HYDROGEN DETECTION STUDY

FINAL REPORT

by

J.W. Shumar and J.D. Powell

September, 1974

SSP Combustible Gas Detector (CGD)
Item No. 178

SSP Electrochemical Depolarized
Concentrator (EDC)

FEATURES EVALUATED

Linearity
Position Sensitivity
Interchangeability
Reproducibility
Ambient Effects
Speed of Response
Recovery Time
Leak Detectability

EXPERIMENTAL
STUDIES

Prepared Under Contract No. NAS2-6478

by

Life Systems, Inc.

Cleveland, Ohio 44122

for

AMES RESEARCH CENTER

National Aeronautics & Space Administration

ER-170-85

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report describes the results of the Hydrogen Detection Study performed under NASA Contract NAS2-6478 by Life Systems, Inc. during the period January 1, 1974 through September 30, 1974.

The Program Manager at Life Systems was F. H. Schubert, with support provided by J. D. Powell and G. D. Kostell in electrical engineering, J. W. Shumar in Product Assurance, F. C. Jensen in mechanical engineering, and J. J. Palagyi in sensor evaluation testing.

The technical management of the program was under the direction of Mr. P. D. Quattrone, Chief, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, California.

TABLE OF CONTENTS

Table of Contents - continued

LIST OF FIGURES

LIST OF TABLES

SUMMARY

A study was performed to assess the effectiveness of a hydrogen (H_2) detection concept for regenerative Environmental Control/Life Support Systems (EC/LSS). The concept evaluated was that utilized for the Electrochemical Depolarized Concentrator (EDC) designed, constructed, and tested under NASA Contract NAS2-6478 for the EC/LSS Space Station Prototype (SSP) program. The EDC contains Combustible Gas Detectors (CGDs) which, for this study, were evaluated with H_2. The CGDs were evaluated for linearity, position sensitivity, reproducibility, ambient effects, repeatability, speed of response, recovery time, and interchangeability. The effectiveness of CGDs located within the EDC for sensing H_2 leaks at various Line Replaceable Units (LRUs) in the subsystem was determined. The effects of H_2 leak rate, H_2 concentration of leaking gas and air currents in the vicinity of the EDC were determined. Proposed improvements for the H_2 detection concept were documented and alternative H_2 detection approaches were identified and analyzed.

INTRODUCTION

Space vehicles for future extended-duration manned spaceflight will require regenerative Environmental Control/Life Support Systems (EC/LSS). Many subsystems currently being developed to make up the EC/LSS utilize or produce hydrogen (H_2) gas. Some of these subsystems are: the Water Electrolysis Subsystem (WES)[1] which generates breathable oxygen (O_2) and produces the by-product H_2; the Bosch[2] or Sabatier[3] Carbon Dioxide (CO_2) Reduction Subsystems which use H_2 in the process of regenerating O_2 from CO_2; the Electrochemical Depolarized Concentrator (EDC)[4] which uses H_2 to depolarize the anode in the process of removing CO_2 from the cabin atmosphere; and the Nitrogen (N_2) Generating Subsystem[5] which use hydrazine (N_2H_4) or ammonia (NH_3) as the primary N_2 source with H_2 as the by-product.

In addition to those subsystems in the EC/LSS that utilize H_2, NASA Modular Space Station (MSS) design studies have included the use of H_2 in the Electrical Power System and Reaction Control System.[6] The energy storage assembly of the Electrical Power System uses regenerative H_2-O_2 fuel cells. The Reaction Control System uses H_2 and O_2 for the engines. This study, therefore, although focused on only one subsystem of the EC/LSS has application to three other subsystems of the EC/LSS and to hardware that makes up the Electrical Power and Reaction Control Systems of a space vehicle.

The Space Station Prototype (SSP) program sponsored by the National Aeronautics and Space Administration Johnson Spacecraft Center (NASA JSC) involved the design, development, fabrication, and assembly of an advanced EC/LSS. The SSP EC/LSS includes three subsystems which produce or utilize H_2: an O_2 Generating Subsystem, an EDC, and a Sabatier-based CO_2 Reduction Subsystem.

The H_2 gas molecule being small and highly mobile can leak through air-tight seals. If it leaks into confined spaces or is permitted to accumulate, it can produce a combustible gas mixture. Prevention of these situations by incorporating H_2 safety design criteria is mandatory. Hence, a definite requirement for future space vehicles is to sense automatically for the presence of H_2 so that corrective measures can be taken before the crew would be exposed to danger.

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(1) References cited are on page 41.

H$_2$ Detection Principles

There are several principles of H$_2$ detection based upon the unique properties of H$_2$ gas. These principles include: the catalytic combustibility of H$_2$, the exothermic absorption of H$_2$ by certain materials, the thermal conductivity of H$_2$ mixtures, and the electrochemical oxidation of H$_2$.

Combustibility

In using the combustibility of H$_2$ gas, a catalyzed hot wire or heated thermistor forms one leg of a Wheatstone bridge arrangement. Combustion of H$_2$ at the surface of the sensing element causes a temperature increase above that of a reference element, resulting in a change in the resistance of the sensing element and an unbalance in the Wheatstone bridge. The magnitude of the unbalance is calibrated to yield the concentration of the H$_2$ gas.

Thermal Conductivity

Thermal conductivity detectors are based upon the principle that a heated filament (resistor) will be cooled by a gas sample according to the thermal conductivity of the gas. This sensor consists of two (2) chambers, each containing identical heated resistors which form adjacent branches of a Wheatstone bridge. One chamber (the sample chamber) contains the gas to be analyzed and the other chamber (a comparison or reference chamber) contains the reference gas. If the atmosphere does not contain H$_2$ gas, the equilibrium temperature of both resistors is the same because the heating current is the same. When the sample gas contains H$_2$, however, the heat loss differs. This changes the equilibrium temperature of the sample chamber resistor in proportion to the inverse of the thermal conductivity of the gas. This changes its resistance which results in an output signal from the Wheatstone bridge circuit that can be calibrated to reflect the concentration of H$_2$ in the sample gas.

Exothermic Absorption

Three types of H$_2$ sensors are based upon the effects of the absorption of H$_2$ on palladium (Pd). One sensor is based on the exothermic absorption of H$_2$ molecules by Pd which, in the presence of O$_2$, is immediately followed by an even more exothermic formation of water. The heat from this reaction can be used to indicate the presence of H$_2$ by using Pd or a similar catalytic material in conjunction with the Wheatstone bridge arrangement similar to that used in the catalytic combustion sensor previously discussed. A second sensor,[7] based on Pd absorption uses the heat from the Pd-H$_2$ and hydride-O$_2$ reactions to change the color of a thermochromic paint. The sensor is constructed in two layers, one layer containing Pd, the other a chromic paint. Hydrogen passing into the sensor eacts with the Pd, creates the heat and changes the color of the paint, thus giving an indication of H$_2$ presence. The third sensor, based on Pd absorption[8] relies on a temperature controlled element composed of a thin film of Pd metal. The electrical conductance of this thin film is a function of the partial pressure of H$_2$ concentration in the sample gas.

Electrochemical Oxidation

A sensor, based on the electrochemical oxidation of H_2[9] consists of a pair of electrodes and an electrolyte gel. A gas permeable membrane fits firmly against the anode of the electrochemical cell. As H_2 passes through the membrane, it is electrolytically oxidized at the anode and current flows between the electrodes. The current flow is a function of the H_2 concentration of the sampled gas.

Miscellaneous Principles

Another H_2 sensor that is being developed is based on the emission of Krypton 85 from the surface of kryptonated metal oxides when exposed to H_2 gas.[10] Another H_2 sensor is based upon the fuel cell principle in which the concentration of H_2 in the sample gas is determined by the magnitude of the cell current of the fuel cell. A general review of additional methods of H_2 detection are discussed[11] and may be referred to for additional information.

Based on the criteria for the selection of subsystems and components for the SSP[12] and based upon the results of a NASA-funded study,[13] in which a critical review of H_2 detection literature was performed and an evaluation of the state-of-the-art of detecting H_2 fires and leaks was made, a CGD based on the catalytic combustion H_2 detection principle, was selected for the EDC.

The SSP program H_2 detection philosophy was based upon strategically locating the CGDs and establishing H_2 concentration shutdown levels that would permit the execution of safety operations before hazardous conditions were reached. The objective of this study was to characterize the H_2 detection concept as used in the EDC developed for the SSP and to identify alternate H_2 detection approaches which would be more effective and applicable to future EC/LSS.

The study involved the evaluation of the CGD in regard to its linearity, position sensitivity, reproducibility, ambient effects, repeatability, speed of response, recovery time and interchangeability. It also included evaluating the effectiveness of the CGDs for sensing H_2 leaks in the EDC, recommending possible improvements for the H_2 detection concept, and suggesting alternate H_2 detection approaches for EC/LSS subsystems.

DISCUSSION

SSP H_2 Detection Philosophy

The SSP program established a H_2 detection philosophy based upon strategically locating CGDs on each subsystem of the EC/LSS. The strategy involved in defining sensor location consisted of evaluating each subsystem for possible H_2 leak sources, areas of stagnation and possible H_2 accumulation areas. The output of each sensor is continuously monitored and, if any one indicates H_2-in-air concentrations 0.5% or greater, subsystem shutdown would be initiated. The SSP H_2 detection philosophy and H_2 safety precautions are further defined by twelve SSP H_2 leakage rules. These are listed in Table 1. Based on the guidelines of the twelve H_2 leakage rules and the results of the January 16-18, 1973 Approval

TABLE 1 SSP HYDROGEN LEAKAGE RULES

1. Each of the H_2-containing subsystems will be built as a ventilated structure, with no enclosures for concentrating H_2 except those components and lines which must contain H_2 in order to perform the principal function of the subsystem.

2. All H_2-containing elements of each subsystem are subject to constant ventilation at a minimum flow of 25 ft/min by circulation of cabin air.

3. Each subsystem, in each distinct test and/or installation configuration, will be explored for stagnation areas where mixing is not constant.

4. No stagnation area which may be subject to H_2 infringement from a leak source will be allowed unless specifically approved by the Engineering Manager and the Safety Specialist.

5. Combustible gas detectors will be mounted as follows:

    a. In stagnation areas and accumulation locations on each subsystem.
    b. Adjacent to the most probable one or two areas of leakage of H_2 in each subsystem.
    c. In a location to monitor the main flow path of the cabin air.

6. Combustible gas detectors shall give the shutdown signal at 0.5% H_2 concentration, and shutdown of H_2-containing subsystems should be complete (including purge) before the concentration reaches 2%.

7. Combustible gas detectors should give notice to crew at about 0.2% H_2 concentration.

8. There should be capability for monitoring any selected combustible gas detector and for identifying that detector which caused a notice or shutdown.

9. There should be capability for identifying any one subsystem which is leaking H_2, upon receipt of a notice, in order to permit minimum shutdown.

10. Hydrogen-containing subsystems shall all be shut down and purged if the circulation of cabin air fails.

11. Physical arrangement of H_2-containing components and lines should ensure that there is no ignition source within 1½ feet of any possible source of H_2 leakage unless there is intervening shielding.

12. No repairing or disconnecting of any H_2-containing component or line shall be allowed without first shutting down and purging the subsystem.

Design Review,[14] the CGDs for the EDC were located as shown in Figures 1 and 2, the front and rear view of the EDC, respectively.

Combustible Gas Detectors, SSP Item Nos. 178-03 and 178-37, are located on the front of the EDC and serve to monitor for possible H_2 leaks from the electrochemical module connections and the electrochemical module gasket and O-ring seals.

Combustible Gas Detectors, SSP Item Nos. 178-01 and 178-02, are located on the rear panel of the CS-6 and in this location monitor for possible leaks from all H_2-bearing Line Replaceable Units (LRUs) located on the back panel. After a H_2 leak has been sensed the subsystem is shut down and N_2-purged. The leaking component is isolated utilizing an appropriate leak detector.

SSP Combustible Gas Detector

The SSP Item No. 178 CGD is a catalytic combustion type CGD modified by the SSP program's prime contractor for incorporation into the EC/LSS. The modifications included:

1. Removing all alarm circuits.
2. Changing the sensor output from 0-1 volts to 0-5 volts.
3. Repackaging to satisfy the maintainability requirements of the SSP.[12]

The Item No. 178 CGD is shown in Figure 3. In operation for H_2 detection, the H_2 air mixtures diffuse through the flame arrestors and the H_2 gas oxidizes on a catalytically-treated sensing bead causing a change in temperature and electrical resistance in proportion to the H_2 gas/air ratio. A reference bead is also included to compensate for ambient temperature variations, humidity changes and pressure differences. The reference bead is inert to H_2. The difference in resistance of the active and reference beads is converted into the sensor output signal by electronic conditioning circuits. The sensor output is a 0 to 5 volt DC signal which represents 0 to 4% H_2-in-air mixtures. The crew warning signal and subsystem shutdown signal according to the SSP H_2 leakage rules were intended to be manually set at 0.2% H_2-in-air and 0.5% H_2-in-air, respectively, in the Acceptance Checkout Equipment (ACE) computer and the subsystem's controllers. This corresponds to output voltages of 0.25V and 0.62V. The specification for the SSP Item No. 178 CGD is listed in Table 2.

Evaluation of SSP Combustible Gas Detector

Several experiments were performed to determine the operating characteristics of the SSP Item No. 178 CGD. The CGDs were evaluated for linearity, position sensitivity, reproducibility, ambient effects, repeatability, speed of response, recovery time, interchangeability, and their ability to detect H_2 leaks on the EDC.

Linearity

In order to facilitate CGD calibration and to assure maximum safety it is important that the CGD response be linear. A linear response would insure an accurate H_2-

Load Transistor Mounting

876-31

Electrical Shutoff Valve

305-34
305-33
305-35

CGD Sensor Head

178-37
178-03

Electrochemical Module,

890-31, -32, -33
890-34, -35, -36

Primary Controller, 871-31

Data Acquisition Unit, 970-4

CGD Electronics

178-37
178-03

Process Air Blower,

543-32
543-31

Process Air Sensor,

875-31
875-32

Emergency Controller, 872-31

FIGURE 1 CS-6 FRONT VIEW

Cooling Air Blower
345-32
345-31

CGD Sensor Head
178-01
178-02

Electrical Shutoff Valves
306-30
306-08

Electrical Shutoff Valves
306-37
306-38

H_2 Flow Sensor & Distribution Mounting
882-31
882-32

Electrical Shutoff Valves
306-07
306-39

Backpressure Regulator
310-32

CGD Electronics
178-01
178-02

Pressure Sensor
877-31
877-33

Manual Shutoff Valve
507-32

FIGURE 2 CS-6 REAR VIEW

Combustible Gas Sensor
(Electronics and
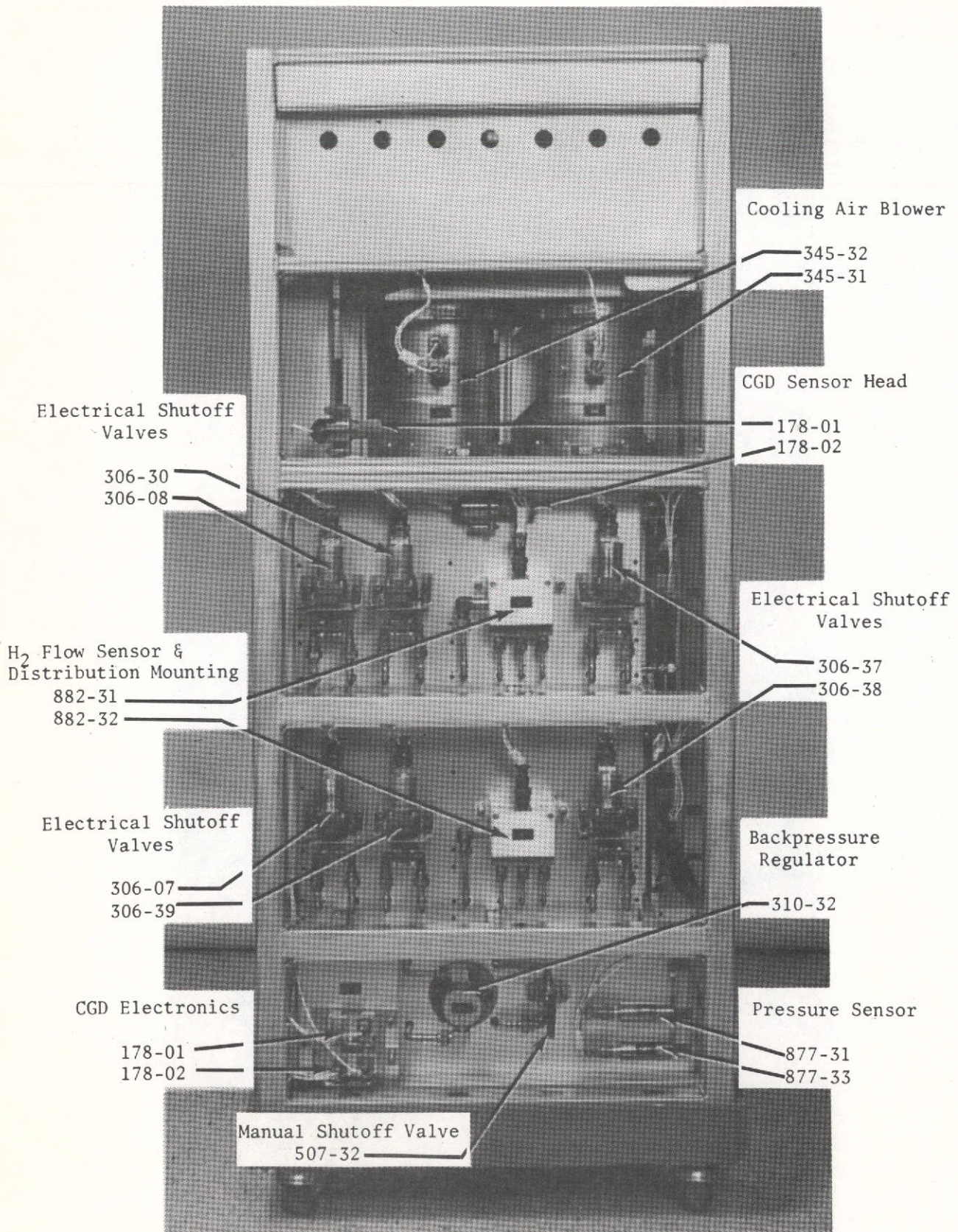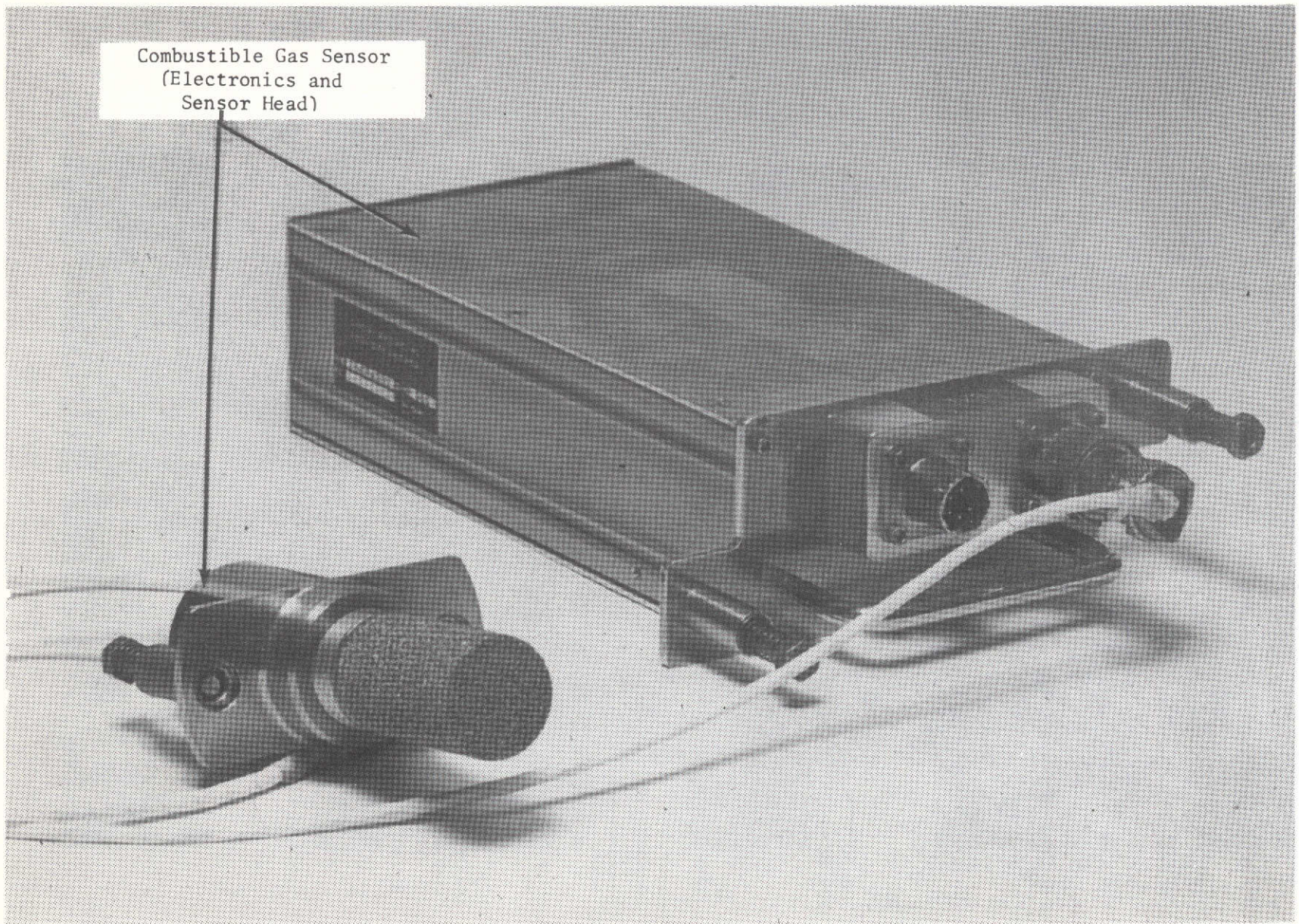Sensor Head)

FIGURE 3   COMBUSTIBLE GAS DETECTOR, SSP ITEM NO. 178

TABLE 2   COMBUSTIBLE GAS DETECTOR SPECIFICATION

Life Systems, Inc.	SPECIFICATION	NO. 178	REVISION LTR. A
CLEVELAND, OHIO 44122	LINE REPLACEABLE UNIT	PAGE 1 OF 2	DATE 2/6/74
TITLE DETECTOR, COMBUSTIBLE GAS		PART DRAWING NO. 436	

FUNCTION:

The combustible gas detector monitors the percentage of H_2 in air.

DESCRIPTION:

Hydrogen/air mixture, diffusing through flame arrestors, oxidizes on a catalytically treated sensing bead, causing a change in temperature and electrical resistance in proportion to the H_2/air ratio. A reference bead, inert to combustible gases compensates for ambient temperature variations, humidity changes, and pressure differences. The differences in resistance of the active and reference beads are converted to sensor signals.

DESIGN DATA:

Performance Characteristics

Sensor
    Ambient temperature range   -65 to 200F
    Response   <1 second (H_2)
    Drift   <5%/year
    H_2 concentration range   0-4%

Controller
    Ambient temperature range   -40 to 150F
    Repeatability   ±2% full scale

Reliability data
    Failure rate 5.0×10^{-6} failures/hr
    MTBF 0.2×10^{6} hr
    Spares   3 (180-mission profile)

Physical Characteristics

Sensor
    Weight   1.06 lb
    Volume   0.00511 ft^3
    Basic Configuration   1.5 in dia x 5 in long

Controller
    Weight   2.81 lb
    Volume   0.0441 ft^3
    Basic Configuration   2.25 x 4.13 x 8.20 in

Material Characteristics

A.   Nonmetallic
            TFE (Teflon), G-10 (Epoxy), Melamine, 1663 Potting Compound (3M),
            Stycast 2651 mm, (Epoxy), Ceramic, Kynar

Table 2 - continued

Life Systems, Inc. CLEVELAND, OHIO 44122	NUMBER 178	REVISION LETTER						PAGE 2

B.   Metallic
Aluminum, Sintered Stainless Steel, Sintered Bronze

Electrical Characteristics

Input voltage   106-122 VAC, 400 hz
Controller output voltage   0-5 VDC

INTERFACES:

Mechanical   Two sensors are mounted above the
                                       module H_2 connections. Two sensors
                                       are mounted above the CS-6 H_2 valves.
                                       (No. 306)

Electrical

Controller connectors   Deutsch AFD50-10-6PN-1A

                                       Deutsch AFD50-10-6PW-1A

Sensor connector   Deutsch AFD56-10-65W-1A

Mounting

Sensor   Via two Deutsch captive fasteners
Electronics package   Via two Deutsch captive fasteners

ENVIRONMENT:

Cabin atmosphere

MAINTENANCE LEVEL AND METHOD:

Replacement of this Line Replaceable Unit is the first level of maintenance.

Time Required: 0.1 hour

in-air indication over the entire range of possible H_2 concentrations without extensive and difficult calibrations.

In order to determine the linearity of the CGDs an environmental chamber was constructed. This chamber is shown in Figure 4. The CGDs were then calibrated by alternately exposing them to N_2 and a 1.9% H_2-in-air calibration gas mixture and making the appropriate zero and span adjustments. Once calibration was completed the CGD output was recorded for the calibration gases and an additional H_2-in-air gas mixture between the calibration points.

The results of this task are presented both graphically and in tabular form in Figure 5. Observation of the data reveals that the detectors are nonlinear over the entire range of H_2 concentrations and also reveals that each sensor departs from the desired linear response by varying degrees. The difference from the expected 0.625 volt response for the 0.5% H_2-in-air concentration is from 0.099 volts for CGD 178-02 to 0.220 volts for CGD 178-01. In all cases, the CGD read high at the 0.5% H_2-in-air concentration. This is good from a safety standpoint but could cause unwarranted subsystem shutdowns. To use these sensors effectively in the SSP it will be necessary to perform calibrations at the safety established H_2 concentrations. Per the SSP H_2 leakage rules in Table 1, these points are 0.2%, 0.5%, and 2.0% H_2-in-air.

The explanation for the observed nonlinearity follows. The catalyzed sensing bead and uncatalyzed reference bead are semiconductor elements with a small positive temperature coefficient. The two beads are connected in series and are powered by a constant current to heat them to about 672K (750F). They are connected as part of a bridge circuit such that small changes in the ratio of the resistances of the two beads produce an output which is amplified and becomes the sensor output signal. For small resistance changes the output will be a linear function of the resistance change. Nonlinearities in the CGD output versus H_2 percent are probably due to thermal and chemical (i.e., catalyst degradation) nonlinearities.

Again, the subject CGDs could be used to warn the crew and initiate automatic subsytem shutdown as long as the warning and shutdown levels correspond to the calibration points of the CGD. It is anticipated that the precise H_2-in-air concentration in the cabin would be accurately and correctly determined by a gas chromatograph or other device which could continuously monitor the quality of the cabin atmosphere for all contaminants.

Position Sensitivity

While working with the EDC it was noted that the CGD output was sensitive to slight variations in its position relative to horizontal. As a result of this observation, an experiment was performed to determine the magnitude of the CGD output variation as a function of the sensor position. The CGD was mounted in the ambient air and its output was recorded as it was rotated 360 degrees about its axes.

In one case, the CGD was rotated about an axis perpendicular to the sensor axis and perpendicular to the "g" vector so that when rotated 90 degrees, the sensor

12
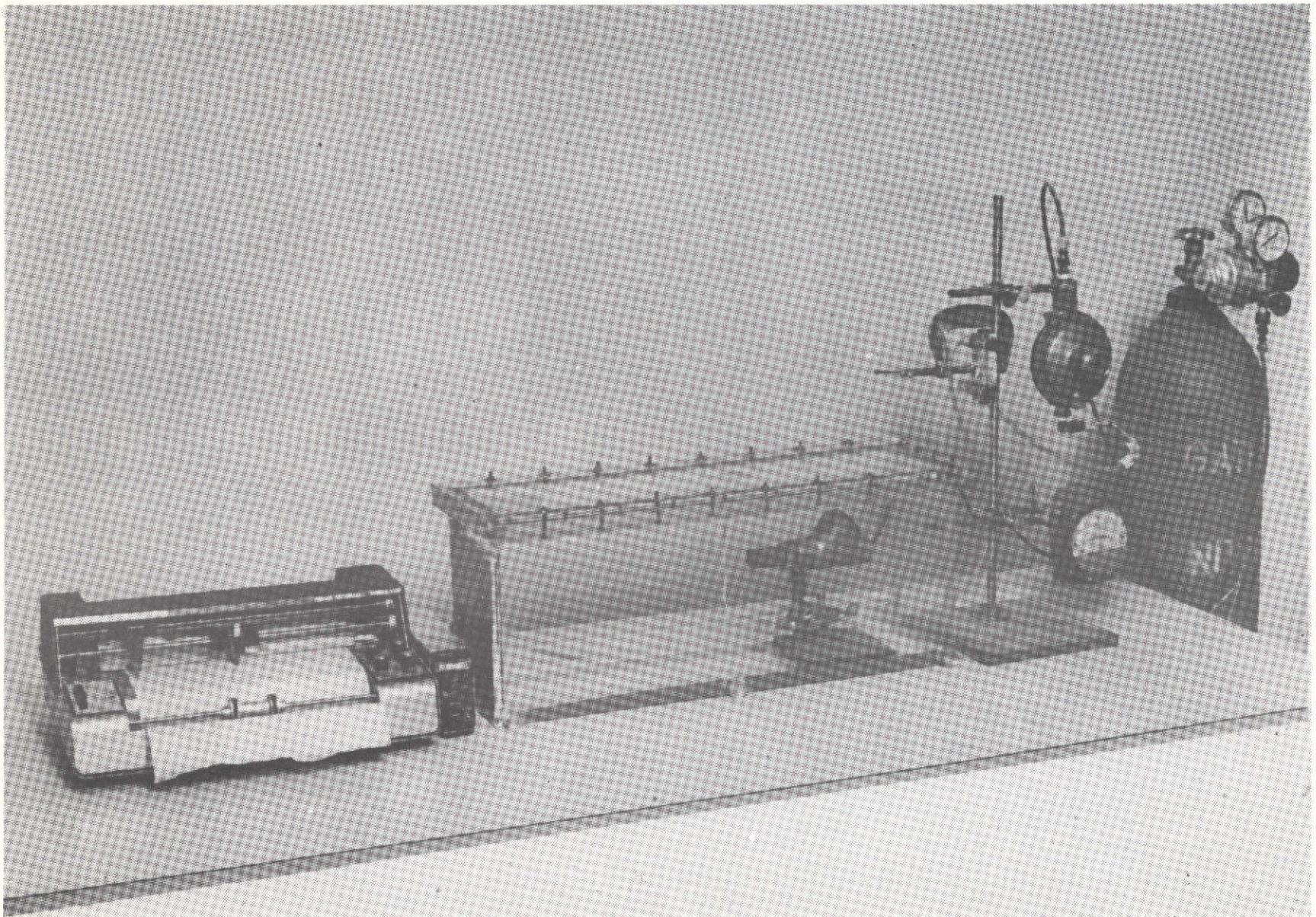
FIGURE 4   ENVIRONMENTAL TEST CHAMBER

CGD Output, Volt

2.5

2.0

1.5

1.0

0.5

0

0   1.0   2.0

H₂-in-Air Concentration, % H₂
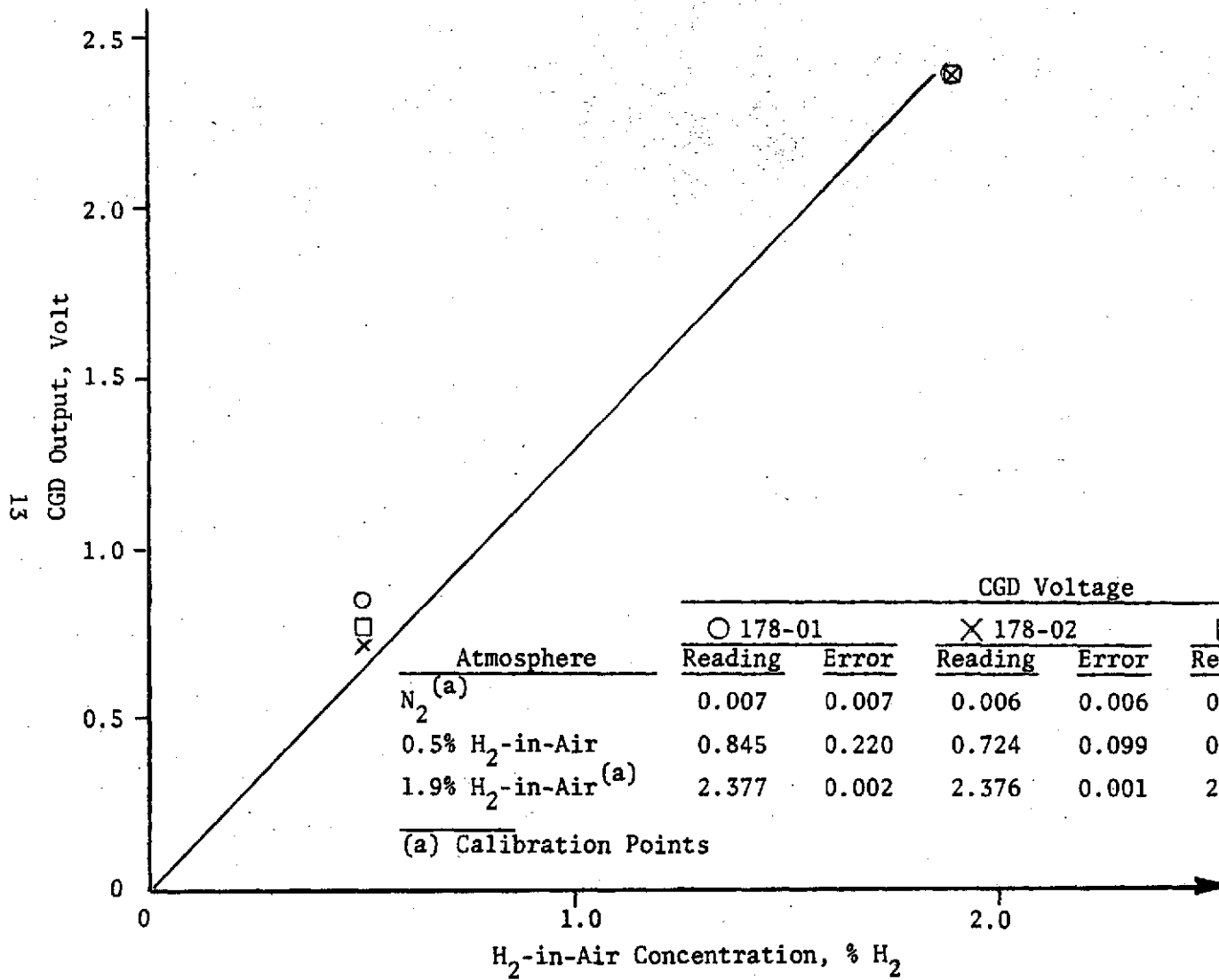
	CGD Voltage						
	O 178-01		✕ 178-02		☐ 178-37		Straight
Atmosphere	Reading	Error	Reading	Error	Reading	Error	Line
N₂ (a)	0.007	0.007	0.006	0.006	0.006	0.006	0.000
0.5% H₂-in-Air	0.845	0.220	0.724	0.099	0.766	0.141	0.625
1.9% H₂-in-Air (a)	2.377	0.002	2.376	0.001	2.376	0.001	2.375

(a) Calibration Points

FIGURE 5   CGD CALIBRATION DATA

head points down and when rotated 270 degrees, the sensor head points up (see illustration in Figure 6). In the second case, the CGD was rotated clockwise about the axis of the sensor head (see illustration in Figure 7).

The results of this experiment are presented graphically in Figures 6 and 7. Both figures show that the sensors are highly sensitive to orientation varying by up to 1.9 volts (38% of full scale). It was determined that this dependence on orientation was created by the fact that the sensing and reference beads in the sensor are heated. When the sensor is oriented such that the two beads are in a vertical line (i.e., one right above the other) with the sensing bead over the reference bead, convective heat transfer will cause the sensing bead to be hotter than the reference bead. This will unbalance the bridge and provide an output. If the sensor is rotated 180 degrees to reverse the two beads, the reference bead will now be hotter than the sensing bead and the output will decrease.

It should be noted that the effect of heat transfer from one bead to another will be significantly different in a zero-g environment and shutdown points set on earth will not remain the same in zero g.

If this CGD were used for actual space flight, it would be imperative to calibrate the sensor as soon as orbit has been established and prior to activating the EC/LSS. This, of course, would be an undesirable activity.

Reproducibility

Since effects of variations in the ambient atmosphere influence the CGD output, it was decided that the best way to characterize the reproducibility of the CGDs would be to:

1. Determine both the short-term and long-term effect of a constant H_2-in-air environment on CGD output.

2. Determine the effect of a constant air flow past the sensor on the CGD output.

3. Determine the effect of input power on the CGD output voltage.

4. Determine the effect of relative humidity of the H_2/air mixture on sensor output.

5. Determine the repeatability of the CGD output.

Short-Term and Long-Term Exposure to Constant H_2-in-Air Mixture. A CGD was mounted in the environmental chamber. The chamber was filled with a H_2-in-air gas mixture. In order not to deplete the H_2 concentration in the chamber as a result of the catalytic combustion reaction, the chamber was constantly fed with 1.57×10^{-5} m³/s (2 cfh) of the gas mixture and the chamber pressure was maintained at 1.87 kN/m² (7.5 inches of water) above atmospheric. This test was run for 25 days. The results are presented in Figure 8.

Data indicate that there was a gradual decrease in sensor output as a function

FIGURE 6   SENSOR VOLTAGE VERSUS ORIENTATION
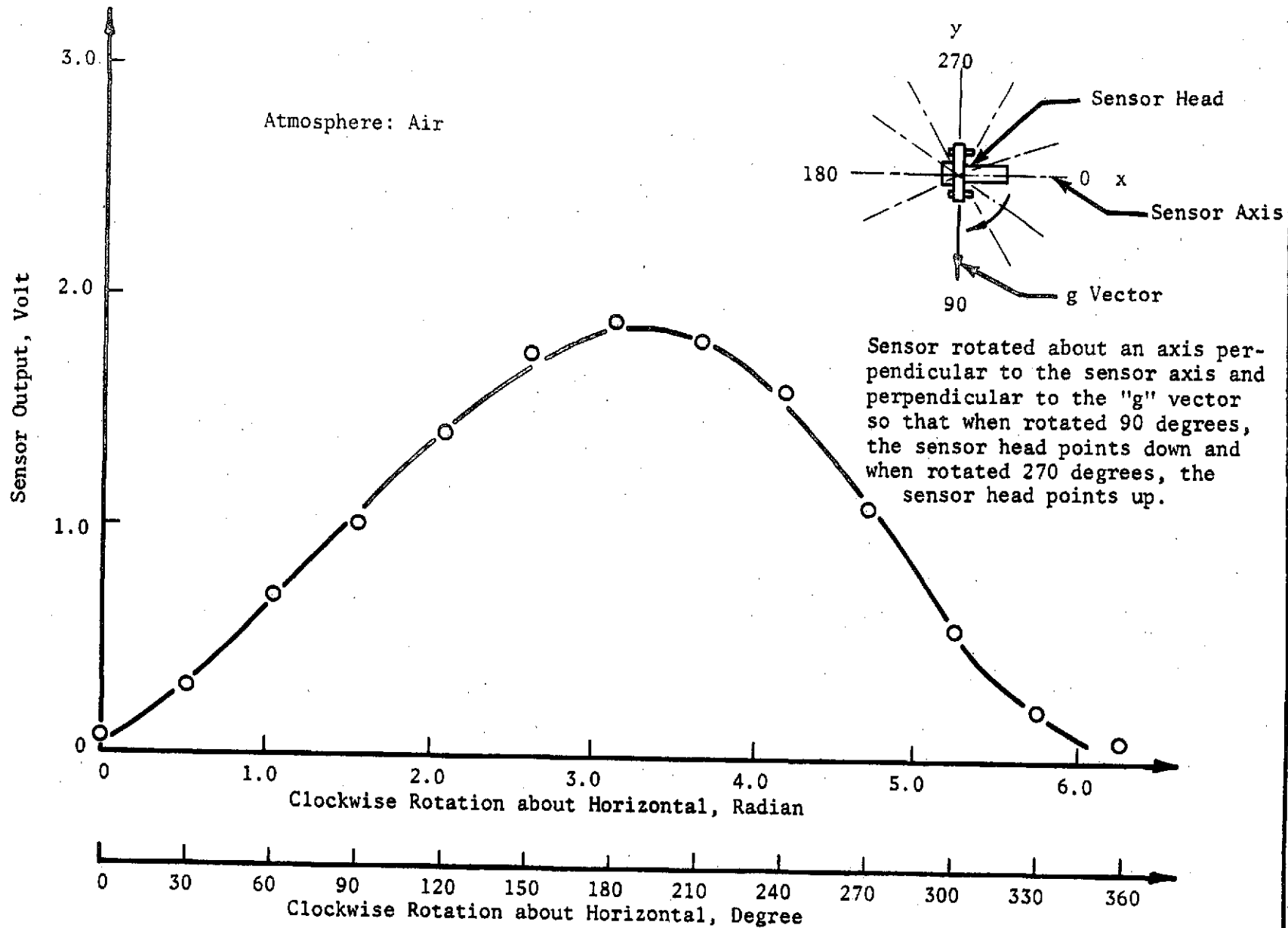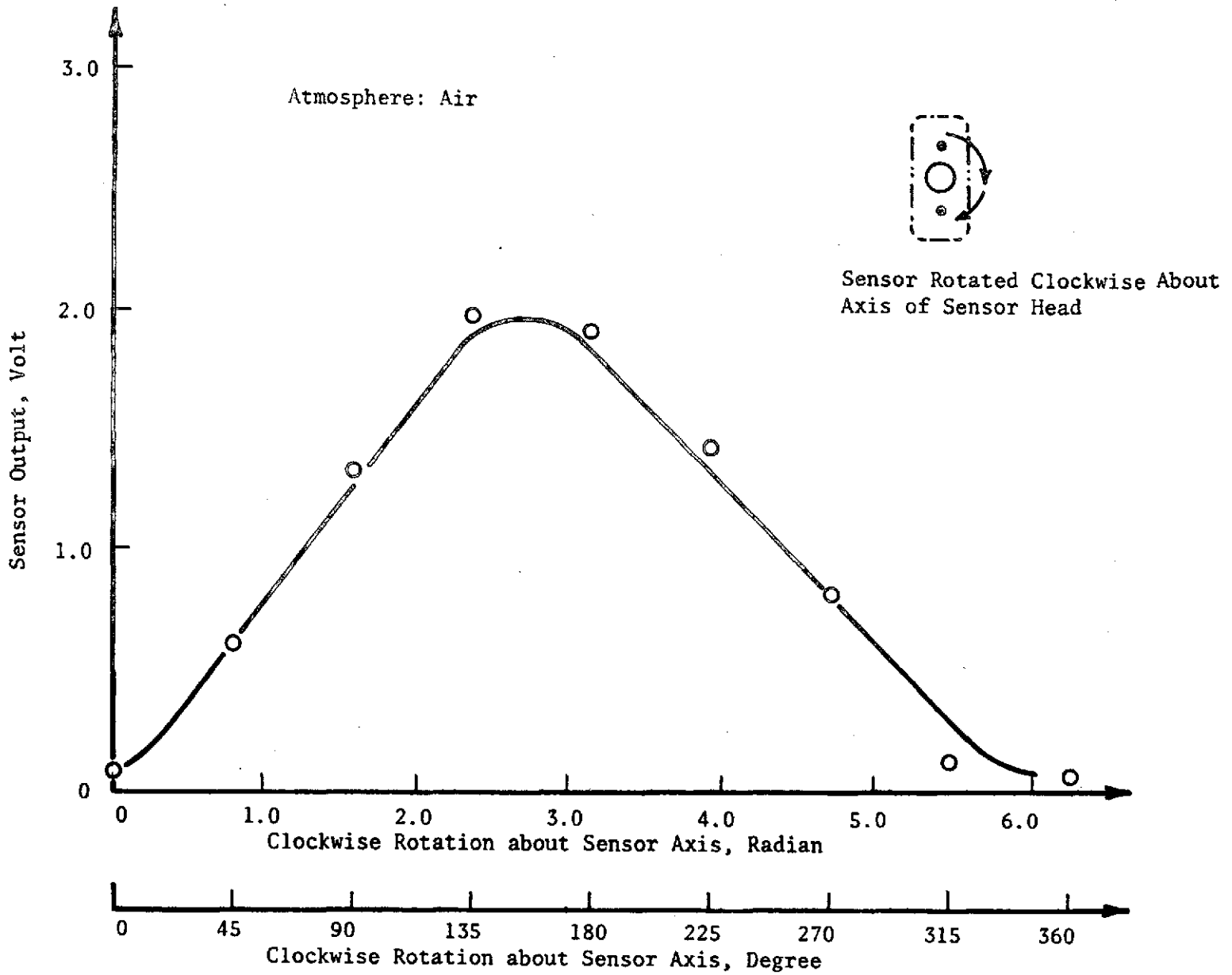(VERTICAL ROTATION)

Atmosphere: Air

Sensor Rotated Clockwise About
Axis of Sensor Head

FIGURE 7   SENSOR VOLTAGE VERSUS ORIENTATION
(HORIZONTAL ROTATION)
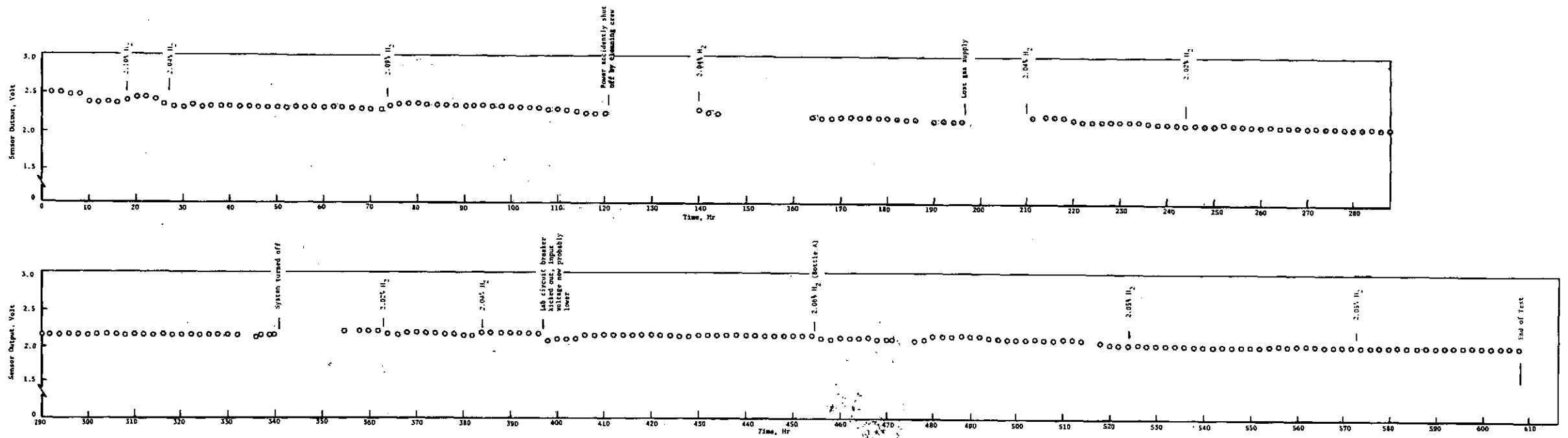
FIGURE 8 SENSOR VOLTAGE VERSUS TIME FOR CONSTANT H₂-IN-AIR MIXTURE

of exposure time to the H_2/air mixture. For the first 24 hours CGD output decreased by 0.060 volts. For the entire test CGD output decreased by 0.500 volts. This corresponds to a change in H_2 concentration of 0.4% and an average 8.0×10^{-4} volt/hour decay rate. At the conclusion of the test, air was admitted to the chamber. The CGD remained on, exposed to ambient air, for four days. After this time 2.06% H_2-in-air was admitted to the chamber and sensor output recorded. The gas mixture used was from the same bottle originally put on stream at 454 hours into the test. The CGD reading peaked and remained at 2.10 volts for three hours after which the test was terminated.

These data indicate that the CGD recovered somewhat as a result of being removed from the H_2-in-air environment for the four-day period. The sensor recovered by 0.175 volts but did not reach the CGD output recorded for 2.05% H_2-in-air at the start of the test, 2.50 volts.

It is postulated that the decrease in CGD output could be attributed to either a loss in the activity of the catalyst due to the constant exposure to H_2-in-air or drift in the electronics or to the sensor bead resistance. In any event, the results of this test point out the need for frequent CGD calibrations.

Exposure to Air Flow. For this test the environmental chamber was modified to incorporate a blower and a 5.08 cm x 15.24 cm (2 in x 6 in) opening was provided to allow air to flow by the sensor. The CGD output was recorded as was the air speed at the chamber exit. The air speed was measured by a Dwyer No. 460 air meter. The results, presented in Table 3, show that the CGD output remained essentially constant for 41 hours at the constant air flow of 292 ±13 cm/s (575 ±25 ft/min). The maximum variation observed was 0.0035 volts.

At the conclusion of this test, the air speed was varied from 0 to 762 cm/s (1500 ft/min) and the CGD output was recorded. These data are listed in Table 4 and show a negligible change in CGD output over the entire flow range.

The data gathered from both tests indicate that air flow rate has an insignificant impact on CGD output. There was concern that the air flow would cool the heated sensing and reference beads in the sensor head and result in a change in CGD output. This does not occur since the dual flame arrestors (porous metal) apparently provide for sufficient protection against air currents.

Variation of Input Voltage. Two CGDs were mounted in an air environment and power to the electronics was supplied through a variable transformer. By manipulating the variable transformer setting the input voltage to the CGD electronics was varied from 110 to 120 volts. The CGD ouptut voltage was monitored as a function of the input voltage. The results of this experiment are presented in Figure 9.

These data indicate that both CGD outputs varied with input voltage and by different amounts. The greatest variation noted was in sensor 178-01. Its reading decreased by 34% as the input voltage was increased from 110 to 120 volts. The SSP voltage specification is 106 to 122 volts rms.[15] Based on this specification and the data obtained, the CGD output would be expected to vary by at least as much as 0.08 mv. This corresponds to 0.064% H_2-in-air.

TABLE 3 CGD OUTPUT VERSUS TIME

Time, Hr	CGD Output, Volt
0	0.040
3	0.041
12	0.040
22	0.042
24	0.039
36	0.039
41	0.038

TABLE 4 CGD OUTPUT VERSUS AIR SPEED

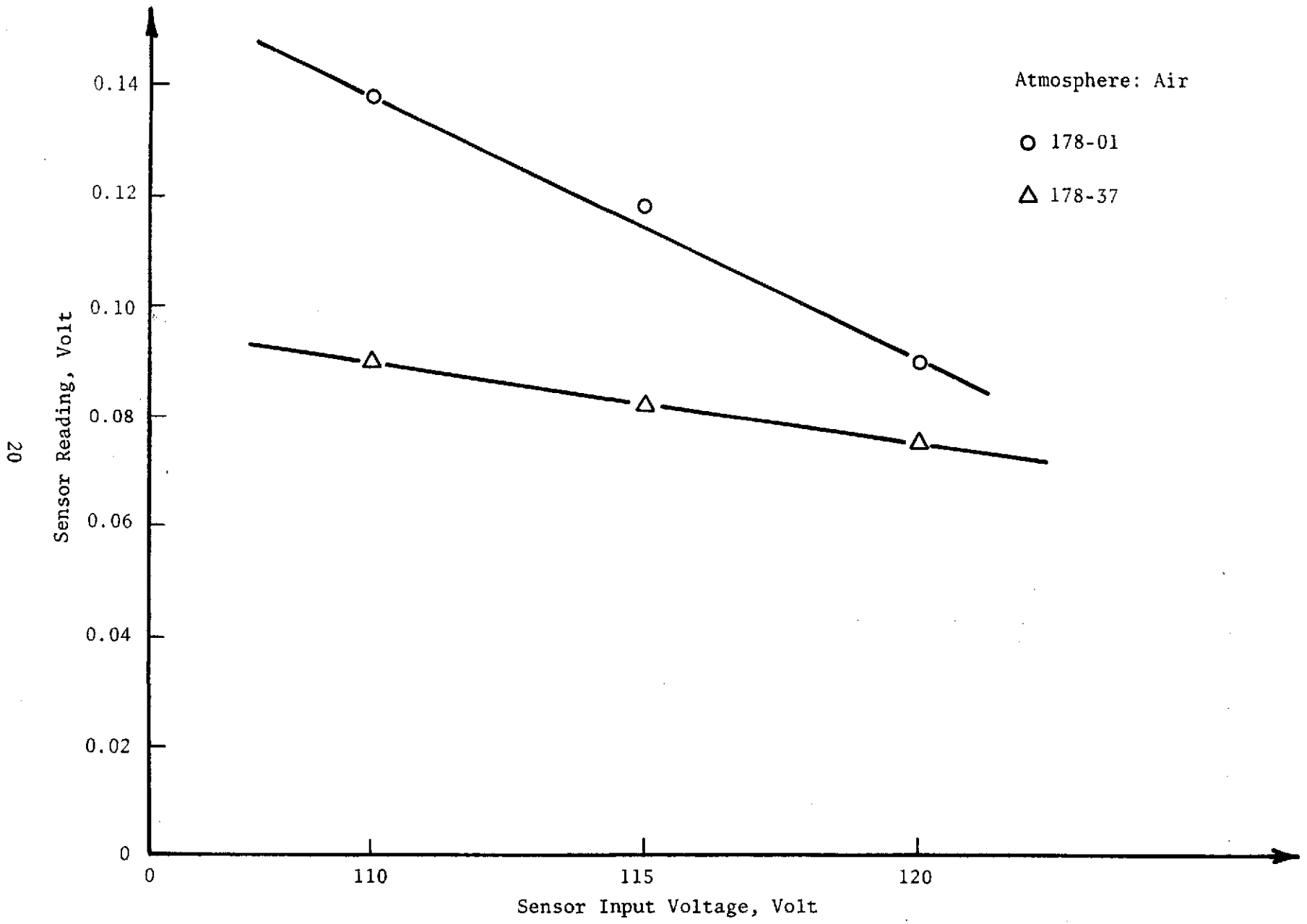| Air Speed, Ft/Min	CGD Output, Volt
0	0.0389
200	0.0387
500	0.0388
1100	0.0388
1300	0.0387
1500	0.0386

FIGURE 9   SENSOR OUTPUT VERSUS INPUT VOLTAGE

Relative Humidity Variations. In order to determine the effect of the relative humidity (RH) of the H_2/air mixture on the CGD output, the test setup shown in Figure 4 was modified by routing the gas inlet line through a flask of heated water. By bubbling the gas through the water via a sparger an 86% RH was attained in the chamber. The chamber pressure was maintained at 1.87 kN/m^2 (7.5 inches of water) at a gas flow of 1.57 x 10^{-5} m^3/s (2 cfh). The CGD output was recorded as the RH within the chamber increased. The results of this test are listed in Table 5.

There was an increase in CGD output as the chamber RH increased. This effect was particularly noted over the RH range of 23 to 58%. From RHs of 58% to 86%, the CGD output remained essentially constant. Since the cabin RH specification for the SSP is 36 to 77%, this test indicates that RH swings within specification will create a 0.075 volt error in the CGD output. This corresponds to 0.06% H_2.

Repeatability of CGD Readings. The repeatability of the CGD was defined by exposing the CGD to a constant H_2-in-air mixture several times and recording the CGD output. The readings of a perfectly repeatable instrument will duplicate themselves when subjected to the same conditions time after time.

For this experiment the chamber pictured in Figure 4 was alternately filled with 1.98% H_2-in-air and N_2. The output of the CGD, when exposed to the H_2/air mixture, was recorded. For five trials with the 1.98% H_2-in-air, the following readings were obtained: 2.50V, 2.40V, 2.55V, 2.45V, and 2.60V. The data indicate that the CGD's repeatability is ±0.10V, or ±0.4%.

Speed of Response and Recovery Time

Speed of response was defined as the time required for the CGD to reach the voltage output which corresponds to the H_2-in-air mixture to which it is being exposed. The recovery time is the time required for the CGD output to return to its normal ambient reading after the H_2/air supply has been removed. Ideally, the CGDs should respond as rapidly as possible to the initial presence of H_2 and to subsequent changes in H_2 concentration.

In order to characterize speed of response of the CGDs, a sensor was mounted in ambient air and a H_2 leak source at 0.5 lpm was simulated 5.1 cm (2 in) below the sensor head. Sensor output as a function of time was recorded. The time period started when the valve turning on H_2 flow was opened. The speed of response was then defined as the time required for the CGD output to reach a peak. The leaking gas was shut off and the recovery time was measured. The recorder data for this test are presented in Figure 10. Response time was 6 seconds and recovery time was 12 seconds.

This technique was chosen because it best represented the maximum response that would be obtained if a H_2 leak occurred at a CS-6 component. It should be noted that response time is very dependent on the method used to determine it and before comparing these data to response times reported by other investigators one should consider the differences in the techniques used to determine the response times. The 6-second response time is considered adequate for this application.

TABLE 5   CGD OUTPUT VERSUS RELATIVE HUMIDITY
OF H_2/AIR MIXTURE

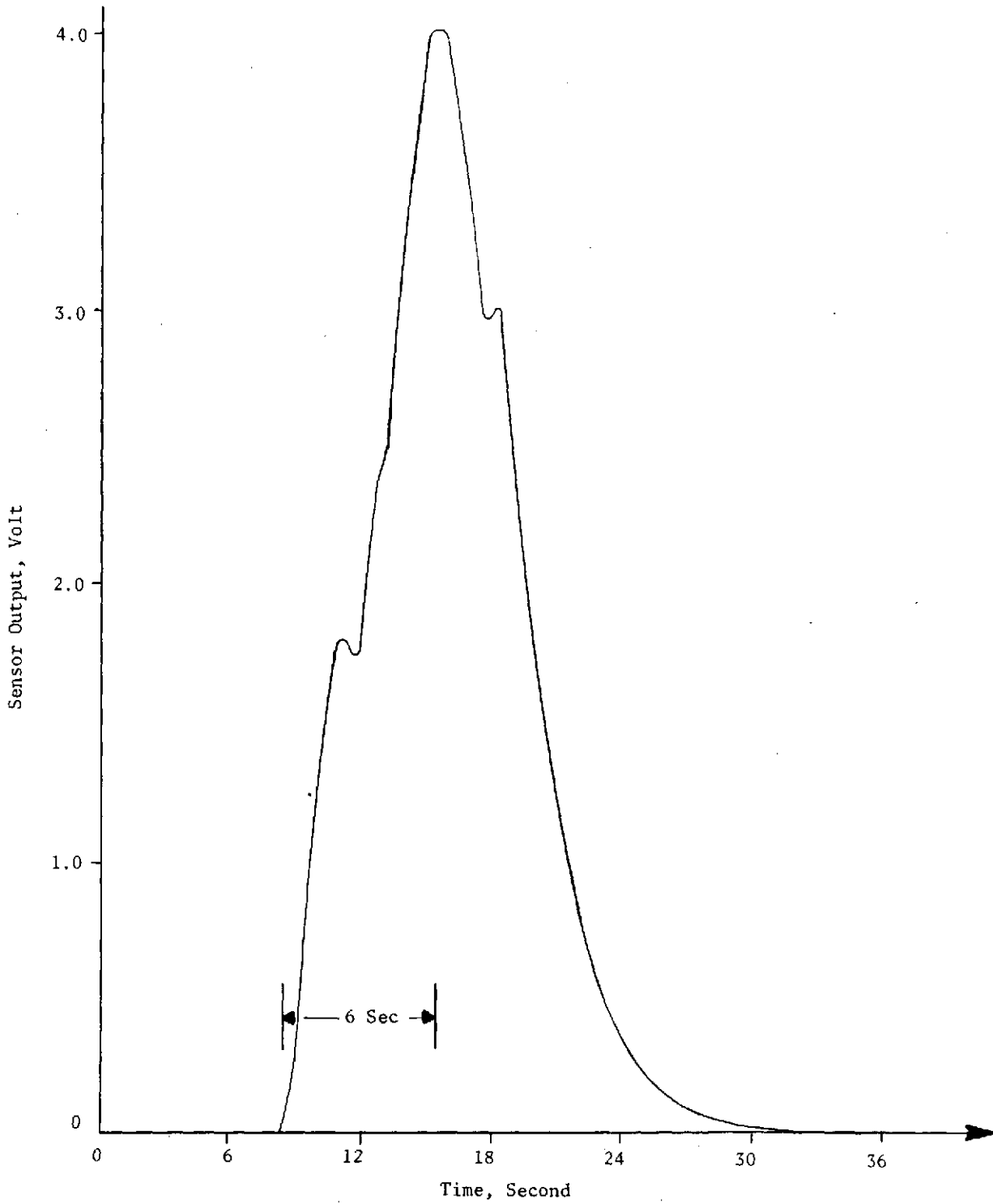| Relative Humidity, Percent	Sensor Output, Volt
23	2.405
29	2.400
37	2.425
42	2.440
47	2.460
52	2.485
58	2.500
63	2.515
70	2.510
80	2.505
86	2.505

FIGURE 10   CGD RESPONSE TIME

Interchangeability of CGDs

The SSP Item No. 178 CGDs consist of a sensing head and an electronic controller as pictured in Figure 3. As seen in Figures 1 and 2, the sensor heads are mounted remotely from their corresponding electronic controllers. Maintenance of the CGDs requires removal of two components from two different locations. In order to facilitate maintenance it was decided to determine if the CGD sensor heads and controllers are interchangeable without requiring a calibration procedure.

Two CGDs, 178-01 and 178-02, were placed in the test chamber (Figure 4) and the chamber was filled with N_2 gas. The sensor readings in N_2 were 0.006 and 0.007 volts, respectively. The sensors were interchanged, e.g., sensor head 178-01 was connected to the controller for 178-02 and vice versa. The readings obtained in this configuration were 0.745 for 178-01 sensor head and 178-02 controller and -0.895 volts for 178-02 sensor head and 178-01 controller. This result points out that the CGD sensor heads and controllers cannot be interchanged without requiring recalibration.

<div align="center">Ability to Detect Leaks on the CS-6</div>

Several experiments were performed to determine if the CGDs as located on the CS-6 are effective in sensing H_2 leaks from the CS-6 H_2 LRUs. These experiments involved:

1. Recording CGD output as a function of H_2 leak rate at the H_2 LRUs.

2. Recording CGD output as a function of the H_2 concentration of the leaking gas. The gas mixtures used were H_2/CO_2.

3. Determining the effect of an air draft across the H_2 LRUs on CGD output while H_2 is leaking at a given flow rate from specific LRUs.

Variation of H_2 Leak Rate

A task was performed to establish effectiveness of the CGDs in sensing H_2 leaks from various LRUs on the CS-6. Leaks were simulated at various CS-6 H_2 LRUs and the output of the CGDs were recorded. The leaks were allowed to continue for two minutes or until the CGD outputs stabilized, whichever was longer. Figures 11 and 12 graphically show the results of this task. The horizontal line at 0.625 volts represents the SSP shutdown point as defined in the 12 SSP H_2 leakage rules (Table 1). This corresponds to 0.5% H_2-in-air.

Table 6 was constructed utilizing the data in Figures 11 and 12. The table shows that for the distribution of CGDs and the shutdown level (0.625 volts) selected for the CS-6, a leak of 1.67×10^{-5} m^3/s (1.0 1/min) at LRUs 306-37, 306-38, 306-39, and 310-32 would have to occur before the CS-6 would be shut down. The table also shows that a 1.67×10^{-5} m^3/s (1.0 1/min) leak at LRU 877-31 would not cause shutdown and that a 0.42×10^{-5} m^3/s (0.25 1/min) leak at all components except LRU 882-31 would not cause subsystem shutdown. The minimum H_2
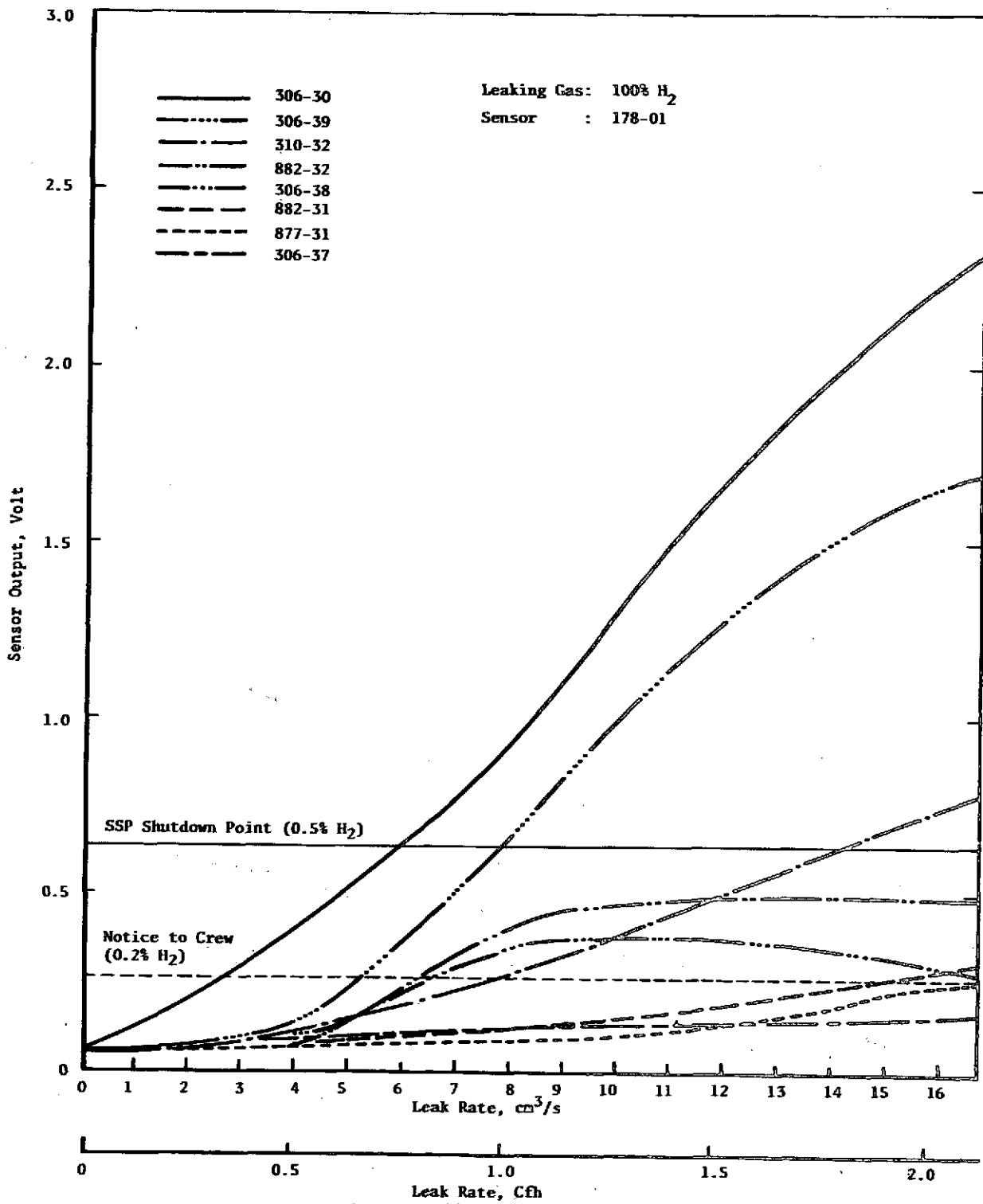
FIGURE 11   SENSOR 178-01 OUTPUT VERSUS H_2 LEAK FLOW RATE
AT INDICATED CS-6 LRUs
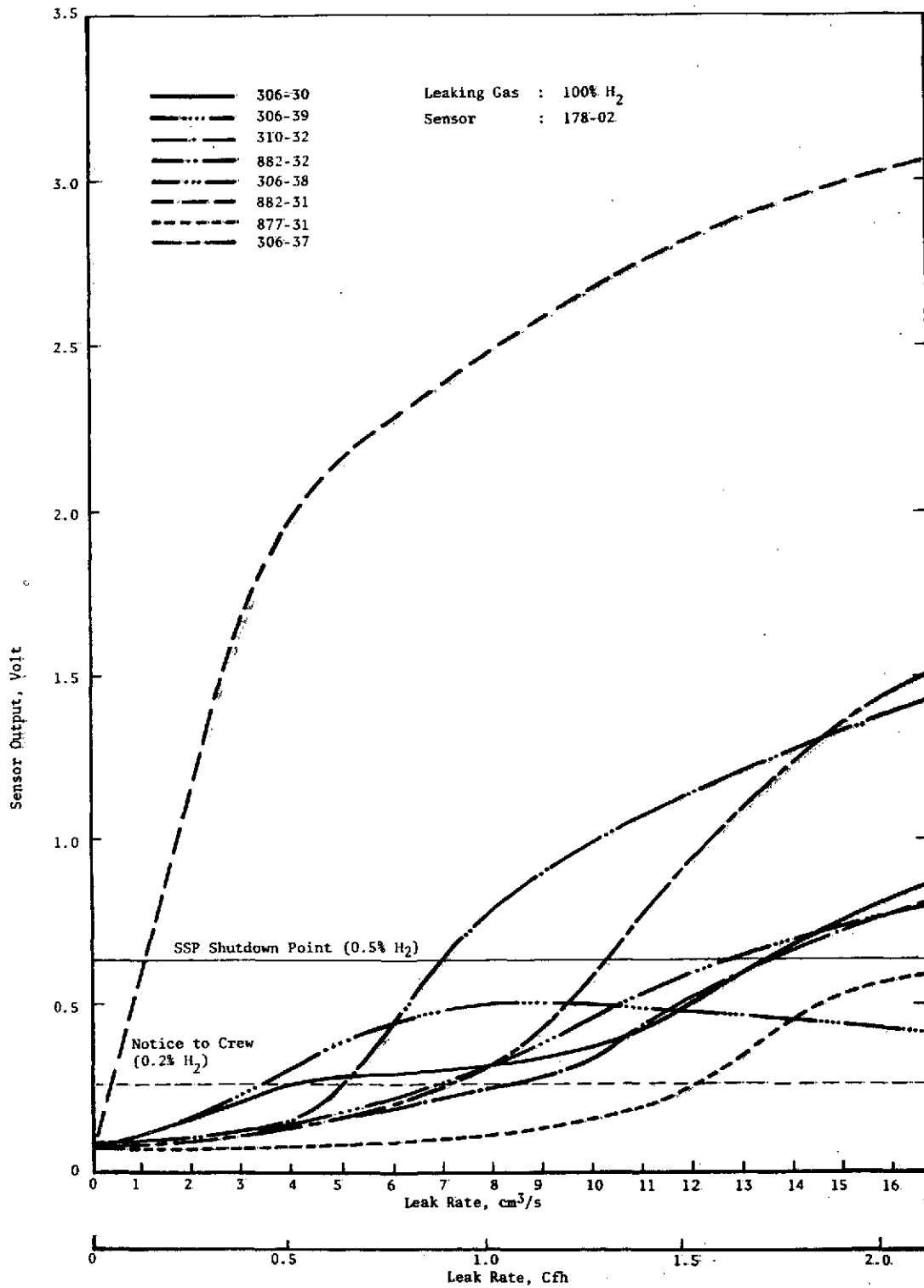
FIGURE 12   SENSOR 178-02 OUTPUT VERSUS H_2 LEAK FLOW RATE
AT INDICATED CS-6 LRUs

TABLE 6   CS-6 HYDROGEN LEAK SHUTDOWNS

Leak Source, CS-6 LRU	H_2 Leak Rate, Lpm		
	0.25	0.5	1.0
306-30		X[a]	X
306-37			X
306-38			X
306-39			X
882-31.	X	X	X
882-32		X	X
877-31			
310-32			X

(a) X - indicates that the listed flow rate at the given CS-6 LRU will be sensed and the subsystem would be shut down by the ACE/IMS. This is based on 0.625 volt or 0.5% H_2-in-air shutdown.

detection level as defined in the 12 SSP H_2 leakage rules corresponds to 0.2% H_2-in-air. Rule 7, Table 1, specifies that the CGDs should give notice to the crew at 0.2% H_2 concentration. The broken horizontal line (0.25 volt) on Figures 11 and 12 represent this concentration of H_2-in-air. Observation of Figures 11 and 12 show that a 0.84×10^{-5} m^3/s (0.5 1/min) leak at LRU 877-31 and 0.42×10^{-5} m^3/s (0.25 1/min) leak at 882-32, 306-38, 310-32, and 877-31 would go completely undetected.

Variation in H_2/CO_2 Concentration

Since the H_2 exhaust of the EDC is a mixture of H_2 and CO_2, it was important to establish the effect of leaking H_2/CO_2 mixtures on CGD output. To accomplish this, H_2/CO_2 leaks at various LRUs were simulated and the outputs of CGDs 178-01 and 178-02 were recorded. The leak rates were maintained at 0.84×10^{-5} m^3/s (0.5 1/min) and the leaks were continued for two minutes or until the CGD readings peaked, whichever was greater. The results of this test are presented in Figures 13 and 14. The graphs indicate that the CGDs are less sensitive to gas leaks downstream of the electrochemical modules in the EDC because this gas is diluted with CO_2. This result was expected since the CGD reacts only to the H_2 component of the H_2/CO_2 mixture and, as the percentage of H_2 in the H_2/CO_2 mixture decreases, the amount of H_2 in the location of the CGD decreases.

Effect of Air Draft on CGD Operation

For this test a blower was set up with a variable transformer so that its speed and resulting air velocity could be varied. Using the blower, a draft was created across the H_2 components on the rear panel of the CS-6. The air velocity of this draft was measured by a Dwyer No. 460 air meter.

Leaks of 1.67×10^{-5} m^3/s (1.0 1/min) H_2 were simulated at H_2 LRUs 306-30 and 882-31 and CGD output was recorded at various air speeds for CGDs 178-01 and 178-02 on the back of the CS-6. The results of this test are presented in Figures 15 and 16. The data illustrate how air movement alters the normal diffusion path of H_2 leaks and, in this case, blows the H_2 away from the CS-6 before the CGDs are capable of completely detecting the leak.

Figure 15 shows that as the air speed past the H_2 components increases from 0 to 1000 ft/min, given a 1.67×10^{-5} m^3/s (1.0 1/min) leak rate at LRU 306-30, sensor 178-01 readings will decrease approximately 2.0 volts, corresponding to 1.6% H_2. This represents a very serious safety problem as gross H_2 leaks could go undetected as a result of air drafts past the subsystem.

Improvements Desirable for EC/LSS H_2 Detection Concept

As a result of this study, several areas for improvement in H_2 detection for future EC/LSSs were identified.

Triple Redundant CGDs

In the interest of safety it would be desirable to have triple redundant CGDs. With the current concept the CGDs on the EDC cannot be fault isolated. There is
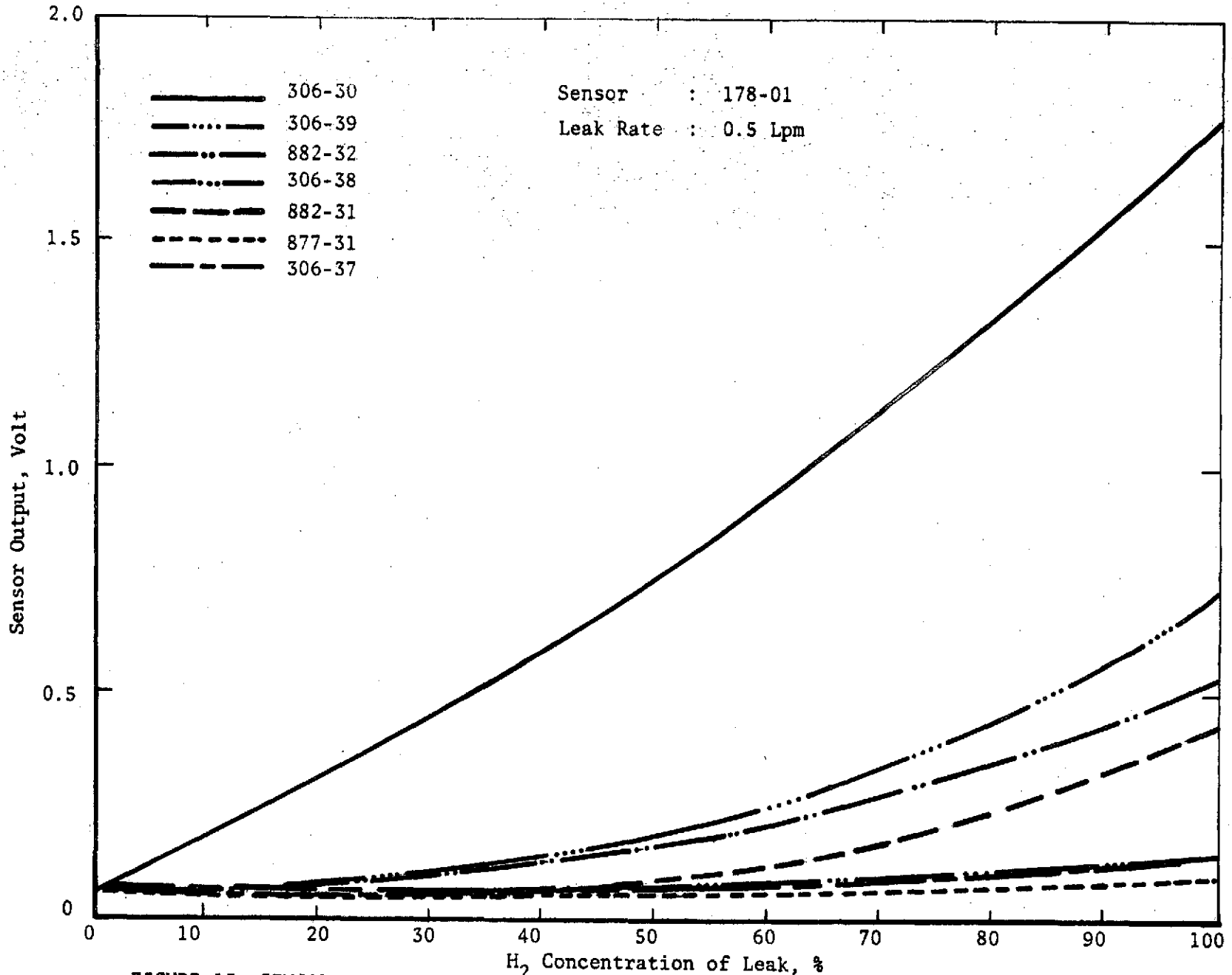
FIGURE 13   SENSOR 178-01 OUTPUT VERSUS H_2 CONCENTRATION OF LEAKING GAS AT INDICATED CS-6 LRUs
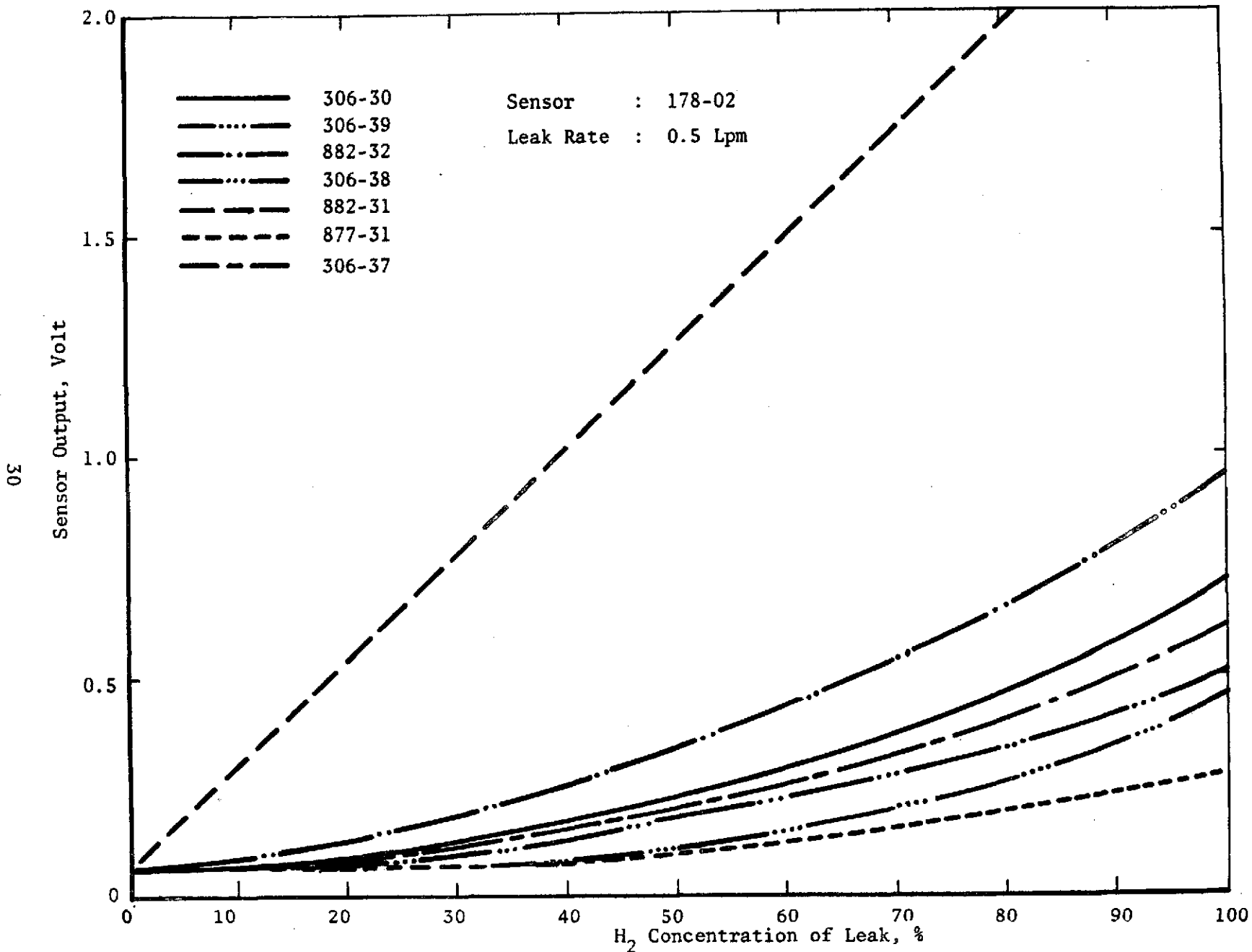
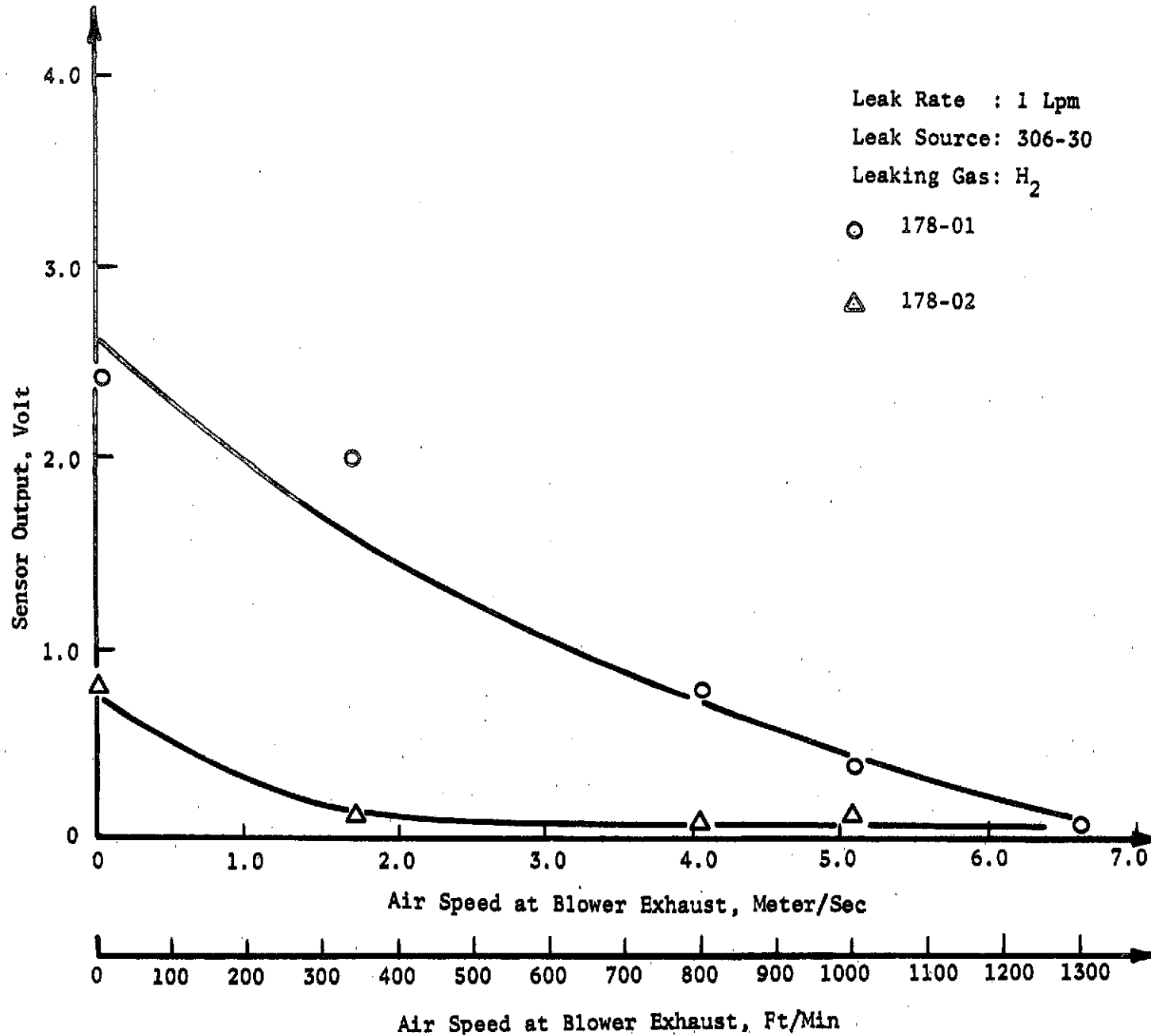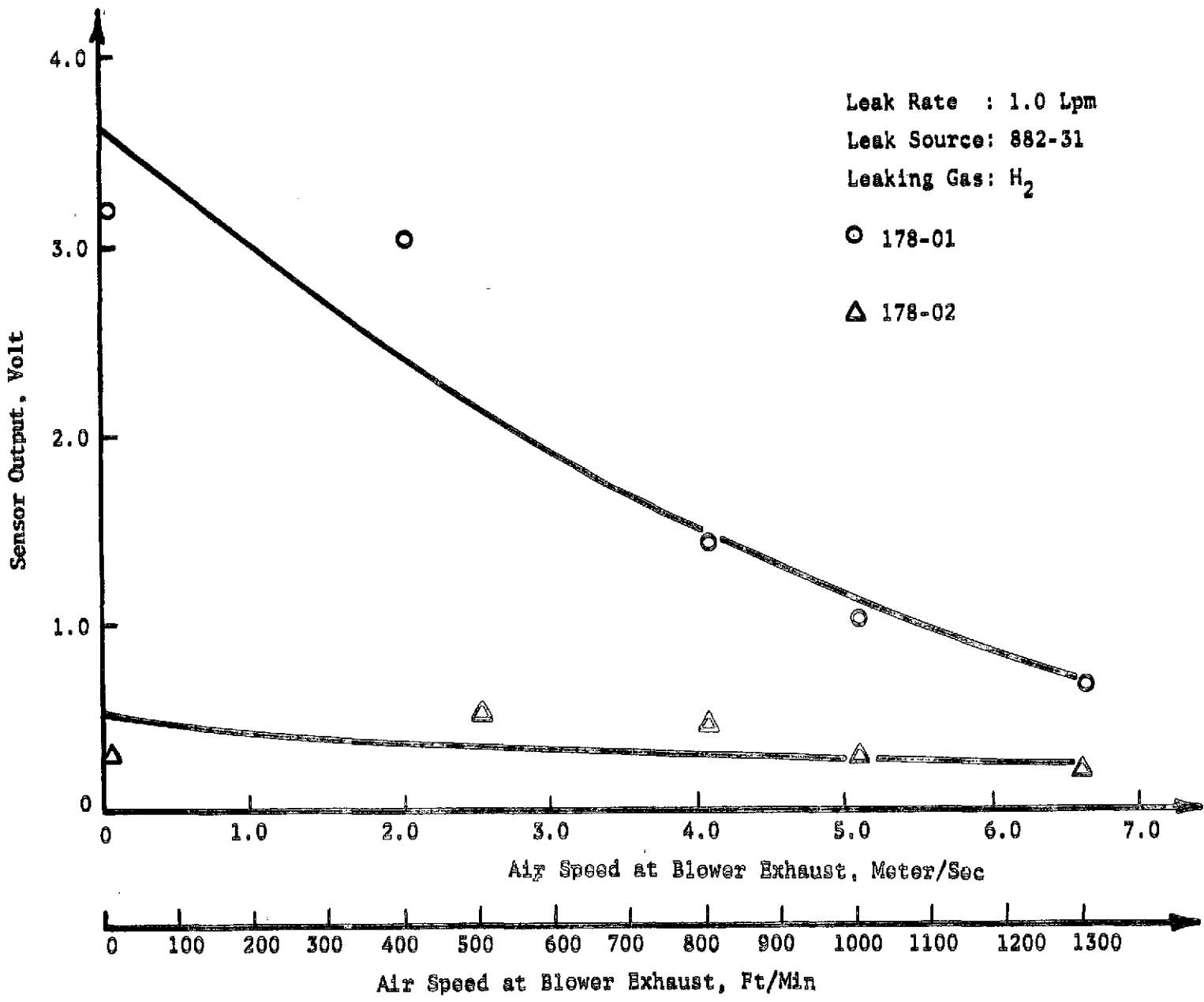FIGURE 14   SENSOR 178-02 OUTPUT VERSUS H_2 CONCENTRATION OF LEAKING GAS AT INDICATED CS-6 LRUs

FIGURE 15   SENSOR OUTPUT VERSUS AIR SPEED ACROSS H$_2$ COMPONENTS

FIGURE 16 SENSOR OUTPUT VERSUS AIR SPEED OVER H_2 COMPONENTS

no way of knowing that a CGD has failed. This represents a safety problem for the fail low failure mode as potential leaks would go undetected. In the case of the fail high failure mode, unnecessary subsystem shutdown (false alarm) and needless leak location efforts would result. Repeated false alarms due to the fail high failure mode may result in the crew tending to ignore the alarm, thereby creating a potential safety hazard.

The current philosophy and configuration violate two basic SSP rules: first, fault detection and fault isolation of a failed CGD is not possible and, second, system safety with regard to detecting leaks from all H_2 components is not possible if a CGD has failed low. Development and incorporation of triply re-dundant CGDs will improve the safety and reliability of EC/LSS with regard to detecting H_2 leaks.

In situ Calibration

This study revealed that the CGDs selected for the SSP exhibited poor long-term reproducibility. This study pointed out the need for frequent CGD calibrations. The calibration procedure recommended for SSP application involved removing the CGD sensor head and electronics package from the subsystem. The CGD sensor head is inserted in a calibration chamber with a known concentration of H_2 and the CGD is adjusted to give the correct reading. Since the maintenance activities involved in removing the CGDs from the subsystem are tedious, requiring removal of two units, and since the CGDs are position-sensitive, a method of in situ calibration would be desirable.

With regard to position sensitivity the calibration performed on the CGDs would be correct only if the CGD sensor heads are mounted in the same orientation as they were in the calibration chamber. A method for performing in situ CGD calibrations would improve the maintainability, accuracy, and safety of the CGDs.

Maintenance

It would be desirable from a maintainability point of view if the CGD consisted only of one package. The SSP CGD, Item No. 178, consists of a sensor head and a remote electronics package (see Figure 3). The maintenance time involved in removing the CGD from the subsystem could be reduced by one-half if the CGD were designed as a single package.

Location of CGDs

The previous section of this report points out that the CGDs as located on the EDC are not capable of detecting leaks from all H_2 components (Table 6). The reliability of and safety provided by the SSP H_2 detection concept could be improved if more sensors were strategically located on the EDC. The strategy for sensor location and the quantity required should be determined by evaluating the H_2 leak profile from all the H_2 LRUs in the operating environment (zero g, air drafts, etc.).

Combustible Gas Detector

Identification and incorporation of a CGD whose output is independent of its orientation, whose long-term reproducibility is better than ±0.10% H_2-in-air for periods greater than two months, whose output is not affected by variations in input power and whose output is linear over the entire H_2 concentration range would improve the reliability of and safety afforded by the CGDs.

Alternate Combustible Gas Detection Approaches for EC/LSS

A study was carried out to identify alternate combustible gas detection approaches. Several concepts were proposed. The five most practical concepts for incorporation into EC/LSS subsystems were selected for comparison:

1. Subsystem Enclosure with Air Flow

   Enclose each subsystem and blow air through the enclosure. Monitor the exit air duct for presence of H_2.

2. H_2 LRU Enclosure

   Monitor the H_2 concentration of an enclosure that contains all the CS-6 H_2 LRUs.

3. H_2 LRU Enclosure with N_2 Blanket

   Monitor the H_2 concentration of an enclosure that contains all the CS-6 H_2 LRUs. Maintain a positive N_2 pressure in this enclosure. A noncatalytic detector is required.

4. Subsystem Air Sampling

   Draw air samples from various points on the CS-6 and monitor these for H_2 concentration.

5. Extensive CGD Coverage

   Increase the number of CGDs on the CS-6 so that all possible leak sources are monitored.

These concepts were evaluated with regard to their power penalty, weight, volume, cost, reliability, and maintainability. The results of this comparison are presented in Table 7. The data presented in the table are based on best judgment knowing current state-of-the-art SSP practices. The first five features in the table are self-explanatory. The reliability was defined by listing the addition or reduction in the expected failures of the subsystem that would occur if the proposed concept were adopted. This was obtained by multiplying the sum of the failure rates of all additional components by the mission time (4320 hours). Maintainability was defined by estimating the time required to maintain any additional components and by adding this to an estimate of the additional time required to maintain all other components because of incorporating the proposed

TABLE 7   COMPARISON OF PROPOSED H_2 DETECTION CONCEPTS

Concept	1	2	3	4	5
Features Compared	Subsystem Enclosure	H_2 LRUs Enclosure	H_2 LRUs Enclosure with N_2 Blanket	Subsystem Air Sampling	Extensive CGD Coverage
Additional Components Required	Subsystem Enclosure, Air Blower, Blower Speed Sensor, Air Flow Sensor	H_2 LRU Enclosure	H_2 LRU Enclosure Motor-Driven Valve Pressure Regulator Pressure Transducer	Sample Pump CGD Gas Chamber Sample Tubing	12 Additional CGDs, Instrumentation for Multiplexing Signals
Power Penalty	30W	0W	4W and 58W while Motor-Driven Valve is running	25W	35W
Weight Added	33.5 Lb	4.5 Lb	10.0 Lb	9.5 Lb	47.0 Lb
Volume Added	0.10 Ft^3	0.05 Ft^3	0.09 Ft^3	0.08 Ft^3	0.53 Ft^3
Additional Cost	$8,500	$3,500	$5,400	$2,500	$14,000
Reliability Penalty (Expected Additional Failure for Six Month Mission)	0.066	0	0.061	0.065	0.259
Maintainability Penalty	49 Min	17 Min	35 Min	20 Min	72 Min
Safety	90	80	95	40	50
Ease of Calibration	Fair	Good	Good	Good	Poor

concept. For example, Concept 1 incorporates two additional components and a subsystem enclosure. The maintainability penalty equals the sum of the time to maintain the additional components plus the additional time to maintain all components within the enclosure because of having to remove the access panel. The safety was given a relative value from 0 to 100 based on a review board assessment of the probability that the given concept would detect all possible H_2 leaks and result in subsystem shutdown before the combustible limit of H_2-in-air is reached. The following paragraphs describe each proposed concept and provide justification for the data presented in Table 7.

Subsystem Enclosure

In this concept, each subsystem would be enclosed with panels and an air flow would be established through the subsystem enclosure. The required duct work and blower would be added to the subsystem. Three CGDs would be mounted in the exit duct and would monitor the combustible gas concentration of the air flowing through the subsystem enclosure. For this concept the CGDs would be triply redundant and would command a subsystem and enclosure N_2 purge when at least two of the three CGDs indicate a H_2 concentration in air at greater than 2%. Because the H_2 leak is confined and ignition sources removed from the enclosure and because the CGDs are triply redundant, it is projected that subsystem shutdown and N_2 purge could be safely carried out when initiated at the 2% H_2-in-air level. This would extend the shutdown point from 0.5% as required by the SSP H_2 leakage rules (Table 1) and should eliminate unwarranted subsystem shutdowns. Unlike the current SSP concept, it would ensure that leaks from all possible leak sources are monitored; it is independent of variation in g (gravity or lack of gravity) and it is not sensitive to normal cabin air movement. This concept would require the addition of two components, an air circulation blower and air flow sensor and the ductwork and paneling required to enclose the subsystem and direct the air flow. It is conceivable that one blower could service the entire EC/LSS as the exit from one subsystem could be connected to the inlet of the next H_2-bearing subsystem. Calibration of the CGDs would be facilitated if used in this manner because a known quantity of H_2 could be injected into the enclosure.

A disadvantage inherent with this technique is that subsystem maintenance would become more difficult. Maintenance is compounded by the fact the enclosure panels would have to be removed prior to actually starting work on the failed LRU. A safety problem could occur if the blower forcing air through the enclosure failed. Without air flow to move the air past the CGDs possible H_2 leaks would not be detected and would, if allowed to persist, reach the combustible limit of H_2-in-air. As a result, it would be necessary to add a blower speed sensor and an air flow sensor to provide total subsystem safety.

H_2 Component Enclosure

For this concept, all the H_2 components of the subsystem would be packaged together and an enclosure would be constructed around them. The only H_2-bearing item in the subsystem not inside the enclosure would be the H_2 inlet and outlet tubing. Ideally, this would be continuous tubing with welded connections and no fittings. Three CGDs would be mounted inside the enclosure and would

monitor the combustible gas concentration. When the H_2-in-air concentration reaches 2%, the subsystem would be shut down and the subsystem and H_2 component enclosure would be purged.

This concept would assure that leaks from all H_2 leak sources are monitored. It is not affected by gravity or normal cabin air movement. This concept would require only the construction of an enclosure. Because the CGDs are mounted within an enclosure, calibration would be simplified as calibration gases could be admitted to this enclosure. It would not be necessary to remove the CGDs from the unit. No additional components would be required for this concept. It is anticipated that the enclosure purge could be accomplished by putting a "T" fitting in the normal subsystem N_2 purge line thereby utilizing the same motor-driven valve for the N_2 purge. This concept has two negative features. First, from a packaging standpoint for some subsystems it may not be practical to package all the H_2 LRUs in one enclosure. Second, since the volume of the enclosure would be relatively small (approximately 6 ft^3), a large H_2 leak could result in a H_2 concentration of greater than 4% in the enclosure before subsystem shutdown occurs.

In order to minimize the latter problem, it would be necessary to set the H_2 concentration shutdown and purge level such that the maximum possible H_2 leak could not create a hazardous condition before shutdown and purge occur. With this concept, the maintenance of the H_2 LRUs would be more difficult because the enclosure would have to be opened prior to beginning the LRU replacement.

H_2 Component Enclosure with N_2 Blanket

This concept is an extension of the previous concept described, but in this case the enclosure would be pressurized with N_2. This would provide an additional margin of safety. Due to the lack of O_2, gross leaks could never result in an explosive mixture within the enclosure before shutdown and purge occurs. This concept would require utilizing CGDs that do not work on the catalytic combustion principle.

Sensor principles acceptable for this concept are thermal conductivity and gas chromatography. This concept would require an additional motor-driven valve and pressure regulator to maintain the positive N_2 pressure within the enclosure and a pressure transducer to monitor the enclosure pressure. The additional maintenance and packaging difficulties inherent in the previous concept also apply to this concept. Also, the calibration of the CGDs in this concept is facilitated because they are mounted in an enclosure and therefore do not require removal from the subsystem to perform calibration. Another safety plus could be achieved if the N_2 pressure in the chamber were maintained well above the H_2 pressure of the subsystem thereby making H_2 leaks practically impossible. In this case, the existence of leaks in the H_2 plumbing could be determined indirectly by monitoring the N_2 pressure of the chamber or by monitoring N_2 flow which would occur as a N_2 pressure regulator opens to allow N_2 into the chamber to maintain pressure.

Air Sampling the Subsystem

For this concept sample ports would be located throughout the subsystem and air

samples would be drawn to an enclosure which would contain three CGDs. The sub-system would be shut down and purged when the triply redundant CGDs indicate H_2 concentration greater than 2%. The improvements of this concept are that the CGDs are truly triply redundant and insitu calibration would be easy to perform as the CGDs would be mounted in a chamber and would not require removal from the system. This approach to H_2 detection would require one additional pump and several sample ports with associated plumbing. The concept has the same problem as the current concept; namely, a leak profile would have to be determined and the sample ports would have to be mounted in areas where H_2 leaks are most likely to occur. The effects of gravity and normal cabin air movements will influence the accuracy of this H_2 detection approach. An additional negative safety feature of this approach is that a combustible concentration can easily be reached in the sample tubes due to their small volume.

Extensive CGD Coverage

For this concept, many CGDs would be mounted on the subsystem in locations established by performing a H_2 leak profile. As many as one CGD for each H_2 LRU may be required. For the sake of comparison in this report it was projected that a total of 12 sensors would be adequate. The signal from the CGDs would be multiplexed and subsystem shutdown and N_2 purge would occur when any one CGD indicates H_2 concentration greater than 2%. This concept would require identi-fication or development of a miniature CGD in order to be competitive with the previous concept. This concept would facilitate leak location by observing which sensors indicate the high H_2 concentration. Although somewhat better than the current SSP concept, this approach is not totally independent of gravity variations and normal cabin air drafts. Because of the incorporation of a great number of CGDs the calibration task would become quite extensive. Like the current SSP approach this concept would not provide any sensor redundancy, and there would be no method of determining whether or not a sensor is functioning properly unless a small triply redundant sensor were developed.

CONCLUSIONS

From the results of the Combustible Gas Detector (CGD) evaluation program conducted, the following conclusions have been drawn:

1. The CGDs, as configured on the Six-Man, Electrochemical Carbon Dioxide Concentrator, were not capable of sensing H_2 leaks from all possible leak sources. Even when the leaks reached a 1.57×10^{-5} m^3/s (1.0 1/min) rate, the CGDs did not sense H_2 from all the leak sources evaluated.

2. The response of the CGDs was affected by air currents. Because air movement carried the leaking H_2 away from the EDC, the CGDs became less effective in detecting H_2 leaks as the air movement in the vicinity of the EDC increased. The impact on CGD output varied depend-ing on leak rate, leak location, CGD location, and the air velocity. For one set of conditions the CGD output decreased by 2.0 volts (1.6% H_2) as the air speed increased from ambient conditions to 305 m/min (1000 ft/min).

3. The CGDs were found to be nonlinear over the 0 to 4% range of H_2-in-air concentration. The degree of nonlinearity was different for each CGD evaluated.

4. The CGDs were position sensitive; their output varied by as much as 1.9 volts out of a 0 to 5 volt scale (equivalent to 1.52% H_2-in-air) when rotated 180 degrees about the axis of the sensor head and about an axis perpendicular to the sensor axis and perpendicular to the g vector.

5. The reproducibility of CGD readings was found to be poor; their readings varied as a function of relative humidity (RH), input voltage to the CGD electronic package, and exposure time to constant H_2-in-air mixture. As the RH increased from 23 to 86% RH the CGD output increased by 0.12 volts, a 4.6% variation. The effect of input voltage on CGD output was different for both CGDs evaluated. The output voltage of the CGDs decreased as the input voltage increased from 110 to 120 volts; one by 0.014 volts, the other by 0.046 volts. This represents a 15% and a 33% variation in output for the respective CGDs. After 25 days of exposure to a constant H_2/air mixture the CGD output decreased by 0.5 volts or by 20% compared to its initial reading.

6. The short-term repeatability, response time, and recovery time of the CGDs when evaluated in a controlled testing environment were found to be acceptable.

7. Calibrations performed prior to launch will not be accurate when the CGD is exposed to zero g due to the change in the thermal environment which the sensor beads (sensing bead and reference bead) are exposed to in zero g. Both the sensing head and the reference bead are heated and they are not thermally insulated from each other. The CGD output signal depends on the difference in temperature between the two beads. Since convection currents are gravity dependent, the bead temperatures and, more important, the difference in their temperatures will change, producing a resultant change in the CGD output.

8. A H_2 detection concept based on strategically locating CGDs in areas where they are most likely to detect leaks is not an effective means for monitoring all the possible H_2 leak sources of a subsystem. The diffusion characteristics of H_2 will vary as the g forces vary from the 1 g prior to launch to zero g in orbit. Attempts to locate the CGDs based on leak profile data would require data at 1 g, 0 g and at the g forces experienced between lift-off and orbit.

9. The CGD electronic package and sensor head are not interchangeable without recalibration. Hence, insitu calibration is a necessity or replacement of either component (sensor head or electronics) requires the simultaneous removal and replacement of the other component.

10. As configured on the CS-6, the CGDs are not triply redundant. Failure of any of the CGDs would result in a degraded safety condition, which would be avoided if the CGDs were triply redundant.

11. The CGDs on the EDC do not include instrumentation for fault isolation. As a result there is no way of knowing that a CGD has failed low or failed high. This represents a safety problem as potential leaks could go undetected because of a failed low CGD or would lead to false alarms if they failed high. False alarms would cause unnecessary subsystem shutdowns and leakage location procedures. If false alarms are frequent they may be ignored by the crew, thus creating a potential hazard.

RECOMMENDATIONS

Based on the results of this investigation, the following recommendations for improving the safety and reliability of the H_2 detection concept for subsystems in EC/LSS are made:

1. Design, develop, fabricate, and test a triply redundant H_2 sensor. Major design emphasis should be on miniaturization. A goal would be to package the three sensors (without electronics) in a volume of less than 16.4 cm^3 (1.0 in^3). The electronics should include three sensor voting logic to allow fault isolation of failed sensors and to provide for improved safety and reliability of sensor output.

2. Design, develop, fabricate, and test CGD insitu calibration equipment and demonstrate the procedure for performing the calibration. Major design emphasis should be on quantifying the equipment required and the complexity of the calibration function.

3. Define a flight experiment to establish the H_2 leak profile from a leak source in zero g and also to evaluate the triply redundant sensor in zero g.

REFERENCES

1. Gillen, R. J., Greenough, B. M., Mills, E. S., Sanderson, W. G., and Schubert, F. H., "Six-Month Test Program of Two Water Electrolysis Systems for Spacecraft Cabin Oxygen Generation," ASME Publication 72-ENAv-5, presented at the Environmental Control & Life Support Systems Conference, San Francisco, CA., August 14-16, 1972.

2. Holmes, R. F., Keller, E. E., and King, C. D., "A Carbon Dioxide Reduction Unit Using Bosch Reactor and Expendable Catalyst Cartridges," Convair Div. of General Dynamics Corp., San Diego, CA, GDC-DBD70-001, prepared under Contract NAS1-8217, March, 1970.

3. Mills, E. S., Linzey, T. J., and Hamkee, J. F., "Oxygen Recovery for the 90-day Space Station Simulator Test," ASME Paper 71-AV-18.

4. Kostell, G. D., Schubert, F. H., Shumar, J. W., Hallick, T. M., and Jensen, F. C., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem for Space Station Prototype (SSP) Application," Final Report, Life Systems, Inc., ER-170-34, NASA CR-114742, prepared under Contract NAS2-6478, May, 1974.

5. Marshall, R. D., "Spacecraft Nitrogen Resupply Technology: Nitrogen/ Hydrogen Separation," ASME Paper 74-ENAs-9, presented at the Intersociety Conference on Environmental Systems, Seattle, WA, July 29-August 1, 1974.

6. Wynveen, R. A. and Schubert, F. H., "Regenerative Fuel Cell Subsystem Design Handbook," Life Systems, Inc., ER-151-3, prepared under Contract NAS9-12509, December, 1972.

7. Rommel, M. and Dayan, V. H., "Simple Visual Detector for Hydrogen," Rocket-dyne Division, North American Rockwell Corporation, Canoga Park, CA, presented at the Pacific Conference on Chemistry and Spectroscopy, Anaheim, CA, October, 1967.

8. Michaels, P. A., "Design, Development, and Prototype Fabrication of an Area Hydrogen Detector," Bendix Corporation, Southfield, MI, NAS8-5282, 1964.

9. Anon., "Polarographic Hydrogen Sensor," Publication SE-1002A, Beckman Instruments, Inc., Fullerton, CA, 1964.

10. Chleck, D., Cucchiara, O., and Donaghue, T., "Detection Techniques for Hazardous Vapors of Elemental Propellants," Parametrics, Inc., Waltham, MA, 1963.

11. Marr, J. W., "Leakage Testing Handbook," S-67-1014, General Electric, Schenectady, NY, 1967.

12. "Design Criteria Handbook," Environmental/Thermal Control and Life Support System SSP, Hamilton Standard Document 9, Rev. A., November 14, 1970.

13. Rosen, B., Dayan, V. H., and Proffit, R. L., "Hydrogen Leak and Fire Detection, A Survey," National Aeronautics and Space Asministration, prepared under Contract NAS8-5604, NASA SP-5092, 1970.

14. Schubert, F. H., "Delta Approval Design Review Meeting Minutes," Life Systems, Inc., ER-170-69, prepared under Contract NAS2-6478, January 18, 1973.

15. "Design and Performance Requirements, General SSP," SVHS 4655, Rev. G.