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TRIPLE REDUNDANT HYDROGEN SENSOR WITH IN SITU CALIBRATION

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FINAL REPORT

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J. B. Lantz, J. D. Powell,
F. H. Schubert and E. P. Koszenski

November, 1980

Prepared Under Contract NAS9-16065

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Life Systems, Inc.
Cleveland, OH 44122

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LYNDON B. JOHNSON SPACE CENTER
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FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, OH under contracts NAS9-14658 and NAS9-16065 during the period July, 1976 through November, 1980. The program managers were Franz H. Schubert and Eugene P. Koszenski. The technical effort was completed by K. A. Burke, E. P. Koszenski, J. O. Jessup, D. W. Johnson, Dr. J. B. Lantz, G. P. Neurohr, J. D. Powell, J. W. Shumar and Dr. R. A. Wynveen.

The contract's technical monitor was Mr. Nick Lance, Jr., Crew Systems Division, Lyndon B. Johnson Space Center, Houston, TX 77058.

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HGM	Hydrogen Gas Monitor
HSC	Hydrogen Sensor Calibrator
IRAD	Internal Research and Development
TRHS	Triple Redundant Hydrogen Sensor
TSA	Test Support Accessories
WVE	Water Vapor Electrolysis

SUMMARY

Several spacecraft Life Support/Environmental Control subsystems are currently being developed that utilize or produce hydrogen. Although these subsystems are designed to minimize the possibility of gas leakage, hydrogen sensor/alarm subsystems are required to warn crew members and shut down equipment to prevent accumulation of hazardous atmospheres should such leakage occur. Periodic calibration of conventional hydrogen sensors, particularly if located in remote locations, is impractical for spacecraft applications. Additionally, conventional sensors provide neither fault detection and isolation nor spare sensor redundancy.

To meet sensing and calibration needs Life Systems developed an in situ calibration technique based on electrolytic generation of a hydrogen/air atmosphere within a hydrogen sensor. The hydrogen is generated from water vapor in the air (no expendables are required) and, being electrical in nature, the in situ calibration can be performed completely automatically in remote locations. The validity of this concept was demonstrated successfully during a previous portion of contract NAS9-14658.

To meet the need for fault detection and isolation and sensor redundancy, Life Systems also developed a Triple Redundant Hydrogen Sensor concept. Triply redundant sensor elements are integrated within a single, compact housing, and digital logic provides inter-sensor comparisons to warn of and identify malfunctioning sensor elements.

The validity of the in situ calibration concept and triple redundancy had been established previously. The objectives of the contractual efforts reported herein were to further evaluate the in situ calibration technique using Life Systems' Triple Redundant Hydrogen Sensor head, to evaluate the detection characteristics of this device and to design, fabricate and checkout test two complete TRHS Subsystems for delivery to NASA. These subsystems included sensor heads, signal conditioning, fault analysis, alarms and shutdowns, readouts and fully automated in situ calibration instrumentation.

Evaluation of the TRHS detection characteristics showed that the sensor output was linear to 2.1% hydrogen, responded to hydrogen concentrations below 0.01% and demonstrated negligible zero drift, 0.02% hydrogen per month span calibration stability, negligible position sensitivity and a temperature sensitivity of only 0.0009% hydrogen/K (0.0005% hydrogen/F) at 0.5% hydrogen. The baseline drift and calibration stability was demonstrated over 8160 hours.

The composition of the hydrogen/air mixture created in the TRHS during the in situ calibration experiments was reproducible to ±0.02% hydrogen over a three month period, during which the relative humidity varied between 40% and 56%. Hydrogen/air mixture composition variations of only ±0.06% were observed over virtually the entire spacecraft temperature/humidity range, 291 K (65 F) to 300 K (80 F) and 26 to 70%, respectively. Position and draft sensitivity were qualitatively observed to be negligible.

Based on the performance of the TRHS sensor head, an electronic automatic background zeroing concept was developed that will permit the sensor to be in situ calibrated without interference due to small, non-hazardous background hydrogen concentrations at the sensor head.

Based on the successful performance of the Triply Redundant Hydrogen Sensor head, a Triple Redundant Hydrogen Sensor Subsystem was developed. These units performed completely automated in situ calibrations with auto background zeroing and provided fault detection/isolation, multiple alarm and monitoring features. The subsystems had nonoptimized total volumes of 9300 cm^3 (570 in^3), weights of 4.6 kg (10.2 lb) and power requirements of 17 watts.

Two Triple Redundant Hydrogen Sensor Subsystems were checkout tested. The sensor outputs were linear to within 0.01% hydrogen. The in situ calibrations were setup to be within 0.02% hydrogen of a standard gas calibration at 48% relative humidity. Some initial effects of nonideal redundant sensor symmetry on the fault detection/isolation logic during autocalibration were eliminated. All autoprotection/fault isolation features performed properly. Additional tests will be performed by National Aeronautics and Space Administration.

It was concluded that the hydrogen sensing subsystem has successfully met the development objectives. Additional efforts to develop, characterize and flight test an improved prototype hydrogen sensing subsystem are recommended.

PROGRAM ACCOMPLISHMENTS

Key program accomplishments were:

- Demonstrated that LSI's Triple Redundant Hydrogen Sensor (TRHS) sensor output was linear over the range 0 to 2.1%, had negligible baseline drift, negligible position sensitivity, 0.02% hydrogen per month span calibration drift at 0.5% hydrogen, better than 0.01% H_2 resolution and only 0.0009%/K (0.0005%/F) temperature sensitivity at 0.5% hydrogen.

- Demonstrated ±0.02% H_2 in situ calibration atmosphere reproducibility over three months and over a 40 to 56% RH range for TRHS sensor head.

- Demonstrated over 340 days of TRHS sensing element operation with no failures.

- Demonstrated successful integration and operation of complete TRHS subsystem with capabilities to in situ calibrate H_2 sensor completely automatically with zero labor, external apparatus or expendables and to provide variety of failure detection/isolation and alarm functions.

INTRODUCTION

Many spacecraft Life Support/Environmental Control subsystems are currently being developed that utilize or produce hydrogen (H_2). These are designed to be leak tight. If a leak should occur, however, and H_2 leaks into confined spaces or is permitted to accumulate, hazardous, potentially explosive gas mixtures can result. Prevention of these situations by incorporating combustible gas safety design criteria is mandatory. Hence, a definite requirement for future space vehicles is to provide detectors for the presence of H_2 so that corrective measures can be taken before the crew is exposed to danger. Such detectors must be periodically zero and span calibrated and require failure detection capabilities to promote operational reliability. This report discusses the development of a unique H_2 sensor subsystem to meet these requirements.

Background

Calibrations of H_2 sensors by conventional means are impractical for spacecraft applications and are tedious and time-consuming. They would involve removing the sensor from its location and providing an environmental chamber and calibration gases or bringing the environmental chamber and calibration gases to the sensor location. Several disadvantages of the existing calibration procedures for H_2 sensors include: the weight penalty at launch for external calibration hardware, the excess crew time required for performing frequent sensor calibrations, and flight maintainability and safety ground rules prohibiting performance of maintenance on subsystems while they are operational[(1)] (requiring subsystem shutdowns or a violation of the maintainability and safety rule).

To overcome these limitations, Life Systems, Inc. (LSI) developed a unique in situ calibration concept, in which hydrogen/air calibration mixtures can be generated integrally within the H_2 sensor, automatically and with no expendables or external calibration apparatus. The advantages of this technique are summarized in Table 1. The validity of LSI's in situ calibration concept was successfully demonstrated under contract NAS9-14658.[(2,3)]

Additionally, fault detection, fault isolation and spare sensor capabilities, although particularly important for spacecraft applications, are not available on conventional combustible gas sensors. The size of most such sensors inhibits their effective consolidation to form the necessary triply redundant subsystems,[(4)] and frequent intercomparison of individual sensor response in a H_2 atmosphere is impractical. To meet these needs, LSI developed a Triple Redundant Hydrogen Sensor (TRHS) concept, in which three independent sets of sensing elements would be integrated into a single, conventional sized sensor head and perpetually compared with each other electronically to provide fault detection and isolation. The advantages of this concept are listed in Table 2.

Concepts

The in situ span calibration method consists of creating a 0.5% hydrogen/air mixture within the flame arrestor cavity of the H_2 sensor with a miniature Water Vapor Electrolysis (WVE) cell (see Figure 1). This cell generates hydrogen from water absorbed from the air by its electrolyte. The hydrogen mixes rapidly with air diffusing through the flame arrestor to create a hydrogen/air mixture of consistent composition, proportional to the electrolysis current of the WVE cell.

A nearly constant concentration of hydrogen can be generated by the WVE cell within 1.5 minutes of the start of an in situ calibration. This is accomplished by applying a sequence of different currents to maintain the WVE cell in a poised condition, to flush out excess air and then to generate a nearly steady-state sensor output plateau, as illustrated in Figure 2. This sensor output plateau corresponds to a fixed hydrogen concentration, as determined by the WVE cell current. The detector can then be calibrated by quickly adjusting

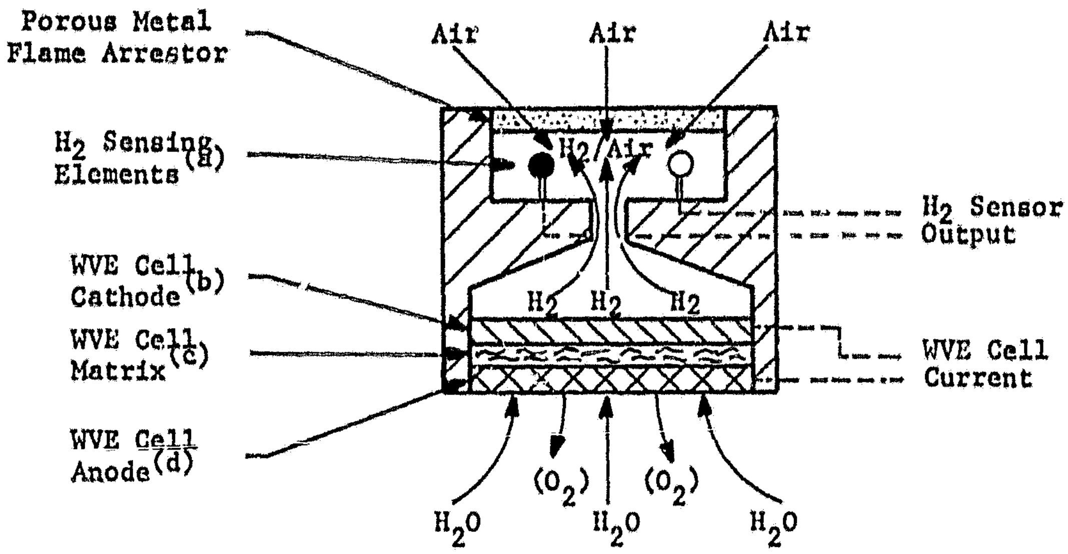
(1) References cited at end of report.

TABLE 1 ADVANTAGES OF IN SITU CALIBRATION

- Provides credibility for sensor output.
- Permits automatic or centrally initiated calibration of remotely-located sensors
- Saves personnel time normally required for calibration
- Eliminates need for support equipment (e.g., calibration gases and apparatus)
- Avoids human error
- Allows increased frequency of calibrations
- Low maintenance makes placement of sensors in relatively inaccessible locations practical

TABLE 2 ADVANTAGES OF A TRIPLY REDUNDANT SENSOR

- Avoids "fail-low" failure mode of single sensor and therefore
  - Eliminates possibility of a leak going undetected
- Allows fault isolation of combustible gas sensor
- Avoids "Fail-high" failure of single sensors and therefore
  - Avoids unnecessary downtime of monitored facilities
  - Avoids unnecessary leak location activities
  - Avoids stress on operators
- Lower volume and weight with three sensors integrated
- Redundant sensor elements eliminate emergency repairs to or replacement of sensor head to maintain safeguard.



(a) Catalyst coated and reference temperature sensors (electrically self-heated)
(b) Generates H_2 which is admitted to H_2 detector sensing cavity
(c) Contains water and electrolyte
(d) Generates O_2 which is admitted to atmosphere

Anode Reaction: $H_2O = \frac{1}{2}O_2 + 2H^+ + 2e^-$

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

Overall Reaction: $H_2O = H_2 + \frac{1}{2}O_2$

FIGURE 1 IN SITU CALIBRATION CONCEPT

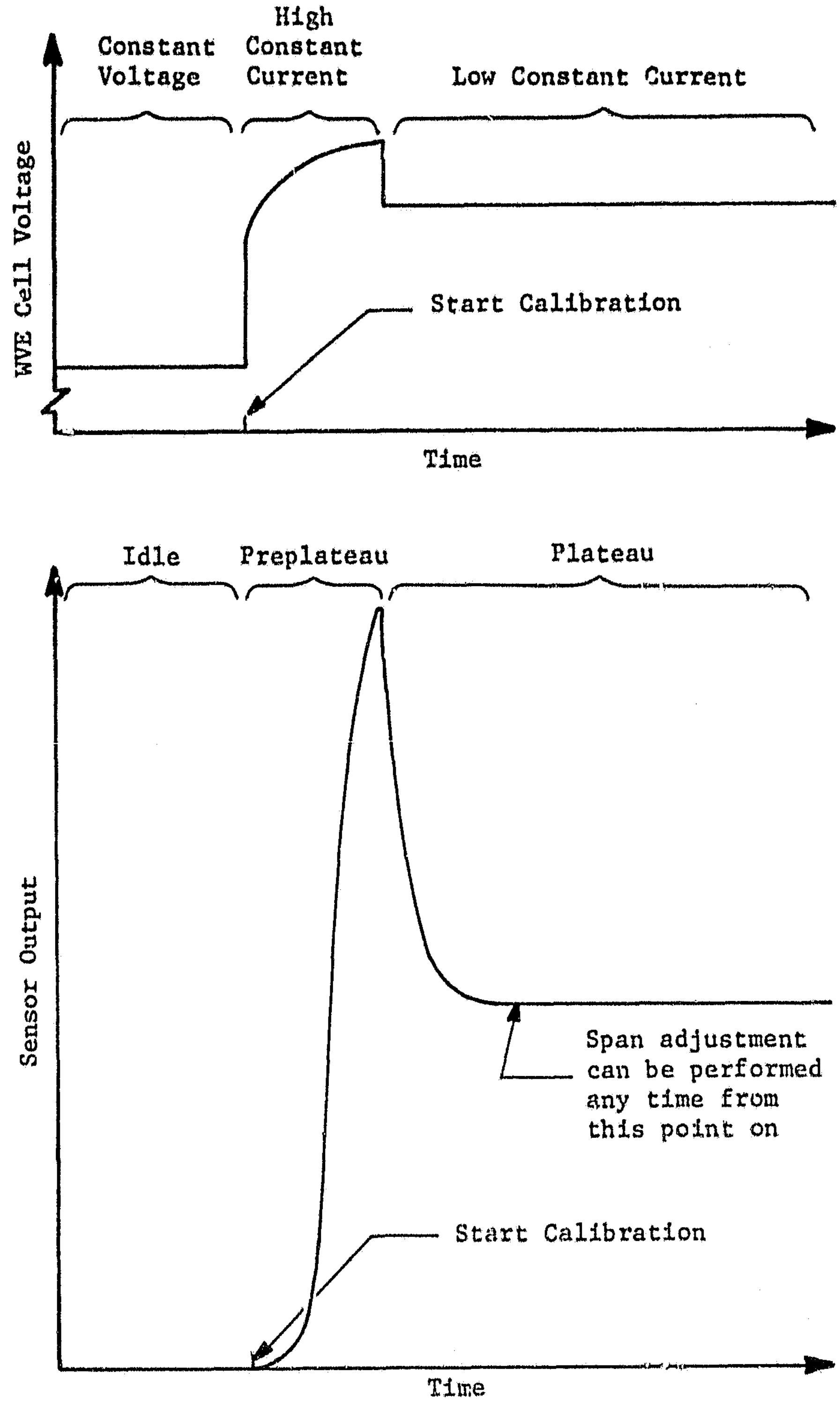


FIGURE 2 ILLUSTRATION OF CALIBRATION PROFILE

the sensor output at the plateau to correspond correctly to the generated H_2 concentration. Being completely electrical in nature, the calibration cycle can be totally automated.

Additionally, an automatic background zeroing concept was developed to nullify the effects of any small (nonhazardous) hydrogen concentration that may be present in the atmosphere that would interfere with the in situ calibration cycle. The corresponding background (H_2 contamination) indication is automatically subtracted from the H_2 sensor output just before the in situ calibration, then restored just after, as illustrated in Figure 3.

In LSI's TRHS concept, three pairs of very low-power, low temperature catalytic combustion-type sensor elements (electrically self-heated) are integrated into a single sensor head. Each element of the six (three catalyst coated, three reference) is isolated from the others, but shares a common flame arrestor. All element pairs are perpetually compared with each other (1 versus 2, 2 versus 3, 3 versus 1) to detect, and warn, if any one of the three pairs have changed output relative to the others, indicating its probable failure. If all three are found to disagree (sensor no longer reliable), alarm/shutdown signals are provided to alert crew and, optionally, shut down any H_2 - containing systems in the sensor's vicinity.

LSI's triple redundancy concept is quite compatable with the in situ calibration technique, and both concepts have been integrated into a single sensor head. Instead of an H_2/air mixture being formed around a single pair of sensor elements, the H_2 generated by the WVE splits and forms an independent, but nearly identical, atmosphere around each element. A sensor combining the triple redundancy/in situ calibration concepts enhances the capabilities by providing for frequent redundant sensor intercomparisons in a H_2 (versus air only) atmosphere.

Objectives

The objectives of the program portions covered by this report were to:

- Further evaluate in situ calibration technique, using a fully integrated WVE cell/H_2 sensor head, LSI's TRHS.
- Evaluate TRHS sensor head detection characteristics.
- Design and fabricate two complete TRHS Subsystems, including sensor heads and signal conditioning, fault analysis, alarms and readout instrumentation and fully automated in situ calibration instrumentation.
- Checkout test the two Subsystems and deliver to NASA for further evaluation.

Report Organization

This report covers two contracts. The work performed under Contract NAS9-14658 between July, 1976, and August, 1978, is discussed in the TRHS Sensor Head Evaluation section. The work performed under Contract NAS9-16065 between February, 1980 and November, 1980 is discussed in the TRHS Subsystem Develop-

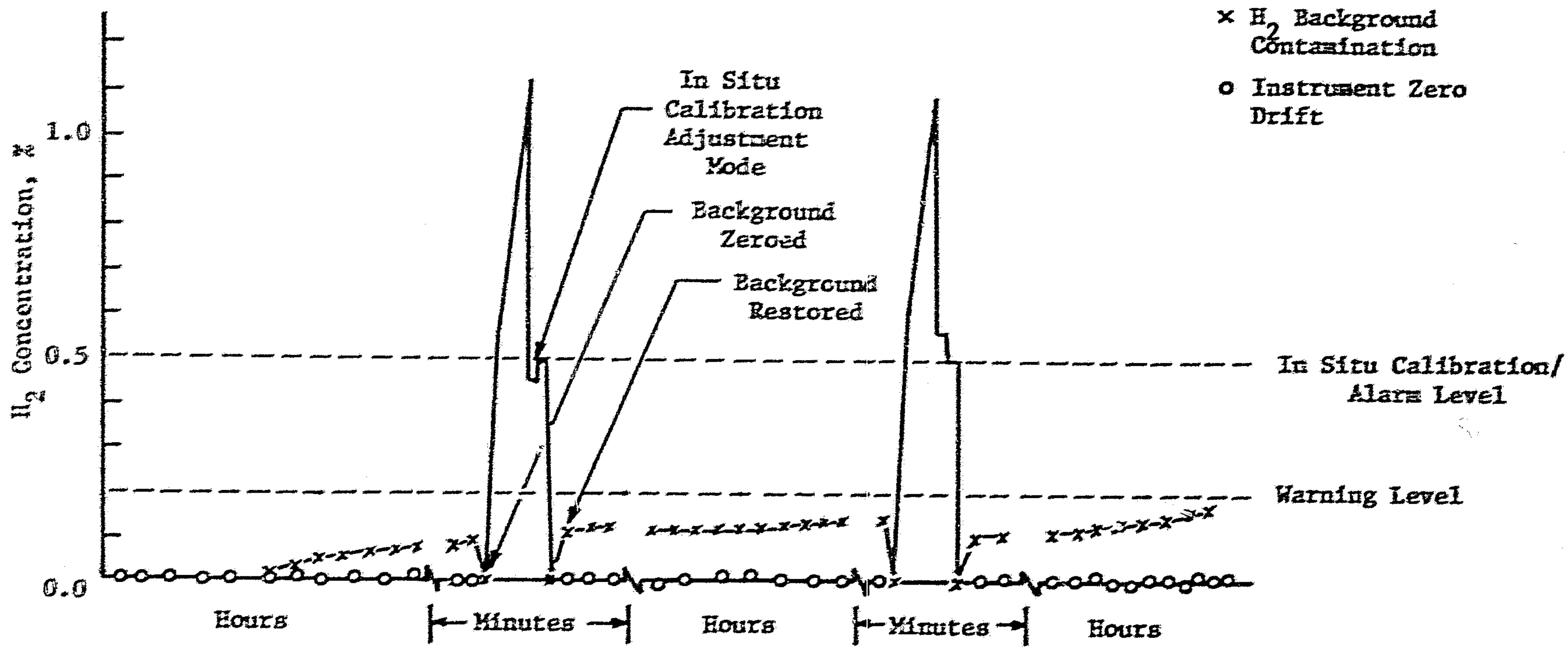


FIGURE 3 AUTOMATIC BACKGROUND ZERO CONCEPT

ment Section. The Conclusions and Recommendations section apply to both contractual efforts, as do the Summary and Introduction sections covered previously.

TRHS SENSOR HEAD EVALUATION

The validity of the in situ calibration technique has been established previously using an experimental breadboard.(2,3) This consisted of a commercial, general purpose combustible gas detector, with flame arrestor removed, interfaced with a special miniature WVE cell and a cylindrical flame arrestor. However, the in situ calibration method had not yet been evaluated with an H_2 sensor specifically designed for this function. These capabilities were therefore evaluated for LSI's TRHS sensor head, which includes triply redundant H_2 sensing elements and a miniature WVE cell integrated into a single compact unit. The detection characteristics of this device were also evaluated.

TRHS Sensor Head

The basic TRHS sensor head is shown in Figure 4. The parts for this device are as shown in Figure 5, except for a few minor modifications that were performed during the test program. Two such sensor heads, labeled PP-1 and PP-2, were evaluated at different points of the test program.

Test Support Accessories

Readout of each of the three redundant elements of the sensors was accomplished with breadboard signal conditioning electronics. Data readings were taken with a digital voltmeter, connected to each of the sensor element outputs sequentially with a selector switch. One channel only of a TRHS sensor head was also monitored with a chart recorder to provide semiquantitative information about the tests. In situ calibration plateau sequences (Figure 2) were timed with a stopwatch. Otherwise, instrumentation for initiating these plateaus was similar to that reported previously.(2,3)

The test setup was also similar to that reported previously,(2,3) except that a heat exchanger was added to the test chamber to permit variable temperature control, and additional gas inlets were added to the test chamber manifold.

Test Procedures

Standard Calibrations

Calibrations with certified H_2/air standards were performed for four purposes: to determine initial sensor calibration curves, to monitor long-term span calibration stability at various times with 0.5% H_2, to provide an atmosphere for evaluating position sensitivity and for comparison of sensor response to standard atmospheres and in situ calibration plateaus. The test chamber was typically purged with the gas standard (typically one hour), followed by recording of the sensor readout at steady-state. After establishing calibration curves, all sensor outputs (as voltages) were subsequently converted to indicated hydrogen concentrations.

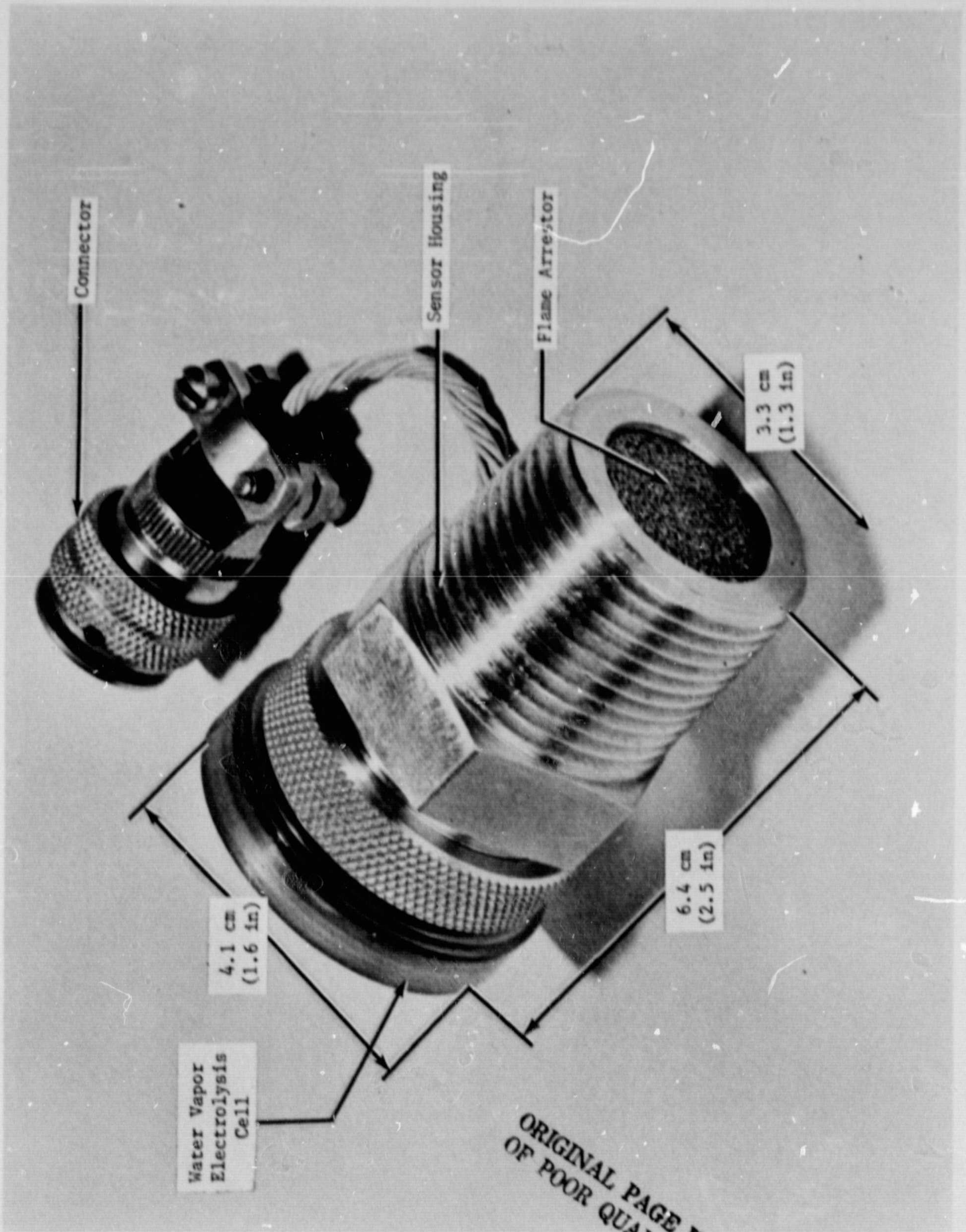


FIGURE 4 TRIPLE REDUNDANT H_2 SENSOR WITH IN SITU CALIBRATION

FIGURE 5 PARTS OF TRIPLE REDUNDANT H_2 SENSOR WITH IN SITU CALIBRATION

In Situ Calibration Plateaus

A test sequence like that shown in Figure 2 was used to obtain calibration plateaus (approximately steady-state hydrogen/air mixtures within the sensor head). The WVE was maintained at an idle voltage of 1.5 V, and the preplateau and plateau were performed at 15 mA/cm^2 and 3.3 mA/cm^2, respectively. The plateau reading was taken after a period of 90 seconds, total (60 seconds for the preplateau and 30 seconds for the plateau). A minimum of eight hours of environmental equilibration was normally allowed between measurements of calibration plateaus.

TRHS Sensor Head Detection Characteristics

The TRHS sensor heads were tested for a variety of detection characteristics to demonstrate their applicability for spacecraft use. The results of these tests are described below.

Calibration Curves

The sensor head should be linear to permit unambiguous H_2 concentration readouts and calibrations. Calibration curves for PP-1 and PP-2 were both linear. Figure 6 shows the calibration curve for sensor PP-1. The curve for PP-2 was only slightly less linear (worst case deviation from a straight line of only 0.04% H_2 over the range of zero to 2.1% H_2).

Baseline Stability

Instrument baseline stability is very important, since it limits meaningful sensor sensitivity, accuracy and in situ calibration reliability. Baselines for both PP1 and PP-2 were extremely stable. The baseline was virtually unchanged after 340 days of operation for PP-1, as shown in Figure 7, and after 170 days for PP-2. Therefore, no zeroing of the TRHS sensor head base-lines will be required (as opposed to auto background zeroing during an in situ calibration).

Sensitivity

High sensor sensitivity permits noting the existence of H_2/air atmospheres long before they become hazardous. The TRHS is very sensitive. Very small hydrogen concentrations in the laboratory due to an accidental discharge of hydrogen coincided with very small deviations observed in the hydrogen sensor baseline (less than 0.01% hydrogen). This pickup was distinguished from very small random baseline variations by the fact that all three channels responded in exactly the same way.

Span Calibration Stability

Span calibration stability limits the reliability of the H_2 sensor between calibrations. Long-term calibration stability, for 0.5% hydrogen, was good for both PP-1 and PP-2, within 0.02% H_2 per month, as illustrated in Figures 8 and 9. Redetermination of calibration curves for sensors PP1 and PP2 after 5.5 and 4.3 months of use, respectively, also showed that linearity was retained.

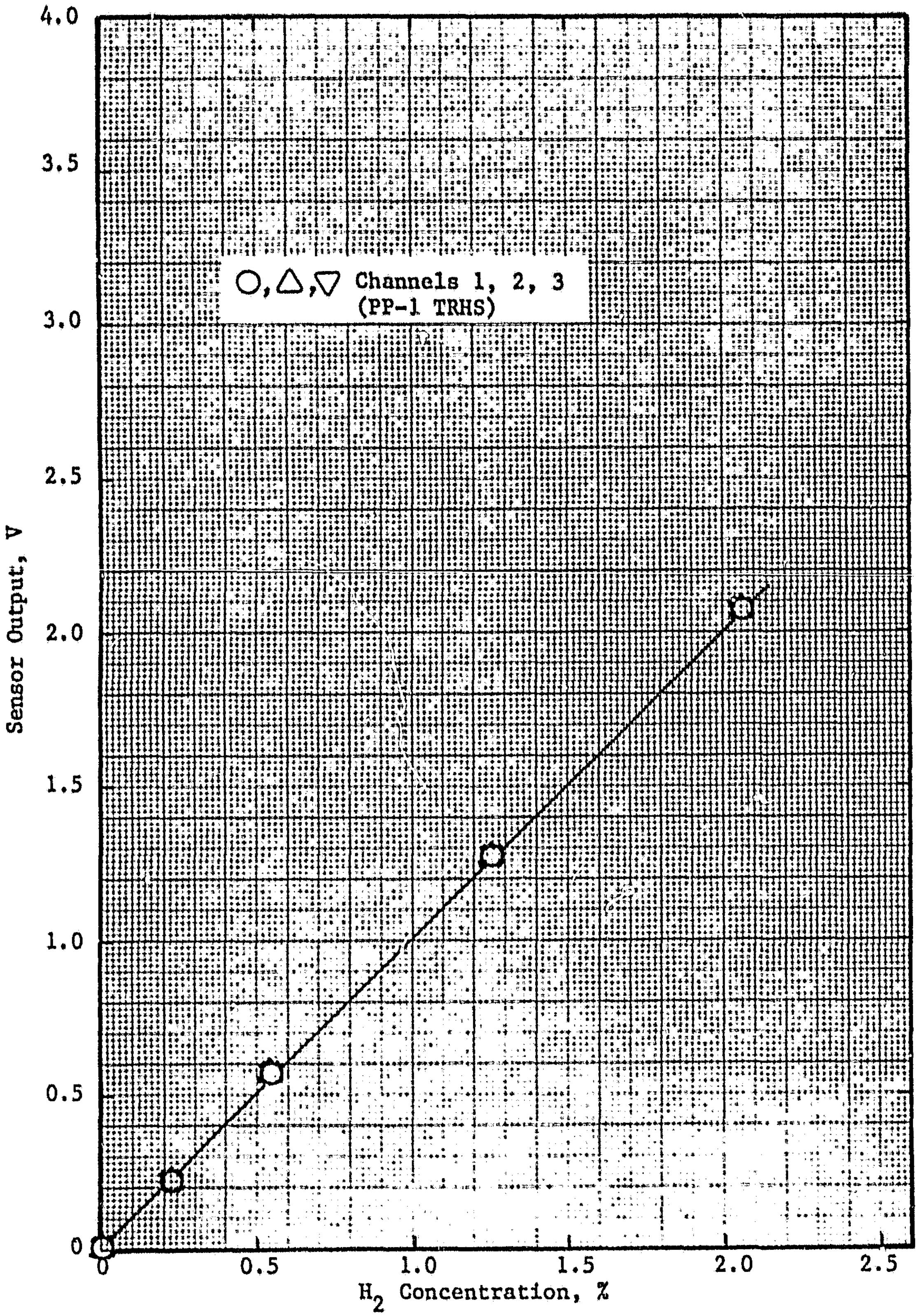


FIGURE 6 TRHS CALIBRATION CURVES (PP-1 TRHS)

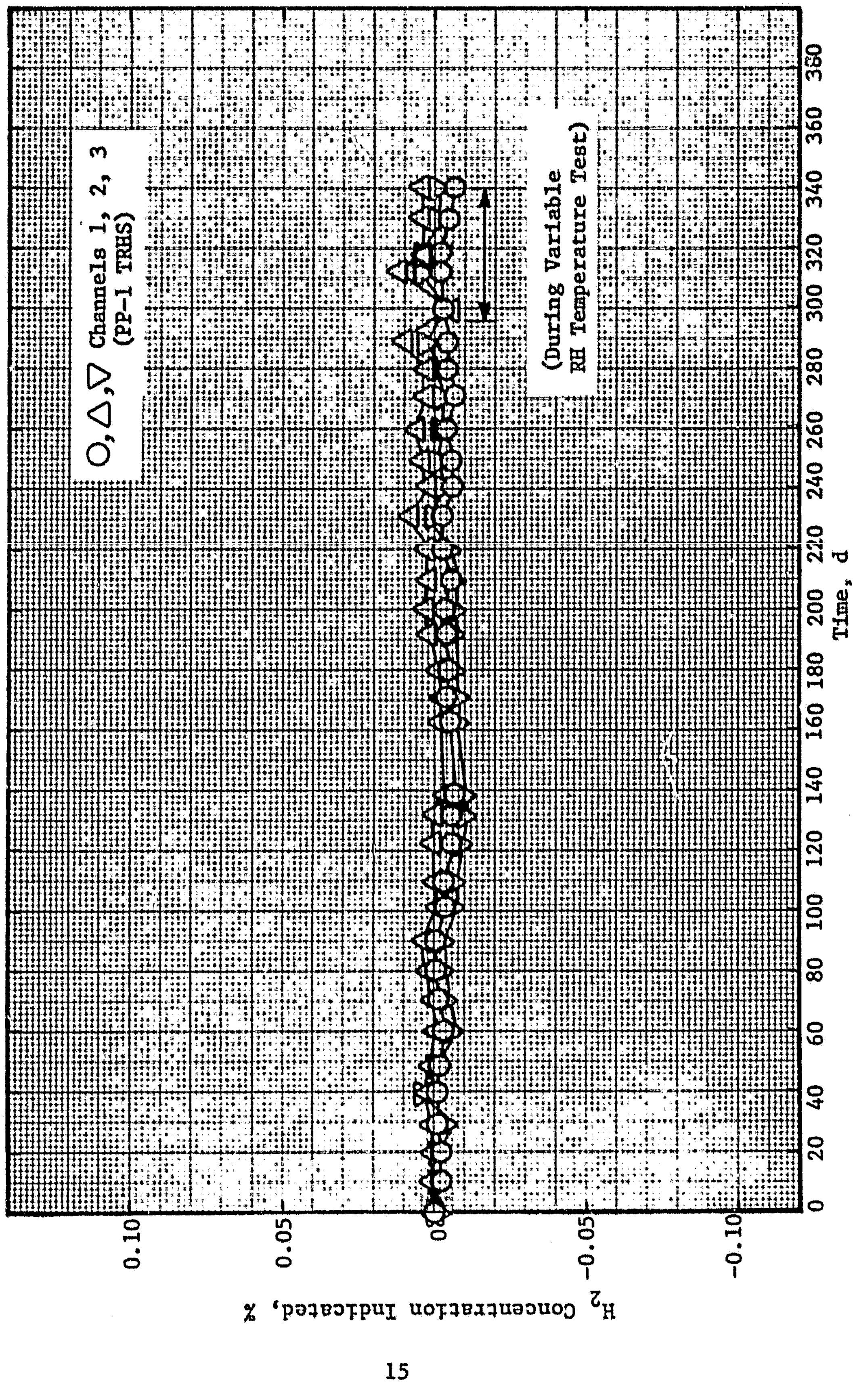


FIGURE 7 SENSOR BASELINE STABILITY

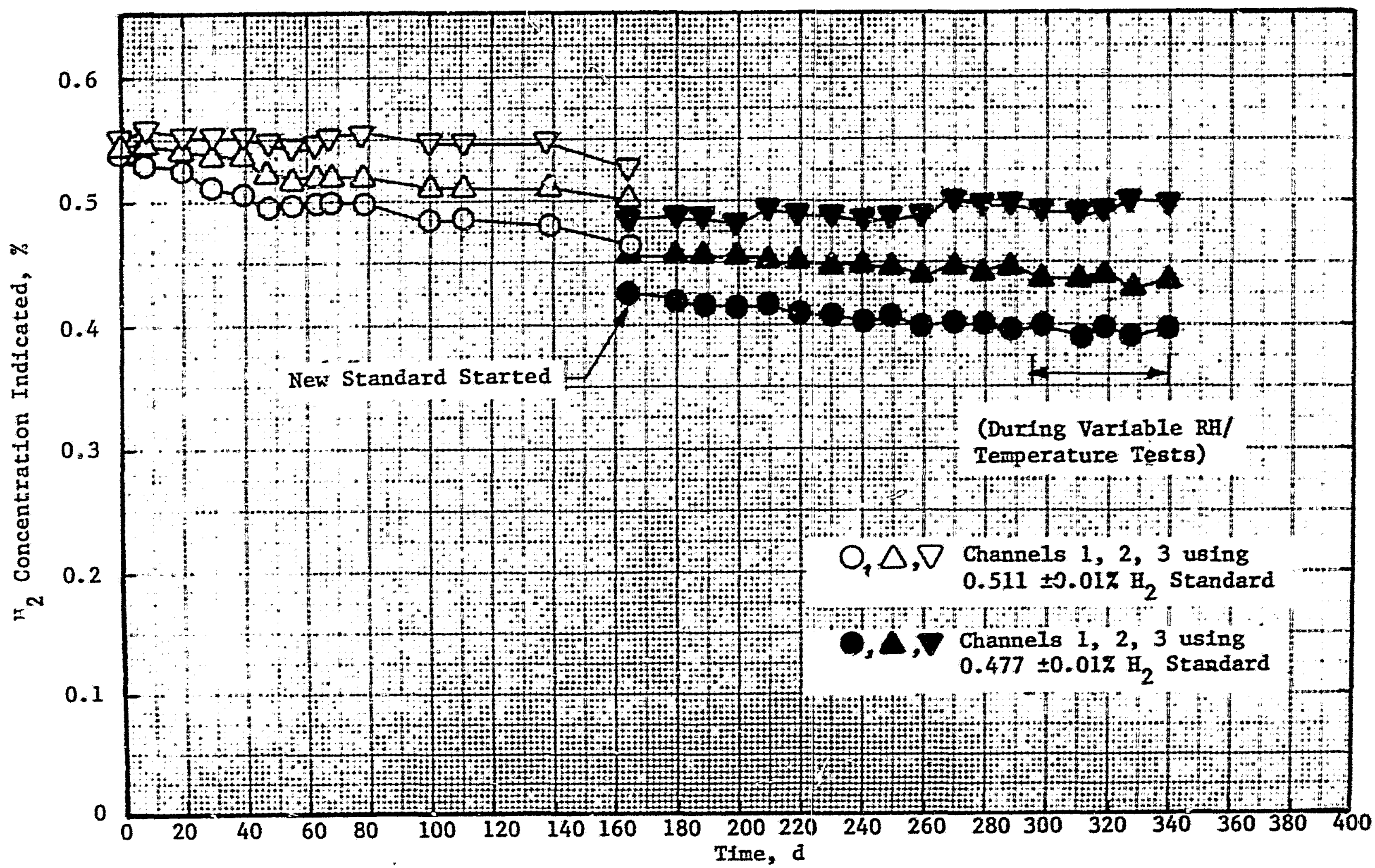


FIGURE 8 SENSOR SPAN CALIBRATION STABILITY (PP-1 TRHS)

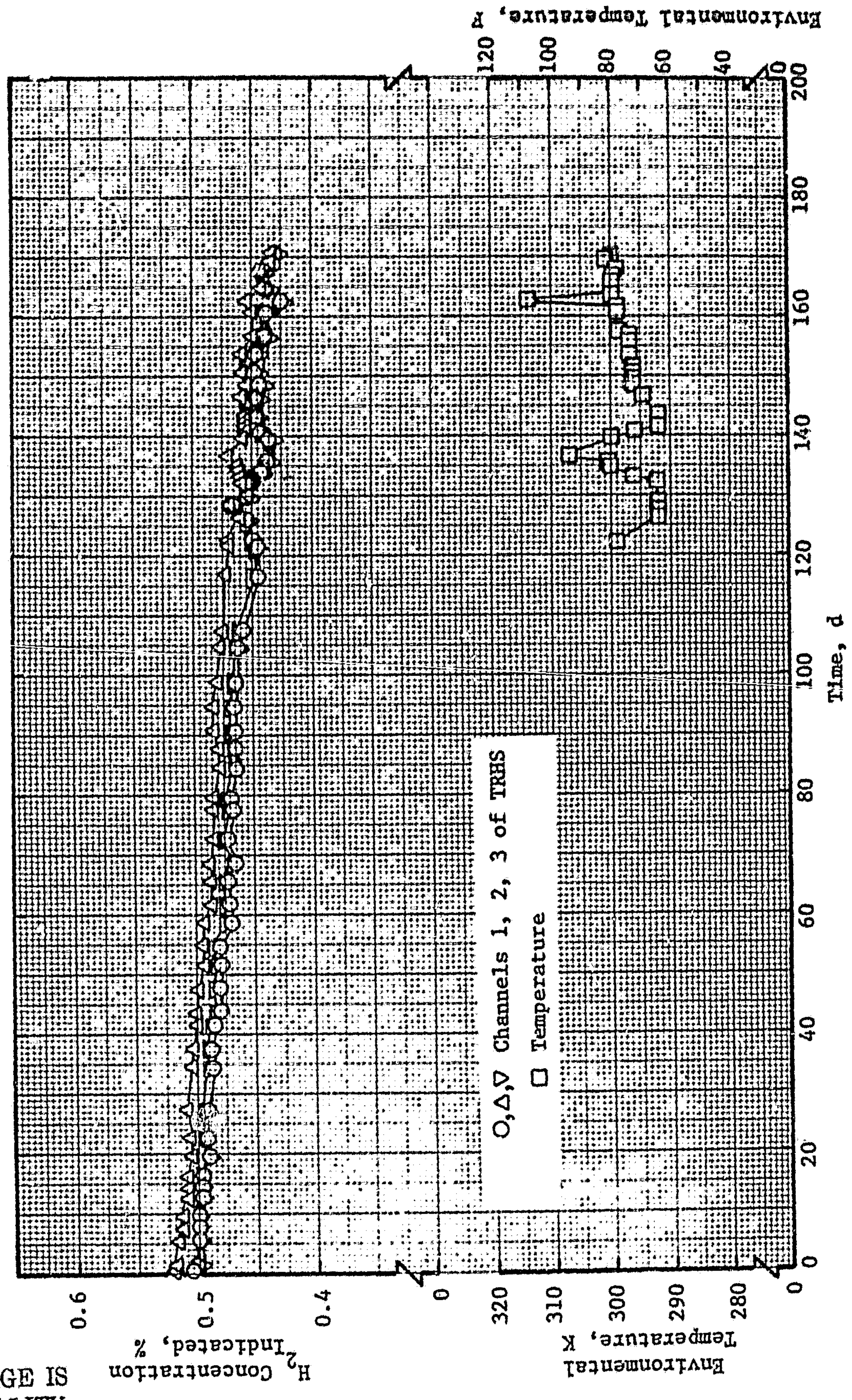


FIGURE 9 SENSOR SPAN CALIBRATION STABILITY (PP-2 TRHS)

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Temperature Effects

Variations in environmental temperature over the range of 291 to 316 K (64 to 109 F) had little effect on detector calibration, as shown in Figure 9. A worst case temperature sensitivity was only 0.0009% H_2/K (0.0005% H_2/F). Therefore, spacecraft protection will not be deteriorated by cabin temperature variations.

Position Sensitivity

Figures 10 through 13 show that the TRHS exhibited essentially no position sensitivity when rotated about both axes. This position insensitivity contrasts sharply with the position sensitivity exhibited by at least one commercial combustible gas detector. (The apparent slight radial position sensitivity in 0.5% H_2 is believed to be due to known inhomogeneities in the test chamber atmosphere due to purge flow direction, not to actual position sensitivity.)[a] It is therefore projected that zero gravity will not affect sensor performance.

In Situ Calibration Characteristics

The effects of various environmental parameters on the in situ calibration plateaus were evaluated to determine the suitability of this technique for spacecraft application.

Calibration Plateau Repeatability

The usefulness of the in situ calibration technology will be limited by the repeatability of the calibration plateaus. Repeatability of in situ calibration plateaus was therefore examined as shown in Figure 14. Despite the limitations of manual readings during the experiment and relative humidity variations in the 40 to 56% RH range, the in situ calibration plateaus for the TRHS sensor head were repeatable: within ±0.02% H_2 over a three month period (days 8 to 100).

Relative Humidity/Temperature Effects

The relative humidity (RH) and temperature of a spacecraft cabin environment will vary over the window outlined in Figure 15. The WVE cell in the TRHS generates H_2 from water vapor absorbed in the electrolyte. The amount of water available in the electrolyte will vary with the dew point and temperature of the surrounding air, which combine to determine the relative humidity. Therefore, it was necessary to determine the effects of these two parameters on the in situ calibration plateau. The PP-2 TRHS was evaluated at the points indicated on Figure 15.

Prior to performing these experiments, the dimensional tolerances of the WVE cell housing (Figure 5) were modified to improve sealing and stacking of the electrode sandwich under the influence of variable relative humidity conditions.

(a) Recent Internal Research and Development (IRAD) tests in an essentially still 0.5% H_2 atmosphere have confirmed that radial response position sensitivity is negligible.

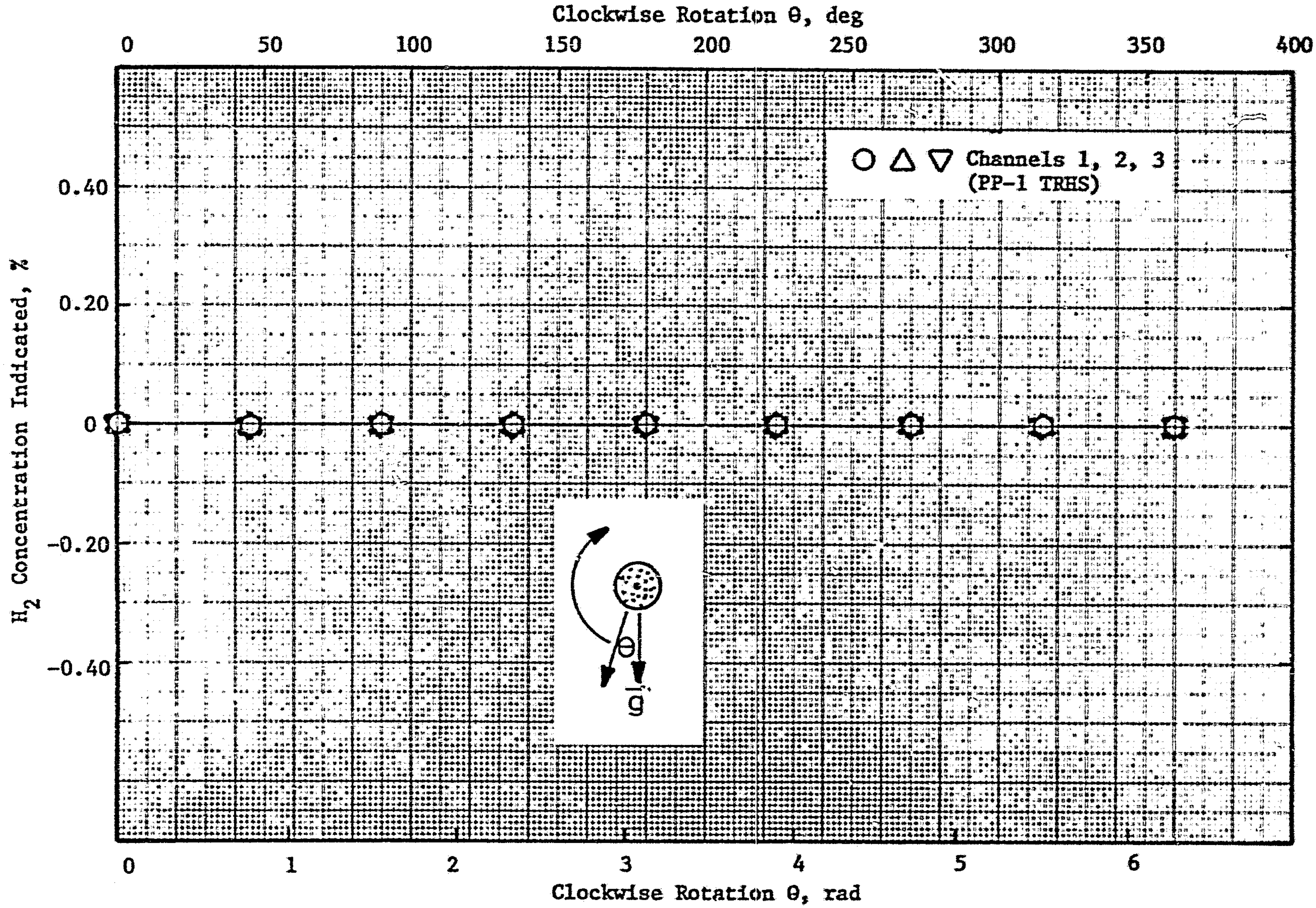


FIGURE 10 TRHS AXIAL POSITION SENSITIVITY IN AIR

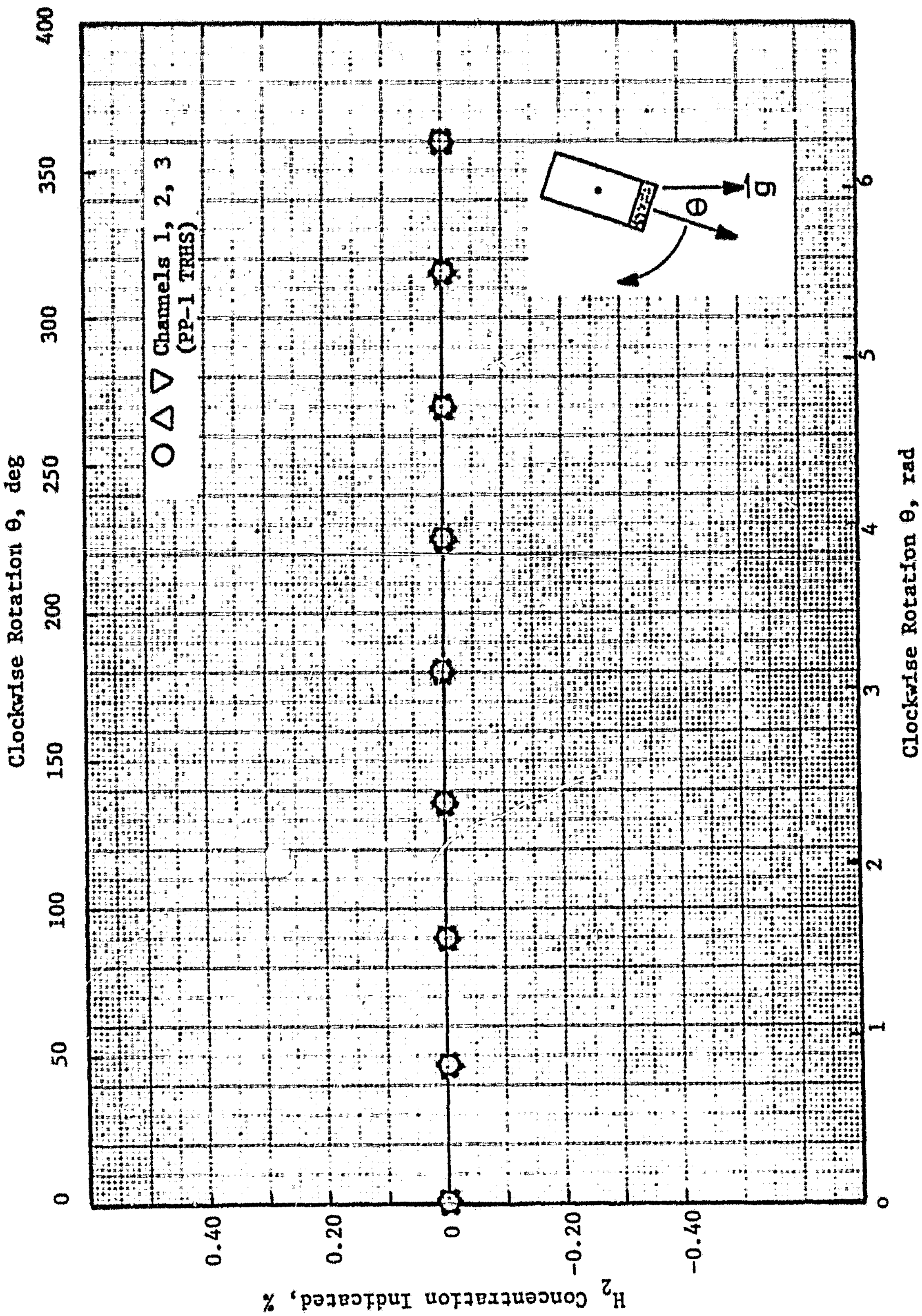


FIGURE 11 TRHS RADIAL POSITION SENSITIVITY IN AIR

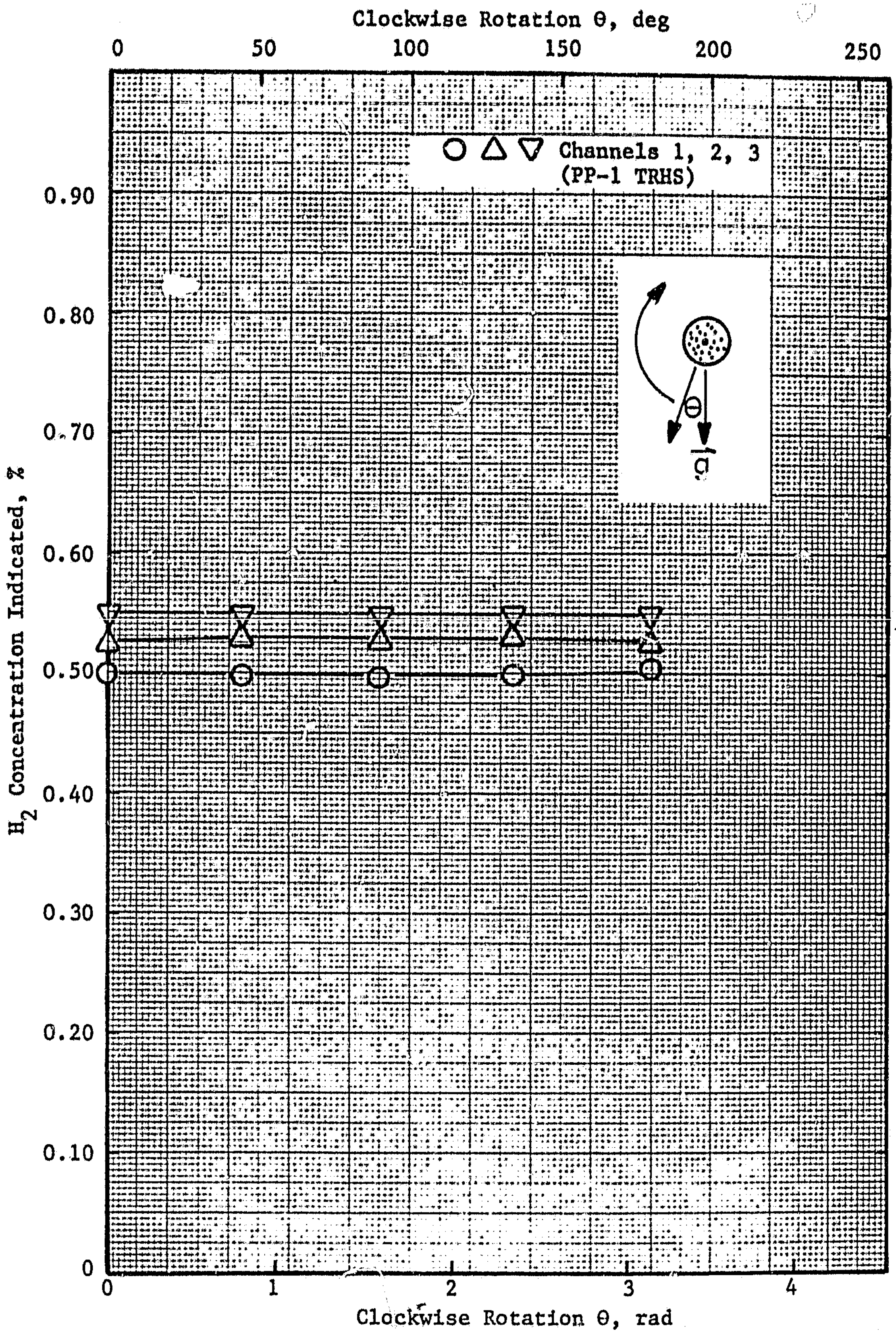


FIGURE 12 TRHS AXIAL POSITION SENSITIVITY IN 0.5% H_2

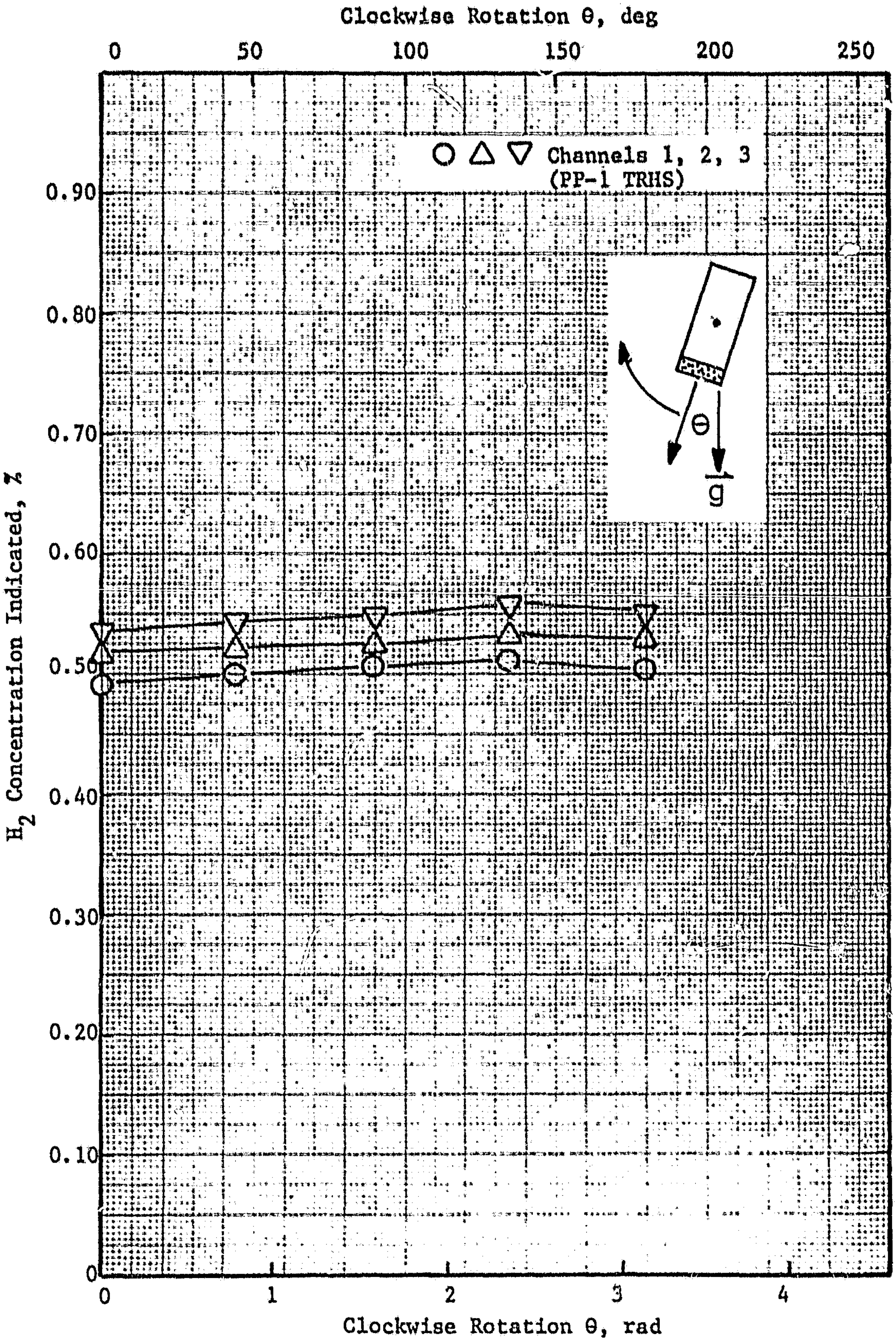


FIGURE 13 TRHS RADIAL POSITION SENSITIVITY IN 0.5% H_2

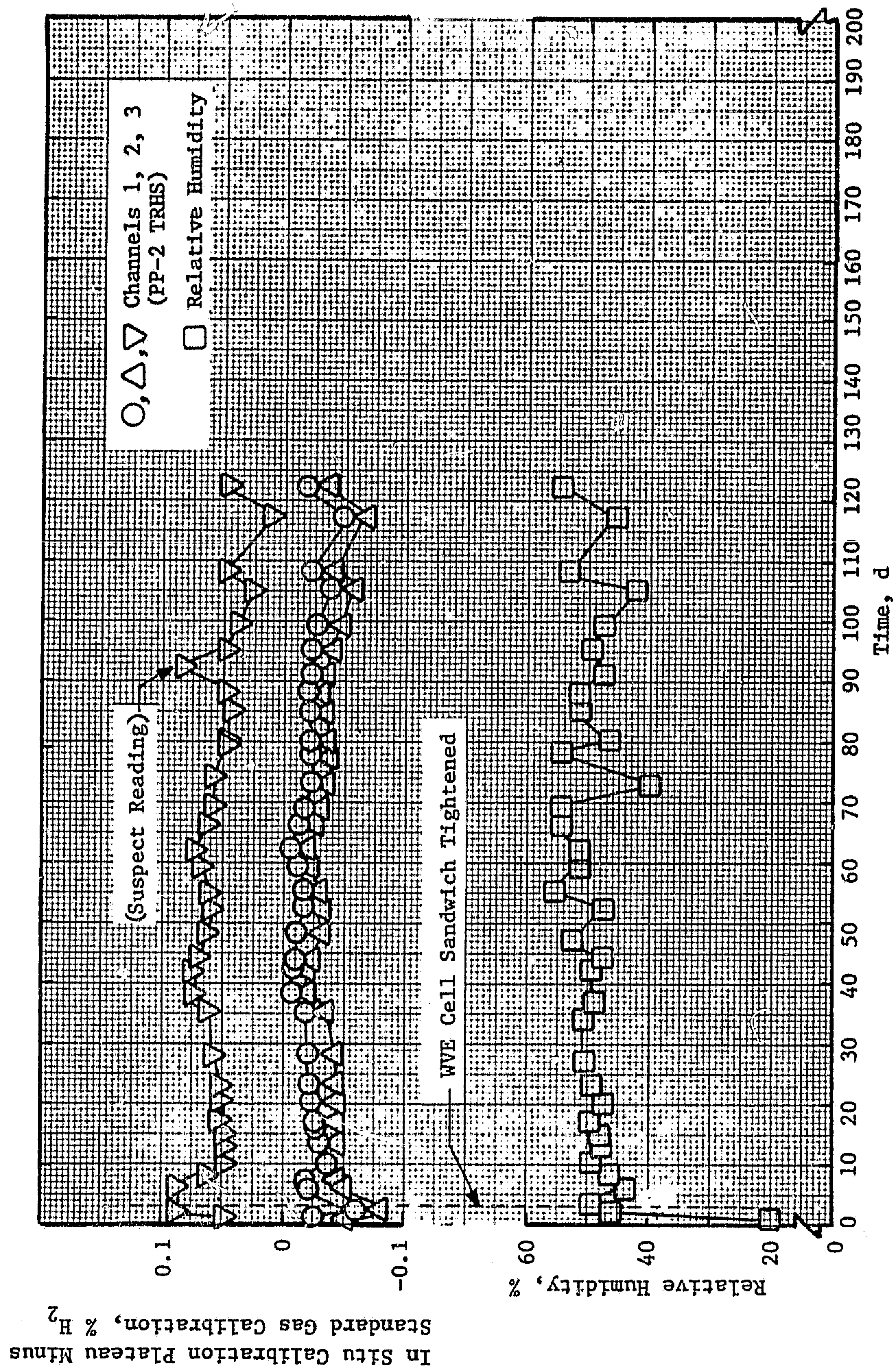


FIGURE 14 IN SITU CALIBRATION PLATEAU REPEATABILITY

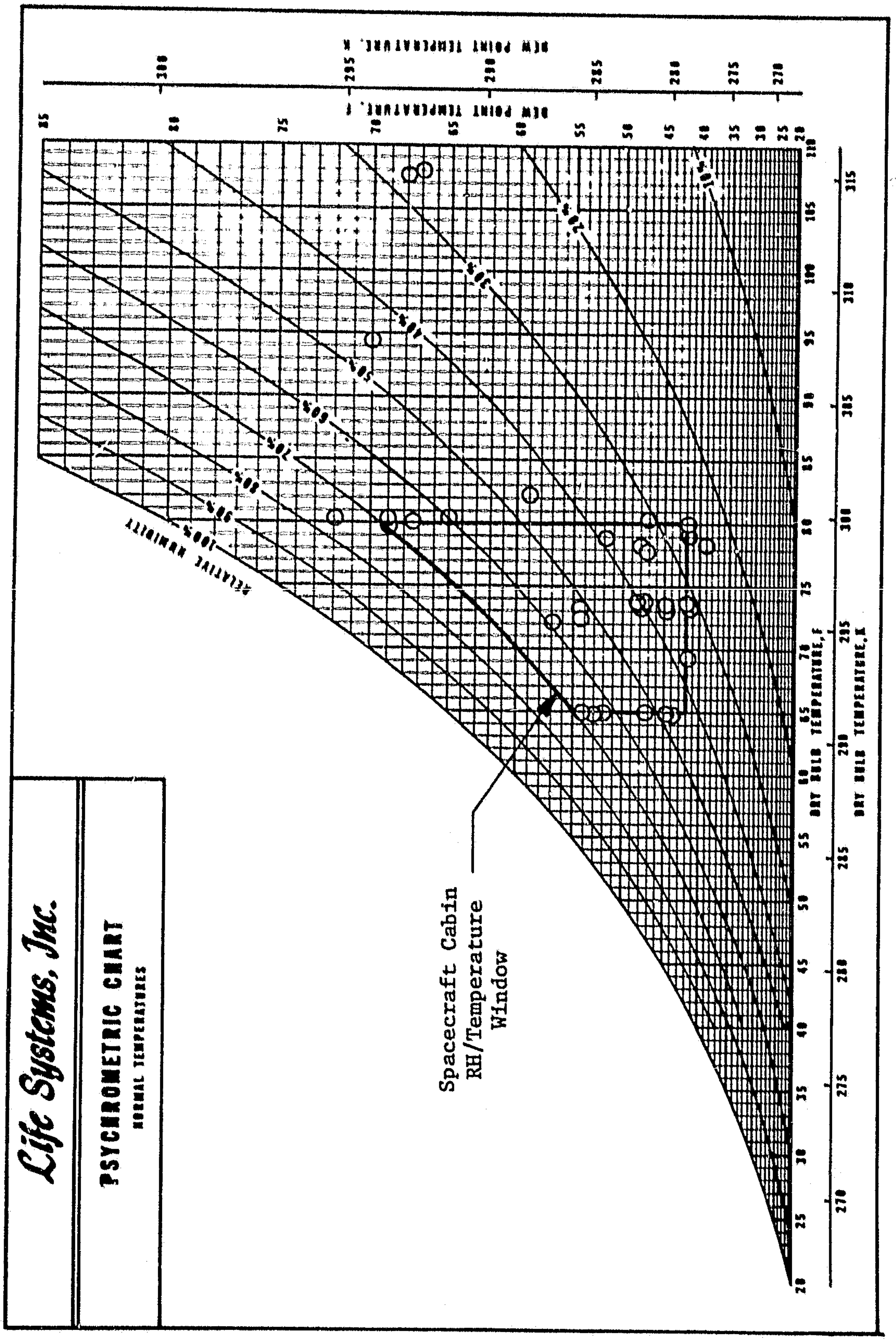


FIGURE 15 RH/TEMPERATURE IN SITU CALIBRATION TEST POINTS VERSUS SPACECRAFT RH/TEMPERATURE WINDOW

Relative Humidity Effects. The effect of variable relative humidity at various temperatures within the spacecraft environmental window are shown in Figure 16. An in situ calibration consistency of ±0.04% was restricted to portions of the window above 38% relative humidity.

However, the anode of the WVE cell was observed to have some curvature, presumably due to inadequate support at the center. It was believed that some loss of anode/matrix contact occurred at low RH due to shrinkage of electrolyte, resulting in inadequate H_2 generation or H_2 leakage and low in situ calibration plateaus.

As a result of these findings, the TRHS in situ calibration plateaus were re-evaluated following implementation of a temporary support that made anode contact with the electrode sandwich more uniformly flat. The results of these tests, in Figure 17, show that ±0.06% in situ calibration plateau consistency can be obtained over virtually the full spacecraft relative humidity/temperature window. This is well within NASA's requirement for a ±10% full scale accuracy (±0.2% H_2 for a 2% linear calibration range). It is believed that this accuracy can be improved with further WVE cell development, since it is not limited fundamentally.

Temperature Effects. No independent temperature effect on in situ calibration plateaus is obvious in Figures 16 and 17, even though the temperature varied between 291 and 315 K (65 and 108 F) (see Figure 15). It was therefore tentatively concluded that an in situ calibration will not be significantly dependent of spacecraft cabin temperature at constant relative humidity.

Position Sensitivity

Because of zero gravity conditions in spacecraft, it is important that the in situ calibration not be position sensitive. Therefore, an experiment was performed in which the sensor head was qualitatively moved into a variety of positions during an in situ calibration plateau. The effects of the sensor positions were nearly insignificant. It is therefore concluded that the in situ calibration is unlikely to be affected significantly by operation in zero gravity.[a]

Draft Sensitivity

The in situ calibration must be performed while nearby spacecraft H_2 using/generating systems are operational. In fact, forced convection may be used around such systems to ensure that combustible gas pockets do not accumulate. Consequently, it was important to evaluate whether air velocity had significant effect on the in situ calibration plateau. It was observed, qualitatively, that variations in air velocity had little effect on the in situ calibration plateaus even when pointing a small blower point blank at the flame arrestor of the TRHS sensor head. It is therefore concluded that the TRHS in situ calibration is essentially draft insensitive.

(a) Recent IRAD tests with an automatically calibrating TRHS subsystem have confirmed that the position sensitivity of the in situ calibration is negligible.

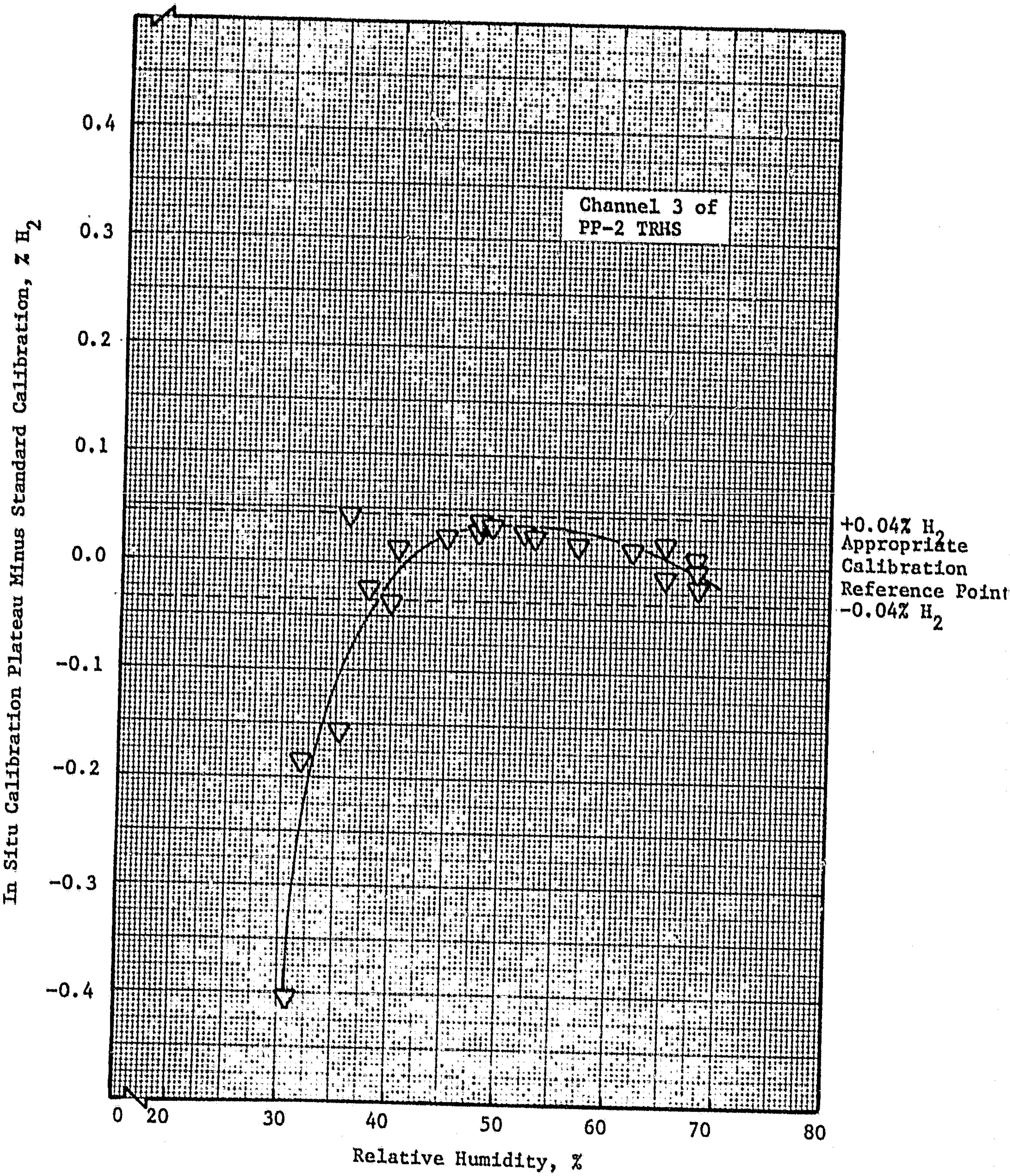


FIGURE 16 EFFECT OF RELATIVE HUMIDITY ON CALIBRATION PLATEAUS

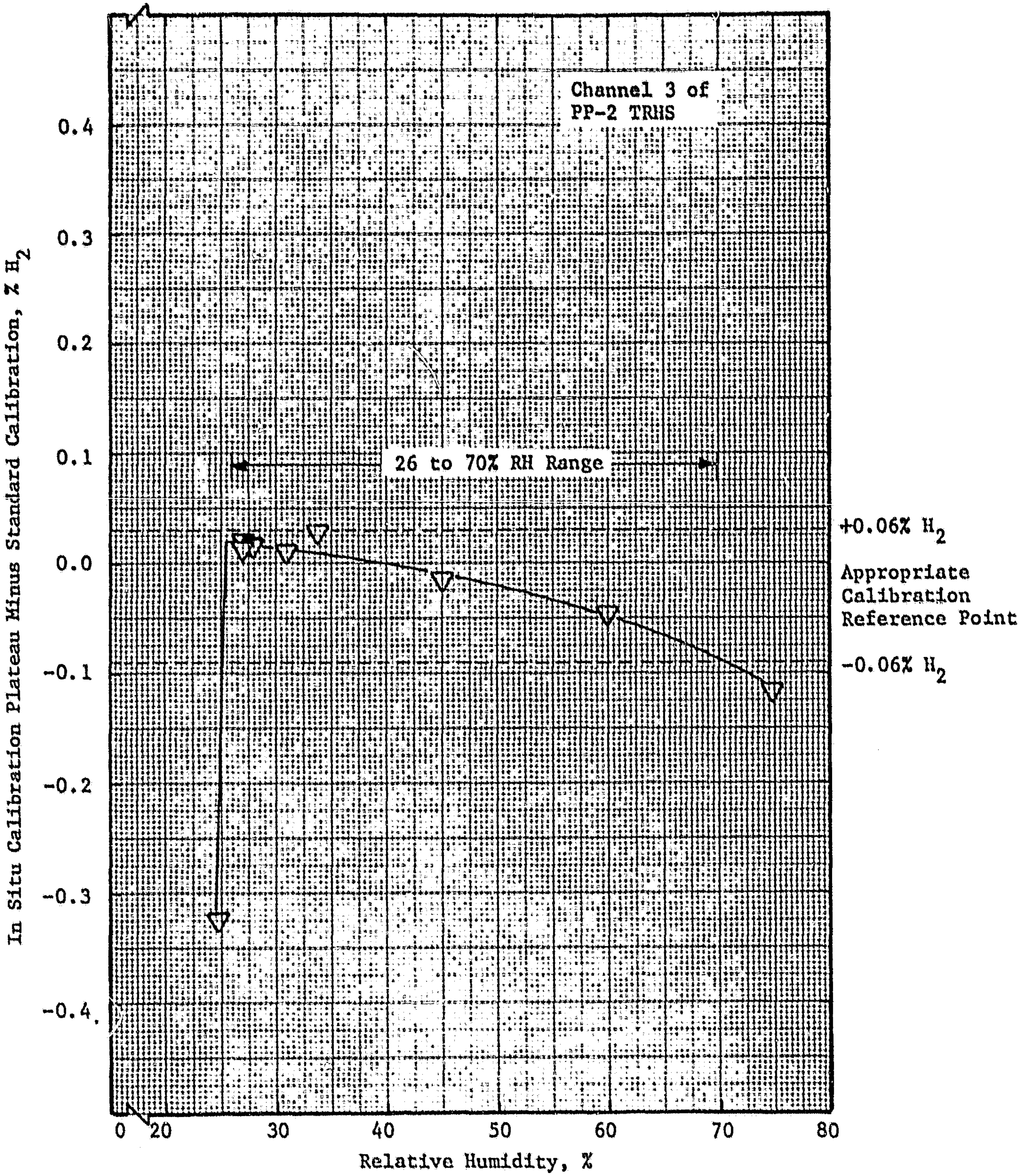


FIGURE 17 EFFECT OF RELATIVE HUMIDITY ON CALIBRATION PLATEAUS AFTER IMPROVED ANODE SUPPORT

Background Zeroing

It is possible that very small (permissible) background H_2 concentrations will sometimes be detected in the vicinity of spacecraft H_2 using/generating subsystems. Experiments showed that sensor outputs due to such backgrounds will add directly to, and interfere with, the in situ calibration plateaus. Therefore, a concept for electronically subtracting this influence prior to the in situ calibration was developed (Figure 3). Initially, prior to establishment of extreme TRHS baseline stability, purging of the TRHS sensor head of background H_2 with O_2 generated by the WVE (reverse polarity) was investigated (unsuccessfully) to enable the electronics to distinguish between instrument baseline drift and background. Since essentially no baseline drift occurs, purging will be unnecessary.

TRHS SUBSYSTEM DEVELOPMENT

Following successful evaluation of the TRHS sensor head, a TRHS Subsystem was developed to integrate this device with fully automatic signal conditioning, failure mode detection/isolation and in situ calibration instrumentation.

Subsystem Design

The autocalibrating TRHS subsystem is defined in Figure 18. The basic TRHS sensor head was developed previously. The designs for the Hydrogen Gas Monitor (HGM) and Hydrogen Sensor Calibrator (HSC) were based on the operational requirements of the TRHS sensor head for signal conditioning, fault analysis, in situ hydrogen atmosphere generation and automatic calibration adjustments. The general design specifications for Subsystem development are listed in Tables 3 and 4.

Subsystem Hardware Description

The complete TRHS Subsystem is shown in Figure 19. The individual components are described functionally below.

Sensor Head

The sensor head is essentially the same as described for the prior TRHS sensor head evaluations. However, based on the results of those evaluations, a perforated reinforcement disk has been added to promote uniform pressure over the anode surface.

Hydrogen Gas Monitor

The HGM is a complete triply redundant sensor system with signal conditioning, fault detection/isolation, multilevel alarm and shutdown logic and an integral H_2 concentration readout. It can be operated independently of the HSC if automatic calibration is not needed.

This device functions as shown in the HGM block diagram, Figure 20. All three redundant sensor signals are converted independently into three (normally) equivalent outputs (numbered 1, 2 and 3) by the Triple Redundant Signal Conditioning. These primary outputs are perpetually compared with each other by Fault Detection and Isolation Logic, which:

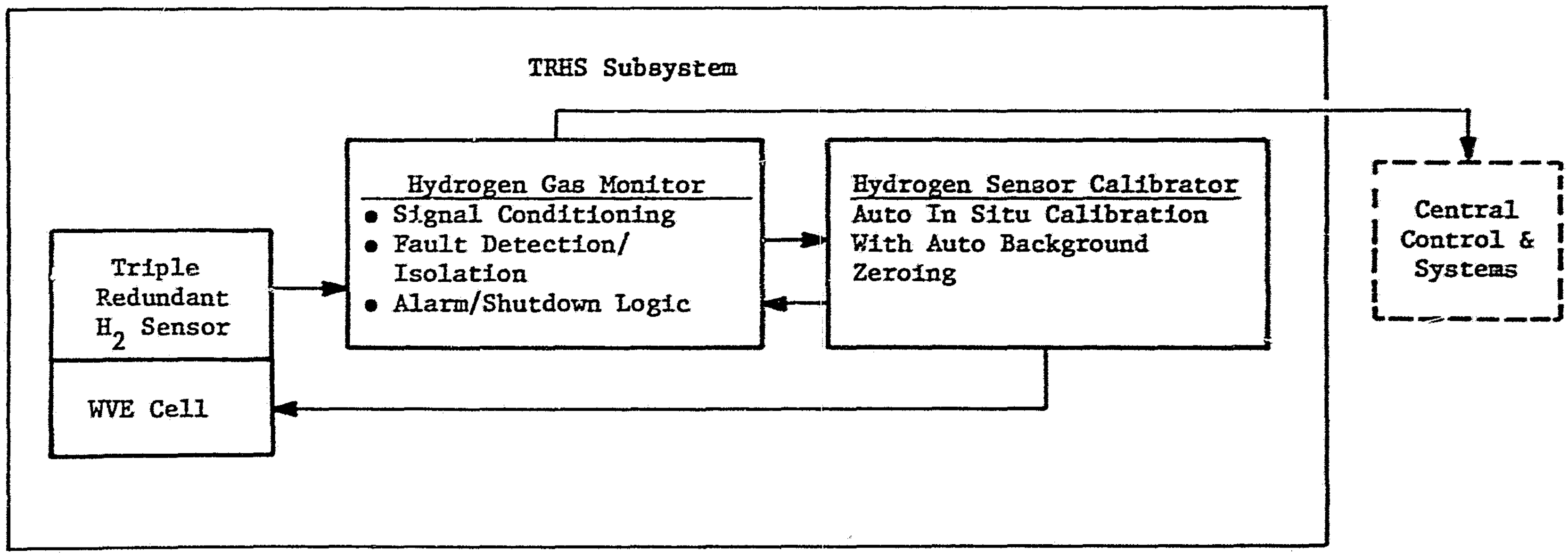


FIGURE 18 TRHS SUBSYSTEM BLOCK DIAGRAM

TABLE 3 TRHS SUBSYSTEM DESIGN GOALS

Range, % H_2-in-air	0 to 2
Stability, % H_2/mo.	
Baseline	±0.003
Span (at 0.5% H_2)	±0.02
Linearity, % FS	±2
Position Sensitivity, % FS	±1
Speed of Response Goal[a] (2% H_2-in-air), s	<5
Recovery Time Goal[a] (after exposure to full scale), s	<30
In Situ Calibration Tolerance, % Full Scale	±10

(a) 90% of final reading.

TABLE 4 WVE OPERATING CHARACTERISTICS
FOR IN SITU H_2 GENERATION

H_2 Calibration Concentration	0.5% H_2-in-air
H_2 Generation Time, s	90
WVE Cell Active Area, cm^2 (in^2)	5.9 (0.92)
WVE Cell Operating Current Density, mA/cm^2 (A/ft^2)	3.3 (3.1)
Expected WVE Cell Voltage, V	1.6
Cabin Atmosphere Relative Humidity, %	26 to 70

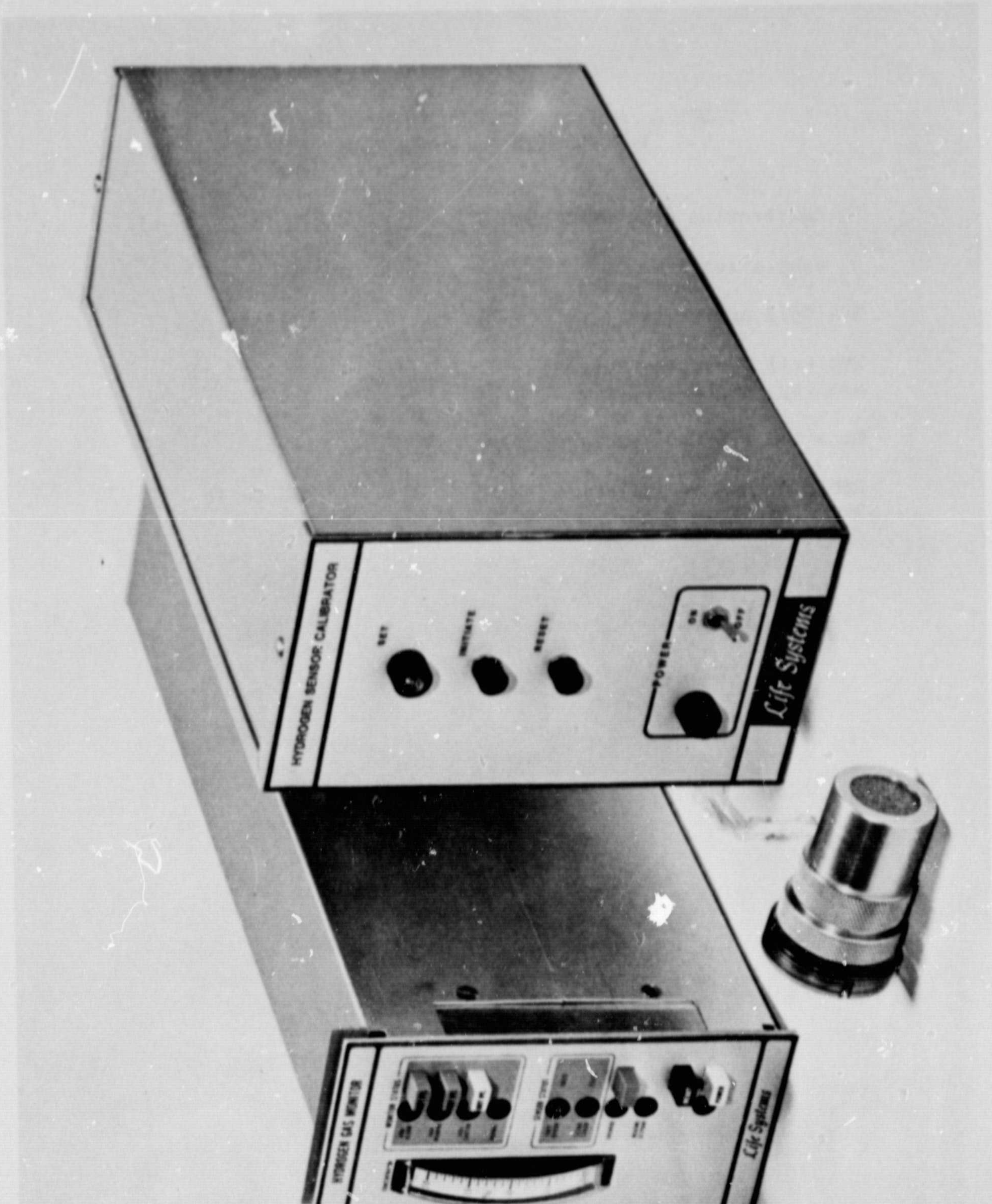
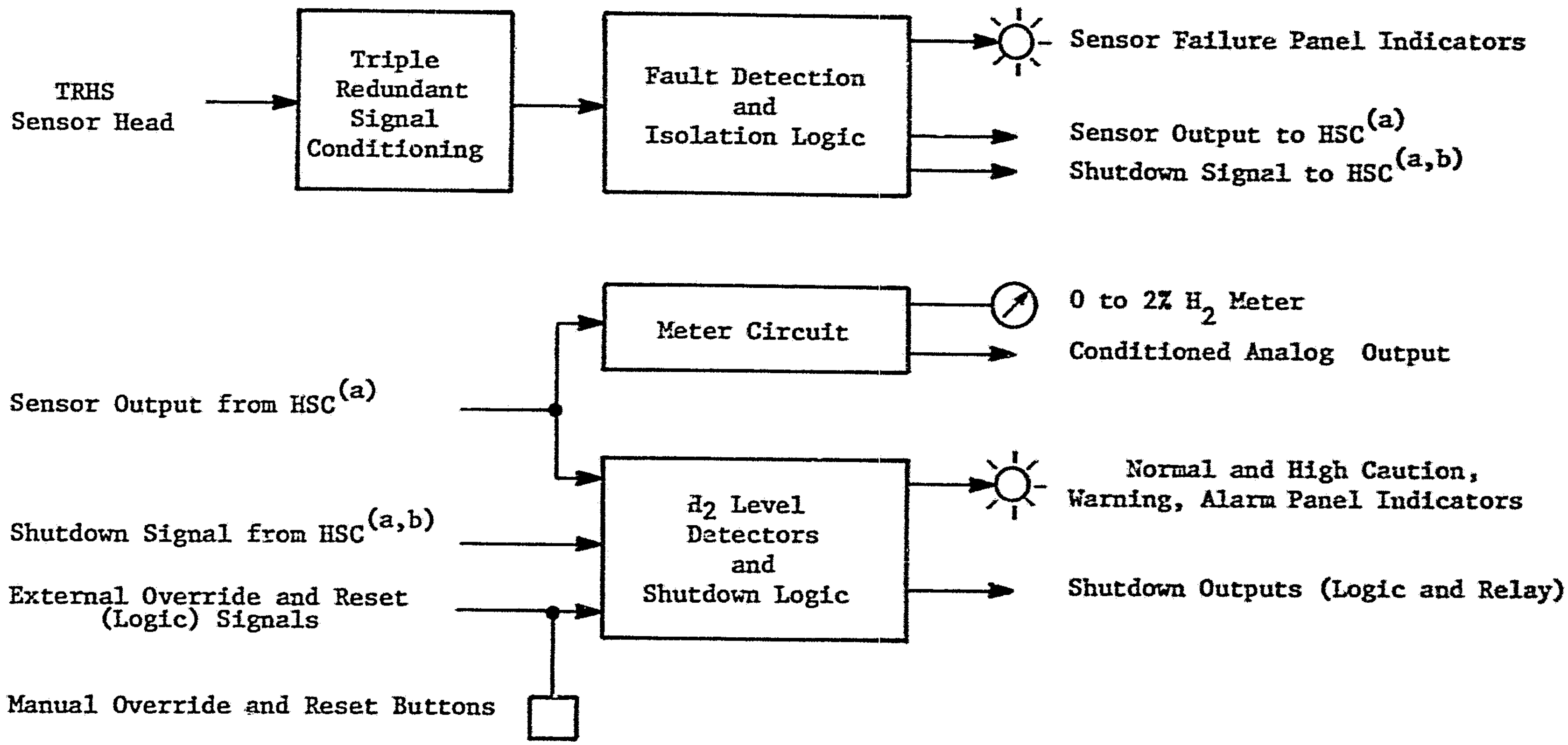


FIGURE 19 TRHS SUBSYSTEM



(a) HSC is bypassed for HGM-only subsystem (output connections and shutdown connections are jumpered).
(b) Use optional.

FIGURE 20 HYDROGEN GAS MONITOR BLOCK DIAGRAM

- Activates and optionally latches "First Sensor Failed" and "Second Sensor Failed" warning lamps if one or two of the sensors, respectively, disagrees with the others.
- Selects a single sensor (normally number 1) for output and automatically replaces it with one of the remaining sensors if it fails (optionally latching).
- Activates and optionally latches a shutdown signal (use optional) if a reliable sensor can no longer be identified ("Second Sensor Failed").

The selected H_2 sensor output is further conditioned for both meter and recorder (analog) readout through a Meter Circuit. This output is also compared with selected setpoints in the H_2 Level Detectors and Shutdown Logic to activate caution, warning and alarm panel indicators at various H_2 concentrations, corresponding to various levels of combustible gas hazard. A shutdown is activated when an alarm H_2 concentration is reached or if either the Fault Detection and Isolation Logic or (optionally) the Fail-to-Calibrate Shutdown Logic of the HSC (Figure 21) indicates a shutdown condition. Latched shutdowns and panel indicators can be reset or perpetually overidden by applying a momentary or constant logic signal to this circuit, respectively, or by depression of reset or override buttons, respectively, on the instrumentation panel.

Hydrogen Sensor Calibrator

The HSC automatically recalibrates the TRHS by electronically amplifying or attenuating the manually calibrated HGM output to correspond to a known, in situ generated H_2/air atomosphere. This in situ calibration is performed as described in Figure 21.

Upon manual activation or upon command from the timers (nominally every 24 hours) the autocalibrated sensor output to the HGM is temporarily frozen by the Analog Storage Circuit (to prevent disturbance of the HGM outputs and level detectors during calibration), and a new in situ calibration begins. The timers and sequencers initiate auto zeroing of the sensor output from the HGM, to eliminate H_2 background effects, and cause the current/voltage controller to produce the preplateau and plateau (see Figure 2). The plateau continues for a fixed time, after which the gain of the Automatically Controlled Amplifier is electronically readjusted, as required, to make the output from the HGM conform to the plateau atmosphere (0.5% H_2). After returning to idle conditions (Figure 2) and a brief recovery period, the autocalibrated ouput to the HGM is restored and normal subsystem monitoring resumes.

In the unlikely event that the calibration adjustment exceeds the range of the Automatically Controlled Amplifier, Fail-to-Calibrate Shutdown Logic triggers the shutdown output of the HGM to be activated (user option).

Operation

Hookup

The HGM and HSC are interconnected by means of terminal boards located at the rear of the two instrumentation packages. The TRHS sensor head interfaces

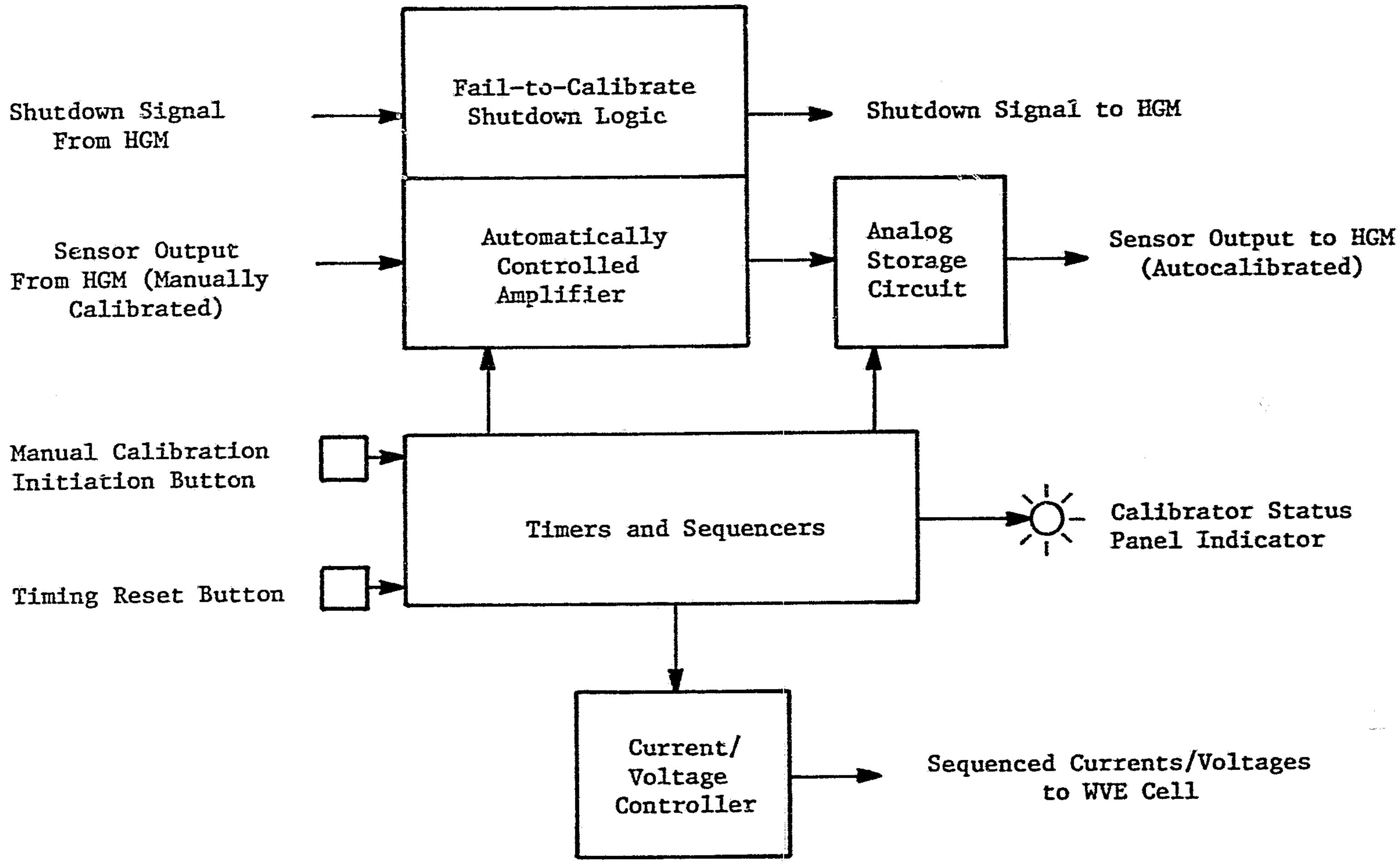


FIGURE 21 HYDROGEN SENSOR CALIBRATOR BLOCK DIAGRAM

directly with the terminal boards of the HGM and HSC with fanning terminal strips. The interconnections between the three subsystem components are described in Tables 5 and 6.

HGM Operation

Controls. The various control actions of the HGM have been described in the previous subsection (Figure 20 and subsequent discussion). These functions are defined specifically in terms of the HGM front panel controls in Table 7.

Manual Calibration. The HGM will have been manually zeroed and calibrated by the manufacturer prior to shipment. The zero adjustment should not require resetting. Also, because the HGM and HSC are supplied to NASA as a complete subsystem, all future calibrations will be performed automatically by the HSC, and no manual calibrations will be subsequently required.

Nonetheless the HGM can be manually recalibrated if it is ever connected as an independent unit (see Figure 20 and Table 5). The calibration is performed by providing a standard calibration gas atmosphere around the TRHS sensor head and adjusting the span potentiometer, R4, at the top edge of each of the three redundant signal conditioning boards, P/N 3, such that the front panel meter reading agrees with the H_2 concentration in the standard atmosphere. The P/N 3 signal conditioning boards for sensors 1, 2 and 3 correspond to sockets J15, J16 and J17 on the mother board, respectively. The front panel meter reading corresponds to the output of one sensor at a time, which can be manually selected with the DIP switch on PC board P/N 40 (mother board socket No. J10). When the lever 1 of the switch is forward (others back) sensor No. 1 is selected. Sensors 2 or 3 are selected similarly. When lever 4 is forward, the normal operating position, sensor No. 1 is replaced automatically should it fail.

HSC Operation

Controls. The operation of the HSC has been described previously in Figure 21. Operation of the instrument is further defined in terms of front panel controls in Table 8.

Autocalibration. The instrument has been setup to automatically recalibrate the HGM output every 24 hours. The nominal time of day in which the calibration starts is selected by depressing the "Reset" button at the time selected for subsequent calibrations. Calibrations will be automatically reinitiated at that time each day until subsequently reset. An in situ autocalibration can also be initiated at other times by depressing the "Initiate" button. It is recommended, however, that in situ calibrations not be initiated more frequently than every eight hours to allow the WVE cell adequate time to reequilibrate.

Subsystem Testing

The objective of the subsystem tests was to manually calibrate the HGM, then to establish that all HGM and HSC subsystem controls and operations were performing properly.

TABLE 5 HGM CONNECTIONS

Terminal Board-Terminal Number	Function
TB101-1	Ground[a]
TB101-2	Ground
TB101-3	External Override/Reset Signal[b]
TB101-4	Optional Shutdown Logic Voltage[b]
TB101-5	Ground
TB101-6	Ground
TB102-1	Sense Thermistor No. 1[c]
TB102-2	Thermistor Common No. 2
TB102-3	Reference Thermistor No. 3
TB102-4	Sense Thermistor No. 4
TB102-5	Thermistor Common No. 5
TB102-6	Reference Thermistor No. 6
TB102-7	Sense Thermistor No. 7
TB102-8	Thermistor Common No. 8
TB102-9	Reference Thermistor No. 9
TB102-10	Ground
TB103-1	Shutdown Out to HSC, TB102-4[d,e]
TB103-2	Shutdown In from HSC, TB102-5[d,e]
TB103-3	Sensor Output to HSC, TB102-2[d]
TB103-4	Sensor Output from HSC, TB102-1[d]
TB103-5	Shutdown Logic Output
TB103-6	Shutdown Relay Output, NO
TB103-7	Shutdown Relay, Output C
TB103-8	Shutdown Relay, Output NC
TB103-9	Conditioned Analog Output +[f]
TB103-10	Conditioned Analog Output -[f]

(a) All grounds identical. One HGM ground must be connected to an HSC ground.
(b) Normally N/C. Permits shutdown outputs other than TTL and CMOS (selected internally). If needed, consult manufacturer.
(c) TRHS terminals (fanning strip).
(d) HSC is bypassed for HGM-only subsystem (output connections and shutdown connections are individually jumpered, TB103-1 to TB103-2 and TB103-3 to TB103-4).
(e) For complete subsystem hookup, if no shutdown due to faulty sensor is desired, leave connection between HGM TB103-1 and HSC TB102-4 open. If no shutdown due to fail-to-calibrate is desired, jumper HGM TB103-1 to HGM TB103-2 (Leave HSC TB102-4 and HSC TB102-5 unconnected). If neither faulty sensor nor fail-to-calibrate shutdowns are desired, leave HGM TB103-1, HSC TB102-4 and HSC TB102-5 open, and jumper HGM TB103-2 to HGM TB101-4.
(f) (Recorder output, 0-5 volts full scale.)

TABLE 6 HSC CONNECTIONS

Terminal Board-Terminal Number	Function
TB101-1	Current to WVE -, Terminal No. 1[a]
TB101-2	Current to WVE +, Terminal No. 2
TB101-3	WVE Voltage Sense -, Terminal No. 3
TB101-4	WVE Voltage Sense +, Terminal No. 4
TB101-5	Ground[b]
TB101-6	Ground
TB102-1	Sensor Output to HGM, TB103-4
TB102-2	Sensor Output from HGM, TB103-3
TB102-3	Ground
TB102-4	Shutdown In from HGM, TB103-1
TB102-5	Shutdown Out to HGM, TB103-2
TB102-6	Ground
TB102-7	N/C
TB102-8	N/C
TB102-9	N/C
TB102-10	N/C

(a) WVE cell terminals on fanning strip. T1 and T2 are jumpered to T3 and T4, respectively, for short wire runs to WVE cell: 2-wire WVE hookup. (For long runs, 4 wire (remote sensing) hookup is used.)
(b) All grounds identical. One HSC ground must be connected to an HGM ground.

TABLE 7 CONTROL FEATURES DEFINITION FOR HYDROGEN GAS MONITOR

Control Feature[(a)]	Function
"Concentration" Meter	Quantitatively displays H_2 concentration.
"Monitor Status"	
• Lamps	Amber, flashing red and red lamps illuminate (latching after 3 seconds) to warn that preset H_2 concentrations, corresponding to three degrees of combustible gas hazard, have been exceeded.[(b)] Green (normal) indicates that no H_2 hazard exists.
• Setpoint Buttons	When button depressed, meter displays the H_2 concentration at which the adjacent status lamp illuminates, permitting observation of caution, warning and alarm setpoints. Does not affect subsystem operation.
"Sensor Status" Lamps	"First Sensor Failed" lamp illuminates when one of the triple redundant sensors does not track the other two within a set tolerance. "Second Sensor Failed" lamp illuminates when a second of the three sensors does not track.[(c)] Both lamps latch (Optional).
"Override" Button and Lamp	Overrides all shutdowns. Also, monitor status lamps normally latch at the highest level observed following detection of a hazardous condition. When "Override" button is depressed current status only is displayed (no latching). Adjacent lamp notifies that Override is in effect.
"Reading Setpoint" Lamp	Notifies operator that meter is indicating a monitor status setpoint, not H_2 concentration.

continued-

(a) (Refer to HGM front panel.)
(b) Shutdown outputs activated when alarm lamp has been illuminated for three seconds.
(c) Shutdown outputs activated (use optional).

Table 7 - continued

Control Feature[a]	Function
"Reset" Button"	Restores latched monitor status, sensor status indicators and automatic sensor selection so that current status only is in force and/or displayed.
"Power" Button and Lamp	Activates and indicates activation of HGM.

(a) (Refer to HGM front panel.)
(b) Shutdown outputs activated when alarm lamp has been illuminated for three seconds.
(c) Shutdown outputs activated (use optional).

TABLE 8 CONTROL FEATURES DEFINITION FOR HYDROGEN SENSOR CALIBRATOR

Control Feature[a]	Function
"Set" Lamp	Always illuminated, except during autocalibration. Shows that the autocalibration adjustment is set and the sensor subsystem is currently responding to H_2 concentrations (WVE in Idle mode). Extinction of lamp indicates that a calibration is occurring.
"Initiate" Button	Depression manually initiates an autocalibration sequence (at any time).
"Reset" Button	Depression resets all timers and fixes the time(s) at which future autocalibration will be automatically initiated.
"Power" Lamp and Switch	Activates and indicates activation of HGM.

(a) Refer to HSC front panel.
(b) Refer to Figure 2.

Test Support Accessories

All tests were performed using Life Systems' TRHS test stand, as described schematically in Figure 22 and pictorially in Figure 23. This test stand provides the capability of maintaining preselected hydrogen concentration, temperature and relative humidity environments for testing of hydrogen sensors.

Checkout Tests

The subsystems based on TRHS heads S/N-01 and S/N-02 were checkout tested to setup the instrument prior to shipment and check basic operational performance. These tests included:

- Electrical verification of all fault detection/isolation and H_2 level detection trip points.
- Conditioning of the H_2 sensing elements in air and H_2/air atmospheres.
- Zeroing of all three sensor channels of each HGM in air and span calibration adjustments of each channel in a 2% H_2 atmosphere.
- Obtaining additional calibration curve points in 0.5% H_2.
- Adjusting HSC conditions, particularly determining the proper plateau current for each sensor head to provide a 0.5% in situ calibration.
- Observing subsystem performance and identifying limitations of the current state-of-the-art.

HGM Calibration Curves. The calibration curves for the two sensor heads supplied to NASA are described in Figures 24 and 25. As for the PP1 and PP2 sensors, good linearity was obtained (worst case deviation of any point from a least squares straight line was 0.01% H_2). This illustrates that the TRHS sensor heads can be manufactured reproducibly.

Level Detectors. The H_2 level detectors were performance checked. Proper detector activation, correct setpoint correspondence of lamp illuminations and the shutdown output and correct latching/reset function were established.

Fault Detection and Isolation Logic. Correct activation and latching of the "first sensor failed" and "second sensor failed" lamps, as well as the second failure shutdown, were established. The circuit performed as designed: the sensor failure indicator illuminated when the preset tolerances were exceeded, redundant sensors replaced "faulty" sensors as required, and shutdown outputs were activated when two sensors "failed."

In Situ Calibration Current Setup. The in situ calibration current of each HSC was set up such that the auto calibrated subsystem output (each HGM channel No. 1) was 0.5 ±0.02% H_2 (48% relative humidity in atmosphere). This was done by first in situ calibrating the sensors at a nominal current setting and then determining the subsystem outputs in a standard 0.5% calibration atmosphere. The currents were then reset to a new values and the in situ calibration/standard gas calibration procedures were repeated. The currents were finally reset to

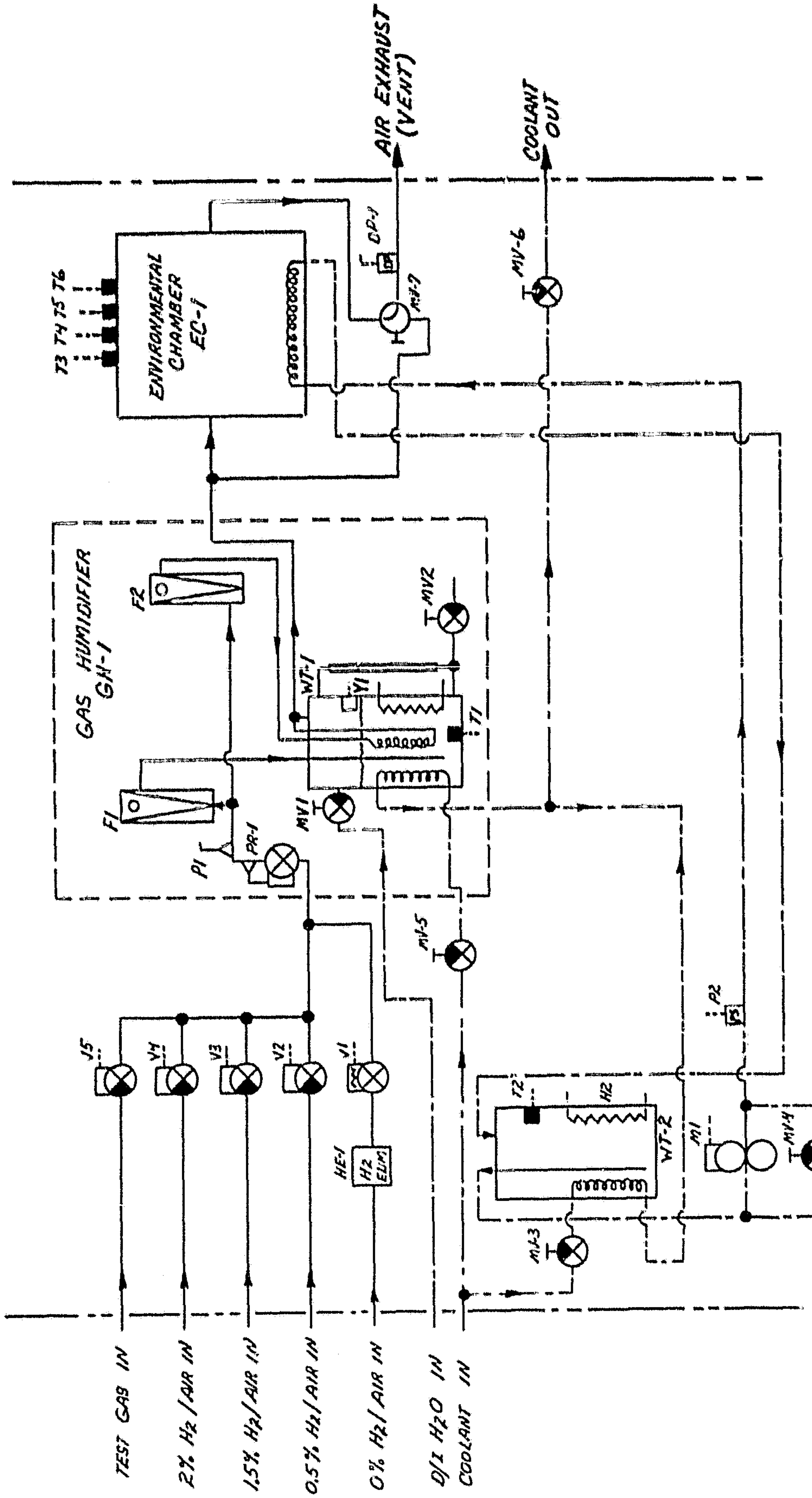


FIGURE 22 TRHS TEST STAND SCHEMATIC

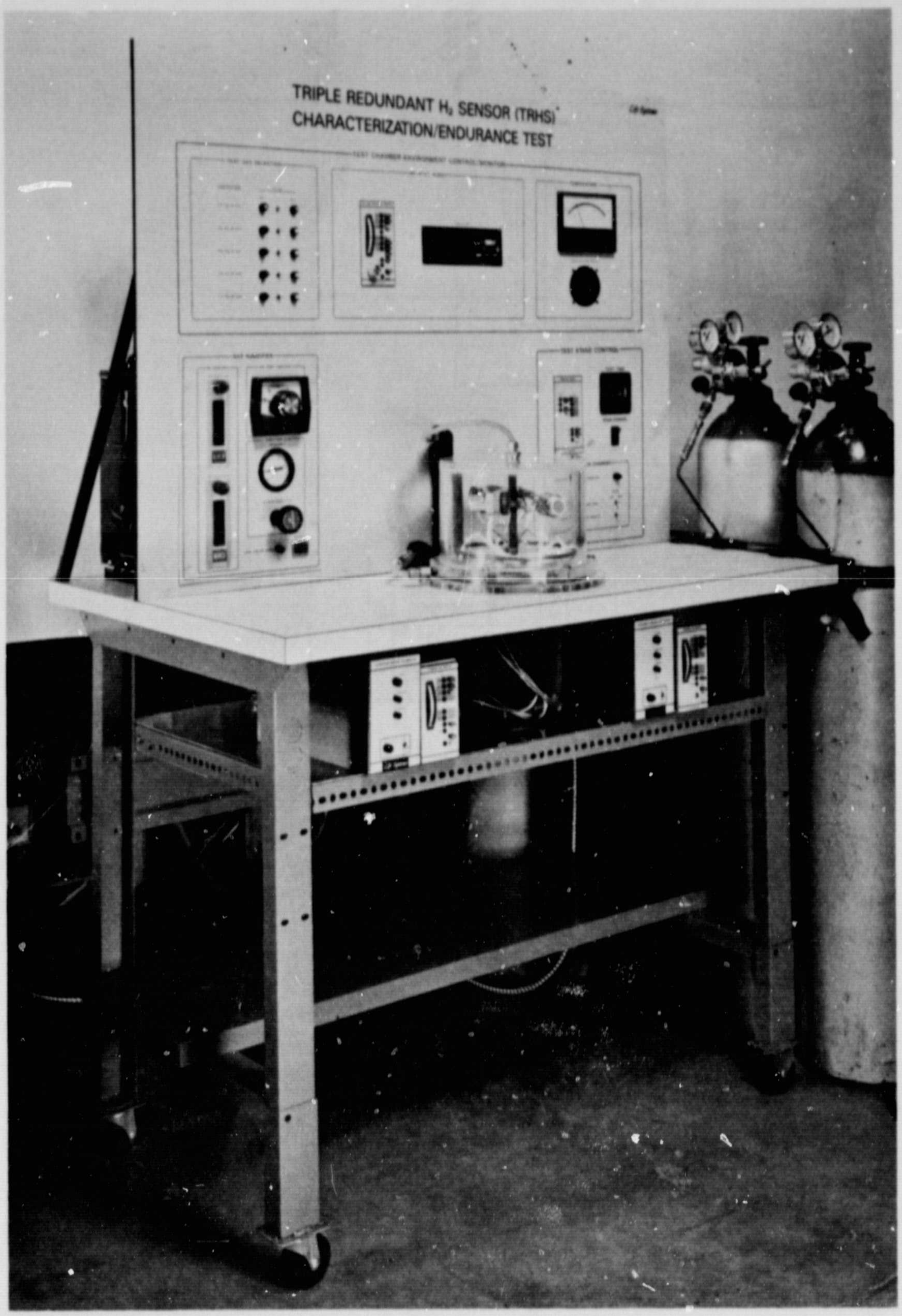


FIGURE 23 TRHS TEST STAND

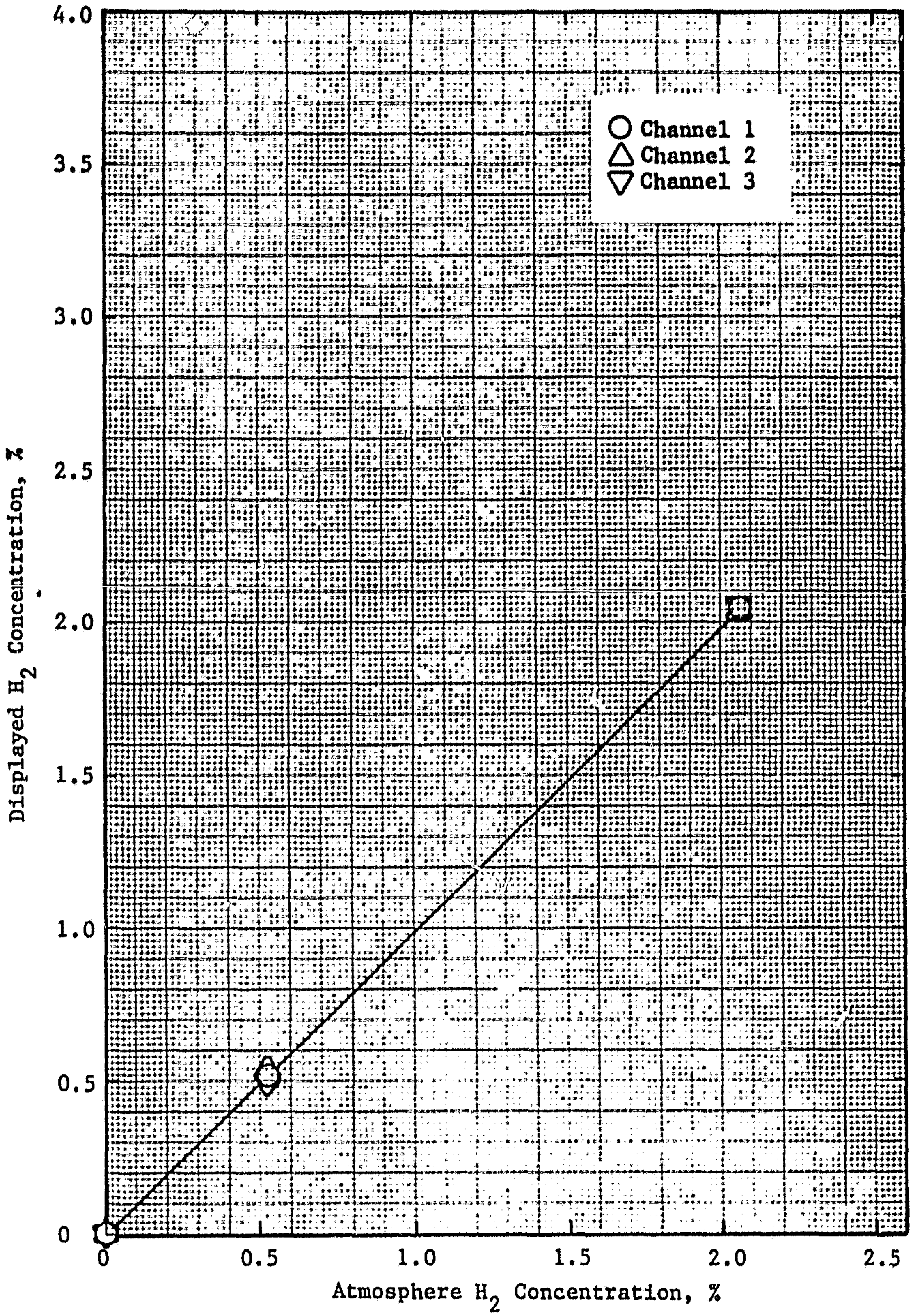


FIGURE 24 CALIBRATION CURVE FOR TRHS HEAD S/N-01

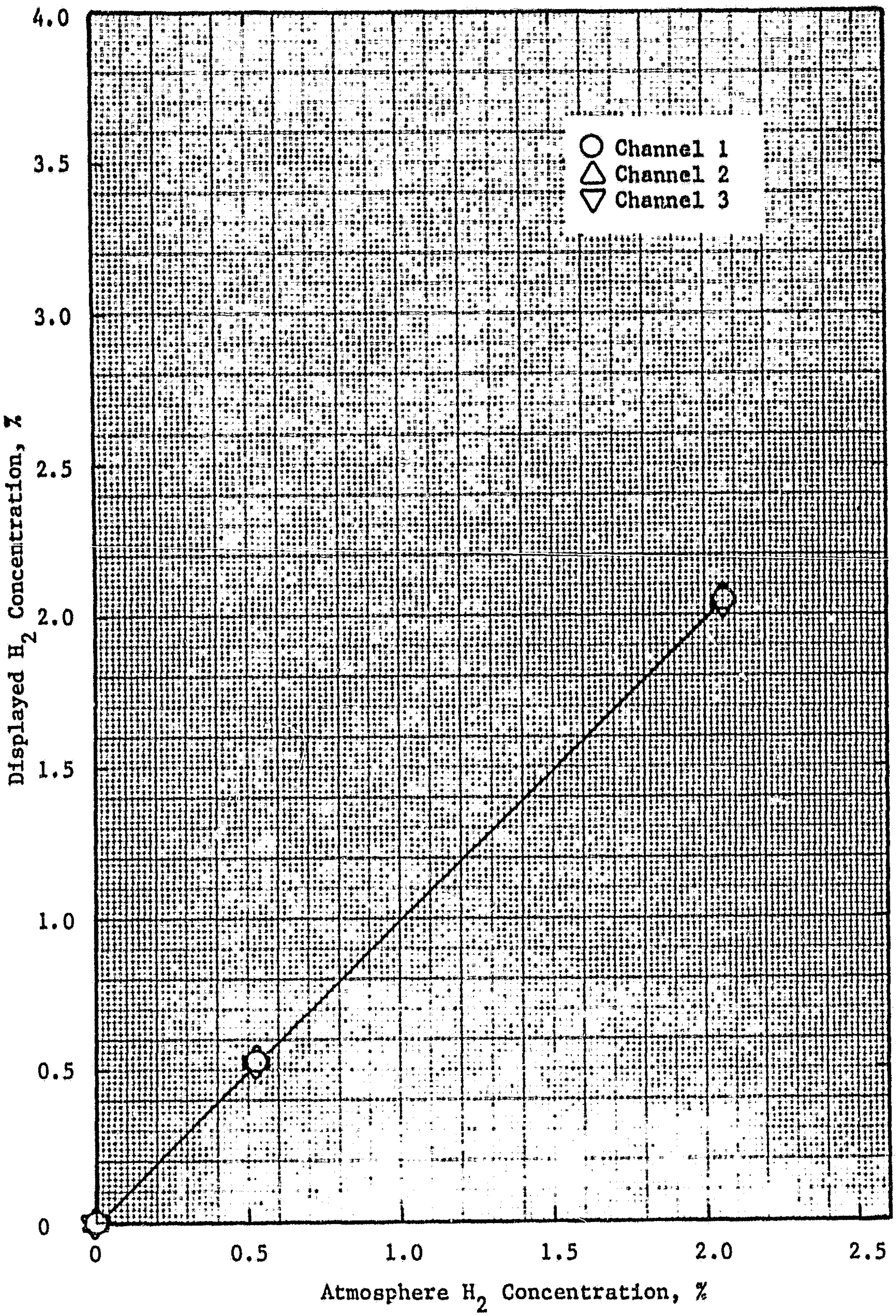


FIGURE 25 CALIBRATION CURVE FOR TRHS HEAD S/N-02

their projected optimum values via interpolation of the prior output versus current data, and the in situ calibration/standard calibration was repeated again to confirm that the accuracy was within the tolerance specified above.

Sensor Element Response Symmetry to In Situ Calibration. The HSC is designed to calibrate a single sensor element in the TRHS head (No. 1), since only one sensor output is utilized by the subsystem. Sensor elements Nos. 2 and 3 exist primarily to warn of failures. Also, at user option, element No. 2 automatically replaces element No. 1 if it fails. As the subsystem is currently adjusted and connected, differences between all redundant sensor element output in heads S/N-01 and S/N-02 exceeding 0.1% H_2 will trigger and (internal option) latch the sensor failure indicators, alarm outputs and sensor replacement.

Initially these indicators and output were also triggered inappropriately during a portion of the in situ calibration preplateau, apparently due to asymmetrical response of the redundant sensor elements to the nonequilibrium H_2 atmosphere generated during that portion of the calibration cycle. That portion of the cycle has no measurement significance. Therefore, the subsystems were subsequently upgraded so that the sensor failure indications, the second sensor failure alarm output and the automatic sensor replacement feature will not latch until just before initiation of the autocalibration adjustment and appropriate (plateau) sensor element intercomparisons. This upgrade will avoid confusion of transient H_2 generation effects with actual sensor failures.

Initially, sensor head S/N-02 also triggered the first sensor failure indicator until the end of the calibration plateau. This condition, found to be due to unequal catalyst coating of the redundant sensor elements, was subsequently corrected by adjustment of the coatings.

Post-Calibration Residual. The HGMs displayed less than 0.1% H_2 residual after the conclusion of the automatic in situ calibration cycle and restoration of the monitoring function (3.5 minute duration, total, including recovery period). Therefore the sensor monitoring function for the two subsystems recovers satisfactorily after an in situ calibration (0.1% H_2 "caution" level detector not activated).

CONCLUSIONS

1. The TRHS sensor head does not need baseline rezeroing, based on a demonstration of negligible baseline change over more than 11 months of sensor operation.

2. The TRHS sensor head will require only infrequent automatic in situ calibrations, e g. biweekly or monthly, based on a demonstrated span calibration drift of only 0.02% H_2 per month. (Relatively frequent in situ calibrations, e.g. daily, may still be desirable, however, to maximize the effectiveness of TRHS fault detection/isolation capabilities and maximize reliability in critical applications.)

3. The TRHS is linear to within ±0.04% H_2 over the range of zero to 2.1% H_2. This linearity is retained after extended operation, as demonstrated after greater than five months of continuous operation.

4. The TRHS sensor head is virtually position insensitive, within ±0.005% H_2, for a 360 degree rotation about either of its major axes.

5. The TRHS is essentially temperature insensitive over the spacecraft cabin temperature range of 291 K (65 F) to 300 K (80 F).

6. The in situ calibration technique, as implemented in the TRHS sensor head, is position insensitive and appears to be draft insensitive.

7. The in situ calibration technique, as implemented in the TRHS sensor head, is acceptably immune to spacecraft cabin RH variations of 26 to 70%. Only ±0.06% H_2 in situ calibration plateau variations were observed over this range, versus a specification of ±10% full scale (±0.2% H_2).

8. The in situ calibration technique has been successfully totally automated, requiring no crew involvement or expendables, and could be setup to perform the calibration to within ±0.02% H_2 at 0.5% H_2 (48% RH).

9. Inappropriate latched activation of the fault detection and isolation logic during the in situ calibration (ISC) cycle has been eliminated. Automatic latch repression during the nonmeasurement portions of the cycle and, for one sensor, better equalization of redundant element ISC response were successfully implemented.

10. All autoprotection/fault isolation features including automatic triple redundant sensor intercomparisons, failure warnings and shutdowns, automatic redundant sensor substitution, H_2 concentration alarm and shutdown, and a fail-to-calibrate shutdown were successfully incorporated into the TRHS Subsystem and verified.

11. The TRHS Subsystem has met development objectives.

RECOMMENDATIONS

- Build a prototype TRHS Subsystem with performance goals of reduced weight, volume and power requirement.
- Characterize the prototype TRHS Subsystem extensively with both parametric and endurance tests.
- Perform a flight demonstration test of the prototype TRHS Subsystem.

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