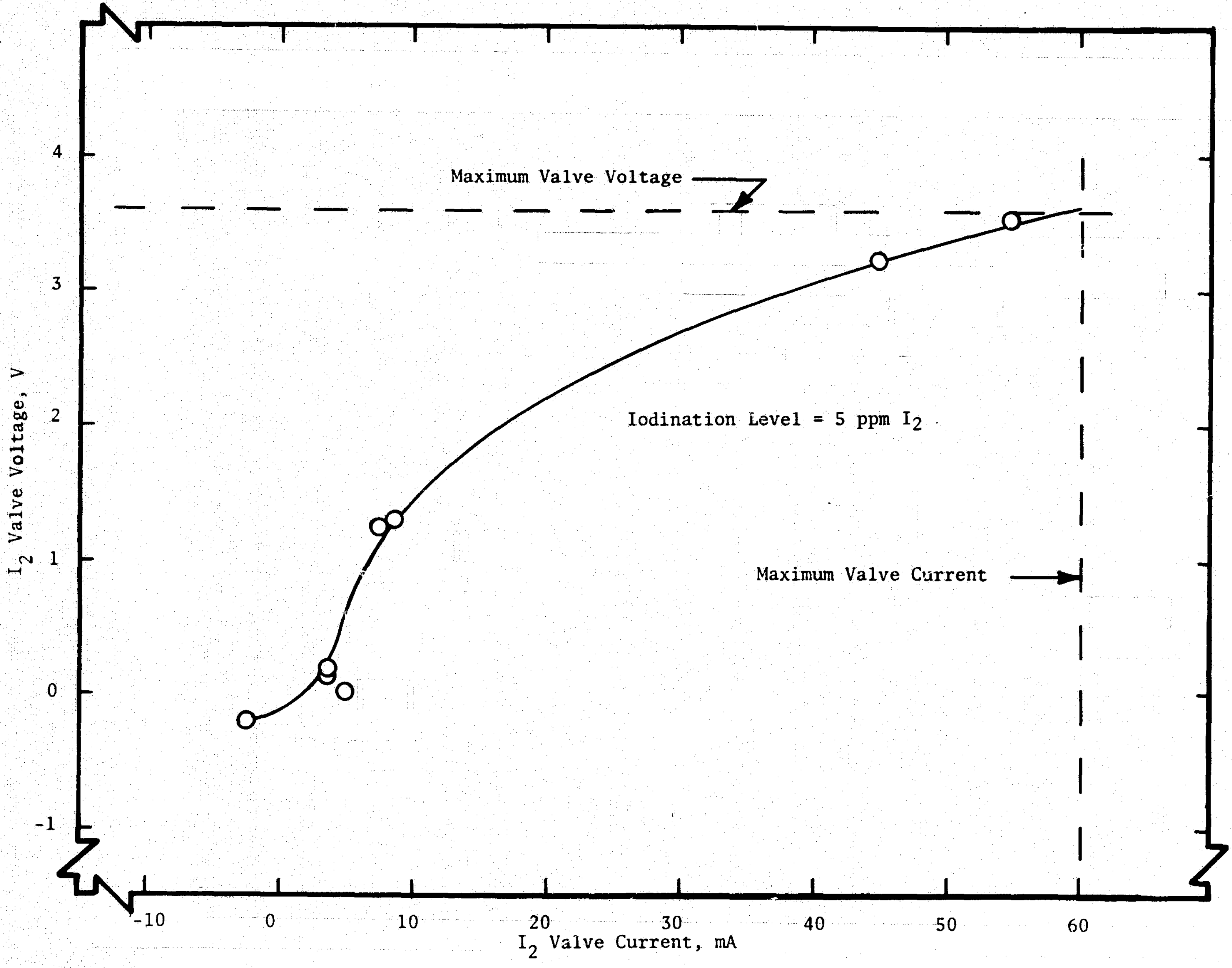


FIGURE 16 VOLTAGE-CURRENT RELATIONSHIP FOR MODEL LSI-100

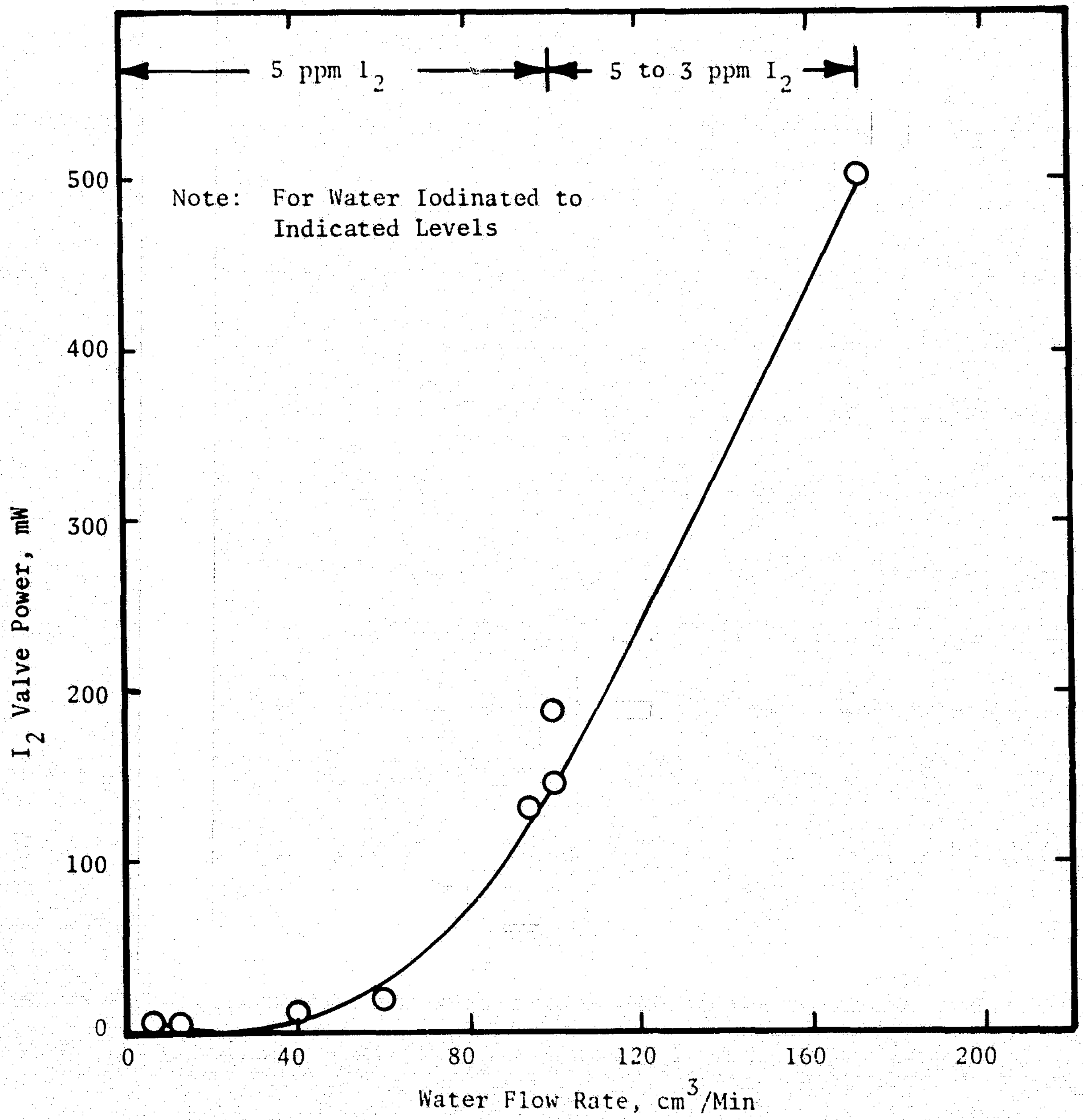


FIGURE 17 I_2 VALVE POWER CONSUMPTION VERSUS WATER FLOW RATE FOR LSI-100 CELL the I_2 generation rate of the Model LSI-100 approaches a limit of about 0.75 g/day. This level is sufficient to iodinate the initial maximum water flow requirements of 100 cm^3/min (317 lb/day) to 5 ppm I_2 and final maximum water flow of 172.5 cm^3/min (547 lb/day) to 3 ppm I_2, as required by the AWIS design specifications. The line representing the current values necessary for those I_2 generation rates if the I_2 valve current efficiency was 100% is also shown.

Figure 14 relates the I_2 valve voltage of the Model LSI-100 as a function of the current density. An I_2 valve voltage of 3.6V was considered the maximum safe value to provide an adequate safety margin for the 5V power supply chosen for use in the Model IX-S. As shown in Figure 14, this maximum valve voltage is obtained with the Model LSI-100 at a current density of 2.7 mA/cm^2 (2.5 ASF). The performance of the Model IX-S was anticipated to be similar to that of the Model LSI-100. Therefore, 2.7 mA/cm^2 (2.5 ASF) was the largest current density expected for the IX-S at the designed maximum flow rate of 100 cm^3/min (317 lb/day).

The I_2 valve current is shown as a function of water flow rate in Figure 15. The Model LSI-100 I_2 Source could iodinate water up to flow rates of 100 cm^3/min (317 lb/day) to 5 ppm with a maximum valve current of 60 ma. The iodination level decreased from 5 to a minimum of 3 ppm at flow rates between 100 and 172.5 cm^3/min (317 to 547 lb/day). The higher flow rates were investigated subsequent to the change in the Shuttle specification. However, the design of the Model IX-S was underway at the time of the specification change, so the Model IX-S was designed to iodinate water up to 100 cm^3/min (317 lb/day) to 5 ppm and from 100 to 172 cm^3/min (317 to 547 lb/day) of water to a minimum of 3 ppm.

The current of 60 mA at the flow rate of 100 cm^3/min (317 lb/day) was well within the maximum current of 100 mA expected from the power supply of the Model IX-S design. This current was chosen as the design point for a flow rate of 100 cm^3/min (317 lb/day). The working area of the I_2 valve was calculated to be 21.9 cm^2 (3.4 in^2) from the maximum allowable current density of 2.7 mA/cm^2 (2.5 ASF) and the maximum current of 60 mA.

A Model LSI-100 I_2 valve voltage versus current is shown in Figure 16. This data was obtained over the range of flow rates of 7 to 100 cm^3/min (21 to 317 lb/day) and the I_2 concentration equalled 5 ppm. The power consumption of the I_2 valve is the product of the I_2 valve voltage and valve current. Therefore, the power consumption of the I_2 valve can be projected as a function of the water flow rate from the data presented in Figure 16 and the flow rates at which each data point was obtained. The power consumption of the I_2 valve is shown in Figure 17 as a function of the water flow rate. From this Model LSI-100 data the I_2 valve in the Model IX-S was anticipated to require approximately 145 mW at a flow rate of 100 cm^3/min (317 lb/day) to iodinate at a level of 5 ppm. At a flow of 172.5 cm^3/min (547 lb/day), the Model IX-S was anticipated to consume 500 mW of power while iodinating to a minimum concentration of 3 ppm I_2. In actual use, however, the completed Model IX-S required less than the anticipated power.

Valve Electrodes and Membrane Shape. Three shapes for the Model IX-S valve electrodes and membrane were considered: rectangular, square, and circular. Testing completed prior to completion of the Model IX-S was performed with cells having a rectangular valve shape. The primary consideration for electrode and membrane shape is to provide uniform distribution of water flow over the anode. In general, a narrow, rectangular shape can provide good distribution, but results in larger cell weight and volume than for either square or circular shapes. A square shape has poorer flow distribution than a circular shape with center water feed and a radial flow pattern.

Based on flow distribution and cell weight and volume considerations, a circular valve shape and center water feed was selected for the Model IX-S design. In addition to the flow distribution and cell size advantages, the circular shape provided the following advantages:

1. Lower manufacturing cost (lathe versus mill work)
2. Adaptable to assembly without nuts and bolts which eliminates the need for electrical isolation of the bolts from other portions of the structure
3. Easier to adapt to space allocated on the Shuttle Orbiter for the water disinfecting system

Dispenser. The I_2 dispenser for the Model IX-S was designed to provide the center water feed and radial flow distribution of water over the anode. Radial water flow was assured through the use of a shallow water cavity surrounding the central water inlet and a deeper circular groove in which the water outlet is located. This configuration produces a uniform pressure drop in all directions from the inlet to the circular groove and dispenser outlet. The effectiveness of this design was verified by an initial test using a transparent Lucite mockup of the Model IX-S I_2 dispenser design. Water was pumped through the mockup, and colored dyes were injected into the inlet stream. It was observed that the dye spread out in a uniform radial pattern in the dispenser.

I_2 Valve Control Circuitry

The electronics of the AWIS controls the I_2 valve current in response to the signal output of the I_2 sensor and its electronics (Figure 18). The I_2 level in the iodinated water is thereby maintained at a constant, though manually variable, concentration.

The I_2 sensor electronics were designed to produce a 0 to 5 VDC signal corresponding to a 0 to 20 ppm I_2 concentration in the iodinated water. This signal is electronically compared to an externally adjustable voltage, representing the desired I_2 concentration. Manual adjustment of a potentiometer, the concentration set pot (Figure 18), determines the voltage level and the corresponding I_2 concentration. The error or difference between the sensor feedback signal and the set pot voltage is amplified and fed into an integrator, whose output modulates a bipolar current source to control the I_2 valve. In this closed loop feedback network, the circuitry is designed to vary the valve current to maintain the sensor feedback signal equal to the set pot voltage.

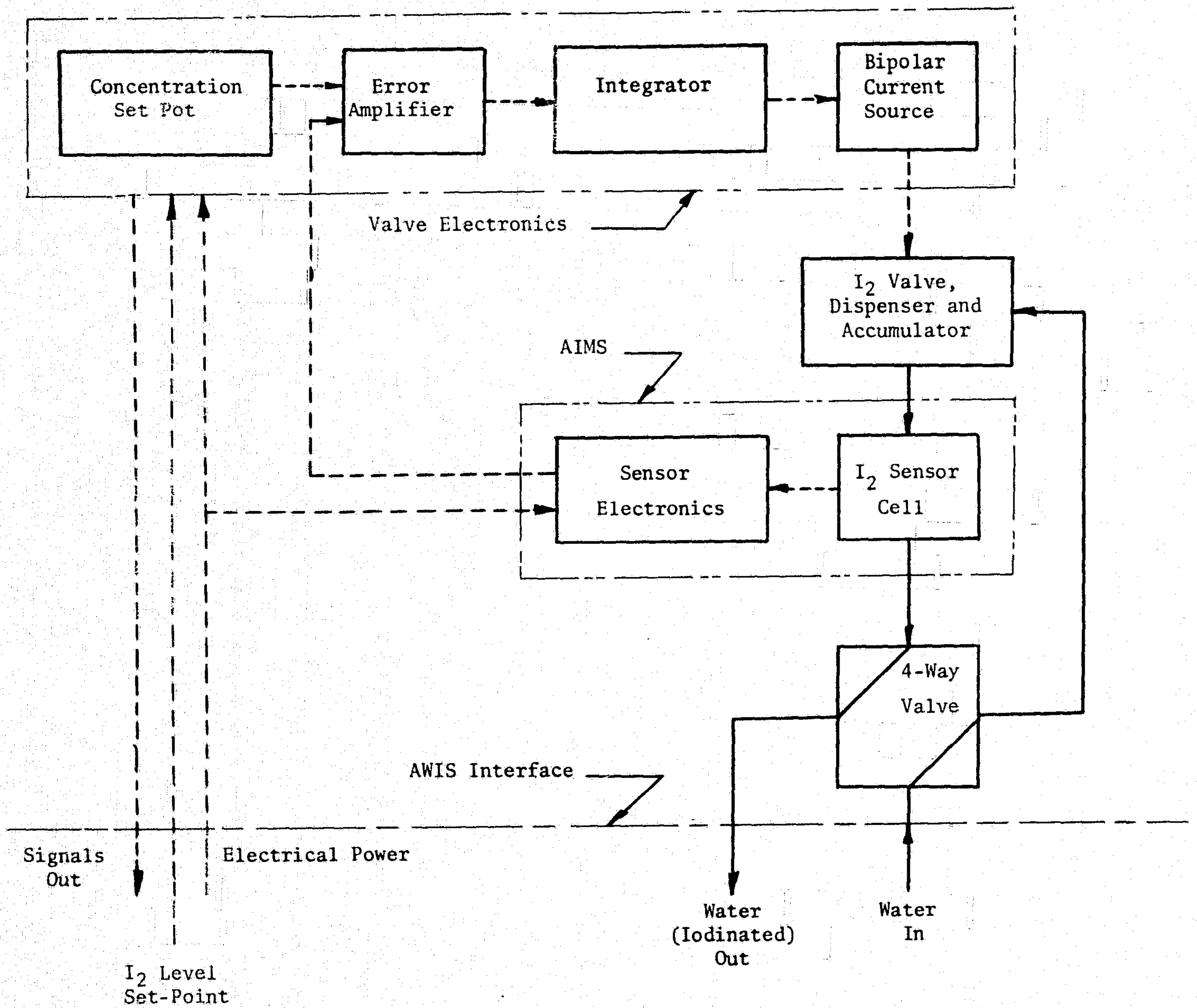


FIGURE 18 AWIS FUNCTIONAL BLOCK DIAGRAM

The integrator was designed with a time constant of 100 to 200 seconds that can be varied by manual adjustment. This time constant was selected to compensate for the time necessary to transport the iodinated water from the I_2 Source to the sensor at the lowest water flow rate of 22.7 cm^3/min (72 lb/day). Shorter time constants would cause oscillation in the feedback network at low water flow rates. A screwdriver adjustment, externally accessible without Model IX-S disassembly, was included in the design for optimizing the time constant to the fastest response at high flow rates without oscillation at the low flow rates.

The bipolar current source was designed with current limits of +100 mA and -10 mA, manually adjustable using trimpots. The reversed polarity value of 10 mA was found during testing of the Model LSI-100 to be sufficient to control the I_2 diffusion through the membrane.

A discrete 0 to 5V signal output was included in the AWIS design to indicate the AWIS operating status. Another 0 to 5V signal output was included to linearly correspond to a 0 to 20 ppm I_2 concentration in the iodinated water. This second signal is generated by electronics designed so the I_2 valve controller operation is continued even though the signal lines may become shorted.

Fault isolation circuits to the component level within the AWIS were not included in the design since a redundant AWIS was to be used for fail-safe operation.

AWIS Configuration and Packaging

The I_2 accumulator, valve, and dispenser and the I_2 valve control circuitry were designed to be mounted within a single housing in order to provide the most compact and lightest package. This design also eliminated the need for external wiring between the electronics and the I_2 valve electrodes.

The I_2 valve control circuitry was mounted on one 8.1 cm (3.2 in) diameter, two-sided printed circuit (PC) card with plated through holes. Electrical connections were made with wires soldered to the PC card. Figure 19 shows the hardware resulting from the design and includes photographs of the blank PC board, the assembled board and the PC board with leads attached. The two power supplies for the electronics and the I_2 valve were fastened to the bottom of the PC board with adhesive. The PC board with the power supply assembly were attached to the cover of the Model IX-S housing with three standoffs. An electrical connector was mounted to the housing cover to connect the I_2 valve control circuitry to the sensor electronics and the AC line power. The assembled electronics package mounts in the IX-S housing above the I_2 Source.

Figure 20 is an assembly drawing of the I_2 Source and Figure 21 is a photograph showing the individual components and parts, developed from program design tasks, that are contained in the I_2 Source. The I_2 Source consists of the membrane (LSI-01) compressed between two Pt electrodes by the Hastelloy C-276 I_2 accumulator, and the polysulfone anode compartment spacer and Hastelloy C-276 baseplate. Compression of the O-ring seals and membrane is achieved when the baseplate is tightened in the housing (torque of 33.9 N-m (25 ft-lb)). The

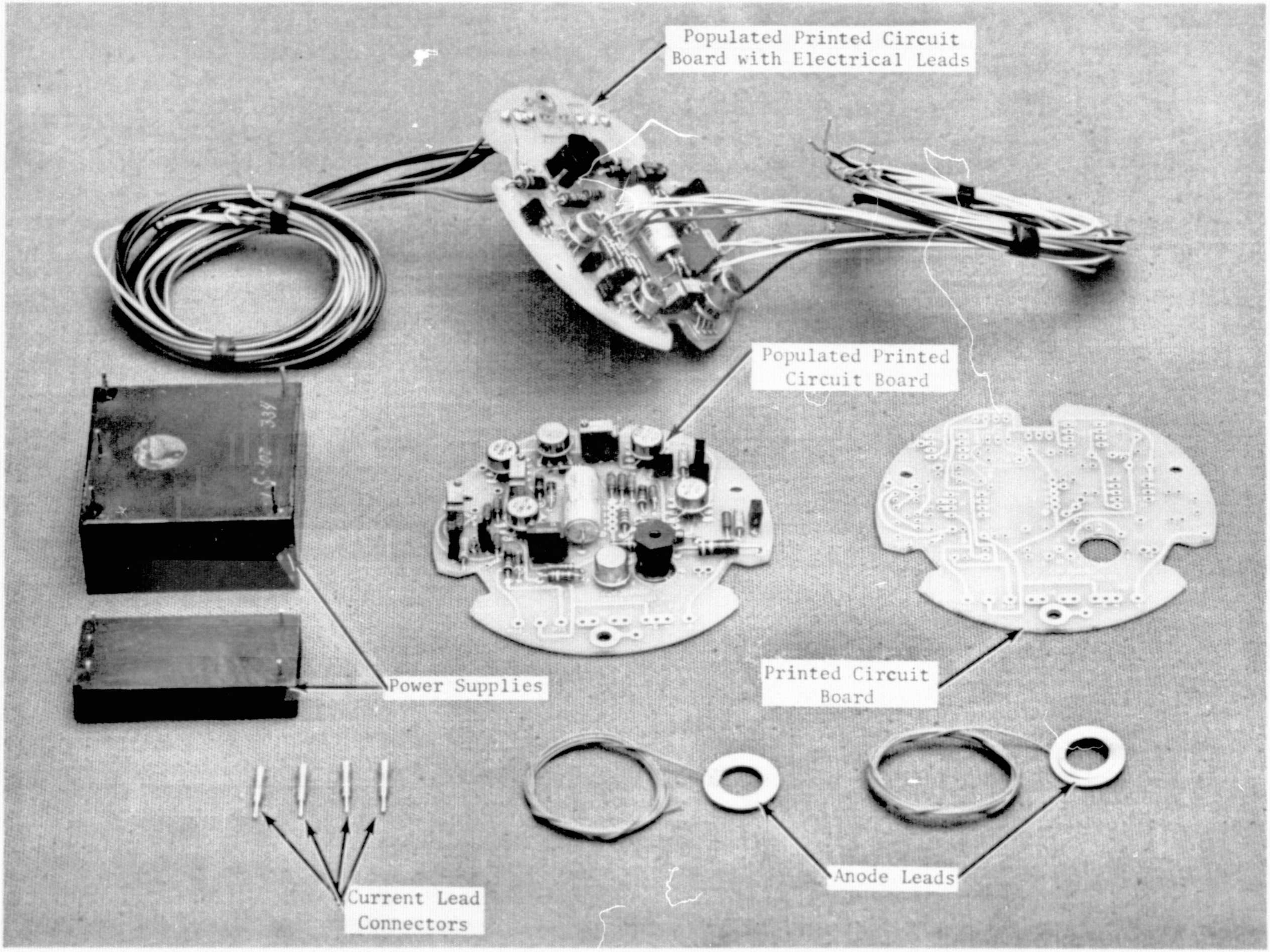
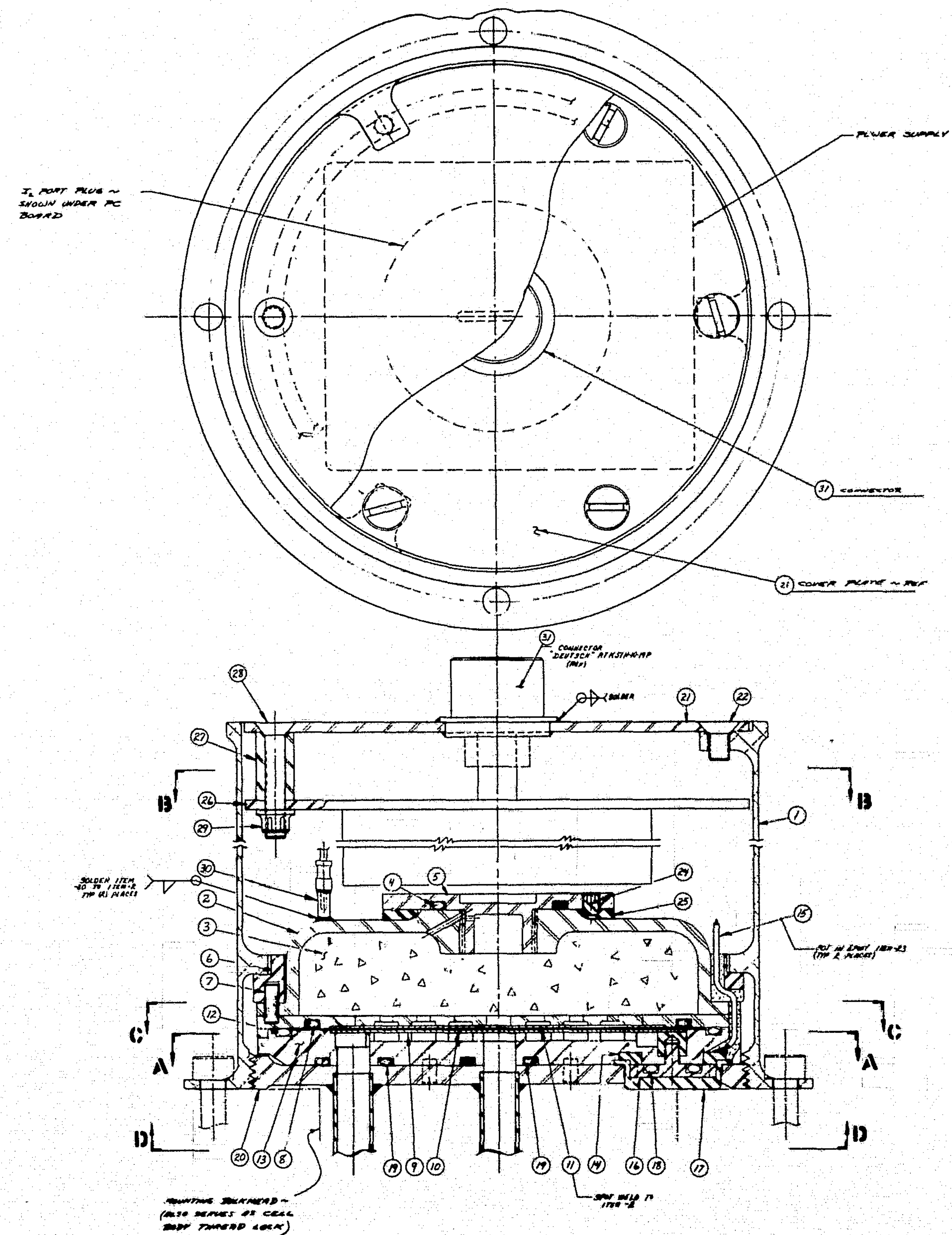
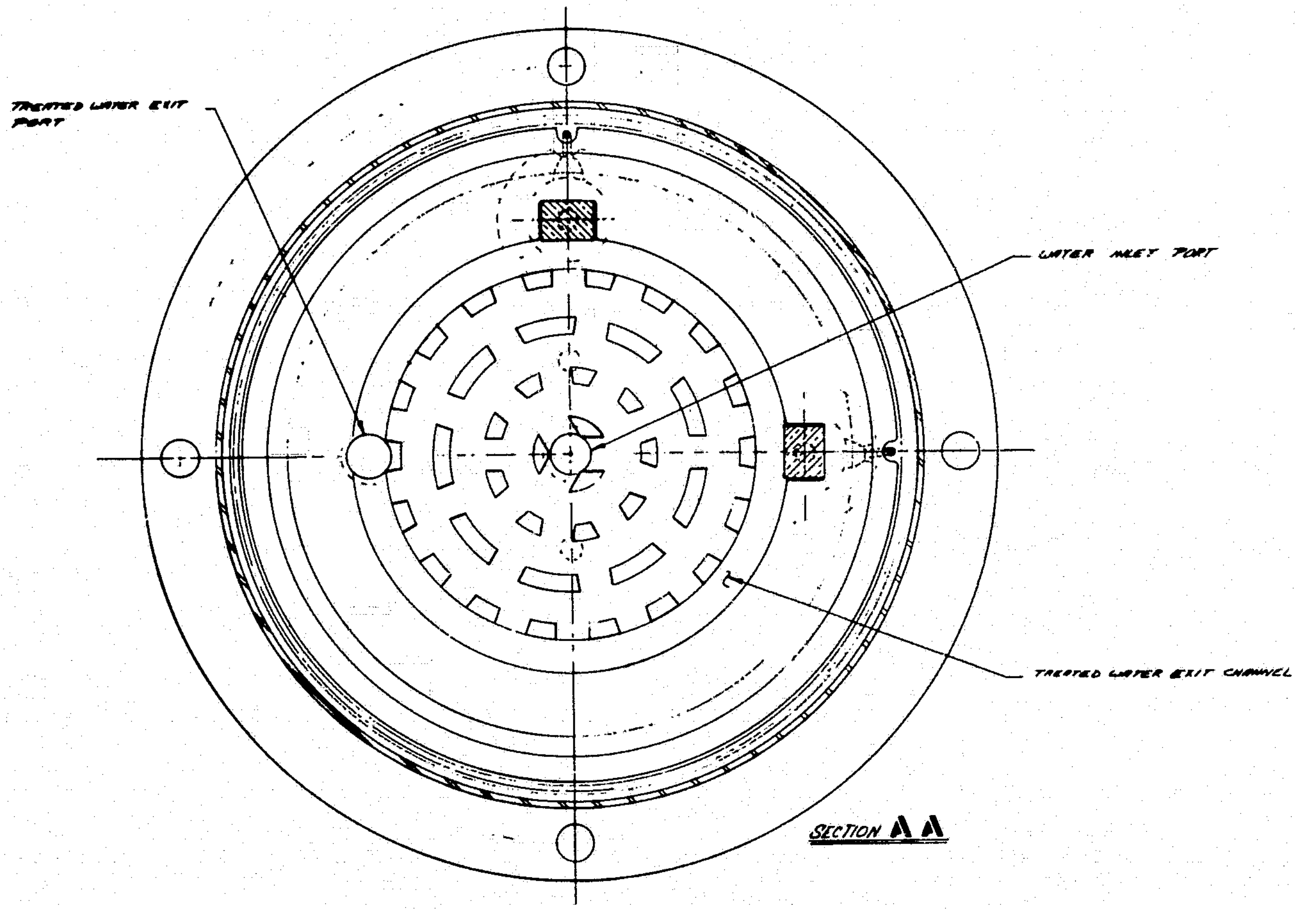


FIGURE 19 AWIS I_2 VALVE ELECTRONICS ASSEMBLY AND COMPONENTS



continued-

FIGURE 20 AWIS I_2 SOURCE ASSEMBLY DRAWING



Item No.	Item Description
1	Housing
2	I_2 Accumulator
3	I_2 Crystals
5	I_2 Accumulator Cover
6	Compression Ring
9	Anode
10	Membrane
11	Cathode
13	Anode Compartment Spacer
14	Anode Lead Ring
16	Anode Lead Bolt
17	Anode Lead Insulation Cap
21	Housing Cover
31	Electrical Connector

FIGURE 20 - continued

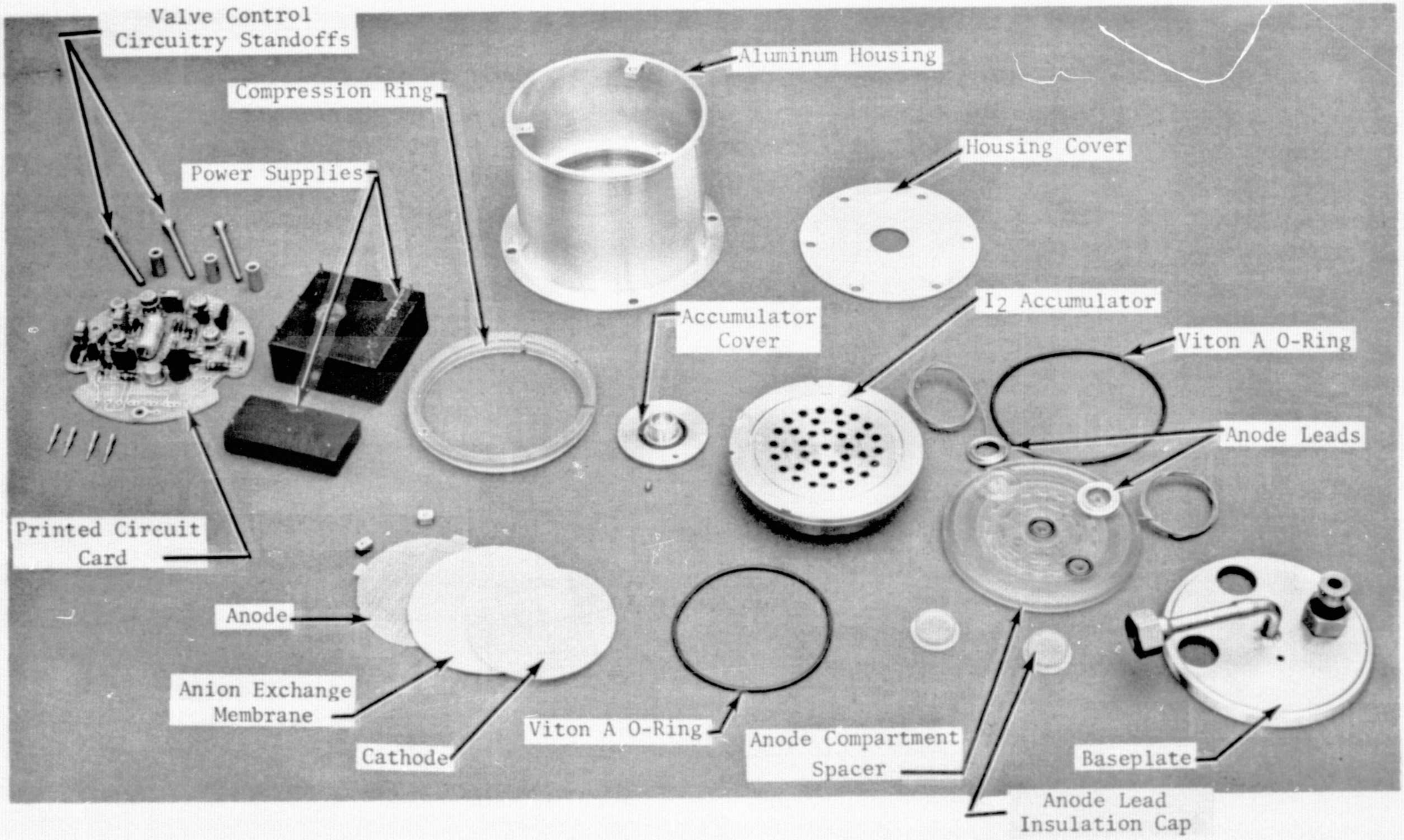


FIGURE 21 AWIS I_2 SOURCE COMPONENTS

membrane and electrodes are supported on each side by raised projections on the accumulator (see Figure 20, Part 1) and on the anode compartment spacer (see Figure 20, Part 2). The projections provide support and ample catholyte/cathode and water/anode contact areas. The projections on the anode compartment spacer also help mix the water flowing through the dispenser and the I_2.

Electrical connections from the I_2 valve control circuitry to the anode are made through dual 22 gauge wires soldered to the anode lead rings which are made of Hastelloy C (Figures 20 and 21). Bolts connect these rings to threaded anode contacts that are spot-welded to the anode. Electrical connection to the cathode is made through dual plug-in contacts on the I_2 accumulator, to which the cathode is spot welded. The accumulator, which is at the potential of the cathode, is electrically insulated from the IX-S housing by the polysulfone compression ring. Polysulfone caps insulate the anode lead bolts from the baseplate and the potable water supply.

The I_2 crystals are inserted in the accumulator through the accumulator port, which is sealed by the accumulator cover (Figures 20 and 21).

Figure 22 is a photograph of the assembled Model IX-S I_2 Source. The overall basic dimensions are a 8.89 cm (3.50 in) diameter and 7.21 cm (2.84 in) height. The volume is 447 cm^3 (27.3 in^3), and the weight is 890 g (1.96 lb) without I_2 and water.

Automated Iodine Monitoring System

The GFE AIMS used in this program had been developed under Contract NAS9-13479.[5] The AIMS consists of a photometric cell, its optical system, and signal conditioning electronics necessary to produce an electrical signal that relates the amount of light transmitted through iodinated water in the sample cell to the concentration of I_2 in that water.[6]

Figure 23 is a schematic of the optical system and photometric cell of the AIMS. The cell has no moving parts and makes two light intensity measurements at two different wavelengths through the same sample cell. This is accomplished by splitting the light beam after it has passed through the sample cell, and sensing each portion of the beam by a separate photodiode positioned behind an optical filter. One photodiode measures the intensity of the transmitted light at 466 nm to determine the concentration of I_2, which absorbs light of that wavelength. The other photodiode monitors the light intensity at 630 nm, a wavelength that I_2 does not absorb. The electronics of the AIMS uses the output of the second photodiode to compensate the output of the 466 nm photodiode for changes in the lamp intensity.

The flow-through cell is made of anodized aluminum (Al) with a length of 5 cm (2.0 in). The water enters and leaves the cell at an angle to generate a washing action on the windows. This washing action, in addition to the 630 nm photodiode that compensates the AIMS output for changes in the light intensity, minimizes the effect on the AIMS performance of dirt films on the cell windows.

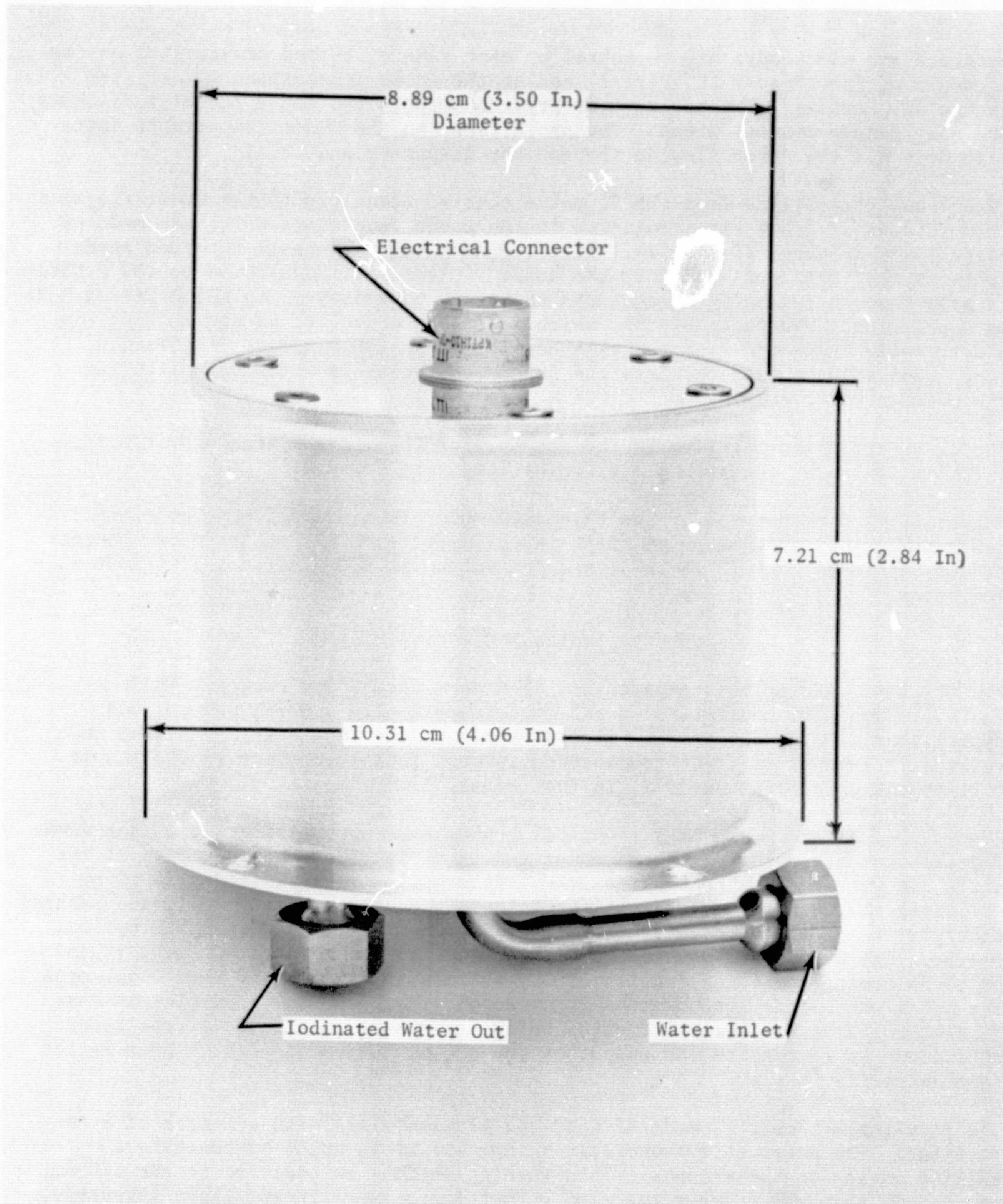


FIGURE 22 ASSEMBLED AWIS MODEL IX-S I_2 SOURCE

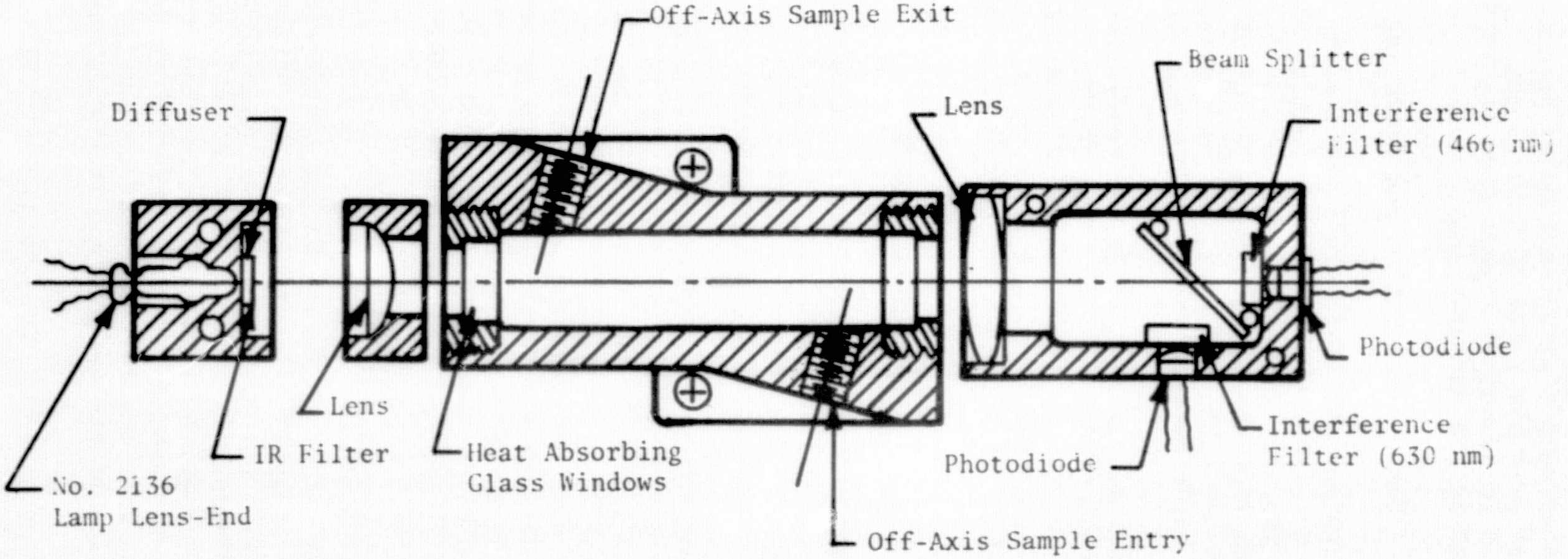


FIGURE 23 SPECTROPHOTOMETRIC CELL AND OPTICS

The AIMS has a panel meter for observing the I_2 concentration during operation. Figure 24 shows the meter output as a function of I_2 concentration. The curve is approximately linear over the range of 0 to 20 ppm I_2. The same linearity would result from the 0 to 5V output signal from the AWIS because the meter reading is proportional to the output signal.

System Integration and Packaging

The Model IX-S I_2 Source and the AIMS were integrated by mounting the AIMS directly behind the Model IX-S on a bracket containing the plumbing between the Model IX-S, AIMS, and four-way valve (Figures 25 and 26). This mounting arrangement required only 5 cm (2.0 in) of 0.64 cm (0.25 in) OD interconnecting tubing between the Model IX-S and AIMS, and provided the shortest possible transportation lag for the iodinated water between the I_2 Source and sensor.

The I_2 concentration set pot is located on the bracket below the AIMS (Figure 26), and allows operation of the AWIS at concentrations of 0.5 to 20 ppm I_2. The plumbing, mounting bolts and their related dimensions at the bracket interface are the same as those specified for the Shuttle Orbiter potable water disinfecting system, should integration of the AWIS with the Orbiter water management system be desired.

PRODUCT ASSURANCE

A mini-Product Assurance Program was implemented during AWIS development so that the impact of the Shuttle Orbiter requirements could be included during the initial design activities. The Product Assurance program included Quality Control, Reliability, Maintainability, Safety, and Materials Control functions. Quality Control was necessary to ensure reproducibility of the Model IX-S design and configuration during subsequent development. Reliability was included to identify and eliminate any failure modes that might prevent application of the AWIS to manned spacecraft such as the Shuttle Orbiter. Maintainability activities were performed to ensure that the subsystem would have a design and configuration that could be operated and maintained by personnel not associated with its development. Safety was included to ensure that no system or system component characteristics would be dangerous to personnel or equipment. Metallic and nonmetallic materials control was included in preparation for the materials specification required of equipment to be operated within manned spacecraft.

Quality Control

The Quality Control activities performed during the fabrication and assembly of the prototype AWIS consisted of (1) performance and documentation of receiving inspection on all vendor supplied parts, (2) maintaining a record of all rejected parts and authorized rework, (3) ensuring that assembly techniques specified in the design drawings are complied with, and (4) configuration control on all design drawings. This minimum activity ensured that no defective components or parts were incorporated into the AWIS and that the design drawings correctly reflected the progression of the design from initial concept through the final engineering drawings.

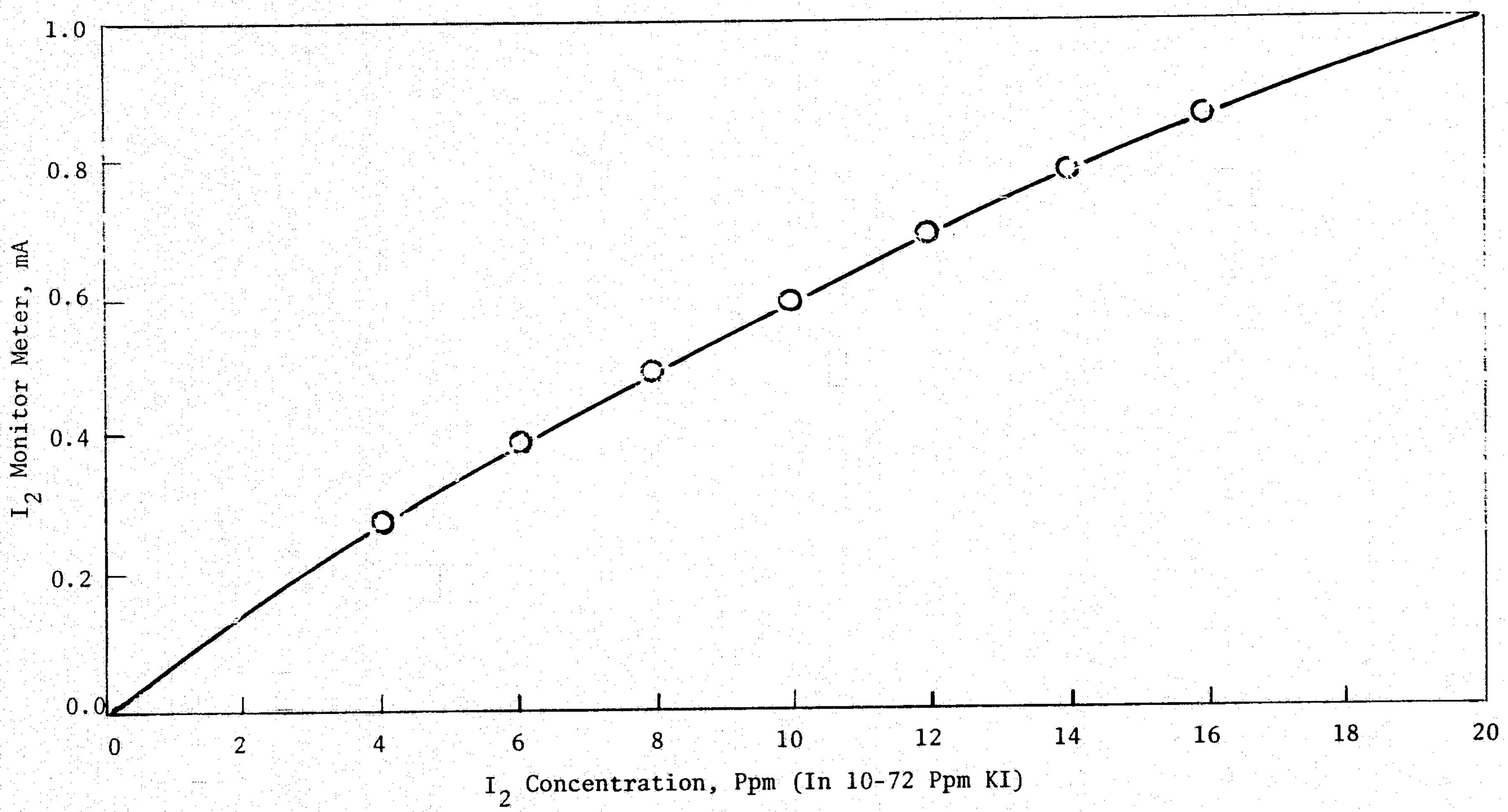


FIGURE 24 IODINATION LEVEL MONITOR CALIBRATION CURVE (5)

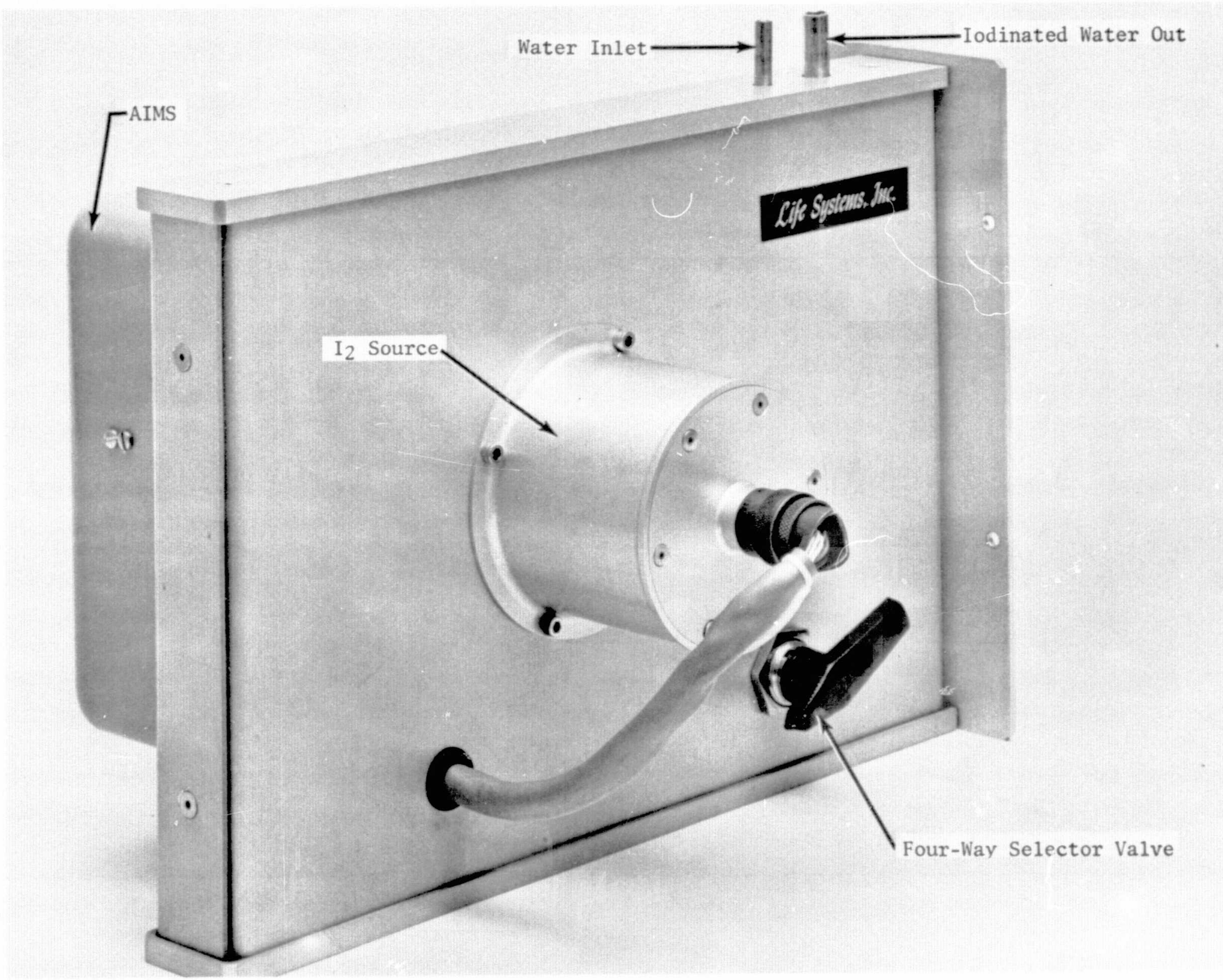


FIGURE 25 AWIS ASSEMBLY SHOWING MODEL IX-S I_2 SOURCE

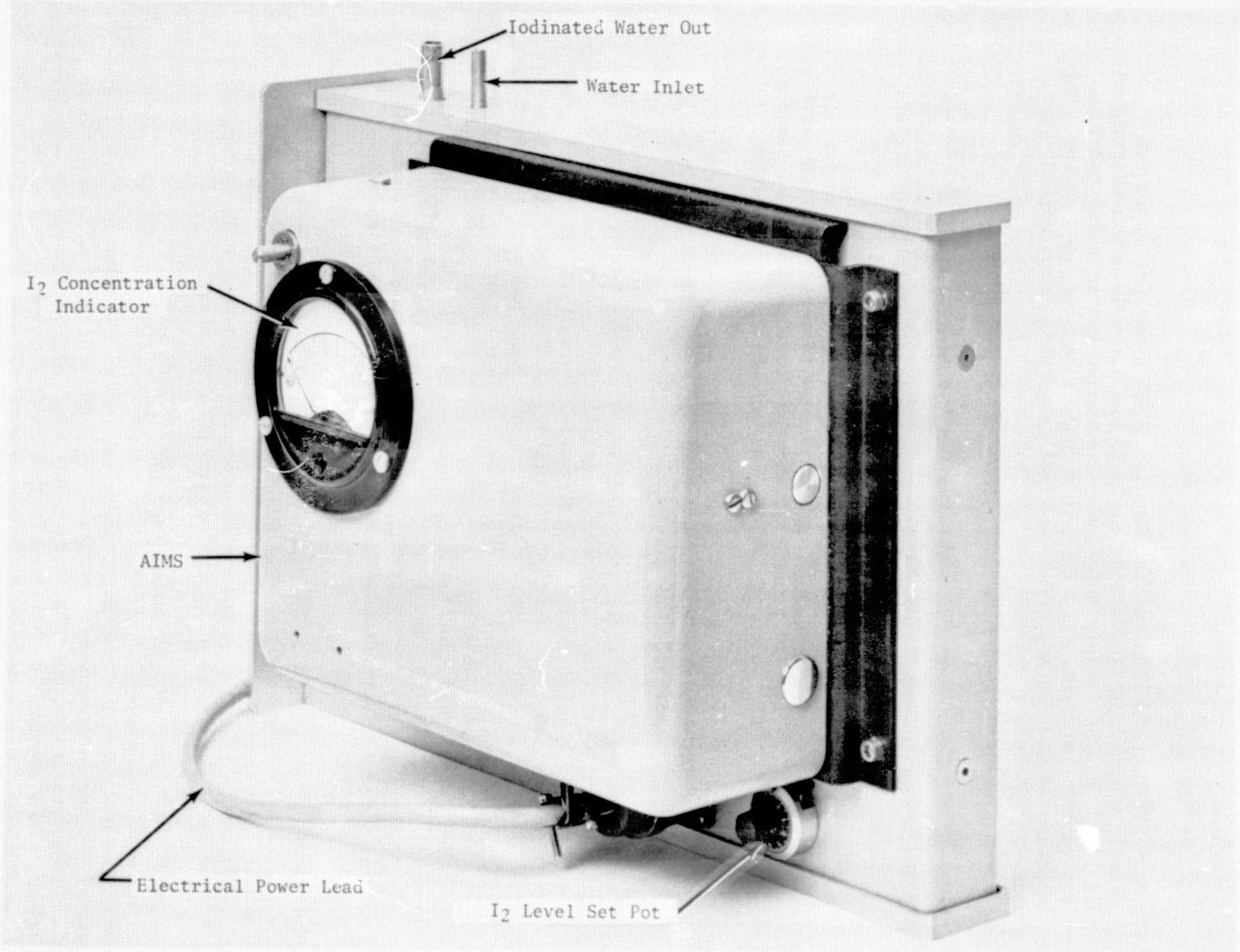


FIGURE 26 AWIS ASSEMBLY SHOWING AIMS

Reliability

A Failure Mode Effects and Criticality Analysis (FMECA) was performed for the possible Shuttle Orbiter application of the AWIS and is included in this report as Appendix 1.[7] Eleven failure modes were identified and investigated for their effect on the component, functional assembly, subsystem, and system. The failure detection method, backup provisions and crew action required for each failure mode was determined and each failure mode was classified according to the criticality levels listed below.

Criticality I	A single failure which could cause loss of personnel.
IIa	A single failure whereby the next associated failure could cause loss of personnel.
IIb	A single failure whereby the next associated failure could cause return of one or more personnel to earth or loss of subsystem functions essential to continuation of space operations and scientific investigation.
III	A single failure which could not result in loss of primary or secondary mission objectives or adversely affect crew safety.

Three criticality IIb failure modes were identified. These failure modes are those associated with the possibility of increasing the I_2 concentration of the potable water to greater than 30 ppm. It was established that water with greater than 30 ppm I_2 could damage the submlimator plates, causing a switch to the redundant sublimators and subsequent mission abort. Subsequent to the identification of this failure mode, heat rejection via a flash evaporator was chosen for the Orbiter in lieu of sublimator plates. Iodine concentrations at the highest possible levels from the AWIS are not expected to impair operation of the flash evaporator. Backup provisions have been incorporated so that the probability of the IIb failures occurring are minimal. A summary of the IIb failure modes, their failure detection method, and backup provisions is presented in Table 6.

Fail-safe operation of the AWIS for a Space Shuttle Orbiter application is possible with a nonoperating redundant iodinator and I_2 sensor (Figure 10) and an additional I_2 sensor only at the use point. In the event of an indicated failure to one unit, the crew could switch over to the standby unit by manipulating two valves. This will allow the mission to continue.

Maintainability

The design was evaluated for maintainability with respect to integration into the Shuttle Orbiter potable water system. The Shuttle Orbiter maintainability philosophy requires installed redundancy which minimizes scheduled and unscheduled maintenance. This concept is reflected in the arrangement of the two AWIS

TABLE 6 SUMMARY OF 11b FAILURE MODES

IIb Failure Mode	Failure Detection Method and Backup Provision
I_2 Control Sensor Fails Low	It is anticipated that a redundant I_2 sensor will be part of the potable water system aboard the Shuttle. The failure will be detected by the redundant I_2 sensor. The signal from both I_2 sensors will be monitored by the Data Management System. If either fails low, the crew will be made aware of the failure. The I_2 sensor has a manual, self-checking feature included which can also be used to verify sensor operation.
Instrumentation Not Capable of Decreasing Current to the Electrochemical Cell	The failure will be detected by the I_2 sensor incorporated into the AWIS and as further backup will also be detected by the redundant I_2 sensor. The signal from both I_2 sensors will be monitored by the Data Management System. The crew will be made aware of a high I_2 reading by either sensor. In the event of this failure, the crew will be able to switch to the redundant leg of the AWIS which will continue to disinfect the fuel cell water and allow the mission to continue.
Membrane Rupture	This failure will be detected by the I_2 sensor that is incorporated into the AWIS. As further backup, the AWIS will contain a redundant I_2 sensor that will also detect this failure. The probability of this failure occurring is minimal for the following reasons: 1. The membrane has been tested to four times the operating pressure without rupture (41.3×10^4 N/m^2 (60 psig)). 2. Manufacturers data indicates that the membrane can be utilized to six times the maximum operating pressure (1.38×10^6 N/m^2 (200 psig)) without rupture. 3. The fuel cell water exit pressure will not exceed 24.8×10^4 N/m^2 (36 psi) as it is controlled by a pressure regulator and relief valve. 4. All membranes incorporated into the AWIS will be pressure checked before assembly. As further backup, the electrode in the I_2 Valve, Dispenser, and Accumulator is a 100 mesh screen. This screen would prevent I_2 crystals from escaping into the water stream in the event of membrane rupture.

with a redundant sensor as shown in Figure 10. The AWIS was designed to eliminate any inflight maintenance. Also, between-flight-servicing was virtually eliminated by sizing the accumulator of the Model IX-S to store sufficient I_2 for 22 seven-day Shuttle missions (water iodination at 5 ppm I_2). Any ground servicing is envisioned as a direct unit replacement basis. Electrical connections are made via a quarter-turn connector while standard, Shuttle baseline captive fasteners and tubing fittings are adaptable to the AWIS design.

Design analyses performed on the AWIS itself indicated no maintenance requirements; e.g., no cartridges or filters need replacing, the unit is a static device, etc.

Safety

An effort was made during the preliminary design phase of the AWIS to include personnel and equipment safety features that would minimize danger to the crew and possible damage to the equipment. The AWIS design, as projected for application aboard the Shuttle Orbiter, was evaluated with regard to system safety. The safety features listed below apply to the AWIS design.

1. A single failure in one component will not cause successive failures in other components.

2. A single failure of any component will not expose personnel to the possibility of injury.

3. The system is designed so that operation and maintenance can be performed without hazard to personnel.

4. As a safety precaution against the possibility of external catholyte or water leakage from the I_2 valve, dispenser and accumulator, the design has welded plumbing wherever feasible and, where fittings are required, double O-ring seals will be utilized whenever possible.

5. A built-in safety feature of the AWIS is the fact that the crew will be able to detect a high I_2 concentration since water with greater than 5 ppm I_2 tastes antiseptic while not being harmful.

6. As a safety precaution against the loss of electrical connection, all internal connections are soldered or welded joints. The cathode/electrical lead connection is tack-welded and in addition, is mechanically held together by the compressive force applied by the cell endplates. Two electrode leads, connected electrically in parallel and at separate points on the electrodes, are used as further protection against a loss of electrical connection.

7. The membrane of the I_2 valve, dispenser, and accumulator could be exposed to 248 kN/m^2 (36 psi) pressure differential. As a safety precaution against membrane rupture all membranes incorporated into

the AWIS will be pressure checked before assembly. The membrane has demonstrated a capability to withstand 412 kN/m^2 (greater than 60 psi) pressure differential. Manufacturers' data indicates the membrane can withstand a pressure differential of six times (or 1.4 x 10^3 kN/m^2 (200 psid)), the maximum P the membrane will experience in the AWIS.

8. All nonmetallic materials to be utilized in the AWIS have been screened and accepted relative to the requirements of DNA-0002, "Procedures and Requirements for the Flammability and Outgassing Evaluation of Manned Spacecraft Nonmetallic Materials."[8]

9. The I_2 valve, dispenser, and accumulator and associated electronics are packaged in a vented metallic (aluminum) container. The electronics are designed to be potted in the container to protect them from salt spray, fog, or other adverse environments.

10. All materials that will come in contact with I_2 solutions have been screened to insure their compatibility with the particular solution.

11. The power supplies that will be utilized in the system have been designed to accept peaks and transients which may occur. Also, the power supplies and electronics are short circuit-proof.

12. Provisions have been made in the Orbiter electrical distribution system so that circuit breakers can be incorporated to protect electrical equipment from unexpected high current.

13. The housing containing the I_2 valve, dispenser, and accumulator and associated electronics is connected to a pin in the Model IX-S electrical connector so that the housing can be grounded.

14. Electrical connectors, plugs and receptacles are positively keyed to prevent incorrect mating with other accessible connectors, plugs or receptacles.

15. In all connectors, the hot electrical connector is the female socket.

16. Electrical circuits are not routed through adjacent pins of an electrical connector if a short between them will constitute a failure that could cause a serious disaster.

17. Redundant electrical leads are routed separately to insure that an event which damages one line is not likely to damage the other.

18. Although packaged in the same housing, the AWIS electronics are located in a separate compartment from the I_2 valve, dispenser, and accumulator. Since the I_2 is in a water-tight container, the possibility of contamination of electronics by I_2 is avoided.

19. The cell assembly has been designed in such a fashion that inadvertent loosening of parts due to vibration, etc. is impossible.

20. The cell was designed utilizing the factors of safety listed in Table 7.

21. Fluid connections to and within the AWIS have been designed so that incorrect mating of lines is impossible.

Materials Control

A materials control program was implemented for the design of the AWIS. This program only involved the Model IX-S since the AIMS was an existing piece of hardware and was GFE to the program. The intent of the materials control program was to select, as a goal, materials of construction, approved by NASA JSC, to comply with Shuttle Orbiter requirements.

Final Shuttle materials specifications were not available during the final design phase of the AWIS. Life Systems, therefore, implemented the materials controls program used for subsystem designs for the Space Station Prototype (SSP) program. A Materials Identification Data Sheet was prepared for the AWIS (without AIMS). This form is shown in Figure 27. Table 8 contains explanatory notes for the columns used on the data sheet shown in Figure 27.

As shown in Figure 27, all nonmetallic materials and metallic materials selected are classified as Code I or VII. Code I materials are acceptable based on documented test results found in NASA Document MSC-02681, "Nonmetallic Materials Design Guidelines and Test Data Handbook."[9]

The Code VII materials are those for which no offgassing or flammability data is available, but based on prior configuration tests of similar hardware are projected to be acceptable. NASA reviewed the Material Identification Data presented with the Final Design Report[10] and requested further offgassing and odor testing of items 23 and 29 listed in Figure 27. The results of the tests performed are listed in Table 9. Both items passed the odor and offgassing tests, resulting in total acceptance of all the nonmetallic materials in the Model IX-S I_2 Source.

GROUND SUPPORT ACCESSORIES

Ground Support Accessories were needed to (1) obtain data for AWIS supporting technology tests, (2) simulate the Shuttle Orbiter and advanced spacecraft potable water systems, (3) obtain exploratory data on Model IX-S and AWIS operation, and (4) measure I_2 concentrations and aqueous solution parameters.

Supporting Technology Test Facilities

The test facilities developed under Contract NAS1-11765 were refurbished to perform the test activities with the Model LSI-100 unit required during supporting

TABLE 7 DESIGN SAFETY FACTORS

Item	Conditions	Factors of Safety	Remarks
General Structures (Factors following take precedence)	Combined Worst Conditions	Strength Limit Stress ≥1.5	Strength limit is fatigue limit for dynamic conditions. Strength limit is yield strength for static conditions.
Hydraulic and Pneumatic Components	Pressures:		
	Liquids:		
	Proof Pressure	$\frac{\text{Proof Pressure}}{\text{Max Operating Press}} > 1.5$	
	Burst Pressure	$\frac{\text{Burst Pressure}}{\text{Max Operating Press}} \geq 2.0$	
	Gases or Liquids plus Gases:		
	Proof Pressure	$\frac{\text{Proof Pressure}}{\text{Max Operating Press}} \geq 2.0$	
	Burst Pressure	$\frac{\text{Burst Pressure}}{\text{Max Operating Press}} \geq 4.0$	
	Structural:		
	Strength-Stress based on Proof Pressure	$\frac{\text{Yield Strength}}{\text{Stress}} \geq 1.1$	
	Strength-Stress based on Burst Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}} \geq 1.2$	
Metal Tubing and Fittings	Max Operating Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}} \geq 4.0$	
		$\frac{\text{Yield Strength}}{\text{Stress}} \geq 2.0$	
Flexible Hosing	Max Operating Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}} \geq 4.0$	

Life Systems, Inc. CLEVELAND, OHIO 44122	MATERIAL IDENTIFICATION DATA	☒ LINE REPLACEABLE UNIT ☐ LINE REPLACEABLE COMPONENT	☐ COMPONENT ☐	REVISION LTR. B
	TITLE ADVANCED WATER IODINATING SYSTEM (AWIS), (WITHOUT SENSOR)	NO.	PAGE 1 OF 2	DATE 2/20/75

ITEM NO.	QTY. REQ'D.	PER UNIT WT. (g)	PER UNIT AREA (cm^2)	TOTAL WT. (g)	TOTAL AREA (cm^2)	MFGR'S. DESIGNATION	MANUFACTURER	MATL. CODE	FUNCTION	MATL. CAT.	MATL. DWG. P/N	MATL. CODE NMA	MATL. CODE MMA	REF.
1	1	200	40	200	40	C-276 Hastelloy C	Stellite Div., Cabot Corp.	EYGIXX	I_2 Chamber and Top Plate	F	D-936		I	
2	1	4	6	4	6	C-276 Hastelloy C	" " "	EYGIXX	Current Collector	F	B-944		I	
3	1	23	12	23	12	C-276 Hastelloy C	" " "	EYGIXX	I_2 Inlet Port	F	C-937		I	
4	2	<4	<1	<4	1	C-276 Hastelloy C	" " "	EYGIXX	Locating Pin	F	D-939		I	
5	1	45	119	45	119	P-1700 Polysulfone	Union Carbide	DKCIXX	Cell Body	F	D-943	I		
6	1	4	30	4	30	P-1700 Polysulfone	" "	DKCIXX	Insulation Ring	F	C-938	I		
7	2	9	1	18	2	P-1700 Polysulfone	" "	DKCIXX	Insulation Cap	B	B-946	I		
8	1	64	1113	64	1113	2011 Aluminum	Alcoa	EYFKXX	Cell Housing, Top Cover		D-935		I	
									and Clamp Ring	B	C-948			
9	1	191	178	191	178	316 Stainless Steel	U. S. Steel	EJGIXX	Tubing		NA[a]			
								EYGIXX	Bottom Plate	B	D-947		I	
10	1	27	3	27	3	C-276 Hastelloy C	Stellite Div., Cabot Corp.	EYGIXX	Current Collector	F	B-945		I	
11	1 ea, 2 of #2-011	<4	<1	<4	<1	#1-036,#1-039,#2-008, #2-017,#2-011,Viton A	Parker Seal	CHDEXX	O-Ring Seals	F	D-934-2 D-934-3,-4 D-934-6 D-934-7		I	
12	2	<4	9	4	18	Platinum	Engelhard	BDGIXX	Electrodes	F	B-940,-942		I	
13	1	<4	44	<4	44	LSI-001 Membrane	Life Systems	DTGUXX	Cell Membrane	F	B-941	VII		
14	4	<4	0	4	0	304 SS	Heli-Coil	BNEIXX	Helicoil Inserts	F	J-934-8		I	
15	4	2	<1	8	1	304 SS	Instock Fasteners	BNEIXX	Screws, Flat Head, #6-32	B	J-934-9		I	
16	As Reqd	27	0	27	0	Eccobond 787 AB	Emerson Cuming	BABGXX	Potting Material	F	D-934-12	I		
17	1	14	13	14	13	Fluorel	Raybestos Manhattan	AHDEXX	Friction Pad	F	D-934-11	I		
18	2	9	0[b]	18	0	FR-4 Fiberglas/Epoxy	Norplex Corp.	CRFVBG	Circuit Board	F	NA	I		
19	4	<1[c]	0	2	0	Diallyl Phythylate	Bourns	BDBYHU	Potentiometers	F	R7,21,[d] 24,27	VII		
20	160 cm	<1	0	3	0	Teflon	E.I. duPont deNemours	BDCOHU	Wire Insulation	F	NA	I		
21	As Reqd	NA	0	1	0	Ceramic	Dale, TI, Teledyne, Erie	BDHOHU	Electrical Components	F	R1-4,8-10, 17-20, U1-5,C1-3, C5-8	VII		
22	As Reqd	NA	0	102	0	Epoxy (Type proprietary)	Datel Systems, Dale, Stackpole, Erie	BDBGXX	Potting matl. for power supply BPM-15/50 and UPM-15/100, Epoxy in electrical components	F	PS1-2, C1-3, C5-8 All resistors	1		
23	As Reqd	NA	0	3	0	Glass	Sprague, Bendix, Motorola	BDIAXX	Glass seal in connector and other electrical components	F	J1,Q1-2, CR1-4	VII		
24	As Reqd	NA	0	<1	0	Gold	Intersil, Motorola, Bourns, Bendix	BDGIXX	Electrical components	F	V1-5, Q1-2, CR1-3, R7, 24, 27, J1		I	
25	As Reqd	NA	0	17	0	Copper	Intersil, Motorola, Bourns, Bendix, Stackpole, Erie, Dale, Sprague	BDGIHN	Electrical components	F	All components		I	

(a) NA = Not Applicable, (b) All components in electronic compartment will be completely encapsulated in Eccofoam EFF-15.
(c) Total weight of electronics is less than 1.0 lb, (d) Part numbers on LSI Drawing LSI-D-950.

FIGURE 27 AWIS MATERIALS IDENTIFICATION DATA

continued-

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Life Systems, Inc.

Life Systems, Inc. CLEVELAND, OHIO 44122	MATERIAL IDENTIFICATION DATA	☒ LINE REPLACEABLE UNIT ☐ LINE REPLACEABLE COMPONENT	☐ COMPONENT ☐	REVISION LTR. B
	TITLE ADVANCED WATER IODINATING SYSTEM (AWIS), (WITHOUT SENSOR)	NO.	PAGE 2 OF 2	DATE 2/20/75

ITEM NO.	QTY. REQ'D.	PER UNIT WT. (g)	PER UNIT AREA (cm^2)	TOTAL WT. (g)	TOTAL AREA (cm^2)	MFGR'S. DESIGNATION	MANUFACTURER	MATL. CODE	FUNCTION	MATL. CAT.	MATL. DWG. P/N	MATL. CODE NMA	MATL. CODE MMA	REF.
26	As Reqd	NA	0	2	0	Nickel	Intersil, Motorola, Bourns	BDGIXX	Electrical components	F	U1-2, Q1-2, R7, 21, 24, 27		I	
27	1	1	0	1	0	Beryllium Copper	Bendix	BDGIXX	Electrical connector	F	J1		I	
28	TBD	TBD	0	TBD	0	Eccofoam EFF-14	Emerson Cuming	BACQGS	Potting matl. for electronics	F	NA	I		
29	12	<1	0	<1	0	Carbon	Stackpole	BDFOXX	Resistors	F	R5-6, R11-15, 22, 23, 25, 26	I		
30	As Reqd	NA	0	<1	0	Silicon	Intersil, Motorola	BDXXXX	Electrical components	F	U1-5, Q1-2, CR1-3	VII		
31	1	<1	0	<1	0	Silicone	Bendix	BDCKDP	Connector	F	J1	VII		
32	1	<1	0	<1	0	Cadmium	Bendix	AKFNXX	Plating on connector	B	J1		(a)	
33	160 cm	<1	0	<1	0	Silver	Alpha	AMGQXX	Wire plating	F	NA		I	
34	1	4	0	4	0	Tantalum	Sprague	BDGIXX	Capacitor	F	C4		I	
35	1	6	0	6	0	Steel	Bendix	EZGIXX	Connector body	B	J1		I	

(a) Cadmium is an unacceptable material for flight or manned chamber test application. The connector must be replaced on units intended for manned chamber testing or spaceflight applications.

FIGURE 27 - continued

ORIGINAL PAGE IS OF POOR QUALITY

Life Systems, Inc.

TABLE 8 EXPLANATORY NOTES FOR MATERIAL IDENTIFICATION DATA FORM

1 ITEM NO. - Taken from engineering drawing or a sequential list.

2 QUANTITY REQUIRED - Number of parts required in the design of the unit or component.

3 WEIGHT - The weight in pounds of the individual part.

4 EXPOSED AREA - The exposed area in square inches of the individual part.

5 TOTAL WEIGHT - The total weight in pounds of all the required parts.

6 TOTAL EXPOSED AREA - The total exposed area (zero if potted) in square inches of all the required parts.

7 MANUFACTURER'S DESIGNATION - This column contains the identification of the material, composite or assembly and the stock or formulation number or other unique designation that a manufacturer has assigned to it.

8 MANUFACTURER - This column contains the name of the manufacturer or producer of the material, component, assembly, etc. which is being used.

9 MATERIAL CODE - A six-letter (three pair) code capable of defining materials, components, subassemblies, etc. generically and functionally. The first pair of letters of these codes describes the functional applications for which the material is being used. The second pair of letters describes the basic chemical composition of the material. The third pair of letters describes additional information, primarily of a chemical nature if available. The coding list can be found in Appendix D of MSC-02681, Revision F, Nonmetallic Materials Design Guidelines and Test Data Handbook.

10 FUNCTION - Description of the part's/item's function.

11 MATERIAL CATEGORY - A citing of Material Category per NASA Flammability and Outgassing Specification No. D-NA-0002, July, 1968.

12 MATERIAL DRAWING P/N - The part number for the component containing the subject material, taken from the engineering drawing.

13 NONMETALLIC MATERIAL ACCEPTABILITY CODE - A code number that indicates the basis of nonmetallic material acceptability. The code and their definition are shown in the following table:

continued-

TABLE 8 - continued

CODE	NONMETALLIC MATERIAL ACCEPTABILITY (NMA) CODE DEFINITION
I	As a result of identified offgassing and flammability data on material available through "Nonmetallic Materials Design Guidelines and Test Data Handbook," MSC-02681, August 6, 1971.
II	An acceptable material, component or configuration contained in container similar to tested containers.
III	An acceptable material, component or configuration contained in a tested container, with redesign if required.
IV	An acceptable material, component or configuration as a result of (a) material, (b) component or (c) configuration testing according to "Nonmetallic Materials Design Guidelines and Test Data Handbook," MSC-02681, August 6, 1971.
V	An acceptable material, component or configuration as a result of testing the "boiler plate" configuration with hazards identified removed.
VI	An acceptable material, component or configuration as a result of NASA accepted deviation employing configuration control.
VII	No data or testing required, but projected to be acceptable in its use configuration.

14 METALLIC MATERIAL ACCEPTABILITY CODE - A code number that indicates the basis of metallic material acceptability. The code and their definitions are shown in the following table:

CODE	METALLIC MATERIAL ACCEPTABILITY (MMA) CODE DEFINITION
I	An acceptable metallic material as a result of correlation with metallic materials known acceptable for crew bay use.
II	An acceptable metallic material as a result of NASA accepted deviation employing configuration control.

15 REFERENCE - A number referencing a source of additional comments or data.

16 DATE OF REPORT - Date report is generated.

TABLE 9 MATERIALS TEST RESULTS

Item Tested	Test No.[a]	Test Description	Acceptance Criteria	Test Results	Test Report No.	Disposition
Eccofoam EFF 14	6	Determin. of organ. offgassing prod. and CO	Total organics shall not exceed 100 µg/g of sample	1.0 µg/g	WSTF-74-4839	Acceptable
			CO shall not exceed 25 µg/g of sample	1.0 µg/g	WSTF-74-4839	Acceptable
Eccofoam EFF 14	7	Odor test	Total score of 25 or less for sum of 10 odor eval. for each sample concentration		WSTF-74-4839	Acceptable
			1 part to 29 parts O_2	2		
			1 part to 9 parts O_2	2		
			No dilution	12		
Power Supply UPM-15/100	6	Determin. of organ. offgassing prod. and CO	Total organics shall not exceed 100 µg/g of sample	7.0 µg/g	WSTF-74-4840	Acceptable
			CO shall not exceed 25 µg/g of sample	0.1 µg/g	WSTF-74-4840	Acceptable
Power Supply UPM-15/100	7	Odor test	Total score of 25 or less for sum of 10 odor eval. for each sample concentration		WSTF-74-4929	Acceptable
			1 part to 29 parts O_2	0		
			1 part to 9 parts O_2	0		
			No dilution	0		

(a) "Procedures and Requirements for the Flammability and Outgassing Evaluation of Manned Spacecraft Nonmetallic Materials," NASA Specification No. D-NA-0002, July, 1968.

technology tests. Figure 4 is a photograph of the facility with its associated control instrumentation. A detailed description of this test facility is found in Reference 2.

Potable Water System Simulator

A new test facility was designed, fabricated, and assembled to simulate the interface between the AWIS and the Shuttle Orbiter Potable Water System. Sufficient flexibility was designed into the new test facility to also enable simulated operation of a circulating type potable water system as found in advanced long-term mission spacecraft.

The Potable Water System Simulator (PWSS) is shown schematically in Figure 28. Figures 29 and 30 are photographs of the front and back of the PWSS. Water flowing through the PWSS contacts only 316 stainless steel, Teflon, glass, and Viton A O-rings. Besides simulating the once-through Shuttle operating mode, the test stand also enables previously iodinated water to be recycled through the AWIS and water storage tank in order to maintain the I_2 concentration of the water at the desired level.

During the recycle mode, noniodinated water can be added to the loop and/or iodinated water can be withdrawn from the loop. Feed water to the test stand is pumped from a water supply tank. Iodinated water is collected either in the stainless steel water storage tank in the recycle loop or in an iodinated water collection tank. Both the supply and collection tanks are made of polyethylene. The stainless steel storage tank was sized to hold 76 kg (176 lb) of water similar to the capacity of the water storage tanks projected for the Shuttle Orbiter.

A detailed description of the PWSS operation in the Shuttle Orbiter mode is as follows. Simulated fuel cell water is contained in the Water Supply Tank that is continuously being agitated by pump P3 (see Figure 28). Pump P1 removes water from the water supply tank and maintains a constant feed pressure, as measured by PG1, upstream of the flow controller FM-1. Flow controller FM-1 is used to adjust the flow rate to the AWIS, simulating the amount of fuel cell water coming from the Shuttle Orbiter fuel cells. In this mode, pump P2 is not operating and the water bypasses the pump through V3. The noniodinated fuel cell water enters the AWIS with a sampling capability located at the AWIS inlet through V4, and temperature and pressure monitored by T1 and PG2, respectively. Iodinated fuel cell water leaving the AWIS can be sampled through V5 and its pressure and temperature recorded by PG3 and T2. The flowmeter, FM-2 is not used to control flow in the Shuttle operating mode. The flowstream can then be directed through V7 either into the Water Storage Tank or through the external Iodinated Water Tank. If the water storage tank is used, total system pressure is adjusted through PR2 with nitrogen (N_2) gas, and the sight gauge in the water storage tank valve shows the level of water within the tank. When the tank is filled it can be drained through V11. Should the water be collected externally in the Iodinated Water Tank, system pressure is maintained through PR1 by directly backpressuring the water. In this mode,

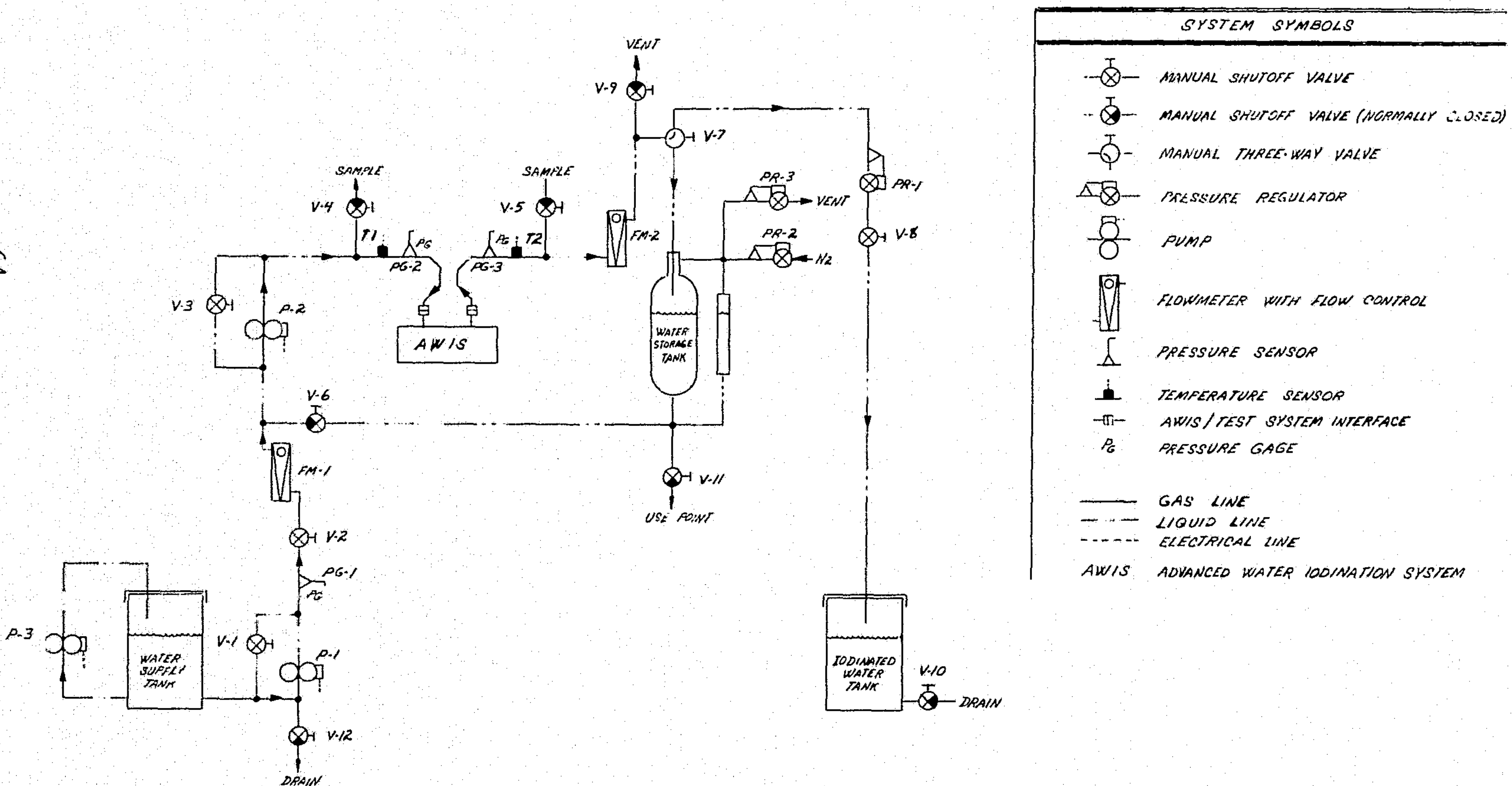

FIGURE 28 SCHEMATIC OF SHUTTLE ORBITER POTABLE WATER SYSTEM SIMULATOR

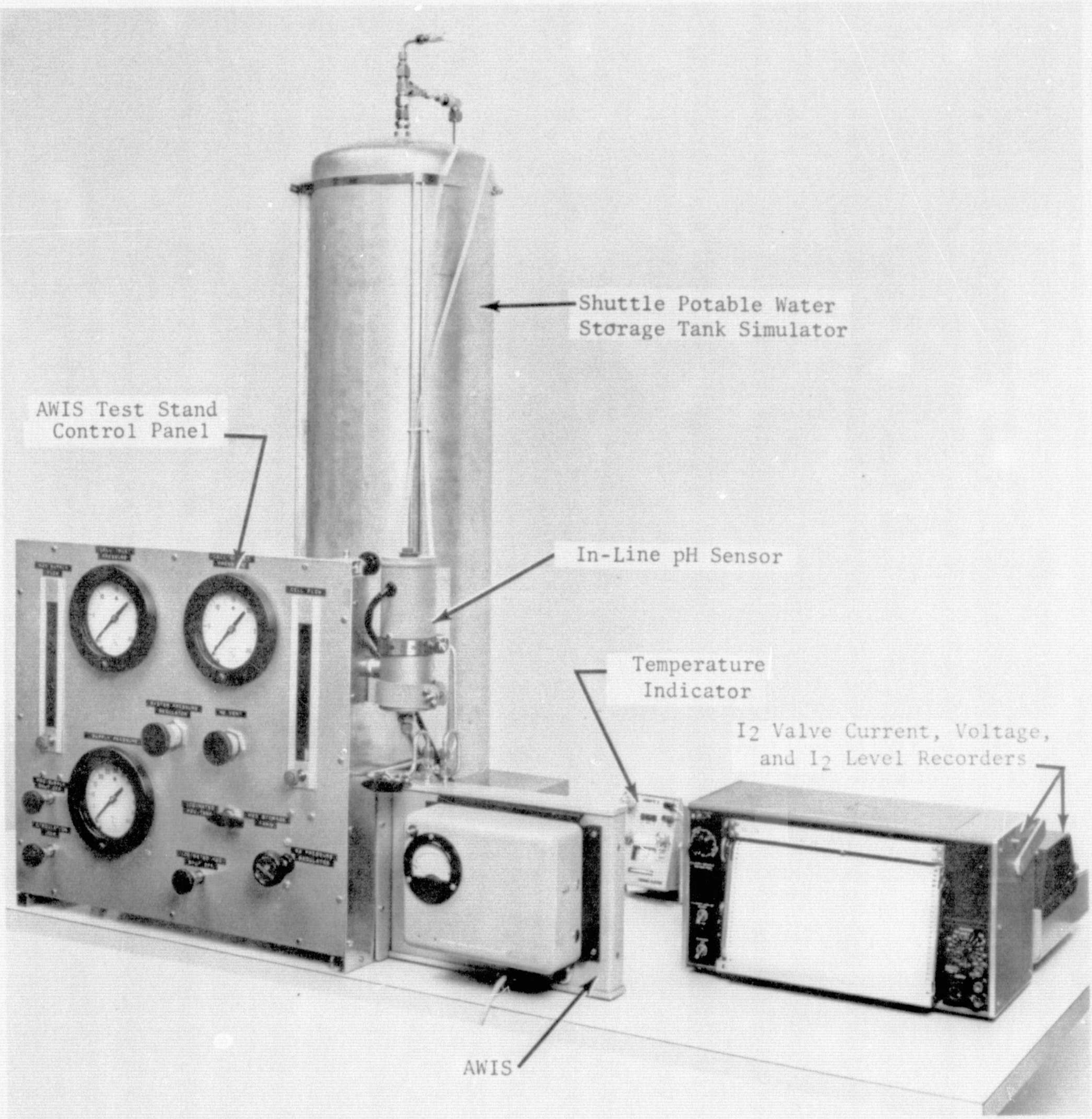

FIGURE 29 POTABLE WATER SYSTEM SIMULATOR, FRONT VIEW

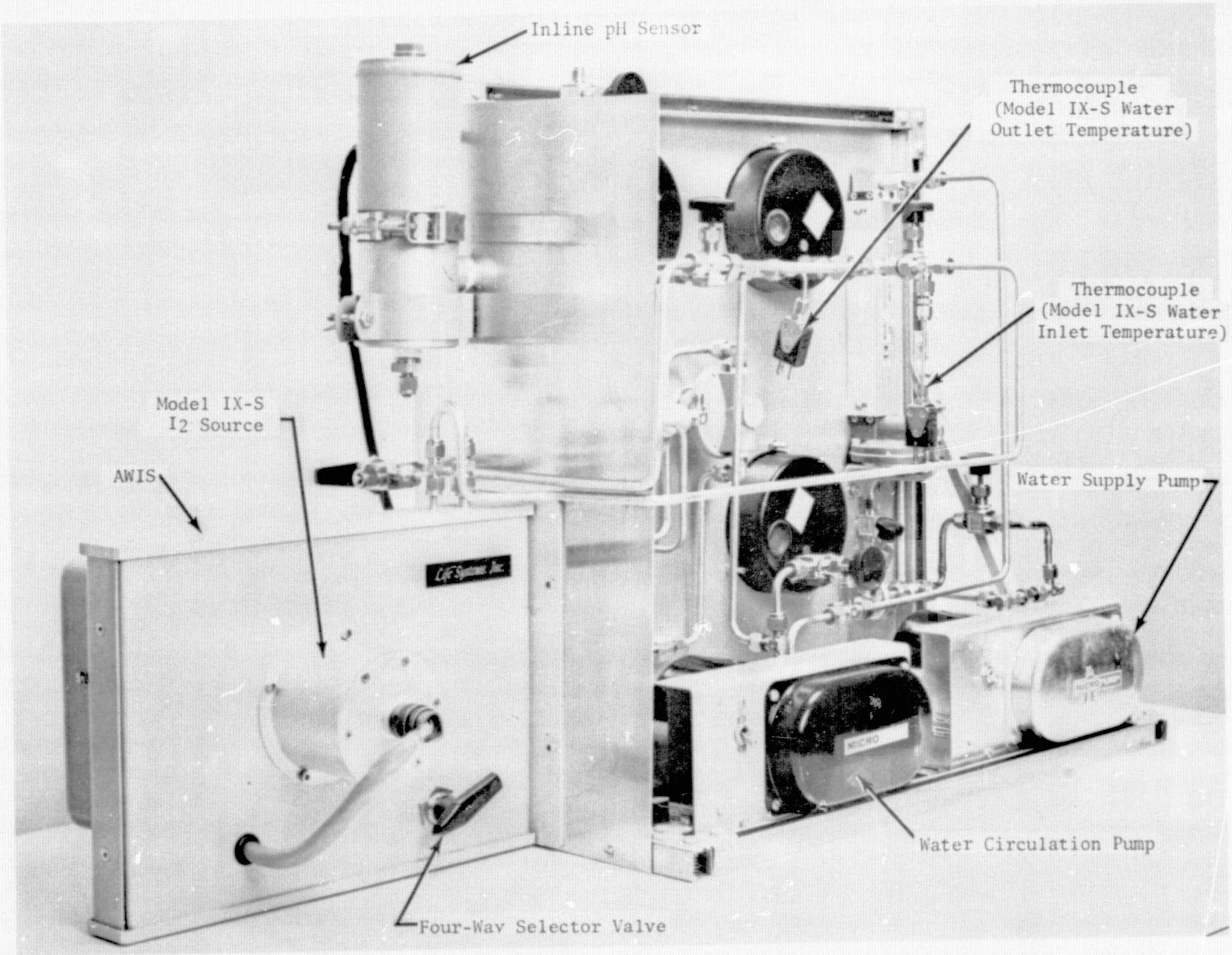

FIGURE 30 POTABLE WATER SYSTEM SIMULATOR, REAR VIEW

water sampling must be done with caution since small volumes taken out of the water stream will result in large pressure fluctuations in the AWIS.

In the recirculating mode, simulating the potable water system of a future long-mission advanced spacecraft, pump P2 circulates the water through the AWIS and the potable water storage tank. The circulating flow rate is controlled by flow controller FM-2. The pressure level of the total system is maintained with N_2 through PR2. As water accumulates and displaces the N_2, PR3 vents N_2 to the atmosphere to maintain a constant system pressure level. Should it be desirable to add noniodinated water to the recirculating flow, pump P1 and flow controller FM1 can be used similarly as in the simulation of the Shuttle potable water system. Water can also be withdrawn in the recirculating mode at the use point, simulated by valve V11. Again pressure levels during water addition or removal are maintained by PR2 and PR3. During initial filling of the system, vent valve V9 is used to remove trapped air from the plumbing. Also, the system can be totally drained through valve V12.

Following assembly of the PWSS, the three pressure gauges (P1, P2, and P3), the two flowmeters (FM1 and FM2), and the two thermocouples (T1 and T2) were calibrated. The calibration curves are shown in Appendix 2.

Strip Chart Recorders

Evaluation of the dynamic response of the AWIS to changes in operating parameters required the addition of chart recorders to the test setup. Simultaneous recording of the I_2 valve current and voltage and of the AWIS I_2 concentration as a function of time was necessary to monitor AWIS performance. Continuous recording was accomplished using an Omniscribe, Series 5000, dual pen strip chart recorder and a Rustrak Model 288. Figure 29 shows the recorders located next to the PWSS. The inaccuracies of the recorders are less than 0.3% full scale.

Analytical Equipment and Procedures

The instrumentation and equipment necessary for analysis of the iodinated and noniodinated simulated fuel cell water is shown in Table 10. The photometric method for the determination of I_2 and I^- concentrations was used as reported by Black and Whittle using leuco crystal violet to react with the I_2 to form a purple, soluble species.[11] To determine I^-, the I^- was oxidized to I_2 with oxone. The total I_2 present then was reacted with leuco crystal violet, and the absorbance of light at 585 nm by this solution determined the concentration of I_2 and I^- in the sample. The concentration of I^- in the sample was found by difference.

Samples were collected from the two sample ports shown in Figure 28. All samples of noniodinated water were collected for analysis from the sample port (V4) just upstream from the AWIS. All samples of iodinated water, other than those samples collected from the iodinated water reservoir in the operating modes test, were collected from the sample port (V5) downstream from the AWIS.

TABLE 10 ANALYTICAL DEVICES USED DURING AWIS TESTING

	Measurement	Device
1.	Iodine (I_2) and Iodide (I^-), Ppm (±1%)[1]	Fisher Electrophotometer II
2.	pH (±1%)	Corning Model 109 Digital pH Meter
3.	Specific Conductivity μmho/cm (±3%)	Beckman Model RC-19 Conductivity Bridge
4.	Turbidity Nephelometric Turbidity Units (NTU) (±2%)	Hach Model 2100A Turbidimeter
5.	Dissolved O_2, Ppm (±1%)	Beckman Fieldlab O_2 Analyzer
6.	Copper (Cu^{+2}), Ppm (±3%)	Hach Model CU-4 Copper Test Kit
7.	Ammonia (NH_3), Ppm (±3%)	Hach Model NI-8 Ammonia Nitrogen Tester

(1) Values in brackets signify expected uncertainty limits of the analysis.

The parametric values related to test stand and AWIS operation were measured using the devices listed in Table 11. The expected accuracy of each device is also listed, along with its location in the test stand or AWIS.

TEST PROGRAM

A test program was designed to characterize the performance of the AWIS for application to the Shuttle Orbiter and future long-term mission spacecraft potable water systems. Prior to initiation of the testing, a Master Test Plan was prepared and approved by Contractor and NASA JSC personnel.[12] The Master Test Plan, besides establishing step-by-step procedures for the individual tests, also established a test methodology. The main items, pertaining to procedures and methodology, contained in the Master Test Plan have been incorporated in this report. A realistic simulated fuel cell water specification was derived rather than testing with the "worst case" simulated fuel cell water used in the supporting technology testing. The realistic fuel cell water composition was based on that obtained from actual fuel cell water analyses.

Specifically, four tests were completed on the AWIS: (1) checkout, (2) Design Verification Testing (DVT), (3) operating modes, and (4) iodination of heated water testing. At the completion of testing, post-test component analyses were made.

Test Methodology

The goal for selection of testing methods and procedures was the generation of accurate test data with minimum manning, minimum downtime for maintenance, and minimum deviations from the Master Test Plan. The test methodology adopted included provision for the collection of data throughout the testing to fully record the testing procedures and results. Provisions were also included to record any unscheduled maintenance operations as well as any deviation from the Master Test Plan. Should such activities occur, the reason for the unplanned action, the action taken, and the length of time the system operated abnormally was to be recorded. Also, for failures during the DVT, the methodology provided for notification of the Technical Monitor within 24 hours of occurrence during the normal work week. Corrective action resulting from such a failure could be performed without his approval unless a failure or correction would be considered detrimental to fulfilling the objectives of the DVT.

Simulated Fuel Cell Water Composition

Table 12 is a Water Analysis Report for three samples of water from a Pratt & Whitney fuel cell.[13] The resistivity of the water is approximately 1 MΩ-cm, and the concentrations of the inorganic species except for potassium (K) are less than the detection limit of the analytical methods used. The pH of the water ranges from 6.45 to 8.43.

TABLE 11 PARAMETRIC TEST INSTRUMENTATION

Type of Measurement	Instrument	Measurement Location	Expected Accuracy
1. Temperature	Marlin Thermocouple U-57-J-4-C4	1. Upstream of AWIS 2. Downstream of AWIS	±2K (4F) over range of 273-550K (32-530F)
2. Pressure	Ashcroft Pressure Gauge 1377-S-02B, 0-30 Psig 316 Stainless Steel	1. Upstream of AWIS 2. Downstream of AWIS	±2% full scale
3. Pressure	Ashcroft Pressure Gauge 1377-S-02B, 0-60 Psig	1. Downstream of noniodinated water supply pump	±2% full scale
4. Flow Rate	Brooks Flow Controller Model 1355-8800, 0-220 cc water/Min	1. Downstream of Ashcroft 0-60 Psig pressure gauge	±2% full scale
5. Flow Rate	Brooks Flow Controller Model 1355-8800, 0-502 cc water/Min	1. Downstream of AWIS in water recirculation loop	±2% full scale
6. I_2 Concentration	Beckman Photometer	1. In AWIS	±2% full scale
7. I_2 Concentration	Omniscribe Recorder, Series 5000	1. In AWIS	±0.3% full scale
8. I_2 Valve Current	Omniscribe Recorder, Series 5000	1. In AWIS	±0.3% full scale
9. I_2 Valve Voltage	Hewlett Packard Recorder, Model 17501A	1. In AWIS	±0.3% full scale

TABLE 12 ANALYTICAL RESULTS FROM PRATT AND WHITNEY FUEL CELL WATER

Determination	Specification Limits	1072-10[a]	1072-25	1172-15
pH	6-8	8.43	6.45	7.88
Resistivity (MΩ-cm at 298K (77F)	Reference	1.00	0.8	1.2
Total Solids, ppm	TBD but <500	1.8	1.9	0
Organic Carbon, ppm	TBD but <100	5.0[b]	5.0	4.5
Inorganic Carbon, ppm	Reference Only	<1.0	<1.0	<1.0
Cadmium as Cd, ppm	0.01	<0.01	<0.01	<0.01
Chromium as Cr^{+6}, ppm	0.05	<0.005	<0.005	<0.005
Copper as Cu, ppm	1.0	<0.05	<0.05	<0.05
Iron as Fe, ppm	0.3	<0.2	<0.2	<0.2
Lead as Pb, ppm	0.5	<0.5	<0.5	<0.5
Magnesium as Mg, ppm	Reference Only	<0.01	0.025	<0.01
Manganese as Mn, ppm	0.05	<0.05	<0.05	<0.05
Mercury as Hg, ppm	0.005	<0.005	<0.005	<0.005
Nickel as Ni, ppm	0.005	<0.5	<0.5	<0.5
Potassium as K, ppm	Reference Only	0.17	0.04	0.09
Silver as Ag, ppm	0.05	<0.05	<0.05	<0.05
Sodium as Na, ppm	Reference Only	<0.01	<0.01	<0.01
Zinc as Zn, ppm	Reference Only	<0.01	<0.01	<0.01
Ammonia as N	0.5	<0.02	<0.02	<0.02
Fluoride as F^-, ppm	20.0	<0.05	<0.05	<0.05
Nitrate as NO_3^-, ppm	TBD	<0.05	<0.05	<0.05
Sulfate as SO_4^{-2}, ppm	For Reference Only	<1.0	<1.0	<1.0
Chloride as Cl^-, ppm	1.0	<0.25	<0.25	<0.25

(a) Pratt and Whitney Sample Number.
(b) < indicates the concentration of the species is less than the detection limit of the analytical technique or instrument.

Water, deionized through a mixed-bed resin, typically has a pH in the range of 6.0 to 8.0. The resistivity of the water is approximately 0.03 MΩ-cm. Therefore, deionized water is less pure than Shuttle fuel cell water is anticipated to be.

Previous testing with the Model LSI-100 I_2 Source proved the compatibility of that I_2 Source with simulated "worst case" fuel cell water of the composition shown in Table 3. Although this simulated fuel cell water had little effect on the performance of the I_2 Source, the water was not a realistic representation of actual fuel cell water. Deionized water is both more impure than Shuttle fuel cell water and a better simulation of fuel cell water than the "worst case" water of the composition in Table 3. Therefore, deionized water, but containing projected Shuttle water particulate matter, was used as a simulated fuel cell water for all AWIS testing. The particle size and concentration as shown below was simulated with "Arizona Road Dust" at a concentration of 20 ppm.

Size Range, Microns	Particles/Liter
0 - 10	2000
10 - 25	2000
25 - 50	400
50 - 100	200
100 - 200	20

All AWIS testing was conducted using water previously collected in the Water Supply Tank (see Figure 28). The water added to the tank was passed through ion exchange beds. Indicators located at the exit of these beds provide a continous signal corresponding to the conductivity of the water being added. The limit of the conductivity indicator is set at 5 x 10^{-6} mhos/cm and the indicator was continuously monitored during tank refilling to insure that no water was added where conductivity was greater than 5 x 10^{-6} mhos/cm.

Test Procedures and Results

The AWIS testing was grouped into four distinctive tests: (1) checkout, (2) DVT, (3) operating modes, (4) heated water, and post-test component analyses. Detailed, step-by-step procedures were established for the four tests to ensure that the results would satisfy the objectives of the overall test program. The AWIS test program was conducted using the Model IX-SA integrated with the GFE AIMS.

Definitions

For purposes of the AWIS testing, current efficiency and baseline conditions were defined as noted below.

1. Current Efficiency - The current efficiency of the Model IX-S, during iodination, is defined as the percent of the quantity of

electricity (in coulombs) flowing through the I_2 valve which results in generation of I_2 in the I_2 dispenser. The percent current efficiency can be computed as shown below:

$$X = 1.67 \times 10^{-3} \frac{FCV}{NI_v} \qquad (3)$$

where X = Current efficiency, %
F = Faraday's Constant, 9.65×10^4 coulombs/equivalent of I_2
C = Concentration of I_2 in the iodinated water, ppm
V = Flow rate of the iodinated water, cm^3/min
N = Equivalent weight of I_2, 126.9 g/equivalent
I_v = I_2 valve current, mA

Equation 4 is a sample calculation:

$$X = 1.67 \times 10^{-3} \frac{(9.65 \times 10^4)\ (5.1\ \text{ppm})\ (32.0\ \text{cm}^3/\text{min})}{(126.9\ \text{g/equivalent})\ (6.0\ \text{mA})} = 34\% \qquad (4)$$

2. Baseline Conditions for Testing - The baseline conditions for the eight-hour shakedown test, the Operating Modes Test, and the DVT are shown in Table 13. The preliminary checkout test additionally utilized water flow rates from 22.7 to 172.5 cm^3/min (72 to 547 lb/day).

Checkout Test

The first test performed on the AWIS was the Checkout Test.

Objective. The objective of the Checkout Test was to assemble and verify the operational integrity of the integrated AWIS (IX-SA plus AIMS) in preparation for succeeding tests, and to characterize its performance over the expected Shuttle Orbiter water flow rate range of 22.7 to 172.5 cm^3/min (72 to 547 lb/day). Also the indicating devices in the test stand were to be calibrated, and the individual parts of the IX-S were to be weighed prior to assembly for comparison to the weights to be obtained during the post-test inspection.

Procedure. The following procedure was established for the AWIS checkout testing:

1. Weigh the individual components of the IX-SA, including O-rings and membrane prior to assembly.

2. Assemble and weigh the IX-SA.

3. Pressure check the membrane in the I_2 Source. Fill the I_2 Source with water so that at no time during the pressure test is the membrane exposed to gas on either side. Pressurize the I_2 accumulator with N_2 in 69 kN/m^2 (10 psi) increments to 515 kN/m^2 (74.7 psia). Each

TABLE 13 BASELINE CONDITIONS FOR MODEL IX-S I_2 SOURCE TESTING

Water Supply	
Composition	See page 71
Flow Rate, cm^3/Min (Lb/Day)	32.2 (102)
pH at 298K (77F)	6 to 8
Temperature, K (F)[a]	295 ±4 (72 ±8)
I_2 Concentration, Ppm[b]	5 ±1
Temperature, K (F)	295 ±4 (72 ±8)
Pressure Above Ambient, kN/m^2 (Psig)	83 to 117 (12 to 17)
Water Recirculation Rate, cm^3/Min (Lb/Hr)[c]	337 (44.5)
Water Consumption Rate, kg/d (Lb/Day)[c]	18 (39.6)

(a) Water temperature study completed at 338K (149F).
(b) Second nine-day mission of DVT completed at 10 ppm ±2 I_2.
(c) Operating Modes Tests only.

incremental pressure level shall be maintained for a 300 second (5 minute) duration. Maintain the I_2 dispenser at ambient pressure, and measure the rate of water diffusion through the membrane due to the pressure differential of 414 kN/m^2 (60 psi). A membrane failure would be recognized by a sudden flow of water into the I_2 dispenser.

4. Mount the AIMS on the AWIS mounting bracket and calibrate the AIMS I_2 concentration readout according to the procedure in Appendix 3.

5. Fill the I_2 accumulator with I_2 crystals and water. Insert the electronics in the Model IX-SA housing and mount the unit on the AWIS mounting bracket. NOTE: Provisions for the electrical connections to the dual pen recorder (for I_2 level and cell current) and single pen recorder (for cell voltage) must be made.

6. Connect the AWIS to the test stand.

7. Verify the calibration curves of the indicating devices in the test stand (at one level for each parameter, only).

8. Adjust and verify with laboratory analytical techniques the I_2 concentration set point to 5 ppm.

9. Check out Model IX-SA power supply and circuitry for the specified power output to the I_2 Source (5V at 100 mA).

10. Adjust RC constant in the Model IX-SA feedback network to an optimum value (critically damped system, as a goal) using water flow rate of 22.7 cm^3/min (72 lb/day). Initially disconnect the 110VAC power to the Model IX-SA and AIMS. Turn power on and record I_2 valve current and AIMS feedback signal on strip chart recorder. Repeat preceeding process after adjusting integrator time constant potentiometer in I_2 valve control circuitry until only two to three oscillations are observed in trace of I_2 valve current from electrical activation on to steady-state valve operation.

11. Operate AWIS at flow rates of 22.7 to 172.5 cm^3/min (72 to 547 lb/day). Use strip chart recorders to simultaneously record I_2 valve current, valve voltage and AIMS I_2 concentration output signals while iodinating water to 5 ppm +1,-2 I_2 (as a goal). Adjust water flow rates to 22.7, 32.0, 93.8, 172.5, and back to 32.0 cm^3/min (72, 102, 298, 547, and back to 102 lb/day) allowing current and I_2 level to come to equilibrium (cell current and voltage essentially constant). Repeat for a step change in water flow from 22.7 to 172.5 cm^3/min (72 to 547 lb/day) and back.

12. Compare AIMS I_2 concentration readout to results obtained using the standard laboratory photometric method for I_2. Whenever there is a substantial difference noted between AIMS and laboratory standards, the AIMS will be recalibrated at the correct (laboratory standard, one single point) I_2 level and test data will be corrected as necessary.

13. Flush cell and test loop with deionized water and recheck AIMS calibration.

14. After any necessary adjustments have been made, operate the AWIS for eight hours using the baseline conditions listed in Table 13 for a final operational certification test.

Results. The response of the AWIS to electrical activation, as used to optimize the RC constant, and to changes in the water flow rate is shown in Figure 31. The 0-5V AIMS feedback signal and the Model IX-SA I_2 valve voltage and current oscillate slightly after electrical activation with the flow rate equalling 22 cm^3/min (70 lb/day). Electrical activation at larger flow rates caused less oscillation because the transportation lag time is less at those flow rates. Increases in the flow rate cause an initial increase in the AIMS feedback signal, followed by a decrease that is due to dilution of the I_2 dispensed by the Model IX-SA by the larger flow of water. The initial increase in the feedback signal is probably due to a transient in the system pressure that causes some I_2 from the accumulator to pass through the valve membrane into the I_2 dispenser.

The decrease in the AIMS feedback signal, following an increase in the water flow rate, causes the I_2 valve current to increase. The valve voltage increases as required to overcome the internal resistance and polarization in the I_2 valve. As shown in Figure 31, steady-state operation is achieved fastest for small changes in flow rate.

Figure 32 shows the required I_2 generation rates as a function of water flow rate for iodination levels of 3, 5 and 5.5 ppm I_2. The results of the Model IX-SA characterization are shown in Figures 32 to 36 and are compared to similar curves obtained with the Model LSI-100 I_2 Source. The average I_2 concentration was 5 ppm for the LSI-100 tests, while a nominal level of 5.5 ppm I_2 was used for the IX-SA tests. Both concentration levels, however, were within the specification range of 5 +1, -2 ppm I_2.

The corresponding values of I_2 generation rate versus water flow rate for the two I_2 concentrations were calculated and are shown in Figure 32. The measured I_2 valve current required for each I_2 Source (Model IX-SA and Model LSI-100) to generate I_2 at the rates given in Figure 32 is shown in Figure 33. A straight line corresponding to the current required at 100% current efficiency for those I_2 generation rates is also shown. The slope of the curve from the Model IX-SA more closely approaches that of the 100% current efficiency line than does the Model LSI-100 curve. In order to generate 0.58 g (1.3×10^{-3} lb/day) I_2/day, which is the amount necessary to iodinate to 5.0 ppm water flowing at 80 cm^3/min (253.6 lb/day), the Model LSI-100 I_2 Source required a valve current of 26 mA while the Model IX-SA required only 12 mA. The current efficiency at this flow rate is 20% for the Model LSI-100 and 43% for Model IX-SA.

Part of the apparent higher current efficiency of Model IX-S may be due to a higher rate of diffusion of I_2 through the membrane than in the LSI-100 I_2

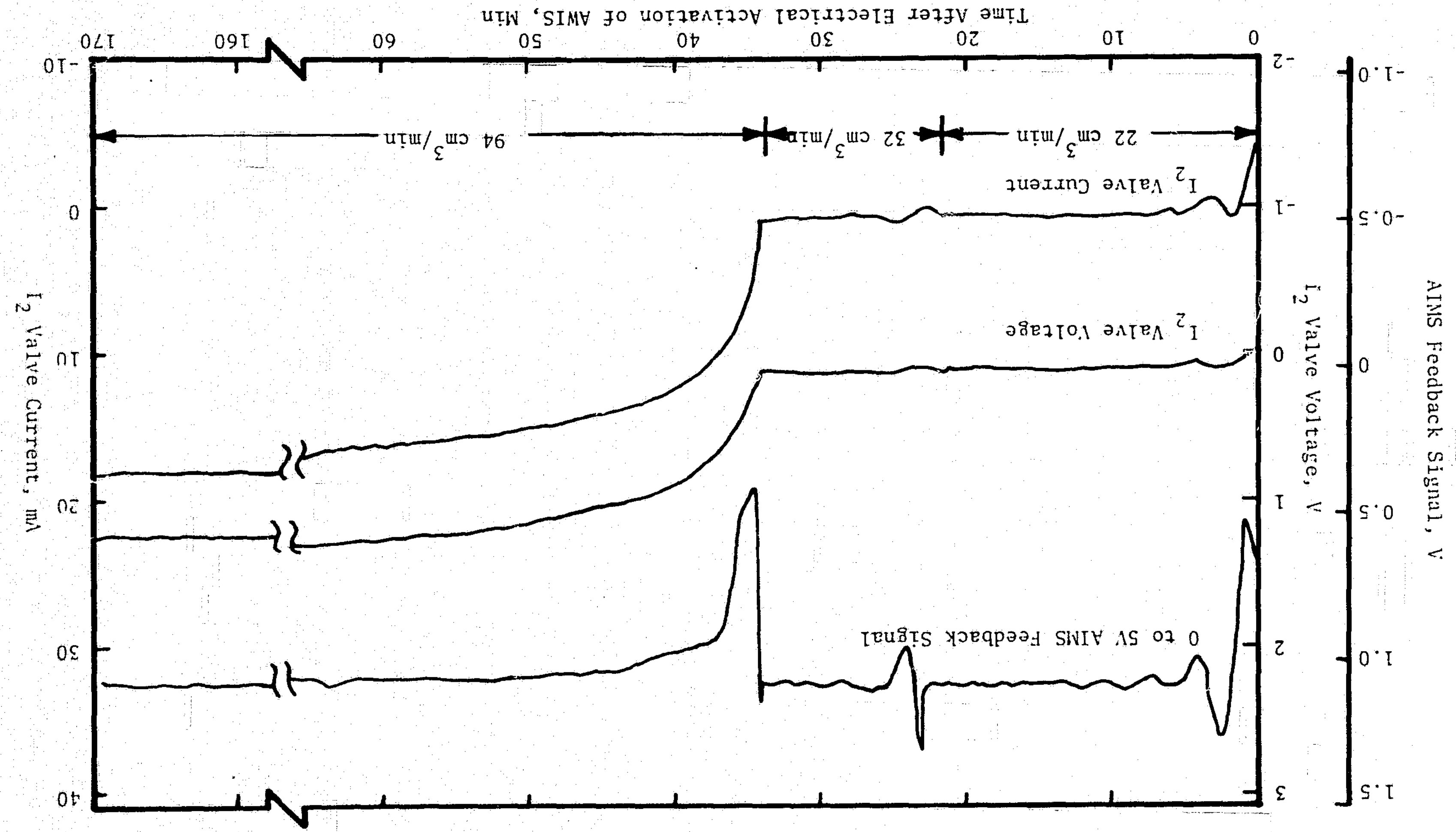

FIGURE 31 AWIS RESPONSE TO ELECTRICAL ACTIVATION AND WATER FLOW RATE CHANGES

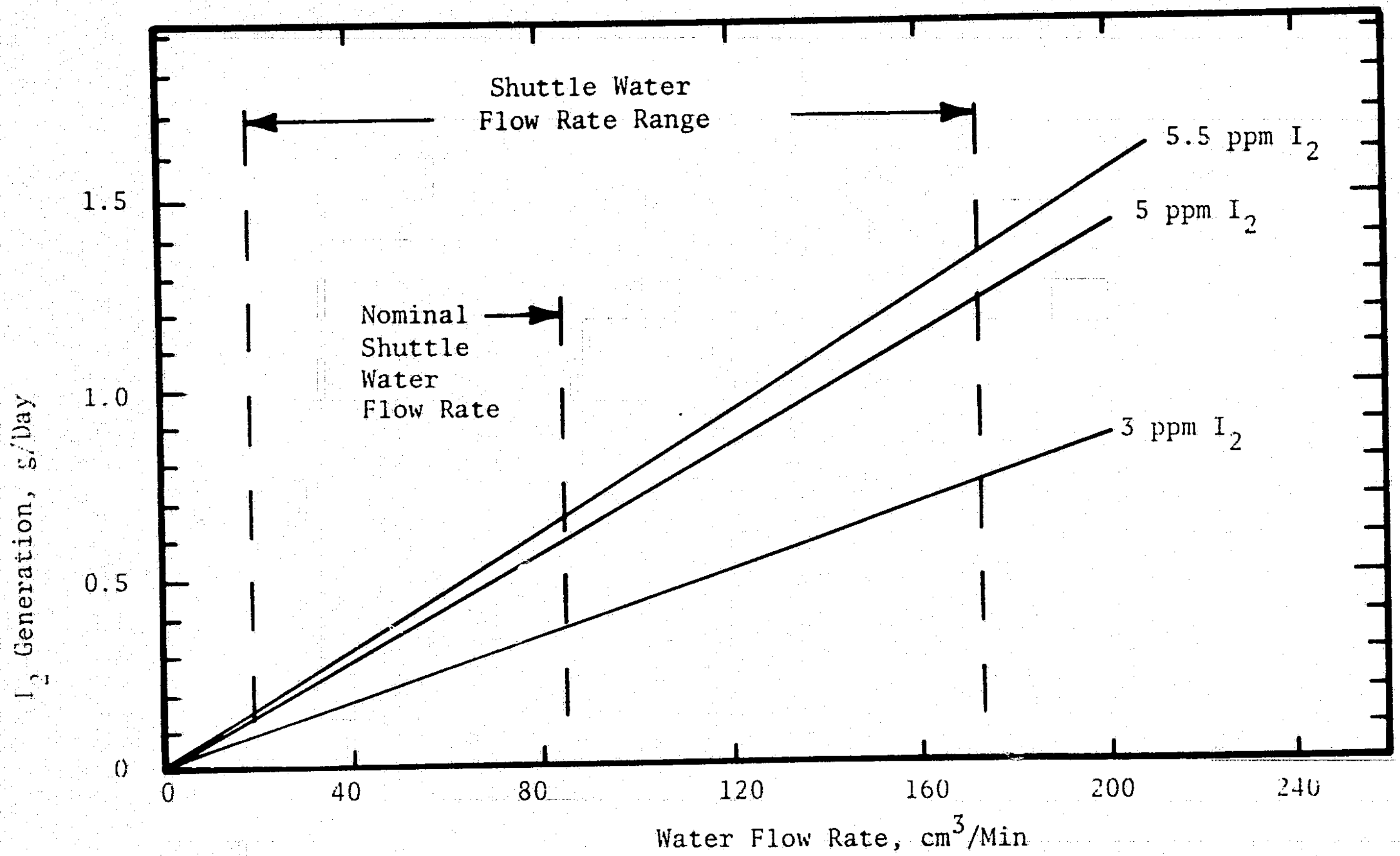

FIGURE 32 I_2 GENERATION IN TERMS OF I_2 CONCENTRATION AND WATER FLOW RATE

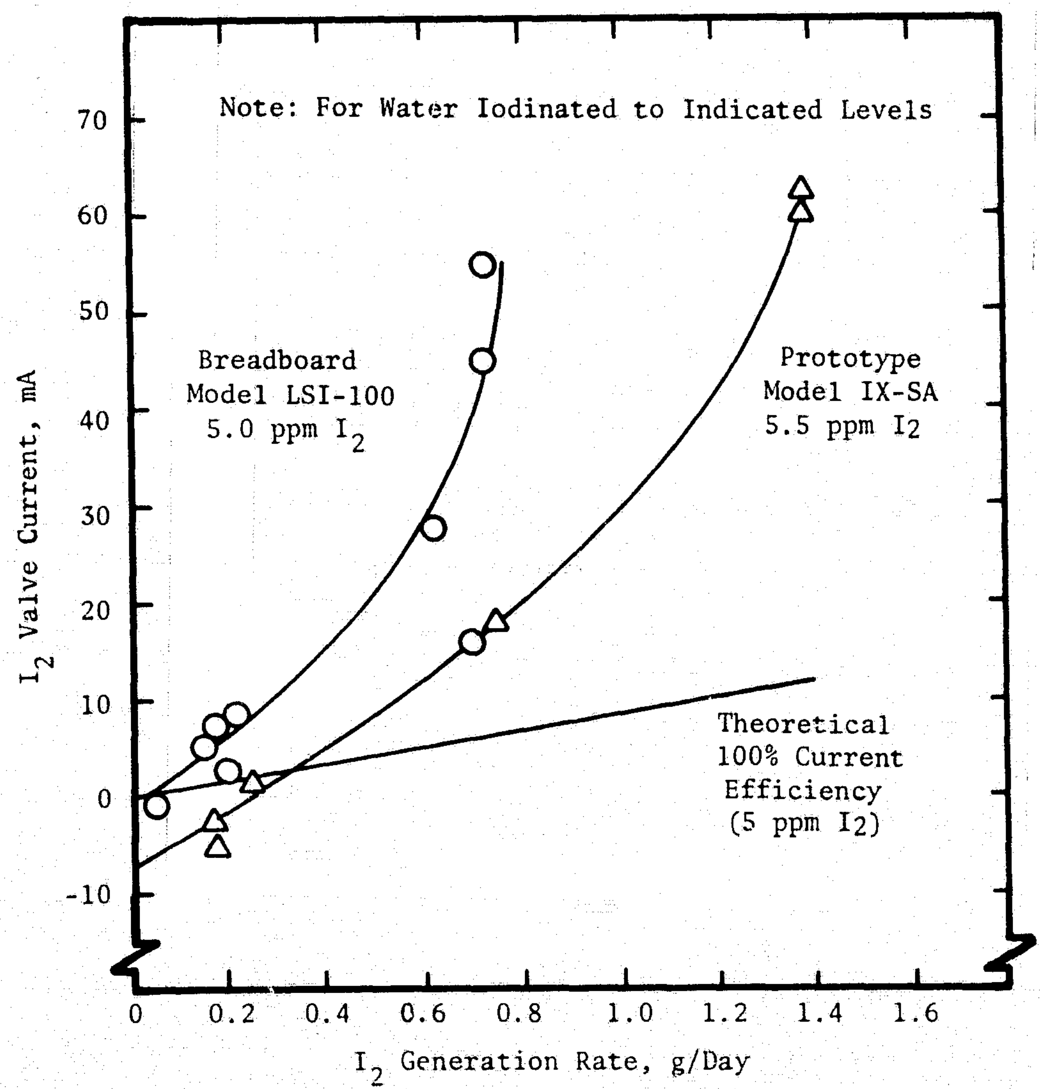

FIGURE 33 COMPARISON OF I_2 VALVE CURRENT VERSUS I_2 GENERATION RATE FOR MODELS LSI-100 AND IX-SA

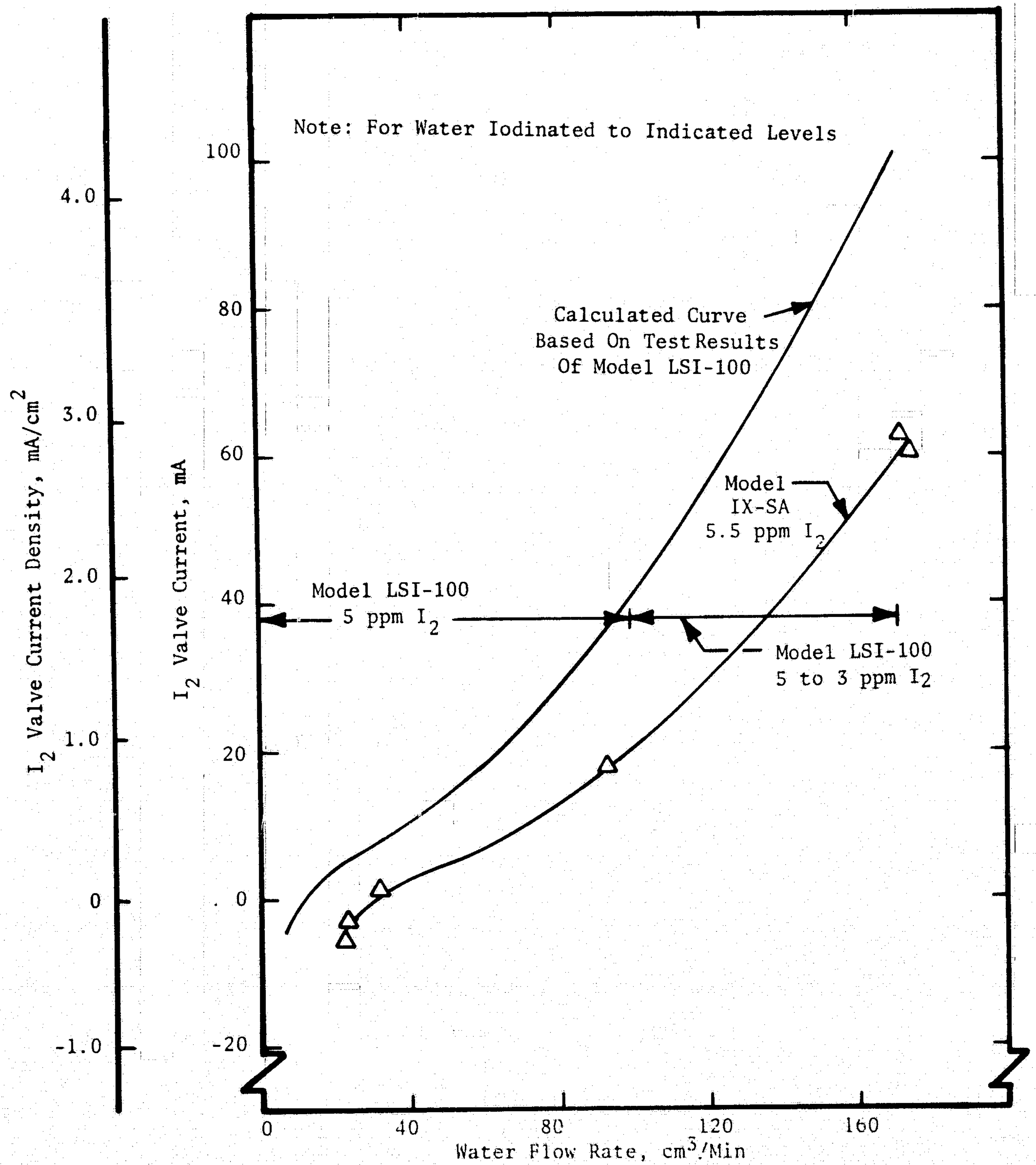

FIGURE 34 COMPARISON OF I_2 VALVE CURRENT VERSUS WATER FLOW RATE FOR MODELS LSI-100 AND IX-SA

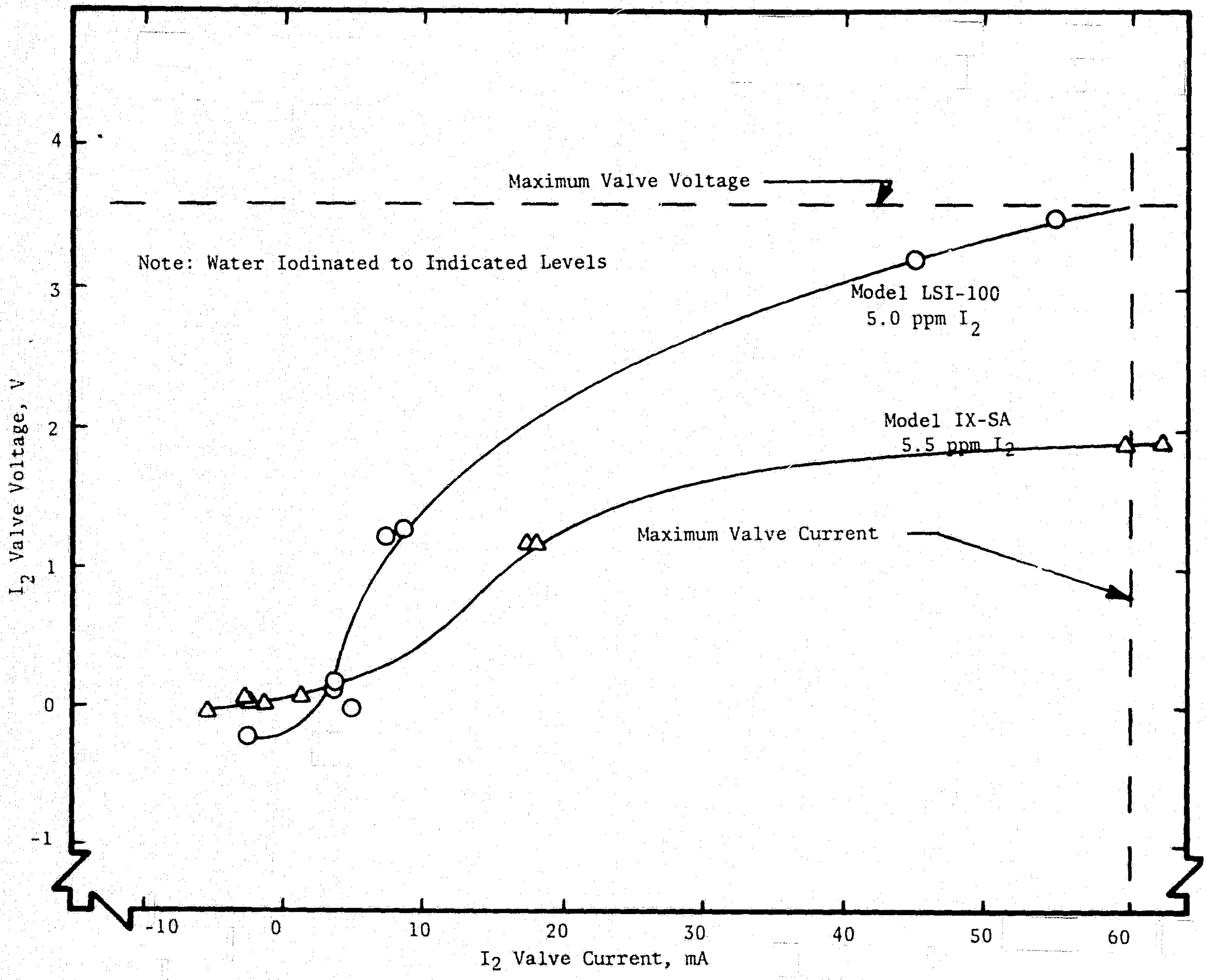

FIGURE 35 COMPARISON OF I_2 VALVE VOLTAGE VERSUS CURRENT FOR MODELS LSI-100 AND IX-SA

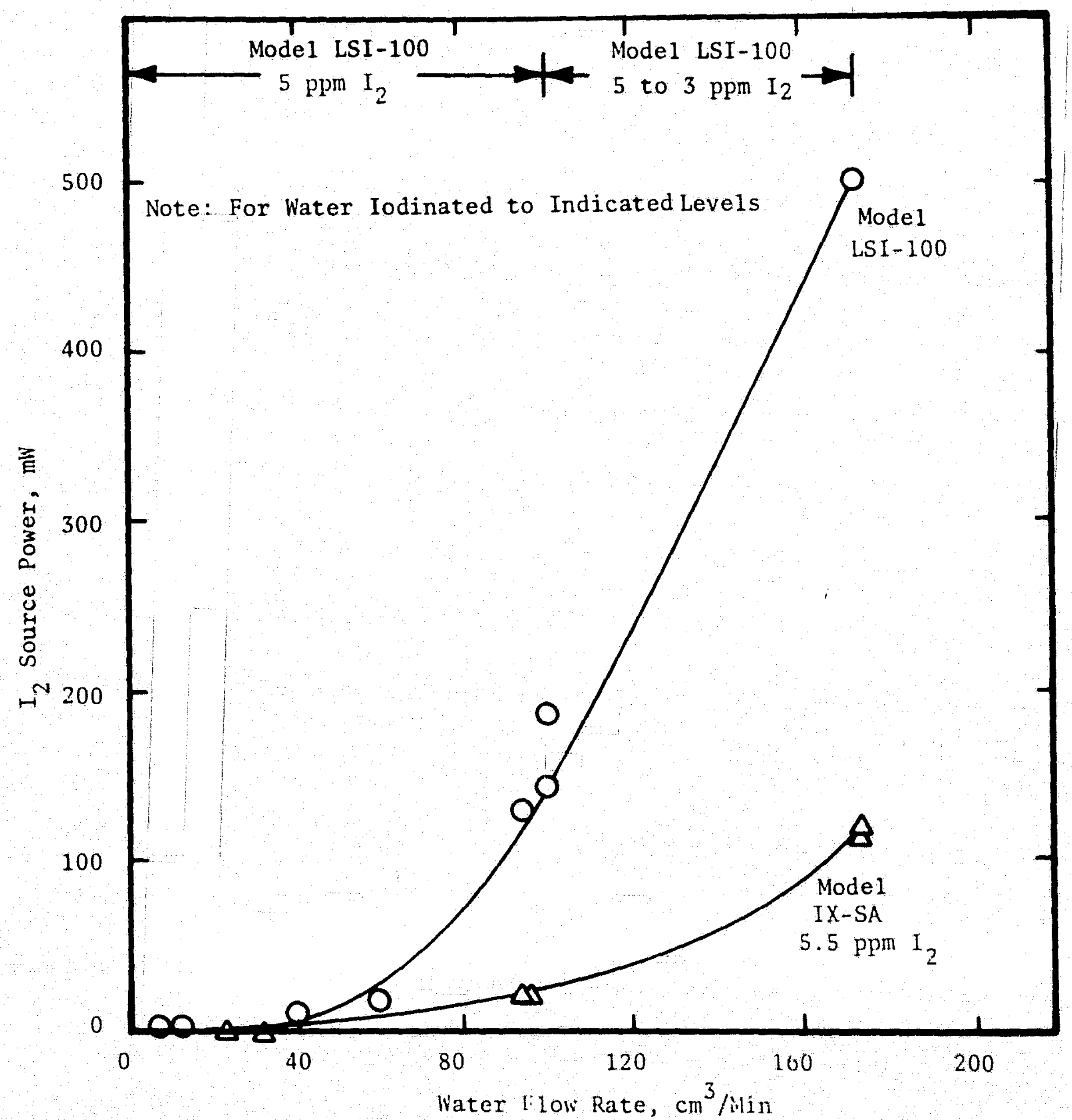

FIGURE 36 COMPARISON OF I_2 VALVE POWER CONSUMPTION VERSUS WATER FLOW RATE FOR MODELS LSI-100 AND IX-SA

Source. The IX-S required operation with negative currents (reversed polarities) at very low I_2 generation rates (i.e., low water flow rate) in order to prevent over-iodination of the water because of the I_2 diffusion rate (Figure 33). The diffusion rate was larger for the Model IX-SA than the Model LSI-100, as shown by the larger negative currents required by the Model IX-SA at the low flow rates. The reason for the different I_2 diffusion rates is probably the different flow configurations in each Model with the Model IX-SA having a design which enhances mixing, hence, which tends to increase I_2 diffusion.

The I_2 generation rate of the I_2 Source consists of the sum of the I_2 transported through the valve due to the valve current, and the I_2 that diffuses through the membrane in response to the concentration gradient across the membrane. The amount of I_2 that diffuses may vary with the applied valve current. Therefore, the I_2 generation rate cannot be corrected for I_2 diffusion because the relationship, if any, between the diffusion and valve current is not known.

The I_2 valve current versus water flow rate for each I_2 Source Model is shown in Figure 34. As discussed in the section "Valve Active Electrode Area and Shape," the Model LSI-100 was incapable of iodinating water at flow rates greater than 100 cm^3/min (298 lb/day) to 5 ppm. Above that flow rate, the I_2 concentration decreased from 5 ppm to 3 ppm (with 3 ppm at 172.5 cm^3/min (547 lb/day)). The Model IX-SA was capable of iodinating water to 5 ppm over the entire flow rate range of 22.7 to 172.5 cm^3/min (72 to 547 lb/day) as demonstrated by the data points plotted in Figure 34. The Model IX-SA, therefore, achieved its design goal.

The Model IX-SA I_2 Source operated at lower cell voltages than did the Model LSI-100 I_2 Source. The greater rigidity of the IX-SA, compared to that of the LSI-100 which was made of Lucite, likely produced better electrode/membrane contact which probably resulted in the lower valve voltages as shown in Figure 35. Lower voltages were observed at both current polarities.

Since the greater efficiency of Model IX-SA requires lower valve currents, and the valve voltage is also smaller in the Model IX-SA than in the Model LSI-100, the power consumption of the I_2 valve in the Model IX-SA was considerably less than that of the Model LSI-100, as shown in Figure 36. Even at 172 cm^3/min (547 lb/day) the power consumed in the IX-SA I_2 valve was only 120 mW.

Design Verification Test

The second test performed on the AWIS was the DVT.

Objective. The objective of the DVT was to simulate the automatic, "hands-off" operation of the AWIS during three, nine-day, Space Shuttle missions using simulated fuel cell water (deionized water with 20 ppm "Arizona Road Dust"). The water was to be characterized before and after iodination by chemical and physical analyses carried out both at Life Systems, Inc. (LSI) and Johnson Space Center (JSC). The first and third nine-day missions were to be completed using the AWIS design specification of 5 ppm ±1 I_2. The first half of the second nine-day mission was to be completed at an I_2 level of 10 ppm ±2 while the second half was to be completed at 20 ppm ±4, which is four times the design goal of the IX-S. The other experimental parameters were to be at the baseline values listed in Table 13.

Procedure. The following procedure was established for the AWIS DVT.

1. Accumulate 570 liters (150 gallons) of simulated fuel cell water in the polyethylene water supply tank. Analyze this water for dissolved O_2, I_2, I^-, specific conductance, copper (Cu), ammonia (NH_3), turbidity, and pH.

2. Flush cell and test loop with simulated fuel cell water and recheck AIMS calibration.

3. Operate the AWIS using the baseline conditions listed in Table 13 during each of the three nine-day periods. The simulated fuel cell water in the polyethylene tank will be pumped into the test stand and iodinated to 5 ppm ±1 for the first nine-day test, 10 ppm ±2 for the first half (4.5 days) and 20 ppm ±4 for the second half (4.5 days) of the second nine-day test, and 5 ppm ±1 for the third nine-day test.

4. Monitor the I_2 valve current and voltage with the strip chart recorder during each nine-day period.

5. Analyze the iodinated water daily (every 24 ±2 hours) for I_2, I^-, and pH during each nine-day period. On the first, fifth, and ninth days of each operational operiod, determine the dissolved O_2, Cu^{+2}, NH_3, turbidity, specific conductance, and pH.

6. Between each nine-day period, refill the polyethylene tank and repeat the analysis listed in Step 1 to characterize the noniodinated fuel cell water simulant. The AWIS will be shut down for a maximum of three working days between each nine-day test period to fill the tank and perform the analyses.

7. Collect and send water samples to NASA JSC for further analysis. These samples will be collected in 500 cm^3 (16 oz) polypropylene bottles. Samples will be collected from each batch of noniodinated fuel cell water simulant before and after each nine-day period, and from the iodinated water on the first, fifth, and ninth day of each operational period. Samples will be sent to JSC as a batch for each nine-day period.

Results. The results of the chemical and physical analyses are presented in in Figures 37 to 42. Table 14 lists the results of the analyses of the noniodinated water. The corresponding curves of Model IX-SA valve characteristics during the DVT are shown in Figures 43 and 44. The results of the sample analyses performed at NASA JSC are summarized and discussed in Appendix 4.

The first and third missions were completed with an I_2 concentration in the iodinated water of 5 ppm ±1 with the exceptions of the fourth and eighth days of the first mission (Figure 37). An unsoldered electrical connection in the AIMS caused the lamp in the light source of the sensor to fail. This occurred in the eighth day of the first mission, and the cause of the failure was not identified and repaired until the sixth day of the second mission. Following consultation with the Program Technical Monitor, it was decided that during the days that the AIMS was inoperative, the I_2 valve would be controlled by the electronics package of the Model LSI-100, operating in the constant current mode. The iodinated water was frequently sampled and analyzed to adjust the current at the value so the desired I_2 concentration was maintained. The high I_2 concentration on the eighth day of the first mission and the variation in I_2 concentration shown in Figure 37 for the first five days of the second mission, resulted from this manual current adjustment. The low value on the fourth day of the first mission may be due to particulate interference or air bubbles in the light path of the AIMS. Air bubbles had previously been observed to cause such erroneous results.

On the fifth day of the second mission the AIMS was repaired and feedback control was reinstated. Operation at 20 ppm I_2 was then attempted, but was found to be impossible with long-term operation of the IX-S regardless of the water flow rate. During testing of the Model LSI-100 Source, the formation of crystalline I_2 on the anode was observed when the Source was operated at 20 ppm I_2 at any flow rate the Model LSI-100 Source was capable of iodinating to that I_2 level. This is thought to have also occurred in the Model IX-SA. It is thought that the I_2 crystals form on the anode because the rate of electrochemical injection of I_2 into the dispenser apparently exceeds the rate of dissolution of I_2 into the water for a concentration setting of 20 ppm I_2. The I_2 crystals on the anode decrease the effective working area of the electrode, thereby decreasing the capacity of the valve to transport I_2 into the water. Iodination in less than 10 hours to 20 ppm appears to be possible at flow rates of 32.2 cm^3/min (102 lb/day) until the I_2 crystals accumulate on the anode. At much higher flow rates, the maximum I_2 valve current is insufficient to iodinate to 20 ppm I_2.

Because of this problem and subsequent failure to obtain a persistent I_2 concentration at 20 ppm, the second mission was altered for operation at a 10 ppm ±2 I_2 concentration. Long-term operation at 10 ppm ±2 I_2 was successfully demonstrated. A concentration of 20 ppm I_2 was a NASA chosen specification that may be unrealistic for any specific application since an I_2 concentration in potable water higher than 7 ppm has a very adverse affect upon taste. However, should a 20 ppm I_2 concentration become justifiable, an electrochemical valve could be designed to maintain the 20 ppm concentration without the previously noted problem.

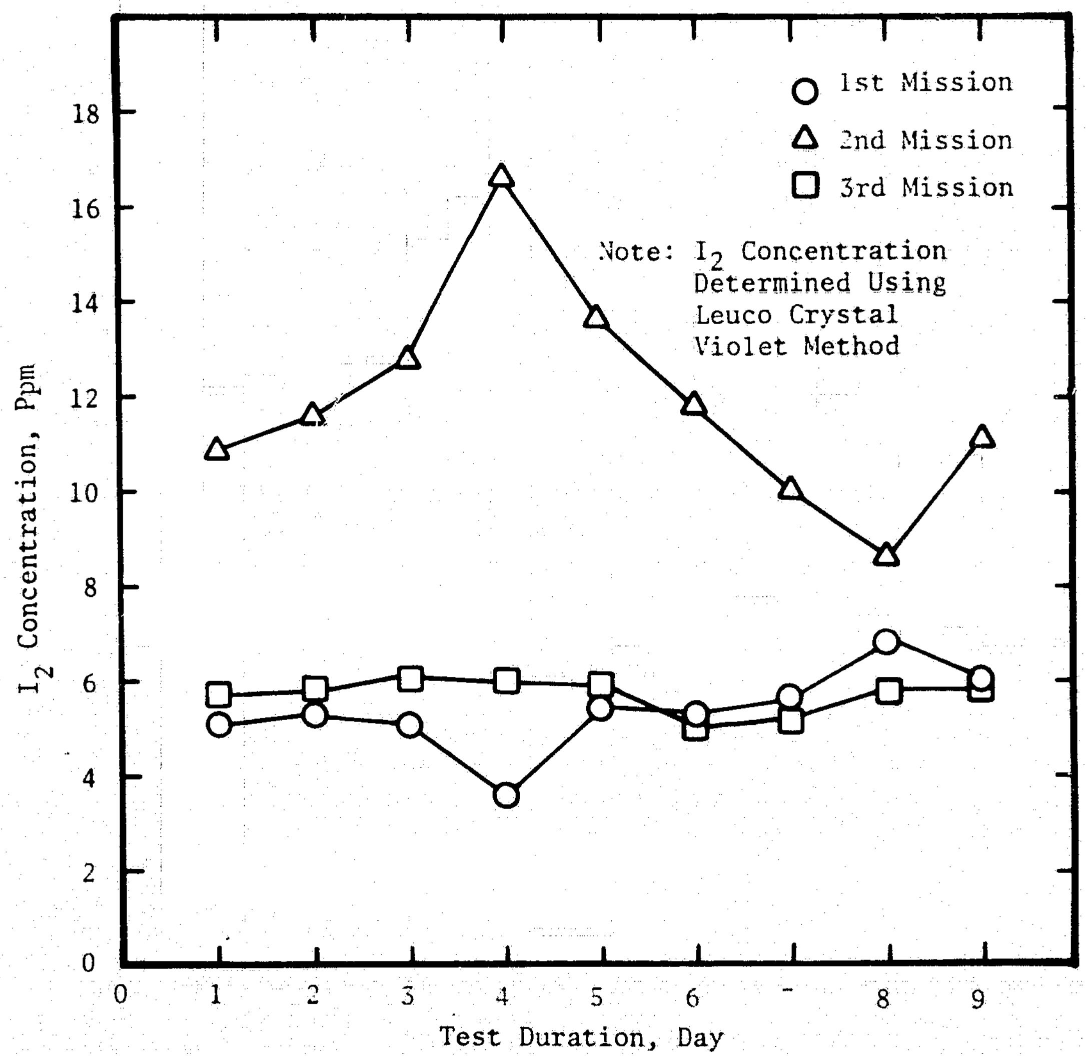

FIGURE 37 I_2 CONCENTRATION VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

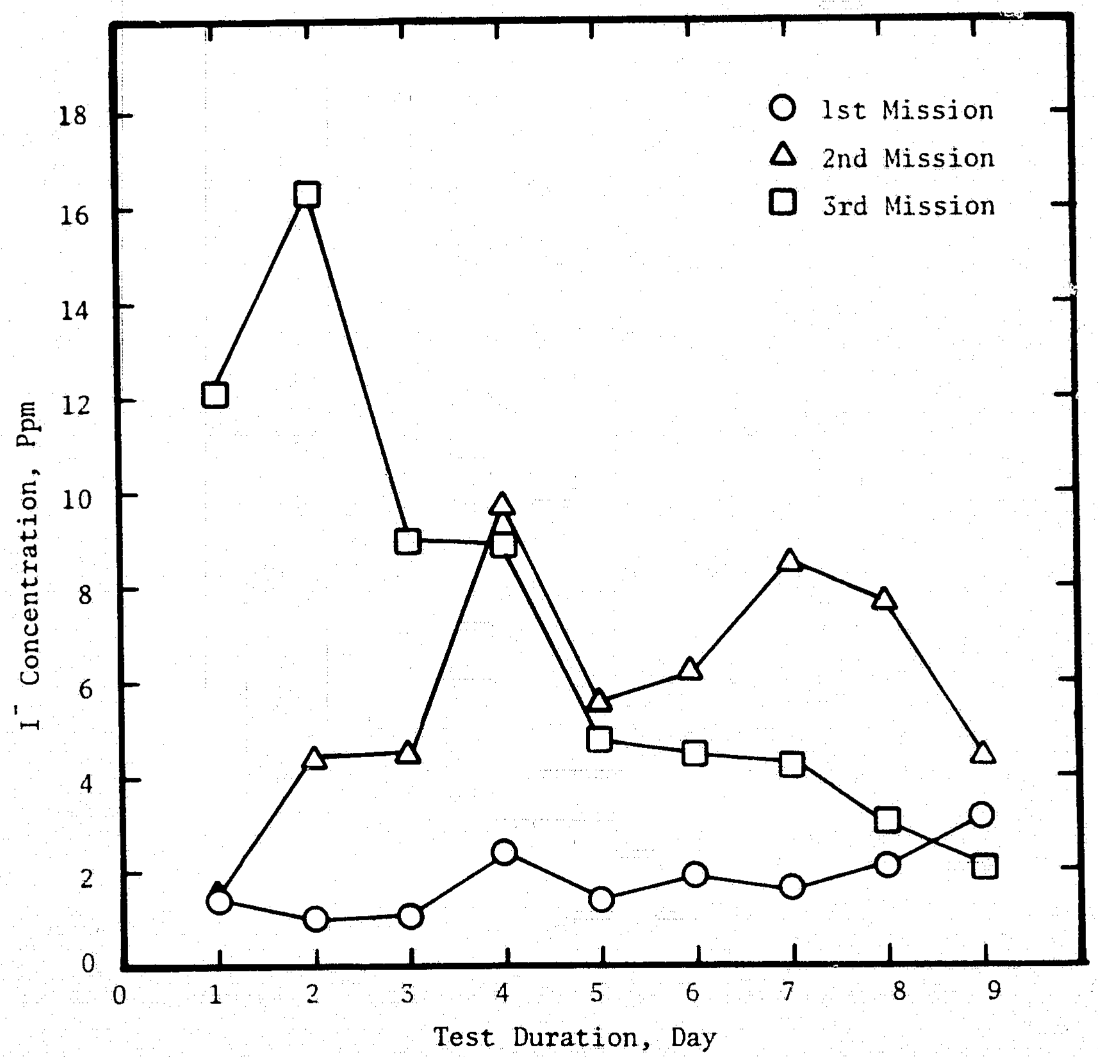

FIGURE 38 I- CONCENTRATION VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

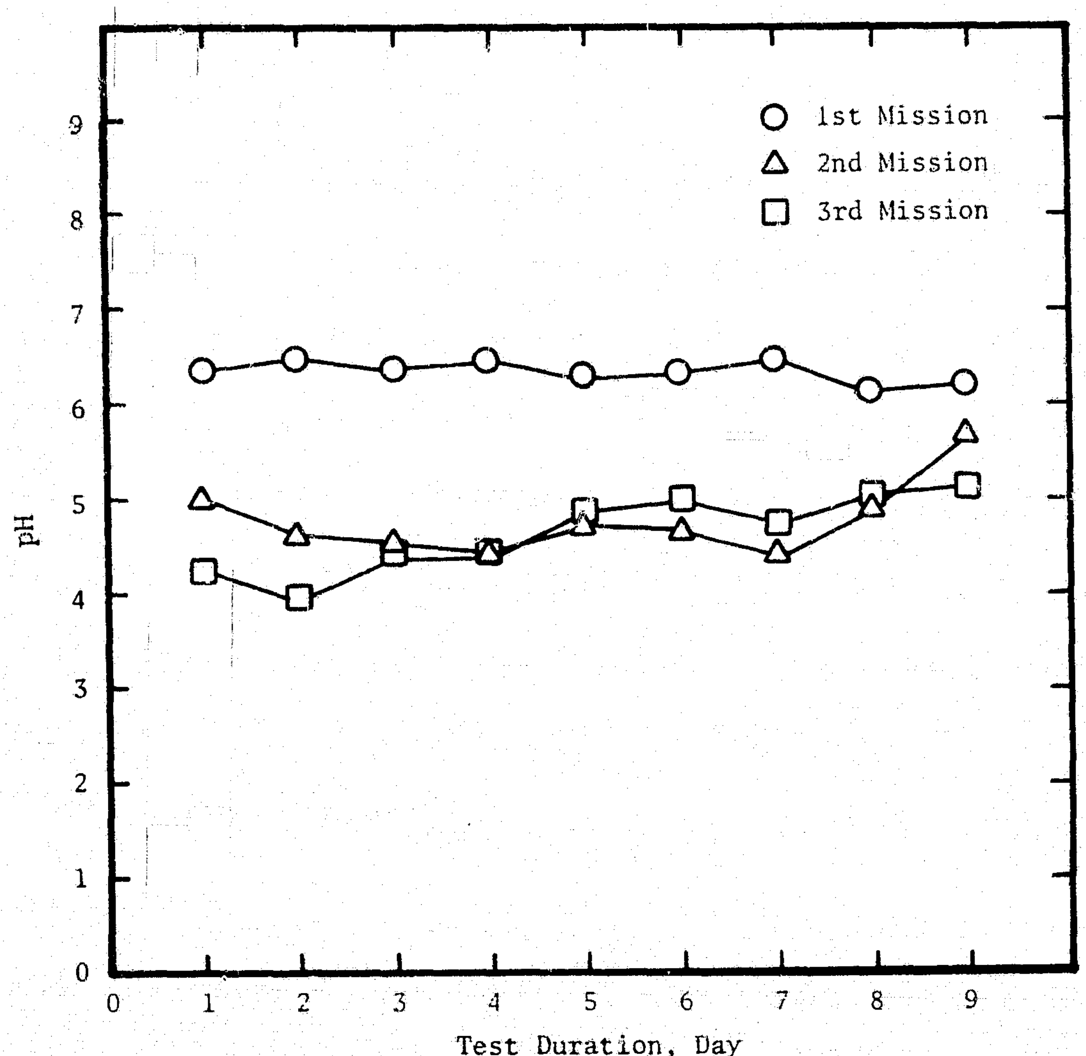

FIGURE 39 pH VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

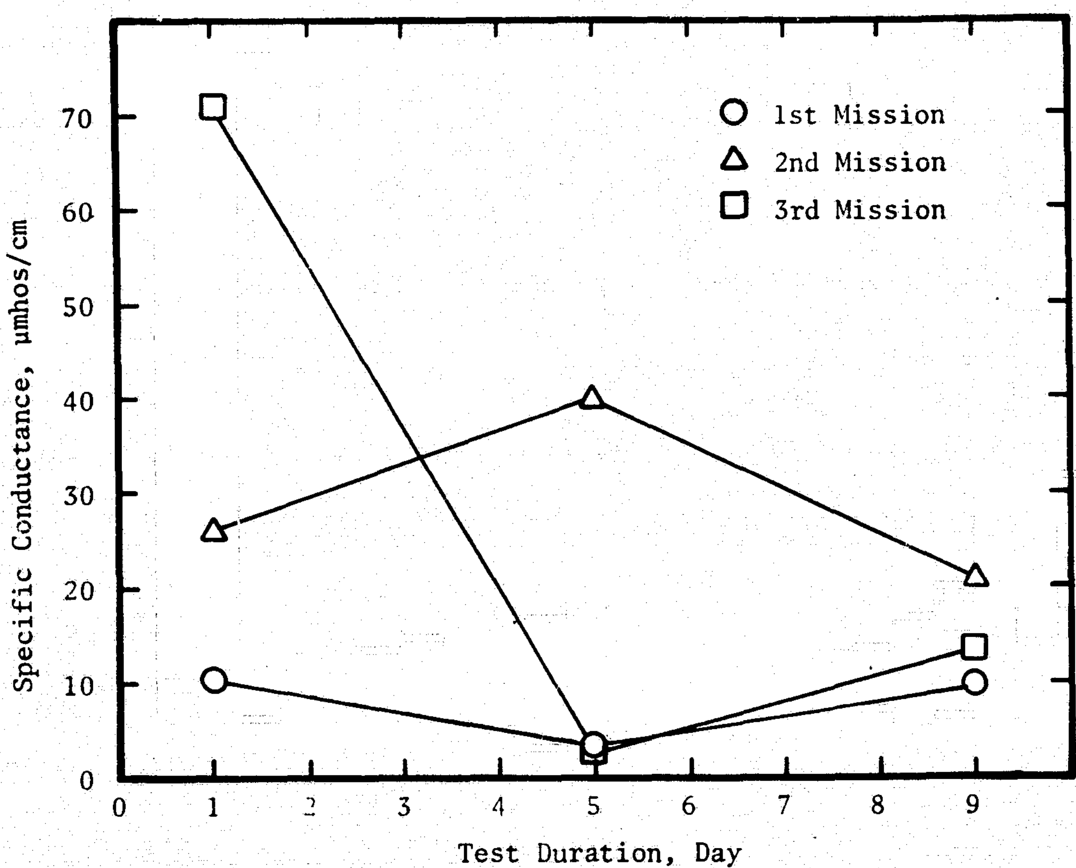

FIGURE 40 SPECIFIC CONDUCTANCE VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

C-2

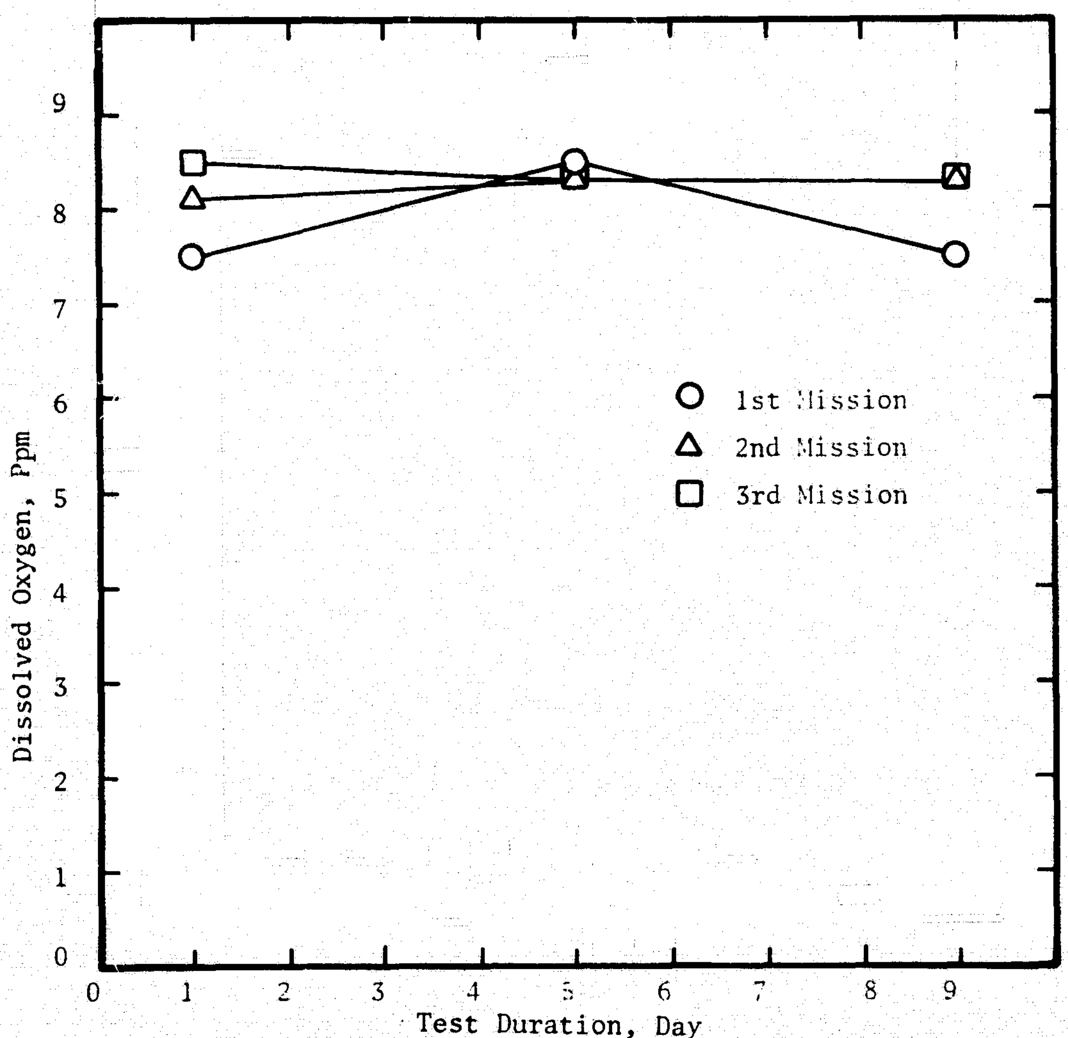

FIGURE 41 DISSOLVED OXYGEN VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

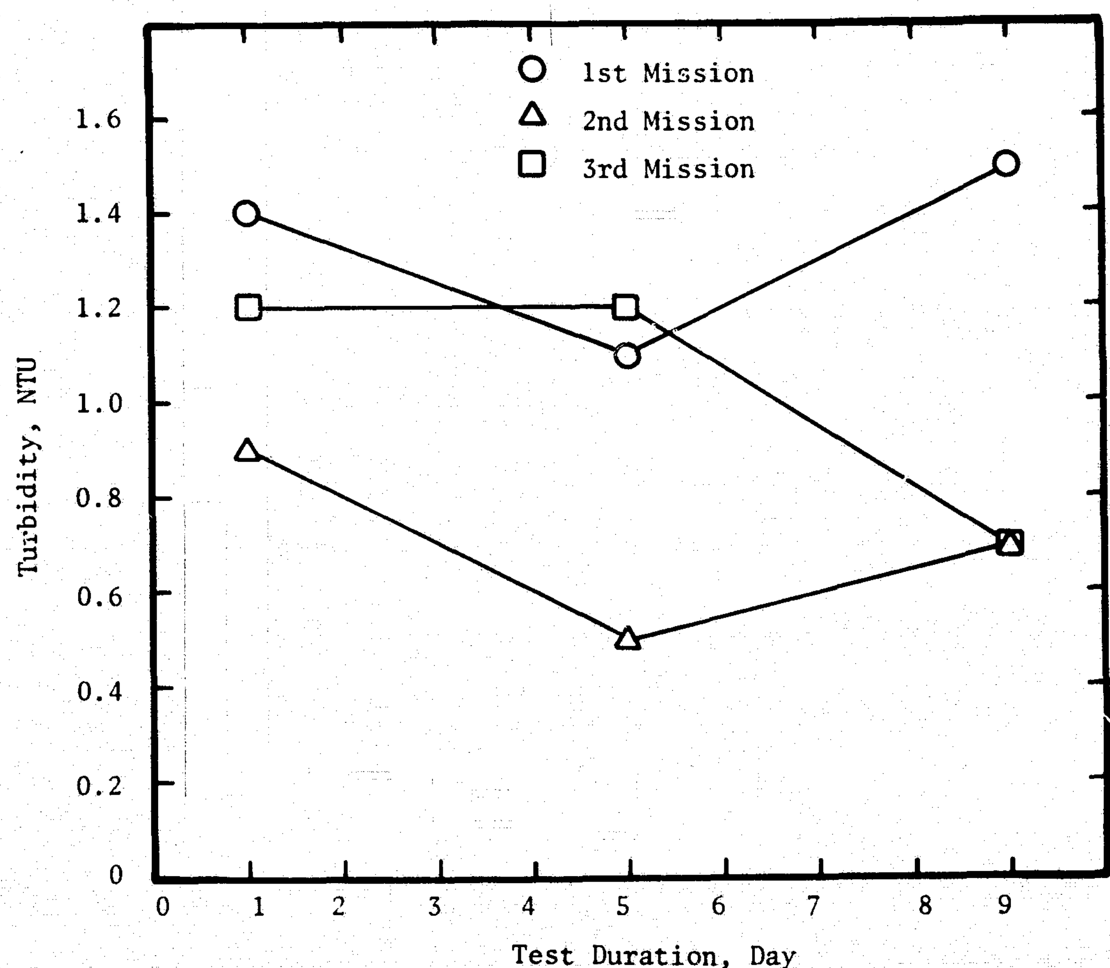

FIGURE 42 TURBIDITY VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

TABLE 14 ANALYSIS OF NONIODINATED FEED WATER FROM DVT

Analyte	First Mission		Second Mission		Third Mission	
	Initial	Final	Initial	Final	Initial	Final
I_2, Ppm	0.0	0.0	0.0	0.0	0.0	0.0
I^-, Ppm	0.0	0.0	0.0	0.0	0.0	0.0
pH	7.11	7.03	7.63	7.00	6.77	6.03
Cu^{+2}, Ppm	0.0	0.0	0.0	0.0	0.0	0.0
NH_3, Ppm	0.0	0.0	0.0	0.0	0.0	0.0
Dissolved O_2, Ppm	7.6	8.1	5.7	8.5	8.4	8.3
Turbidity, NTU	1.30	1.00	1.20	0.80	1.30	0.70
Conductance, μmho/cm	6.00	7.16	9.53	17.80	4.83	5.07

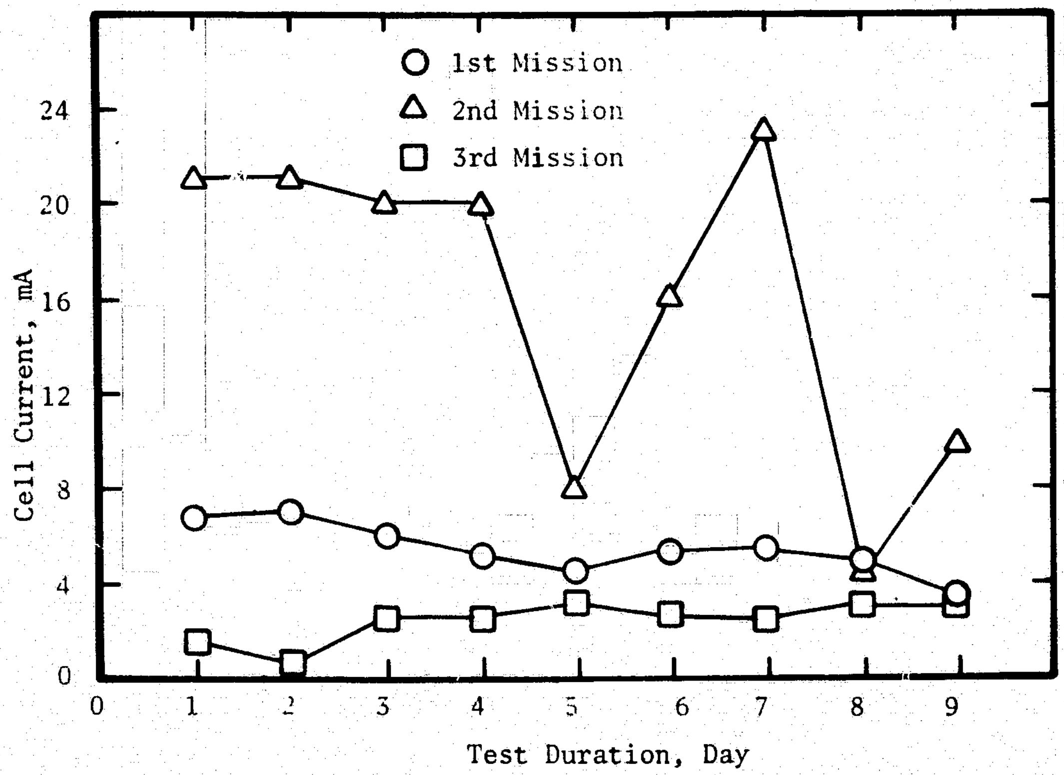

FIGURE 43 CELL CURRENT VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

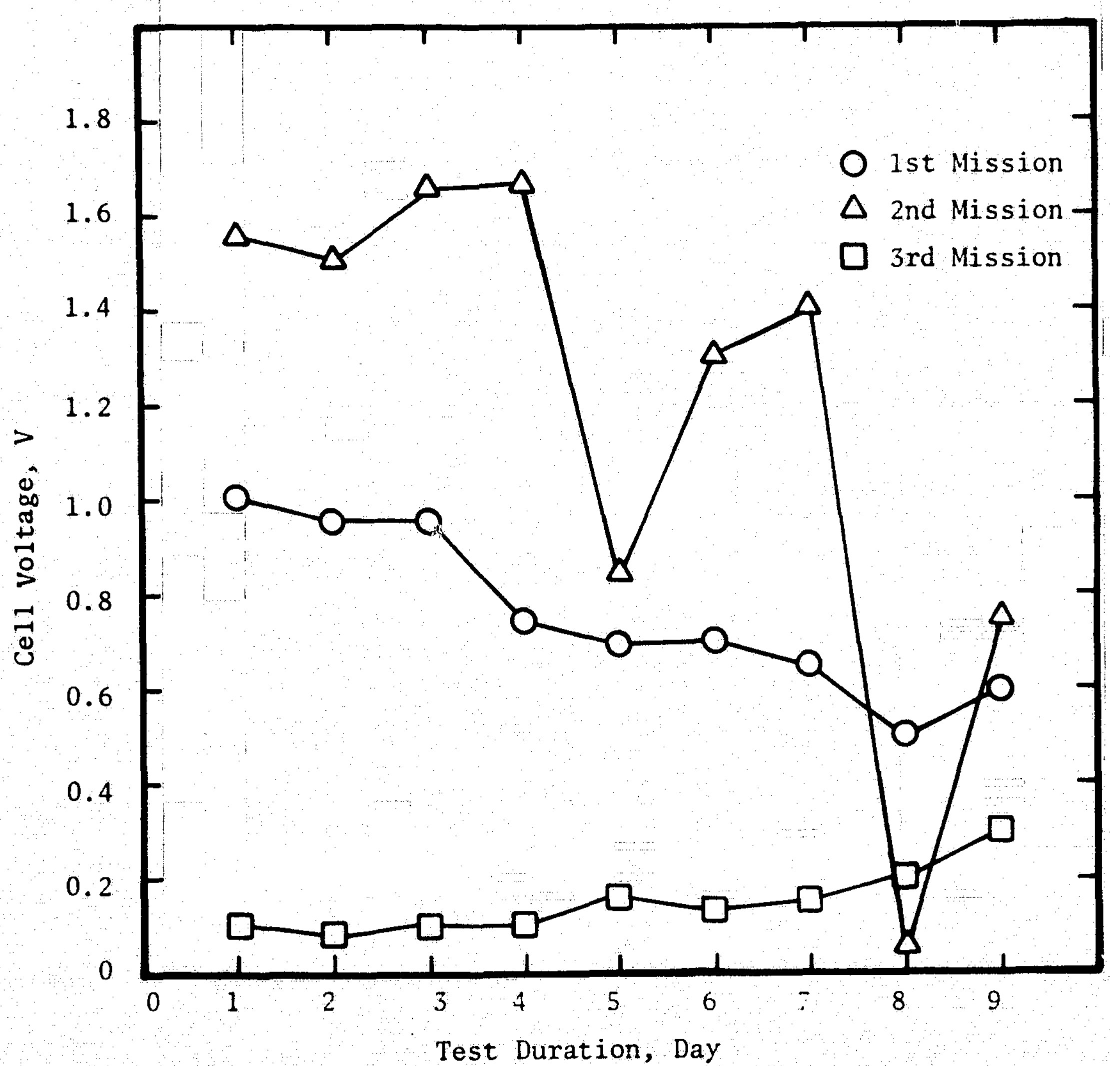

FIGURE 44 CELL VOLTAGE VERSUS TIME DURING DESIGN VERIFICATION TEST OF MODEL IX-SA

The concentration of I^- in the iodinated water is normally approximately 2 ppm when the I_2 level is 5 ppm (Figure 38). During the second mission the I^- level increased to values of 1.5 to 9.7 ppm because of the increased I_2 concentration. At the beginning of the third mission, the I^- concentration reached 16.4 ppm and then steadily decreased until it reached the normal value of 2.1 ppm by the end of the mission. The initially large I^- concentration following a decrease in I_2 concentration from 10 ppm to 5 ppm is a phenomenon that was observed during testing of the Model LSI-100 prior to development of the Model IX-SA. The reason for it is assumed to be changing I_2 and I^- concentration gradients at the cathode and membrane surface. It is desirable for the I^- concentration in the iodinated water to be as low as possible because injection of I^-, which has little bacteriocidal activity, depletes the I_2 supply in the I_2 accumulator and decreases the number of Shuttle Orbiter missions during which the I_2 Source can be operated without refilling the accumulator.

The pH of the iodinated water remained nearly a constant value of 6.4 during the first mission (Figure 39). The pH decreased to about 4.5 during the second mission. Operation at higher I_2 generation rates lowers the current efficiency of the I_2 valve (see Figure 33). The reaction competing with the oxidation of I^- at the anode is the oxidation of water:

$$2H_2O = O_2 + 4H^+ + 4e^- \tag{5}$$

This competing reaction decreases the pH of the water when the iodination level increases. However, during the second mission, the pH increased to 5.8 because the larger valve current used during the mission apparently produced a large concentration of I^- at the cathode. This larger concentration of I^- slowly reached the anode, so that the concentration of I^- at the anode increased during the mission. The fraction of the valve current consumed in Reaction 5 decreased as the I^- concentration at the anode increased and the pH of the iodinated water, therefore, increased.

The I^- at the cathode apparently continued to diffuse to the I_2 dispenser during the beginning of the third mission (Figure 38). The negative charge of the I^- ions was neutralized by H^+, resulting in the temporarily low pH at the beginning of the third mission (Figure 39). The pH increased during the third mission from a value of 4.3 to 5.7 by the end of the mission. The specific conductance of the iodinated water is shown in Figure 40 and reflects the variations in I^- and H^+ concentrations in the water. The dissolved O_2 concentration in the iodinated water remained at approximately 8.3 ppm during the entire DVT (Figure 41). The turbidity of the water, however, varied in an unpredictable way (Figure 42). The variations are probably the result of experimental uncertainties in the measurements.

The I_2 valve voltage (Figure 44) followed the changes in valve current (Figure 43) during the DVT and did not exceed 1.66V even during the second mission. The valve current and voltage were lower during the third mission than during the first, apparently because the membrane had become well saturated with I^- and I_2.

Operating Modes Test

The third test performed on the AWIS was the Operating Modes Test.

Objective. The objective of the Operating Modes Test was to demonstrate the ability of the AWIS to maintain the I_2 concentration within the potable water stores of a long-term mission advanced spacecraft where water reclaimed from urine and other sources is recirculated. This test was to be performed both with and without noniodinated feed water added to the recycle loop to simulate operating of a portion of the spacecraft's Water Management System.

Procedure. The following procedure was established for the AWIS Operating Modes Test:

1. Recycle iodinated water, collected previously in the water storage tank, through the AWIS at a flow rate of 337 cm^3/min (1040 lb/day). (This recycle loop flow rate was chosen based on SSP specifications.)[14] At the same time, add noniodinated water to the recycle loop at a rate of 32 cm^3/min (102 lb/day). Operate in this mode with other test conditions being those listed in Table 13. Record the I_2 valve current and AIMS I_2 concentration level signal with a strip chart recorder. Determine the I_2 and I^- concentrations and pH of the water in the water storage tank.

2. Recycle the iodinated water through the AWIS at a flow rate of 337 cm^3/min (1040 lb/day). During this test, no noniodinated water will be added to the loop. The test conditions will be those listed in Table 13, and the I_2 valve current and AIMS signal will be recorded on a strip chart recorder. Determine the concentrations of I_2 and I^- and pH of the water in the reservoir.

Results. The AWIS operated with noniodinated feed water mixing at a rate of 32 cm^3/min (102 lb/day) with recycling iodinated water flowing at 337 cm^3/min (44.8 lb/hr) in the recycle loop. The I_2 level of the water in the recycle loop and the concentration set point were 4.0 ppm. This concentration was considered acceptable because it was within the specified limits of 5.0 ±1 ppm, and it was a convenient value because the corresponding concentration set point value was known. The I^- concentration was 1.6 ppm, and the pH of the recycling water was 3.98. The valve current was 5.0 mA and the valve voltage was 1.7V. These current and voltage values are normal for Model IX-SA operation in the 5.0 ±1 ppm I_2 concentration range. The recordings of the AIMS feedback signal and valve voltage and current versus time are straight lines, indicating that long-term operation with recycled iodinated water and the simultaneous addition of noniodinated water to the system is feasible.

The AWIS was also operated in the recycle mode without the addition of noniodinated feed water. The initial I_2 concentration in the water was 6.9 ppm and the I^- level was 5.8 ppm. The pH equaled 4.54. The diffusion of I_2 through the membrane slowly increased the I_2 concentration in the water to 8.9 ppm.

The I^- concentration also increased to 8.4 ppm and the pH was 4.48. As the I_2 concentration increased, the I_2 valve current decreased from an initial value of 3 mA to a value of -6 mA. The AWIS automatically attempted to reduce the I_2 concentration of the water, but became current limited in the negative polarity.

A failure of the light source lamp of the AIMS interrupted the first portion of the Operating Modes Test, and lamp replacement activities were initiated. Available replacement lamps were not rated for continuous service and two additional lamp failures subsequently occurred, requiring additional lamp replacement and AIMS recalibration. Interruptions to the Operating Modes Test occurred because of lamp failures, but necessary test data was obtained and the interruptions did not influence the accuracy of the data.

Iodination of Heated Water

The fourth test performed with the AWIS was iodination of water heated to Shuttle Orbiter fuel cell operating temperatures.

Objective. The objective of this test was to determine the capability of the AWIS to iodinate water heated to 338K ±2.8 (150F ±5). Successful iodination of water at this temperature would eliminate the need for water chillers upstream of the AWIS should it be used in the Shuttle Orbiter potable water system.

Procedure. The following procedure was established for the AWIS heated water test.

1. Adjust the I_2 level setting of the AIMS to a value of 5 ppm ±1 I_2.
2. Use the baseline test conditions listed in Table 13 and operate the AWIS for eight hours, iodinating simulated fuel cell water heated to 338K ±2.8 (150F ±5). The noniodinated simulated fuel cell water is to be heated in a heat exchanger prior to entering the AWIS.

Results. The AWIS operated normally during the eight-hour test and the recordings of the AIMS feedback signal, I_2 valve current and voltage versus time were straight lines. The average I_2 concentration in the iodinated water was 5.7 ppm. The I^- concentration was only 0.3 ppm and the pH of the water varied from 6.53 to 6.62. No detrimental effects of the heated water were observed on either the performance or materials of the AWIS.

Post-Test Component Analysis

The final test performed on the AWIS was the Post-Test Component Analysis.

Objective. The objective of the Post-Test Component Analysis was to evaluate the compatibility of the Source components with the aqueous I_2 and hypoiodous acid (HI) in the Source during its operation.

Procedure. The following procedure was established for the AWIS Post-Test Component Analysis.

1. Collect the solution from the I_2 accumulator. Determine the pH, I_2, and I^- concentrations in the solution.

2. Dissassemble the I_2 Source. Rinse the interior surfaces with deionized water and dry. Inspect all surfaces and the Teflon coating in the I_2 accumulator. Record any signs of corrosion or discoloration. Inspect spot welds and thermal seals on the electrodes for mechanical integrity.

3. Weigh each component of the I_2 Source and compare this weight to that obtained initially.

4. Inspect all Viton A O-rings for possible deterioration and leakage paths.

Prior to the start of the DVT, a slight leakage of iodinated water was observed near the housing and baseplate of the I_2 Source. At that time, approximately 100 hours of total operation had been accumulated and the Model IX-SA had been filled with iodine for 30 days. The Model IX-SA was disassembled and the leakage was traced to corrosion occurring on the stainless steel (316) baseplate opposite the two O-rings that seal the water inlet and water outlet. The corrosion pattern in each location was circular, occurred directly underneath the sealing area of the Viton A O-rings, and spread slightly toward the wetted side of the seal. During disassembly of the I_2 Source from the AWIS it was also noted that corrosion had occurred on the 316 stainless steel/O-ring seal fitting (CPV fittings) water interfaces. Corrosion was immediately adjacent to the sealing area of the Viton A O-ring. An investigation of the corrosion revealed the following:

1. The 316 stainless steel had been previously found acceptable for iodine service.[15]

2. Viton A O-rings had been previously found acceptable for iodine service.[2]

3. A combination of Viton A O-rings with 316 stainless steel exposed to long-term operation with the Model LSI-100 cell showed no corrosion.[2]

4. Welded stainless steel in the AWIS exposed to iodine solutions without the presence of O-ring seals showed no corrosion.

5. Corrosion was observed only where Viton A O-rings contacted stainless steel (316) surfaces that had been heated during a welding operation.

6. Welded Hastelloy C with or without Viton A O-ring seals as used in the I_2 accumulator part of the IX-SA showed no corrosion.

On the basis of these findings, it was concluded that iodine is retained by Viton A in sufficiently high concentrations to cause corrosion of welded 316 stainless steel. A subsequent literature search and metallurgical consultation revealed that the corrosion resistance of welded 316 stainless steel decreases due to carbide precipitation. Heat treatment following welding will normally restore the corrosion resistance.

Three possible options were considered; (1) fill-in the corroded surfaces by welding, machine to required finish, and heat treat, (2) remachine baseplates, for both Models IX-SA and IX-SB, from Hastelloy C-276 or 316L stainless steel (the latter has a very low carbon content and carbide precipitation is virtually eliminated), and (3) after refinishing the sealing surfaces, coat both existing baseplates with Teflon. The second option was selected and new baseplates for the IX-SA and IX-SB were constructed from Hastelloy C-276, with welded Hastelloy water inlet and outlet tubing. The O-ring fittings were replaced by Swagelok fittings which do not use O-rings nor require welding (CPV fittings are not commercially available in Hastelloy C). Teflon coating the baseplate was rejected because an impervious uniform coating would be difficult to achieve. Heat treatment was rejected because of the technique development necessary to insure no baseplate warpage.

In order to continue the testing, the stainless steel baseplate of the IX-SB was inserted in the IX-SA. To minimize high I_2 or HI concentration buildups near the baseplate during AWIS nonoperative or standby periods, water was continuously circulated through the I_2 dispenser during such periods. No additional corrosion was noted while tests were completed.

During the Post-Test Component Analysis, the catholyte was removed from the accumulator and found to contain 480 ppm I_2 and 30 ppm I^-. The pH of the catholyte was 3.07 as compared to a catholyte pH in the Model LSI-100 Source of 1 to 2, and an I^- concentration of about 3×10^4 ppm after long-term (30 days) operation. The lower concentration and the higher pH in the catholyte of the Model IX-S reflect that it operated more efficiently than the Model LSI-100.

The accumulator contained 70.8 g (0.16 lb) of I_2 crystals. During the approximately 30 days of operation since the start of the DVT, the AWIS had consumed 29 g (0.064 lb) of the original 99.8 g (0.22 lb) of I_2 in the accumulator. The small accumulator port made filling the accumulator difficult and prevented insertion of the entire 182 g (0.401 lb) of I_2 for which the accumulator was sized. Therefore, future I_2 accumulator designs should include a larger diameter port plug.

The rate of I_2 consumption of the IX-SA was approximately 0.97 g/day (0.0021 lb/day), which is much less than anticipated in the design of the Model IX-S. At this consumption rate, the Model IX-SA would be able to iodinate the water from approximately 27 Space Shuttle missions to an I_2 level of 5 ppm. The decrease in I_2 consumption is, of course, due to the lower I^- concentrations in the iodinated water than had been anticipated in sizing the I_2 accumulator.

Upon disassembly of the Model IX-SA, each component was weighed, and the weights are listed in Table 15. The weights obtained before initial Model IX-SA assembly are also listed for comparison.

Photographs comparing the three major components/subassemblies of the Model IX-SA with new equivalent parts are shown for the I_2 accumulator, baseplate, and Anode Compartment Spacer (ACS) are shown in Figures 45 to 47.

Slight corrosion was observed on the 316 stainless steel baseplate at the O-ring seats, as expected. The use of Hastelloy C baseplates will prevent future corrosion there. No corrosion in the Hastelloy I_2 accumulator or accumulator cover were observed. The interior of the accumulator cover had been Teflon-coated and the coating was not affected by the catholyte.

No corrosion on the Hastelloy C or cathode on the I_2 accumulator was visually apparent. The 120 mg (2.6×10^{-4} lb) listed in Table 15 as the loss in weight of the accumulator is due to corrosion of the brass electrical contacts on the accumulator, caused by the leakage of iodinated water from the IX-S prior to the DVT.

The polysulfone anode compartment spacer was discolored by the I_2 but was not deteriorated. The anode with the attached anode contacts lost 87.8 mg due to some material loss of the Hastelloy C contacts. These were at the potential of the anode during operation, and this accelerated the rate of corrosion. The corrosion was slight and was the accumulation of approximately 80 days of total operation.

The membrane was darkened by the I_2, but was still resilient and flexible. The weight gain of 655 mg was due to the absorbed I_2 and some "Arizona Road Dust" on the surface facing the dispenser.

The other components of the IX-SA gained or lost negligible weight, and all parts, including O-rings, were in nearly new condition. The O-rings were smooth and pliable.

ANALYTICAL MODEL

A mathematical representation of the performance of the AWIS is desirable for sizing future I_2 Sources or predicting AWIS performance when integrated into future advanced potable water systems. For this representation, the AWIS performance was characterized by the curves of I_2 valve current versus I_2 generation rate, valve current versus water flow rate, valve voltage versus valve current, and I_2 valve power consumption versus flow rate, shown in Figures 33 to 36. A preliminary mathematical representation of AWIS performance was prepared by performing least squares polynomial curve fits for the characterization curves in Figures 33, 34, and 36, and performing a hyperbolic tangent curve fit for the curve in Figure 35. The equations closely follow the characterization curves and their projected extrapolations. The extrapolations

TABLE 15 IX-SA PRE- AND POST-TEST COMPONENT WEIGHTS

	Pre-Test Weight, g	Post-Test Weight, g	Weight Gain or Loss, mg
Stainless Steel Baseplate[a]	170.8	170.8	-
Polysulfone Flow Chamber	27.7516	27.7666	+ 15.0
Polysulfone Insulation Ring	9.0626	9.0542	- 8.4
Current Collector Bolt			
Bolt No. 1	2.0894	2.0896	+ 0.2
Bolt No. 2	2.0881	2.0877	- 0.4
Polysulfone Current Collector Insulator			
Insulator No. 1	0.6787	0.6785	- 0.2
Insulator No. 2	0.6890	0.6888	- 0.2
O-Ring			
No. 1 (Water Flow Chamber)	1.0462	1.0513	+ 5.1
No. 2 (Accumulator)	0.8817	0.8913	+ 9.6
No. 3 (Accumulator Plug)	0.2727	0.2765	+ 3.8
No. 4 (Water Inlet)	0.1291	0.1299	+ 0.8
No. 5 (Water Outlet)	0.1323	0.1332	+ 0.9
No. 6 (Current Collector No. 1)	0.1028	0.1036	+ 0.8
No. 7 (Current Collector No. 2)	0.1049	0.1057	+ 0.8
I_2 Accumulator with Cathode	236.3942	236.2740	-120.2
I_2 Accumulator Plug with Teflon (without set screw)	26.1573	26.1595	+ 2.2
Anode With Current Collector Blocks	3.6453	3.5575	- 87.8
Membrane (air-dried)	1.5032	2.1582	+655.0
Aluminum Housing (without cover)	87.0832	87.1024	+ 19.2

(a) IX-SB constructed with Hastelloy C-276 baseplate.

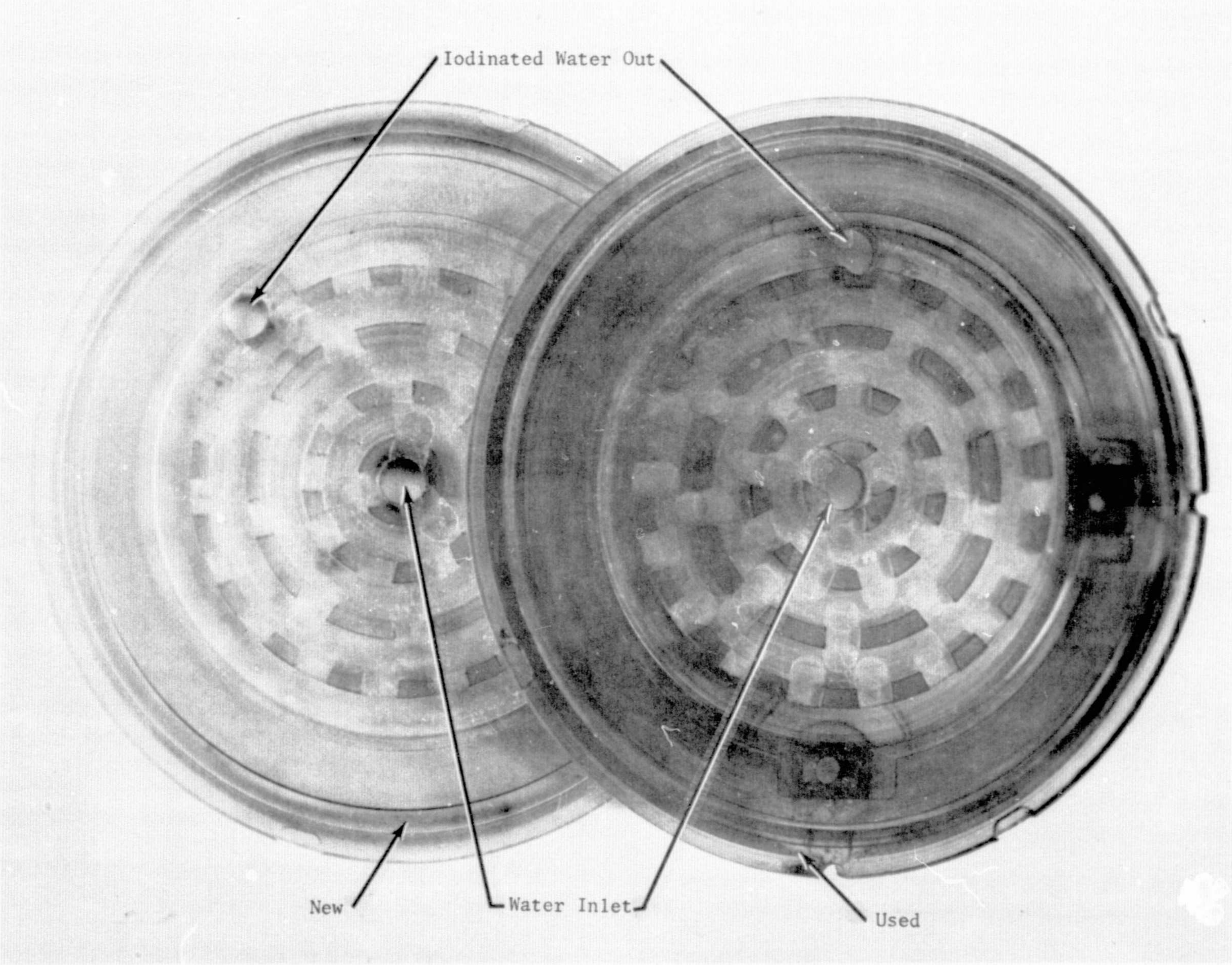

FIGURE 45 COMPARISON OF NEW AND USED MODEL IX-SA ACCUMULATORS

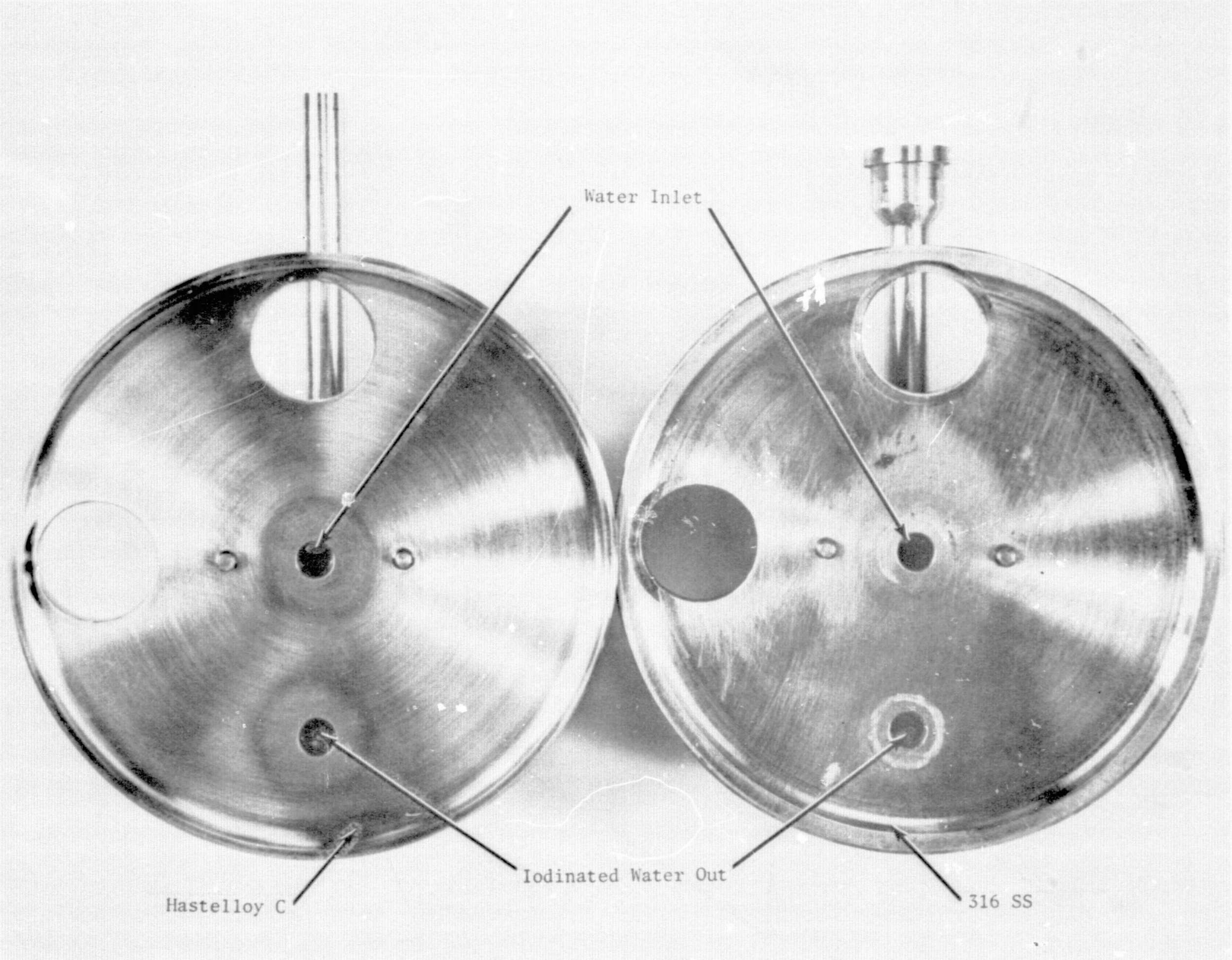

FIGURE 46 COMPARISON OF HASTELLOY C AND 316 SS BASEPLATES

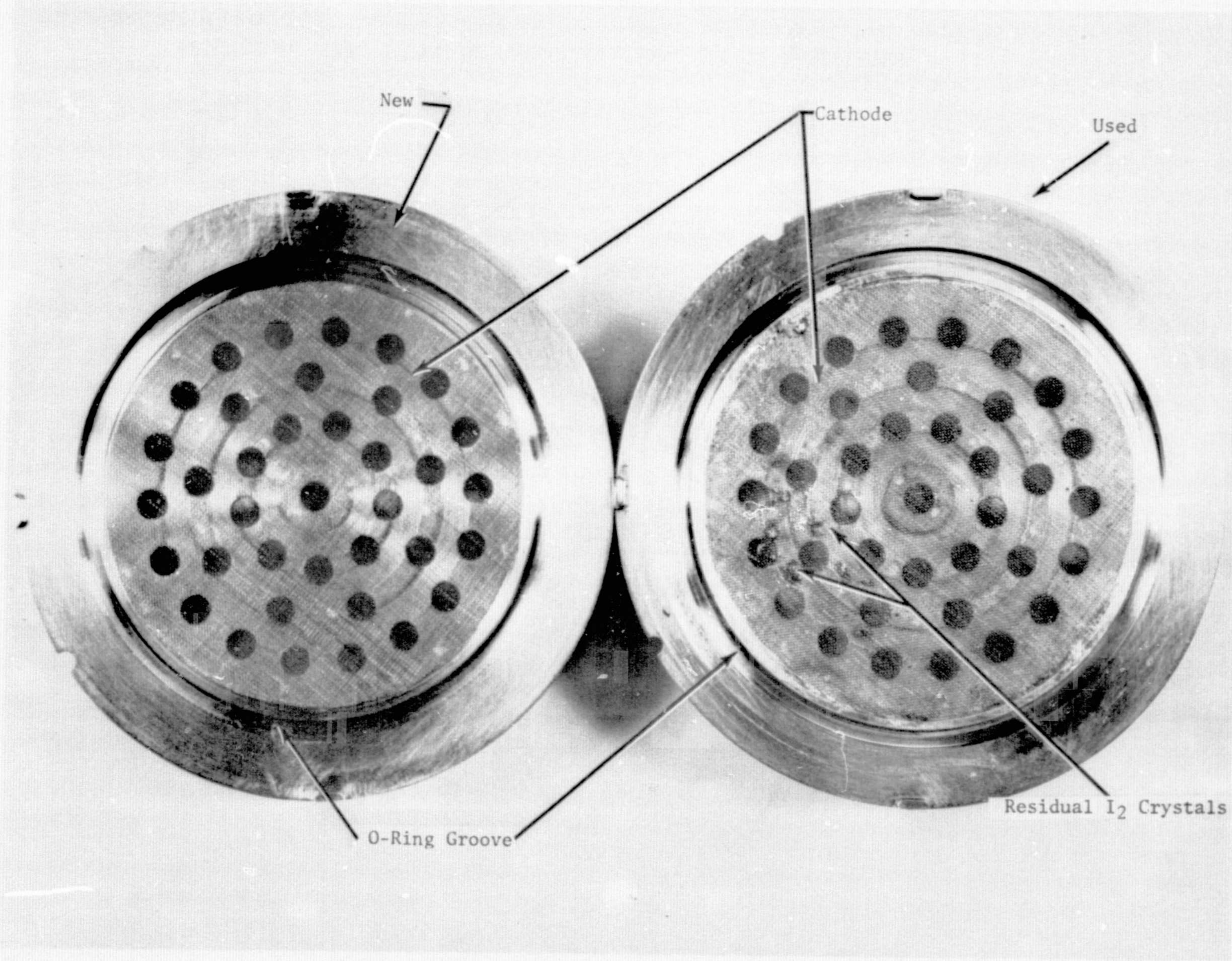

FIGURE 47 COMPARISON OF NEW AND USED MODEL IX-SA ANODE COMPARTMENT SPACERS

allow characterization of the AWIS performance projected for flow rates greater than 172.5 cm^3/min (547 lb/day) or at I_2 concentrations greater than 5 ppm.

The equations representing the four Model IX-SA characterization curves are given below:

I_2 valve current versus I_2 generation rate

$$A = -7.851 + 5.9924 \times 10^{1}B - 1.6217 \times 10^{2}B^{3} - 2.4447 \times 10^{2}B^{4} + 6.9463 \times 10^{1}B^{5} \qquad (6)$$

where

$A = I_2$ valve current, mA

$B = I_2$ generation rate, g/day

I_2 valve current versus water flow rate

$$A = -1.4449 \times 10^{1} + 5.4379 \times 10^{-1}B - 4.8249 \times 10^{-3}B^{2} + 3.6805 \times 10^{-5}B^{3} - 8.5301 \times 10^{-8}B^{4} + 7.2139 \times 10^{-11}B^{5} \qquad (7)$$

where

$A = I_2$ valve current, mA

$B =$ Water flow rate, cm^3/min

I_2 valve voltage versus I_2 valve current

$$A = 8.1 \times 10^{-1} \tanh (1.17 \times 10^{-1}B - 1.69) + 5 \times 10^{3}B + 7.9 \times 10^{-1} \qquad (8)$$

where

$A = I_2$ valve voltage, V

$B = I_2$ valve current, mA

I_2 valve power consumption versus water flow rate

$$A = -3.9938 \times 10^{-1} + 1.0269 \times 10^{-1}B + 5.5730 \times 10^{-4}B^{2} - 6.9064 \times 10^{-6}B^{3} + 1.9034 \times 10^{-7}B^{4} - 3.3242 \times 10^{-10}B^{5} \qquad (9)$$

where

A = I_2 valve power consumed

B = Water flow rate, cm^3/min

CONCLUSIONS

Integration of the prototype Model IX-SA I_2 Source with the GFE AIMS was successful, and 24 days of automatic, "hands-off" operation of the AWIS were completed. The AWIS is capable of long-term iodination of water flowing at 22.7 to 172.5 cm^3/min (72 to 547 lb/day) to 5 ppm ±1 I_2 or iodination of water flowing at the contractual flow rate of 32.3 cm^3/min (102 lb/day) to 10 ppm ±2 I_2. Short-term iodination to a concentration of 20 ppm I_2 is possible, although long-term operation at 20 ppm is limited. For iodination of water at flow rates much larger than 172.5 cm^3/min (547 lb/day) or for long-term iodination at concentrations above 10 ppm, multiple Model IX-S units or units with larger active areas must be used.

The basic design concepts incorporated in the AWIS have been successfully demonstrated. For instance, the AWIS has proven the effectiveness of the bipolar I_2 valve current control to limit I_2 diffusion through the anion exchange membrane in the Model IX-S. The radial water flow distribution in the I_2 dispenser and the rigid design of the I_2 valve produce more efficient operation than anticipated from studies of the Model IX-S predecessor, Model LSI-100. A result of the more efficient operation is that the Model IX-S injects only approximately 2 ppm I^- into water iodinated to 5 ppm, whereas the Model LSI-100 injected approximately 5 ppm I^-. The capacity of the Model IX-S is therefore more than anticipated from the studies of the Model LSI-100.

The AWIS is compatible with simulated fuel cell water containing the particulate matter projected for Shuttle Orbiter fuel cell water, even when the water is heated to 338K ±2.8 (150F ±5), the temperature of the Orbiter fuel cells. The use of a four-way valve in the AWIS insures compatibility with steam sterilization of the potable water system, although a sterilized membrane was tested in the Model LSI-100 and found to operate normally. From these tests, it is concluded that the AWIS is compatible with the Orbiter potable water system, and filters to remove particulate matter, or water chillers upstream of the AWIS are unnecessary.

Materials compatibility studies and the AWIS testing program have proven Hastelloy C-276, polysulfone, and Viton A to be compatible with the I_2 and HI present in the Model IX-S. Because of the excellent corrosion resistance of the Hastelloy C, Teflon coating the interior of the I_2 accumulator is unnecessary. The original 316 stainless steel baseplate of the IX-SA corroded because of the combination of Viton A O-rings seated on welded portions of the baseplate. Studies showed that the Viton A absorbed sufficient I_2 to corrode stainless steel heated during the welding process. The baseplate is now constructed of

Hastelloy C, and further corrosion is not anticipated. Polysulfone and the Viton A O-rings themselves, were found to be compatible with the I_2 and HI in the Model IX-S.

The GFE AIMS operated well and demonstrated successfully the concept of continuous feedback control of the I_2 valve current. Failures encountered with the AIMS were not the result of conceptual design flaws. A loose electrical connection caused one failure which would not be anticipated in a flight-qualifiable unit. The other failure was the lamp in the light source of the AIMS. The period of operation accumulated with this lamp at LSI and during the AIMS development prior to shipment to LSI is unknown. The operating period and on/off cycles probably exceeded the design envelope for the lamp. A flight-qualifiable I_2 sensor would be designed with a certified nominal lamp life.

The AWIS achieved the goal of self-contained and automatic operation and has the characteristics of low weight, pressure drop, and reasonably compact design. Based on the results of this program, an Advanced Combined I_2 Dispenser Detector (ACIDD), consisting of an advanced I_2 sensor integrated with an I_2 dispenser patterned after the Model IX-S design and having a total weight of 1.8 kg (4.0 lb) and power requirement of only 6 watts, is feasible. The ACIDD is expected to be competitive to the baseline Orbiter biocide system for controlling the microbial growth in the Orbiter potable water system.

RECOMMENDATIONS

The Model IX-S and GFE AIMS used in this program were integrated as efficiently as possible; however, the AIMS was not designed specifically for integration with the Model IX-S. For instance, the water inlet of the AIMS is not positioned for the fastest transport of iodinated water from the IX-S to the AIMS. Faster transportation of water between the I_2 Source and sensor would allow faster AWIS feedback control response and closer control of the I_2 concentration during periods of nonsteady-state operation. Also, the AIMS was packaged in a container that is 23.0 cm x 17.5 cm x 9.0 cm (9.0 in x 6.9 in x 3.5 in). This volume is considerably larger than that required by the sensor optics and electronics. They can be repackaged in a form much smaller and lighter than that presently used.

Because the AIMS was not designed specifically to integrate with the Model IX-S, it is suggested that the AIMS be repackaged in a smaller, advanced form that is highly compatible with the Model IX-S design. Electronic components such as power supplies, presently used independently in both the IX-S and AIMS, can be shared in the repackaged form to further reduce total weight and volume.

An alternative to the photometric I_2 sensor would be an electrochemical sensor. The electrochemical sensor requires no light source and optical detectors. Therefore, it may be even more compact than a photometric sensor and consume less power. Even greater weight and power savings would be realized if the need for an I_2 sensor was eliminated altogether. A parameter of the potable water system, such as water flow rate or fuel cell current output, may be adapted to control the I_2 valve current instead of the feedback signal of the AIMS. If such a suitable parameter was found, the I_2 sensor could be eliminated. It is suggested that the use of an electrochemical sensor and the feasibility of the use of a water system parameter in place of a sensor be investigated.

The AWIS has been shown to be compatible with the Shuttle Orbiter potable water system and fuel cell water at the operating temperature of the Orbiter fuel cells. The AWIS also has been designed for compatibility with the steam sterilization of the water system. An additional compatability study is necessary to evaluate the AWIS with dissolved H_2 as present in the Orbiter fuel cell water. The possible effects of the H_2 upon I_2 in the water, the electrochemical reactions at the Model IX-S anode, and the materials in the AWIS should be considered in the study.

The applicability of the AWIS to other advanced spacecraft water systems should be evaluated. These include potable, wash, and fecal water systems. The results of this evaluation would assure the timely technological readiness for the efficient integration of the AWIS into advanced Environmental Control Life Support System (ECLSS) such as a spacelab regenerative ECLSS flight experiment.

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APPENDIX 1 AWIS FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

This document is a Failure Mode, Effects and Criticality Analysis (FMECA) performed on the Advanced Water Iodination System (AWIS). An AWIS schematic, as projected for application aboard the Space Shuttle, is presented in Figure A1-1. All failure modes of the AWIS were analyzed for their effect on the component, functional assembly, subsystem and system. The failure detection method, backup provisions and crew action required for each failure mode is presented. In addition, each failure mode is classified according to the criticality levels as listed below.

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

The FMECAs for each failure mode of AWIS are found on the following pages of this document. This analysis identifies safety hazards and single failure points[a] and is used to verify the instrumentation requirements of the system.

The FMECA reveals that there are no single point failures in the AWIS. The highest criticality level assigned to failure modes in the AWIS is IIb. These are those failure modes associated with the possibility of increasing the I_2 concentration of the potable water to >30 ppm. It was established that water with >30 ppm I_2 damages the sublimator plates causing a switch to the redundant sublimator and subsequent mission abort. Backup provisions, as detailed on the individual FMECA forms, have been incorporated so that the probability of the IIb failures occurring are minimal.

(a) A single point failure is a single failure which could cause loss of personnel, could cause return of one or more people to earth or could make it possible for the next associated failure to cause loss of personnel.

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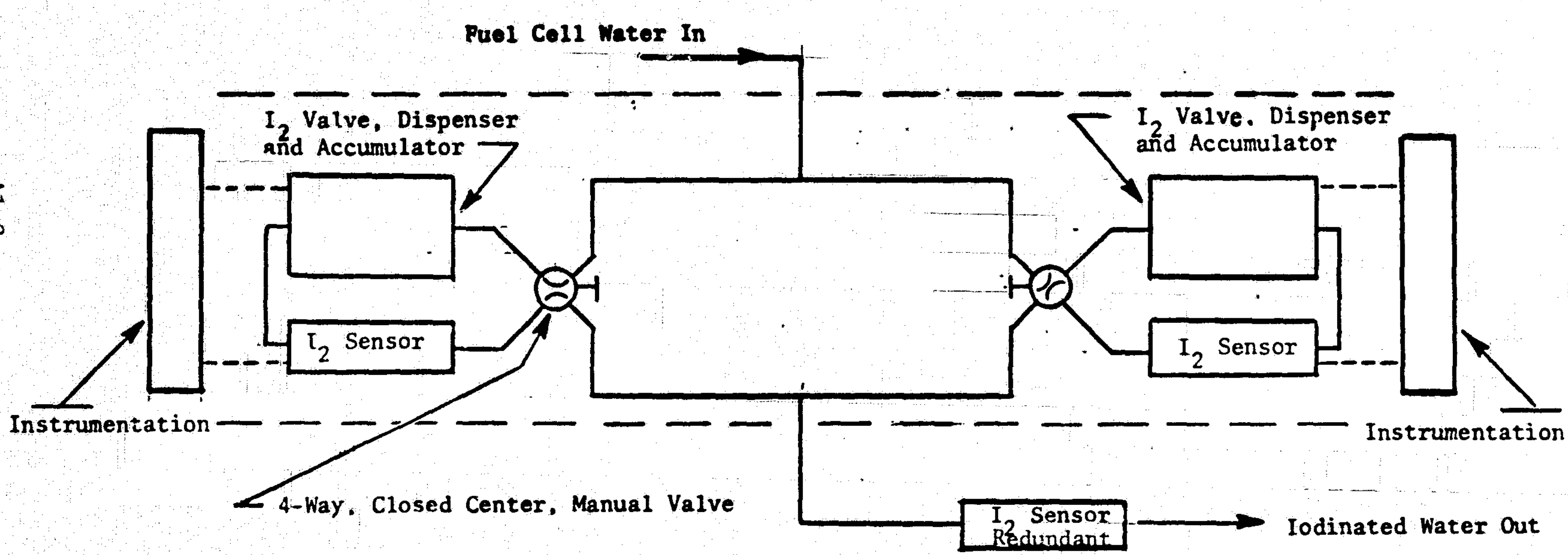

FIGURE A1-1 AWIS SCHEMATIC

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TITLE ADVANCED WATER IODINATING SYSTEM (AWIS) — ☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Sensor (Control)	To sense the I_2 concentration in the potable water system and serve as the feedback in the I_2 concentration control loop.

FAILURE MODE AND CAUSE:
Sensor reads low

CRITICALITY
IIb

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
The AWIS Instrumentation, upon receiving a low I_2 concentration signal from the failed control sensor, will increase the current to the electrochemical cell of the I_2 Valve, Dispenser and Accumulator. This will be automatically done in order to increase the I_2 concentration of the potable water stream.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
The fuel cell water will be constantly iodinated at the maximum iodine generation rate. The concentration of iodine in the potable water storage tanks will increase. At the calculated maximum I_2 generation rate resulting from the "fail low" failure mode of the I_2 sensor, it was established that the I_2 concentration of the potable water tank could reach 17 ppm. This water could possibly cause damage to the sublimator plates requiring a switch to the redundant sublimator and subsequent mission abort even though past experience (Apollo Programs) has shown that sublimator plates are not affected by water containing <20 ppm I_2.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
The failure will be detected by the redundant I_2 sensor (Figure A1-1). It is anticipated that a redundant I_2 sensor will be part of the potable water system aboard the shuttle. The signal from both I_2 sensors will be monitored by the Data Management System. If either fails low, the crew will be made aware of the failure. The I_2 sensor has a manual self-checking feature included which can also be used to verify sensor operation.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Isolate the failed sensor by utilizing the manual self-checking feature of the I_2 sensor. Power down the failed loop of the AWIS and divert to the redundant loop by manually reconfiguring two valves.	1440 s (0.4 hr) est.	

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS) — ☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Sensor (Monitor)	To monitor I_2 concentration and serve as a redundant I_2 sensor.

FAILURE MODE AND CAUSE:	CRITICALITY
Sensor reads low	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
The automatic redundant I_2 sensing feature of the system would be lost.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
In the event the monitor sensor fails low, the automatic redundant I_2 sensor feature of the system would be lost. However, the crew would be alerted and would be required to assume the function of the redundant sensor by periodically checking the performance of the control sensor utilizing the self-checking feature included in the I_2 sensor.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
The failure will be detected by the operating I_2 sensor (Figure A1-1). It is anticipated that a redundant I_2 sensor will be part of the potable water system aboard the shuttle. The signal from both I_2 sensors will be monitored by the Data Management System. If either fails low, the crew will be made aware of the failure. The I_2 sensor has a manual self-checking feature included which can also be used to verify sensor operation.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Isolate the failed sensor by utilizing the manual self-checking feature of the I_2 sensor. Assume the function of the redundant I_2 sensor by checking the function of the control sensor once each 8 hours by utilizing the manual self-checking feature incorporated in the I_2 sensor	1440 s (0.4 hr) est.	

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TITLE: ADVANCED WATER IODINATION SYSTEM (AWIS) — ☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Valve, Dispenser and Accumulator	To store I_2, meter I_2 and dispense the required amount to maintain the I_2 concentration in the potable water system at 1 to 5 ppm.

FAILURE MODE AND CAUSE:	CRITICALITY
External leakage	
(a) of catholyte	III
(b) of water	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
(a) Approximately 50 cc (0.1 pint) of 0.1M HI and 0.001M I_2 solution would contaminate cabin. The I_2 Valve, Dispenser and Accumulator cell voltage would increase and the AWIS would not be capable of iodinating the fuel cell water.
(b) Water would leak from the AWIS. If downstream of the I_2 Valve, Dispenser and Accumulator, then disinfected water would be admitted to the cabin; otherwise unprocessed water would contaminate the cabin.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
(a) The potable water in the storage tank would not contain the required concentration of I_2. Localized corrosion of components exposed to the catholyte would occur.
(b) The cabin would be contaminated with water and there would be a reduced availability of disinfected water.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
(a) This failure would be detected by the I_2 sensor incorporated in the AWIS.
(b) The water pressure sensor in the fuel cell water line would detect large leaks. Small leaks could be detected by crew observation.
Backup provisions include a design incorporating welded plumbing wherever feasible and where fittings are required, double O-ring seals will be utilized. In the event this failure mode occurs, the crew could switch to the redundant loop of the AWIS which is capable of disinfecting the fuel cell water and will allow the mission to continue.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
(a and b) Power down the leaking loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

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TITLE: ADVANCED WATER IODINATION SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Valve, Dispenser and Accumulator	To store I_2, meter I_2 and dispense the required amount to maintain the I_2 concentration in the potable water system of 1 to 5 ppm.

FAILURE MODE AND CAUSE:	CRITICALITY
(a) Partial loss of electrical connection.	III
(b) Complete loss of electrical connection.	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
(a) For a partial loss of electrical connection, the operating voltage of the electrochemical cell would increase due to the increase in resistance of the electrical connection. The cell would consume more power.
(b) For complete loss of an electrical connection, the electrochemical cell would not function, as the current flow path through the cell would be destroyed. It would be impossible to increase current when required.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
(a) No effect except for higher operating cell voltage and higher power consumption.
(b) The I_2 concentration of the potable water in the storage tank will decrease.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS: (a) None. (b) This failure will be detected by the I_2 sensor in the AWIS. In the event this failure occurs, the crew could switch to the redundant loop of the AWIS, which will continue to disinfect the fuel cell water and allow the mission to continue. The AWIS electrical connections will be soldered or welded joints. The electrode/electrical lead connectors will be tack welded and in addition, will be mechanically held together by the compressive force applied by the cell endplate assembly. In addition, the I_2 Valve, Dispenser and Accumulator has been designed with redundant power leads.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
(a) None. (b) Remove power to failed loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	(a) 0 (b) 1080 s (0.3 hr) est.	

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS) — ☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	AWIS Instrumentation	To control the feed rate of I_2 to the fuel cell water based on the feedback from the I_2 sensor.

FAILURE MODE AND CAUSE:

Instrumentation is not capable of applying or increasing current to the electrochemical cell. The possible causes are:

(a) Shorted power transistor
(b) Failure of power supply
(c) Error amplifier component failure
(d) Integrator component failure

CRITICALITY: III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

The I_2 Valve, Dispenser, and Accumulator will not be capable of increasing the I_2 dispensing rate as required to maintain the I_2 concentration of the potable water at the desired 1 to 5 ppm.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

The I_2 concentration of the potable water in the storage tank will decrease. If this condition is allowed to persist the fuel cell water may not be sufficiently disinfected.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

The failure will be detected by the I_2 sensor incorporated into the AWIS. As further backup, the AWIS has a redundant I_2 sensor. The signal from both I_2 sensors will be monitored by the Data Management System. If either detects low I_2 concentration, the crew will be made aware of the failure. In the event this failure occurs, the crew will be able to switch to the redundant loop of the AWIS, which will continue to disinfect the fuel cell water and allow the mission to continue.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Power down the failed loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	AWIS Instrumentation	To control the addition rate of I_2 to the fuel cell water based on feedback from the I_2 sensor.

FAILURE MODE AND CAUSE:

Instrumentation is not capable of decreasing current to the electrochemical cell. The possible causes are:

(a) Shorted power transistor in bipolar current source
(b) Failure of power supply
(c) Error amplifier component failure
(d) Integrator component failure

CRITICALITY: IIb

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

The I_2 Valve, Dispenser, and Accumulator will continually run at or near the peak I_2 dispensing rate. At the nominal water generation rate from the fuel cell system (120.1 kg (264 lb/day)) the concentration of I_2 would increase to approximately 17 ppm.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

The I_2 concentration of the potable water in the storage tank will increase. If this condition persists then its I_2 concentration will approach 17 ppm. This water could possible cause damage to the sublimator plates, requiring a switch to the redundant sublimator and subsequent mission abort even though past experience (Apollo Program) has shown that sublimator plates are not affected by water containing <20 ppm I_2.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

The failure will be detected by the I_2 sensor incorporated into the AWIS and as further backup will also be detected by the redundant I_2 sensor. The signal from both I_2 sensors will be monitored by the Data Management System. The crew will be made aware of a high I_2 reading by either sensor. In the event of this failure, the crew will be able to switch to the redundant leg of the AWIS which will continue to disinfect the fuel cell water and allow the mission to continue.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Power down the failed loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Sensor (Control)	To sense the concentration of I_2 in the potable water stream and serve as the feedback in the I_2 concentration control loop.

FAILURE MODE AND CAUSE:	CRITICALITY
Sensor reads high	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
As a result of receiving a high I_2 concentration signal, the AWIS instrumentation will throttle the I_2 Valve, Dispenser, and Accumulator such that an insufficient amount of I_2 is dispensed to the fuel cell water.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
The I_2 concentration of the potable water in the storage tank(s) will decrease. If this condition is allowed to persist the fuel cell water will not be sufficiently disinfected.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
The failure will be detected by the redundant I_2 level sensor that is anticipated for inclusion in the potable water system of the shuttle. The signal from both I_2 sensors will be monitored by the Data Management System. If either fails high, the crew will be made aware of the failure. The I_2 sensor has a manual self-checking feature included which can also be used to verify sensor operation. If this condition occurs, the crew will switch to the redundant loop of the AWIS, which will continue to disinfect the fuel cell water and allow the mission to continue.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Isolate the failed sensor by utilizing the manual self-checking feature of the I_2 sensor. Power down the failed loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1440 s (0.4 hr) est.	

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Sensor (Monitor)	To monitor I_2 concentration and serve as a redundant I_2 sensor.

FAILURE MODE AND CAUSE:	CRITICALITY
Sensor reads high	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
The automatic redundant I_2 sensing feature of the system would be lost.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
In the event the monitor sensor fails high, the automatic redundant I_2 sensor feature of the system would be lost. However, the crew would be alerted and would be required to assume the function of the redundant sensor by periodically checking the performance of the control sensor by utilizing the self-checking feature of the I_2 sensor.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
The failure will be detected by the redundant I_2 level sensor that is anticipated for inclusion in the potable water system of the shuttle. The signal from both I_2 sensors will be monitored by the Data Management System. If either fails high, the crew will be made aware of the failure. The I_2 sensor has a manual self-checking feature included which can also be used to verify sensor operation. If this condition occurs, the crew will switch to the redundant loop of the AWIS, which will continue to disinfect the fuel cell water and allow the mission to continue.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Isolate the failed sensor by utilizing the manual self-checking feature of the I_2 sensor. Assume the function of the redundant I_2 sensor by checking the function of the control sensor once each 8 hours by utilizing the manual self-checking feature of the I_2 sensor.	1440 s (0.4 hr) est.	

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TITLE: ADVANCED WATER IODINATION SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Valve, Dispenser and Accumulator	To store I_2, meter I_2 and dispense the required amount to maintain the I_2 concentration in the potable water system at 1 to 5 ppm.

FAILURE MODE AND CAUSE:

Separation of membrane from the electrode

CRITICALITY: III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

Separation of the cathode from the membrane will not prevent operation of the I_2 source. The cathode is immersed in a saturated solution of I_2 and generates sufficient I^- that the I^- concentration in the catholyte is at least as large as the I_2 concentration after a few hours of operation. The I^- thus generated will migrate through the anion-exchange membrane in order to carry the I_2 valve current whether or not the cathode touches the membrane.

(see page 2 for continuation)

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

The AWIS will still be capable of disinfecting the fuel cell water; however, it will consume more power if the subject failure mode exists.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

With the instrumentation projected for the AWIS, this failure mode will not be detected. Because of the minimal effect on the system and because of the backup provisions inherent in the AWIS design, it was decided that it was not necessary to incorporate additional instrumentation to detect this failure mode. Backup provisions include a cell design incorporating precisely machined 0.23 cm^2 (0.093 in^2), electrode supports on both sides (anode and cathode) spaced on 0.63 cm (0.25 in)

(see page 2 for continuation)

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
None		

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

If the anode is separated from the membrane, the cell internal resistance will increase because the anode no longer is in contact with a higher conducting medium. However, the anode is still capable of oxidizing the I^- diffusing to it and will continue to iodinate the water so long as the I_2 valve voltage is less than the maximum voltage output of the control instrumentation I_2 supply. The maximum voltage output of the power supply presently used is about 12V. Iodination of water flow rates of 120 kg/day (264 lb/day) to 5 ppm I_2 requires approximately 20 mA. Therefore, the maximum internal cell resistance allowable for operation at these values is 400 ohm. Normal cell resistances are about 100 ohms.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

centers. These were designed to provide 0.005 cm (0.002 in) pinch on the electrode/membrane/electrode sandwich. In addition, the electrodes are firmly (spot welded) attached along their circumference to the cell endplates and the cell is held together by the bottom plate and housing threads precisely torqued to insure good electrode/membrane contact.

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TITLE	
ADVANCED WATER IODINATING SYSTEM (AWIS)	☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Valve, Dispenser and Accumulator	To store I_2, meter I_2 and dispense the required amount of I_2 to maintain the I_2 concentration in the potable water system at 1 to 5 ppm.

FAILURE MODE AND CAUSE:	CRITICALITY
Membrane rupture.	IIb

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

All the dissolved I_2 present in the I_2 Valve, Dispenser and Accumulator can be admitted to the potable water stream. In addition, the solid I_2 crystals will begin to dissolve in the flowing water stream.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

The potable water in the water storage tank will become contaminated with excess I_2. Based on the maximum amount of I_2 and a 75.8 kg (167 lb) tank, the concentration of I_2 in the tank can exceed 40 ppm. This water will damage the sublimator plates requiring a switch to the redundant sublimator and subsequent mission abort.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

This failure will be detected by the I_2 sensor that is incorporated into the AWIS. As further backup, the AWIS will contain a redundant I_2 sensor that will also detect this failure. The probability of this failure occurring is minimal for the following reasons:

(see page 2 for continuation)

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Power down the failed loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:

1. The membrane has been tested to four times the operating pressure without rupture (41.3×10^4 N/m^2 (60 psig)).

2. Manufacturers data indicates that the membrane can be utilized to six times the maximum operating pressure (1.38×10^6 N/m^2 (200 psig)) without rupture.

3. The fuel cell water exit pressure will not exceed 24.8×10^4 N/m^2 (36 psi) as it is controlled by a pressure regulator and relief valve.

4. All membranes incorporated into the AWIS will be pressure checked before assembly.

As further backup, the electrode in the I_2 Valve, Dispenser and Accumulator is a 100 mesh screen. This screen would prevent I_2 crystals from escaping into the water stream in the event of membrane rupture.

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TITLE: ADVANCED WATER IODINATING SYSTEM (AWIS)

☒ SUBSYSTEM ☐ LOOP ☐ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Valve, Dispenser and Accumulator	To store I_2, meter I_2 and dispense the required amount of I_2 to maintain the I_2 concentration in the potable water system at 1 to 5 ppm.

FAILURE MODE AND CAUSE:	CRITICALITY
Plugging of water compartment.	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:
Water flow through AWIS will decrease. Water pressure in the I_2 Valve, Dispenser and Accumulator will increase unless plugging is at the inlet of the AWIS, in which case the pressure will remain constant as the pressure is referenced to the water storage tanks.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:
Pressure of water exhaust line in the fuel cell system will increase. Flow rate of water through AWIS will decrease, resulting in longer time required to fill the potable water tanks.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS:
Water pressure sensor in fuel cell system. The AWIS will consist of redundant legs. In the event that one loop plugs, the crew will be able to switch to the redundant loop which will continue to disinfect the water and allow the mission to continue. The I_2 Valve, Dispenser and Accumulator is designed so that the smallest orifice is larger than the maximum solid particle (250 μm) that is expected in the fuel cell water.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
Power down the plugged loop of the AWIS and switch to the redundant loop by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

APPENDIX 2 PWSS CALIBRATION CURVES

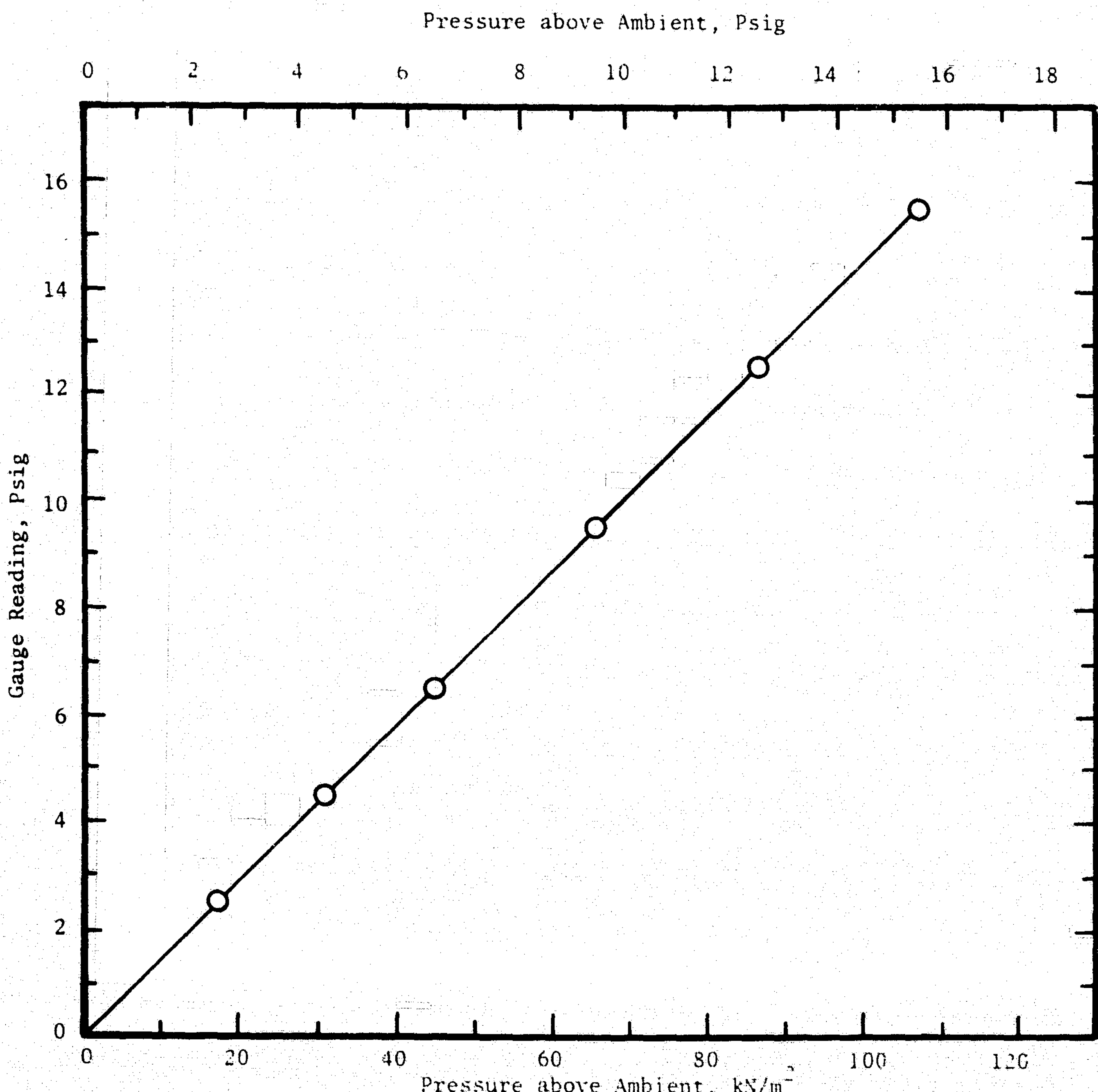

FIGURE A2-1 CALIBRATION OF CELL INLET PRESSURE GAUGE, PG-2, AWIS TEST STAND

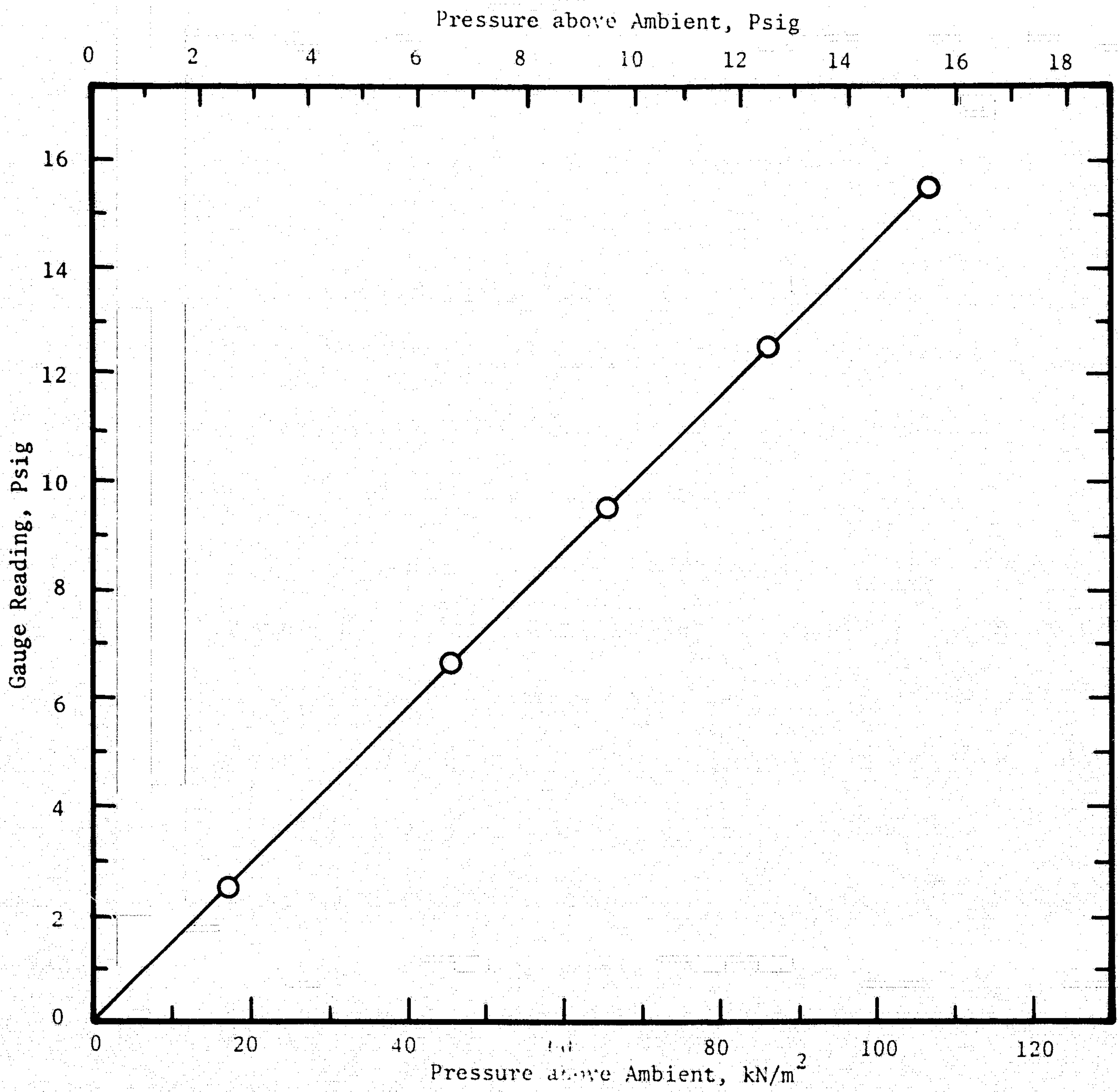

FIGURE A2-2 CALIBRATION OF FEED WATER SUPPLY PRESSURE GAUGE, PG-1, AWIS TEST STAND

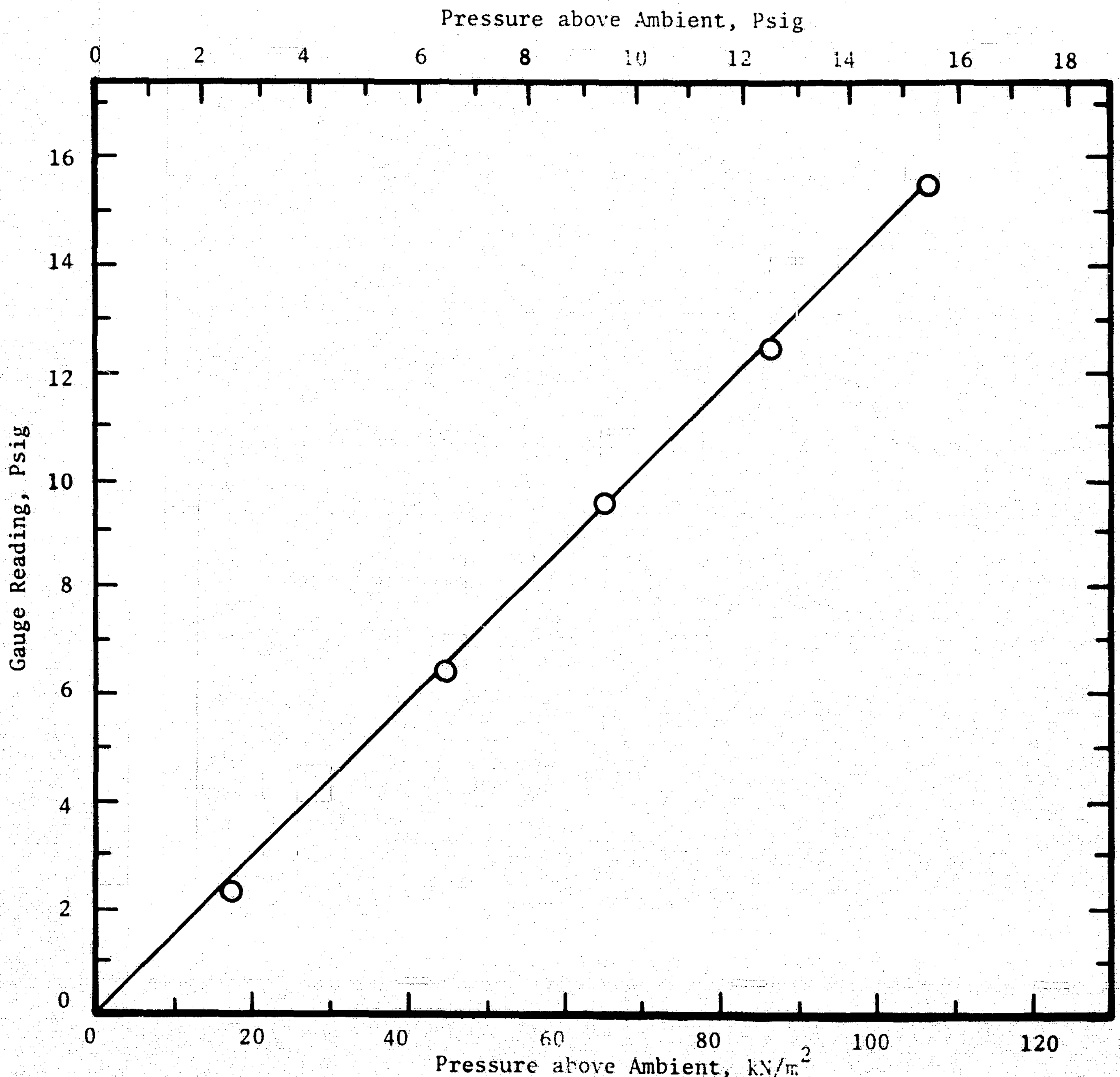

FIGURE A2-3 CALIBRATION OF CELL OUTLET PRESSURE GAUGE, PG-3, AWIS TEST STAND

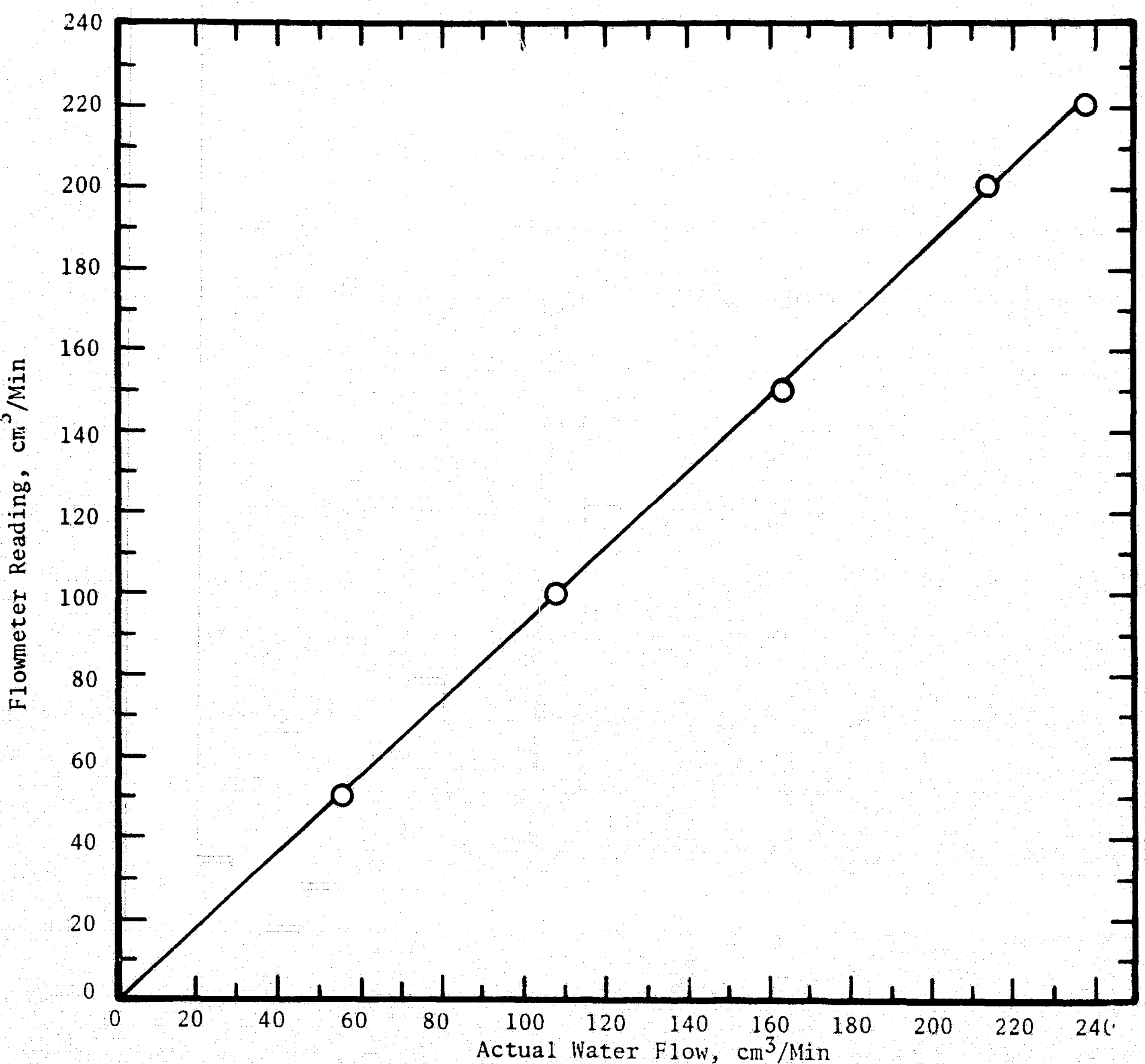

FIGURE A2-4 CALIBRATION OF FEED WATER SUPPLY FLOWMETER, FM-1, AWIS TEST STAND

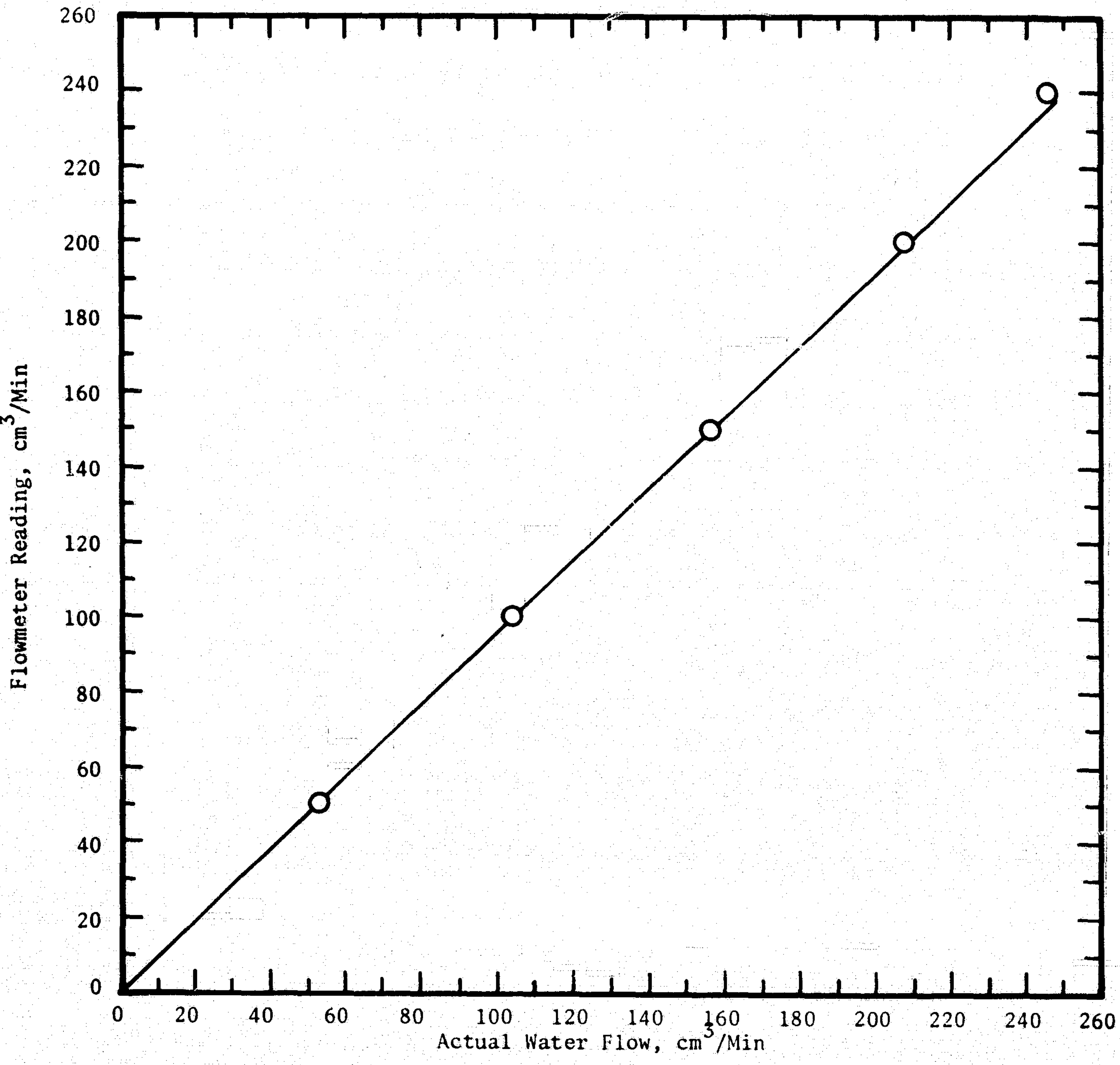

FIGURE A2-5 CALIBRATION OF RECIRCULATION FLOWMETER, FM-2, AWIS TEST STAND

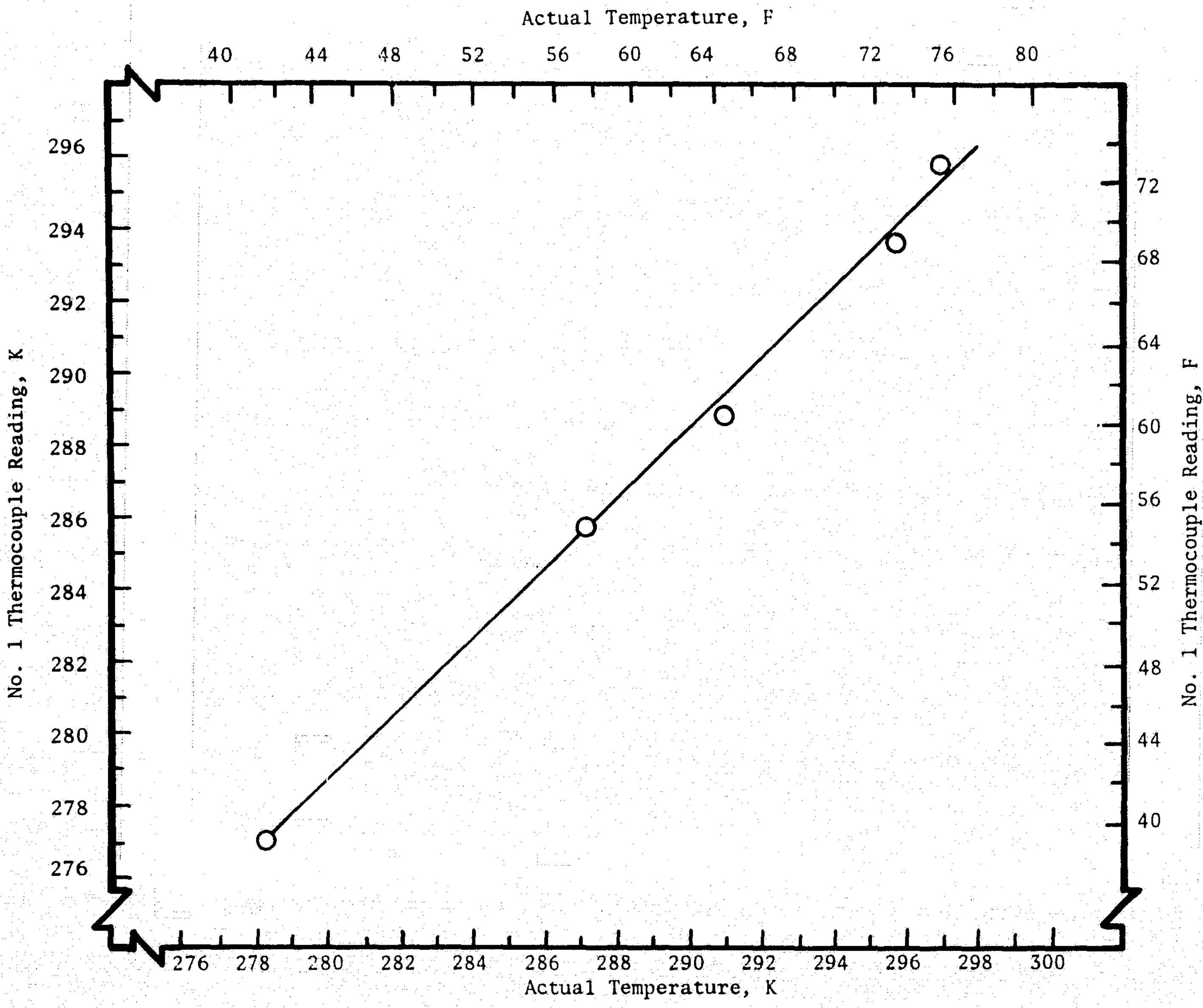

FIGURE A2-6 CALIBRATION OF THERMOCOUPLE NO. 1, AWIS TEST STAND

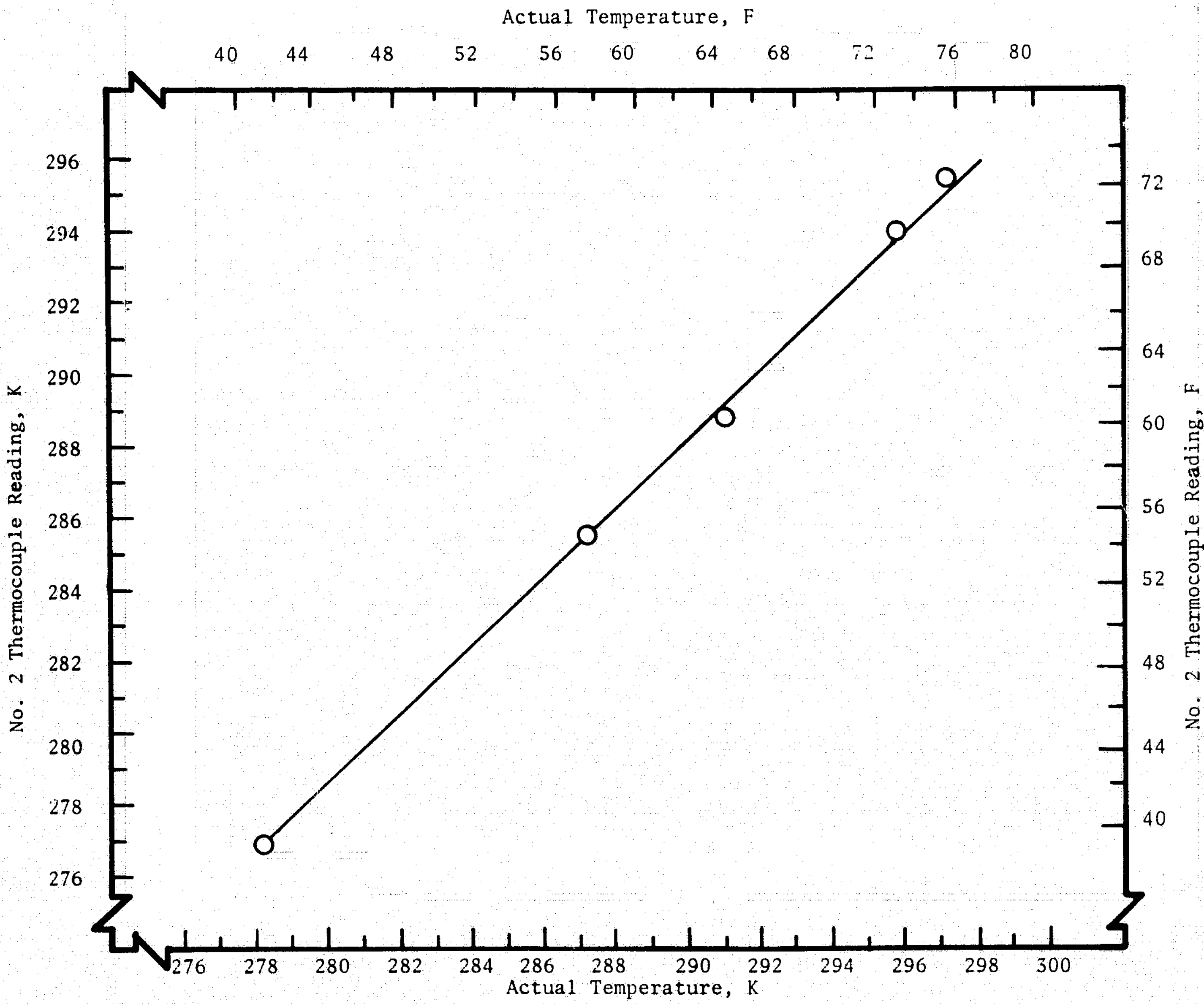

FIGURE A2-7 CALIBRATION OF THERMOCOUPLE NO. 2, AWIS TEST STAND

APPENDIX 3 AIMS CALIBRATION PROCEDURE

1. Pump the noniodinated water to be used during testing through the cell. Assure that the cell is aligned properly in the light beam.

2. Adjust the "zero" adjustment resistor until the meter reads 0.0 ppm I_2.

3. Pump a known solution of approximately 5 ppm I_2 (prepared with simulated fuel cell water) through the cell. Verify that the meter readout is accurate. If it is not, adjust the span control until the reading is accurate.

4. Repeat Steps 2 and 3 as required.

5. Repeat Step 3 with two solutions of different concentrations (approximately 2 and 4 ppm) and record readings.

6. NOTE: Insure that the cell is bubble-free and insure that I_2 solutions are fresh (I_2 decay as a function of time).

APPENDIX 4 RESULTS OF JSC ANALYSIS OF AWIS DVT WATER SAMPLES

The results of the analyses of the water samples from the AWIS DVT that were sent to JSC are shown in Table A4-1. The results of the determinations of the I_2 concentrations performed at LSI are compared to results from JSC. The JSC values for the first and third missions are lower than the LSI values because the I_2 in the samples probably diffused out of the water and into the polypropylene sample bottles during shipment to JSC. The JSC values of the third mission are closer to the LSI values because these samples probably spent less time in the bottles prior to analysis. The JSC results of samples 7 and 8 are higher than the LSI results, whereas the result for sample 9 is slightly lower, as expected. The higher results for samples 7 and 8 are probably due to the combined experimental uncertainties of the analytical methods used at LSI and JSC.

From Table A4-1 it can be concluded that the AWIS does not inject organic or inorganic carbon, chromium (Cr(VI)), or nickel (Ni) into the iodinated water. In each case the noniodinated water contains as much of these substances as does the iodinated water.

The water samples of the first mission contained less than 10 ppb iron (Fe) whereas the other samples contained from 15 to 58 ppb Fe. Again, for these samples, the noniodinated water contained as much as the iodinated water, showing that the AWIS was not the source of the Fe. The sudden presence of Fe in the water during the second mission is probably due to corrosion of the feed water/recirculation pump or some other portion of the test stand upstream of the noniodinated water sample port.

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TABLE A4-1 RESULTS OF JSC ANALYSIS OF AWIS DVT WATER SAMPLES

Sample Number	Mission/Day Number	Water Type	Analyte Concentration						
			I_2, Ppm		Organic Carbon, Ppm[b]	Inorganic Carbon, Ppm[c]	Cr(VI), Ppb[d]	Ni Ppb[d]	Fe Ppb[d]
			LSI[a]	JSC					
1	1/0	Noniodinated	0.0	-	2.0	1	<1.0	<10	<10
2	1/1	Iodinated	5.1	0.4[e]	2.5	<1	5.0	<10	<10
3	1/5	Iodinated	5.4	0.5[e]	2.0	<1	4.0	<10	<10
4	1/9	Iodinated	6.0	0.4[e]	2.5	<1	2.0	<10	<10
5	1/9	Noniodinated	0.0	-	2.0	1	2.0	<10	<10
6	2/0	Noniodinated	0.0	-	3.0	1	<1.0	<10	15
7	2/1	Iodinated	10.9	15.0[f]	2.0	1	3.7	<10	22
8	2/5	Iodinated	13.6	20.0[f]	2.0	1	1.6	<10	58
9	2/9	Iodinated	11.1	10.0[f]	3.5	<1	<1.0	<10	58
10	2/9	Noniodinated	0.0	-	2.5	1	<1.0	<10	46
11	3/0	Noniodinated	0.0	-	2.5	1	<1.0	<10	50
12	3/1	Iodinated	5.7	3.0[e]	3.0	<1	<1.0	<10	54
13	3/5	Iodinated	5.9	2.0[e]	3.0	<1	<1.0	<10	36
14	3/9	Iodinated	5.8	2.0[e]	3.0	<1	<1.0	<10	25
15	3/9	Noniodinated	0.0	-	2.0	1	<1.0	<10	42

(a) Experimental Uncertainty: ±0.2 Ppm
(b) Experimental Uncertainty: ±0.1 Ppm
(c) Experimental Uncertainty: ±0.03 Ppm
(d) Experimental Uncertainty: ±10 Ppb
(e) Experimental Uncertainty: ±0.5 Ppm
(f) Experimental Uncertainty: ±2 Ppm