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ADVANCED COMBINED IODINE DISPENSER AND DETECTOR

FINAL REPORT

by

J.B. Lantz, F.H. Schubert,
F.C. Jensen and J.D. Powell

January, 1977

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Prepared Under Contract NAS9-14624

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

LYNDON B. JOHNSON SPACE CENTER
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FOREWORD

This report describes the results of the development and testing of an Advanced Combined Iodine Dispenser/Detector (ACIDD). The work was conducted by Life Systems, Inc. during the period June, 1975 through November, 1976 under NASA Contract NAS9-14624.

The Program Manager at Life Systems was F. H. Schubert, with technical support provided by the following:

Personnel	Area(s) of Responsibility
• R. J. Davenport, PhD	Iodine chemistry and electrochemistry, analytical studies
• F. C. Jensen	ACIDD engineering, design, packaging
• K. K. Kacholia	Analytical studies
• E. P. Koszenski	ACIDD testing
• M. L. Kruszynski	ACIDD assembly, test stand fabrication
• J. B. Lantz, PhD	ACIDD and supporting technology studies testing, analytical studies
• C. A. Lucas	Documentation
• J. D. Powell	System electronics design
• M. Prokopcak	Engineering drawings
• N. Sasso	Electronics assembly
• J. W. Shumar	Product Assurance
• D. C. Walter	ACIDD mechanical design
• R. A. Wynveen, PhD	Systems analysis

The contract's technical monitor was H. E. Winkler, Crew Systems Division, NASA Johnson Space Center, Houston, TX 77058. Mr. O. K. Houck, also of Crew Systems Division, was responsible for the initiation of the overall program.

Technical guidance in the area of spacecraft potable water iodination requirements and needs was furnished by R. L. Sauer of Bioengineering Systems Division, NASA Johnson Space Center, Houston, TX 77058.

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LIST OF ACRONYMS

ACIDD	Advanced Combined Iodine Dispenser/Detector
AIMS	Automatic I_2 Monitor System
AWIS	Automatic Water Iodinating System
C/M I	Control Monitor Instrumentation
FMECA	Failure Mode, Effects and Criticality Analysis
GFE	Government-Furnished Equipment
RLSE	Regenerative Life Support Experiment
SSP	Space Station Prototype
TSA	Test Support Accessories

SUMMARY

The potable water on future long-term manned spacecraft missions will be recycled water which will be inherently susceptible to microbial contamination. Other spacecraft such as the Shuttle Orbiter will use fuel cell-generated water as the source of potable water. Although very pure when produced, it can become back-contaminated with microorganisms at the use points.

Iodine has been shown to have a superior microorganism annihilation potential at low dosages and dose rates. In previous NASA-sponsored programs, Life Systems, Inc. has demonstrated the feasibility of automatically dispensing iodine into a flowing water stream by using an electrochemical valve concept in combination with an iodine detector/feedback system.

The primary objective of this program was to develop and test a self-contained Advanced Combined Iodine Dispenser/Detector. The unit was to incorporate the successful design features of iodinators and iodine monitors developed under previous programs, but have flight-qualifiable weight, volume and power requirement characteristics, as well as improved maintainability and reliability.

The Advanced Combined Iodine Dispenser/Detector developed by Life Systems, Inc. was designed to iodinate (to 5 ppm iodine) the fuel cell water generated during 27 seven-day Orbiter missions (equivalent to 18,500 kg (40,700 lb) of water) before the unit must be recharged with iodine crystals. The Advanced Combined Iodine Dispenser/Detector incorporated the following previously proven design features: membrane and electrode types, water flow configuration, automatic, bipolar current feedback control, photometric iodine detection and corrosion-resistant materials.

A total weight of 1.23 kg (2.7 lb), a total volume of 1213 cm^3 (74 in^3), and an average power consumption of 5.5W was achieved in the Advanced Combined Iodine Dispenser/Detector by integrating the Detector with the Iodine Source, arranging all iodinator components within a compact package and lowering the parasitic power to the Detector and electronics circuits. These achievements surpassed the design goals of 1.36 kg (3.0 lb), 1671 cm^3 (102 in^3) and 8W. The reliability and maintainability were improved by reducing the Detector lamp power, using an interchangeable lamp concept, making the electronic circuit boards easily accessible, providing redundant water seals and improving the accessibility to the Iodine Accumulator for refilling.

In the Design Verification Testing, the Advanced Combined Iodine Dispenser/Detector maintained the specified nominal iodine concentration band of 5 (+1, -2) ppm in the treated water automatically for 30 days over a variety of induced water flow rate and temperature combinations. The flow rates were varied from 23 to 178 cm^3/min (72 to 564 lb/day) and the temperatures from 292 to 322K (66 to 121F). The only significant off-range concentration produced, 7 ppm, was apparently due to Detector window fogging which was discovered and permanently corrected shortly thereafter.

During operating modes testing, variations of feed water pH between 3 and 8 were demonstrated to have no effect on iodine concentration in the iodinated water or Advanced Combined Iodine Dispenser/Detector operation. Also, the Advanced Combined Iodine Dispenser/Detector Iodine Source was shown to be capable of iodinating high temperature (339K(151F)) water to 5.8 ppm at the 83 cm^3/min (263 lb/day) average Shuttle Orbiter flow rate.

A series of Supporting Technology Studies were completed to further characterize Iodine Source operation analytically and experimentally, and to investigate the feasibility of operating the iodinator without an iodine detector. Operation based on the fuel cell current feedback signal (proportional to water generation/flow) and constant current operation was considered.

During operation of the Iodine Source at ambient temperature using a simulated Shuttle Orbiter fuel cell feedback current signal, iodination to 4.3 ±0.3 ppm over the nominal 70 to 123 cm^3/min (222 to 390 lb/day) flow range was achieved. A 3.2 ±1.4 ppm iodination level was achieved over the entire 23 to 173 cm^3/min (72 to 549 lb/day) Shuttle Orbiter flow range. Iodination with the Iodine Source at constant current was also shown to be feasible but over a more limited water flow range.

Experimental and analytical investigations were performed to study and characterize the influence of water flow rate, temperature, pressure and pressure spikes, dissolved hydrogen in water, pH, iodide and iodine levels within the catholyte, and anode materials on Iodine Source performance.

Iodine adsorption from solution by 316 stainless steel plumbing was investigated experimentally. Iodine concentrations in iodinated water will diminish negligibly in the plumbing after a small volume of iodinated water has passed through.

It is concluded that the Advanced Combined Iodine Dispenser/Detector is an effective system for providing desired quantities of a biocide to potable water stores of manned spacecraft. Furthermore, successful Advanced Combined Iodine Dispenser/Detector operation during testing indicates that it is a contender for use in the Shuttle Orbiter water management system. Continued development of iodination techniques is recommended to investigate the use of the Advanced Combined Iodine Dispenser/Detector for other identified spacecraft applications. Successful completion of this development will provide a water biocide system very competitive with the baseline system for the Shuttle Orbiter and will produce timely technology necessary to plan future advanced Environmental Control and Life Support System programs and experiments.

PROGRAM ACCOMPLISHMENTS

- Successfully integrated the Iodine (I_2) Source and Iodination Level Detector into a self-contained unit.

- Surpassed weight, volume and power design goals - 1.23 kg (2.7 lb) 1,213 cm^3 (74 in^3) and 5.5W achievements versus 1.36 kg (3.0 lb), 1,671 cm^3 (102 in^3) and 8.0W goals, respectively.
- Demonstrated a total of 60 days of successful operation - parametric and endurance testing.
- Characterized I_2 Source performance as a function of key operating parameters.
- Incorporated intrinsic reliability and maintainability into Iodination Level Detector light source.
- Developed and demonstrated a technique to use Shuttle Orbiter fuel cell current signal to reduce iodination system weight, volume and power by nearly 50%.

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. Water reclaimed with regenerative life support systems is inherently susceptible to microbial contamination. Water generated by fuel cells is very pure when delivered but may become backcontaminated at crew and passenger use points. In either water generation or reclamation systems, therefore, provisions must be made for microbial control.

Background

Certain methods for water disinfection offer distinct advantages in terms of weight, volume, cost, and power consumption. Once 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 iodine (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 into the potable water systems as a microbial control agent.

Under Contract NAS1-11765 a program was successfully completed that demonstrated the feasibility of dispensing I_2 into a flowing water stream using the electrochemical valve concept.(2)

Under Contract NAS9-13931, an Advanced Water Iodination System (AWIS) was

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(1) References cited in parentheses are at the end of this report.

developed that completely automated the water iodination process. Signals from an Iodination Level Detector were used to maintain a constant I_2 concentration by feeding back current corrections to the I_2 Source.(3)

The AWIS consisted of an integrated I_2 Source and an Iodination Level Detector, each containing its own instrumentation and control circuits. The I_2 Source, including its electronics, was optimized for low weight, volume and power consumption. Strict Product Assurance requirements, including maintainability, reliability, safety and materials control. The Iodination Level Detector, called the Automatic I_2 Monitor System (AIMS), had been previously developed(4) and was Government-Furnished Equipment (GFE) to the contract to demonstrate integrated operation.

While the AWIS demonstrated the automatic water iodination process, it was not packaged into a self-contained unit, nor was it totally optimized for low weight, volume and power consumption. Also, the Product Assurance requirements had only been applied to the I_2 Source of the AWIS.

The program reported herein and conducted under Contract NAS9-14624 was initiated for the development of a lightweight Advanced Combined Iodine Dispenser/Detector (ACIDD). This unit was to advance hardware maturity, as well as demonstrate complete automation of biocide addition to spacecraft water and waste management systems.

Program Objectives

The primary program objective was to develop an improved automatic water iodinator for microbial control in the potable water stores of the Shuttle Orbiter or other advanced spacecraft. The ACIDD was to be designed with the same basic operating principles and hardware considerations that were successfully incorporated into the previous AWIS, but with the following important improvements:

1. One self-contained integrated system
2. Reduction in overall weight
3. Reduction in overall volume
4. Reduction in total power consumption
5. Incorporation of maintainability, reliability, safety and materials specification into the Iodination Level Detector

The weight, volume, configuration, pressure drop and electrical characteristics were to be compatible with Shuttle Orbiter specifications, as well as with long duration, manned mission requirements.

Program Organization

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

1. Design, develop, fabricate and assemble an ACIDD to inhibit microbial growth in the Shuttle Orbiter or other advanced spacecraft potable water systems.

2. Design, develop, fabricate, assemble, functionally check out and calibrate Test Support Accessories (TSA) for testing the ACIDD under simulated Shuttle Orbiter and other advanced spacecraft potable water operation.
3. Establish, implement and maintain a mini-Product Assurance Program throughout the contractual period of performance.
4. Perform checkout, verification and operating modes testing to demonstrate the hardware maturity of the ACIDD and demonstrate all known performance and design limits.
5. Complete supporting technology studies to further expand the technology base associated with spacecraft water iodination.
6. Prepare and submit the program's documentation and data requirements.
7. Incorporate program management needed to successfully meet the program's cost, schedule, and technical performance objectives to result in customer satisfaction.

Report Organization

The objectives of the program were met. The following sections review the automated water iodination concepts, the design specifications, the results of the work completed, the conclusions reached and the recommendations made.

AUTOMATED WATER IODINATION CONCEPT

The automated water iodination concept is depicted in block diagram form in Figure 1. The concept combines an I_2 Source and an Iodination Level Detector with Control/Monitor Instrumentation (C/M I). Iodine is electrochemically metered into a flowing water stream. The I_2 metering rate is controlled by a feedback signal from the Iodination Level Detector to achieve a preselected I_2 concentration.

I_2 Source

The I_2 Source consists of an I_2 Valve, an I_2 Accumulator and an I_2 Dispenser, as shown in Figure 2. The electrochemical valve consists of an anion exchange membrane between two noble metal electrodes. 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, 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 3 depicts the I_2 Valve reactions. Oxidation of the specific anion transferred, however, determines the process efficiency. If 100% of the

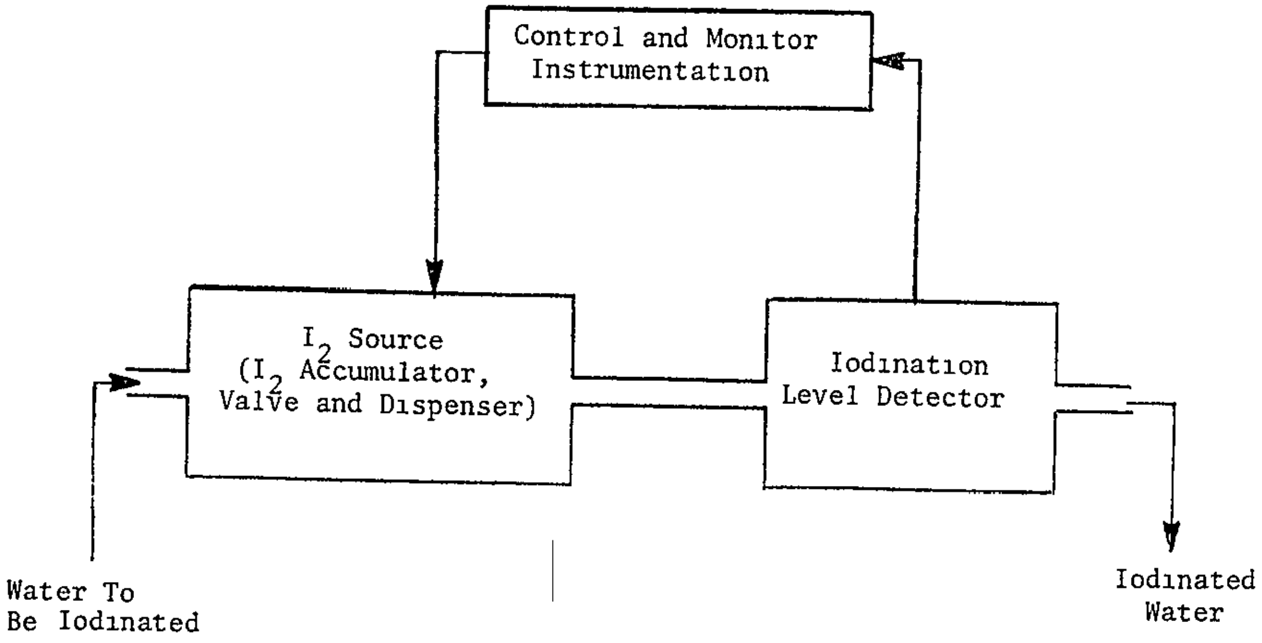


FIGURE 1 AUTOMATED WATER IODINATION CONCEPT

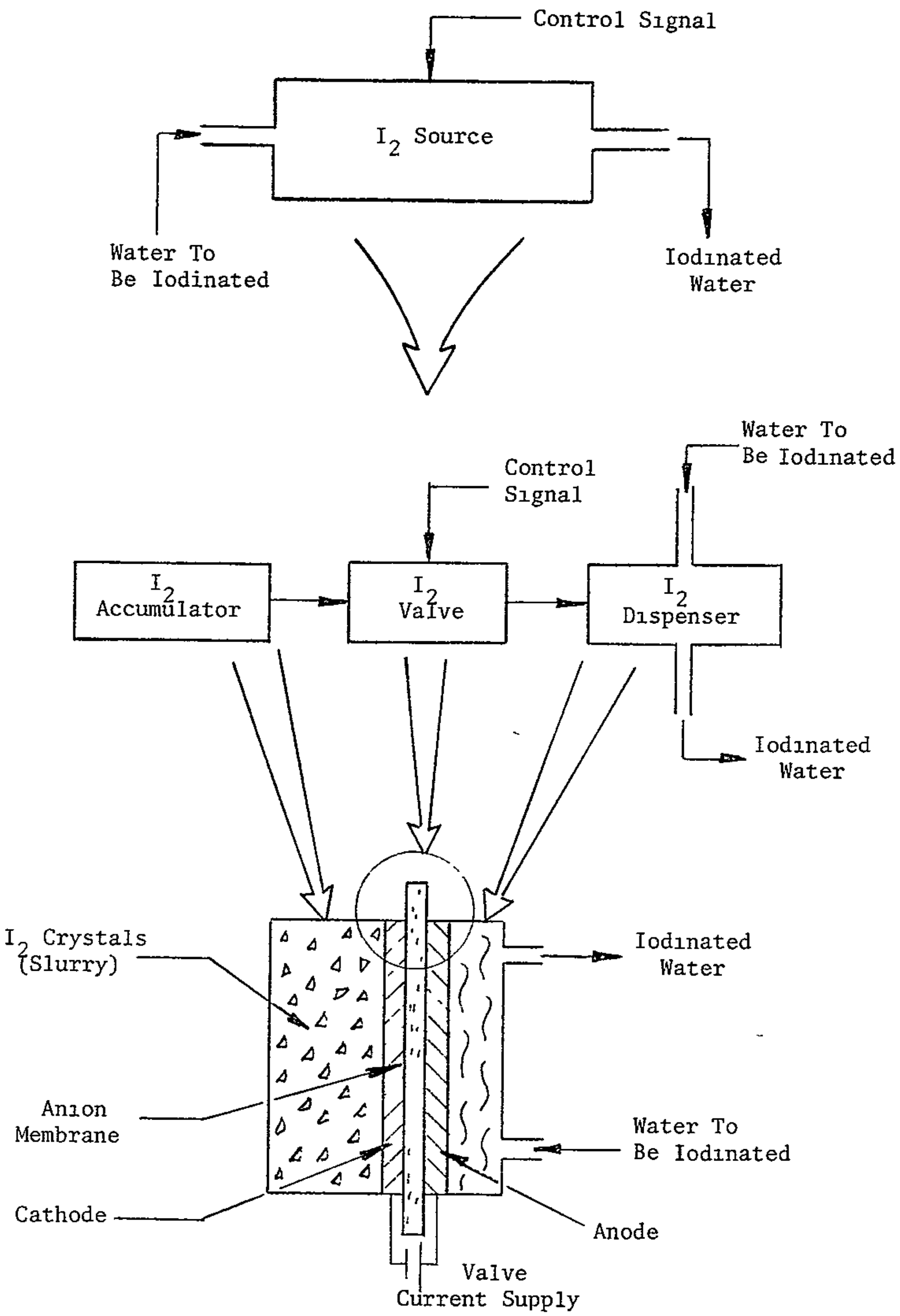
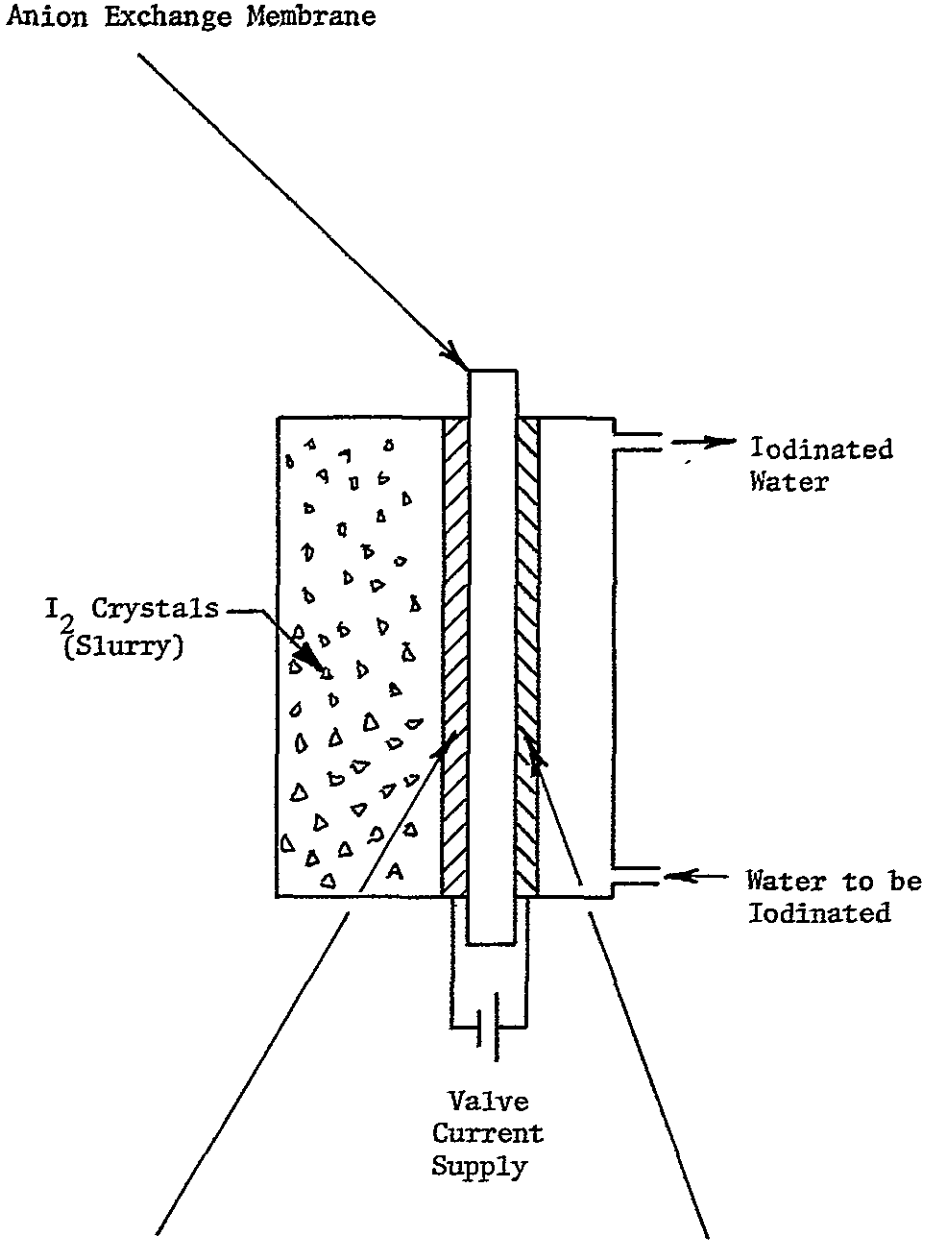


FIGURE 2 I_2 SOURCE SCHEMATIC



Cathode		Anode
$I_2 + 2e^- = 2I^-$	Principal	$2I^- = I_2 + 2e^-$
$3I_2 + 2e^- = 2I_3^-$	Competing	$2I_3^- = 3I_2 + 2e^-$
		$H_2O = \frac{1}{2} O_2 + 2H^+ + 2e^-$

FIGURE 3 I_2 VALVE REACTIONS

current flow is via I^-, the current efficiency will be 100%, via triiodide (I_3^-), the current efficiency will be 300%. For oxidation of water at the anode instead of I^-, the current efficiency will be 0%. Actual operation indicates a complex combination of all three reactions.

Iodination Level Detector

The Iodination Level Detector concept(4) is described in Figure 4. White light passes through the iodinated water. The blue portion of the light is attenuated by the I_2 in water. The intensity level of the blue portion of the light is detected selectively and converted into an electrical signal by a photodetector/filter combination.

The red component of the light passing through the iodinated water is unattenuated by the I_2 and therefore serves as a reference. The intensity of the red component of the light is sensed by a second photodetector/filter combination. A beam splitter focuses equal amounts of light on the two photodetector/filters.

The signal corresponding to the unattenuated red light component is scaled to be equivalent to unattenuated blue light (zero I_2 concentration) to compensate for the difference of the intensity of these components in the white light. The ratio of the attenuated blue signal to the equivalent unattenuated blue signal is determined electrically. The resulting readout is proportional to the I_2 concentration, as illustrated on the bottom half of Figure 4.

Control and Monitor Instrumentation

The signal from the Iodination Level Detector is continuously compared with a constant reference voltage set to correspond to the desired I_2 concentration to be maintained. If the signal from the Detector is too low (I_2 concentration too low) the integrator/current source of the C/M I increases current flow to the I_2 Source until the desired I_2 concentration is achieved. The current then stays constant. The opposite action occurs when the I_2 concentration is too high.

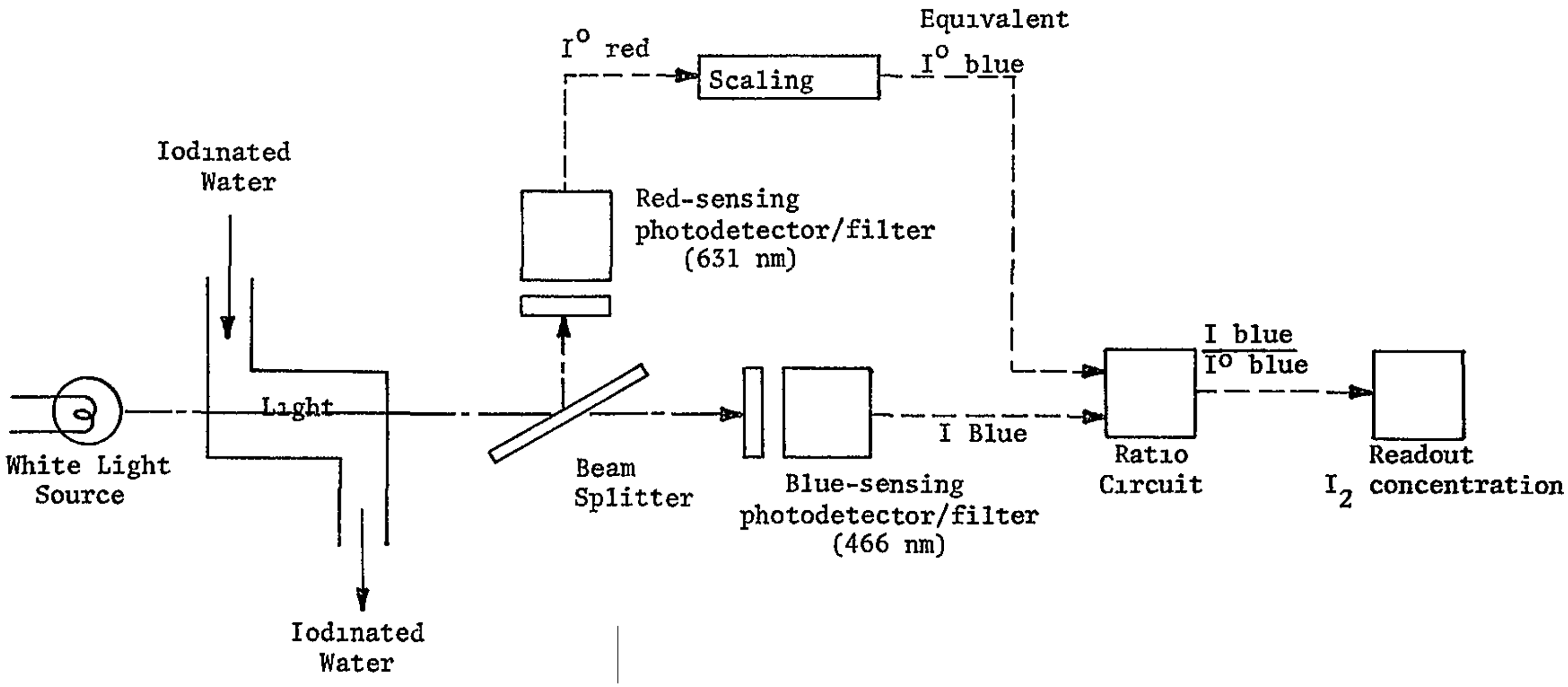
ACIDD DESIGN SPECIFICATION

The design specifications used for the ACIDD were primarily governed by the requirements of the Shuttle Orbiter Potable Water System. Secondary emphasis was placed on design requirements of future long-duration advanced spacecraft missions where all water within the spacecraft environment would be recycled.

Although the specifications presented herein are limited with respect to the ACIDD's application to the Regenerative Life Support Evaluation (RLSE) Experiment,(5) the ACIDD is projected for use as a part of that experiment, and its requirements have been given consideration in the evaluation of ACIDD performance.

Detailed Design Specifications

Table 1 lists the contractual design specifications for the ACIDD. Table 2, which references Tables 3 through 6, is an expanded design specification



Term definition:

I_o = light intensity signal attenuated by I_2
I^o = light intensity signal unattenuated by I_2
C - concentration of attenuating species (I_2)

Readout is approximately linear because

$C \propto I$ blue/I^o blue, approximately

Beer's Law of
light attenuation: $I/I_o = e^{-kc} = 1-kC$ when $kC \ll 1$ ($C=$ small)
(k = constant)

FIGURE 4 IODINATION LEVEL DETECTOR CONCEPT

TABLE 1 GENERAL SYSTEM SPECIFICATION (CONTRACTUAL)

Water Supply	From Fuel Cells
Supply Flow Rate, kg/kW-h (Lb/kW-h)	0.34 to 0.43 (0.75 to 0.95)
Fuel Cell Exit Temperature, K (F)	339 to 352 (150 to 175)
System Pressure, kN/m^2 (Psia)	103 to 413 (15 to 60)
Known Contaminants, pH	6.5 to 7.5
Water Use Flow Rate, kg/h (Lb/Day)	Up to 27.3 (1440)
Water Use Temperature, K (F)	
Hot	339 to 352 (150 to 160)
Cold	277 to 289 (40 to 60)
Water Use Pressure, kN/m^2 (Psia)	207 (30) at 22.7 kg/h (1200 Lb/Day)
Fuel Cell Power, kW	5 Nominal [a] 7 Maximum [b]
Nominal I_2 Concentration, Ppm	5 (+1, -2)
Hardware Configuration	Flight Qualifiable
Design Parameters to be Minimized	Maintenance, Weight (1.36 kb (3 Lb) maximum as a goal) Volume 21.6 x 10.2 x 7.6 = 1674 cm^3 (8.5 x 4 x 3 In = 102 In^3) as a goal Power (<8W as a goal) Servicing Initial and Operating Costs
Materials	Meet NASA MSCM-8080 Standards and SE-R-0066, Rev. A. Specifications

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(a) 28.4 cm^3/Min (90.2 Lb H_2O/Day)
(b) 50.3 cm^3/Min (159.7 Lb H_2O/Day)

TABLE 2 ACIDD DESIGN SPECIFICATIONS

Water Supply (Shuttle Orbiter)	
Composition (Worst Case)	See Table 3
Composition (Expected)	See Table 4
Flow Rate,(a) cm^3/Min (Lb/Day)	
Nominal	83.2 (264)
Maximum	172.5 (547)
Minimum	22.7 (72)
pH at 298K (77F)	6 to 8
I_2 Concentration, Ppm	
Nominal	5 (+1, -2)
Range	0 to 10
Temperature, K (F)	
Nominal	294 (70)
Maximum	344 (160)
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 Orbiter)	
Mission Duration, Day	7
Water Processed/Mission, kg (Lb)	841 (1850)
I_2 Needed/Mission (Nominal 5 Ppm)	
Weight, g (Lb)	4.19 (0.0092)
Volume, cm^3 (In^3) at 4.93 g/cm^3 (0.178 Lb/In^3)	0.851 (0.052)
Number of Shuttle Missions (Reusability)(b)	22
Capacity (RLSE Experiment, 3 Men)	
Mission Duration, Day	30
Urine Processed, kg/Day (Lb/Day)	
Nominal	6.0 (13.2)
Minimum	1.7 (3.8)
Maximum	12.0 (26.4)

continued -

(a) Contractual requirements specify a water flow rate range of 28.4 to 50.3 cm^3/Min (90 to 160 Lb/Day).

(b) For iodination level of 5 Ppm of I_2 and 25% of accumulator volume allotted for water to make slurry.

Table 2 - continued

Capacity (RLSE Experiment, 3 Men) - continued	
Flush Water Requirement, kg/Day (Lb/Day)	1.8 (4.0)[a]
I_2 Needed/Mission (Nominal 5 Ppm)	TBD
Weight, g	TBD
Volume, cm^3 at 4.93 g/cm^3	TBD
Number of Missions (Overcapacity)	TBD
Capacity (Long-Term Mission)	
Mission Duration, Day	180
Water Sources, kg/Day (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 (Lb)	30.3 (0.0667)
Volume, cm^3 (In^3)	6.15 (0.375)
Number of Missions (Overcapacity)	2.5
Total Weight (Goal), kg (Lb)	$\leq$1.36 (3.0)
Pressure Drop, kN/m^2 (Psid) at 172.5 cm^3/Min (548 Lb/Day)	$\leq$6.89 (1.0)
Overall Dimensions (Goal), cm (In)	21.6 x 10.2 x 7.6 (8.5 x 4 x 3)
Total Power (Goal), W	8.0
Vibration and Shock Levels (Goal)	See Table 5
Electrical Power	
Type, Volt AC/Phase	115/Single
Range in Cycles, Hz	360 to 440
Design Safety Factors	See Table 6

(a) Estimated; based on past projections for urine flush requirements.
(b) Cabin Temperature and Humidity Control Subsystem.
(c) Carbon Dioxide Reduction Subsystem (Sabatier).

TABLE 3 WORST CASE COMPOSITION OF FUEL CELL WATER

Property	Level
pH at 298K (77F)	6 to 8
Total Solids	20 Ppm
Odor	None at Threshold (Odor Number of 3)
Turbidity	11 Units
True Color	15 Units
Total Organics	10 Ppm
Particulate Matter (Number of particles per 500 ml fluid)	
0 - 10 microns	Unlimited
10 - 25 microns	1000
25 - 50 microns	200
50 - 100 microns	100
100 - 250 microns	10
Al	For Reference Only
Cd^{+2}	0.01 Ppm
Cl^{-}	1.0 Ppm
Cr^{+6}	0.05 Ppm
Cu^{+2}	0.3 Ppm
Fe^{+3}	0.3 Ppm
Pb^{+2}	0.05 Ppm
Mg^{+2}	For Reference Only
Mn^{+2}	0.05 Ppm
Hg^{+2}	0 005 Ppm
Ni^{+2}	0.05 Ppm
K^{+}	For Reference Only
Se^{+4}	0.05 Ppm
Silica	For Reference Only
Ag^{+}	0.05 Ppm
NH_4^{+}	0.5 Ppm
Zn^{+2}	5.0 Ppm

TABLE 4 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	5.0	4.5
Inorganic Carbon, ppm	Reference Only	<1.0(b)	<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

TABLE 5 LIFT OFF/BOOST RANDOM VIBRATION AND SHOCK LEVELS(a)

Vibration

20 to 80 Hz at 3 db/octave increase

80 to 180 Hz at 0.06 G^2/Hz

180 to 200 Hz at 12 db/octave increase

200 to 400 Hz at 0.1 G^2/Hz

400 to 450 Hz at - 12 db/octave decrease

450 to 2000 Hz at 0.06 G^2/Hz

Shock

Contractual Requirements

±6G, Any Direction

Design Specification Used

20G terminal sawtooth pulse for 10 millisecond duration

(a) Used for design considerations only.

TABLE 6 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	$\frac{\text{Burst Pressure}}{\text{Max Operating Press}}$ ≥2 0	
	Gases or Liquids plus Gases		
	Proof Pressure	$\frac{\text{Proof Pressure}}{\text{Max Operating Press}}$ ≥2 0	
	Burst Pressure	$\frac{\text{Burst Pressure}}{\text{Max Operating Press}}$ ≥4 0	
	Structural		
	Strength-Stress based on Proof Pressure	$\frac{\text{Yield Strength}}{\text{Stress}}$ ≥1 1	
	Strength-Stress based on Burst Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}}$ ≥1 2	
Metal Tubing and Fittings	Max Operating Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}}$ ≥4 0	
		$\frac{\text{Yield Strength}}{\text{Stress}}$ ≥2 0	
Flexible Hosing	Max Operating Pressure	$\frac{\text{Ultimate Strength}}{\text{Stress}}$ ≥4 0	

adopted by Life Systems, Inc. (LSI) as a goal.(6) Table 2 includes specifications applicable to the Shuttle Orbiter,(6) the specifications generally accepted for a 90-day resupply mission for a six-man crew (as reflected in the Space Station Prototype Program (SSP)) and limited specifications for the RLSE mission. The specified water flow rate range of 22.7 to 172.5 cm^3/min (72 to 547 lb/day) exceeds the contractual requirements of 28.4 to 50.3 cm^3/min (90.2 to 159.7 lb/day).

Tables 3 and 5 contain the "worst case" composition of the synthetic fuel cell water and the Shuttle Orbiter lift off/boost random vibration levels, respectively. These specifications were used for design considerations only, although compatibility of the iodination concept with "worst case" water was demonstrated by the iodinator developed under the previous contract.(3) The actual analytical results of Pratt and Whitney's fuel-cell generated water, Table 4, indicate that it is very pure. Program testing was performed with water of purity comparable to that reflected in Table 4.

Table 6 lists the design safety factors that were employed in the design of the ACIDD hardware. The safety factors correspond to those listed in the Shuttle Orbiter specification.(6)

Shuttle Orbiter Potable Water System

The ACIDD must be compatible with the projected Potable Water System of the Space Shuttle. A schematic of the system, with proposed ACIDD integration, is presented in Figure 5. 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 growth.

Figure 5 shows that an installed redundancy concept is proposed for ACIDD utilization. Both an operating and non-operating unit is installed with a redundant Iodination Level Detector downstream of the two units.

System Interfaces

The ACIDD must interface with the potable water system, the electrical system for power, onboard data management and the structural system of the Shuttle or other advanced spacecraft. These interfaces are described and quantified in Table 7. The mounting arrangement for the ACIDD and dimensional information are described in Figure 6.

PREDESIGN CONSIDERATIONS

The iodination system developed under the previous contract (AWIS, NAS9-13931) was shown to be effective in maintaining 5 (+1, -2) ppm over an extended time period and operating conditions.(3) Thus, the proven design features of the AWIS were maintained while pursuing the objectives of integrating the I_2 Source and Iodination Level Detector and reducing weight, volume and power for the design of the ACIDD. Improved maintainability and reliability of the integrated unit were also established as a goal.

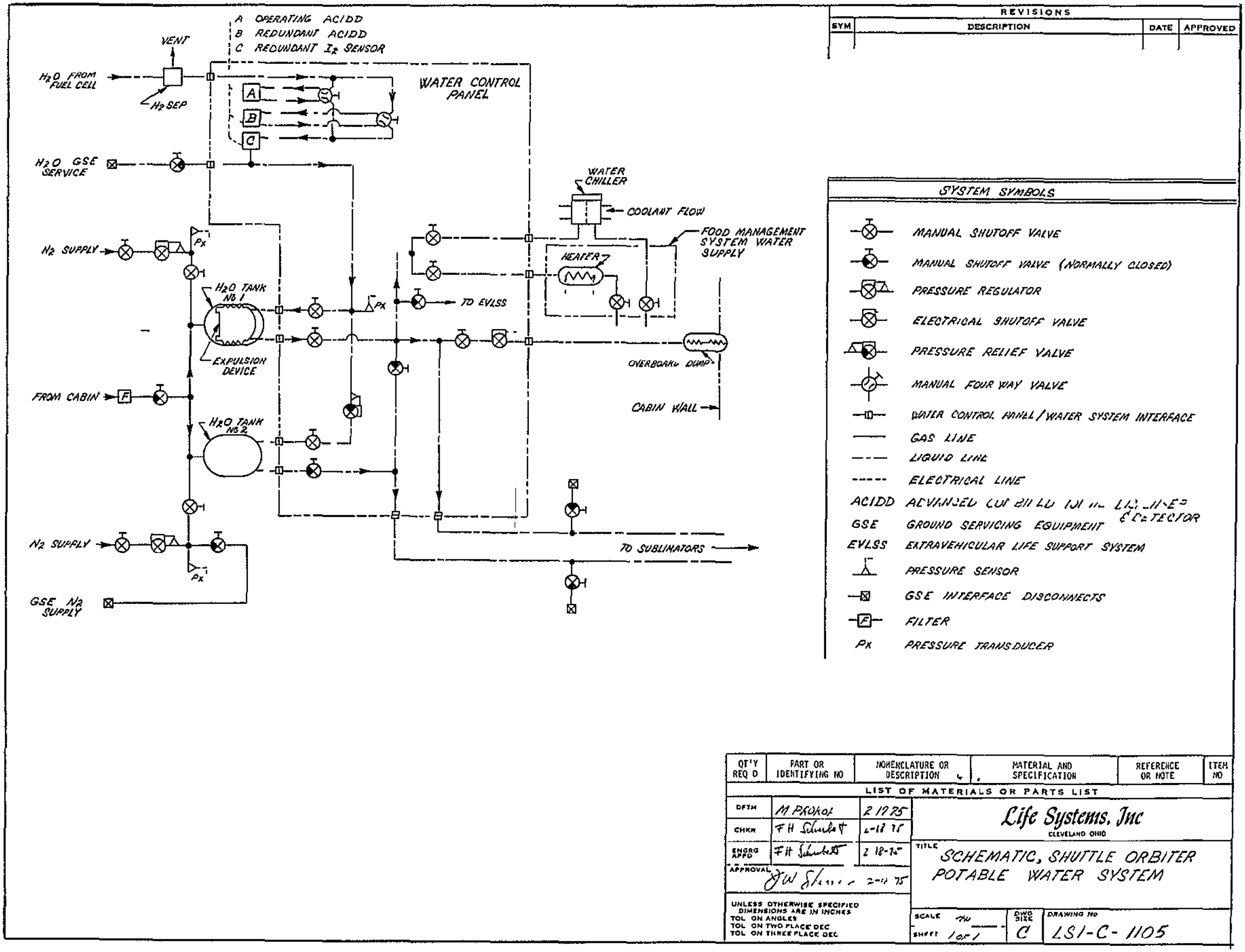
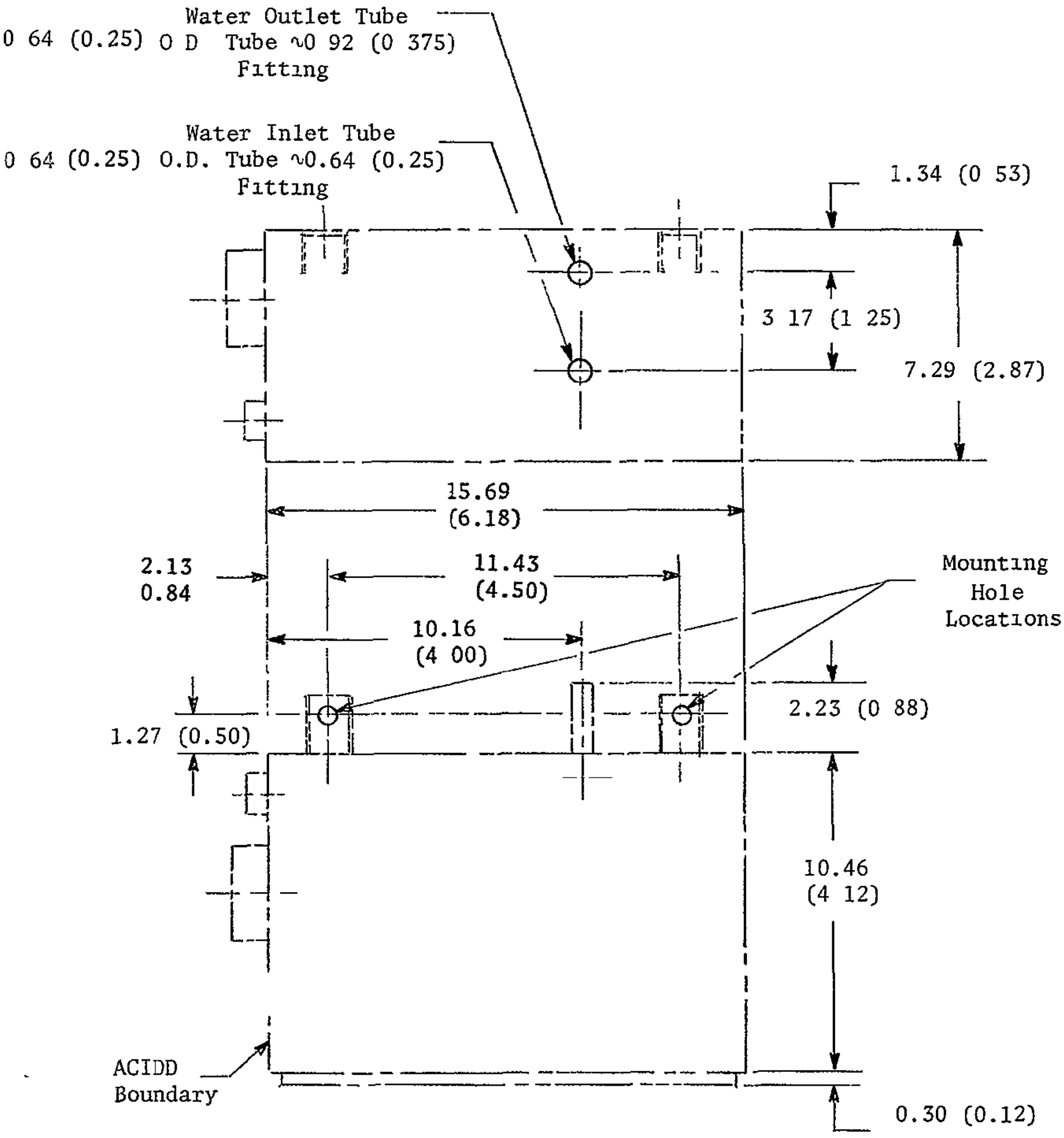


FIGURE 5 PROPOSED ACIDD INTEGRATION INTO THE SHUTTLE ORBITER POTABLE WATER SYSTEM

TABLE 7 ACIDD INTERFACES AND RANGES

Electrical	
Power Input	
Voltage Level, VAC	115
Phase	Single
Frequency, Hz	360 to 440
Power Level, W	8
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 4
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)
Temperature, K (F)	277 to 344 (40 to 160)
Pressure, kN/m^2 (Psia)	55 to 248 (8 to 36)
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)
Temperature, K (F)	277 to 344 (40 to 160)
Pressure, kN/m^2 (Psia)	48 to 248 (7 to 36)
Structural	
Mounting Bolts	1/4-28 NF Socket Head Cap Screws
Mounting Arrangement	See Figure 6



NOTE. Dimensions shown in cm with inches in parenthesis

FIGURE 6 ACIDD MOUNTING ARRANGEMENT

The following proven AWIS design features were incorporated into the ACIDD design:

1. Anion exchange membrane for the I_2 Source: (LSI-001)
2. Noble metal screen electrodes.
3. Highly corrosion-resistant materials in all portions of the ACIDD that contact either I_2 or iodinated water.
4. Materials resistant to atmospheric corrosion for parts not contacting liquid.
5. Radial water flow distribution in the I_2 Dispenser.
6. Bipolar control of I_2 Valve current to permit conversion of excess I_2 dispensed into the water at low flow rates into I^- for return to the accumulator.
7. Use of dual wavelength photometric Iodination Level Detector principle(4) for providing an electrical signal proportional to I_2 concentrations.
8. Automatic feedback control of the current required to iodinate the water to a given level, using RC integration.

Weight and Volume Reduction

The AWIS built and tested under the previous program was quite heavy and bulky. Even though the I_2 Source alone had a weight and volume of only 0.89 kg and 447 cm^3, (1.96 lb and 27.3 in^3), respectively, the overall unit weighed 5.2 kg (11.4 lb) and had a volume of 7,620 cm^3 (465 in^3). A picture of the AWIS is shown in Figure 7.

The contractual requirements for the ACIDD (see Table 1) called for a maximum dry weight of 1.36 kg (3.0 lb) and overall dimensions of 21.6 x 10.2 x 7.6 cm (8.5 x 4 x 3 in) requiring a substantial design effort to achieve the reductions in weight and volume of the combined unit.

The initial design approach called for the I_2 Source of the AWIS to be integrated with a more compact government-furnished Iodination Level Detector.(7) This unit, when delivered, weighed 1.295 kg (2.85 lb), not including any of the required detector electronic assemblies. The combined weight of the two units would have greatly exceeded the 1.36 kg (3.0 lb) requirement for the ACIDD. A decision was therefore reached with NASA JSC to design a completely integrated, lightweight ACIDD that would meet the weight goal, as well as significantly reduce the volume of the unit.

The following factors were considered for weight and volume optimization:

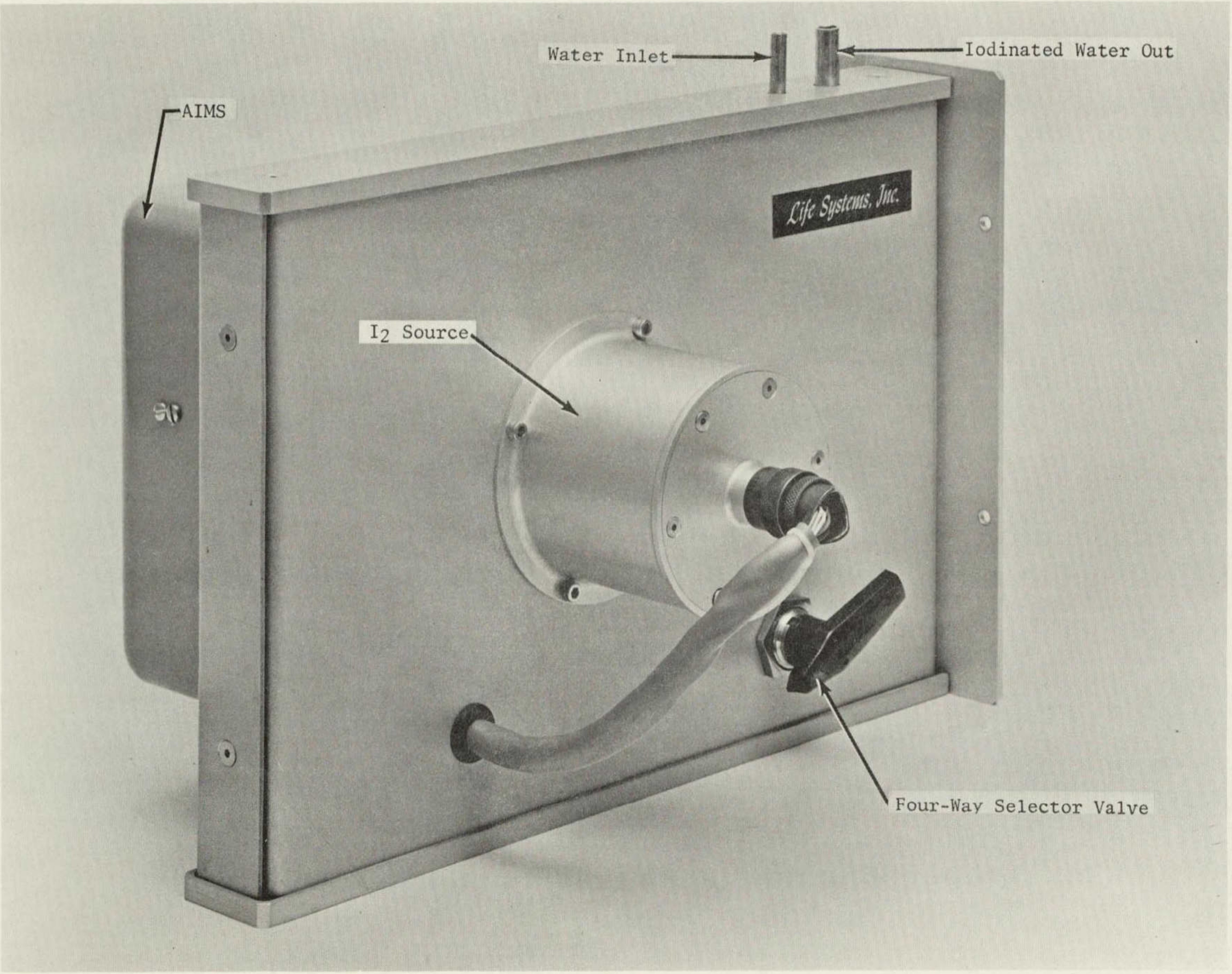


FIGURE 7 AWIS ASSEMBLY

1. Removal of all structurally unnecessary materials from both the detector and I_2 Source.

2. Full integration of the I_2 Source and detector to form a single compact unit with shared structural members and no interconnecting plumbing.

3. Elimination of off-the-shelf separate power supplies by designing and fabricating light, efficient, common power supplies for both the Detector and C/M I circuits.

4. Efficient packaging of electronic components and designing of customized circuit boards to fit into available spaces around the I_2 Source and Detector.

Power Reduction

The power requirements for previously built detector light sources (including associated circuitry) were typically 9W.(7) A requirement of a total ACIDD power of 8W was specified (see Table 1). Reduction in the lamp voltage and current, therefore, was selected as the major technique for reducing the ACIDD power requirements. Also, use of two, highly efficient, customized power supplies for all the circuitry was selected to decrease power consumption.

Improved Reliability and Maintainability

The following reliability and maintainability features were in the ACIDD design.

1. Design of electronic circuit such that all components in the present unit can be replaced with specially screened and burned-in electronic components (i.e., HI-REL3E parts) for a flight unit.

2. Inclusion of redundant seals for a backup containment of water in the I_2 Detector in case of sample-cell window breakage (sealing of the focusing lenses, as well as the regular sample-cell windows against the sample-cell tube).

3. Improvement in the service life and reliability of the I_2 Detector source lamp by lowering the filament voltage.

4. Provision for simple lamp replaceability and interchangeability.

5. Provisions for lamp replacement without tools or cover removal.

6. Widening of the filling port of the I_2 Source Accumulator and modification of its configuration to facilitate complete filling of its internal volume with I_2 crystals.

7. Mounting of electronic circuit boards with components in an accessible position to allow for ease in replacement, adjustment and troubleshooting.

ACIDD HARDWARE DEVELOPMENT

The overall development of the ACIDD hardware was based on previously proven concepts, i.e., the AWIS(3) and the Iodination Level Detector.(4) To achieve the integration both electrically and mechanically and to meet the stringent requirements of weight, volume and power, a breadboard of the electronic circuits was developed and tested and a full-scale mock-up was fabricated. Based on the results of these tests and configuration investigations the actual ACIDD hardware was developed.

Breadboard Iodinator

A Breadboard Iodinator Unit was assembled incorporating the AWIS Model IX-SA I_2 Source,(2) the government-furnished optical bench of an Iodination Level Detector and a breadboard integrated electronics package. The electronics package contained all the circuits for I_2 detection and for supplying and controlling the I_2 Valve current feedback. This Breadboard Iodinator is shown in Figure 8. It was used to successfully (1) develop and test the ACIDD integrated electronics circuit design, (2) develop a reduced-power light source and test it for effective operation, (3) test the suitability of the Iodination Level Detector configuration for incorporation into the ACIDD system and (4) project the capability of the actual ACIDD hardware.

A portion of the Supporting Technology Studies was also performed using the Breadboard Iodinator (see Section on Supporting Technology Studies).

ACIDD Mock-Up

Two detailed mock-ups of the ACIDD were designed and constructed to assist in developing the packaging and mounting configurations of the ACIDD components to meet system weight and volume goals. These mock-ups also permitted physical manipulation of components to determine and demonstrate ease of system maintainability.

The first mock-up constructed demonstrated that the weight and volume goals could be met with the actual ACIDD hardware. The mock-up also showed that these goals could be exceeded with a modified configuration. The modifications were incorporated into a second mock-up which is pictured in Figure 9.

System Hardware

The actual ACIDD hardware was designed and fabricated incorporating the water iodination concepts and results of the Iodinator Breadboard and mock-up activities.

Concept

The overall operating principle of the ACIDD was summarized in Figure 1.

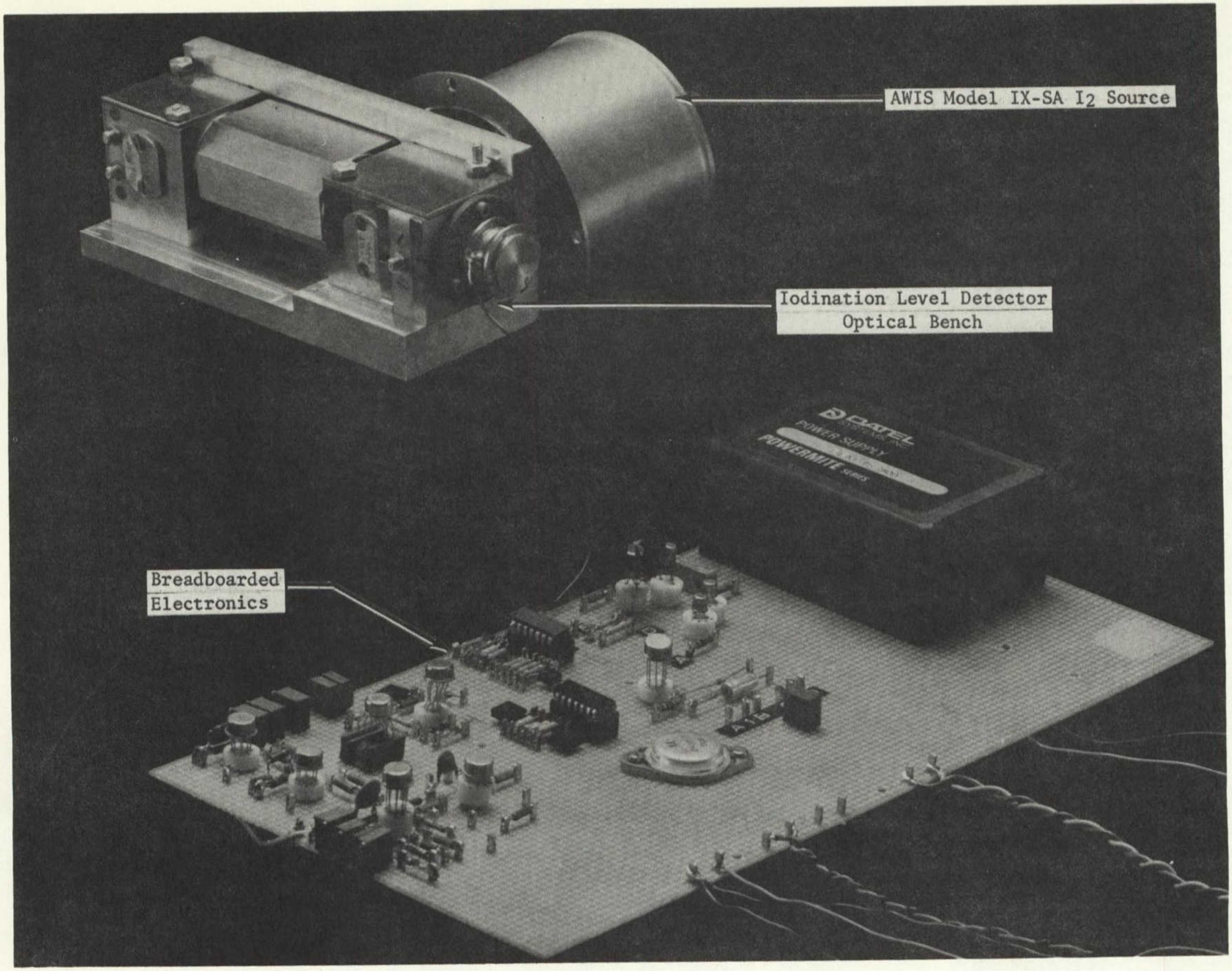


FIGURE 8 BREADBOARD IODINATOR

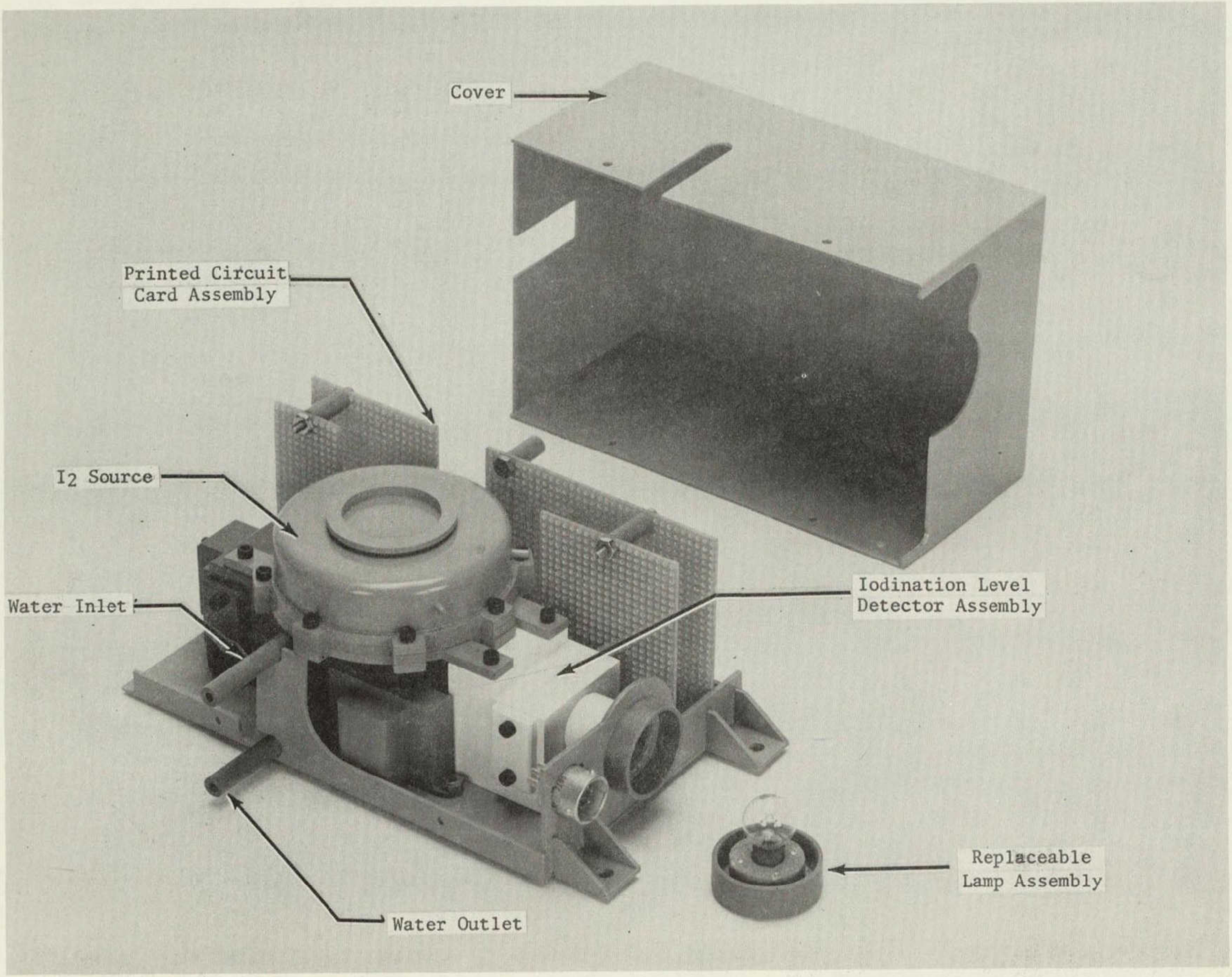


FIGURE 9 ACIDD MOCKUP

Water to be treated passes into the I_2 Source where it is iodinated to a level controlled by the valve current flowing to the Source. The iodinated water then flows through an Iodination Level Detector which puts out an electrical signal proportional to the I_2 concentration. This signal causes the C/M I to adjust the current to the Source until water is iodinated to the desired level. The Detector then "sees" the proper concentration of I_2 and the current to the Source becomes constant. If the flow rate changes, a different I_2 generation rate will be required to maintain a constant I_2 concentration and the appropriate current adjustment will be made automatically.

A more detailed ACIDD functional block diagram, shown in Figure 10, describes the control circuitry. The signals from the blue-sensing and red-sensing photodetector/filters (see Figure 4) are amplified and scaled such that their ratio equals 1 or less, corresponding to zero or greater I_2 concentration. A ratio amplifier puts out a signal proportional to this ratio. The difference between this signal and a fixed set point signal, corresponding to the desired I_2 concentration, is computed by an error amplifier. The resulting error signal in turn causes the output of an integrator to decrease if the Iodination Level Detector signal is higher than the set point or increase if the Detector signal is lower. The current from the bipolar current source to the I_2 Source will then decrease or increase, respectively, until the Detector "sees" the I_2 level corresponding to the set point. The circuit includes an internally adjustable set point signal in addition to the provision for external control of the set point.

The lamp control feedback circuit, utilizing a photodetector, maintains the light output from the Iodination Level Detector light source at a constant level by varying the lamp voltage up or down as necessary. This circuit will permit compensation for aging in the lamp filament and/or deposition of tungsten on the lamp envelope, either of which can change the light output of the lamp.

Integrated ACIDD

Figure 11 is a photograph of the assembled ACIDD with its cover removed. The figure shows the efficient space utilization of the design. This entire unit weighs only 1.23 kg (2.7 lb) and occupies a total volume of only 1213 cm^3 (74 in^3). The major assemblies, i.e. the I_2 Source Assembly, the Iodination Level Detector Assembly and the Printed Circuit Card Assembly, are identified in Figure 11.

Water flows into the center of the baseplate of the I_2 Source. The iodinated water outlet from the I_2 Source exits into the Iodination Level Detector sample-cell through an internally sealed connection. The baseplate of the I_2 Source forms one-half of the optical bench structural support and the aluminum baseplate for the total ACIDD assembly forms the other half.

The electronic circuit cards are mounted to conform to the contour of the integrated I_2 Source/Detector. The power transformers and power transistors in the circuit (not shown) are likewise mounted in spaces remaining in the enclosure to optimize space utilization. For flight use electronics will be protected by potting.

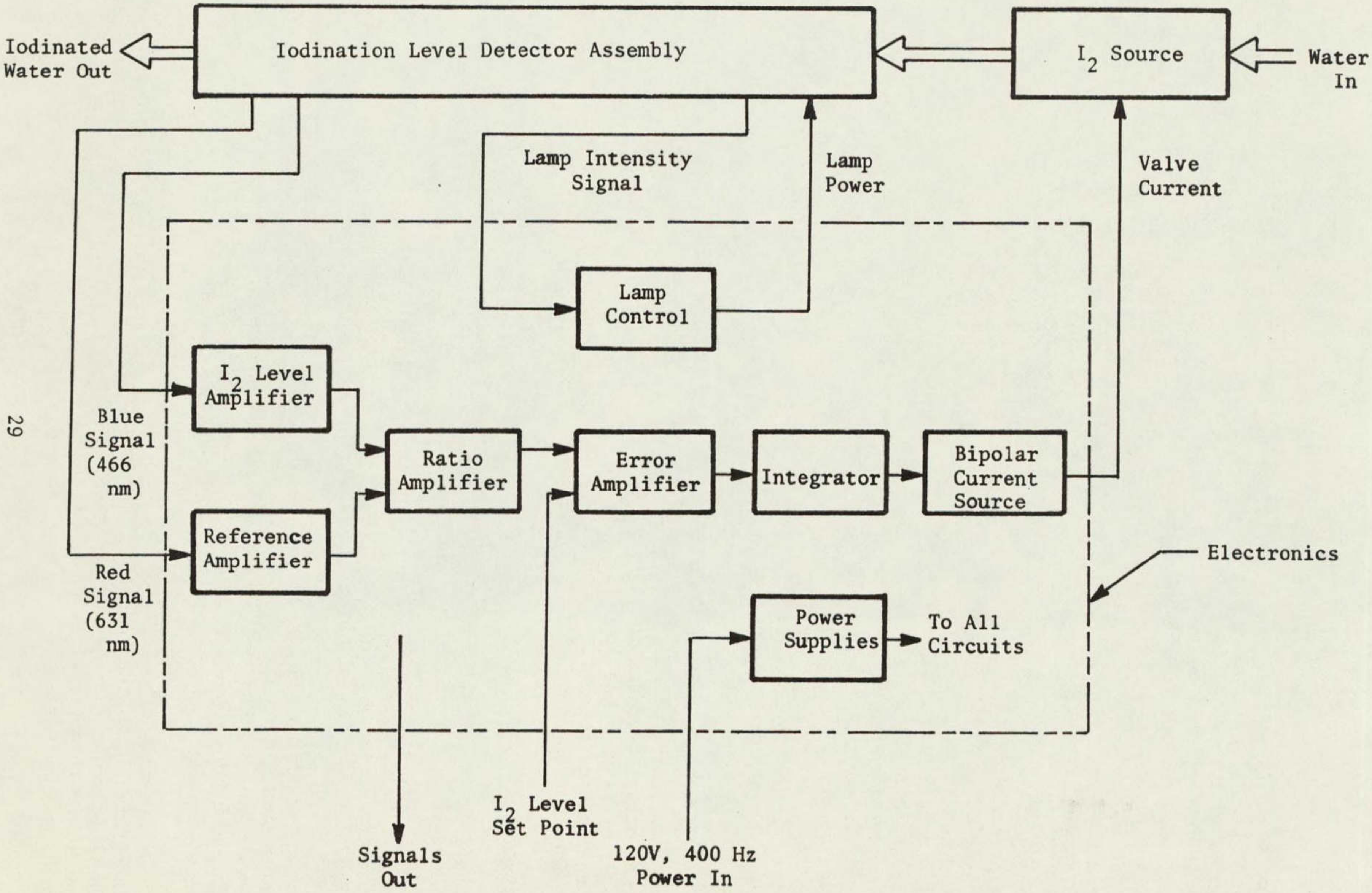


FIGURE 10 ACIDD FUNCTIONAL BLOCK DIAGRAM

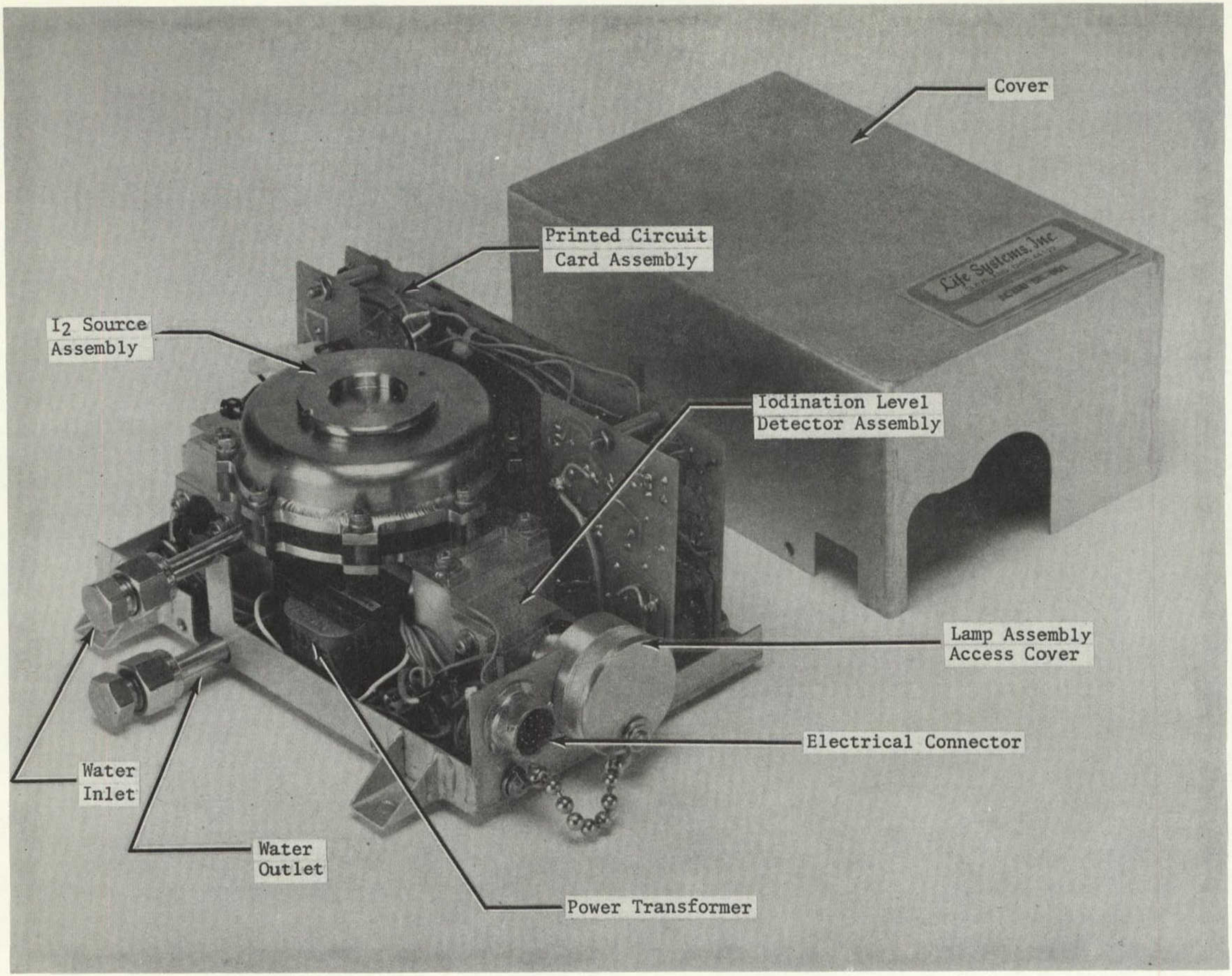


FIGURE 11 ASSEMBLED ACIDD

ACIDD Interface Configuration

Figure 12 is a photograph of the fully-assembled ACIDD illustrating the mechanical, electrical and water interfaces. The overall outside dimensions are also indicated. The detector lamp access cap permits replacement of the light source lamp without removal of the cover of the ACIDD.

Hardware Achievements versus Design Goals

The design goals of reduced weight, volume and system power were surpassed. These achievements are summarized below.

1. ACIDD actual weight of 1.23 kg versus 1.35 kg design goal (2.7 lb versus 3.0 lb).
2. ACIDD actual volume of 1213 cm^3 versus 1671 cm^3 design goal (74 in^3 versus 102 in^3).
3. ACIDD actual average system power of 5.5W versus 8.0W design goal.
4. ACIDD actual dimension of 15.7 x 7.3 x 10.5 cm versus 21.6 x 10.2 x 7.6 cm design goal. (6.2 x 2.9 x 4.1 in versus 8.5 x 4 x 3 in).

PRODUCT ASSURANCE

A mini-Product Assurance Program was implemented during the ACIDD 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 ACIDD design and configuration during subsequent development. Reliability was included to identify and eliminate any failure modes that might prevent application of the ACIDD to manned spacecraft such as the Shuttle Orbiter. Maintainability activities were performed to ensure that the ACIDD 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 ACIDD operating characteristics would not 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 ACIDD 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 of all design drawings. This minimum activity ensured that no defective components or parts were incorporated into the ACIDD and that the design drawings correctly reflected the progression of the design from initial concept through the final engineering drawings.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

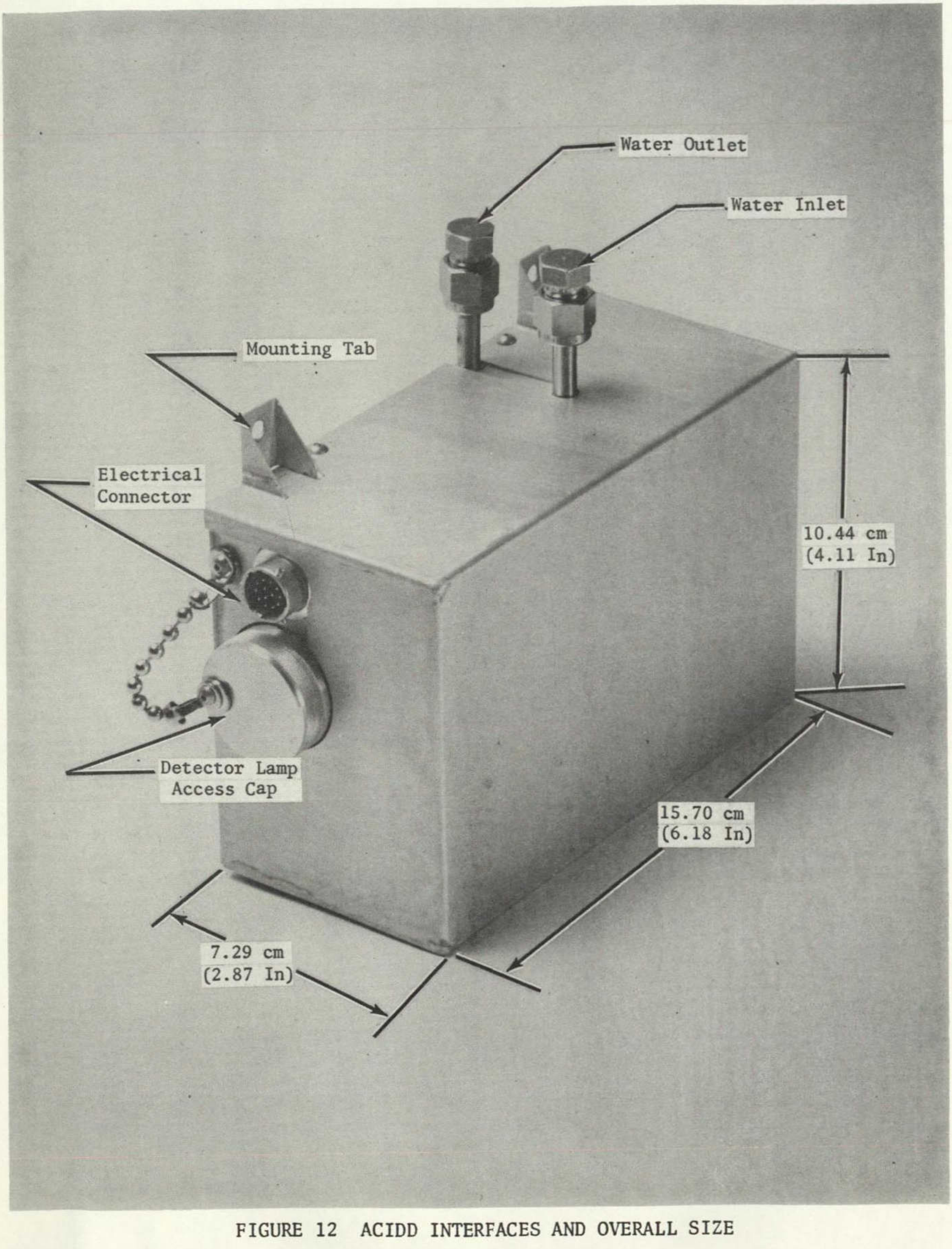


FIGURE 12 ACIDD INTERFACES AND OVERALL SIZE

Detector (see Figure 13). In the event of an indicated failure to one unit, the crew could switch over to the standby unit by manipulating two valves. This would allow the mission to continue.

Maintainability

The ACIDD 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 ACIDDs with redundant sensor as shown in Figure 13.

The ACIDD was designed to eliminate in-flight maintenance. In addition, between-flight servicing was virtually eliminated by sizing the accumulator of the ACIDD to store sufficient I_2 for 22 seven-day Shuttle missions. Any ground servicing is envisioned as a direct unit replacement with the exception of detector light bulb failure. The lamp was designed to be easily replaced. The ACIDD was also designed so that standard Shuttle fasteners and fittings can easily be incorporated into the hardware.

Safety

The ACIDD was designed to include personnel and equipment safety features that minimize danger to the crew and possible damage to the equipment. The ACIDD design, as projected for application aboard the Shuttle Orbiter, was evaluated with regard to system safety. No inherent safety hazards were identified. Other safety activities performed included: monitoring the ACIDD design to insure that the established safety design criteria were followed, evaluating the safety consequences of ACIDD failure modes with regard to personnel and equipment safety, and insuring that proper safety precautions were taken during the fabrication and testing of the ACIDD.

Materials Control

A Materials Control Program was implemented for the design of the ACIDD. The intent of the Materials Control Program was to select, as a goal, materials of construction that comply with Shuttle Orbiter flammability, odor and offgassing requirements, and that are compatible with the operating environment of the ACIDD. The materials analysis process consisted of reviewing the ACIDD drawings and listing all the materials. During this process unacceptable materials were identified and suggestions were made to design engineers listing candidate acceptable materials. Acceptable materials were selected and design drawings were revised to incorporate the new materials. The major metallic and nonmetallic materials that are incorporated into the ACIDD are listed in Table 8.

The major nonmetallic materials were established as acceptable, based on documented test results found in NASA Document MSC-02681, Nonmetallic Materials Design Guidelines and Test Data Handbook.(8)

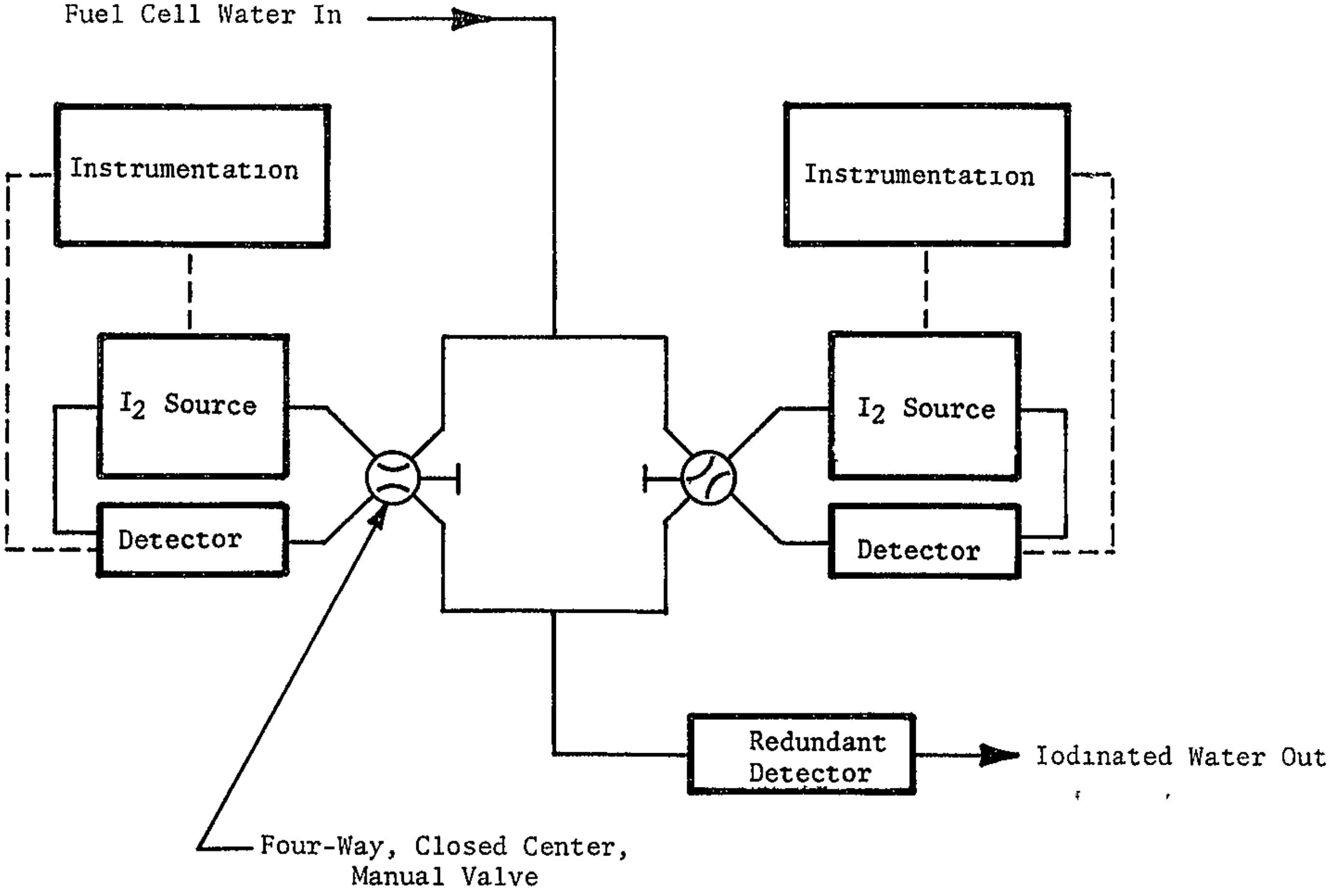


FIGURE 13 FAIL-OPERATIONAL/FAIL-SAFE CONCEPT

TABLE 8 MATERIALS SUMMARY

Major Metallic Materials

Stainless Steel, 304, 18-8
Aluminum, 6061T6, 2011T3, 6060T6
Hastelloy C
Brass
Gold
Copper
Nickel
Silver
Solder 60/40

Major Nonmetallic Materials

Polysulfone
Viton A
Glass
Teflon
Eccobond 787AB Epoxy
Fiberglass/Epoxy (FR4)
Eccofoam EFF-14

For some minor nonmetallic materials (<0.1 lb) there is no offgassing or flammability data available. These materials (silicone, epoxy, diallyl phthalate, polyvinyl chloride, nylon and varnish) are contained in electrical components. These materials, based on prior configuration tests of similar hardware, are projected to be acceptable. Final acceptance of these materials for Shuttle Orbiter application will depend upon the amount of similar materials which may be present in other components of the crew bay.

TEST SUPPORT ACCESSORIES

Test Support Accessories were needed to (1) simulate the Shuttle Orbiter and advanced spacecraft potable water systems, (2) obtain data for the ACIDD Supporting Technology tests, (3) obtain explanatory data on ACIDD operation and (4) measure I_2 concentrations and aqueous solution parameters.

Potable Water System Simulator

The Potable Water System Simulator used for the ACIDD testing is shown schematically in Figure 14. Laboratory facility water is treated for Cl_2 removal with a charcoal filter and is deionized prior to being stored in the water supply tank. Pump P1 pumps a portion of this water through the ACIDD via flow controller FC1 and the remainder is bypassed back into the water supply tank through V3. Adjustment of the bypass flow through V3 adjusts the supply pressure, normally 273.7 to 308.2 kN/m^2 (39.7 to 44.7 psia).

If the supply pressure falls below 239.2 kN/m^2 (34.7 psia) for more than five seconds, an automatic redundant pump controller turns on redundant pump P2 and opens isolation valve V5. Pump P1 and associated valve V4 are simultaneously deenergized so that system pressure and flow are maintained at required levels. Should, for some reason, the second pump fail to maintain proper supply pressure, power to the ACIDD is shut down after five seconds to avoid generation of I_2 into a static body of water. The pressure condition is indicated electrically to the pump controller with an in-line pressure switch and is visually observed with pressure gauge PG1.

Flow controller FC1 both regulates and indicates the flow to the ACIDD which normally is routed around circulating pump P3 through valve V7. The temperature of the water is adjusted to a desired level before passing into the ACIDD. This is accomplished with a heat exchanger immersed in the constant temperature bath.

Valves V11 and V12 provide for sampling of feed water and iodinated water, respectively. A portion of the iodinated water flows continuously through V12 and through an automatic sampling device into the drain. Iodinated water constantly flushes out a calibrated volume in the sampling device such that the precise sample volume of water required for I_2 and I^- analyses may be removed at any time without waiting for a sample to accumulate. Because the calibrated volume is virtually completely enclosed and an insignificant surface area of liquid is exposed to the atmosphere (except when withdrawing a sample), errors in analyses due to evaporation of I_2 are minimized. This characteristic is especially valuable when water at elevated temperatures must be sampled.

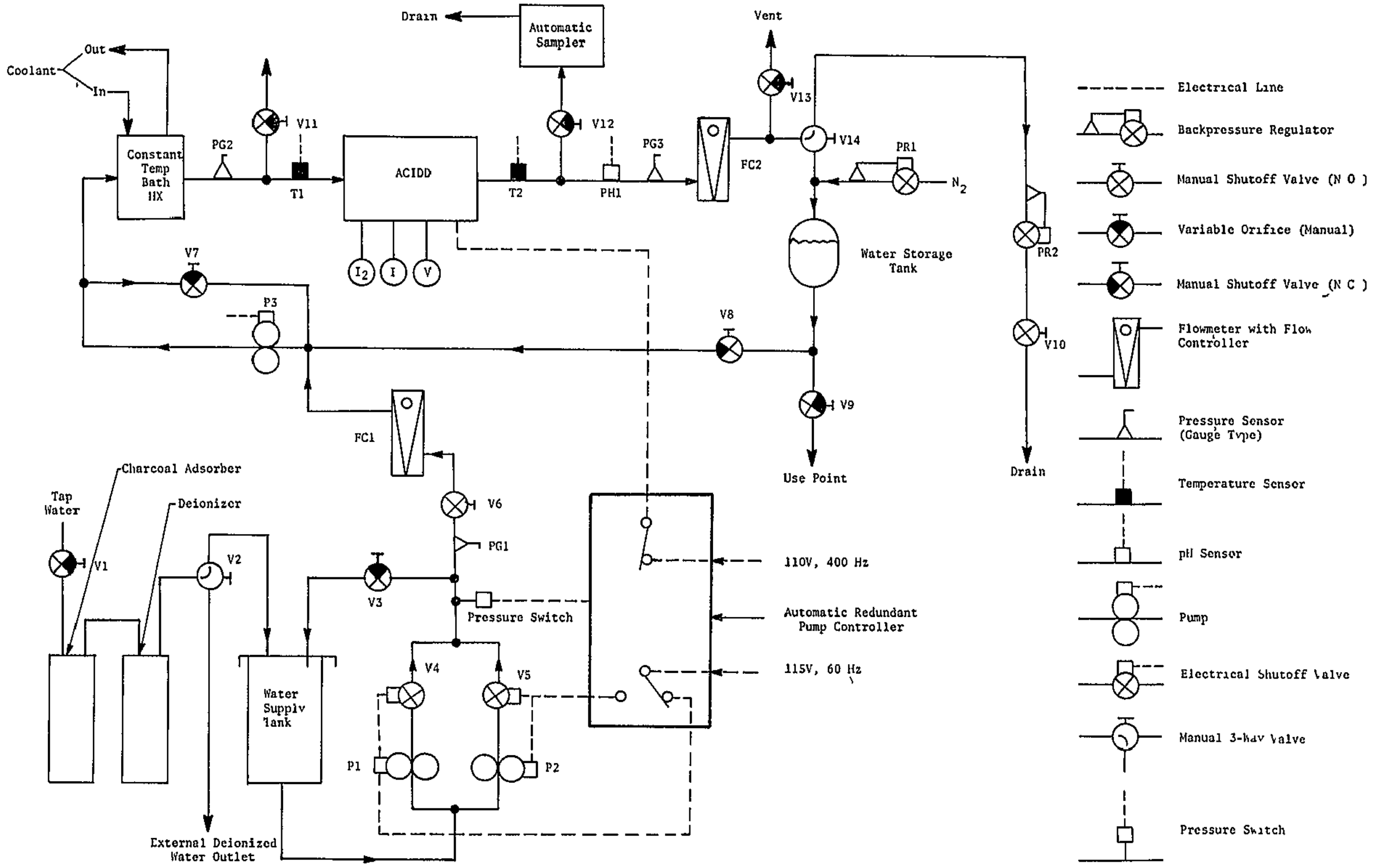


FIGURE 14 ACIDD POTABLE WATER SYSTEM SIMULATOR

Thermocouples T1 and T2, in combination with a temperature readout, permit monitoring of the feed water and iodinated water temperatures, respectively. Pressure gauges PG2 and PG3 permit monitoring of inlet and outlet pressures as well. Backpressure regulator PR2 regulates the operating pressure of the treated water.

Recirculating pump P3, the water storage tank, regulator PR1, flow controller FC2 and several associated valves were included in the test stand. This feature permitted simulation of potable water systems for which a recirculation mode of operation is required.

The I_2 level signal from the Iodination Level Detector and the valve current and voltage signals were recorded continuously by potentiometric recorders.

Front and rear views of the ACIDD test stand are shown in Figures 15 and 16, respectively. The specifications for the stand are listed in Table 9.

Supporting Technology TSA

The test stand for the Supporting Technology studies was similar to that used for ACIDD testing but somewhat less sophisticated. This test stand, described in Figure 17, is a modification of apparatus used in previous program testing.(2)

Analytical Equipment and Procedures

The required analyses were performed using the equipment listed in Table 10. Water samples were analyzed with the spectrophotometer for I_2 and I^- by the procedure of Blank and Whittle.(9) The other parameters (pH, specific conductivity, turbidity, and dissolved oxygen (O_2)) were measured directly on the instruments listed.

ACIDD TEST PROGRAM

The test program was designed to characterize the performance of the ACIDD 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 NASA JSC.(10) 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.

The test program was divided into four tests: (1) Checkout Tests, (2) Operating Modes Tests, (3) Design Verification Test (DVT) and (4) Shutdown and Restart Test. 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

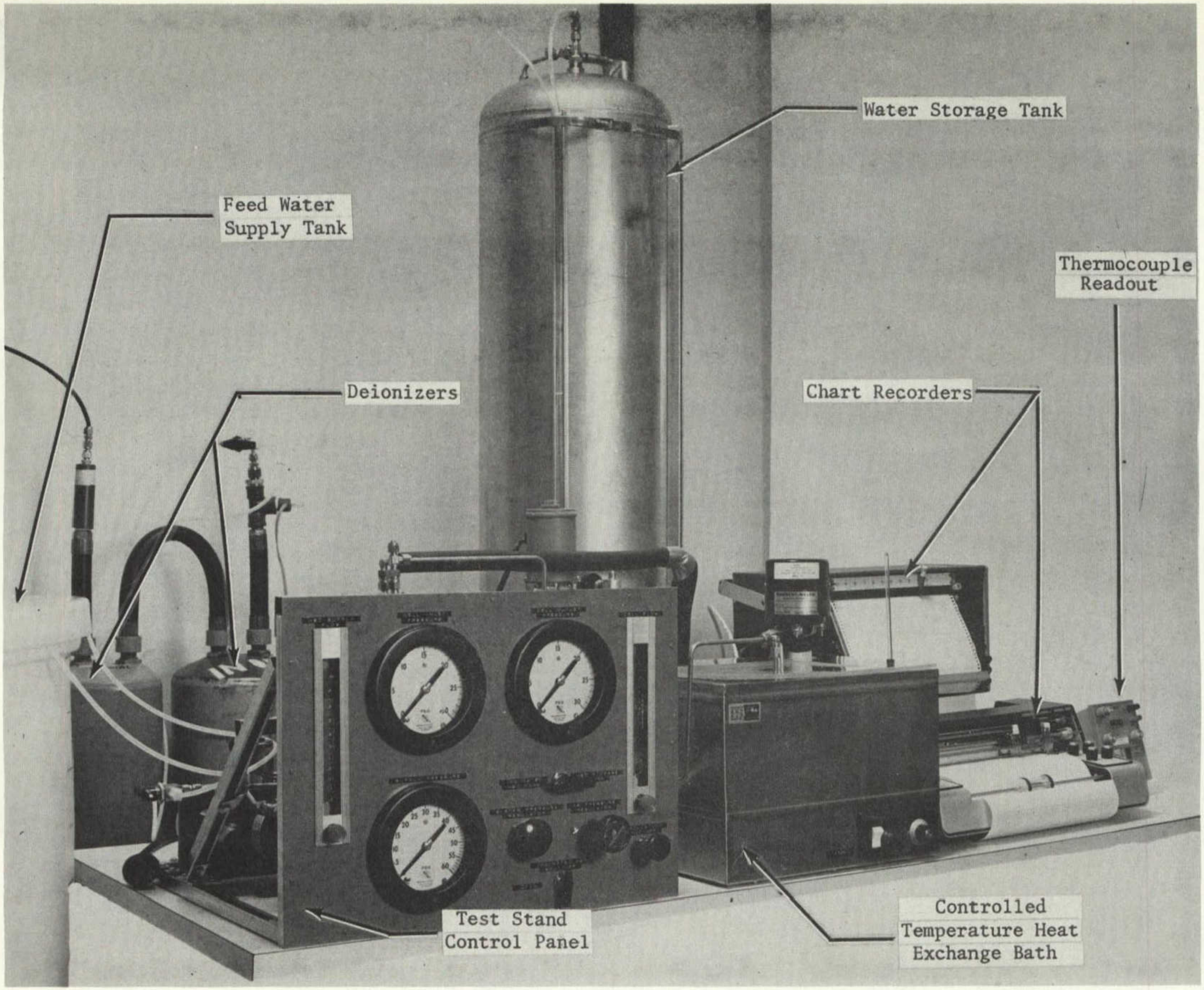


FIGURE 15 ACIDD TEST STAND, FRONT VIEW

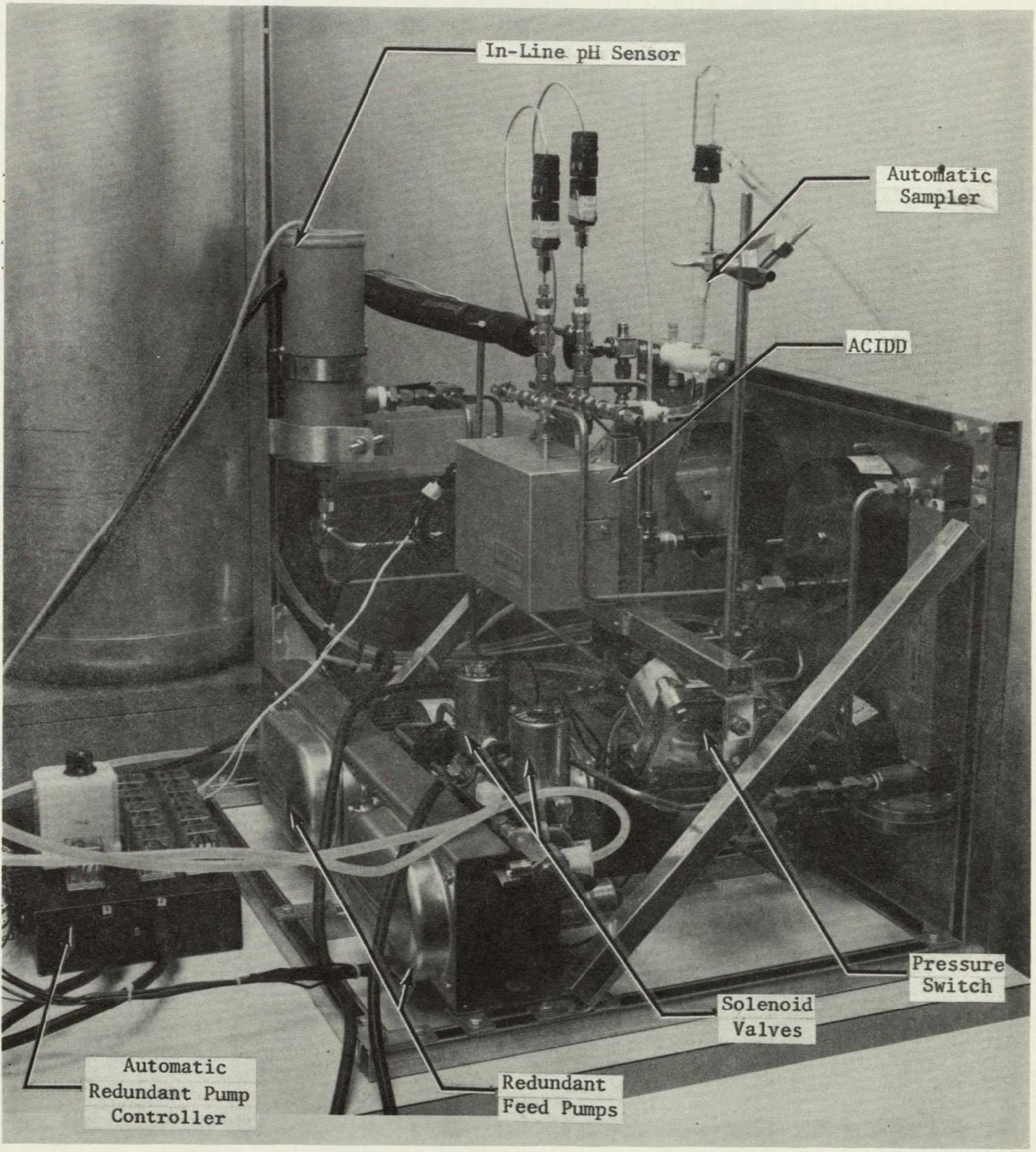


FIGURE 16 ACIDD TEST STAND, REAR VIEW

TABLE 9 ACIDD TEST SUPPORT ACCESSORIES SPECIFICATIONS

Water Supply	From External Storage Tank
Water Flow Rate Range, cm^3/min (Lb/Day)	20 to 200 (63.4 to 634)
Water Composition	Deionized, Pretreated with Activated Carbon(a)
Water Recirculation Rate Range, cm^3/min (Lb/Day)	150 to 700 (476 to 2220)
Water Storage Tank Capacity, kg (Lb)	75.9 (167)
Maximum Operating Pressure, kN/m^2 (Psia)	413 (60)
Water Temperature, K (F)	278 to 344 (40 to 169)
Materials (Wetted Parts of Test Rig)	316-SS, Teflon, Rulon and Glass
Parameters that can be Monitored	Cell Voltage(b) Cell Current(b) I_2 Concentration(b) Water Supply Pressure Water Pressure Cell Inlet Water Pressure Cell Outlet Water Temperature Cell Inlet Water Temperature Cell Outlet Water Feed Rate Water Circulation Rate
Redundant Components	Water Feed Pumps, with Automatic Switch-over Control System(c)

(a) Commercially available water treatment columns
(b) Continuously monitored
(c) Second pump takes over automatically 'if first fails'

TABLE 10 ANALYTICAL METHODS

1.	I_2 and I^-, Ppm (±1%)[a]	Beckman Model 24 Double Beam Spectrophotometer
2.	pH (±1%)[b]	Markson Model 4404 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

(a) Values in parentheses signify expected uncertainty limits of the analysis.
(b) Limited by low water specific conductivities.

included provision for the collection of data and for recording 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 each occurrence. 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 4 is a Water Analysis Report for three samples of water from a Pratt and Whitney fuel cell. 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.

Water, deionized through a mixed bed resin, has a resistivity of approximately 1 MΩ-cm or less. Therefore, deionized water has a purity less than or similar to that of the anticipated Shuttle Orbiter fuel cell water.

A previous study, using the LSI-100 and AWIS I_2 Sources, proved the compatibility of those units with simulated "worst case" fuel cell water (including particulates) of the composition shown in Table 3.(3) Although this simulated fuel cell water had little effect on the performance of these units, the water was so "impure" that to use water of that composition in this testing would not realistically prove the performance of the ACIDD. Deionized water, pretreated with activated carbon to remove Cl_2 found in tap water, was used as the water for all ACIDD testing.

Definitions

The various parameter levels that are subsequently referred to as "Baseline Conditions" are listed in Table 11. These conditions correspond to the average conditions under which the ACIDD would be expected to operate when installed in the Shuttle Orbiter potable water system.

Current efficiency, as used in this report, is the percentage of the total applied valve current which actually results in I_2 generation. The remainder of the current is utilized in harmless side reactions (such as electrolysis of water to form O_2.

Checkout Testing

The goal of the checkout testing was to assemble and check out the ACIDD in preparation for succeeding tests and to characterize its performance over the expected Shuttle Orbiter flow rate range of 22.7 to 172.5 cm^3/min (72 to 547 lb/day) with and without I_2 concentration feedback. The parametric measuring devices in the test stand were calibrated and the individual parts of the ACIDD were weighed prior to assembly.

TABLE 11 BASELINE CONDITIONS FOR ACIDD TESTING

Water Supply	
Composition	Deionized (See previous Section)
Flow Rate, cm^3/Min (Lb/Day)	83.2 ±10 (264 ±32)
pH at 298K (77F)	6 to 8
Temperature, K (F)	295 ±4 (72 ±8)
I_2 Concentration, Ppm	5 (+1, -2)
Temperature, K (F)	295 ±4 (72 ±8)
Pressure above Ambient, kN/m^2 (Psig)	55 to 117 (8 to 17)

Test Stand Calibrations

The calibrations of the flow meters, the thermocouples and pressure gauges of the test stand were checked and, if necessary, recalibrated. The test stand was additionally checked out to make sure all components functioned properly.

Assembly and Mechanical Checkout of the ACIDD

All individual components of the ACIDD were weighed prior to assembly. Then the ACIDD was assembled and the dry weight for the entire system was measured. The dry weight of the ACIDD was 1.23 kg (2.7 lb).

The assembled ACIDD was then pressure checked. All fluid-containing cavities were filled with water, the outlet and I_2 filling port were sealed off and the inlet was pressurized to 515 kN/m^2 (74.7 psia). No exterior leakage was observed.

Water flow across the membrane and membrane seals in the I_2 source and the ability of the membrane to withstand high differential pressures was determined by observing the rate of water flow from the open Accumulator filling port as the inlet pressure was increased incrementally to 515 kN/m^2 (74.7 psia). No sudden increase in flow was observed, indicating that the membrane was sound.

Calibration of the Iodination Level Detector

The Iodination Level Detector of the ACIDD was calibrated by first adjusting the Detector I_2 concentration output signal to approximately zero volts while pure water flowed through the system. This "zeroing" procedure was followed by measurements of the detector output when I_2 solutions of various concentrations passed through. The calibration data indicated that the Detector output was linear over the projected operating range of 0 to 10 ppm.

I_2 Filling Procedure

The Accumulator was filled with I_2 crystals. The remaining dead space in the Accumulator was then filled with water. When the Accumulator was full it was sealed shut with the loading cap.

Initial Measurements and Adjustments

After connecting the ACIDD to the test stand the internal I_2 set point was adjusted until water was iodinated to approximately 5 ppm, as verified by analysis of the sample stream.

The electrical output signal from the red (631 nm) photodetector was then measured. The lamp voltage of the light source was also measured, as well as the electrical output of the light source control photodetector. These signals were measured so that comparison with similar measurements at the end of all testing could be made. Comparison of the data would permit one to determine whether any changes in the light source intensity or attenuation of the light path (e.g., by sample cell window dirtying) had occurred.

The valve current responded virtually without oscillation when step changes in water flow rates were induced during ACIDD testing. This observation indicated that the RC time constant of the ACIDD feedback system integrator had been properly adjusted during assembly and that the system was properly damped.

Flow Rate Test

The water flow rate was varied between 14 and 177 cm^3/min (44 to 562 lb/day) to determine the level of current and voltage required by the ACIDD Source to maintain approximately 5 ppm I_2 and to determine the effect of iodination at these flow rates on total system power. The valve current and voltages plotted versus flow rate in Figures 18 and 19, respectively, are nearly identical to those obtained for the previous AWIS iodinator.(3) Thus, the objective of reproducing AWIS operating characteristics in the ACIDD was met.

Figure 20 shows how the ACIDD system power varied with water flow rate during the initial tests. A maximum of 7.4W was required at the 173 cm^3/min (549 lb/day) flow rate point (5.2 ppm analyzed I_2 concentration).

Constant Current Operation

The purpose of this experiment was to determine over what range of water flow rate a 5 (+1, -2) ppm I_2 concentration could be maintained when operating the I_2 Source with a fixed current level (no Iodination Level Detector feedback signal). The current level was adjusted manually by connecting an external voltage signal to the input of the current source in place of the integrator.

The I_2 concentration varied with flow rate as shown in Figure 21 when the ACIDD was operated at a constant 19.1 mA. The incipient change in curve shape below water flow rates of 60 cm^3/min (190.5 lb/day) is not surprising because previous experimental data has indicated that solid iodine can precipitate on the anode at low flow rates and high iodine concentrations.

The projected variation of I_2 concentration with flow rate, also plotted in Figure 21, was calculated by assuming a fixed I_2 generation rate at constant valve current (constant current efficiency) except for a minor variation of I_2 diffusion across the membrane with water flow rate. The two curves would have, in fact, essentially coincided for water flow rates above 60 cm^3/min (190.5 lb/day) if the fixed I_2 generation rate had been chosen slightly higher. The near coincidence of the two curves indicates that current efficiency and, therefore, I_2 generation rate at constant current are essentially independent of flow rate above 60 cm^3/min (190.5 lb/day). The constant I_2 generation rate as a function of water flow rate is shown in Figure 22.

The data also illustrates that water at constant temperature can be iodinated to 5 (+1, -2) ppm I_2 between baseline (83.2 cm^3/min (264 lb/day)) and maximum (172.5 cm^3/min (547 lb/day)) Shuttle Orbiter water flow rates when the ACIDD is operated at constant current. The band of water flow rates in which this I_2 concentration range is obtained may be adjusted by changing the magnitude of the constant current.

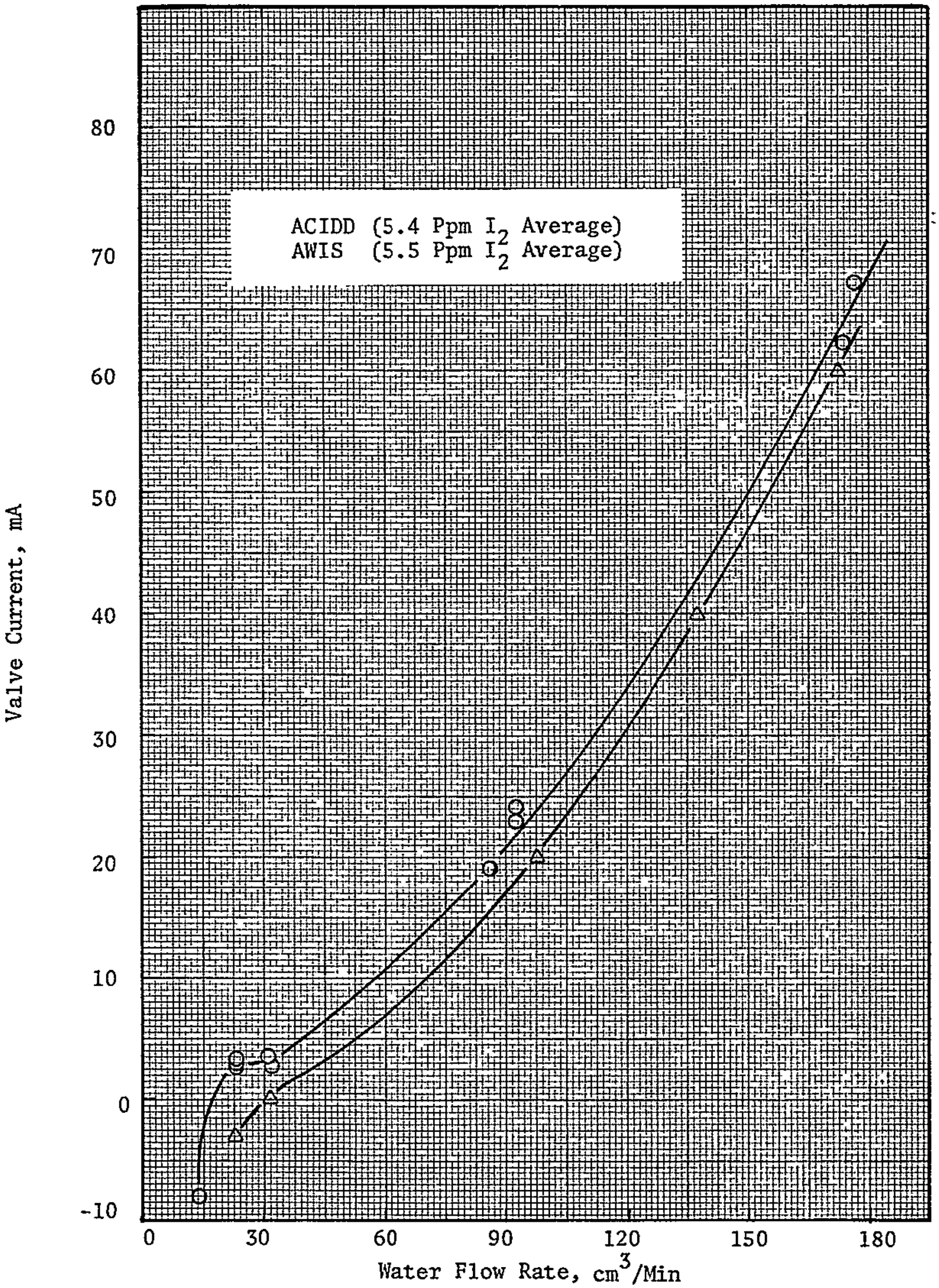


FIGURE 18 REQUIRED VALVE CURRENT OVER SHUTTLE FLOW RATE RANGE

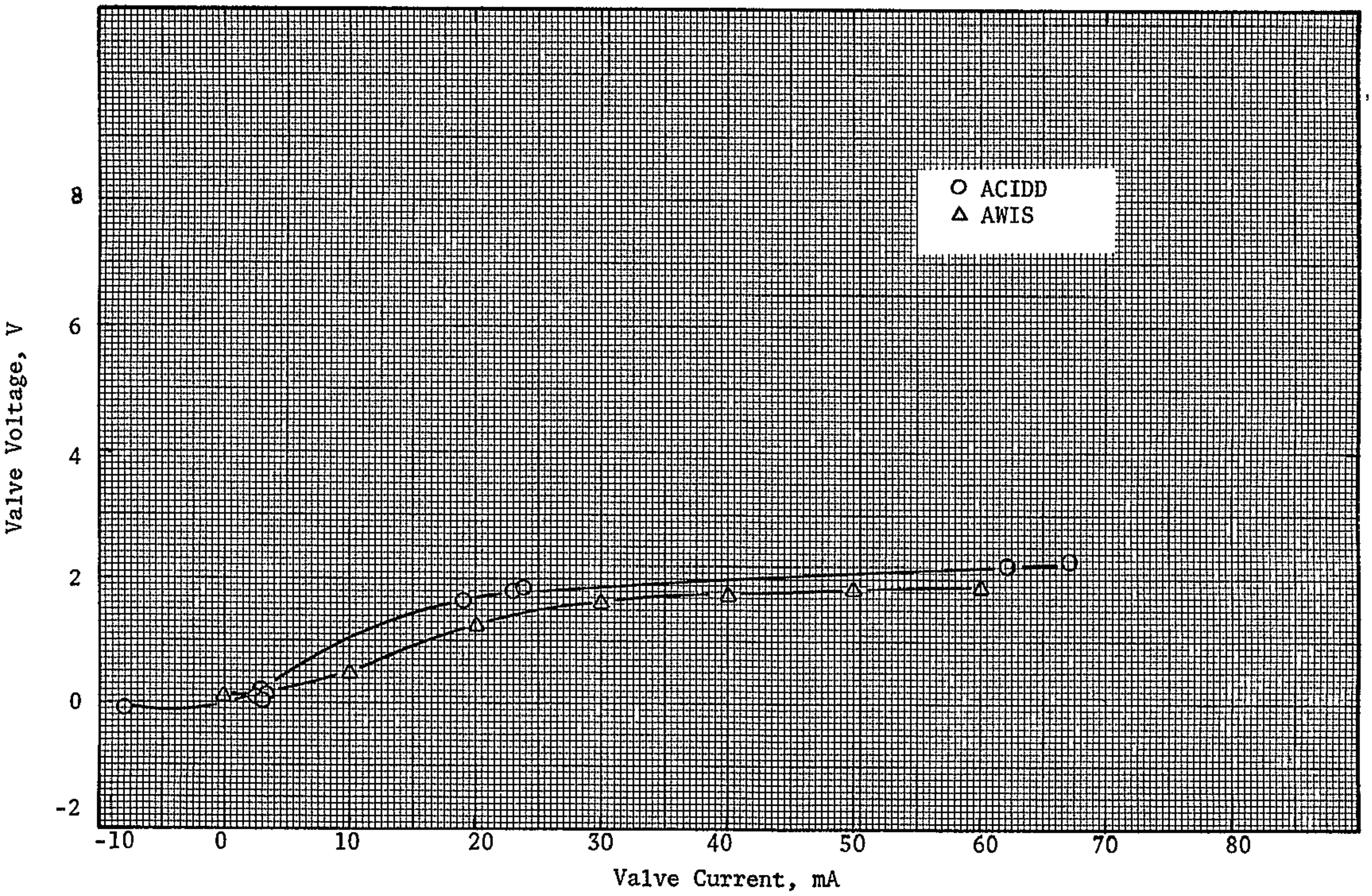


FIGURE 19 VOLTAGE REQUIRED TO MAINTAIN VALVE CURRENT

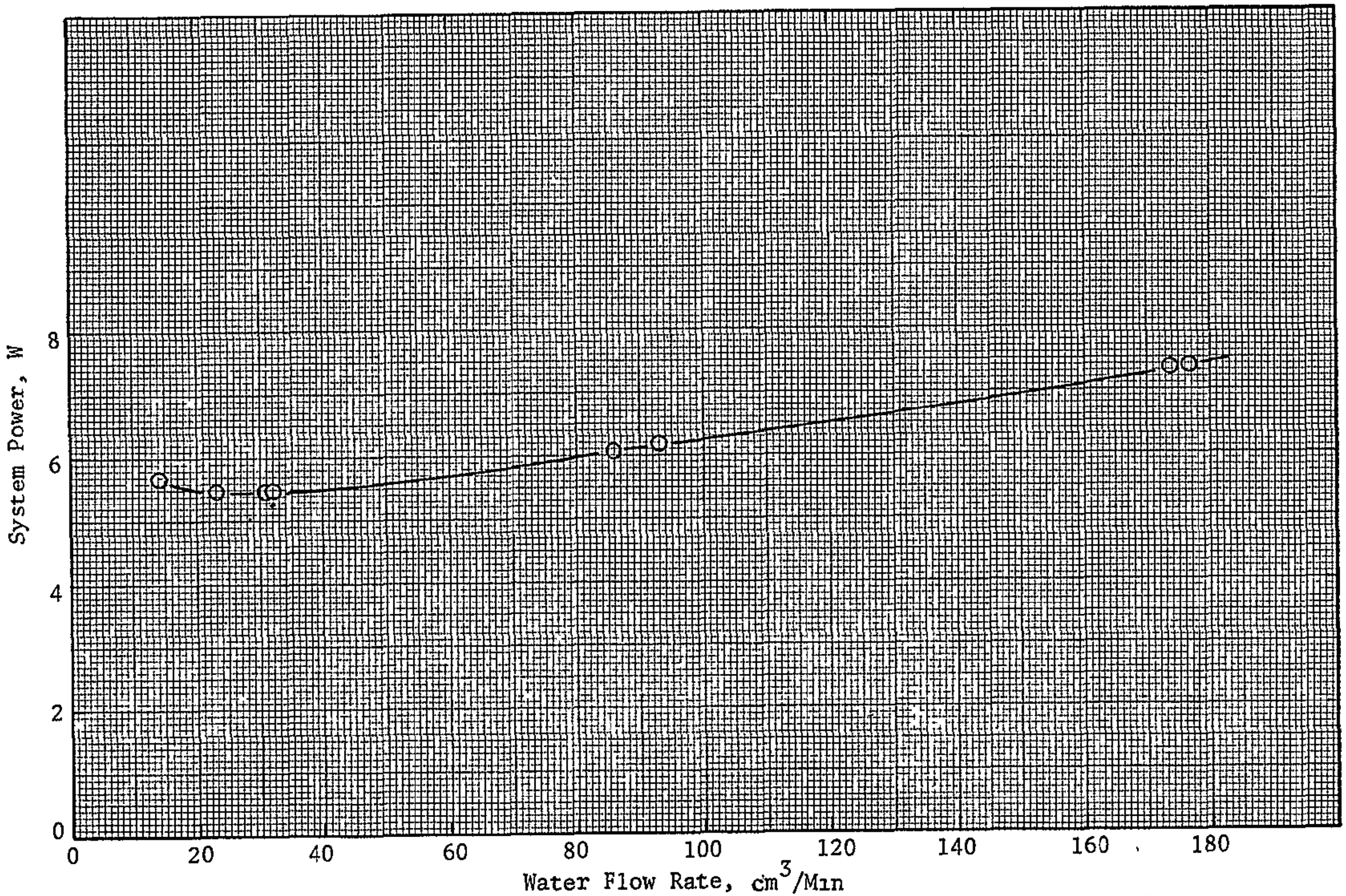


FIGURE 20 ACIDD SYSTEM POWER REQUIRED OVER SHUTTLE WATER FLOW RATE RANGE

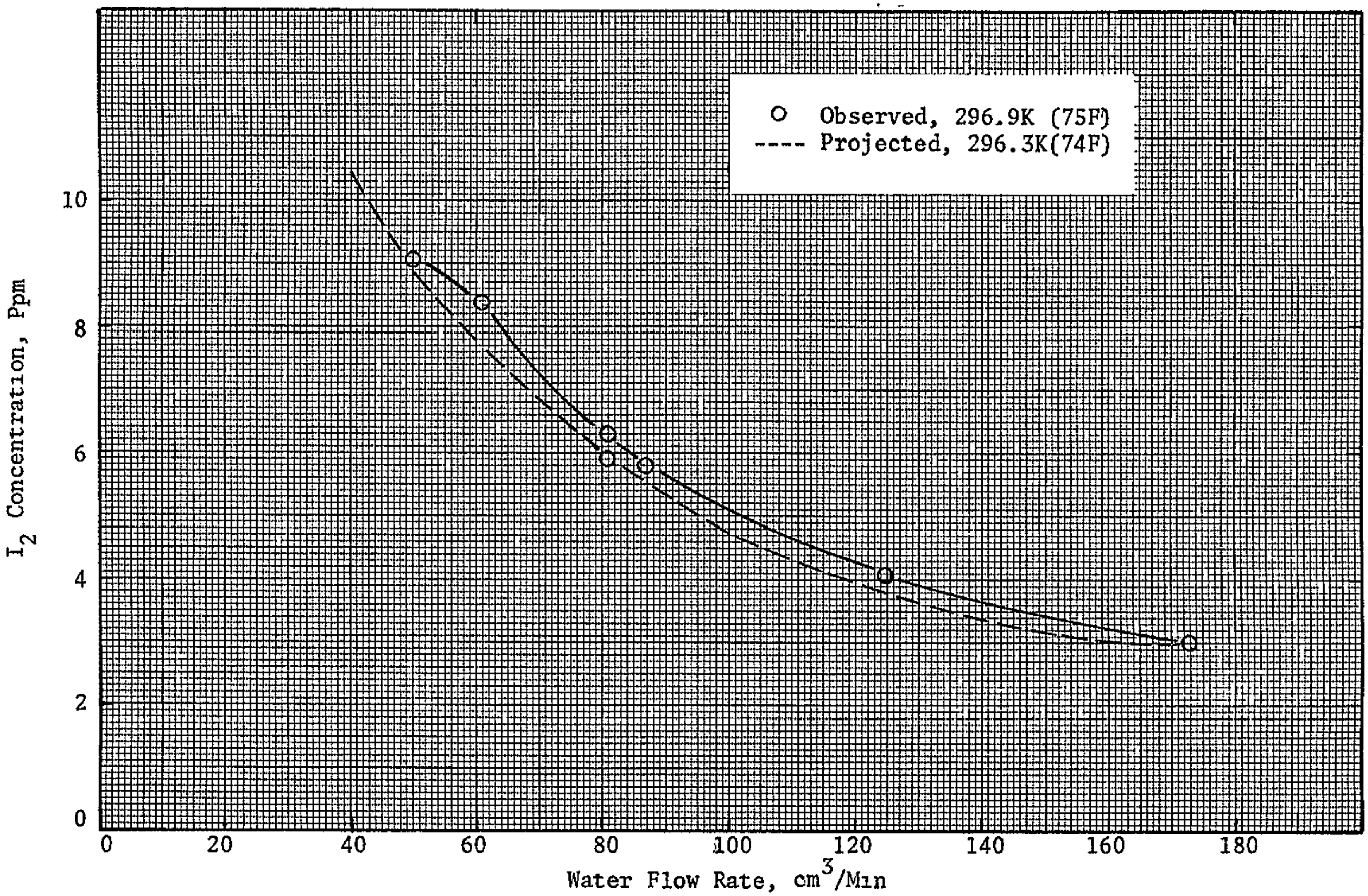


FIGURE 21 I_2 CONCENTRATION VERSUS WATER FLOW RATE FOR CONSTANT CURRENT OPERATION OF ACIDD

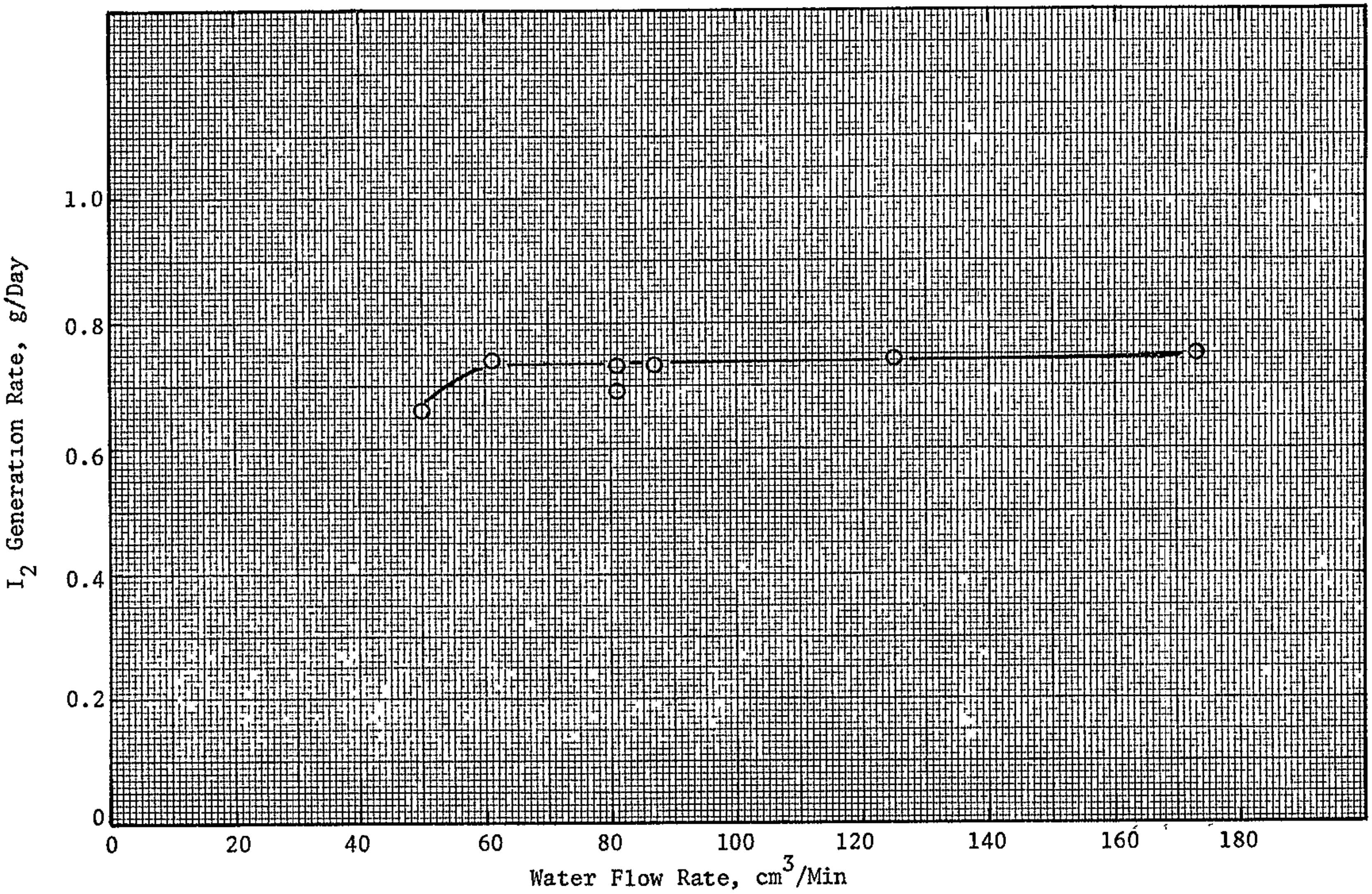


FIGURE 22 I_2 GENERATION RATE VERSUS FLOW RATE FOR CONSTANT CURRENT OPERATION OF ACIDD

Operating Modes Testing

The object of the operating modes testing was to see how variations in feed water pH and temperature would affect operation of the ACIDD. The feed water of the Shuttle Orbiter will be supplied from its fuel cells and the pH will vary between at least 6 and 8. The temperature will possibly vary from several degrees above ambient at a high flow rate to ambient at the lowest flow rates.

Effect of Feed Water pH

At high pHs, a portion of the active I_2 in iodinated water will be in the form of hypoiodous acid (HOI). Iodine in this form will not be "seen" by the Iodination Level Detector. The ACIDD, however, will attempt to maintain a constant 5 ppm concentration of detectable I_2. Therefore, the total concentration of I_2 in the water could exceed this limit substantially if the percentage of I_2 in the form of HOI were large enough. There could be an objectionable taste in the iodinated water at high total I_2 concentrations.

The equilibrium equation below illustrates how I_2 in the solution dissociates to form the photometrically undetectable species, HOI.(11)

$$I_2 + H_2O = HOI + H^+ + I^- \qquad (1)$$

The equilibrium expression for this reaction is:(11)

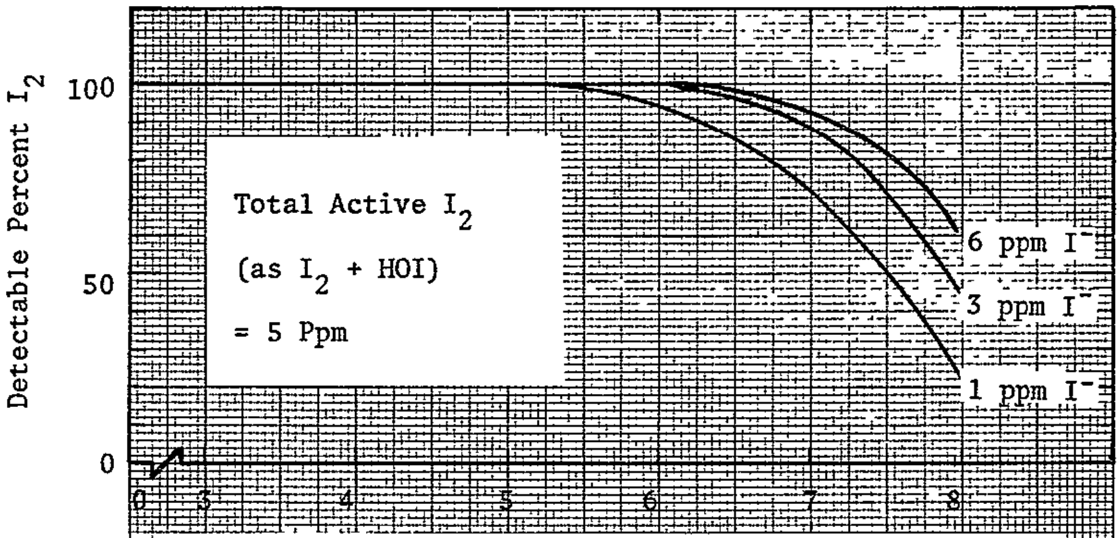
$$\frac{(HIO)(H^+)(I^-)}{(I_2)} = K_h, \qquad (2)$$

for which K_h is 3×10^{-13} at 298K (77F). When either hydrogen ion (H^+) and/or I^- concentrations are high, this equilibrium expression indicates that formation of HOI will be inhibited. When the H^+ concentration is low (pH high) and I^- concentration is low, however, an appreciable portion of the total I_2 in the solution will be in the form of non-detectable HOI.

The percentage of I_2 that is detectable, as calculated from this expression, is plotted versus pH on the upper portion of Figure 23. As shown, essentially 100% of the I_2 is detectable for iodinated water pH's below 6.

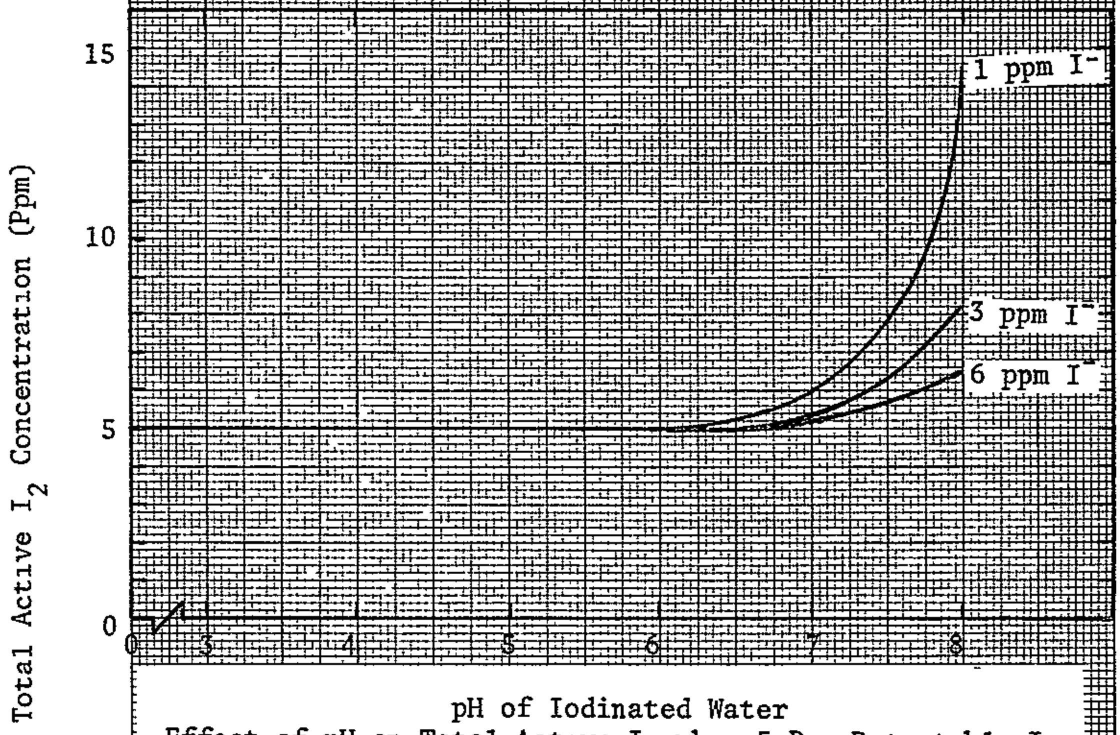
The total I_2 concentration produced by an iodinator, in its attempt to produce 5 ppm detectable I_2, is plotted versus iodinated water pH in the lower portion of Figure 23. The data indicates that an iodinated water pH below 6 has no effect on ACIDD operation. In fact, little effect is noticed until beyond a pH of 7, especially when considering that the iodinated water typically has an I^- concentration of at least 3 ppm.

To quantify the effect of pH on total I_2 present in the water through actual operation, the ACIDD was tested in the baseline current feedback mode and the I_2 and I^- concentrations, the iodinated water pH, and the Iodination Level Detector signal output were monitored as the feed water pH was varied from 3.4 to 8.2. The I_2 concentration analyzed(9) was the total I_2 concentration (I_2 + HOI). The data from this experiment is plotted in Figure 24. The average I_2



pH of Iodinated Water

Effect of pH on Detectable Fraction of Total Active I_2



pH of Iodinated Water

Effect of pH on Total Active I_2 when 5 Ppm Detectable I_2 is Maintained by ACIDD

FIGURE 23 PROJECTED EFFECTS OF IODINATED WATER pH ON ACIDD OPERATION

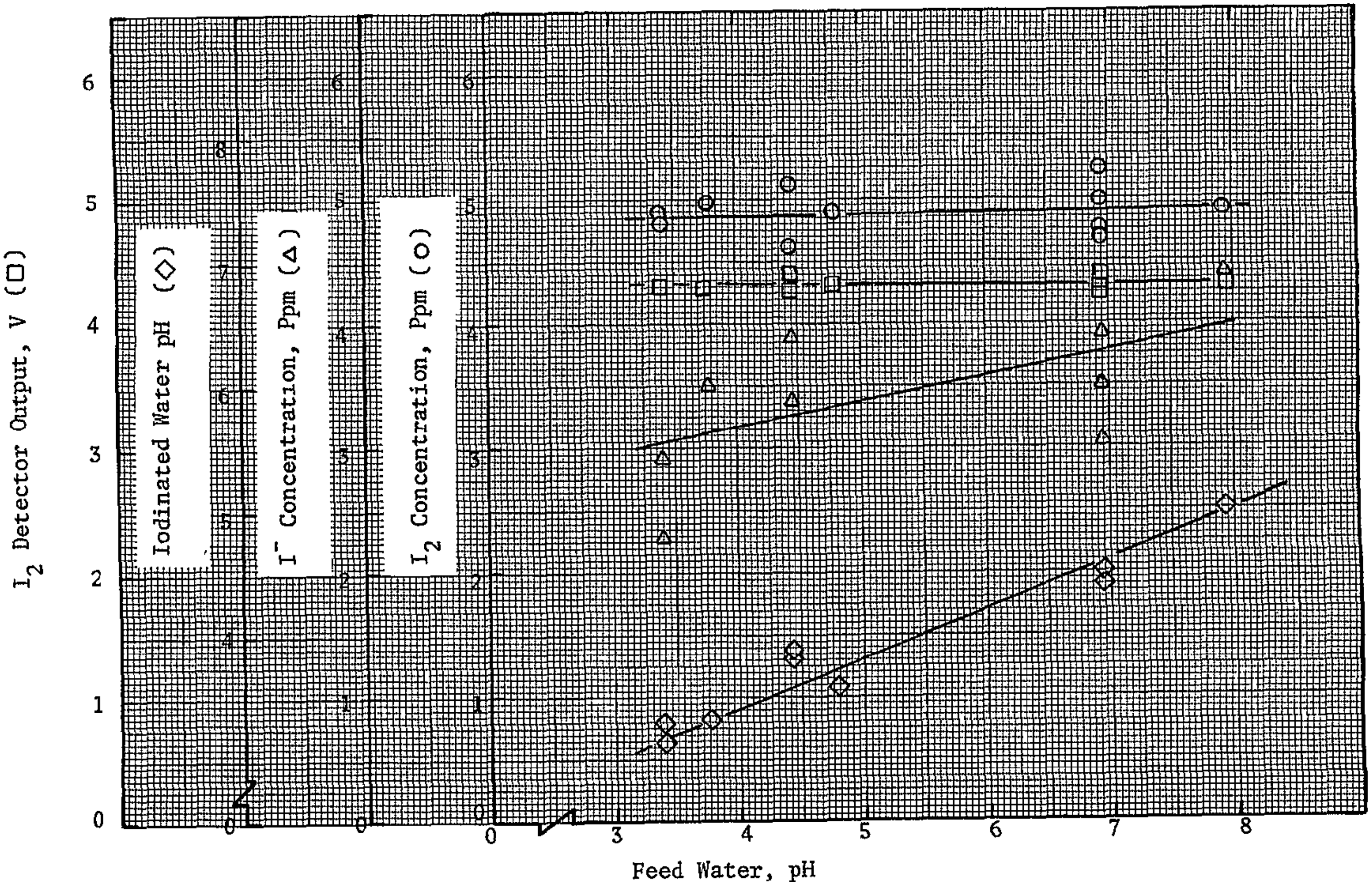


FIGURE 24 OBSERVED EFFECT OF FEEDWATER pH ON ACIDD OPERATION

concentration produced and the I_2 detector output were essentially constant over the entire range of pH covered, up to a feed water inlet pH of 8. The total I_2 concentration therefore corresponded to what the detector "saw" and the feed water pH, over the range tested, had no effect on the operation of the ACIDD.

The maximum iodinated water pH of 5 in Figure 24 corresponds to a feed water pH of 8. Thus, the iodination process itself reduces the pH to a sufficiently low level so that all the I_2 is in a detectable form.

These effects are consistent with the findings of previous Iodination Level Detector development.(13)

Effect of Feed Water Temperature

The anion exchange membrane in the I_2 Source of the ACIDD is not perfectly impermeable to I_2 in the elemental form but will pass small amounts from the I_2 Accumulator to the Dispenser by diffusion. Transport of I_2 across the membrane by diffusion thus accounts for a minor portion of the total I_2 generation rate at average water flow rates and temperatures. At very low water flow rates (e.g., 23 ml/min (73.0 lb/day)) the diffusion process alone is sufficient to iodinate the water to 5 ppm, and application of a small negative valve current to the anode is sometimes required to convert excess I_2 diffusing across the membrane into I^-. The ACIDD feedback system is designed to provide up to -10 mA for this purpose.

As the water temperature increases, however, the diffusion rate will increase such that negative current must be applied at somewhat higher water flow rates to maintain a 5 ppm I_2 level. The influence of the effect on ACIDD operation was investigated with the following objectives:

1. Quantify the effect of temperature on required valve current.
2. Determine the maximum water inlet temperature at baseline water flow rate and I_2 concentration level.
3. Compare temperature behavior between the ACIDD I_2 Source and the AWIS I_2 Source (relatively new versus well aged membrane).

Significance of Temperature Effect. With the ACIDD operating with current feedback and with the water flow at baseline, the feed water inlet temperature was raised incrementally. Samples of iodinated water were removed and analyzed(9) for I_2 following stabilization of each temperature and of the Iodination Level Detector output voltage.

The I_2 generation rates obtained, the corresponding I_2 concentrations and the valve currents required to maintain these I_2 generation rates are plotted versus feed water inlet temperature in Figure 25. Figure 25 shows that the valve current requirements at higher temperatures apparently level off as the temperature increases, whereas valve current requirements increase rather

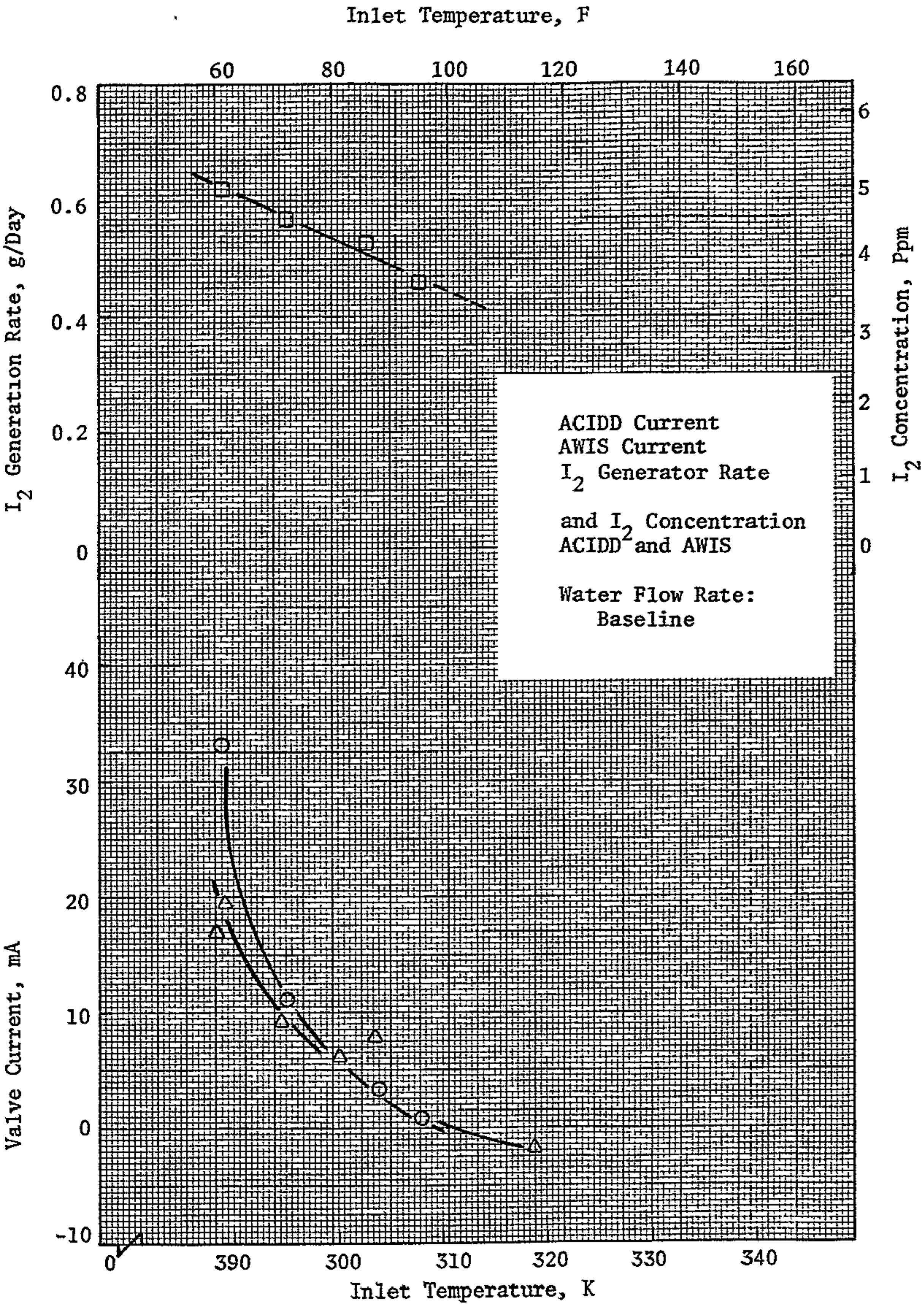


FIGURE 25 EFFECT OF TEMPERATURE VARIATIONS ON VALVE CURRENT AND I_2 GENERATION

sharply at low temperatures. These effects, however, are exaggerated since the analytically determined I_2 concentration levels at the low temperatures are over 1 ppm higher than those at the high temperatures.

The observed drop in I_2 concentration with increasing temperature is assumed to be caused by variations in the detector calibration with temperature. Such an effect could be eliminated or compensated for electronically. (See Section on DVT for further discussion.)

The decreasing current requirement with increasing temperature is most likely due to the increasing contribution of the I_2 diffusion across the membrane to the total I_2 flux required to produce the 5 (+1, -2) ppm level. Eventual mechanical mass transport limitations of the membrane would apparently limit the degree of diffusion at higher temperatures and cause the temperature effect to level out.

The relatively large increase of valve current at low temperature is assumed to be partially due to decreased diffusion and possibly to disposition of slight amounts of solid I_2 on the anode, due to the decrease in solubility of I_2 at the lower temperatures. Deposition of I_2 had been previously observed following operation at low water flow rates and high I_2 concentration levels.(3) Considering that the solution rate of solid I_2 is generally low it probably preferentially deposits on the anode as a solid when mass transport of water to remove it is low. At lower temperatures, however, the solution rate is even lower and the solid deposition phenomena then likely extends to higher flow rate and lower I_2 concentration conditions.

Comparison with AWIS. The AWIS Model IX-SA I_2 Source was operated at various fixed temperatures and variable, manually adjusted currents. Iodine concentrations were analyzed(9) after each parameter change, typically after one hour or more of equilibration. The variation of valve current with I_2 concentration is plotted for each temperature in Figure 26.

The valve currents corresponding to the I_2 concentrations in Figure 25 were cross-plotted versus temperature in Figure 25 for comparison with ACIDD temperature behavior. The temperature behaviors of the two I_2 Sources are nearly identical despite the great differences in membrane age and conditioning. This observation further demonstrates that I_2 Sources can be built reproducibly and shows that the temperature behavior of the Sources is predictable.

Maximum Temperature Test. With water flowing at the average Shuttle Orbiter flow rate of 83 cm^3/min (263.5 lb/day) the temperature of the inlet water was increased and the valve current was decreased manually until the I_2 concentration in the treated water approached 6 ppm and valve current was at its negative limit. At a water inlet temperature of 339K (151F) and a negative current limit of -8.2 mA the I_2 concentration was 5.8 ppm.

Design Verification Testing

The DVT was performed to observe ACIDD performance during simulated automatic "hands off" operation during 30 days of testing, with continuous operation as a goal.

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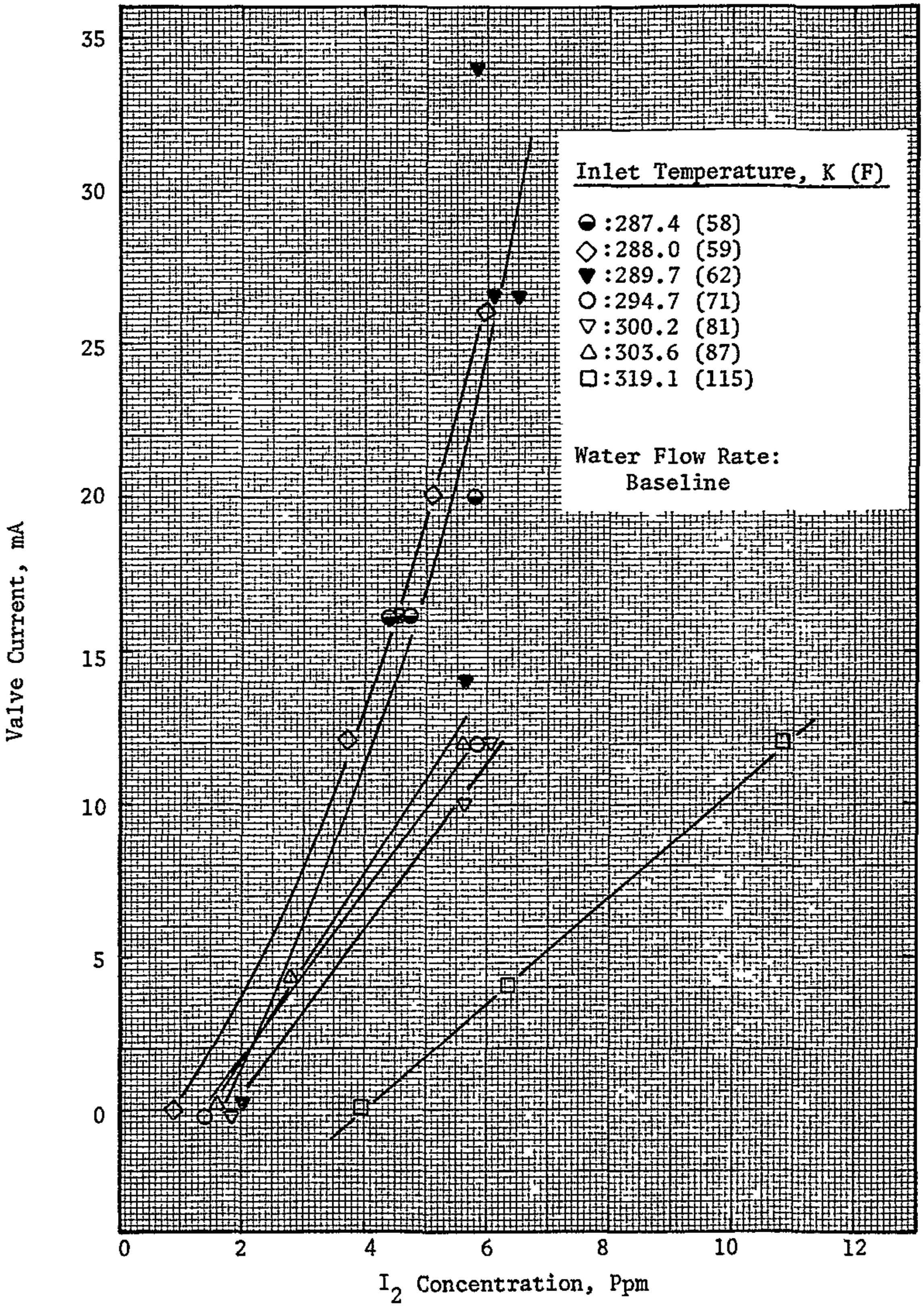


FIGURE 26 EFFECT OF CURRENT ON I_2 CONCENTRATION AT VARIABLE TEMPERATURES

Procedure

The principal independent ACIDD operating parameters, water flow rate and water temperature, were varied during portions of the test period to simulate variations in these parameters as may occur when iodinating the Shuttle Orbiter fuel cell water.

Primary and supporting ACIDD operating data, such as the analyzed I_2 and I^- concentrations, valve current and voltage, and detector output were numerically recorded daily. Additionally, valve current and voltage and Iodination Level Detector output signals were monitored continuously during the DVT with chart recorders. Samples of iodinated water and feed water were collected in 500 cm^3 (1 pt) polyethylene bottles periodically for analysis by NASA JSC. The independent parameter variatión and data collection schedule followed during the DVT is summarized in Figure 27.

Results and Discussion

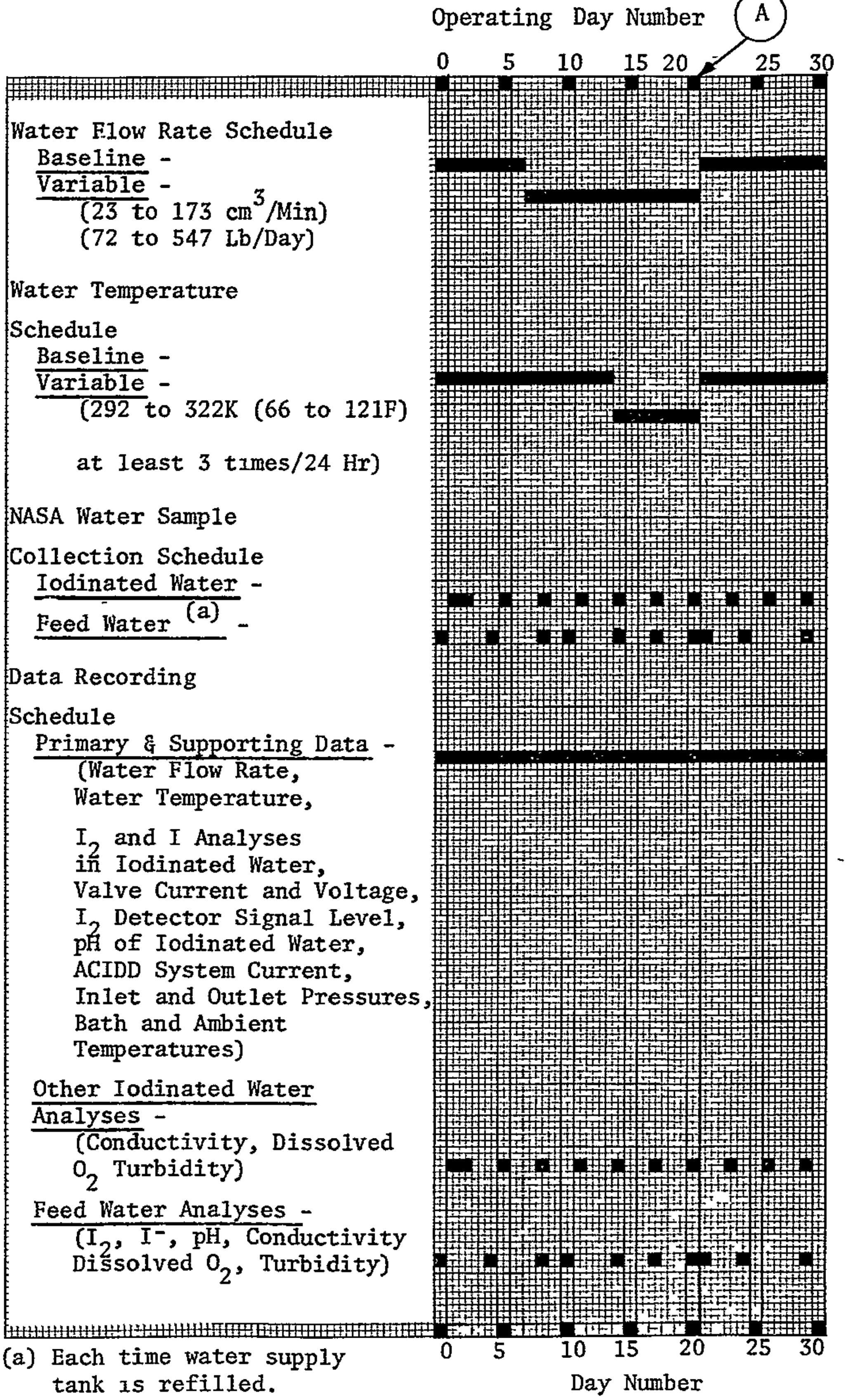
Figure 28 shows I_2 concentration, water flow rate and water inlet temperature as a function of operating days for the DVT.

The I_2 concentration remained essentially within the specified nominal concentration band of 5 (+1, -2) ppm despite the wide changes in water flow rate and temperature induced. Only a single significant off-range concentration (7 ppm) was observed shortly before anomalous detector behavior was noted. This anomality was due to window fogging at the 20-day point. (Indicated by the circled A notation on Figures 27 through 33.) It is assumed that the detector did not operate properly at that point, (day 19).

The detector window fogging problem caused the DVT to be interrupted for a one week period to identify and successfully correct the fogging problem. The main symptom of the anomalous behavior was a very large I_2 signal output (e.g. 5V or more) for zero (analyzed) I_2 concentration.

The problem was traced to minute water droplets that had condensed on the sample cell window, causing scattering of light nonuniformly away from the photodetector/filters. The source of the water was traced to the insertion of wetted O-rings at assembly to promote sealing and installation. This water evaporated from the sealing surfaces during high temperature operation of the ACIDD and condensed on the windows when the temperature was lowered. Water vapor leakage across the O-rings from the sample cell appeared unlikely since the O-rings were observed to be in excellent condition. The cell was reassembled using dry O-rings.

Following correction of the fogging problem and recalibration, the I_2 concentration was very stable and the Iodination Level Detector output signal was remarkably noise free. A comparison of the I_2 concentration obtained during the last eight days of the DVT with the concentrations obtained during the first six days indicate that the detector window fogging condition may have existed earlier in the DVT. The results, however, were nonetheless satisfactory.



(a) Each time water supply tank is refilled.

FIGURE 27 EVENT SCHEDULE FOR DVT

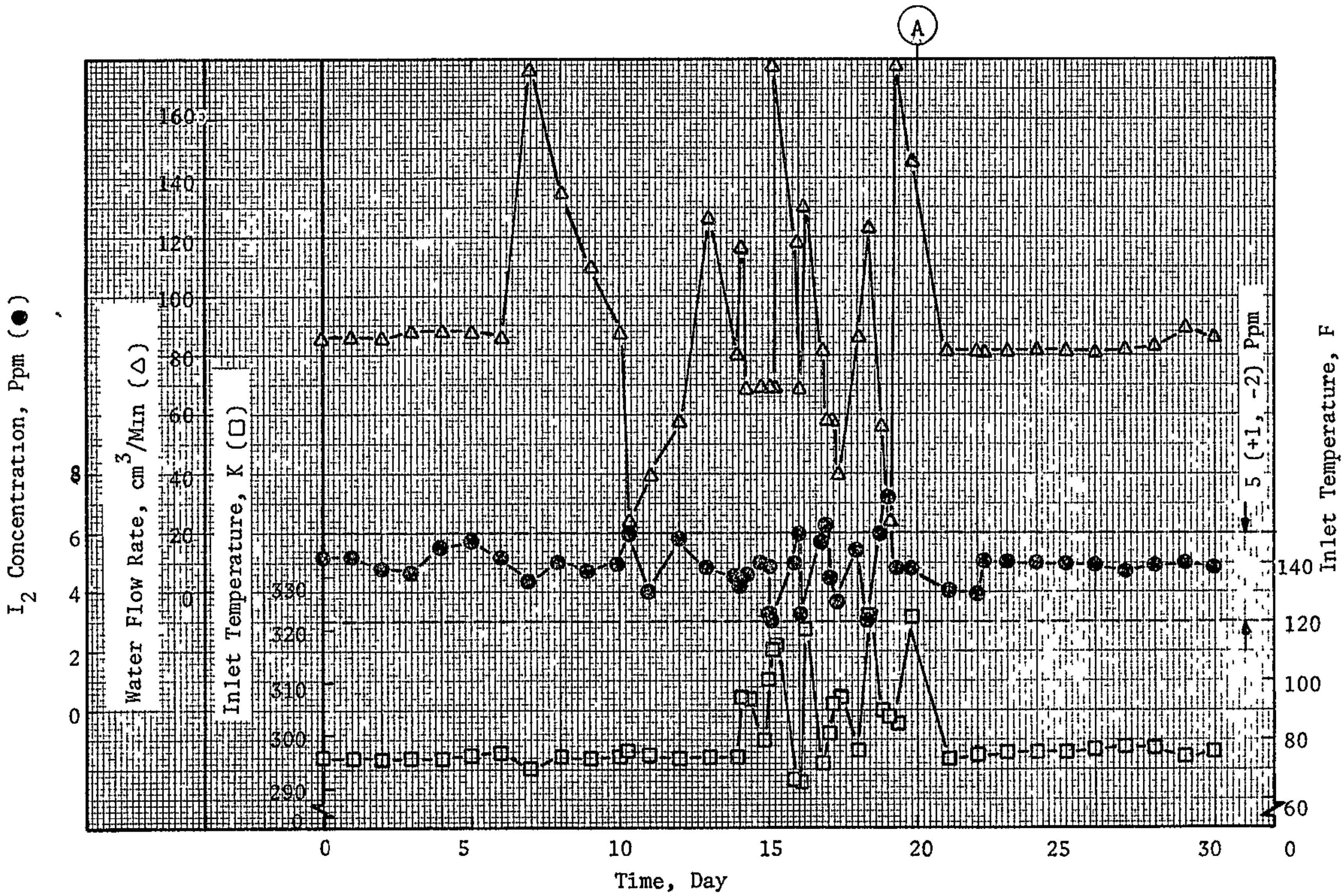


FIGURE 28 I$_2$ CONCENTRATION VERSUS TIME DURING INDUCED WATER FLOW RATE AND TEMPERATURE VARIATIONS

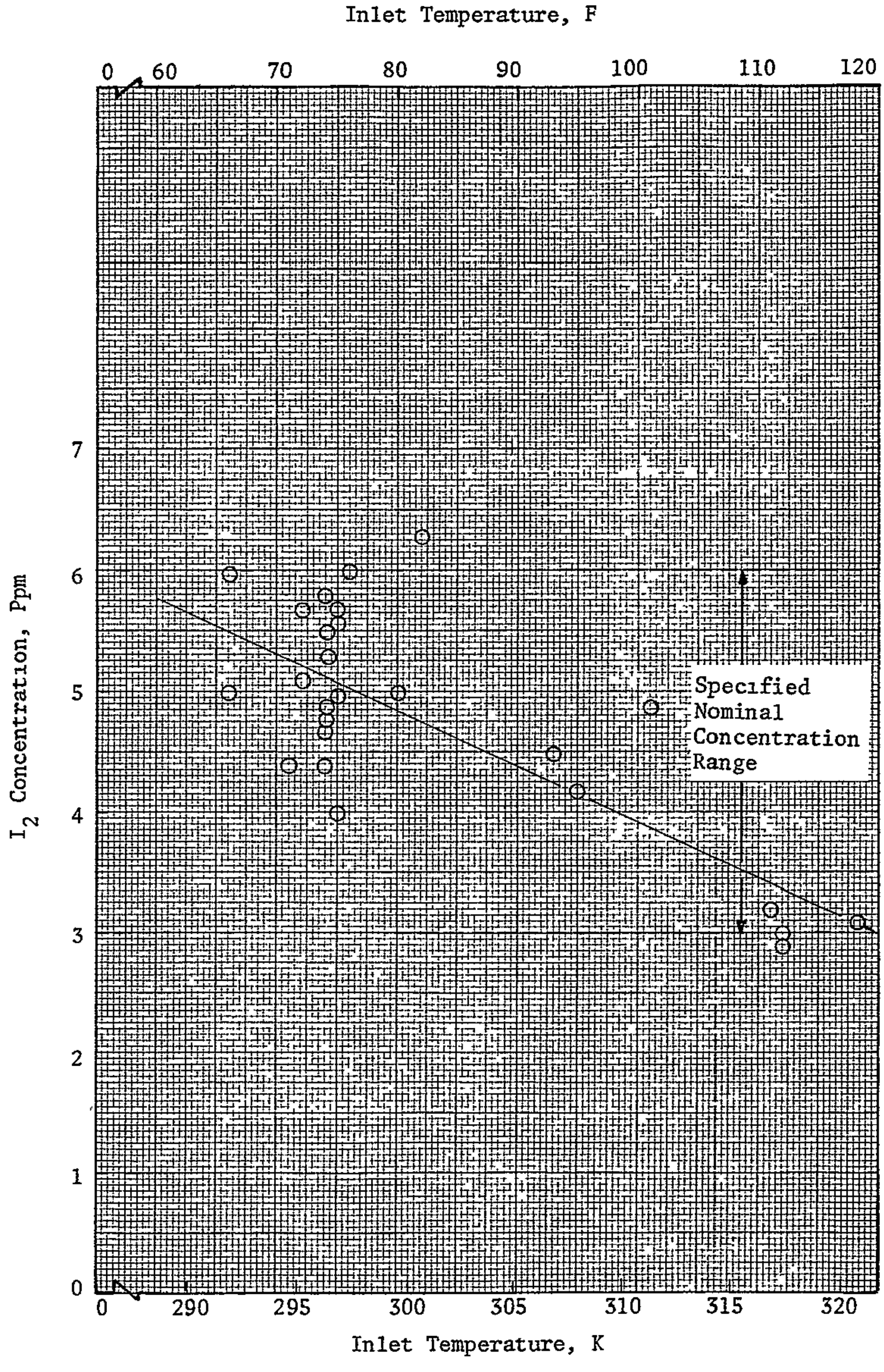


FIGURE 29 EFFECT OF TEMPERATURE ON I_2 LEVEL PRODUCED

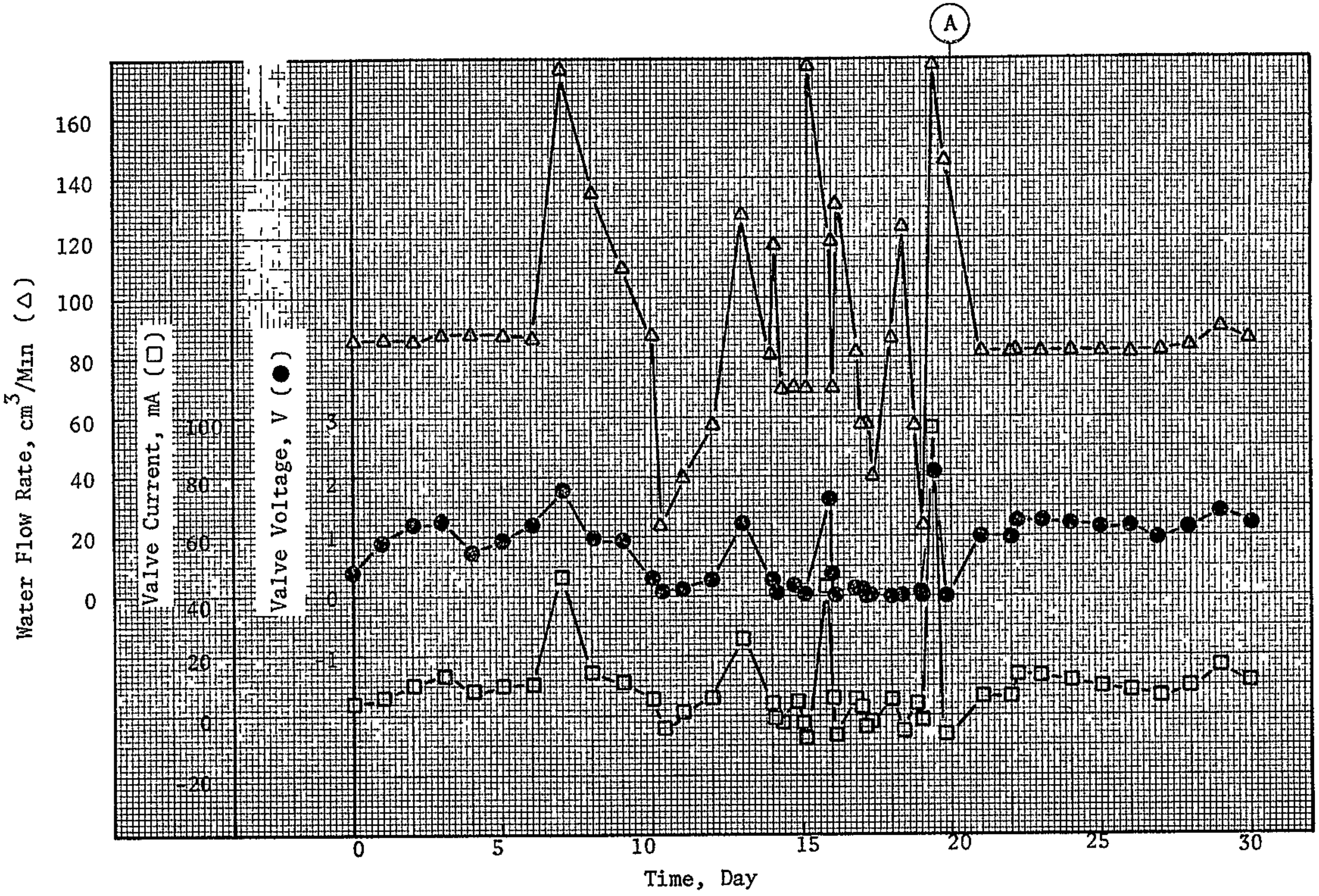


FIGURE 30 VALVE CURRENT AND VOLTAGE AND WATER FLOW RATE VERSUS TIME

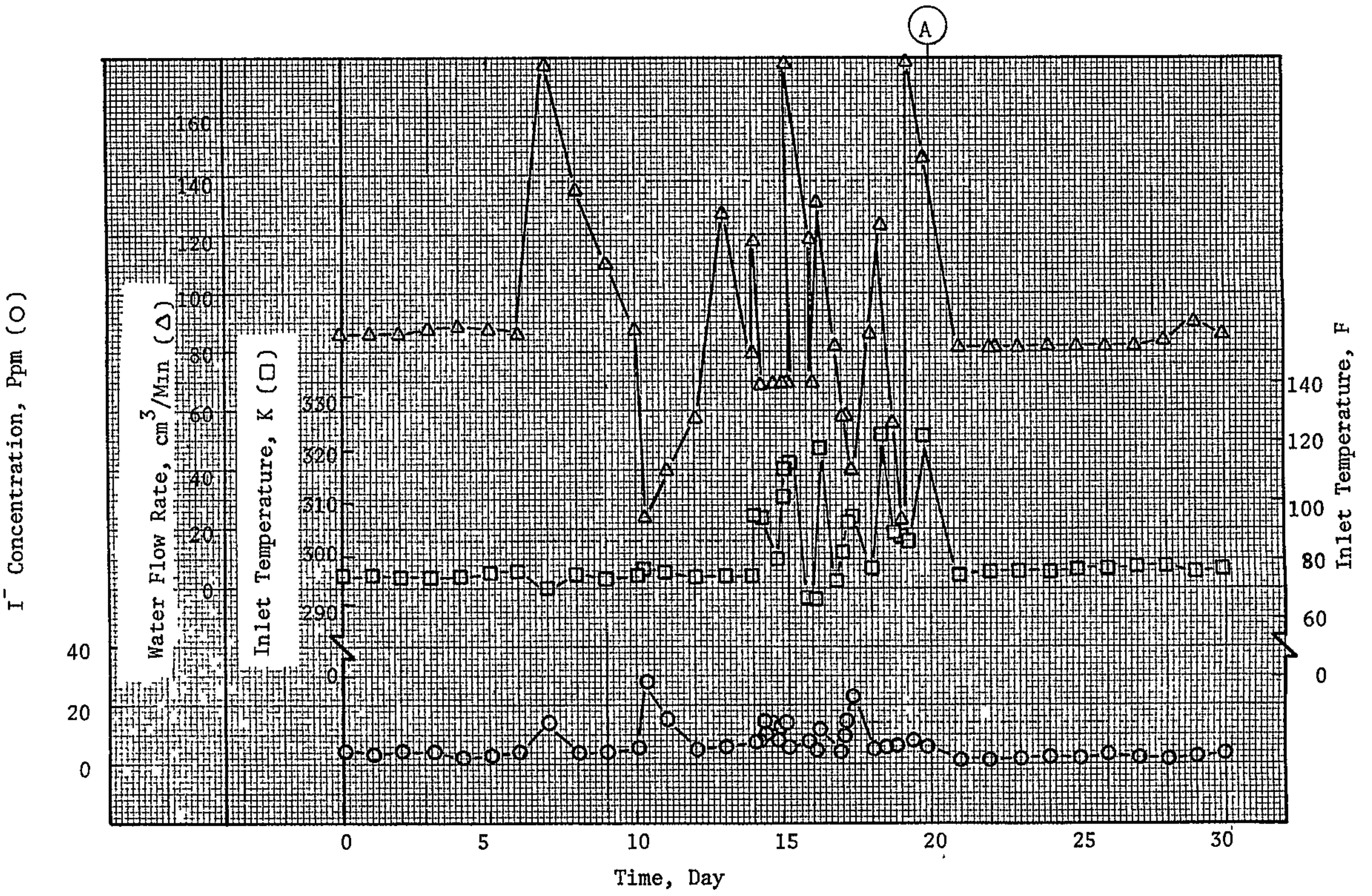


FIGURE 31 I$^-$ VERSUS TIME DURING INDUCED WATER FLOW RATE AND TEMPERATURE VARIATIONS

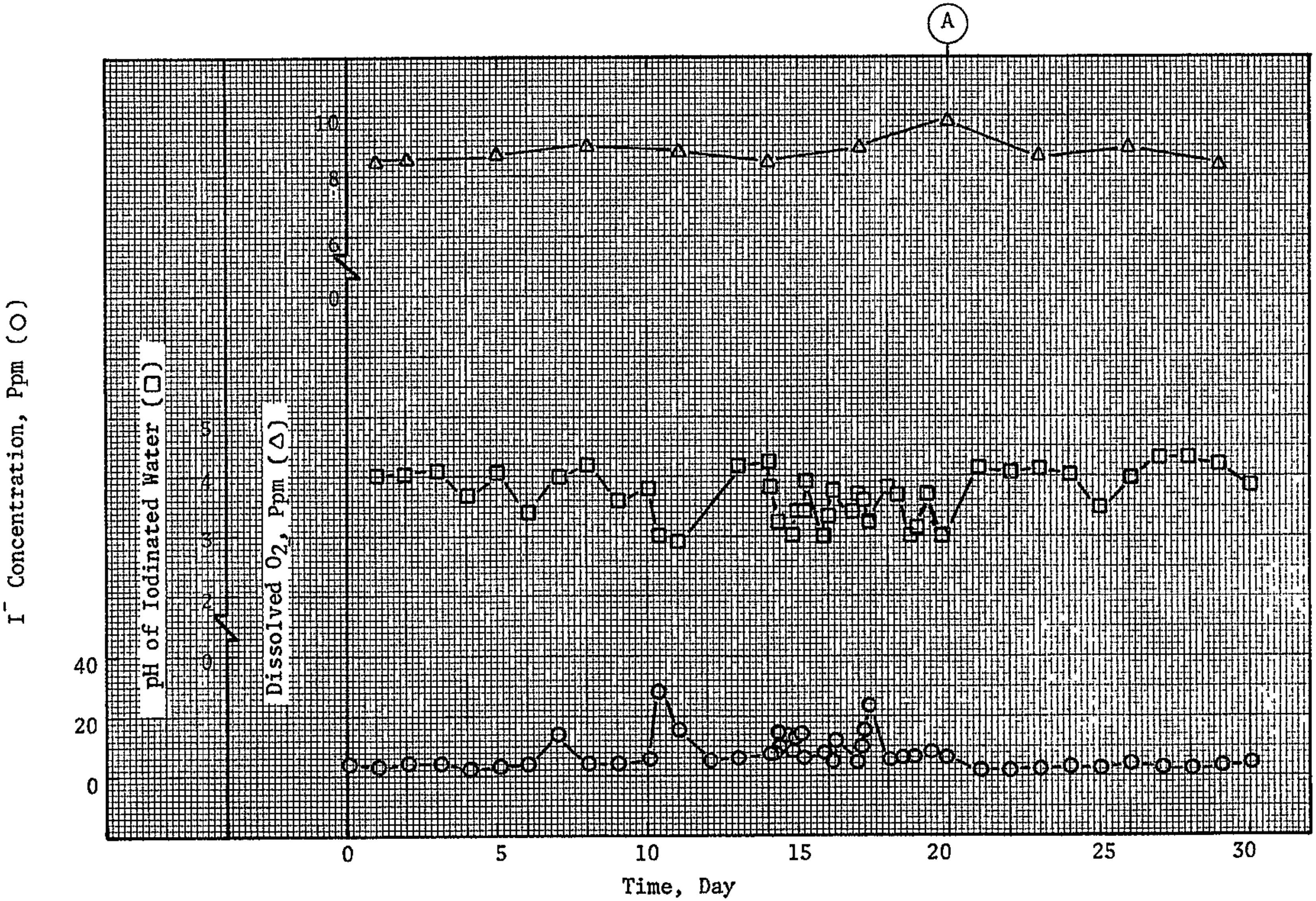


FIGURE 32 I$^-$, pH, AND O_2 IN IODINATED WATER VERSUS TIME

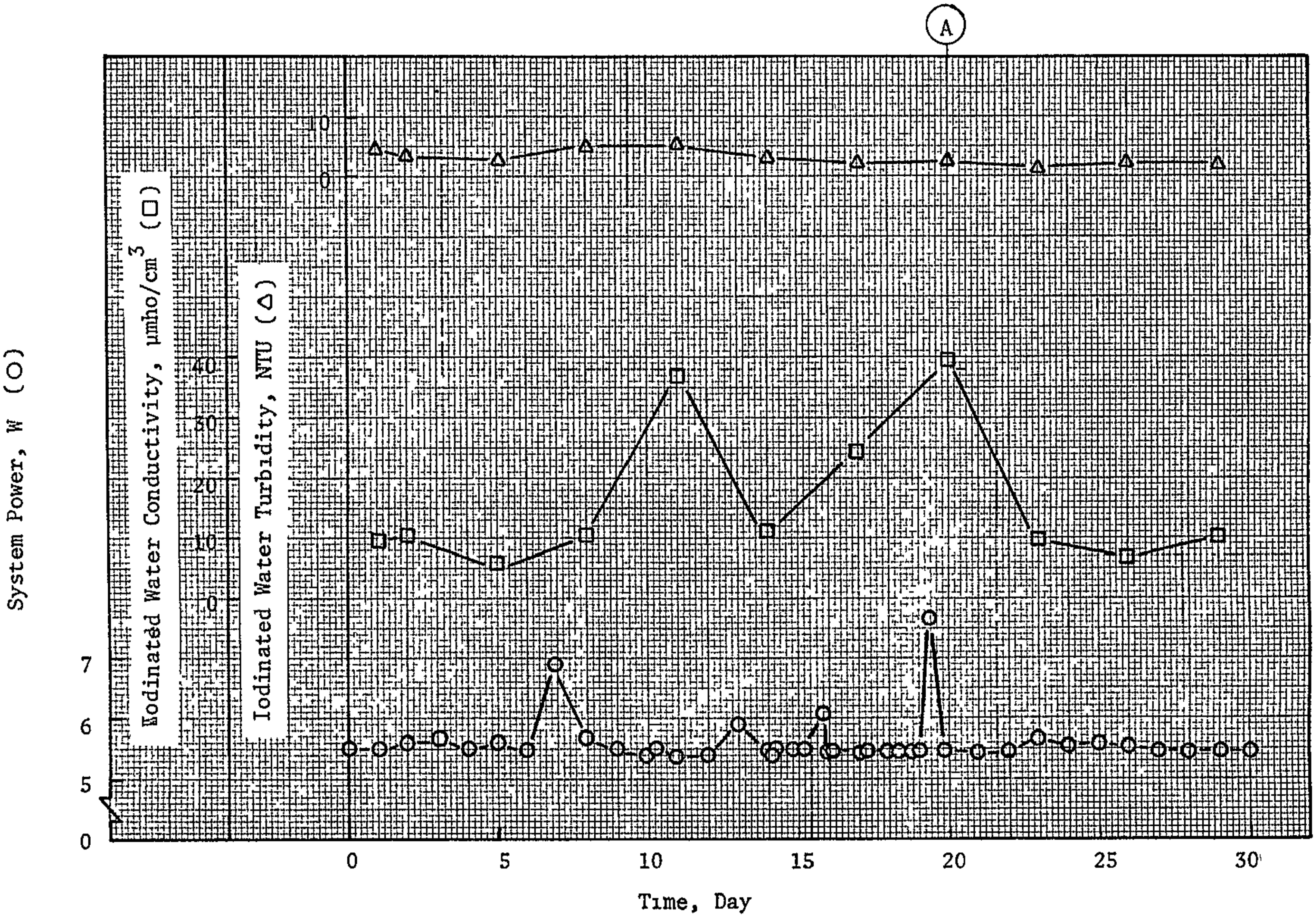


FIGURE 33 ACIDD SYSTEM POWER AND IODINATED WATER CONDUCTIVITY AND TURBIDITY VERSUS TIME

A decrease in I_2 concentration, as measured analytically, with increasing feed water temperature (see Figure 25) was observed and assumed to be due to possible I_2 Detector calibration variations with temperature. A plot of I_2 concentrations obtained during the DVT versus water temperature shown in Figure 29 indicates that this effect was apparently characteristic. The I_2 concentration versus temperature slopes in Figures 25 and 29 were determined to be nearly equal. The trend may be due to some slight changes with temperature in either the optical system of the detector or in the electrical characteristics of the circuits. The effect did not prevent operation within the required specifications (5 (+1, -2) ppm I_2). Should a tighter tolerance be desired for future applications, temperature compensation and other modifications may be necessary.

Figure 30 shows valve current and voltage and water flow rate variations with time during the DVT. The voltage and current remained within the ACIDD design limits of less than 5.0V and +100 to -10 mA.

Figure 31 shows how I^- concentration varied with time during the induced water, temperature and flow variations of the DVT. The I^- variation is somewhat random although high I^- concentrations were consistently found during operations at low water flow rates. This is most likely due to I_2 reduction to I^- by the negative currents to counteract I_2 diffusion.

Figure 32 shows how the observed I^- concentration varied with simultaneous variations in iodinated water pH and dissolved O_2. As expected, the dissolved O_2 recorded was approximately the equilibrum concentration of O_2 in water equilibrated with ambient air. This effect was due to unavoidable exposure of water samples to air during the specialized sampling operation. Iodide did not systematically vary with pH.

Figure 33 shows total ACIDD system power and iodinated water conductivity and turbidity with time during the DVT. Average system power was 5.5W, slightly lower than the average system power observed at the beginning of the test program (6W). The system evidently became somewhat more efficient after aging. This performance is considerably superior to the design goal of 8W average system power consumption for the ACIDD. Higher power levels of up to 7.7W are noted only at high water flow rates.

Iodinated water conductivity corresponds to high H^+ concentration (low pH) as would be expected. The turbidity of iodinated water was low and essentially constant. No effect on the operation of the detector is attributed to observed turbidity levels.

Iodination Level Detector Consistency

The voltage of the Iodination Level Detector light source lamp and the output of the photodetector used to control the filament voltage were measured prior to starting ACIDD testing and were measured again at the conclusion of the DVT. The results of these measurements are reported below:

- Change in filament voltage, 0.6%
- Change in photodetector voltage, 0.5%

The essentially identical before and after operating conditions of the light source indicates that no deterioration occurred during the testing.

Pre-and post-test signals from the reference photodetector/filter (631 nm) are not reported. Deliberate adjustments of these parameters were required after Detector reassembly, following correction of the window fogging condition. Visual observation of these windows during the Post-Test Component Analyses indicated that these windows remained clean.

Water Analyses

The results of the feed water analyses, as indicated in the DVT events schedule, (Figure 27) are listed in Table 12. Analyses of water samples sent to NASA are listed in Appendix 2.

ACIDD Shutdown and Restart Test

A high I_2 concentration can build up in the anode compartment of an I_2 Source after standing inoperative for long time periods. This effect was assumed to be due to diffusion of the concentrated I_2 solution in the accumulator across the membrane to the anode compartment. The experiments below were performed to quantify this behavior.

Procedure

The ACIDD I_2 Source was electrically isolated from the current feedback system and the water flow was shut off for 4-1/2 hours. The I_2 Detector signal was recorded during this period. At the end of this period, water flow and normal feedback were restored to the I_2 Source and water exiting the ACIDD test stand was collected in two portions over 30.5 minutes. The iodinated water coming out of the sample port was also sampled and analyzed at different intervals to provide a more instantaneous indication of the I_2 concentration in the treated water. The Iodination Level Detector output was also recorded during this time.

Results

Iodine concentration exiting the sample port is plotted versus time in Figure 34. The excess I_2 that was accumulated in the anode compartment (Dispenser) was apparently dissipated within ten minutes of resumed ACIDD operation. The first sample taken, within a few seconds of restarting the ACIDD, was too concentrated to be measured by the standard colorimetric technique(9) (approximately greater than 50 ppm I_2).

Sixteen minutes after restarting the ACIDD a quantity of 1290 cm^3 (2.84 lb) of water, with an analyzed I_2 concentration of 24.8 ppm, was collected. The sample of water collected in the remaining 14.5 minutes, however, had an

TABLE 12 RESULTS OF DVT FEED WATER SAMPLES ANALYSES

Sample Number	Day Number	pH	I_2, ppm	I^-, ppm	Dissolved O_2, ppm	Conductivity, mho/cm	Turbidity, NTU
N-1	0	4.5	0.0	0.0	8.3	3.0	0.4
N-2	4	4.1	0.0	0.0	8.5	1.35	0.3
N-3	8	5.0	0.0	0.0	8.7	3.05	0.52
N-4	10	4.49	0.0	0.0	8.8	2.49	0.35
N-5	14	5.29	0.0	0.0	8.4	4.65	0.35
N-6	17	4.40	0.0	0.0	8.6	1.14	0.26
N-7	20	5.20	0.0	0.0	8.5	2.80	0.26
N-8	21	4.40	0.0	0.0	8.8	6.85	0.22
N-9	24	4.59	0.0	0.0	8.7	2.38	0.30
N-10	29	4.85	0.0	0.0	8.3	1.00	0.26

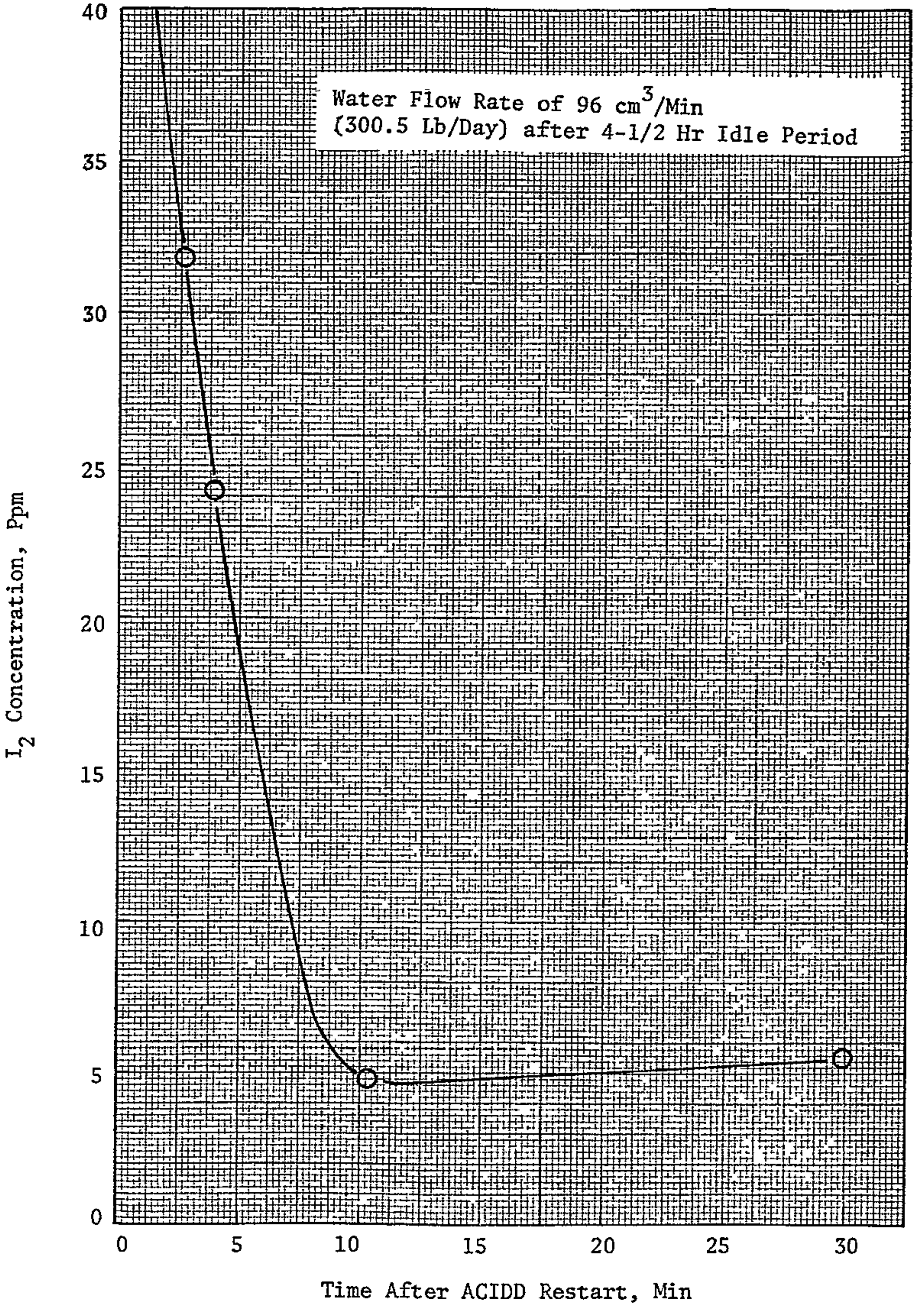


FIGURE 34 I_2 LEVEL VERSUS TIME PROFILE AFTER IDLE PERIOD analyzed I_2 concentration of 5.5 ppm, corresponding to the normal operation of the ACIDD. These results show that although concentrated I_2 solutions can build up in the iodinated water compartment of the ACIDD they are quickly dissipated and the ACIDD quickly resumes normal operation.

Should large transient concentrations in the iodinated water be objectionable following a shutdown of the system, a small negative current could perhaps be used to retard transport of I_2 into the anode compartment.

Post-Test Component Analyses

All parts of the ACIDD were examined subsequent to testing to verify their ability to withstand conditions in the fluid-containing sections of the ACIDD. Total exposure time of the ACIDD components to catholyte and iodinated or noniodinated water was 90 days at the end of the DVT. The catholyte solutions were also analyzed to determine what I_2, I^- and H^+ concentrations resulted from long-term operation of the ACIDD.

Analysis of the Catholyte

Samples of the ACIDD catholyte solution were analyzed and found to contain the following. 2.2×10^4 ppm I_2, 3.6×10^4 ppm I^- and a pH of approximately 0.5. These analyses compare favorably with similar analyses of the catholyte solution in the AWIS I_2 Source (IX-SA) which had been used over a long period of time (1.0×10^4 ppm I_2 and 1.5×10^4 ppm I^-).(3) The ratios of I_2/I^- concentration, which influence current efficiency, are nearly identical. This information confirms that the catholyte fluid reaches essentially a steady state condition with time.

Component Inspection

The interior of the Accumulator, the inner surface of the I_2 loading cap and the interior of the Detector sample cell were visually inspected and were in excellent condition. The weight of the filling cap, for example, was 27.166 g versus 27.079 g at initial assembly, further indicating that no observable corrosion had taken place. Furthermore, all welds appeared in good condition.

All of the optical surfaces, including the sample cell windows, the focusing lenses and the light source and detector parts were clean and free of dirt. One of the aluminum compression rings that held the sample cell windows in place had a slight whitish deposit, possibly due to the moisture being trapped in this portion of the detector (see discussion of DVT).

All O-rings were in excellent condition, except for one of the redundant O-rings that sealed the passage of water from I_2 Source to the detector sample cell. The O-ring showed a cut apparently resulting from ACIDD assembly. Although no water leakage was observed past the redundant O-ring, this seal should be handled carefully during assembly or possibly be redesigned.

The O-ring that sealed the I_2 loading cap to the accumulator showed an increase in weight from 0.391 g to 0.394 g. This weight increase was typical for other ACIDD O-rings and was also nearly identical to that observed for similar O-rings in the AWIS. The Viton O-rings have shown excellent resistance to concentrated I_2 solutions.

The polysulfone compartment spacer showed no signs of attack or deterioration except for a slight staining by the I_2. A small crack, noticed prior to assembly for the DVT, near one of the anode contact pins was more readily observable since some I_2 stained its surfaces. No change in its size was observed. The weight of the spacer had increased by 0.2%, or from 27.079 g at assembly to 27.166 g, probably due to a small amount of I_2 absorption.

The electrodes appeared in excellent condition. The anode was essentially free of solid I_2 deposits at the areas where flowing water contacts it. There was a slight film of solid I_2 on the sections of the anode that were in contact with the anode compartment spacer. Some spot welds of electrodes to the accumulator and to the connector pins had become detached. This was not considered detrimental, however, since contact pressure is the main means of insuring current continuity.

One of the redundant Hastelloy C anode pins showed some evidence of etching on its upper half. No deterioration in ACIDD performance was noted during the testing. However, the anode contact pin could be made out of Pt in the future to prevent any possible long-term voltage rise.

The membrane was in good condition with no evidence that the sealing surfaces had deteriorated. The membrane had a blackish color as usual, indicating that it had absorbed I_2.

SUPPORTING TECHNOLOGIES STUDIES

The general objective of these studies was to expand the technology base associated with spacecraft water iodination. The principal thrust was to investigate the effects of operating parameter variations and possible characteristic changes in the I_2 Source on I_2 generation. The goal was to determine whether satisfactory iodination can be achieved without the use of an Iodination Level Detector and its associated current feedback system. Elimination of these portions of the iodinator would permit reductions in weight, volume and power and would increase reliability by reducing complexity.

Summary of Activities

The supporting technology studies included the following activities:

1. Defining and sorting of operating parameters that affect I_2 transport and current efficiency in the I_2 Source.
2. Testing to verify the significant parameter effects identified.

3. Evaluating techniques to allow for elimination of the Iodination Level Detector.

4. Testing to empirically demonstrate whether it is feasible to achieve acceptable iodinator operation without a current feedback control loop.

5. Completing a study to quantify the decrease, if any, of the I_2 concentration in water contained in a 316 SS water system due to adsorption of I_2 on the metal.

6. Deriving a mini-math model, based on empirical data, to allow sizing of an ACIDD for arbitrarily chosen applications.

Definition and Sorting of Operating Parameters

During operation of the ACIDD, the current to the I_2 Source is controlled to supply the desired I_2 concentration regardless of changes in operating parameters. If the I_2 Detector feedback is to be eliminated, the current must be supplied to the I_2 Source in some regular pattern. Because variations in certain parameters will change the I_2 generation rate obtained for a fixed current pattern, it was necessary to determine which parameter effects are significant, which can be minimized and which may require compensation.

The transport of I_2 across the membrane from the accumulator to the dispenser is governed by Migration, Diffusion, Bulk Transport and Current Efficiency. The effect of pertinent operating parameters on each of these was examined analytically and the results are summarized in Table 13. The parameters that were deemed to have an insignificant effect on any of the I_2 transport factors over the range of interest for Shuttle Orbiter application are indicated as "none."

The water flow rate will influence the diffusion rate of I_2 only slightly. The main effect will be indirectly on current efficiency when the I_2 Source is operated with variable current to maintain a constant I_2 concentration. The current must then increase with water flow rate and current efficiency drops with increasing current.

The principal effect of temperature variations will be to affect the I_2 diffusion rate. Changes in temperature may also slightly influence the degree with which side reactions compete with I_2 generation.

Static water pressure was not expected to affect I_2 transport at all because chemical reactions in solution are essentially pressure insensitive in the low pressure ranges of potable water systems.

Negative step changes in the water pressure can cause some transient increases in I_2 concentration due to bulk transport. If air is entrapped in the accumulator, it will expand, forcing a small slug of catholyte solution across the membrane during pressure equalization. This effect can be minimized, as was done for the ACIDD.

TABLE 13 PARAMETRIC EFFECTS ON IODINE GENERATION RATE

	Iodine Generation Factors			
Parameter	Migration	Diffusion	Bulk Transport	Current Efficiency
Water Flow Rate	None	Yes	None	Yes (a)
Temperature	None	Yes	None	Yes
Pressure (Static)	None	None	None	None
Pressure (step change)	None	None	Yes	None
H_2-in-H_2O	None	None	None	Yes
Catholyte pH	None	None	None	None
Catholyte Iodide (I^-)	Yes	Yes	None	Yes
Solid I_2 in Catholyte	None	Yes	None	Yes
Anode Material	None	None	None	Yes

(a) Varies with current required to maintain constant I_2 concentration.

Hydrogen in the water is expected to reduce the current efficiency because it will compete effectively with I^- for oxidation at the anode and thus will utilize some of the current that would normally generate I_2.

Catholyte pH would be expected to interfere with current efficiency only if an appreciable concentration of OH^- exists in the catholyte to compete with I^- for transport across the membrane. The concentration of OH^- ions will be so low for the pH conditions in the catholyte that the concentration of OH^- is practically nil.

An increase in ratio of I^- to I_2 species in the catholyte will increase the current efficiency due to the higher percentage of I_2 in the complex I_3^-. This ratio was shown to reach a steady state condition during ACIDD testing. This steady state condition is established quickly (days) and will therefore not affect ACIDD operation.

The effect of solid I_2 level in the accumulator will be minimized by refilling it after the equivalent of 22 Shuttle Orbiter missions, even though the accumulator is sized for 27 missions.

The type of anode material may influence the current efficiency by determining the ease with which side reactions compete with I_2 generation.

In summary, variations in four operating parameters were considered to have significant effects on the I_2 generation: water flow rate, water temperature, H_2 content of the water and anode material. Each of these parameters was investigated analytically and/or experimentally using Iodinator Breadboard test set-ups (e.g., see Figure 8). The results are discussed in later sections.

Shuttle Orbiter Water Supply

In the Shuttle Orbiter, the water to be treated by the iodinator is produced by fuel cells at a rate dependent upon their electrical power output.

An analysis of this power output over the first 50 hours (typical) of a Shuttle Orbiter mission enables a profile of the water output of the fuel cell to be determined. Some numerical characteristics of this profile are listed in Table 14.

Greater than 99% of all the water flows are between 69.8 and 124 cm^3/min (221.3 and 392.2 lb/day). In fact, only one flow rate outside the nominal range occurs, and that only for a very short period of time: 170.4 cm^3/min (540.4 lb/day) for the initial eight minutes in the 50-hour period. Thus, maintenance of the 5 (+1, -2) ppm I_2 concentration will rarely be required for water flows outside this relatively narrow range. Control of current to the I_2 Source without an Iodination Level Detector and its associated feedback loop can thereby be simplified.

The cumulative volume of water produced over the first 50-hours of Shuttle Orbiter fuel cell operation is plotted versus time in Figure 35. This volume

TABLE 14 FUEL CELL WATER OUTPUT RATES FOR THE SHUTTLE ORBITER[a]

Nominal Range (>99% of all water flow), cm^3/Min (Lb/Day)	
Highest Flow	124 (392.2)
Lowest Flow	69.8 (221.3)
Maximum Range (100% of all water flow), cm^3/Min (Lb/Day)	
Highest Flow	170.4 (540.4)
Lowest Flow	69.8 (221.3)
Average Flow, cm^3/Min (Lb/Day)	86.5 (274.1)

(a) From analysis of Shuttle Orbiter fuel cell power rates during first 50 hours of operation (typical).

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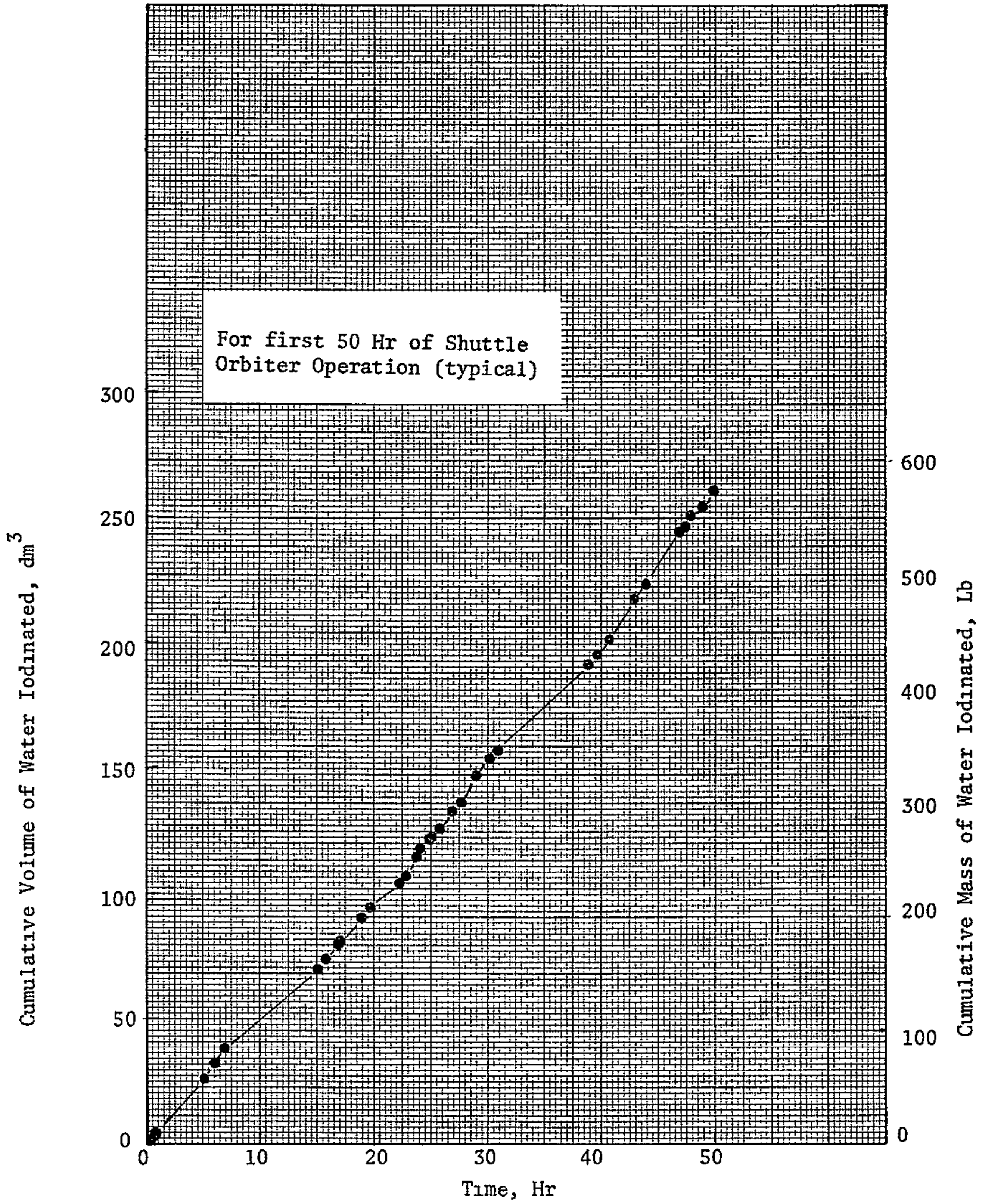

FIGURE 35 CUMULATIVE VOLUME OF WATER IODINATED VERSUS TIME

represents the amount of water which has passed through the iodinator and into the storage tank of the Shuttle Orbiter. The water builds up in the tank in nearly a linear function with time so that the I_2 concentration in the tank water would correspond to the I_2 concentration obtained at an average water flow rate. Thus, not only does water pass through the iodinator at a very narrow range of water flow rates, but the I_2 concentrations produced in the treated water will be averaged out to a very narrow band by the integrating effect of the storage tank. The water actually used by the astronauts will have the I_2 concentration of the water contained in this storage tank rather than the I_2 concentration of the water exiting the iodinator.

I_2 Diffusion Considerations

While operating the iodinator at constant current, the I_2 generation rate will increase slightly with flow rate due to a mildly increasing I_2 diffusion component. The diffusion component also increases with temperature.

To investigate these effects, current was disconnected from the AWIS I_2 Source (Model IX-SA), the temperature and flow rate of water entering were varied and samples of the treated water were analyzed for I_2. The resulting data in Figure 36 indicates that the diffusion rate varies slightly with water flow rate and is a relatively small component of the total normal I_2 generation rate, except at low flow rates.

The diffusion rate increases with temperature, though not to the degree expected (see Figures 25 and 26). Discovery of a very low I_2 charge remaining in the accumulator (approximately 4 g) subsequent to this indicates that I_2 diffusion may have been limited, however, due to mass transfer of I_2 within the accumulator. The accumulator was reloaded with I_2 prior to carrying out all other Supporting Technology task experiments.

Investigation of Operation Without an Iodination Level Detector

Some effects of the significant operating parameters identified in the previous section were investigated in combination with analytical and experimental studies to determine the feasibility of operating an iodinator without an Iodination Level Detector. Two operating modes were considered for regulating the current signal to generate I_2.

1. Constant current operation, in which the I_2 generation rate is approximately constant but the I_2 concentration increases or decreases in proportion to water flow rate over some acceptable range.

2. Linearly variable current operation, in which the current increases linearly with the water flow rate to maintain a more constant I_2 concentration. A current signal proportional to the Shuttle Orbiter fuel cell current would be acceptable because the fuel cell current is proportional to its water output.

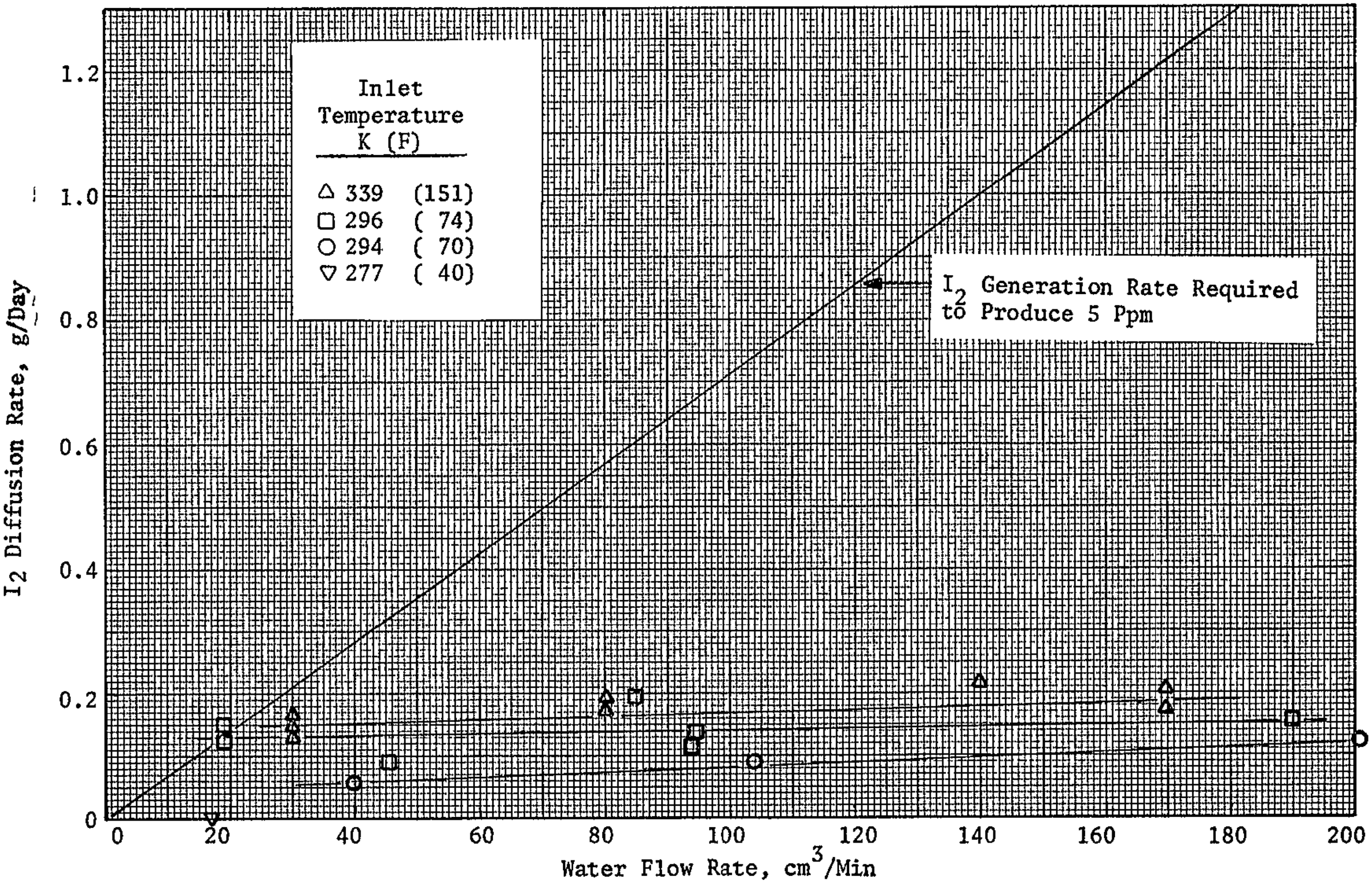

FIGURE 36 I_2 DIFFUSION RATE VERSUS WATER FLOW RATE

Constant Current Operation of Iodinator

If the current supplied to the I_2 Source is constant the I_2 concentration obtained will be inversely proportional to the water flow rate. Five (+1, -2) ppm I_2 was considered to be maintainable with this mode of operation over a restricted range of water flow rates.

Iodination of Pure Water. The projected variation of I_2 concentration with water flow rate is plotted in Figure 37 for constant current operation of an I_2 Source. A constant I_2 generation rate was assumed (constant current efficiency) such that 5 ppm I_2 was obtained at the minimum water flow rate in Table 14, and at an average temperature of 294K (70F). The influence of diffusion rate at other temperatures (Figure 36) was included in calculating data for curves corresponding to other temperatures. Based on the data in these curves, a 2.3 to 5.9 ppm of I_2 could be maintained over the nominal flow rate range.

The reliability of this type of projection and the confirmation of essentially constant current efficiency during constant current operation, over the nominal water flow range, was demonstrated in the ACIDD Test Program. Experimental I_2 concentration versus water flow rate data for constant current operation of the ACIDD shown in Figure 21 compare favorably with projected data similar to that in Figure 36. (The projected curves can, of course, be moved up and down by varying the constant current.)

Iodination of Water That Contains Hydrogen. If the water to be treated contains H_2 a portion of this gas will react electrochemically at the anode and compete with the I_2 generation reaction for the valve current. Less of the valve current will, therefore, be utilized to produce I_2.

The water produced by the Shuttle Orbiter fuel cells, after pretreatment to remove most of the H_2, will contain a maximum H_2 residual of approximately 0.01 cm^3 H_2/cm^3 of water.(12) It was therefore necessary to project what effect this H_2 might have on constant current operation of the I_2 Source.

The I_2 concentration versus water flow rate curves in Figure 38 were calculated on a similar basis to curves in Figure 37, except that various percentages of H_2 in the fuel cell water were assumed to react at the anode. Under this assumption, the total amount of H_2 that reacts per unit time is directly proportional to the water flow rate. The highest flow rates correspond to points where almost no current is left for generation of I_2.

Neglecting temperature effects, Figure 38 shows that a rather acceptable 2.4 to 4.8 ppm concentration band should be obtainable over the nominal Shuttle Orbiter flow range, assuming 1% of the H_2 residual in the water reacts (is oxidized).

Linearly Variable Current Operation of Iodinator

The current required to maintain a constant I_2 level in the water deviates from a straight line. Nonetheless, varying the valve current of the I_2

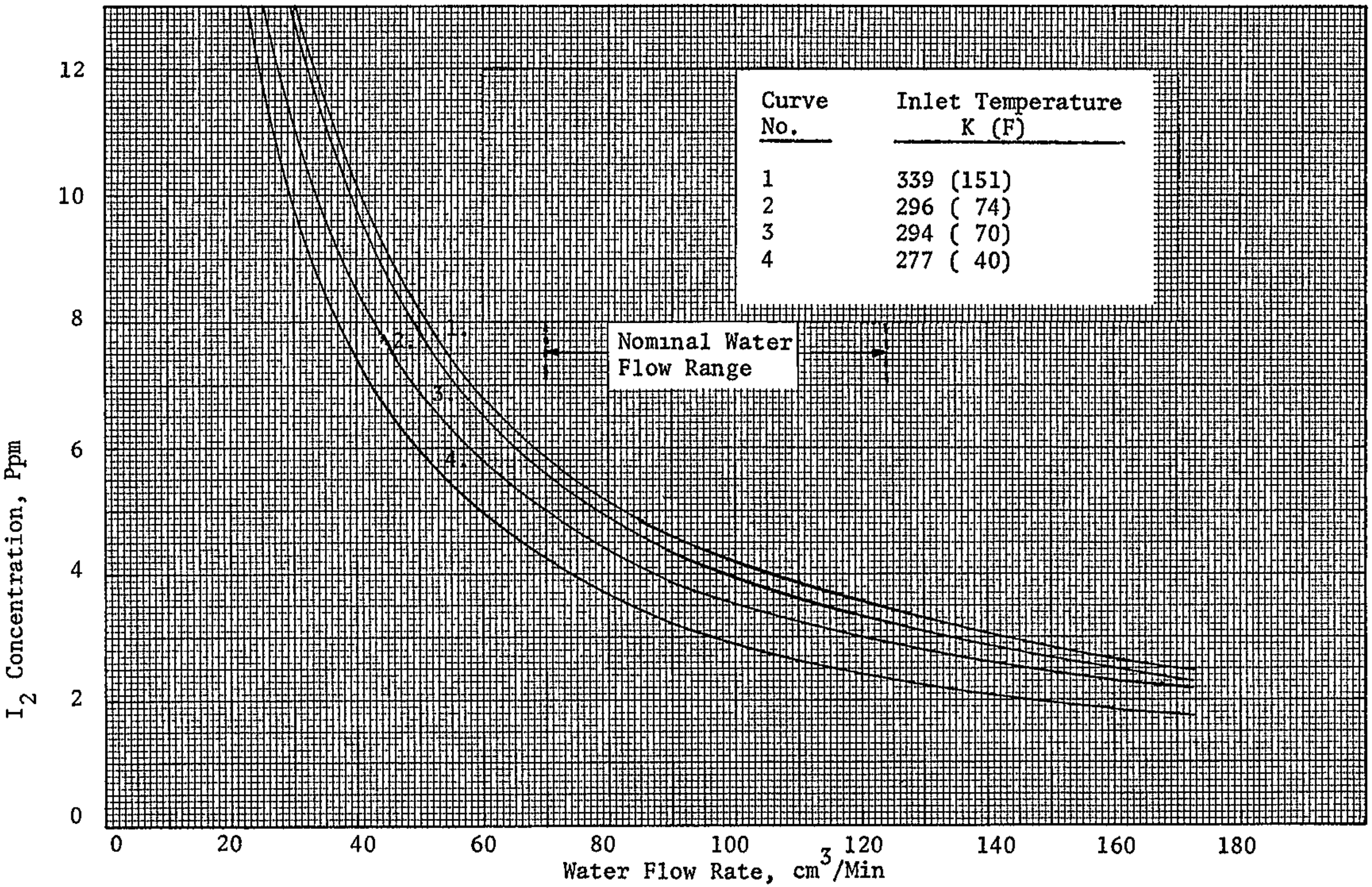

FIGURE 37 PROJECTED I_2 CONCENTRATION VERSUS WATER FLOW RATE: CONSTANT CURRENT OPERATION

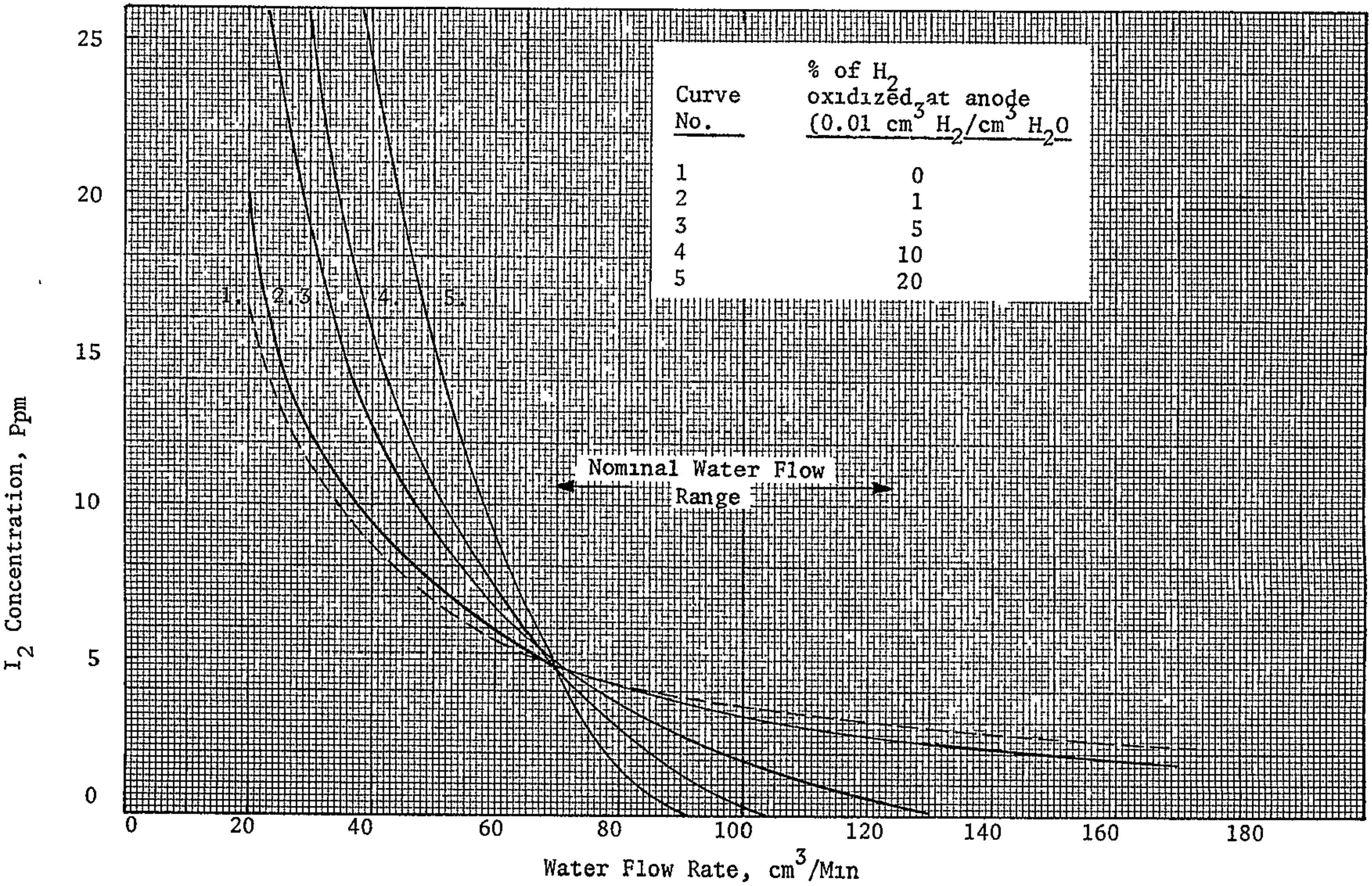

FIGURE 38 PROJECTED I_2 CONCENTRATION VERSUS WATER FLOW RATE: H_2 SATURATED WATER, CONSTANT CURRENT OPERATION

Source linearly with water flow rate would produce a much narrower range of I_2 concentrations in the treated water compared to constant current operation, provided an appropriate current/flow rate relationship was chosen.

The Shuttle Orbiter fuel cell current varies linearly with water flow rate through the iodinator. This current signal can therefore be used to control valve current.

Selection of Linear Current Relationship. The linear current relationship will have the form,

$$i = a + bF$$

where

i = the valve current, (mA)

a = a constant current, (mA)

b = the variable current slope, $(\frac{\text{mA-min}}{\text{cm}^3})$

F = the water flow rate, $(\frac{\text{cm}^3}{\text{min}})$

This relationship would be chosen to approximate the actual non-linear current/water flow rate relationship required to maintain a fixed I_2 concentration. The slope "b" could be a fraction of the Shuttle Orbiter fuel cell current/water flow rate slope and the constant "a" could be a constant current signal simply added to or subtracted from the total current signal.

Figure 39 shows how an estimate of the proper current relationship can be selected. The actual valve currents required for the AWIS I_2 Source (Model IX-SA) to iodinate to 5.5 ppm I_2 are plotted versus water flow rates in curve 1. Curves 2 through 4 are linear approximations of curve 1. Current supplied to the I_2 Source according to one of these linear relationships would be expected to produce satisfactory I_2 concentrations over a wide range of water flow rates, as discussed below.

Iodination of Pure Water. Linear current/water flow rate relationships 2 through 4 in Figure 39 were combined with I_2 generation rate/valve current data to yield projected I_2 concentration/water flow rate relationships. These relationships, plotted as curves 1 through 3 in Figure 40, project that 5 (+1, -2) ppm I_2 should be maintainable over the entire 22.7 to 172.5 cm^3/min (72 to 547 lb/day) Shuttle Orbiter water flow rate range.

Operation of the AWIS I_2 Source according to current relationship 2 in Figure 40 was tested experimentally. The water flow rate through the I_2 Source was

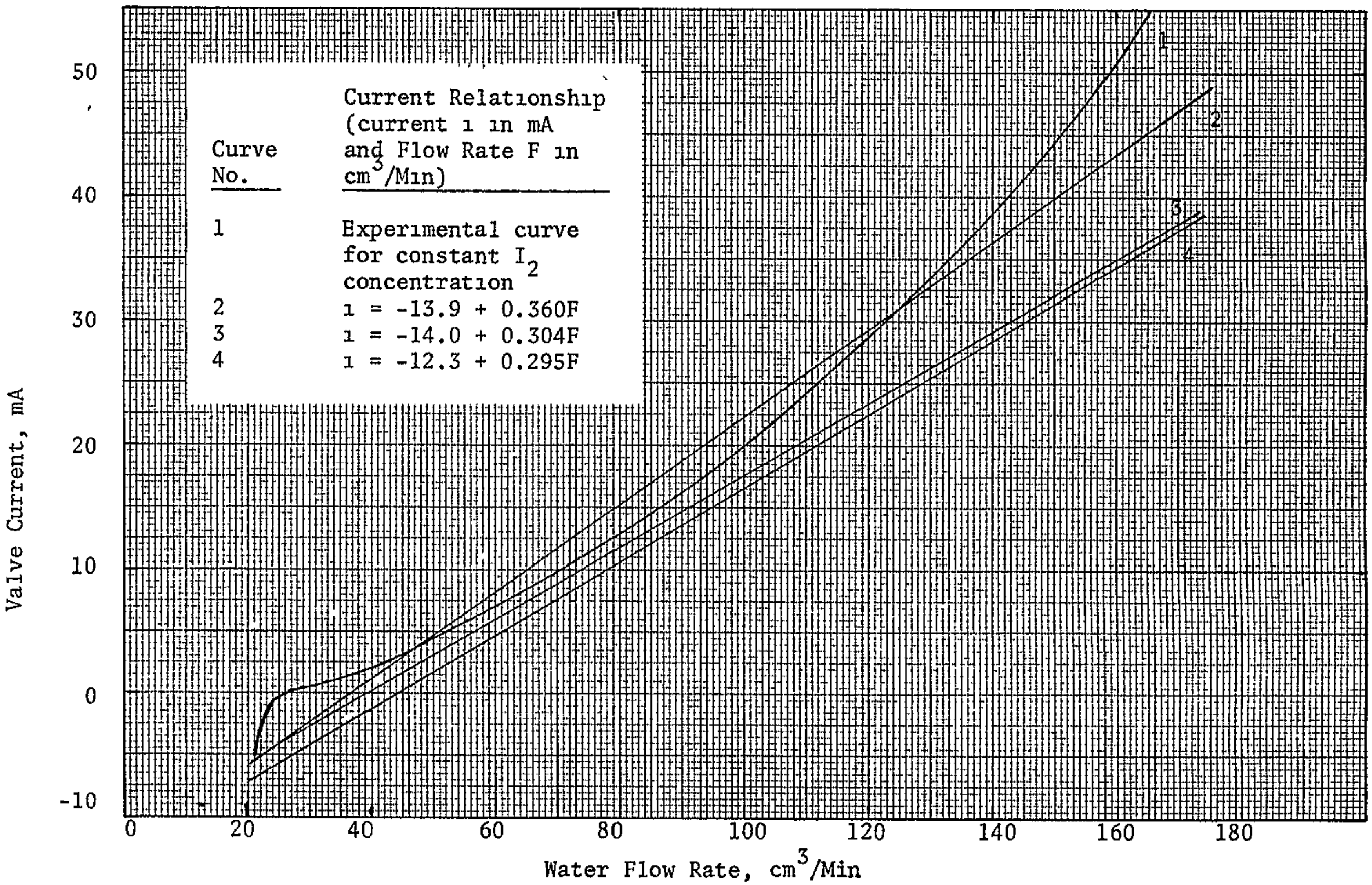

FIGURE 39 SELECTION OF CURRENT RELATIONSHIP FOR LINEARLY VARIABLE CURRENT OPERATION

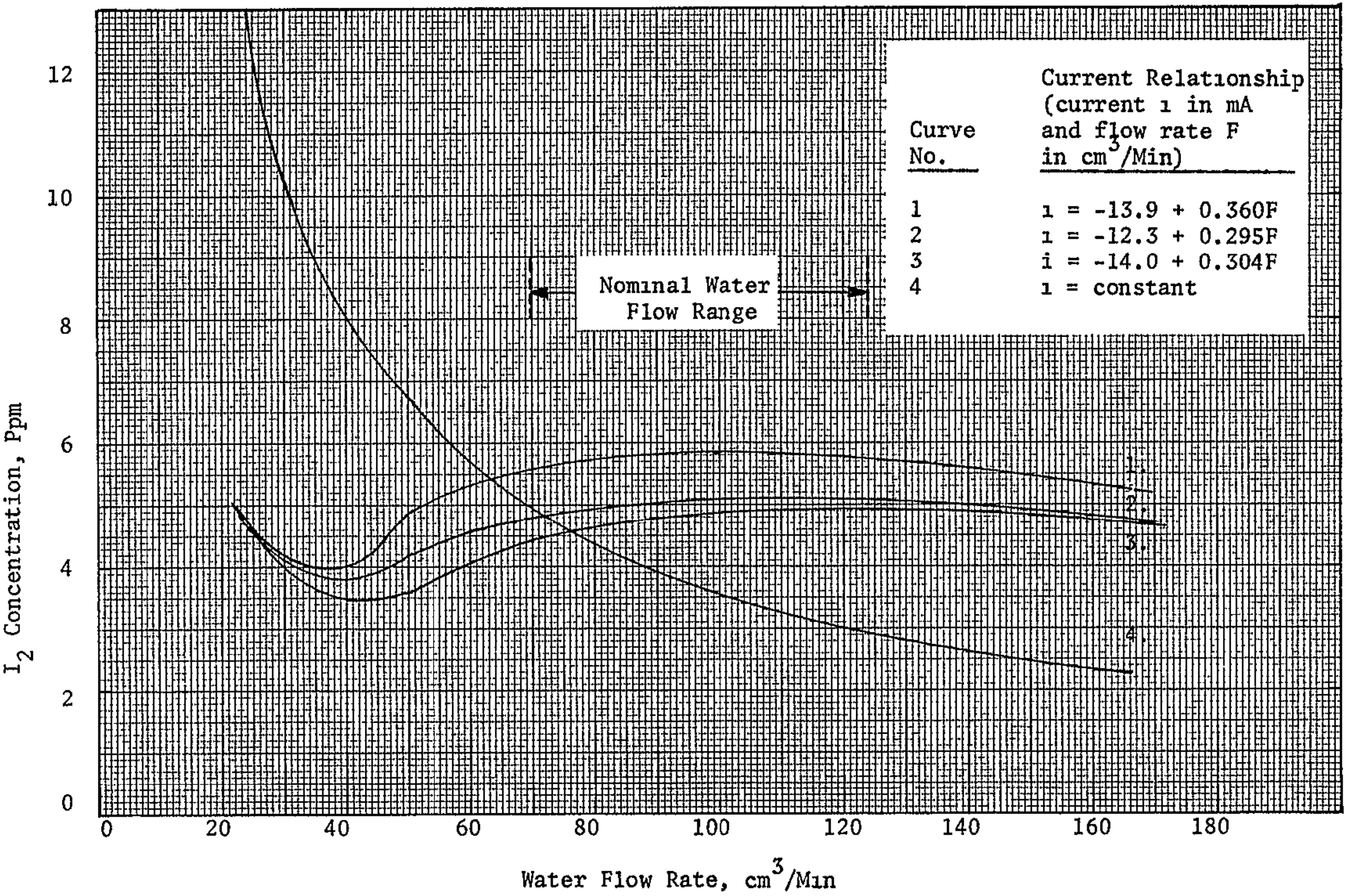

FIGURE 40 PROJECTED I_2 CONCENTRATION VERSUS WATER FLOW RATE: LINEARLY VARIABLE CURRENT OPERATION

varied, the current was adjusted to correspond to current relationship 2 and the iodinated water was sampled and analyzed after equilibrium was obtained. The I_2 concentrations obtained are plotted versus water flow rate in Figure 41.

The form of the curve compares favorably with the corresponding projected data, curve 2 in Figure 40, except that the actual I_2 concentrations obtained are lower. Nonetheless, a 3.2 ± 1.4 ppm iodination level was achieved over the entire 22.7 to 172.5 cm^3/min (72 to 547 lb/day) Shuttle Orbiter flow range. This concentration band can probably be raised to 5 (+1, -2) ppm I_2 by using a different current relationship.

More importantly, however, a 4.3 ±0.3 ppm I_2 concentration band was achieved over the nominal flow range (Table 14). Furthermore, even this small variation in I_2 concentration level in the iodinated water will be averaged by the integrating effect of the Shuttle Orbiter water storage tank.

Iodination of Water Containing H_2. As discussed earlier, the presence of H_2 in the feed water will cause some of the valve current to be diverted to oxidation of H_2. Larger total valve currents will therefore be required to obtain a given I_2 concentration.

Projected I_2 concentration versus water flow rate data are plotted in Figure 42. These data were calculated similarly to those in Figure 40, but for feed water containing 0.01 cm^3 H_2/cm^3 water. Five percent of all H_2 in the water was assumed to be oxidized. The chosen current slopes reflect the increased current requirement.

Curve number 2 of Figure 42 projects that nearly 5 (+1, -2) ppm could be achieved over most of the nominal water flow rate range listed in Table 14, even for such a high degree (5%) of H_2 interference. Comparison of curves 2 through 5 with curve 1 indicates that the performance of the I_2 Source improves dramatically when operated with a linearly variable instead of a constant current signal.

Experimental observations have indicated, however, that H_2 does not interfere nearly to the extent projected. Experimental I_2 generation rate versus current data were obtained for iodination of water containing approximately 0.019 cm^3 H_2/cm^3 water, using the AWIS iodinator in the normal I_2 detector feedback mode. This H_2 concentration is nearly twice the maximum expected in the Shuttle Orbiter feed water.

This data is plotted in terms of I_2 generation rate versus valve current as curve 2 in Figure 43. The I_2 generation rate for feed water containing H_2 is lower than for pure water, curve 1. It is significantly higher, however, than the projected I_2 generation rate, curve 3. Curve 2 is also surprisingly linear, indicating a constant current efficiency over the entire current range studied.

Data from curve 2 were also replotted semiempirically as I_2 concentration versus water flow rate in Figure 44, curve 1. Linear current feedback operation was assumed. This curve implies that a constant I_2 concentration would have been obtained under these conditions.

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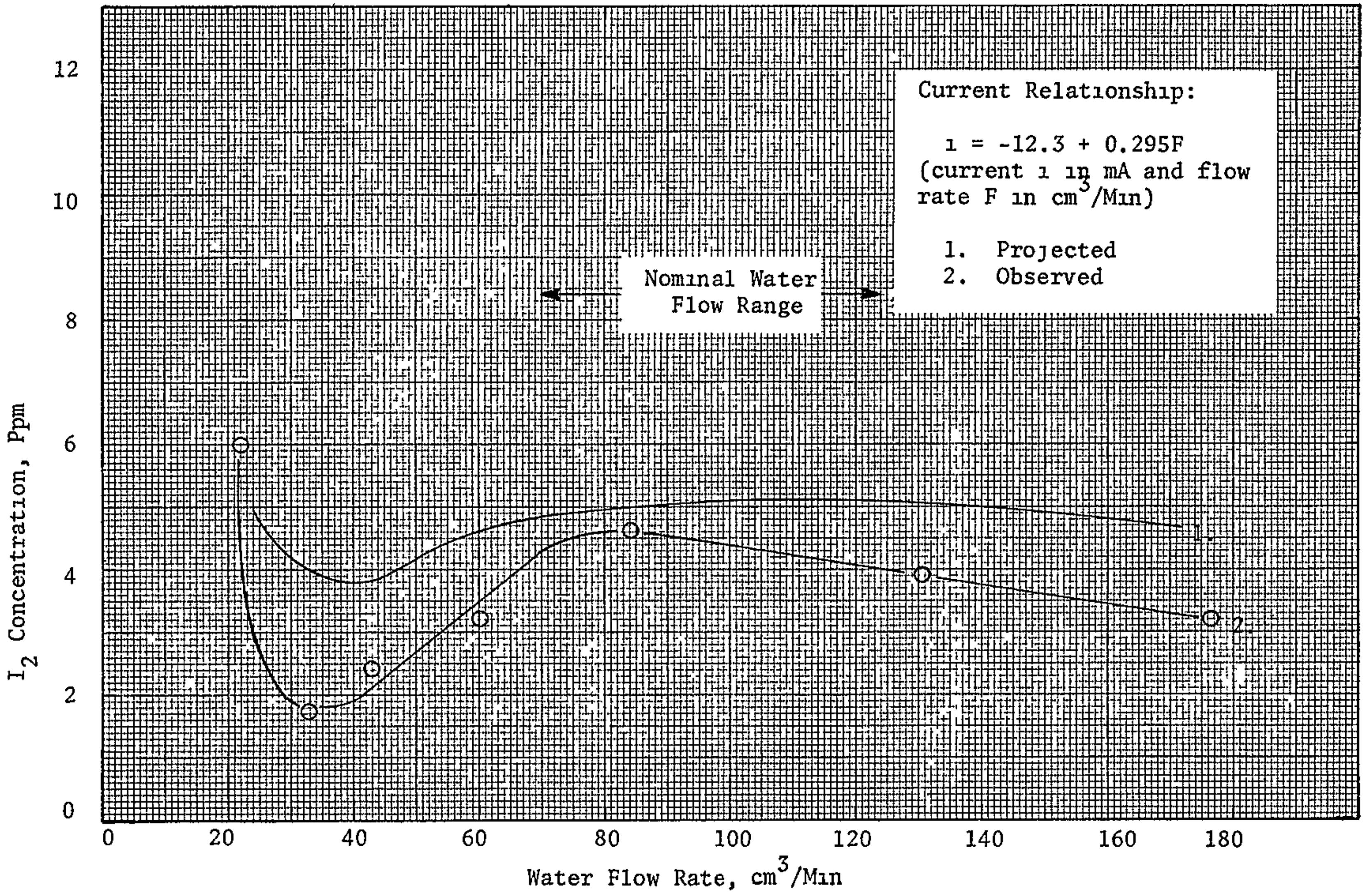

FIGURE 41 OBSERVED AND PROJECTED I_2 CONCENTRATION VERSUS WATER FLOW RATE: LINEARLY VARIABLE CURRENT OPERATION

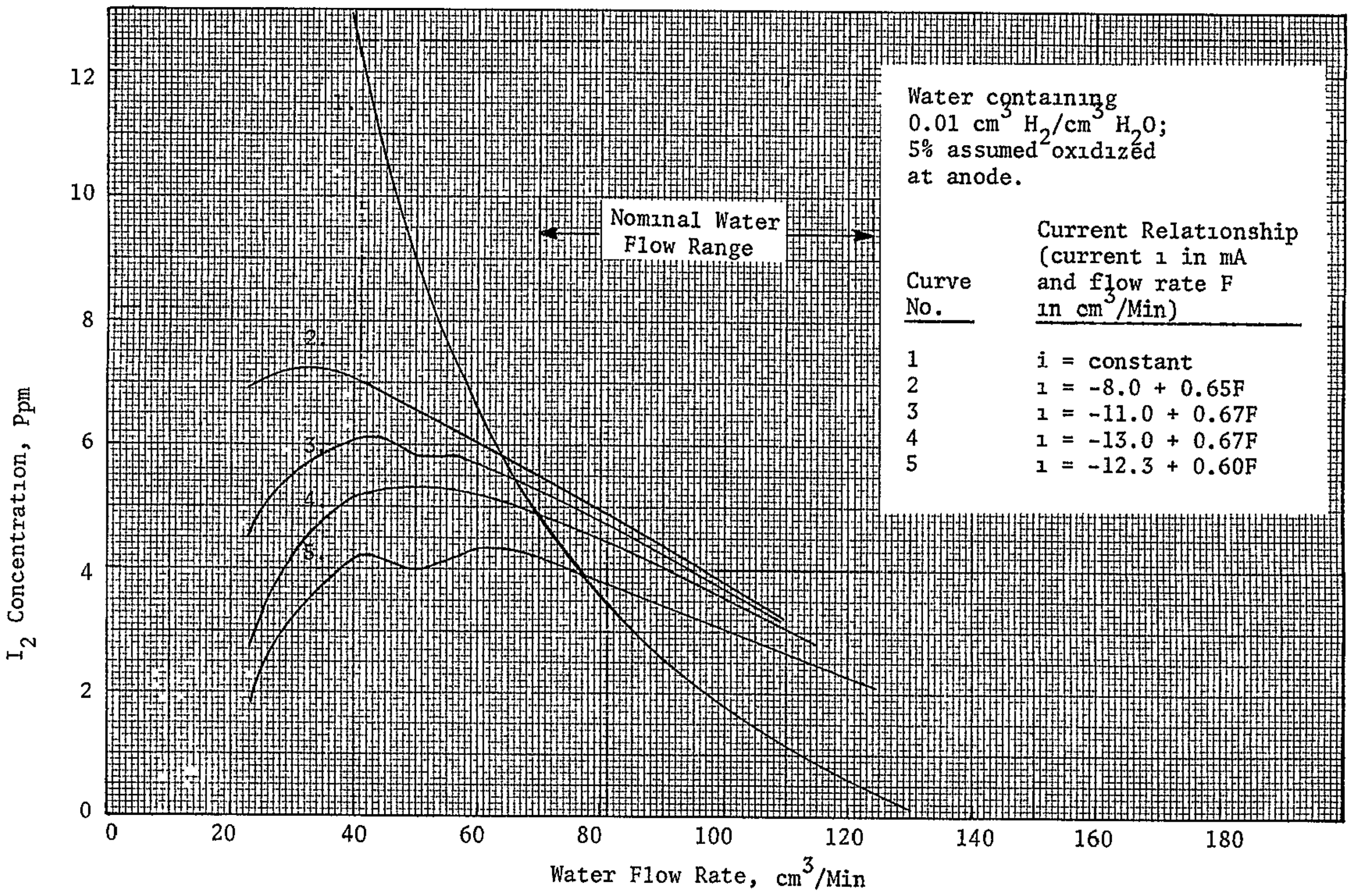

FIGURE 42 PROJECTED I_2 CONCENTRATION VERSUS WATER FLOW RATE: H_2 SATURATED WATER, LINEARLY VARIABLE CURRENT OPERATION

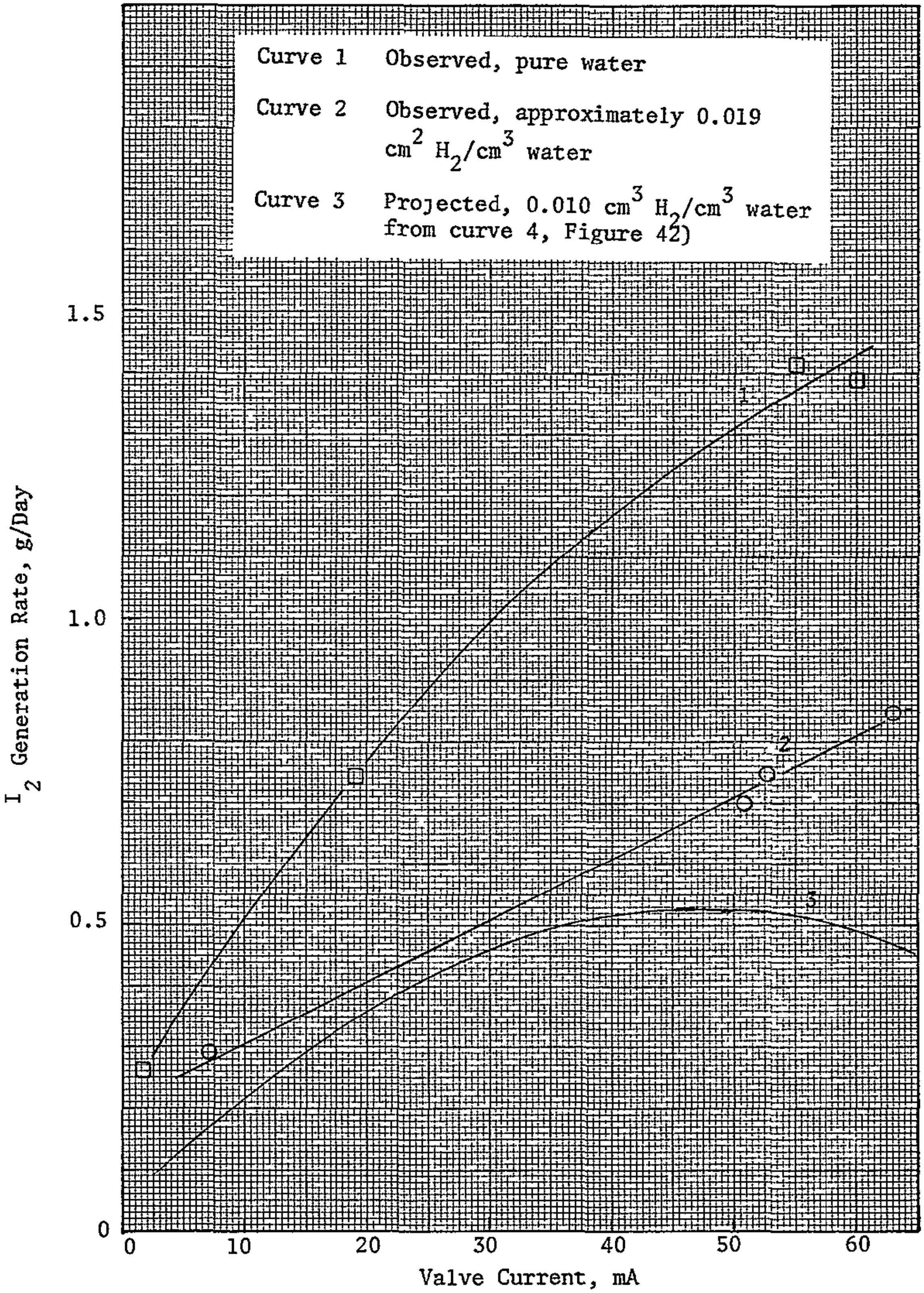

FIGURE 43 OBSERVED AND PROJECTED I_2 GENERATION FOR H_2 SATURATED WATER

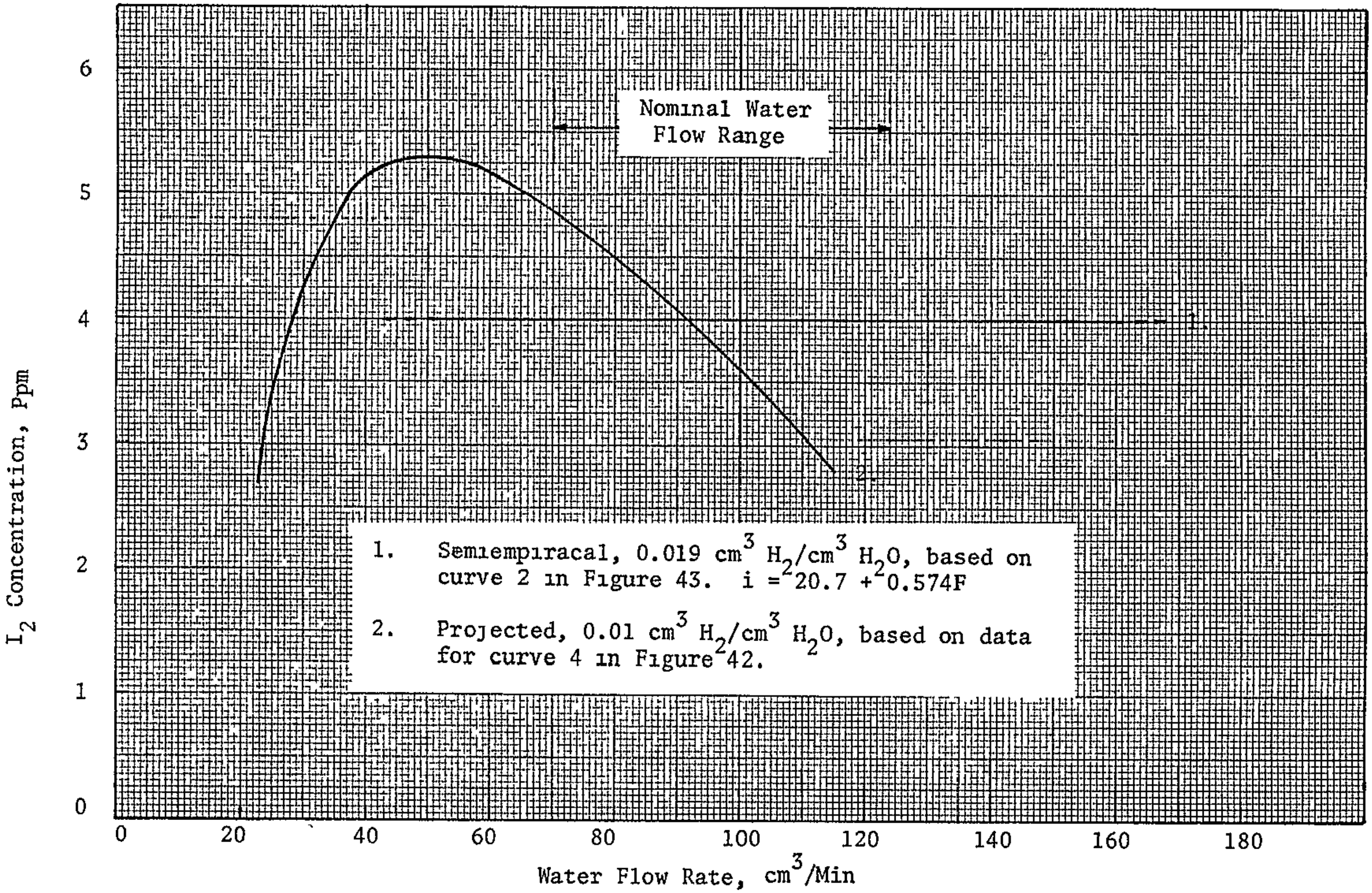

FIGURE 44 SEMIEMPIRICAL AND PROJECTED I_2 CONCENTRATIONS: H_2 - SATURATED WATER, LINEARLY VARIABLE CURRENT OPERATION

Suitability of Titanium as an Anode Material

The water oxidation reaction competes with the I_2 generation reaction for valve current, causing a less than ideal current efficiency.

Water oxidation was known to occur on titanium (Ti) at unfavorably high anode potentials. Iodine current efficiencies were postulated to greatly improve through the use of Ti as an anode material, provided substitution of this material for the baseline anode was not detrimental to the I_2 generation reaction. Voltammetric electrolysis experiments using a rotating Ti disc electrode in solutions with and without I^- (Figure 45) were performed. The results indicated that both I_2 generation and water oxidation occurred at unfavorably high anode voltages as indicated in Figure 45. Titanium was therefore unsuitable as an anode material for I_2 generation.

I_2 Adsorption Studies

There was concern that the I_2 concentration in iodinated water might diminish during storage in potable water systems by adsorbing on stainless steel surfaces of tanks and plumbing. To investigate this possibility, a simulated Shuttle Orbiter iodinated water storage tank was filled with approximately 90 liters of solution containing 4.2 ppm I_2 and 1 ppm I^- (as hydroiodic acid (HI)). This solution simulated the effluent of the ACIDD operating near its design point. The outlet of this tank was connected to a 20 ft length of 0.67 cm (0.25 in) outside diameter 316 stainless steel tubing having a 0.46 cm (0.18 in) bore.

The stainless steel tube was filled with water from the tank and allowed to remain there for several hours. Water samples were taken from the tube and analyzed at intervals during this period to see to what degree the I_2 concentration diminished with time. This experiment was repeated three more times following preconditioning of the tube by flushing it with increasing volumes of I_2 solution from the tank.

Figure 46 shows that the I_2 concentrations diminished rapidly with time in the untreated tube and decreased very slowly with time after only 8400 cm^3 of iodinated water had passed through. A plot of initial I_2 adsorption rates (initial curve slopes from Figure 46) versus volume of iodinated water passing through the tubing was plotted in Figure 47. The data indicates that the I_2 adsorption becomes negligible with little additional conditioning.

It is apparent that after only a few liters of iodinated water have passed through the tubing the surface of the tubing reaches a steady state condition that minimizes or eliminates further adsorption of I_2. It is concluded that adsorption of I_2 on the stainless steel tubing is a temporary phenomenon and one that may be overcome by initial conditioning of the tubing.

Samples of water stored in the tank were withdrawn and analyzed as a function of time. Figure 48 shows that the I_2 concentration decreased slowly with time. This decrease was certainly due in part to I_2 vaporization into the air pocket at the top of the tank that occurred when I_2 solution was drained from

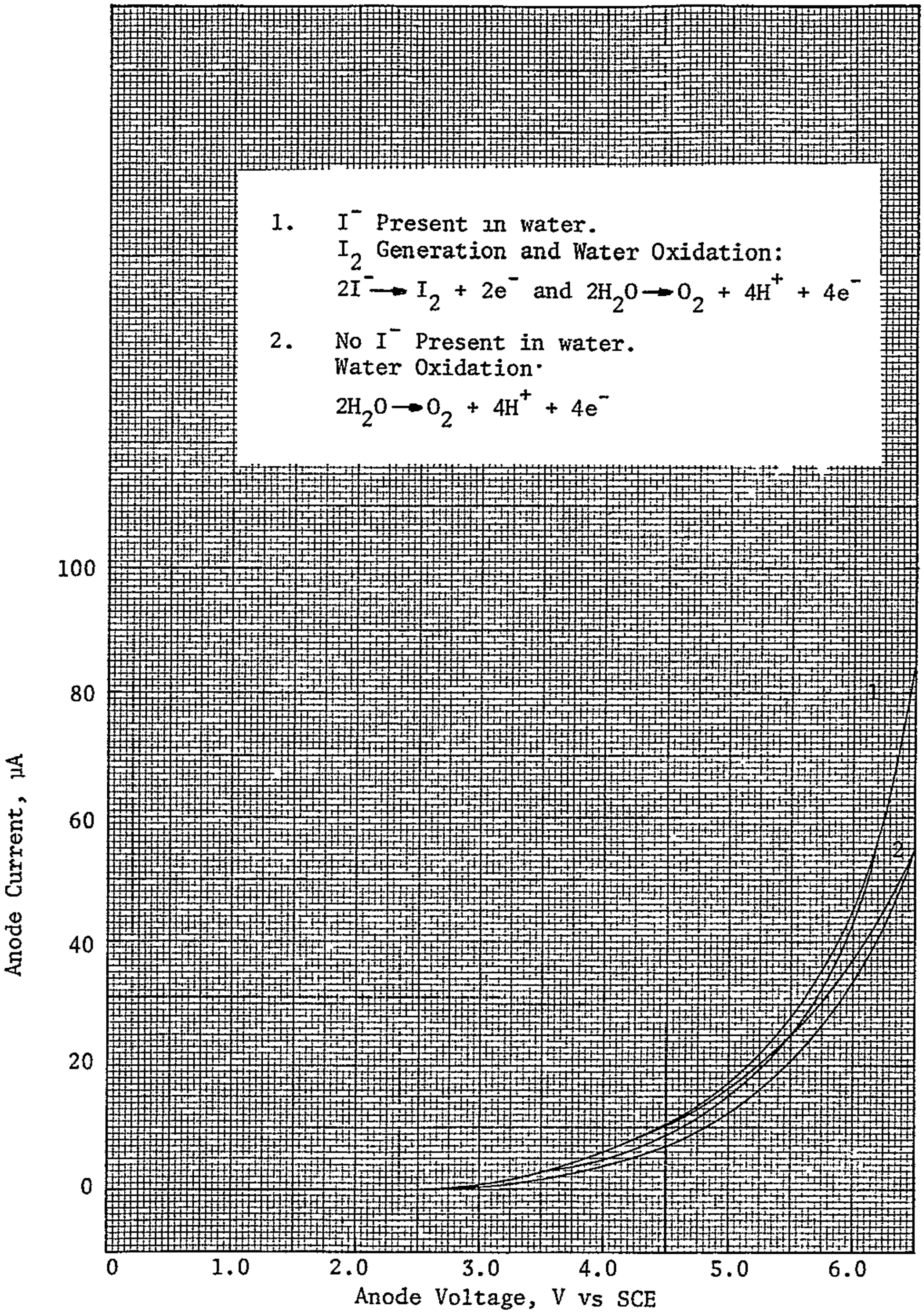

FIGURE 45 VOLTAGES REQUIRED FOR I_2 PRODUCTION AND WATER OXIDATION. TITANIUM ANODE

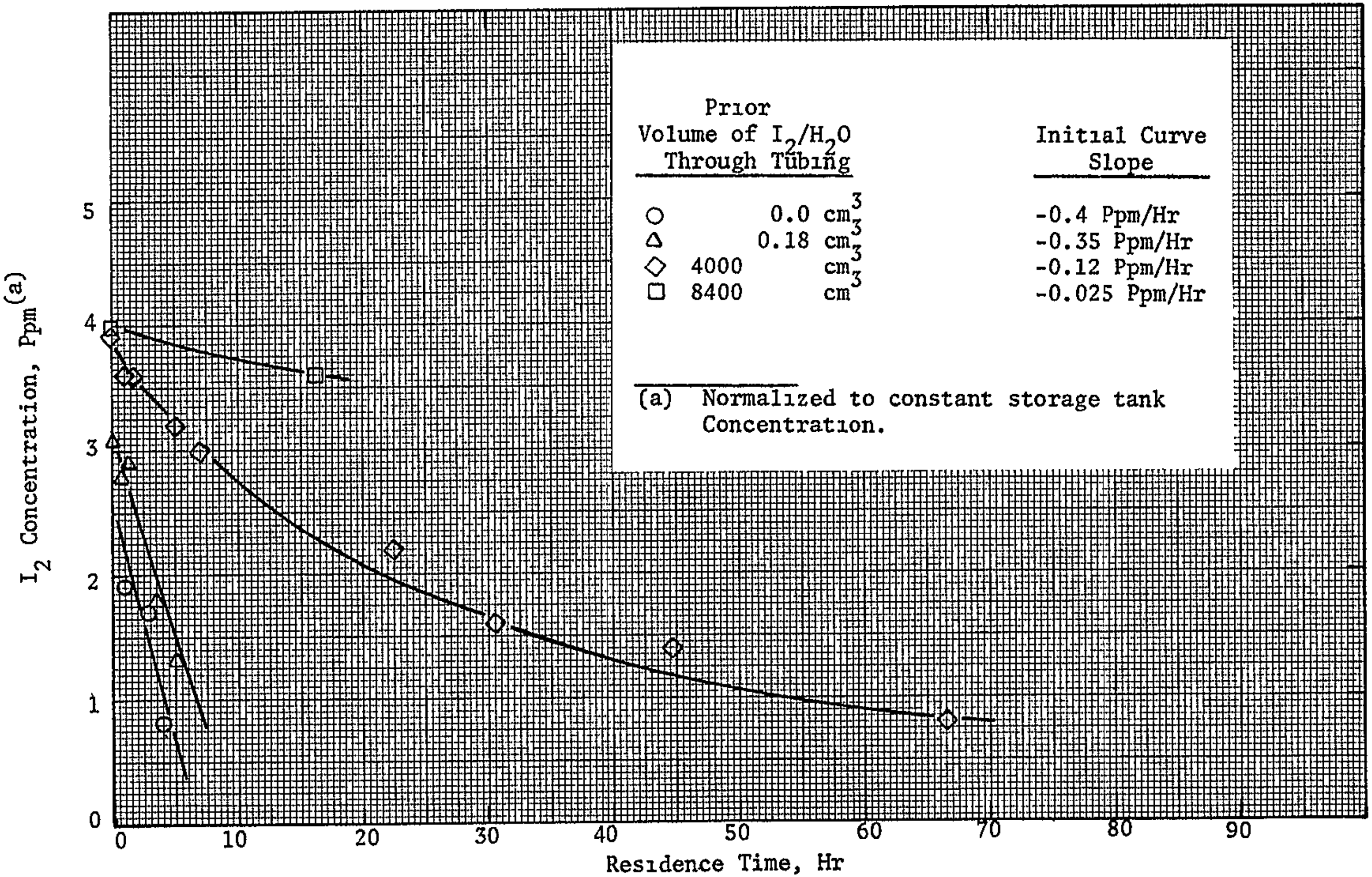

FIGURE 46 I_2 ADSORPTION IN STAINLESS STEEL TUBING: EFFECT OF PRECONDITIONING

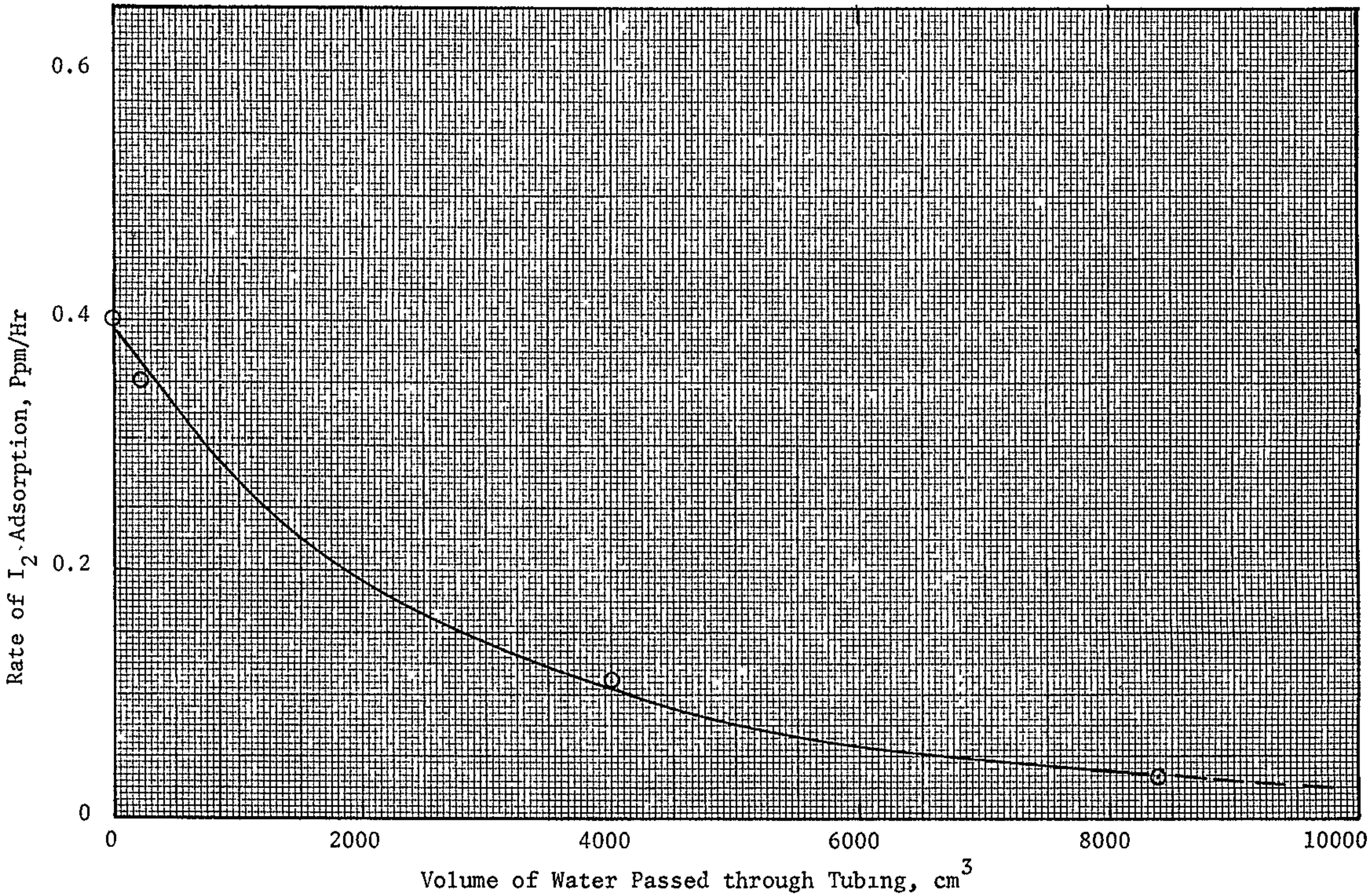

FIGURE 47 DEPENDENCE OF I_2 ADSORPTION RATE ON PRECONDITIONING

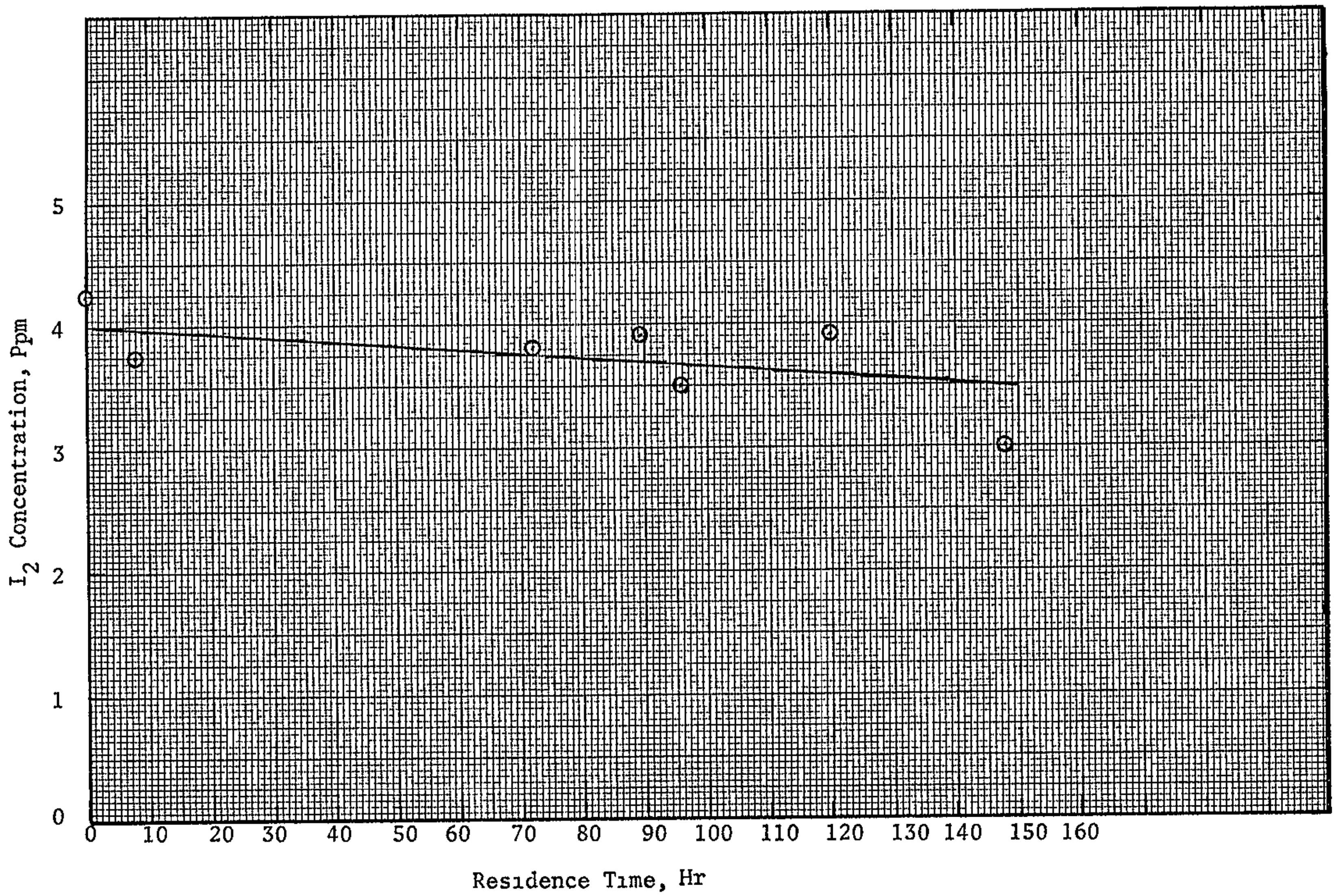

FIGURE 48 RATE OF I_2 ADSORPTION IN STORAGE TANK

it. Any I_2 loss due to adsorption will be virtually eliminated by preconditioning the tank with iodinated water.

Analytical Model for ACIDD

A mini-analytical model was derived based on the overall test program and Supporting Technology Study results. The objective of the model is to provide designers with a technique for sizing of an ACIDD for a variety of applications within spacecraft water and waste management systems.

Electrode Area Sizing

The minimum required electrode area for an I_2 Source will be proportional to the ratio of the maximum I_2 generation rate required for water iodination to the maximum I_2 generation rate available for a given electrode area, as illustrated in the equation below:

$$\text{Minimum Electrode Area Required, cm}^2 = \frac{\text{Maximum } I_2 \text{ Generation Rate Required (g/Day)}}{\text{Maximum } I_2 \text{ Generation Rate/Area (g/Day - cm}^2)} \qquad (3)$$

The numerator in equation (3), the maximum I_2 rate required, will be proportional to the highest flow rate anticipated for the water to be treated and the I_2 concentration level specified for the effluent.

$$\text{Maximum } I_2 \text{ Generation Rate Required, g/Day} = 1.44 \times 10^{-3} \begin{pmatrix}\text{Max Water Flow} \\ \text{Rate, cm}^3\text{/Min}\end{pmatrix} \begin{pmatrix}\text{Specified } I_2 \\ \text{Concentration, Ppm}\end{pmatrix} \qquad (4)$$

The denominator in equation (3), the maximum I_2 generation rate available/area, is based on ACIDD test data as illustrated in Figure 49. The maximum I_2 generation rate/area was found to be 0.0570 g/day cm^2 at 4.57 mA/cm^2 (4.25 ASF), the maximum desirable valve current density for I_2 Source operation. By inserting this result and equation (4) into equation (3) the minimum electrode area can also be calculated:

$$\text{Minimum Electrode Area Required, cm}^2 = 0.0253 \begin{pmatrix}\text{Max Water Flow} \\ \text{Rate, cm}^3\text{/Min}\end{pmatrix} \begin{pmatrix}\text{Specified } I_2 \\ \text{Concentration, Ppm}\end{pmatrix} \qquad (5)$$

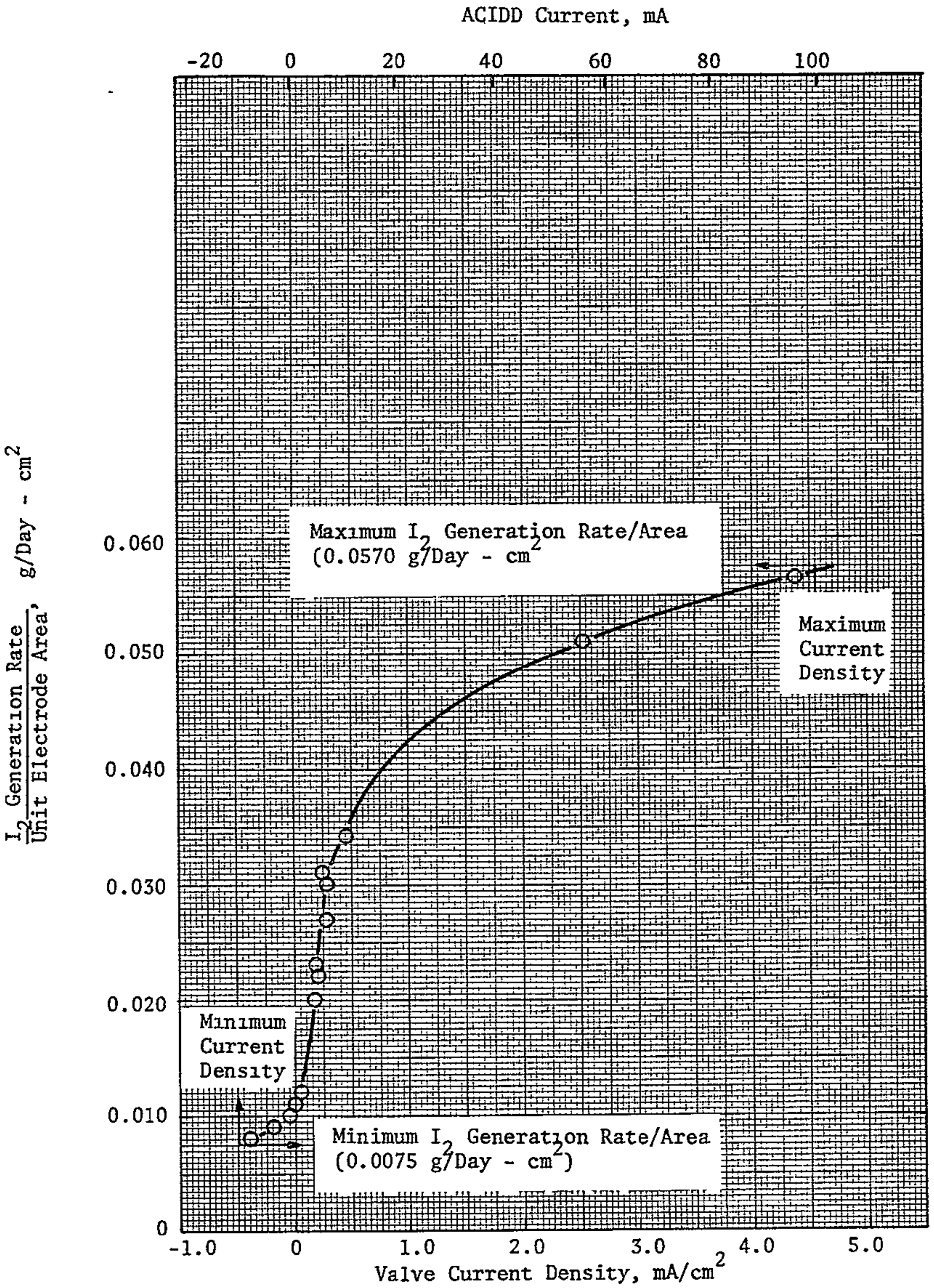

FIGURE 49 I_2 GENERATION RATE DENSITY VERSUS CURRENT DENSITY

Minimum water flow rate requirements must also be observed and are of equal importance to maximum flow rate requirements. The maximum electrode area should be sized with an analogous equation based on the 0.0075 g/day-cm^2 minimum I_2 generation rate identified in Figure 49:

$$\text{Maximum Electrode Area Permissible, cm}^2 = 0.192 \begin{pmatrix}\text{Minimum Water Flow}\\ \text{Rate, cm}^3\text{/Min}\end{pmatrix} \begin{pmatrix}\text{Specified } I_2\\ \text{Concentration, Ppm}\end{pmatrix} \qquad (6)$$

If maximum water flow rate equals nominal water flow rate, the calculated minimum area should be multiplied by 1.2 as a safety consideration. If minimum flow rate equals nominal flow rate, the maximum permissible electrode area should be divided by 1.2.

Based on ACIDD test results, the ratio of the maximum allowable water flow rate to the minimum allowable flow rate can be determined. This value will assist designers in sizing an ACIDD, based on required ranges in water flow. From Figure 49 this ratio is 7.6. In equation form this reduces to

$$\begin{matrix}\text{Maximum Allowable}\\ \text{Water Flow Rate}\end{matrix} = \begin{matrix}\text{7.6 (Minimum Allowable}\\ \text{Water Flow Rate)}\end{matrix} \qquad (7)$$

If I_2 concentration tolerances are specified, such as 5 (+1, -2) ppm, the permissible water flow rate range will be much broader.

Limits

Equations 5 and 6 will be valid within the limits listed below for feed water parameters.

Flow Rate Ratio, Maximum/Minimum:	7.6/1 (for constant I_2 concentration)
Temperature, K (F):	297.4 to 299.7 (76 to 80)
pH:	4 to 8
Pressure, kN/m^2 (Psia):	101 to 308 (14.7 to 44.7)

The chosen I_2 concentration to be maintained should be within 0 to 6 ppm.

CONCLUSIONS

The following conclusions were reached based on the development program

1. An ACIDD is capable of automatically dispensing I_2 biocide into potable water at a level of 5 (+1, -2) ppm over the entire Shuttle

Orbiter water flow range of 23 to 173 cm^3/min (72 to 547 lb/day). This capability was demonstrated over a 30-day Design Verification Test, including operation over wide ranges in water flow rate and temperature.

2. A functional integrated I_2 Source, Iodination Level Detector and electronics assembly was constructed having a weight, volume and average power requirement of 1.23 kg (2.7 lb), 1213 cm^3 (74 in^3) and 5.5W, respectively.

3. The ACIDD power consumption and light source lamp life can be improved substantially by lowering lamp voltage without apparent loss in iodination capability.

4. The reproducibility of I_2 Source operating characteristics was demonstrated, since the ACIDD nearly duplicated the performance of a previously developed I_2 Source.

5. Water with a pH variation of 3 to 8 can be successfully iodinated without adverse effects on ACIDD operation.

6. The electrochemical valve current capability of the ACIDD is sufficient to iodinate Shuttle Orbiter fuel cell water containing dissolved H_2 even at high flow rates. The presence of H_2 in feed water at the levels projected for the Orbiter increases the amount of current required by approximately 25%.

7. Although iodination current requirements were found to decrease with increasing temperature of the feed water, water at 339K (151F) can be iodinated to within 5 (+1, -2) ppm at average or higher Shuttle Orbiter flow rates.

8. Shuttle Orbiter fuel cell water can be successfully iodinated without an I_2 detector signal at average water temperatures by using the fuel cell current signals in a feedback mode to control valve current. Iodination levels to 5 (+1, -2) ppm can be maintained over a water flow rate range of at least 60 to 173 cm^3/min (190 to 549 lb/day). Constant current control of the iodinator will suffice over a narrower water flow rate range.

9. Titanium will not work as an iodinator anode, as demonstrated through rotating disc electrode tests. Iodine production on this material is retarded to the same extent as interfering reactions.

10. Iodine concentrations at biocidal levels can be maintained in stainless steel (316) potable water stores. Losses due to adsorption on metal surfaces are negligible after minimal preconditioning with iodinated water.

11. Concentrated I_2 solutions will build up in the ACIDD I_2 Dispenser when water flow and current are stopped for a few hours. The ACIDD will resume normal 5 ppm iodination within a few minutes after startup.

RECOMMENDATIONS

The following recommendations are made as a result of the work completed under this program:

1. The ACIDD has been selected as the preprototype water biocide for the Regenerative Life Support Evaluation (RLSE) experiment. Required hardware modifications and operational concepts should be identified and performed. The resulting ACIDD hardware should then be experimentally characterized to quantify the effects of specific RLSE requirements, such as the lower water flow rate and temperature ranges, iodine demand of the water and cyclic operation with zero flow/zero current operation.

2. Overall ACIDD power requirements were reduced as part of this program by identifying lower power-consuming light source lamps and reducing lamp voltages. The use of customized lamp power transformers is now possible and the design, fabrication and testing of such transformers should be performed to provide for further weight and power reductions.

3. A qualification unit ACIDD should be fabricated and tested according to vibration and shock requirements of the RLSE experiment to demonstrate flight readiness of the ACIDD concept.

4. The ACIDD should be tested with water containing varying amounts of dissolved hydrogen as is experienced by the water biocide dispenser aboard the Shuttle Orbiter. An actual Hydrogen Separator developed by Life Systems for Rockwell International could be made available for testing.

5. Using lightweight components of the ACIDD to the maximum extent possible, an Iodine Monitor (without I_2 Source and associated electronics) should be constructed and tested. As part of this test program the apparent effects of temperature on monitor performance should also be investigated.

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APPENDIX 1 ACIDD FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

This document is a FMECA performed on the ACIDD. A schematic of the Shuttle Orbiter Potable Water System incorporating the ACIDD is presented in Figure A1-1. All failure modes of the ACIDD 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	Potential Effect of Failure
1	Loss of life or vehicle.
2	Loss of mission.
3	All others.
3_I	Criticality 3 items which meet one or more of the following categories a. Redundant elements are not capable of checkout during normal ground turnaround; or b. Loss of a redundant element is not easily detectable in flight, or c. All redundant elements can be lost by a single-credible event or cause.

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

The FMECAs reveal that there are no single point failures in the ACIDD. The highest criticality level assigned to failure modes in the ACIDD is two. 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. Crew safety is not impaired by the high I_2 concentration of the potable water as water with as little as 5 ppm I_2 tastes antiseptic. Ingestion of harmful quantities of I_2 is precluded since iodinated water with >5 ppm I_2 is not palatable. Backup provisions, as detailed on the individual FMECA forms, have been incorporated so that the probability of criticality two 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.

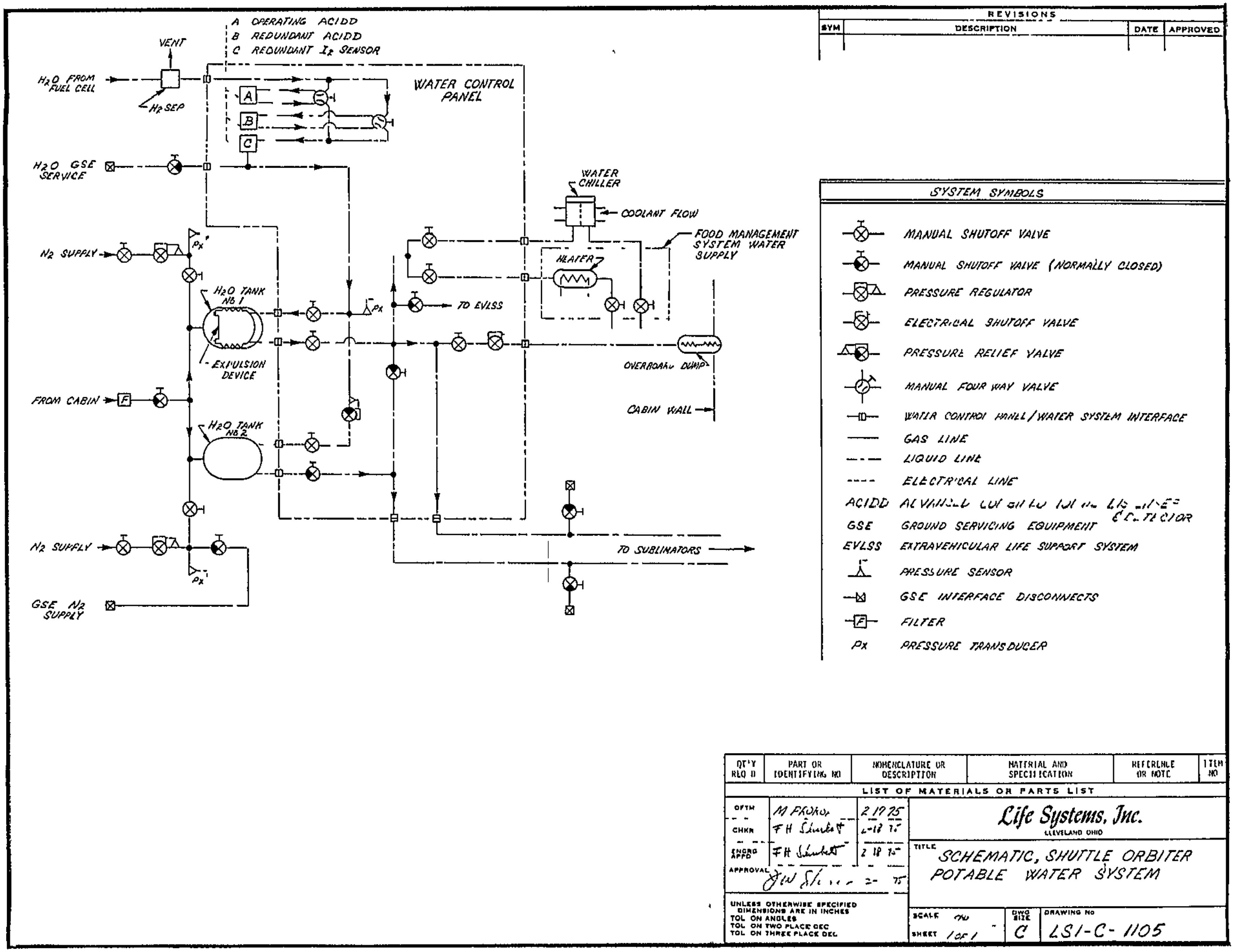

FIGURE A1-1 ACIDD INTEGRATION INTO THE SHUTTLE ORBITER POTABLE WATER SYSTEM

Life Systems, Inc. CLEVELAND, OHIO 44122	**FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS**	PAGE 1 OF 2	REVISION LTR
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TITLE	
ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)	☐ SUBSYSTEM ☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	ACIDD 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
(e) Failure of Blue Signal Amplifier (see Page 2 for continuation)

CRITICALITY

2

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 possibly 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

The failure will be detected by a redundant I_2 sensor incorporated into the Shuttle Orbiter Potable Water System. 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 ACIDD 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 ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0 3 hr) est	

Continuation Sheet

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FAILURE MODE AND CAUSE

(f) Failure of Red Reference Amplifier
(g) Failure of Divider/Amplifier
(h) Failure of Lamp Control circuit

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TITLE
ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ SUBSYSTEM
☐ LOOP ☒ COMPONENT

PART NO	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	ACIDD 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
(e) Failure of Blue Signal Amplifier (see Page 2 for continuation)

CRITICALITY

3 I

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 iodinated to prevent water contamination

FAILURE DETECTION METHOD

The failure will be detected by a redundant I_2 sensor incorporated into the Shuttle Orbiter Potable Water System. 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 ACIDD 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 ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0.3 hr) est	

Continuation Sheet

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FAILURE MODE AND CAUSE

(f) Failure of Red Reference Amplifier
(g) Failure of Divider/Amplifier
(h) Failure of Lamp Control circuit

Life Systems, Inc. CLEVELAND, OHIO 44122	**FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS**	PAGE 1 OF 2	REVISION LTR
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TITLE
ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ 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 (b) of water	 3_I 3_I

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

(a) Approximately 50 cc (0 1 pint) of 0 1<u>M</u> HI and 0 001<u>M</u> I_2 solution would contaminate cabin The I_2 Valve, Dispenser, and Accumulator cell voltage would increase and the ACIDD would not be capable of iodinating the fuel cell water

(b) Water would leak from the ACIDD If downstream of the ACIDD, 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

(a) This failure would be detected by either the I2 Detector of the ACIDD or by the redundant I_2 sensor in the Shuttle Orbiter Potable Water System.

(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

(see Page 2 for continuation)

CREW ACTION REQUIRED	TIME REQD	TIME AVAIL.
(a and b) Power down the leaking ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0 3 hr) est	

Continuation Sheet

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FAILURE DETECTION METHOD

this failure mode occurs, the crew could switch to the redundant ACIDD which is capable of disinfecting the fuel cell water and will allow the mission to continue

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TITLE
ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ 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	3_I
(b) Complete loss of electrical connection	3_I

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

(a) None

(b) This failure will be detected by either the I_2 detector of the ACIDD or the redundant I_2 sensor incorporated into the Shuttle Orbiter Potable Water System In the event this failure occurs, the crew could switch to the redundant ACIDD, which will continue to disinfect the fuel cell water and allow the mission to continue The ACIDD electrical connections will be soldered or welded joints

(see Page 2 for continuation)

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

Continuation Sheet

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FAILURE DETECTION METHOD AND BACKUP PROVISIONS

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.

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TITLE ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)	☐ 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
Separation of membrane from the electrode	3_I

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. 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

(see page 2 for continuation)

FAILURE EFFECT ON SYSTEM/SUBSYSTEM

The ACIDD 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

With the instrumentation designed for the ACIDD, this failure mode will not be detected Because of the minimal effect on the system and because of the backup provisions inherent in the ACIDD 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),

(see page 2 for continuation)

CREW ACTION REQUIRED	TIME REQD	TIME AVAIL.
None		

Continuation Sheet

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FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

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 ohm.

FAILURE DETECTION METHOD AND BACKUP PROVISIONS

electrode supports on both sides (anode and cathode) spaced on 0 63 cm (0 25 in) 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 between the bottom plate and housing by eight bolts precisely torqued to insure good electrode/membrane contact.

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TITLE
ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ 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	2

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

This failure can be detected by either the I_2 detector of the ACIDD or by the redundant I_2 sensor that is incorporated into the Shuttle Orbiter Potable Water System. 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 ACIDD and switch to the redundant ACIDD 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 psid)).

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 psid)) 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 ACIDD 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 COMBINED IODINE DISPENSER/DETECTOR (ACIDD)	☐ 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	3_I

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

Water flow through ACIDD will decrease. Water pressure in the I_2 Valve, Dispenser and Accumulator will increase unless plugging is at the inlet of the ACIDD, 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 ACIDD will decrease, resulting in longer time required to fill the potable water tanks.

FAILURE DETECTION METHOD

Water pressure sensor in fuel cell system. ACIDDs are contained in redundant water plumbing runs. In the event that one ACIDD plugs, the crew will be able to switch to the redundant ACIDD which will continue to disinfect the water and allow the mission to continue. The ACIDD 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 ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0.3 hr) est	

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TITLE ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ SUBSYSTEM
☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Detector (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
External leakage	3_I

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

Water would leak from the ACIDD.

FAILURE EFFECT ON SYSTEM/SUBSYSTEM

The cabin would be contaminated with water and there would be a reduced availability of disinfected water.

FAILURE DETECTION METHOD

The water pressure sensor in the fuel cell water line would detect large leaks. Small leaks could be detected by crew observation. The O-ring sealed optical lenses serve as redundant seals against external leakage.

CREW ACTION REQUIRED	TIME REQD.	TIME AVAIL.
Power down the leaking ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0 3 hr) est.	

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TITLE
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☐ SUBSYSTEM
☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Detector (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	CRITICALITY
Detector reads low caused by. (a) Source lamp burning out (b) Failure of Red Reference Detector (no or low output) (c) Red filter becomes cloudy or dirty	2

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

The ACIDD instrumentation, upon receiving a low I_2 concentration signal from the failed control detector, will increase the current to the electrochemical cell of the ACIDD. 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 I_2 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 Detector, 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

The failure will be detected by the redundant I_2 sensor that is included in the Shuttle Orbiter Potable Water System. 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.

CREW ACTION REQUIRED	TIME REQD	TIME AVAIL.
Isolate the failed detector. Power down the failed ACIDD and divert to the redundant ACIDD by manually reconfiguring two valves.	1080 s (0.3 hr) est.	

Life Systems, Inc. CLEVELAND, OHIO 44122	**FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS**	PAGE 1 OF 1	REVISION LTR.
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TITLE ADVANCED COMBINED IODINE DISPENSER/DETECTOR (ACIDD)

☐ SUBSYSTEM ☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
NA	NA	I_2 Detector (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

Detector reads high caused by:
- (a) Failure of Blue Signal Detector (no or low output)
- (b) Failure of Lamp Detector (no or low output)
- (c) Blue Filter becomes cloudy or dirty
- (d) Lamp Filter becomes cloudy or dirty
- (e) Sample cell windows become cloudy or dirty
- (f) Optical lenses become cloudy or dirty

CRITICALITY 3_I

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY

As a result of receiving a high I_2 concentration signal, the ACIDD 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

The optical train is totally enclosed, therefore, minimizing the probability of dust and dirt entering the internal sensor spaces. The failure will be detected by the redundant I_2 level sensor that is included in the potable water system of the Shuttle Orbiter. 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. If this condition occurs, the crew will switch to the redundant ACIDD 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. Power down the failed ACIDD and switch to the redundant ACIDD by reconfiguring two manual valves.	1080 s (0.3 hr) est.	

APPENDIX 2 RESULTS OF JSC ANALYSES OF ACIDD DVT WATER SAMPLES

The samples analyzed at NASA JSC are identifed in Table A2-1. The analyses of these samples are reported in Table A2-2.

Twenty-one water samples were analyzed for total carbon, inorganic carbon, ammonia, nitrogen, nickel, chromium and iron. Eleven samples were analyzed for I_2 content.

The lower I_2 concentrations reported in Table A2-2, relative to the corresponding analyzed I_2 concentrations plotted in the DVT, are due to diffusion of I_2 through the walls of polyolefin sample bottles during storage and shipment. Bottles of a lower permeability material, such as glass, are recommended for containment of future iodinated water samples.

TABLE A2-1 WATER SAMPLE IDENTIFICATION

NASA Sample Number	LSI Sample Number	Type Water	Bottle[(a)]	Collection Date	Collection Time
876-138	I-1	Iodinated	PE	7/6/76	1:29 p.m.
876-139	I-2	Iodinated	PE	7/8/76	10:45 a.m.
876-140	I-3	Iodinated	PE	7/11/76	12:45 p.m.
876-141	I-4	Iodinated	PE	7/14/76	11:35 a.m.
876-142	I-5	Iodinated	PE	7/17/76	
876-143	I-6	Iodinated	PE	7/20/76	1:35 p.m.
876-144	I-7	Iodinated	PP	7/23/76	
876-145	I-8	Iodinated	PP	7/26/76	1:50 p.m.
876-146	I-9	Iodinated	PP	8/5/76	1:45 p.m.
876-147	I-10	Iodinated	PP	8/8/76	11:36 a.m.
876-148	I-11	Iodinated	PP	8/11/76	
876-149	N-1	Feed	PE	7/6/76	1:29 p.m.
876-150	N-2	Feed	PE	7/10/76	12:45 p.m.
876-151	N-3	Feed	PE	7/14/76	11:50 a.m.
876-152	N-4	Feed	PE	7/16/76	11:35 a.m.
876-153	N-5	Feed	PE	7/20/76	1:50 p.m.
876-154	N-6	Feed	PP	7/23/76	
876-155	N-7	Feed	PP	7/26/76	2:00 p.m.
876-156	N-8	Feed	PP	8/3/76	1:40 p.m.
876-157	N-9	Feed	Linear PE	8/6/76	1:35 p.m.
876-158	N-10	Feed	PP	8/11/76	

(a) PE - Polyethylene Bottle
PP - Polypropylene Bottle

TABLE A2-2 WATER ANALYSIS RESULTS

Sample Number	Total Carbon, ppm	Inorganic Carbon, ppm	Ammonia as N, ppb	Nickel, ppb	Chromium, ppb	Iron, ppb	Iodine, ppm
876-138	2	<1	<10	<10	<10	40	<0.05
876-139	3	<1	13	<10	<10	34	<0.05
876-140	2	<1	<10	<10	<10	38	0.15
876-141	2	<1	<10	<10	<10	32	<0.05
876-142	1	<1	<10	<10	<10	28	0.20
876-143	2	<1	<10	<10	<10	32	0.15
876-144	1	<1	<10	<10	<10	20	2.5
876-145	1	<1	<10	<10	<10	13	1.8
876-146	4	1	<10	<10	<10	13	2.5
876-147	3	<1	<10	<10	<10	13	2.5
876-148	2	<1	<10	<10	<10	20	2.5
876-149	5	<1	<10	<10	<10	36	-
876-150	3	<1	<10	<10	<10	34	-
876-151	4	<1	<10	<10	<10	38	-
876-152	3	<1	<10	<10	<10	24	-
876-153	6	<1	16	<10	<10	32	-
876-154	1	<1	<10	<10	<10	25	-
876-155	4	<1	<10	<10	<10	18	-
876-156	6	4	10	<10	<10	13	-
876-157	2	2	13	<10	<10	24	-
876-158	2	<1	<10	<10	<10	24	-