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INVESTIGATION OF THE APPLICABILITY OF USING THE TRIPLE REDUNDANT HYDROGEN SENSOR FOR METHANE SENSING

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FINAL REPORT

by

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by

Life Systems, Inc.
Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER
National Aeronautics and Space Administration

FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, OH under contract NAS9-16638 during the period June, 1982 through April, 1983. The Program Manager was Dr. R. A. Wynveen. The technical effort was completed by Dr. B. J. Chang, S. Czernec, R. W. Ellacott, J. O. Jessup, Dr. J. B. Lantz, F. H. Schubert 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. The Contracting Officer's Representative was Mr. Farris Tabor, Lyndon B. Johnson Space Center, Houston, TX 77058.

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LIST OF ACRONYMS

CRS	CO_2 Reduction Subsystem
EC/LSS	Environmental Control/Life Support Subsystem
GFE	Government-Furnished Equipment
HGM	Hydrogen Gas Monitor
HSC	Hydrogen Sensor Calibrator
IRAD	Internal Research and Development
LFL	Lower Flammability Limit
MGM	Methane Gas Monitor
MSC	Methane Sensor Calibrator
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
RH	Relative Humidity
S/N	Serial Number
SSP	Space Station Prototype
TRHS	Triple Redundant Hydrogen Sensor
TRMS	Triple Redundant Methane Sensor
WVE	Water Vapor Electrolysis

SUMMARY

Many regenerative environmental control and life support subsystems use and/or produce combustible gases such as hydrogen and methane in the process of controlling and regenerating the composition of spacecraft atmospheres. The escape of such combustible gases from any such subsystems could present a safety hazard if not detected. In response to the requirement for an improved combustible gas sensor that would also eliminate the need for frequent manual calibration, a sensor specifically applicable to hydrogen sensing was developed under Contract NAS9-14658. Two preprototype Triple Redundant Hydrogen Sensors with in situ calibration were supplied to NASA JSC under contract NAS9-16065. The present contractual efforts investigated the applicability of the preprototype quality hydrogen sensor for methane sensing and determined what design adjustments were necessary to provide for the sensing of both hydrogen and methane.

Application specifications for the methane sensor were assembled and design guidelines, development goals and evaluation criteria were formulated. This was done to provide a framework to evaluate sensor performance and any design adjustments to the preprototype sensor that could be required to provide methane sensitivity. Good response to hydrogen was experimentally established for four hydrogen sensor elements to be later evaluated for methane response. Prior results were assembled and analyzed for other prototype hydrogen sensor performance parameters to form a comparison base.

The four sensor elements previously shown to have good hydrogen response were experimentally evaluated for methane response in 2.5% methane-in-air. No response was obtained for any of the elements, despite the high methane concentration used (50% of the Lower Flammability Limit). It was concluded that the preprototype sensing elements were insensitive to methane and were hydrogen specific.

Alternative sensor operating conditions and hardware design changes were considered to provide methane sensitivity to the preprototype sensor, including a variety of different methane sensing techniques. Minor changes to the existing sensor elements, sensor geometry and operating conditions will not make the preprototype hydrogen sensor respond to methane. New sensor elements that will provide methane and hydrogen sensitivity require replacement of the existing thermistor type elements. Some hydrogen sensing characteristics of the modified sensor will be compromised (larger in situ calibration gas volume and H_2 nonspecificity). The preprototype hydrogen sensor should be retained for hydrogen monitoring and a separate methane sensor should be developed.

A technique to convert the preprototype hydrogen sensor to a methane sensor was established. The methane sensor would be based on the use of modular, catalytic combustion-type sensing elements with known characteristics. It was projected that modifications would provide both methane and hydrogen response with the needed parametric performance, little change in the sensors' external configuration, weight (plus 5%) and power (plus 1 W), and minimal changes in electronics. The modified sensor concept can readily accommodate modified elements that are resistant to catalyst poisons (such as vapors of silicone, sulfide and lead compounds) should this feature be required for spacecraft application.

Very linear methane response was demonstrated for sensing elements of the type established for the methane sensor concept. The hydrogen response for these elements was less linear (3% full scale calibration point scatter from a least squares line) but adequate for warning of hydrogen gas hazards. The prospective methane sensor should probably be calibrated using methane gas, versus hydrogen, due to potential differences in relative hydrogen and methane sensitivity that might occur with time.

It was projected the needed design changes to convert the preprototype hydrogen sensor to a methane sensor can be implemented with a high probability of success. It is therefore recommended a Triple Redundant Methane Sensor incorporating the conceptualized design modifications be developed and parametrically evaluated, that techniques to in situ calibrate such sensors with methane be investigated and that, optionally, microprocessor-based instrumentation be developed for signal conditioning and in situ calibration of the sensor.

ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Assembled a Triple Redundant Hydrogen Sensor (TRHS) performance base for hydrogen sensing
- Established the baseline TRHS is a hydrogen-specific sensing device insensitive to methane and should be retained as the sensor of choice for H_2 monitoring
- Projected that the TRHS can be converted to a Triple Redundant Methane Sensor (TRMS) using catalytic combustion-type sensing elements with:
  - —Little changes in TRHS external configuration and <5% change in weight
  - —No changes in the in situ calibration WVE or automatic calibration electronics, and no increase in calibration time
  - —Minimal changes in signal conditioning circuitry and subsystem power (from 19 to 20 W)
  - —Sensing elements having established characteristics
- Experimentally demonstrated the type of catalytic combustion sensing element projected for use in the TRMS concept has the needed sensitivity and linearity.

INTRODUCTION

Many regenerative environmental control and life support subsystems use and/or produce combustible gases such as hydrogen (H_2) and methane in the process of controlling and regenerating the composition of spacecraft atmospheres. The escape of such combustible gases from any of such subsystems could present a safety hazard if not detected. Prior methane or combustible gas sensors have exhibited characteristics such as poor repeatability, poor response and recovery time and position sensitivity that make them unacceptable for spacecraft application. The frequent and time consuming calibration of these sensors is also undesirable.

Background

In response to the requirement for an improved combustible gas sensor that would also eliminate the need for frequent manual calibration, a sensor, specifically applicable to H_2 sensing, was developed under Contract NAS9-14558.(1-3) Two preprototype sensors with in situ calibration were supplied to NASA JSC under Contract NAS9-16065,(3) as shown in Figures 1 and 2.(a) It is ultimately desired that sensors possessing these capabilities be able to sense methane as well as H_2 and to, in the future, be able to differentiate between the two gases. It was the purpose of the present contractual efforts to investigate the applicability of the preprototype quality H_2 sensor for methane sensing and to determine what design adjustments were necessary to provide for the sensing of both H_2 and methane.

Objectives

The objectives of the program were to investigate the suitability of the Triple Redundant Hydrogen Sensor (TRHS) for methane sensing, to determine by analysis the design adjustments to achieve adequate methane response or improve response and to project the effects of design adjustments on H_2 sensing ability. It was the intent that the design adjustments could result in a sensor that is effective for detection of both H_2 and methane.

Program Organization

The program Life Systems followed in meeting the objectives of the proposed contract consisted of the four tasks summarized below:

1.0 Obtain a current baseline performance of the H_2monitor's sensing elements in H_2.(b)
2.0 Determine H_2 sensing element response to methane.
3.0 Determine adjustments needed to H_2 sensing element design to enable methane sensing.

(1-3) Superscript numbers in parenthesis are references listed at the end of this report.

(a) Hydrogen Sensor Calibrator shown is Life Systems' unit with upgraded packaging.

(b) The H_2 Monitor employs triple redundant H_2 sensing elements in the sensor portion of the monitor.

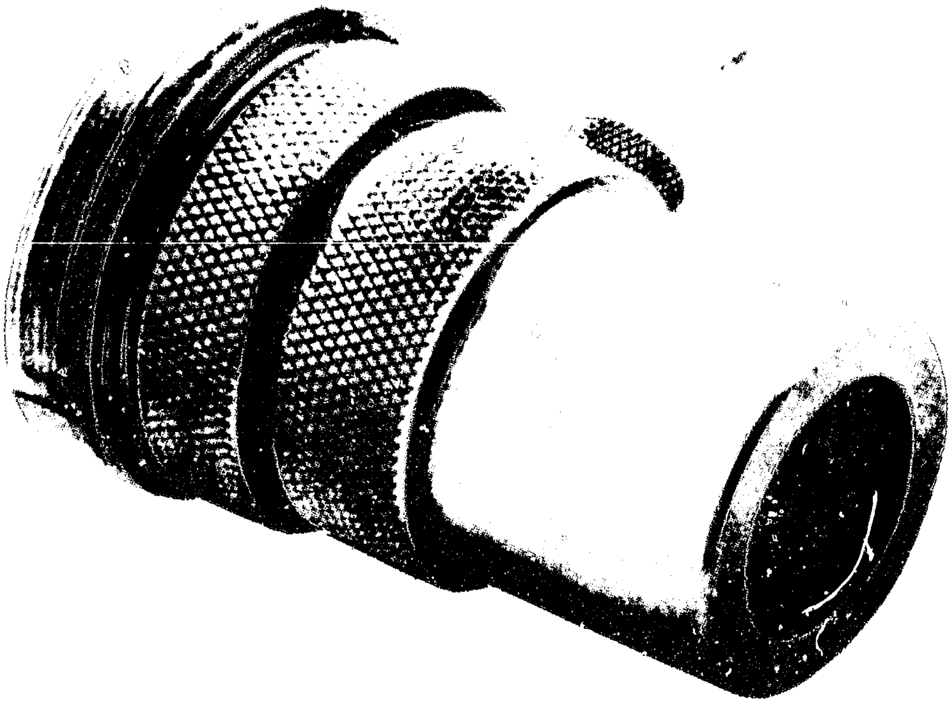

FIGURE 1 TRIPLE REDUNDANT HYDROGEN SENSOR
WITH IN SITU CALIBRATION

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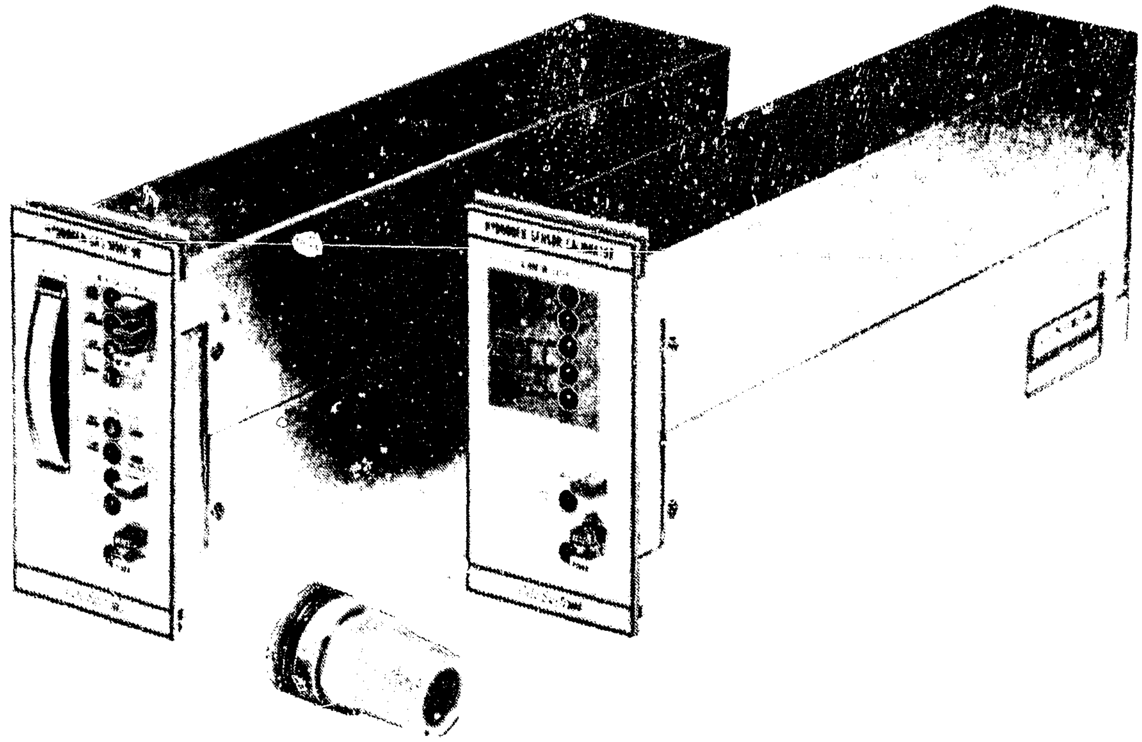

FIGURE 2 TRHS SUBSYSTEM

4.0 Analytically/intuitively determine effects of modified H_2 sensing element design on existing or inherent H_2 sensing performance characteristics.

This Report discusses the results of these program efforts.

APPLICATION ASPECTS

Application specifications were assembled and design guidelines, preliminary goals and evaluation criteria were prepared. These provide a framework for methane sensor developments, both with regard to any concepts formulated during the present contractual activities and designs implemented in the future.

Application Specifications

Application specifications that define the technical requirements for the methane sensor were assembled. These were generated so monitor designer and user clearly recognize the environment in which the monitor must operate and that the impact of potential contaminants must be ascertained at some time, since maximum concentrations are not compatible with expected monitor performance and certainly not all maximum concentrations at the same time. They are presented in Appendix 1 as Tables A1-1 through A1-4 and Figures A1-1 and A1-2.

Design Guidelines

A list of design guidelines was prepared to ensure the program focuses according to preestablished guidelines. These guidelines were to provide clear but qualitative objectives to be met when modifying a TRHS and developing a TRMS. Meeting these objectives ensures attractive, adaptable space station monitor results. They are provided as Table 1.

Development Goals

Methane monitor development goals were prepared, as shown in Table 2. They provide quantitative objectives for the modification of a TRHS and development of a methane sensor, in terms of performance, operating capabilities, features and packaging. These condense various ideas that have been generated for this development and are useful in comparing guidelines with development goals.

Evaluation Criteria

A methane monitor evaluation criteria list was prepared, Table 3. It presents evaluation criteria that can be used to compare one approach over another. An extensive list was assembled to ensure any overlooked criteria were made visible to the designer. This list emphasizes Space Station end-item application. Note, besides the essential criteria it was broken down into two categories: quantitative and qualitative criteria.

HYDROGEN SENSOR BASELINE PERFORMANCE

A primary objective of the subject program was to evaluate the response of a TRHS unit to methane. However, the current response of this unit to hydrogen (H_2) needed to be established first as a baseline for comparison. This was done using the three available TRHS units, Table 4, and the TRHS test stand, Figure 3. Figure 4 shows the results of simultaneously exposing four different sensing elements to H_2 concentrations of 0.54%, 1.28% and 2.07%. For sensing elements 1, 2 and 3 of TRHS S/N-04, good linearity was retained and calibration slopes were retained within approximately 10% of the initial value, worst case, after 19 months of service.[a] The slope and linearity of TRHS S/N-02, returned to Life Systems from NASA for evaluation, were retained following two-way shipment.

(a) After nearly three years of service, the response curves of TRHS S/N-03 were no longer linear and the response of two of the three channels to 0.54% H_2 differed significantly (0.34% was indicated for one of the channels and 0.6% for another). This indicated this unit had reached the end of its lifetime.

TABLE 1 PRELIMINARY DESIGN GUIDELINES LIST: METHANE MONITOR

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

2. Minimize expendables — goal is to require none or have those needed be regenerable.

3. Avoid toxic or corrosive chemicals — if required (1) incorporate fail-safe packaging and (2) ensure risk-free disposal methods are incorporated.

4. Avoid production of hazardous gaseous contaminants — if essential (1) incorporate fail-safe retention design and (2) resolve how disposal will be handled (e.g., vent to catalytic oxidizer, neutralize, absorb).

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

6. Incorporate techniques which will result in a monitor whose performance is characterized by:
   a. Sensitivity only to methane or methane and hydrogen(a)
   b. Freedom from interferences (e.g., trace contaminants)
   c. Reliable performance

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

7. Avoid scheduled maintenance. Incorporate straight-forward in-flight unscheduled maintenance features. Repair by replacement of system sensor (line replaceable unit) or instrumentation printed circuit cards (line replaceable component) shall be permitted.

8. Design in accordance with automatic fault detection and isolation requirements.

9. Applicable to a Space Station's design guidelines.

(a) Latter will probably not be possible since sensing element sensitive to methane will probably be sensitive to other combustible gases.

TABLE 2 PRELIMINARY METHANE MONITOR GOALS

Performance Goals

1. Range	0 to 2.5% Max. methane-in-air
2. Detection Limit	0.1% (1,000 ppm)
3. Repeatability	± 2% of full scale
4. Linearity	± 1% of full scale(a)
5. Accuracy	± 2% of full scale (with linearizer)
6. Drift	± 1% of full scale in 24 hours (non-cumulative)
7. Response Time	Fast (e.g., 1 minute to 90% of final value)
8. Interferences	
Chemical Origin	None(b)
Environmental Origin	None (e.g., temperature changes, vibration, EMI)
9. Parameter Readout	Direct methane percent
10. Overboard Venting	None
11. Catalyst Sensitivity	None, insensitive to poisons
12. Active Cooling	No liquid or air cooling needed
13. Touch Temperature, K (F)	<322 (120)

Operation Goals

1. Warmup Time	None (less than 1 min)
2. Signal Output	0 to 5 VDC, 5 mA max.
3. Sample Requirement	
Air Suspended Solids	Compatible with filtered air
Ventilation Rate (Draft)	See Table A1-1,(c) item 8
Temperature	See Table A1-1, item 7a
Pressure, kPa (psia)	101 (14.7), See Table A1-1, item 1 for tolerance
4. Operating Environment	See Table A1-1 for temperature, pressure, relative humidity range (item 7b)
5. Materials of Construction	Per NASA NHB 8060.1 and SE-R-0006A
6. Nonmetallic Materials	Per Doc. No. CSD-SS-012(d)
7. Expendables	None (or easily generated)
8. Gravity	0 to 1 G plus launch conditions
9. Calibration	Needed infrequently and easily done (e.g., automatic, in situ calibration with auto zero and auto span)
10. Sampling	Continuous (versus batch), on-line — no data gaps
11. Unattended Operation	90 days
12. Leakage	None
13. Noise Level	None

—*continued*

(a) This will be accomplished by the incorporation of a linearizing circuit into the electronics.

(b) Although it may be desirable to differentiate between H_2 and methane (other combustible gases). Reaction to CO may be considered an interference.

(c) In Appendix 1.

(d) A Master Log of Nonmetallic Materials will not be prepared.

Table 2 — *continued*

14. Vibration Level	None
15. Applicability	In immediate vicinity of CO_2 Reduction Process
16. Vented Products	Non-noxious gases

Operating Feature Goals

1. Automated Startup, Shutdown(a)	Manually or electronically initiated
2. Automatic Calculation(a)	Methane concentration
3. Accept Command Inputs(a)	Initiation of operating mode transitions
4. Transmittal of Status Indicators(a)	Parameters measured, operating mode and operating mode transition underway
5. Autoprotection(a)	Reject incorrect commands
6. Fault Detection(a)	Detect monitor failures
7. Fault Isolation(a)	Display codes identifying incorrect commands or component causing shutdown
8. Fail-Safe	Automatic Shutdown
9. Crew Time	Less than 1 hour/month

Packaging Goals

1. Configuration	Self-contained, with electronics able to be packaged with ARS computerized instrumentation
2. Readout	Direct Concentration
3. Maintainability	Direct front access for LRU (Sensor) and top for LRUs (printed circuit cards)
4. Sensor Location	Flexible depending on subsystem selections
5. Low Price	$2,000 to $4,000 per system
6. Weight, kg (lb)	0.5 to 1.8 (1 to 4)
a. Sensor	0.1 to 0.2 (0.2 to 0.4)
b. Electronics	0.4 to 1.6 (0.8 to 3.6)
7. Volume, dm^3 (ft^3)	8.5 to 3.7 (0.3 to 0.13)
8. Packaging Density, kg/dm^3 (lb/ft^3)	0.5 (30)
9. Number of Line(b) Connections	0
10. Power	10 to 30 watts
a. AC	0
b. DC	10 to 30 watts
11. Reliability	0.9999
12. Availability	99.9% of time/90 days
13. Shelf Life	10 years
14. Operating Life	5 years
15. Structural	Shock and vibration resistant

(a) A benefit of being microcomputer-based.

(b) Gas or liquid lines.

TABLE 3 DESIGN EVALUATION CRITERIA LIST: METHANE MONITOR

Essential

- Available/Confidence
- Must work/do the job
- Fail-Operational/Fail-Safe

Quantitative

- Weight
  - Sensor Head
  - Instrumentation
- Power
  - Average Power
  - Peak Power - cannot be used for any other needs
  - Light Side Only Power
- Volume
- Dimensions
- Heat Rejection
- Reliability
- Maintainability
  - Line Replaceable Unit
  - Line Replaceable Components
- Crew Time Required
- Equivalent Weight
- Expendable (Use Rate)
- Number of Interfaces
- Number of Connections (Gas)
- Number of Connections (Liquid)
- Resupply Volume (90 days)
- Resupply Weight (90 days)
- Development Cost
- Hardware Cost - Initial and Operating
- Training Cost
- Inventory Cost
- Stowage Size Requirements
  - (Size = weight, power, volume)
- Pressurized Volume Needed
- Ratio of Fixed to Variable Weight
- Noise Correction Penalty
- EMI Noise

Qualitative

- Safety
- Leakage Potential
- Contamination Potential (Reagents, Waste Products)
- Flexibility
  - Mission - support range of missions at early date
  - Operational
- Growth Potential
- Duty Cycle (continuous or cyclic)
- Ability to Start, Idle (Stand-by) and Stop Frequently
- Complexity
- Modularity
- Commonality (of Components, Functions)
- Shelf Life
- Operating Life
- Ground Operations Needed
- Data Recording/Reduction/Storage Needed
- Special Equipment Needed
- Applicable to Automation

TABLE 4 HYDROGEN SENSOR IDENTITY

TRHS Serial Number	Disposition
01	Characterized and then supplied to and retained by NASA.
02	Characterized, supplied to NASA and then returned for present contractual effort.
03	Endurance tested at Life Systems.
04	Endurance tested at Life Systems.

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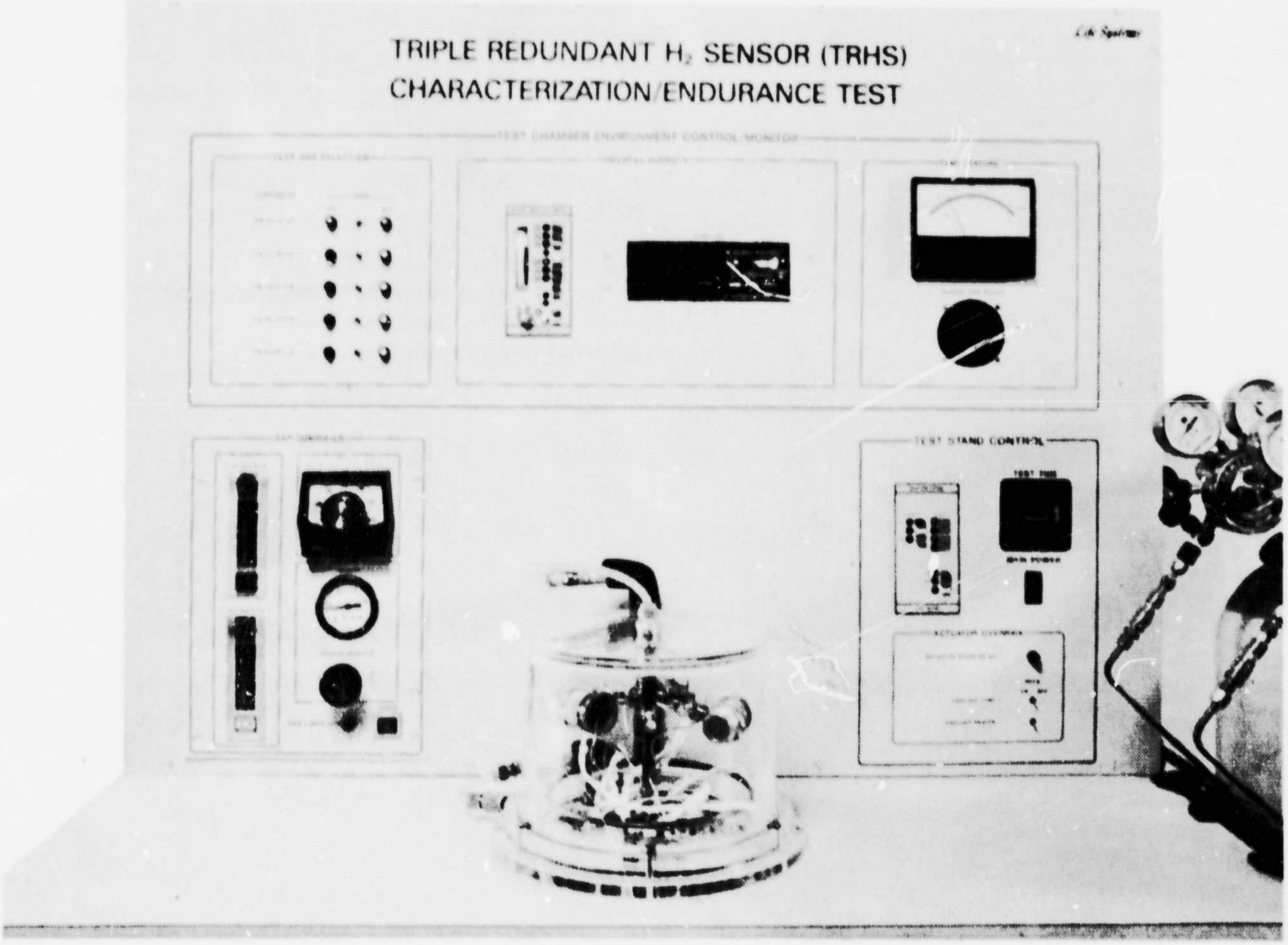

FIGURE 3 TRHS TEST STAND

TABLE 5 TRHS PERFORMANCE

Parameter	Goal	Performance
Reproducibility,[a] % Full Scale Display[b]	± 2	± 2
Position Sensitivity (Full Circle Radial and Axial Rotation), % Full Scale		
In Air	± 1	<0.5
In 0.5% H_2	± 1	<0.5
Linearity, % Full Scale	± 2	± 2
Response Time (to 90% of Value), sec	<5	<4
Recovery Time (to 90% of Value), sec	<30	4
Baseline Stability		
Zero Drift (in Air), % Full Scale/yr	2	1
Span Drift[c] (Measured with 0.5% H_2 Sample), % Full Scale/30 days	1	2
RH Sensitivity (over the Range 26-70% RH), % Full Scale/% RH	0.05	<0.05
Temperature Sensitivity, Over Range 283-311 K (50-100 F), % Full Scale/K (% Full Scale/F)	0.05 (0.03)	<0.05 (0.03)
Draft Sensitivity, % Increase in Displayed H_2 Concentration at 7.6 m/min (25 ft/min)	10	6

(a) Considered same as linearity.
(b) Hereafter, simply "Full Scale." Full Scale is assumed to be 2% H_2.
(c) Change in sensor output, exclusive of zero shifts, due to sensitivity losses of the sensing element.

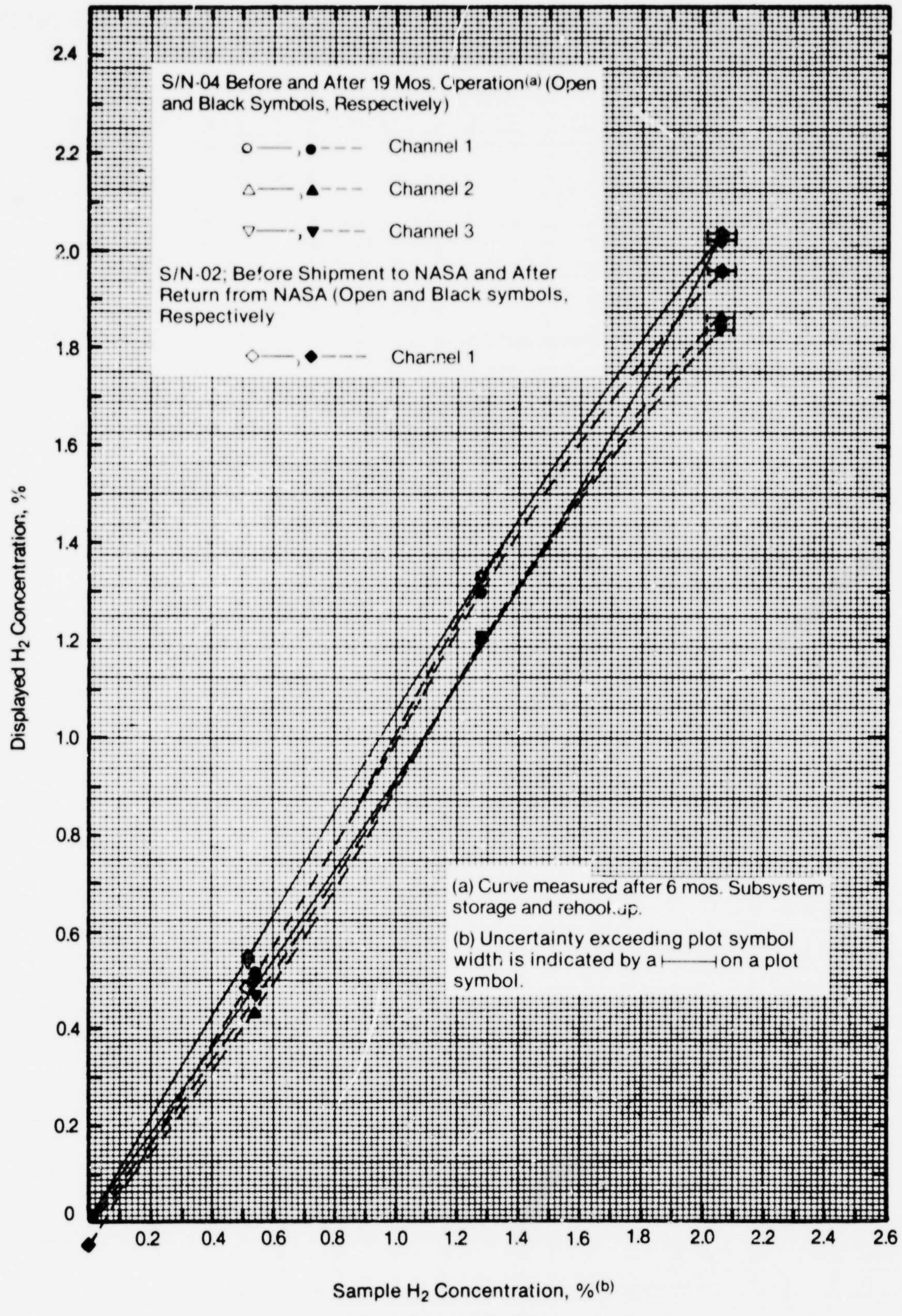

FIGURE 4 TRHS RESPONSE CURVES

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It was concluded the experimental H_2 response of these sensors would provide stable, consistent data points against which to compare experimental methane response.

The performance baselines assembled were needed both as a background for any TRHS design adjustments that might be required to establish adequate response to methane and as a base for comparing the effects of any such design adjustments. Except for draft sensitivity, direct experimental data was available for each parameter of contractual interest. They resulted from prior contractual efforts or Life Systems' Internal Research & Development (IRAD) activities. Draft sensitivity was estimated based on an analysis of some indirect observations. The prior performance results are summarized in Table 5, presented graphically in Appendix 2 (Figures A2-1 to A2-12) and discussed below.

Linearity and Reproducibility

The presented linearity of the TRHS reflects the worst case deviation from perfect straight-line output versus concentration response. Reproducibility reflects the ability to reproduce such TRHS response characteristics with different sensors. These two quantities can be considered together as the largest deviation range from a straight line drawn through the calibration data points for multiple sensors.

Figure A2-1 shows a combined linearity and reproducibility plot, based on the calibration curves for four TRHS units (S/N-01 through S/N-04). The worst case deviation from a least squares straight line drawn through the data points was 0.032% H_2, or 1.6% of full scale. This is good linearity, considering that it is within the analysis precision limits of the calibration gas used, ± 2% relative, which was found to be the best precision normally available for H_2-in-air mixtures.

Position Sensitivity

The terrestrial position sensitivity of a TRHS is caused by gas convection currents in the vicinity of the sensing bead, which will vary with gravitational forces. The TRHS will be subjected to varying, but minimal, gravitational conditions within a spacecraft, primarily during the transition between launch and orbit. The terrestrial position sensitivity of the TRHS must be minimal to ensure readings are not dependent upon how an operator installs the unit. As shown in Figures A2-2, A2-3 and A2-4, the position sensitivity of a TRHS head is nil for rotation about both its axes when measured in air and 0.5% H_2-in-air atmosphere.

Response Time

Should a spacecraft H_2 leak cause rapid accumulation of this gas in the surrounding area, it is imperative that the TRHS response time be rapid so the H_2 can be detected quickly and remedial measures can be rapidly implemented (e.g., shutting down H_2 generating or using subsystems and increasing the air circulation).

To measure response times for the TRHS, the sensor head was mounted in the side of a test chamber with the flame arrestor flush with the inside surface. The sensor was isolated from the chamber atmosphere by a rubber plug. This chamber was then purged with a 2% H_2-in-air mixture. The plug was rapidly removed (a step exposure to the H_2, within e.g., 0.1 sec) and the analog voltage output of the sensor was recorded versus time from the precise moment of plug removal. As shown in Figure A2-5, the response time was rapid, less than 4 sec to 90% of final value

Recovery Time

Once remedial action concerning a H_2 leak is completed, it is important that the TRHS rapidly recovers to indicate if the reduction in H_2 concentration occurred. To measure recovery time, the analog output from a TRHS was recorded from the precise moment at which the sensor was removed into H_2-free-air from a test chamber containing approximately 2% H_2 (a step change, e.g., within 0.1 sec). The results in Figure A2-5 show that recovery was also rapid, to within 90% of the sensor's output in air in 4 sec.

Stability

Instrument zero, or baseline, stability affects sensor accuracy. As Figure A2-6 shows, the zero stability of three separate preprototype sensing elements (equivalent to the outputs of three separate sensors) is very good. Also, the S/N-03 displayed baseline output in air was only + 0.03% H_2 after 32 months of service and for S/N-04 + 0.01% H_2 after 19 months of service. Interim fluctuations, not routinely recorded were typically within the range 0.00 to 0.02% H_2.

Span stability reflects the ability of the TRHS to correctly indicate H_2 concentrations without in situ calibration after extended sensor operation. Average drifts in displayed H_2 concentration were -0.005% H_2/30 days for Figure A2-7 (three sensors), -0.014% H_2/30 days for Figure A2-8 (three sensors) and -0.004% H_2/30 days for Figure A2-9. (See also discussion of Figure 4 in the previous section.)

Relative Humidity Sensitivity

The relative humidity (RH) of the spacecraft atmosphere will normally vary between approximately 26% to 70%. The ability of the TRHS to reliably indicate H_2 concentrations in the cabin atmosphere must not be compromised by these RH variations. As Figure A2-10 shows, no significant TRHS RH sensitivity exists over this range of RH values.

Temperature Sensitivity

The temperature in the spacecraft cabin will vary (e.g., over a range of 291 to 297 K (65 to 75 F). It is important that such temperature variations cause no significant errors in TRHS response. As Figure A2-11 shows, the TRHS is essentially temperature insensitive over at least a 288 to 298 K (59 to 78 F) temperature range.

Draft Sensitivity

In spacecraft cabins forced air convection replaces natural thermal convection, which is not available in zero gravity, to provide for heat removal from crew and hardware. An average air velocity of 7.6 m/min (25 ft/min) is therefore induced in the cabin atmosphere. It is important that such air currents in the vicinity of a TRHS measurement location do not significantly change sensor response to H_2.

The TRHS draft sensitivity was estimated as only a 6%-of-value increase in all displayed H_2 concentrations at a 7.6 m/min (25 ft/min) air velocity, as shown in Figure A2-12. This projection was based on observations during a prior contractual effort. Increased TRHS sensitivity had been recorded during operation of small fans in the vicinity of a preprototype sensor head, with velocities of the air movement due to the fans estimated.

HYDROGEN SENSOR RESPONSE TO METHANE

A primary objective of the program was to determine the potential of the existing TRHS to perform as a methane sensor. Therefore, response to 2.5% methane-in-air was determined for the same four TRHS elements for which good H_2 response characteristics had been previously established (see Hydrogen Sensor Baseline Performance section). The TRHS test stand (Figure 3) was used for these measurements.

All four TRHS elements were found to be insensitive to methane. Because 2.5% is a high methane concentration (the highest bottled gas mixture concentration commercially available and 50% of the Lower Flammability Limit (LFL), it was concluded the existing TRHS design is insensitive to methane and is H_2 specific.

Hydrogen specificity is an advantage because the TRHS can be used in combination with a general combustible gas sensor, responsive to both methane and H_2, to distinguish which of these two gases is present in the monitored atmosphere. However, a sensor responsive to methane is also needed, and design adjustments to the TRHS to provide methane sensitivity are required. Possible changes and their effects are considered in the next two sections.

PROJECTED EFFECTS OF POSSIBLE CHANGES TO HYDROGEN SENSOR

An evaluation of what adjustments might be needed to the sensor or sensor element design and operating conditions to achieve an adequate or improved output response to methane was completed. Various optional approaches to modifying the TRHS design and operating conditions were evaluated. These are discussed on the following pages.

Design Changes

Changes of the catalyst, the sensor geometry and the sensor element type were evaluated as possible ways to promote methane sensitivity in the TRHS.

Catalyst Changes

The projected effects of the following catalyst changes were evaluated for the existing thermistor-bead sensor design: use of a higher surface area catalyst to enhance activity, use of a higher catalyst-to-binder ratio to reduce masking of the catalyst surface, and conversion to a new catalyst material. Each could enhance inadequate response of the TRHS to methane. However, it is very unlikely the first two types of catalyst changes themselves would change nonexistent response into adequate response. Rather, it was concluded a much higher sensor temperature (discussed subsequently) in combination with a suitable catalyst to oxidize the rather refractory methane gas was needed.

Geometry Changes

The projected effects of the following geometry changes were considered: changing the flame arrestor geometry, increasing flame arrestor porosity and reducing the thermistor mass. It was projected that benefits of such changes in combination with the existing thermistor sensing elements would be negligible, particularly considering that the sensitivity of these elements to methane was demonstrated to be nil.

Sensor Element Type Changes

The projected effects of changing the sensor element type were considered. It was concluded that methane sensitivity can be attained in this way. Examination of several alternative methane sensing techniques during a primarily Internal Research and Development (IRAD) effort showed that the catalytic combustion principle successfully used in the TRHS would best be retained, but with modifications to provide adequate methane response. Appropriate elements utilize high temperature ceramic beads instead of thermistors. Their practical sensitivity is adequate (less than 0.1% methane or H_2), and their response is linear over greater than 50% of the LFL, making them suitable for direct reading, analog output instrumentation. These elements replace the thermistors, but will not eliminate the need for the TRHS as shown below. Their characteristics will be discussed in subsequent sections of this Report in terms of a separate Triple Redundant Methane Sensor (TRMS).

Operating Parameter Changes

Changes in the TRHS operating parameters were also considered to potentially promote methane sensitivity.

Operating Temperature Changes

Increasing the operating temperatures of the TRHS thermistors would definitely help provide methane sensitivity if a high enough operating temperature could be obtained. However, the normal upper operating temperature limit of negative temperature coefficient thermistor beads, as used in the TRHS, is 473 K (572 F), at which their temperature measuring sensitivity would be greatly reduced. This is well below the temperature at which catalytic methane-sensitive elements typically operate (e.g., greater than 723 K (842 F). Even if response could be obtained at the upper temperature limit of the thermistors, a modified catalyst would have to be incorporated. The precious metal black catalyst currently used would lose surface area rapidly at this temperature due to sintering.

Operating Pressure Changes

It is believed that increasing the pressure by a small amount (e.g., negligible to 34 kPa (5 psi) will not change the sensor nonresponsiveness. Even if large pressure increases could result in methane sensitivity, the significantly increased equivalent weight penalty that would be incurred in such an approach (e.g., due to the need for a pump), is considered unattractive.

In practice, it is desirable that sensor response not be pressure sensitive, since spacecraft cabin pressures will vary (e.g., ± 1.4 kPa (± 0.2 psi) nominal for the Space Station). The pressure sensitivity of the candidate methane sensing elements is estimated to be only about 0.25% of the reading/kPa (1.7% of the reading/psia).

Relative Humidity Changes

Humidity changes are expected to negligibly affect the ability of methane to react with oxygen at the sensor bead. In practice, such effects would be undesirable because they would restrict the relative humidity operating range of a sensor. However, water vapor is projected not to interfere with the response of the candidate methane sensing elements considered for incorporation into the TRHS, both on the basis of published specifications for the elements and on the function of the reference bead to compensate for changes in the thermal conductivity of the monitored atmosphere due to variable humidity.

Draft Variations

It is expected an intentional "draft," in terms of forced mechanical convection of the atmosphere to the sensing elements, would hurt sensor response. Such convection would likely carry more heat away from the sensing elements than would be gained by improved mass transfer of methane, and higher reaction rate, at an already insensitive element. Also, an equivalent weight penalty for the mechanical convection device would be incurred.

METHANE SENSOR CONCEPT

Based on analytic and intuitive evaluations and prior IRAD efforts it was concluded that changes to the existing sensor elements and operating conditions will not add a methane sensing capability to the TRHS. A separate methane sensing element must be used.

Design adjustments to convert the TRHS to a TRMS were conceptualized, and the effects of these adjustments on sensor performance and certain operating parameters were projected. These will now be reviewed.

It was projected the TRMS would have essentially the same external configuration and hardware as the TRHS (Figure 1). Projected features are listed in Table 6. Catalytic combustion-type sensing elements available to original equipment manufacturers (OEM's) would be incorporated, slightly modified to fit the TRHS envelope. Use of such alternative elements is highly advantageous, as shown in Table 7. These elements utilize ceramic beads suspended by a fine, but strong, wire between metal posts versus thermistor beads mounted directly to a printed circuit board through heavier wire leads, as shown in Figure 5. It is projected these sensing elements could be mounted on a printed circuit board of the same diameter as that of the TRHS. The elements would be surrounded by a modified but larger volume sensor cavity insert, which separates the elements and provides distribution of calibration gas during in situ calibration of the sensor. A larger cavity would be undesirable for a TRHS since more in situ generated H_2 for calibration would be needed. This is another reason the TRHS should be retained as a sensor for H_2.

Characteristics of the conceptualized TRMS are projected in Table 8. Projections are compared with preliminary design goals (Table 2) in Table 9.

Catalytic combustion-type sensor elements, such as those considered for the TRMS, have a good reliability record so long as catalyst poisons are not present.[4] (See Performance, item 11, in Table 9.) Lead and phosphorous compounds are unlikely to be present in spacecraft atmospheres. Silicone and sulfide compounds are likely to be present only at very small concentrations, although these have not been established as being present for spacecraft. Table A1-2 in Appendix 1 lists some sulfide *maximum* Space Station concentration *limits* for several sulfide compounds and one silicone compound. However, these are based primarily on toxicological exposure limits and are not indicative of expected concentrations to be found in spacecraft. Nonetheless, if required, sensor elements that are generally poison resistant (and specifically shown to be resistant to silicone, sulfide and lead compounds) can be substituted for the lower power (e.g., by 2 W), more developed elements considered for the TRHS design adjustments (see Tables 6 and 7).

The sensing elements considered for the TRMS utilize an alumina-supported palladium catalyst, stable at the 823 K (1,022 F) sensing bead operating temperature, instead of precious metal blacks, which are unstable at adequate temperatures for methane response. Temperature and humidity variations have little effect on the performance of such elements.

TABLE 6 PROJECTED TRIPLE REDUNDANT METHANE SENSOR FEATURES

- Configurational commonality with TRHS
  - Identical external configuration
  - Same housing
  - Same WVE cell (if H_2 used for calibration)
  - Same flame arrestors
  - Printed circuit board mounting of sensing elements still used
  - Same light gauge wiring as TRHS (24 gauge)
  - No increase in the number of wires (nine for the TRHS)
  - No changes in electronics circuits other than signal conditioning (if H_2 used for in situ calibration)
  - Minimal changes in signal conditioning electronics
- Sensing element amenability to application
  - Proven, predictable performance: utilize available, pretested elements
  - Shock and vibration resistance remains to be verified
  - Minimal modifications to available sensing elements required
  - Minimal increase in subsystem power requirement over TRHS level (projected 5%)
  - Minimal sensitivity to cabin pressure variation of ± 1 to maximum 2 psia
  - Long lifetime (over two years in absence of poisons)
  - Alternative backup element types available(a)
- In situ calibration capability
  - No increase in times for in situ calibration/zeroing over TRHS values
  - Required H_2 generation current densities should be within range of existing Water Vapor Electrolysis (WVE) cell (e.g., ≤ 50 mA/cm^2) and instrumentation
  - Uniform distribution of H_2 to redundant sensors felt retainable
- Manufacturable sensor
  - Machining operations are still minimized and critical tolerances avoided
  - One piece, injection moldable sensor cavity insert retained
  - Uncomplicated assembly of sensor retained
- Retains H_2 sensitivity
  - Similar response curves for methane and hydrogen(b)
  - Acceptable changes in H_2 parametric performance over TRHS

(a) Regular and *low* power versions and *limited* poison resistant and more poison resistant versions. Underline reflects version selected. More poison resistant versions are less developed, hence not selected for primary approach, but still excellent candidate.

(b) Question remains if poisons will impact the methane sensing response at a different rate than the H_2 response. If so, could lose ability to rely on one sensor for both gases while poison effects remain uncertain.

TABLE 7 ADVANTAGES AND DISADVANTAGES OF USING OEM-TYPE SENSOR ELEMENTS

Advantages

1. Established, predictable performance characteristics.
2. Mass production quality control capabilities.
   a. Thousands of elements made per month.
   b. Elements prematched and pretested.
3. Rugged.
   a. Designed for use in mines and around mining machinery.
   b. Tested for shock and vibration resistance.
4. Can be fit into our existing TRHS head and used with our existing WVE cell.
5. Available in lower power (0.4 W each) versions.
6. Avoids development costs/risks/time.
7. Available as small assemblies, easily handled and installed.
8. Alternative capabilities presently available.
   a. Types available: silicone resistant; sulfide, silicone and lead resistant.
   b. Low and "high" power levels.(a)
   c. Stability against "burn-out" in gas concentrations above the Lower Flammability Limit.
9. Applicable to combustible gases other than methane.

Disadvantages

1. Sensor design limited to available sensor element configuration. This applies particularly with respect to in situ calibration.
2. Not specific for methane (see also No. 9 above).

(a) High power levels more sensitive with power difference between low and high types only less than 3 watts.

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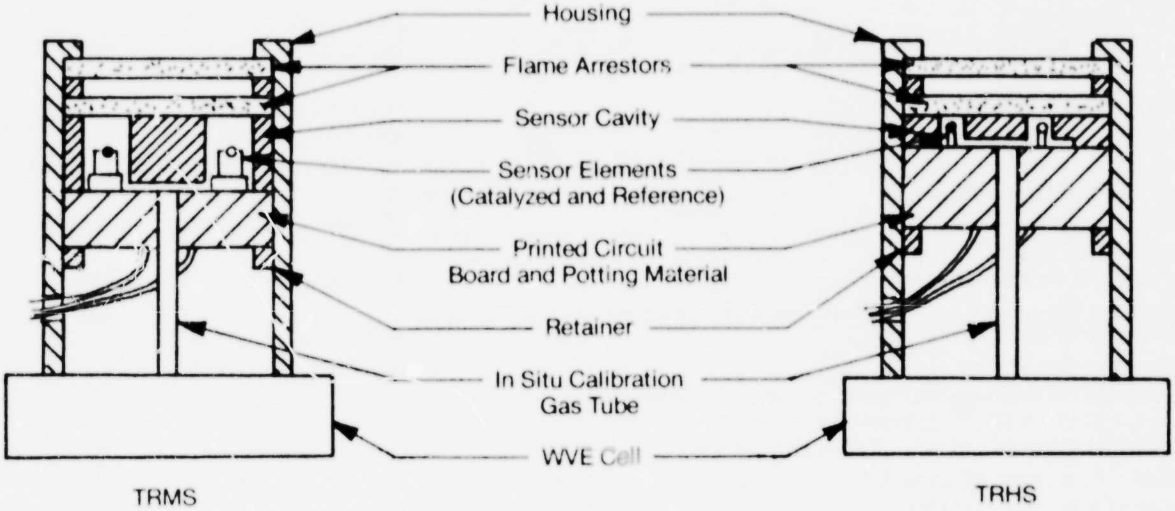

FIGURE 5 COMPARATIVE ILLUSTRATION OF PROSPECTIVE TRIPLE REDUNDANT METHANE SENSOR AND TRHS

TABLE 8 PROJECTED TRIPLE REDUNDANT METHANE SENSOR CHARACTERISTICS

Sensing Elements	Modified Commercial Unit(a)
Specificity	Applicable to Various Combustible Gases, Including H_2 and CH_4
Size (Configuration)	1.6 in Diameter x 2.5 in Long
Weight, g (lb)	175 (0.38)
Mounting	Boss
Power, W	1.23 Maximum (High Power would be <5)
Sensor Cavity Volume, cm^3 (in^3)	1.53 (0.093)
Sensing Principle	Catalytic Combustion
Linear Range, % CH_4 in Air	0 to 3
Design Range, % CH_4 in Air	0 to 2.5
Storage Temp. Range, K (F)	233 to 328 (-40 to 131)
Operating Temp. Range, K (F)	268 to 313 (23 to 104)
Operating Pressure Range, kPa (psia)	101 ± 14 (14.7 ± 2)
Sensing Element Temp. K (F)	823 (1022)
Sensor Life	>2 Years (Absence of Certain Poisons)
Response Time (90% of Value), s	20 (2.5% CH_4 in Air)
Recovery Time (90% of Value), s	25 (After Exposure to 2.5% CH_4 in Air)
Span Drift, % Full Scale/30 days	<2
Baseline Drift, % Full Scale/year	4 (Typical)
Sensor Position Sensitivity, Full Circle Radial and Axial Rotation	
In Air, % Full Scale	± 2 (Typical)
In 0.5% CH_4, Full Scale	± 2 (Typical)
Draft Sensitivity, % increase in Displayed CH_4 Concentration at 7.6 m/min (25 ft/min) Sample Velocity	6
Temperature Sensitivity, Maximum Change in Baseline over Operating Temperature Range, % Full Scale	4
Pressure Sensitivity, % of CH_4 Reading/kPa (% of CH_4 Reading/psia)	0.25 (1.7)
RH Sensitivity, over the Range 26-70% RH, % Full Scale/% RH	Insensitive(b)
Repeatability, % Full Scale	± 2
Linearity, % Full Scale	± 3
Shock Tolerance	250 g, 5 Blows Each Plane
Vibration Tolerance	20 g, 24 Cycles from 100 to 3,200 Hz
Redundant Flame Arrestors	Porous Stainless Steel

(a) Low power, pretested general combustible gas sensing elements.

(b) No interference from water vapor is expected for sensor elements to be employed.

TABLE 9 PROJECTED CHARACTERISTICS VERSUS PRELIMINARY GOALS FOR METHANE MONITOR

Performance	Goal	Projected Actual
1. Range	0 to 2.5% Max. methane-in-air	0 to 2.5% max. methane-in-air
2. Detection Limit	0.1% (1,000 ppm)	<0.1% (1,000 ppm)
3. Repeatability	± 2% of full scale	± 2% of full scale
4. Linearity	± 1% of full scale[a]	± 1% of full scale[a,b]
5. Accuracy	± 2% of full scale (with linearizer)	± 2% of full scale
6. Drift	± 1% of full scale in 24 hours (non-cumulative)	± 2% of full scale/30 days
7. Response Time	Fast (e.g., 1 minute to 90% of final value	20 sec to 90% of full scale
8. Interferences		
Chemical Origin	None[c]	Halogen compounds[d]
Environmental Origin	None (e.g., temperature changes, vibration, EMI)	Minimal - see Table 7
9. Parameter Readout	Direct methane percent	Direct methane percent
10. Overboard Venting	None	None
11. Catalyst Sensitivity	None, insensitive to poisons	Silicone, sulfur, phosphorous, lead compounds[e]
12. Active Cooling	No liquid/air cooling needed	No liquid/air cooling needed
13. Touch Temperature, K (F)	<322 (120)	<322 (120)

Operation	Goal	Projected Actual
1. Warmup Time	None (less than 1 min)	None (less than 1 min)
2. Signal Output	0 to 5 VDC, 5 mA max.	0-5 VDC, 5 mA max.
3. Sample Requirement		
Air Suspended Solids	Compatible with filtered air	Compatible with filtered air
Ventilation Rate (Draft)	See Table A1-1, item 8	Operable at 61 m/min (200 ft/min)
Temperature, K (F)	See Table A1-1, item 7a	268-313 (23 to 104) Range
Pressure, kPa (psia)	101 (14.7), See Table A1-1, item 1 for tolerance	101 ± 14 (14.7 ± 2) Range
4. Operating Environment	See Table A1-1 for temperature, pressure, relative humidity range (item 7b)	Humidity insensitive (see above for temperature and pressure ranges)
5. Materials of Construction	Per NASA NHB 8060.1 and SE-R-0006A	Per NASA NHB 8060.1 and SE-R-0006A

—*continued*

(a) This will be accomplished by the incorporation of a linearizing circuit into the electronics.

(b) ± 3% max., without linearizer. However, ± 1% was demonstrated experimentally for nonlinearized response of methane sensitive sensor elements.

(c) Although it may be desirable to differentiate between H_2 and methane (other combustible gases). Reaction to CO may be considered an interference.

(d) Inhibit response at concentrations exceeding 0.1% (unlikely in spacecraft).

(e) At low ppm levels. Poison resistant elements can be substituted if silicone and sulfur levels are in atmosphere (lead and phosphorous compounds not expected).

Table 9—*continued*

Operation	Goal	Projected Actual
6. Nonmetallic Materials	Per Doc. No. CSD-SS-012	Per Doc. No. CSD-SS-012
7. Expendables	None (or easily generated)	None(a)
8. Gravity	0 to 1 G plus launch conditions	0 to 1 G plus launch conditions
9. Calibration	Needed infrequently and easily done (e.g., automatic, in situ calibration with auto zero and auto span)	Needed infrequently and performed by automatic in situ calibration with auto zero and auto span(a)
10. Sampling	Continuous (versus batch), on-line — no data gaps.	Continuous, on-line — no data gaps
11. Unattended Operation	90 days	90 days
12. Leakage	None	None
13. Noise Level	None	None
14. Vibration Level	None	None
15. Applicability	In immediate vicinity of CO_2 Reduction Process	In immediate vicinity of CO_2 Reduction Process
16. Vented Products	Non-noxious gases	None

Operating Features	Goal	Projected Actual
1. Auto. Startup, Shutdown(b)	Manually or electronically initiated	Manually or electronically indicated
2. Automatic Calculation(b)	Methane concentration	Methane concentration
3. Accept Command Inputs(b)	Initiation of operating mode transitions	Initiation of operating mode transitions
4. Transmittal of Status Indicators(b)	Parameters measured, operating mode and operating mode transition underway	Parameters measured, operating mode and operating mode transition underway
5. Autoprotection(b)	Reject incorrect commands	Reject incorrect commands.
6. Fault Detection(b)	Detect monitor failures	Detects monitor failures
7. Fault *Isolation*(b)	Display codes identifying incorrect commands or component causing shutdown	Display codes identifying incorrect commands or component causing shutdown
8. Fail-Safe	Automatic shutdown	Automatic shutdown
9. Crew Time	Less than 1 hour/month	Less than 1 hour/month

—*continued*

(a) For in situ calibration with H_2

(b) A benefit of being microcomputer-based.

Table 9—*continued*

Packaging	Goal	Projected Actual
1. Configuration	Self-contained, with electronics able to be packaged with ARS computerized instrumentation	Self-contained, with electronics able to be packaged with ARS computerized instrumentation
2. Readout	Direct Concentration	Direct Concentration
3. Maintainability	Direct front access for LRU(b) (Sensor) and top for LRUs (printed circuit cards)	Direct front access for LRU (Sensor) and top for LRUs (printed circuit cards)
4. Sensor Location	Flexible depending on subsystem selections	Flexible depending on subsystem selections
5. Low Price	\$2,000 to \$4,000 per system ('82 \$)	\$2,000 to \$4,000 per system ('82 \$)
6. Weight, kg (lb)	0.5 to 1.8 (1 to 4)	4.5 (9.9)(c)
a. Sensor, kg (lb)	0.1 to 0.2 (0.2 to 0.4)	0.17 (0.4)
b. Electronics, kg (lb)	0.4 to 1.6 (0.8 to 3.6)	4.3 (9.5)(c)
7. Volume, dm^3 (ft^3)	0.9 to 3.7 (0.03 to 0.13)	8.2 (0.29)(c)
8. Packaging Density, kg/dm^3 (lb/ft^3)	0.5 (30)	0.5 (33)
9. Number of Line(d) Connect	0	0
10. Power	10 to 30 watts	20 watts
a. AC	0	0
b. DC	10 to 30 watts	20 watts
11. Reliability	0.9999	0.9999
12. Availability	99.9% of time/90 days	99.9% of time/90 days
13. Shelf Life	10 years	10 years
14. Operating Life	5 years	>2 years(e)
15. Structural	Shock and vibration resistant	Shock and vibration resistant

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(a) For in situ calibration with H_2

(b) Line replaceable unit.

(c) Preprototype units as presently developed. No projections made for flight hardware.

(d) Gas or liquid lines.

(e) In clean air (no catalyst poisons).

Such sensors respond similarly to H_2 and methane, and the response to the total, combined concentration of the two gases, if simultaneously present, should be approximately the same as the sum of the responses for the individual gases. Figure 6 illustrates the calculated relative response of catalytic elements to H_2, methane and other combustible gases.[5] The actual relative response of complete sensors (versus elements alone) will vary somewhat, in part due to the effect of flame arrestors and configuration on the diffusion characteristics of different gases. The sensor will respond to a large variety of combustible gases. However, it is believed that methane and H_2 are the only ones likely to be potentially present at measurable concentrations in the spacecraft atmosphere.

It is projected that any changes in the H_2 response of the sensor elements with time will not occur at the same rate as changes in methane response, as illustrated in Figure 7. Less demanding catalytic conditions are required for oxidation of H_2 at the sensor bead surface than for methane, so catalyst changes that slow down methane oxidation might not affect H_2 oxidation. Therefore, calibration with H_2 is not considered totally reliable for this methane sensing application. Some form of a methane-in-air source must be used to ensure the sensor's response to methane remains in calibration. Development of a methane generation technique for in situ calibration is recommended.

A methane response curve was obtained for sensor elements of the type considered for the TRMS (see in Figure 8). Linearity was very good. The largest deviation from a least squares straight line through the data points was 1% of full scale (defined as 2.5% methane).

By contrast solid state, metal oxide semiconductor (MOS) elements, considered among the alternatives, are grossly nonlinear, and the calibration curves for methane and H_2 are very different, although these elements are typically less costly and more sensitive at lower levels of combustible gas concentration. Typically, such elements are not used for gas concentration measurement because they are suitable primarily for go-no-go (versus analog) output only.[6,7] Methane and H_2 simultaneously present in the monitored air compete at the sensor surface, resulting in a lower combined response than would be expected based on the responses for the individual gases.[6] Typical MOS sensors are humidity and temperature sensitive and are considered less reliable. The MOS sensing elements were not considered to be a good choice for adding methane sensing capability to the TRHS.

PROJECTED METHANE SENSOR PERFORMANCE AS H_2 SENSOR

As a goal it had been desired that the TRMS retain the ability to perform as an H_2 sensor following design adjustments. This would permit monitoring of H_2 and methane with one sensor if relative responses to the two gases were consistently the same (that is, related to each other by a constant factor). If so, only one gas (i.e., in situ generated H_2) would need to be used for calibration. This section discusses the projected impact of TRHS design adjustments on the ability of the prospective TRMS to sense H_2 and on its relative H_2/methane response characteristics.

The established characteristics and the availability of methane test information enabled extrapolation of many H_2 sensing performance characteristics. The balance of the projections were based on analysis and intuition. The results and bases for these projections are summarized in Table 10. These projections indicate that the TRMS could provide the H_2 sensing performance needed to protect spacecraft from the hazards of potential H_2 leaks but not as optimally as the TRHS.

H_2 Sensing Ability

For some parameters, such as response time and draft sensitivity, the TRMS will potentially perform better than the TRHS as a H_2 sensor. Zero drift was projected to be larger than for the TRHS, but only about 0.1% H_2 per year, typical, well below the 0.5% H_2 alarm threshold.

A H_2 response curve, as well as a methane response curve (Figure 8), was experimentally obtained for sensor elements similar to those considered for the TRMS. The two curves are plotted together in Figure 9. The relative H_2/methane response differs from the calculated (Figure 6). This was expected, because the dual flame arrestors used in the breadboard test sensor restrict diffusion of the larger, heavier methane molecules more than the H_2 molecule. The flame arrestor area exposed to the sensing elements in the prospective TRMS would be somewhat larger than in the breadboard test sensor, and the relative responses could be closer. The H_2 response is not as linear as the methane response, but is satisfactory to indicate approximate levels of H_2 in the atmosphere and can be linearized electronically. The largest deviation of the data points from a least squares line (dotted in Figure 9) was 3% of full scale. The reduced linearity is possibly due to elevation of the reference bead temperature by reaction of the very easily oxidized H_2 at its surface. The TRMS reference bead operates at a higher temperature and is less inert than the corresponding TRHS bead. If so, the TRMS linearity for H_2 can potentially be improved. Alternatively, but only if the sensor were used for H_2 alone, a linearizing circuit can be incorporated in the electronics.

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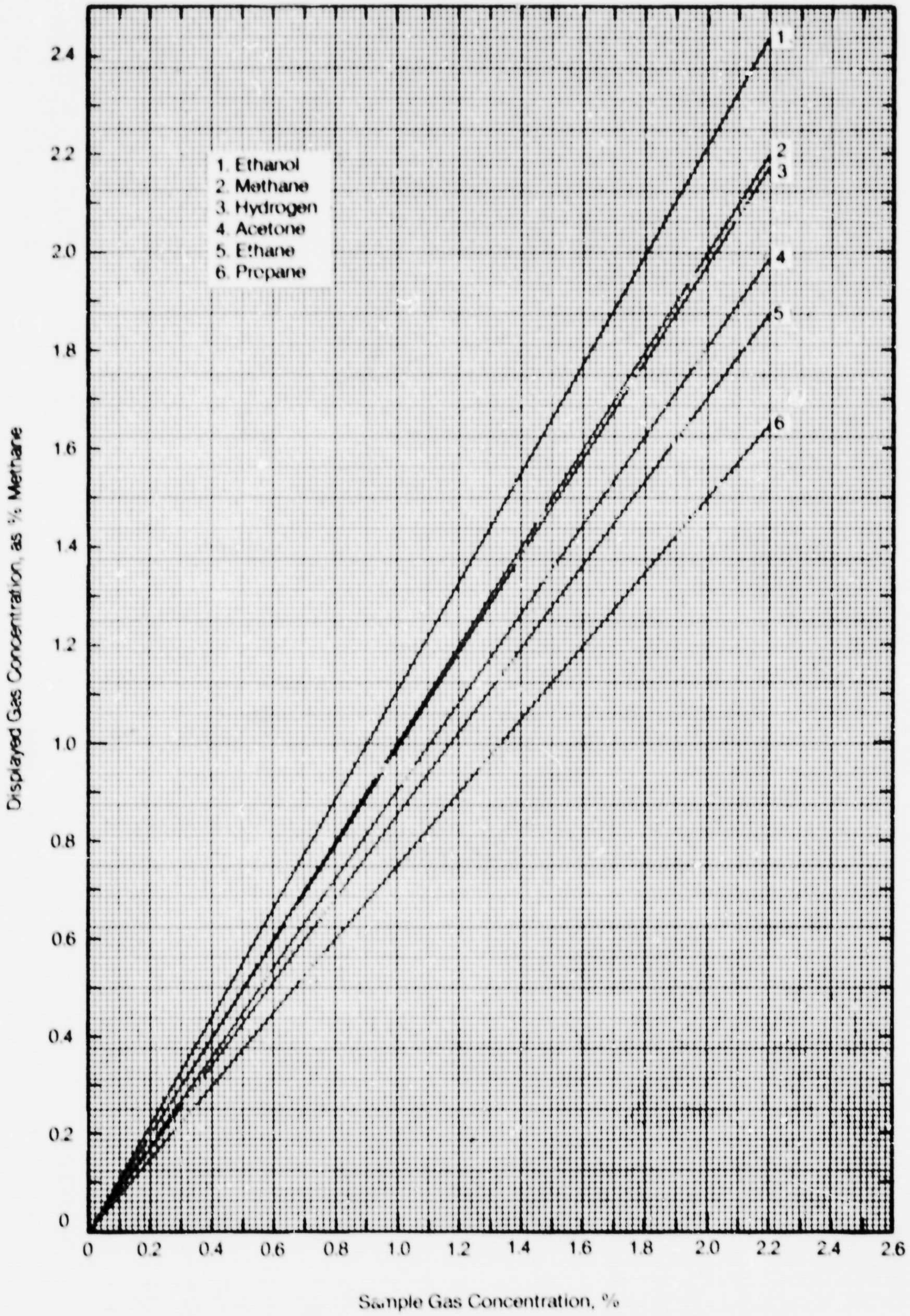

FIGURE 6 CALCULATED RELATIVE RESPONSE TO VARIOUS GASES BY A CATALYTIC COMBUSTIBLE GAS SENSOR CALIBRATED FOR METHANE

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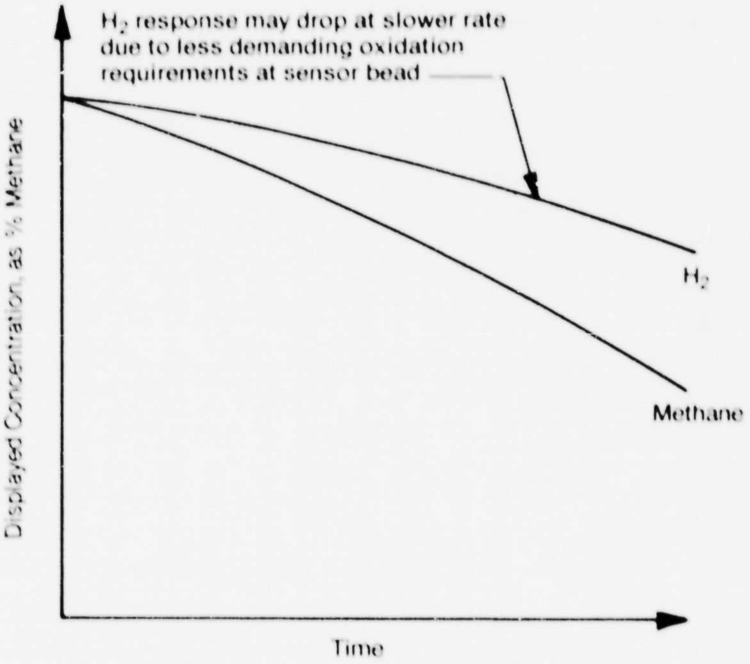

FIGURE 7 ILLUSTRATION OF HOW RELATIVE HYDROGEN/METHANE RESPONSE COULD CHANGE WITH TIME

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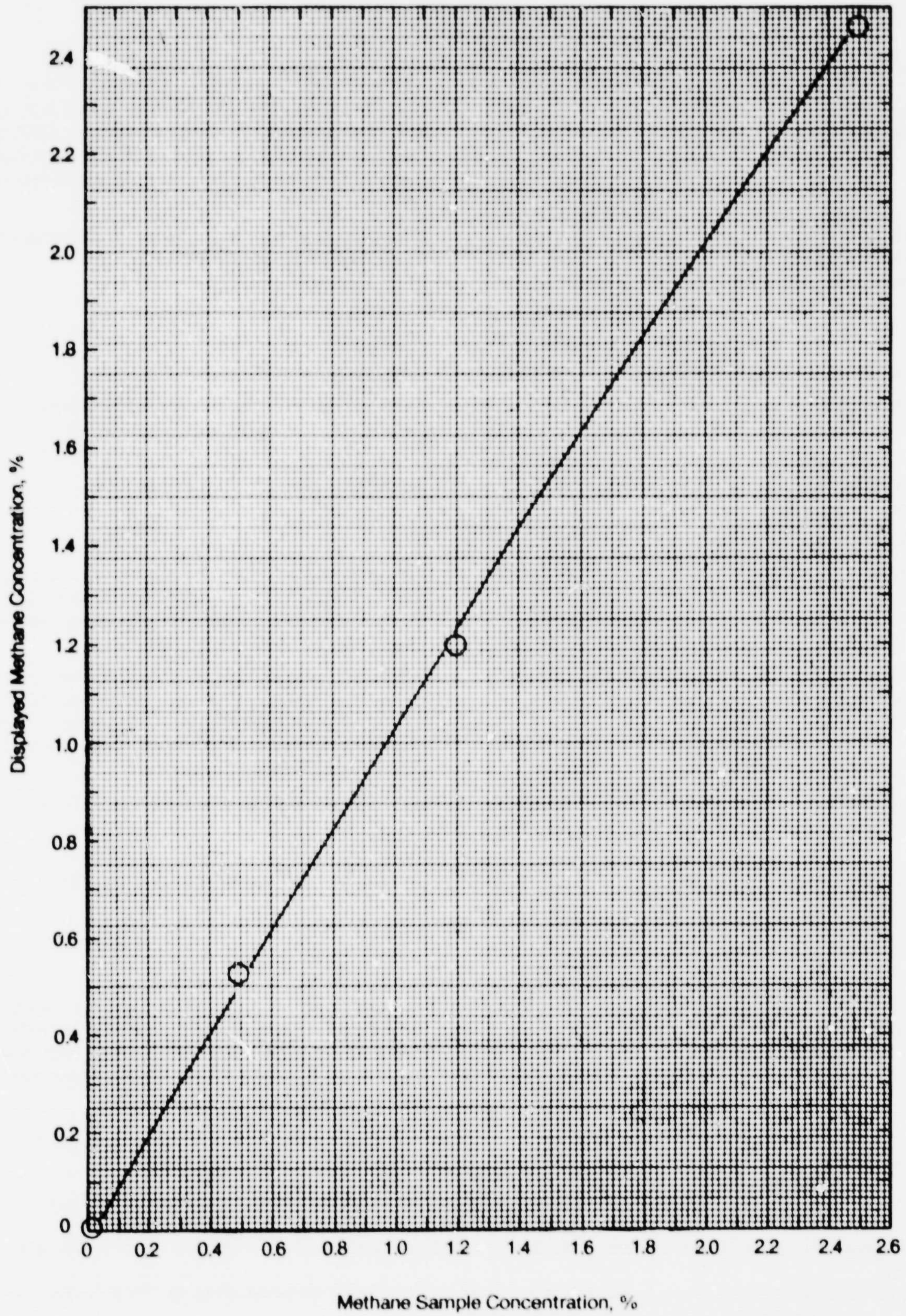

FIGURE 8 RESPONSE OF ALTERNATE SENSOR ELEMENTS TO METHANE

TABLE 10 PROJECTED EFFECTS OF DESIGN/OPERATING ADJUSTMENTS ON H_2 SENSING ABILITY

	Performance as H_2 Sensor		
Parameter	TRHS, Performance	TRMS, Projection	Bases for TRMS Projections
Reproducibility[a], % Full Scale Display[b]	± 2	± 3 Max.	Sensing element manufacturer indicated that linearity specifications of British, Canadian and American Organizations (such as Factory Mutual and Instrument Society America) are met; Canadian specification was consulted for projection.
Position Sensitivity (Radial and Axial Rotation), % Full Scale			Discussions with sensing element manufacturer on their observations of position sensitivity.
In Air	<0.5	3 Typical	
In 0.5% H_2	<0.5	3 Typical	
Linearity, % Full Scale	± 2	± 3 Max.	(See Reproducibility)
Response Time (to 90% of Value), sec	<4	2	Faster diffusion of H_2 to TRMS elements due to 8.2 X larger usable flame arrestor area than for TRHS but only 4.5 X larger sensor cavity volume to fill.
Recovery Time (to 90% of Value), sec	4	<3	Same reasoning as for response time.
Baseline Stability			
Zero Drift (in Air), % Full Scale/yr.	1	5 Typical	Typical level, based on discussions with sensing element manufacturer. (Slightly higher than CH_4 performance projections[c] because expressed relative to 2% H_2 (versus 2.5 % CH_4) full scale.)
Span Drift[d] (Measured with 0.5% H_2 Sample), % Full Scale/30 days.	2	2	Discussion with sensing element manufacturer indicated that sensitivity is approximately constant over several years unless poisoning occurs. There is no steady decrease. Should be at least as good as or better than TRHS specification.
RH Sensitivity (over the Range 26-70% RH), % Full	0.05	No Interference	Sensing element manufacturer's specification.
Temperature Sensitivity, Over Range 283-311K (50-100F), % Full Scale/K (% Full Scale/F)	0.05 (0.03)	0.11 Max.[e] (0.06) Max.	Sensing element manufacturer's specification.
Draft Sensitivity, % Increase In Displayed H_2 Concentration at 7.6 m/min. (25 ft/min)	6	3	Faster diffusion of H_2 to TRMS elements due to 8.2 X larger usable flame arrestor area than in TRHS, but only a 4.5 X larger cavity to fill. Makes thickness of the laminar gas layer at the flame arrestor surface less critical for mass transport.

—continued

(a) Considered same as linearity.

(b) Hereafter, simply "Full Scale." Full Scale is assumed to be 2% H_2 as for the TRHS, for comparison purposes.

(c) Table 7.

(d) Change in sensor output, exclusive of zero shifts, due to sensitivity losses of the sensing element in clean atmosphere.

(d) Only a maximum output change was specified for a 268-313 K (23-104 F) temperature range. Output change was divided by temperature range to provide average sensitivity.

Table 10—*continued*

Parameter	Performance as H_2 Sensor TRHS, Performance	 TRMS, Projection	Bases for TRMS Projections
In Situ Calibration			
WVE Idle Voltage, V	1.49 to 1.51	1.49 to 1.51	Same WVE cell type as for TRHS
Preplateau Current Density, mA/cm^2	15	42	8.2 X larger usable flame arrestor area allows more H_2 calibration gas to diffuse out. 4.5 X larger sensor cavity volume to purge is not the limiting factor.
Plateau Current	4	31	Same as for preplateau current
Preplateau H_2 Generation Time, min	1.0	≤ 1.0	The 4.5 X increase in purge volume requirements does not match approximately 8 X greater H_2 generation rate, which should provide more rapid attainment of desired H_2 concentration than in the TRHS.
Plateau H_2 Time, min	0.5	≤ 0.5	Same as for Preplateau Generation Time.
Autocalibration Adjustment Time, sec	≤ 4	≤ 4	Purely electronic. Should not be affected by sensor design change.
Recovery Time, min	2.0	≤ 2.0	Considered TRHS as basis for projecting sensor response/recovery times. In situ calibration recovery time should be improved. However, 2.0 min recovery was not always adequate for TRHS. Therefore, retained 2.0 min for residual to clear H_2 concentration to below 0.1% in TRMS, but improvements desired and possible.
Auto Zeroing			
Time, sec	≤ 4	≤ 4	No change expected.
Additivity of Small Atmospheric Residuals and In Situ Generated H_2 Concentrations.	Satisfactory to 0.2 % H_2 Residual	Satisfactory to 0.2% H_2 Residual	Analysis based on considerations of sensor cavity geometry, catalytic bead size and temperature, H_2 oxidation rate and projected H_2 generation rate during in situ calibration.

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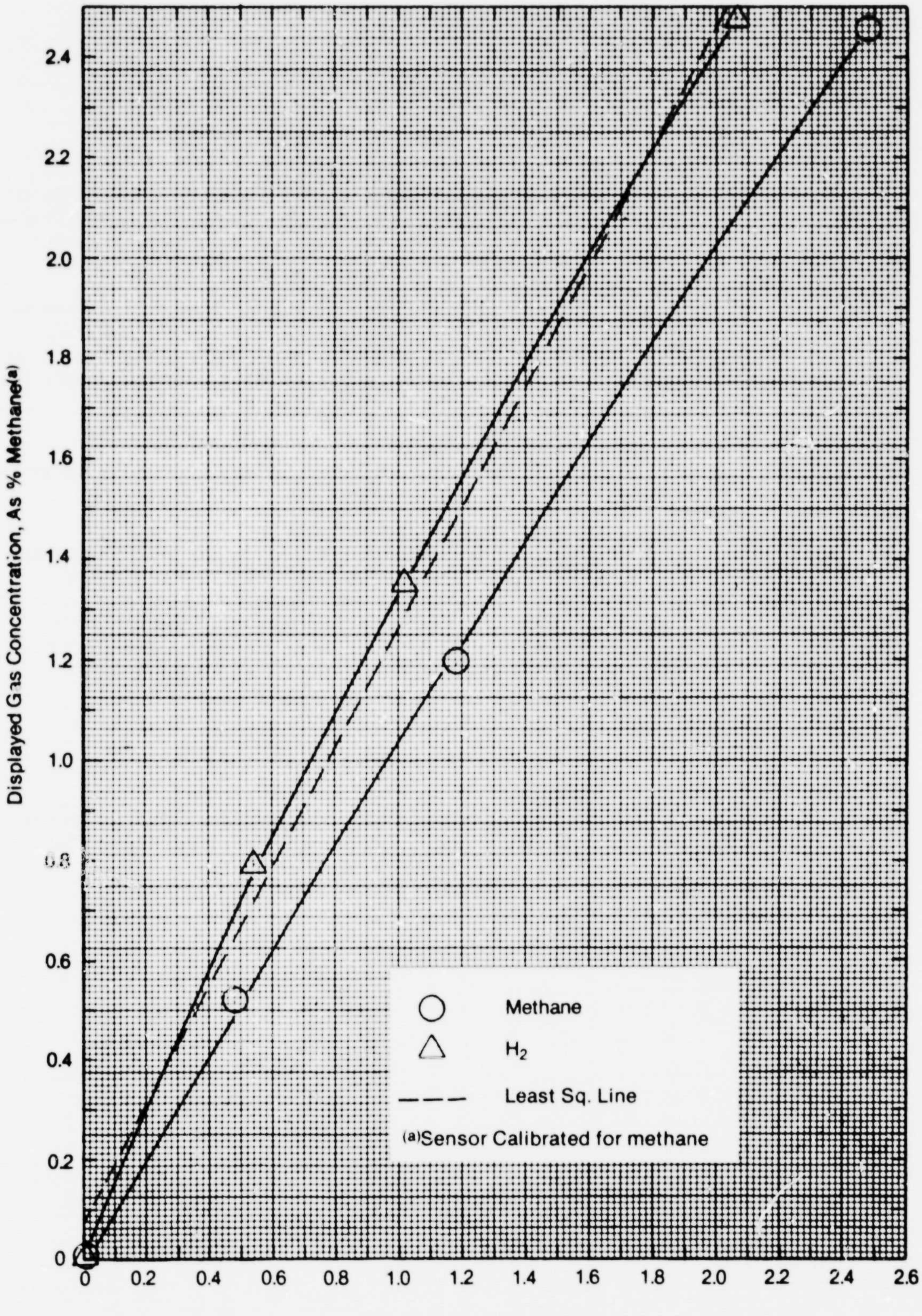

FIGURE 9 RESPONSE OF ALTERNATE SENSOR ELEMENTS TO METHANE AND HYDROGEN

In Situ Calibration

It is projected the prospective TRMS could be calibrated as a H_2 sensor using H_2 generated from a WVE cell. Higher H_2 generation currents will be required than for the TRHS, due to the larger sensor cavity volume to purge and the larger flame arrestor area through which the generated H_2 must diffuse to establish a calibration atmosphere. The projected current requirements are within the capability of the present Hydrogen Sensor Calibrator (HSC) and the present WVE cell.

Auto Zeroing

An adjustment of the TRHS output to zero is automatically initiated just prior to in situ calibration and removed thereafter. This Auto Zeroing enables the sensor span to be correctly matched to the in situ generated H_2 concentration (0.5%) during the calibration time frame, despite the existence of small residual concentrations of H_2 in the monitored atmosphere (up to 0.2%). The influence of such residuals is in effect subtracted during the in situ calibration. However, this requires that the sensor respond in the same way to the residual H_2 both before and during in situ calibration. That is, the response to the residual and in situ generated H_2 atmospheres must be additive.

It was projected that this additivity can be obtained in the TRMS as well as in the TRHS and, therefore, that the TRMS can be auto zeroed in the presence of H_2 residuals as well as the TRHS. This projection is based on an analysis of the effect of external H_2 on the diffusion of in situ calibration H_2 through the flame arrestor and on H_2 consumption at the catalyzed sensor bead. The prospective H_2 generation rate, the size and operating temperature of the sensor bead, the temperature rise of the bead in the presence of H_2 and the sensor cavity geometry were considered.

CONCLUSIONS

1. The TRHS is a H_2-specific sensor. It does not respond to methane.
2. Minor design changes to the existing sensor elements, sensor geometry and operating conditions will not make the TRHS respond to methane.
3. New sensor elements for the TRHS that will provide both methane and H_2 sensitivity are simple replacements for the existing thermistor elements. They will increase, however, in situ calibration gas requirements, their response to H_2 will be less linear than the existing elements and they will not be H_2 specific.
4. Use of a TRHS for H_2-specific sensing in combination with a TRMS for methane sensing will enable determination of whether H_2 or methane is present in the monitored atmosphere.
5. The TRHS can be converted to a TRMS using a different type of catalytic combustion sensor elements and a modified internal configuration. It is projected that negligible changes to the TRHS subsystem external configuration, size, weight and power (e.g., 5%) will be required.
6. Experimental linearity of a laboratory breadboard methane sensor, incorporating elements of the type considered for the TRMS, was very good — 1% of full scale (defined as 2.5% methane).
7. Changes in H_2 sensitivity of a catalytic combustion-type sensor with time may not occur at the same rate as changes in methane sensitivity. Under such conditions the relative response to the two gases will change. For this reason, the TRMS needs to be in situ calibrated with methane rather than H_2.
8. Conventional catalytic combustion-type elements can be poisoned by volatile silicone, sulfide, lead and phosphorous compounds. Lead and phosphorous are unlikely to be present in spacecraft atmospheres. Silicones and sulfides are likely to be present but at small concentrations which have not been established. The developed hardware should be tested in a real world environment, e.g., in Shuttle Orbiter middeck as an experiment for exposing the sensing elements to confines of a manned spacecraft.
9. The changes to convert the TRHS to a TRMS can be implemented with a high confidence of successful conversion.
10. Although the TRHS is much preferred for H_2 sensing, the TRMS could be used for this purpose. In situ calibration of the TRMS with H_2 is projected to require changes only in H_2 generation currents. These currents are expected to be within the operating ranges of the present WVE cell and the subsystem instrumentation. Auto zeroing should be as effective for the TRMS as it is for the TRHS during in situ calibration with H_2. It is projected that small residual concentrations of H_2 in the monitored atmosphere ($\leq 0.2\%$) can be compensated for to avoid interference with the calibration.

RECOMMENDATIONS

1. Retain catalytic combustion, as used in the baseline TRHS, as the sensing principle in the TRMS, because it will provide the greatest overall level of performance and reliability for methane sensing.
2. Design, fabricate and assemble a TRMS, based on modification of the TRHS design to incorporate catalytic combustion-type elements that are sensitive to both methane and H_2. This shall include design, fabrication and assembly of a modified TRMS head, a methane gas monitor and an upgraded HSC, to be used as a Methane Sensor Calibrator.
3. Design and implement improvements/additions to the existing test stand to evaluate the TRMS. This will include development of a draft sensitivity test apparatus and improved position sensitivity and response/recovery time measurement test fixtures.
4. Perform program testing necessary to evaluate the performance of the TRMS, first, as a methane sensor, second, as a H_2 sensor and third, with both gases present. This shall include testing for: response/linearity; response time and recovery time; stability; sensitivity to position, relative humidity, temperature and draft variations; ability to in situ calibrate with H_2; and ability to automatically compensate for background concentrations of H_2 and methane gas during in situ calibration (auto zeroing).
5. Evaluate what poisons must be provided for in flight hardware. Then develop the design modifications needed, and fabricate a TRMS incorporating such elements.
6. Conceptually investigate alternative methods for in situ calibration of the TRMS with methane. Design, build and evaluate a laboratory breadboard of the most promising method.
7. Design a microprocessor-based combined Methane Gas Monitor/Methane Sensor Calibrator. The objective is to define the "size" of the electronics for combustible gas, methane and H_2 monitoring when integrated into the Automated Controller of an EC/LSS subsystem.

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APPENDIX 1

APPLICATION SPECIFICATIONS

TABLE A1-1 METHANE MONITOR EC/LSS DESIGN CRITERIA(8)

1. **Space Station Module(s) Absolute Pressure, psia**	
a. Design point	14.7
b. Range	14.7 - 15.2
c. Control tolerance	
1. Nominal operational level(a)	± 0.2
2. Reduced operational level(a)	± 1.0
3. Emergency operational level(a)	-1.5 to + 2.0
d. Quiescent operation	0.0 to 0.5
2. **Oxygen Partial Pressure, psia**	
a. Partial pressure for nominal operational level will be maintained within the control band shown in Figure A1-1.	
b. During decompression and repressurization, the atmosphere pressure and composition control logic must maintain PO_2 within viable limits but no greater than 3.53 psia.	
c. Reduced and emergency operational level control bands are shown in Figure A1-2.	
3. **Atmosphere Diluent**	
a. Gas	Nitrogen
b. Partial pressure	Diluent
4. **Carbon Dioxide Partial Pressure, mm Hg**	
a. Nominal operational level carbon dioxide partial pressure will be maintained below 3.0 mm Hg for maximum metabolic loads and R.Q. = 0.9 in all habitable areas.(b)	
b. Reduced operational level	3.0 - 12
c. Emergency operational level	12 - 15
5. **Trace Contaminants**	
Listing of expected space station trace contaminants, production rates and their maximum allowable concentrations during nominal, reduced, and emergency operational levels	Table A1-2
6. **Airborne Bacteria**	
Airborne bacteria will be maintained below the level defined (microbes/ft^3).	100
7. **Atmosphere Temperature and Humidity**	
a. Temperature, dry bulb temperature, T_{DP} F	
1. Nominal operational level	
(a) Range	65 - 75
(b) Capability for selecting and maintaining T_{DB} at any value within the range shown shall be provided within each module at an absolute pressure of 14.7 psia	
(c) Control tolerance on selected temperature	± 2
(d) In the event of a single sensible heat exchanger failure, T_{DB} shall be maintained between the range shown but selectability shall not be required.	

—continued

(a) See Table A1-3 for definition of operational levels.

(b) pCO_2 level in shower will be maintained below 4 mm Hg.

Table A1-1—*continued*

2. Reduced operational level	
(a) Lower range	55 - 63
(b) Upper range	77 - 90
3. Emergency operational level	
(a) Lower range	45 - 55
(b) Upper range	90 - 105
4. Range during quiescent period	40 - 110
b. Humidity, dew point temperature, T_{DP}, F	
1. Nominal operational level	46 - 57
2. Reduced operational level	
(a) Lower range	32 - 46
(b) Upper range	57 - 61
3. Emergency operational level	
(a) Lower range	0 - 32
(b) Upper range	61 - 65
4. Atmosphere T_{DP} will be at least 10 F lower than T_{DB} during nominal operational level	
5. Atmosphere relative humidity shall be greater than 5% for all operational levels	
8. Module Ventilation, fpm[a]	
a. Nominal design point	25
b. Range	
1. Nominal operational level	15 to 40
2. Reduced operational level	
(a) Upper	40 to 100
(b) Lower	10 to 15
3. Emergency operational level	
(a) Upper	100 to 200
(b) Lower	5 to 10

(a) Module ventilation rates apply to any free volume normally occupied by the crew in the performance of their routine duties. Supplemental fans

TABLE A1-2 MAXIMUM CONCENTRATION AND PRODUCTION RATE OF TRACE CONTAMINANTS[8]

Contaminant	Production Rates			
	Non-Biological (gm/day)	Biological[a] (gm/day)	Total (gm/day)	Maximum[b] Allowable Concentration (mg/m³)
Acetone	10.20	0.003	10.20	240
Acetaldehyde	2.50	0.0012	2.50	36
Acetic Acid	0.25		0.25	2.5
Acetylene	2.50		2.50	180
Acetonitrile	0.25		0.25	7
Acrolein	0.25		0.25	0.25
Allyl Alcohol	0.25		0.25	0.5
Ammonia	2.50	6.0	8.5	3.5
Amyl Acetate	0.25		0.25	53
Amyl Alcohol	0.25		0.25	36
Benzene	2.50		2.50	8
n-Butane	2.50		2.50	180
iso-Butane	0.25		0.25	180
Butene-1	2.50		2.50	180
cis-Butene-2	0.25		0.25	180
trans-Butene-2	2.50		2.50	180
1, 3 Butadiene	2.50		2.50	220
iso-Butylene	0.25		0.25	180
n-Butyl Alcohol	2.50	0.018	2.52	30
iso-Butyl Alcohol	0.25		0.25	30
sec-Butyl Alcohol	0.25		0.25	30
tert-Butyl Alcohol	0.25		0.25	30
Butyl Acetate	0.25		0.25	71
Butraldehydes	0.25		0.25	70
Butyric Acid	0.25		0.25	14
Carbon Disulfide	0.25		0.25	6
Carbon Monoxide	2.50	0.2	2.7	29
Carbon Tetrachloride	0.25		0.25	6.5
Carbonyl Sufide	0.25		0.25	25
Chlorine	0.25		0.25	1.5
Chloroacetone	0.25		0.25	100
Chlorobenzene	0.25		0.25	35
Chlorofluoromethane	0.25		0.25	24
Chloroform	2.50		2.50	24
Chloropropane	0.25		0.25	84
Caprylic Acid			0.25	155
Cumene	0.25		0.25	25
Cyclohexane	2.50		2.50	100
Cyclohexene	0.25		0.25	100
Cyclohexanol	0.25		0.25	20
Cyclopentane	0.25		0.25	100
Cyclopropane	0.25		0.25	100
Cyanamide	0.25		0.25	45

—continued

(a) This applies to nominal operational levels, reduced and emergency levels are TBD.

(b) For six crewmen.

Table A1-2 — *continued*

	Production Rates			
Contaminant	Non-Biological (gm/day)	Biological[a] (gm/day)	Total (gm/day)	Maximum[b] Allowable Concentration (mg/m^3)
Decalin	0.25		0.25	5.0
1, 1 Dimethyl cyclohexane	0.25		0.25	120
trans 1, 2, Dimethyl Cyclohexane	0.25		0.25	120
2, 2 Dimethyl butane	0.25		0.25	93
Dimethyl Sulfide	0.25		0.25	15
1, 1 Dichloroethane	2.50		2.50	40
1, iso Butyl Ketone	0.25		0.25	29
1, 4 Dioxane	2.50		2.50	36
Dimethyl Furan	0.25		0.25	3.0
Dimethyl Hydrazine	0.25		0.25	0.1
Ethane	2.50		2.50	180
Ethyl Alcohol	2.50	0.06	2.56	190
Ethyl Acetate	2.50		2.50	140
Ethyl Acetylene	0.25		0.25	180
Ethyl Benzene	0.25		0.25	44
Ethylene Dichloride	0.25		0.25	40
Ethyl Ether	2.50		2.50	120
Ethyl Butyl Ether	0.25		0.25	200
Ethly Formate	2.50		2.50	30
Ethylene	2.50		2.50	180
Ethylene Glycol	0.25		0.25	114
trans 1, Methyl 3 Ethyl Cyclohexane	0.25		0.25	117
Ethyl Sulfide	0.25		0.25	97
Ethyl Mercaptan	0.25		0.25	2.5
Freon 11	2.50		2.50	560
Freon 12	2.50		2.50	500
Freon 21	0.25		0.25	420
Freon 22	0.25		0.25	350
Freon 23	0.25		0.25	12
Freon 113	0.25		0.25	700
Freon 114	2.50		2.50	700
Freon 114 unsym	0.25		0.25	700
Freon 125	0.25		0.25	25
Formaldehyde	0.25		0.25	0.6
Furan	0.25		0.25	3
Furfural	0.25		0.25	2
Hydrogen	2.50	0.3	2.8	215
Hydrogen Chloride	0.25		0.25	0.15
Hydrogen Fluoride	0.25		0.25	0.08
Hydrogen Sulfide	0	0.0005	0.0005	1.5
Heptane	0.25		0.25	200
Hexene-1	0.25		0.25	180
n-Hexane	2.50		2.50	180
Hexamethylcyclotrisiloxane[a]	0.25		0.25	240

—*continued*

(a) Silicone-type sensor catalyst poison.

Table A1-2 — *continued*

Contaminant	Production Rates Non-Biological (gm/day)	Biological[a] (gm/day)	Total (gm/day)	Maximum[b] Allowable Concentration (mg/m³)
Indole	0.25	0.6	0.85	126
Isoprene	0.25		0.25	140
Methylene Chloride	2.50		2.50	21
Methyl Acetate	2.50		2.50	61
Methyl Butyrate	0.25		0.25	30
Methyl Chloride	0.25		0.25	21
2-Methyl-1 Butene	0.25		0.25	1430
Methyl Chloroform	2.50		2.50	190
Methyl Furan-	0.25		0.25	3
Methyl Ethyl Ketone	2.50		2.50	59
Methyl Isobutyl Ketone	0.25		0.25	41
Methyl Isopropyl Ketone	2.50		2.50	70
Methyl Cyclohexane	0.25		0.25	200
Methyl Acetylene	0.25		0.25	165
Methyl Alcohol	2.50	0.06	2.56	26
3-Methyl Pentane	0.25		0.25	295
Methyl Methacrylate	0.25		0.25	41
Methan	29.5	3.6	33.1	1720
Mesitylene	0.25		0.25	2.5
mono Methyl Hydrazine	0.25		0.25	0.035
Methyl Mercaptan	0.25		0.25	2
Naphthalene	0.25		0.25	5.0
Nitric Oxide	0.25		0.25	32
Nitrogen Tetroxide	0.25		0.25	1.8
Nitrogen Dioxide	0.25		0.25	0.9
Nitrous Oxide	0.25		0.25	47
Octane	0.25		0.25	235
Propylene	2.50		2.50	180
iso-Pantane	2.50		2.50	295
n-Pentane	2.50		2.50	295
Pentene-1	0.25		0.25	180
Pentent-2	0.25		0.25	180
Propane	2.50		2.50	180
n-Propyl Acetate	0.25		0.25	84
n-Propyl Alochol	2.50		2.50	75
iso-Propyl Alcohol	2.50		2.50	98
n-Propyl Benzene	0.25		0.25	44
iso-Propyl Chloride	0.25		0.25	260
iso-Propyl Ether	0.25		0.25	120
Proprionaldehyde	0.25		0.25	30
Propionic Acid	0.25		0.25	15
Propyl Mercaptan			0.25	82
Propylene Aldehyde	0.25		0.25	10
Pyruvic Acid		2.27	2.27	0.9
Phenol	0.25	2.27	2.52	1.9

—*continued*

Table A1-2 — *continued*

Contaminant	Production Rates Non-Biological (gm/day)	Biological[a] (gm/day)	Total (gm/day)	Maximum[b] Allowable Concentration (mg/m^3)
Skatol			0.25	141
Sulfur Dioxide	0.25		0.25	0.8
Styrene	0.25		0.25	42
Tetrachloroethylene	0.25		0.25	67
Tetrafluoroethylene	0.25		0.25	205
Tetrahydrofurane	0.25		0.25	59
Toluene	2.50		2.50	75
Trichloroethylene	0		0	(a)
1, 2, 4, Trimethyl Bezene	0.25		0.25	49
1, 1, 3 Thrimethyl cyclohexane	0.25		0.25	140
Valeraldehyde			0.25	70
Valeric Acid			0.25	110
Vinyl Chloride	2.50		2.50	130
Vinyl Methyl Ether	0.25		0.25	60
Vinyldene Chloride	0.25		0.25	20
O-Xylene	2.50		2.50	44
m-Xylene	2.50		2.50	44
p-Xylene	2.50		2.50	44

—*continued*

(a) Not allowed on Space Station

Table A1-2 — *continued*

Pertinent Chemical Synonyms for Table 5

2-Butanone = Methyl ethyl ketone
Chlorodifluoromethane = Freon 22
Crotonaldehyde = propylene aldehyde
Decahydronaphthalene = Decalin
1, 2 Dichloroethane = Ethylene chloride = Ethylene dichloride
Dichlorodifluoromethane = Freon 12
Dichlorofluoromethane = Freon 21
Dichlorotetrafluorethane = Freon 114
p-Dioxane = 1, 4 Dioxane
2-Methyl butanone-3 = 3-Methyl 2 Butanone = Methyl isopropyl ketone
Methoxy ethane = Vinyl methyl ether
Propene = Propylene
Propyne = Propine + Methyl acetylene
Pentafluoroethane = Freon 125
Perchloroethylene = Tetrachloroethylene
Trichlorofluoromethane = Freon 11
Trichlorotrifluoroethane = Freon 113
Trifluoromethane = Fluoroform = Freon 23
1, 3, 5 Trimethyl benzene = mesitylene

TABLE A1-3 EC/LSS OPERATION LEVELS(8)

1. The EC/LSS shall have three operational levels: nominal, reduced and emergency.
   a. Nominal operational level is defined as the level of performance for which the system was designed.
   b. Reduced operational level is defined as a level of performance lower than that for which the system was designed, but adequate for personnel safety.
   c. Emergency operation level is defined as a level of performance sufficient only for personnel survival.
2. Operational level and action time after failure or maintenance event shall be as cited in Table A1-4.
3. For Space Station parameter(s) under EC/LSS control, control tolerances will be within the stated operational level limits. Transient deviation of a parameter beyond the stated operational level limits will be allowed to accommodate fault detection instrumentation tolerances. Deviation of a parameter beyond its specified operational limits and which exceeds the fault detection instrumentation tolerances will require the implementation of an alternate[a] means to return the parameter to an acceptable operational level.

(a) An alternate means for performing a Space Station function may be (a) an independent subsystem, (b) additional equipment within a subsystem, (c) a contingency capability of the equipment which is not failed by the same media as the primary capability or (d) a planned contingency procedure.

TABLE A1-4 OPERATIONAL LEVEL AND ACTION TIME AFTER FAILURE OR MAINTENANCE EVENT(8)

Event Description	Resulting Operational Levels	Action Time
The following events will not immediately lead to operation at reduced or emergency levels: a. Failure of any single component b. A subsystem inactive for maintenance c. A subsystem inactive due to isolation of the volume containing the subsystem.	Nominal	System will have sufficient redundancy or capability to permit an eight hour delay before initiating repair action
The following events will not lead to operation at emergency levels: a. Any combination of a failure of a single component in the prime subsystem and a failure in the backup equipment b. Any combination of a subsystem inactive for maintenance and a failure in the backup equipment c. Any combination of a subsystem inactive due to isolation of the volume containing the subsystem and a failure in the redundant subsystem.	Reduced	Crew will immediately initiate repair activities.
The following events may result in an immediate emergency situation:[a] Any combination of inactivity of both the prime and redundant subsystems due to failure, scheduled maintenance, or isolation of a volume and a failure or depletion of expendables in the backup equipment.	Emergency	Crew will immediately initiate emergency procedures including repair activities. If repair is not possible, functions will be maintained at reduced operation level for 14 days using emergency expendables.

(a) An emergency situation is operation in a degraded mode such that a subsequent failure may result in loss of crew.

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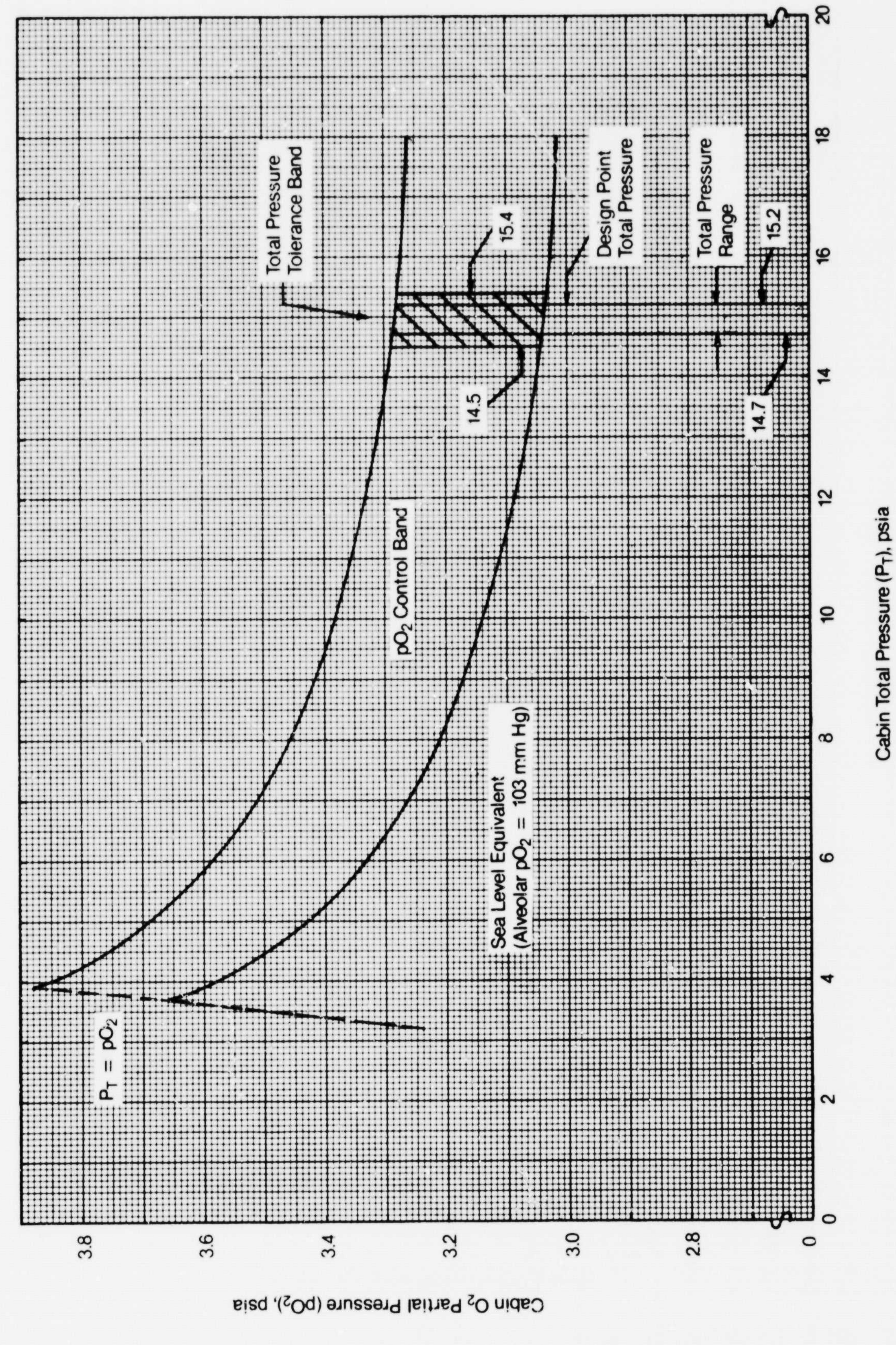


FIGURE A1-1 CABIN pO_2 CONTROL BAND vs CABIN TOTAL PRESSURE FOR NOMINAL OPERATIONAL LEVEL(8)

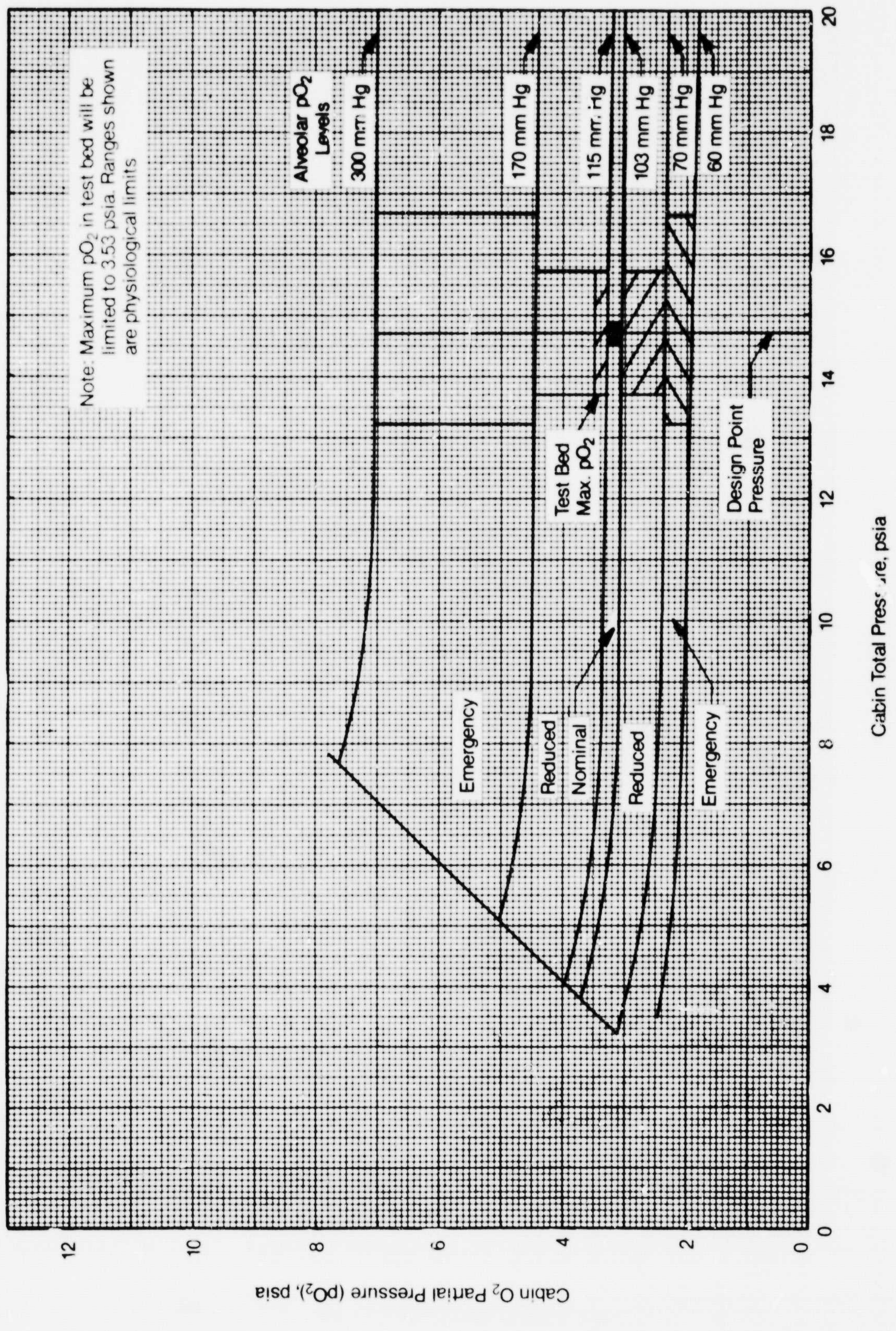


FIGURE A1-2 CABIN pO_2 CONTROL BANDS vs CABIN TOTAL PRESSURE FOR NOMINAL, REDUCED AND EMERGENCY OPERATIONAL LIMITS(8)

APPENDIX 2

H_2 MONITOR PERFORMANCE CHARACTERISTICS

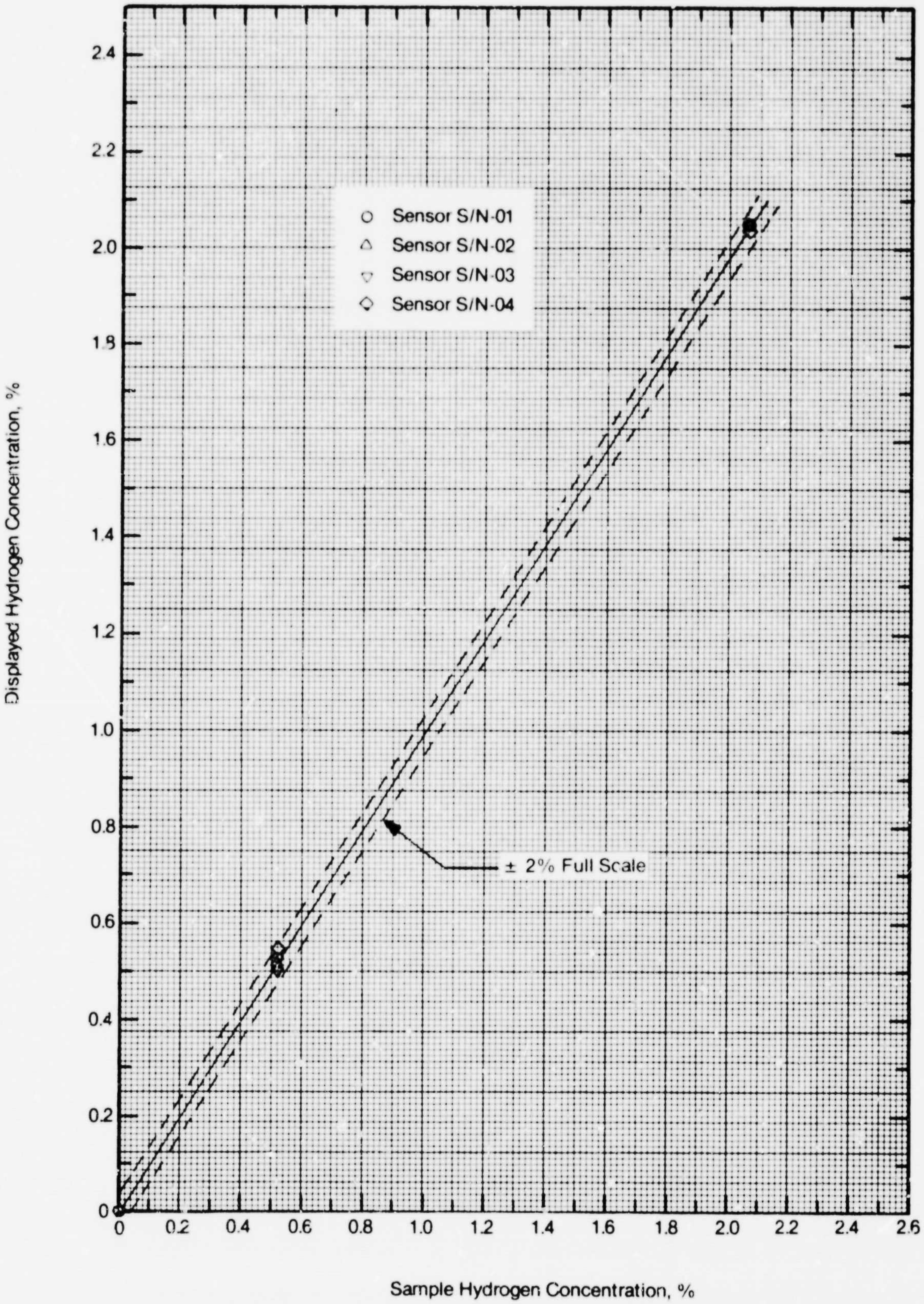


FIGURE A2-1 TRHS LINEARITY AND REPRODUCIBILITY

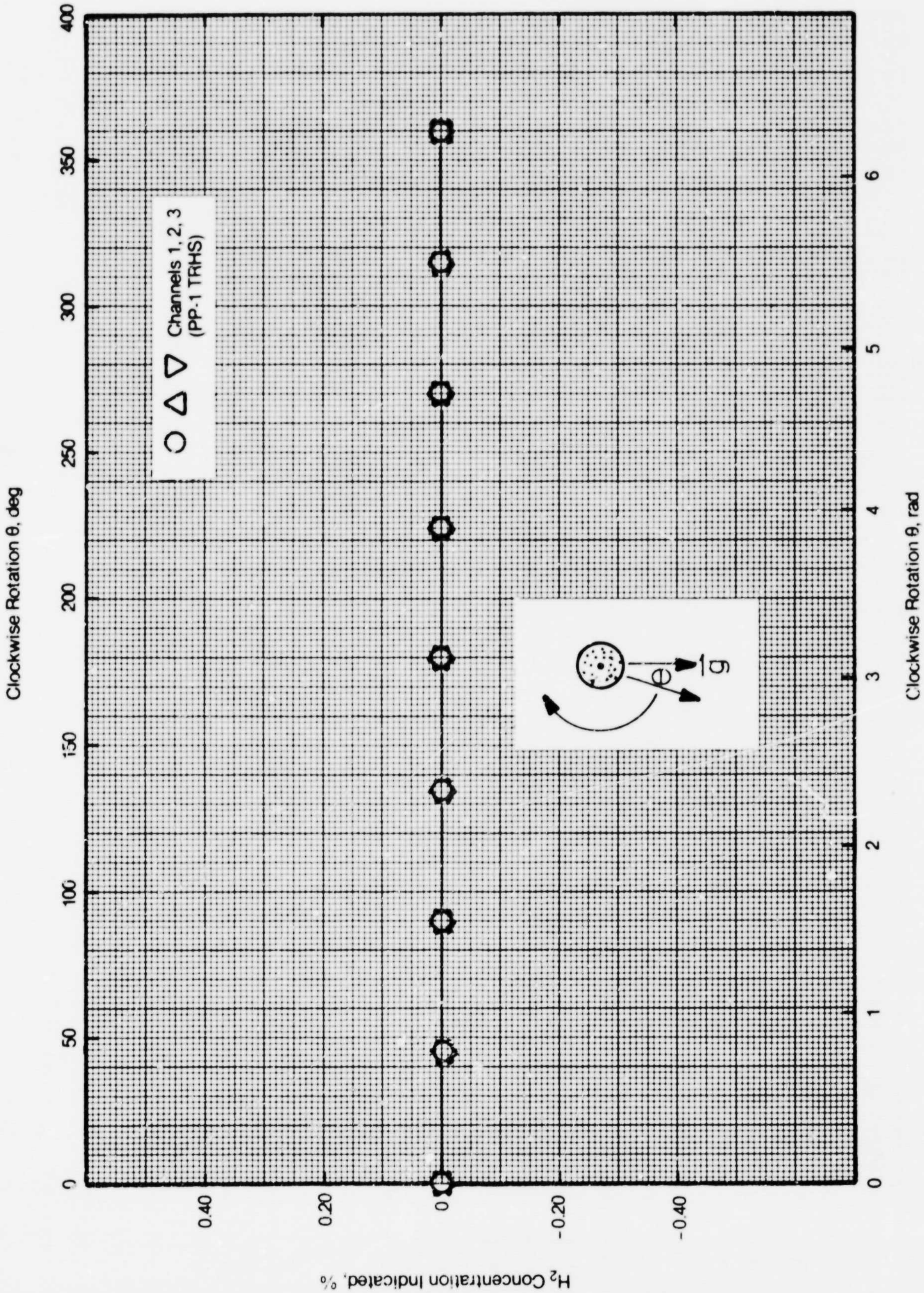


FIGURE A2-2 TRHS AXIAL POSITION SENSITIVITY IN AIR

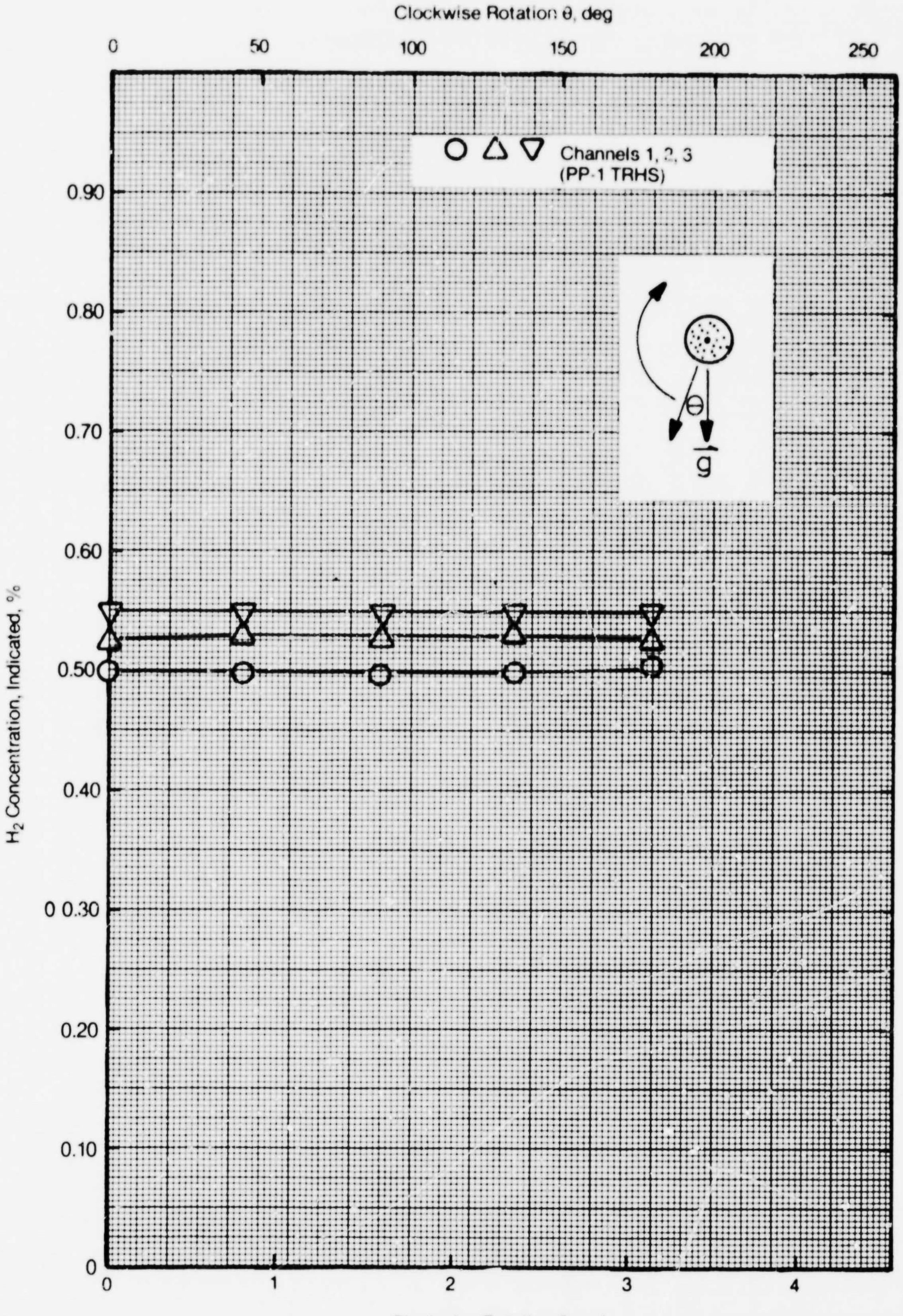


FIGURE A2-3 TRHS AXIAL POSITION SENSITIVITY IN 0.5% H_2

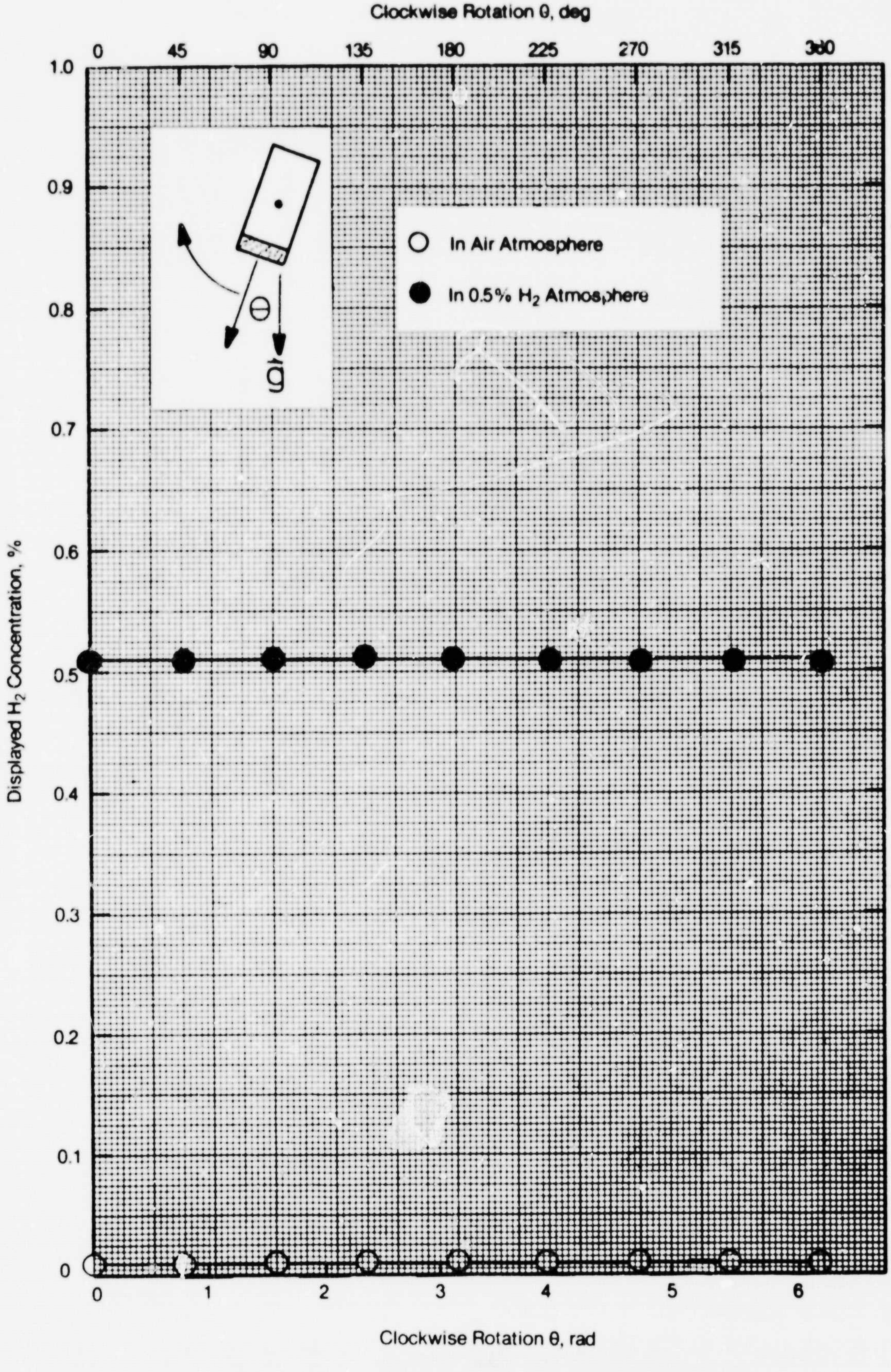
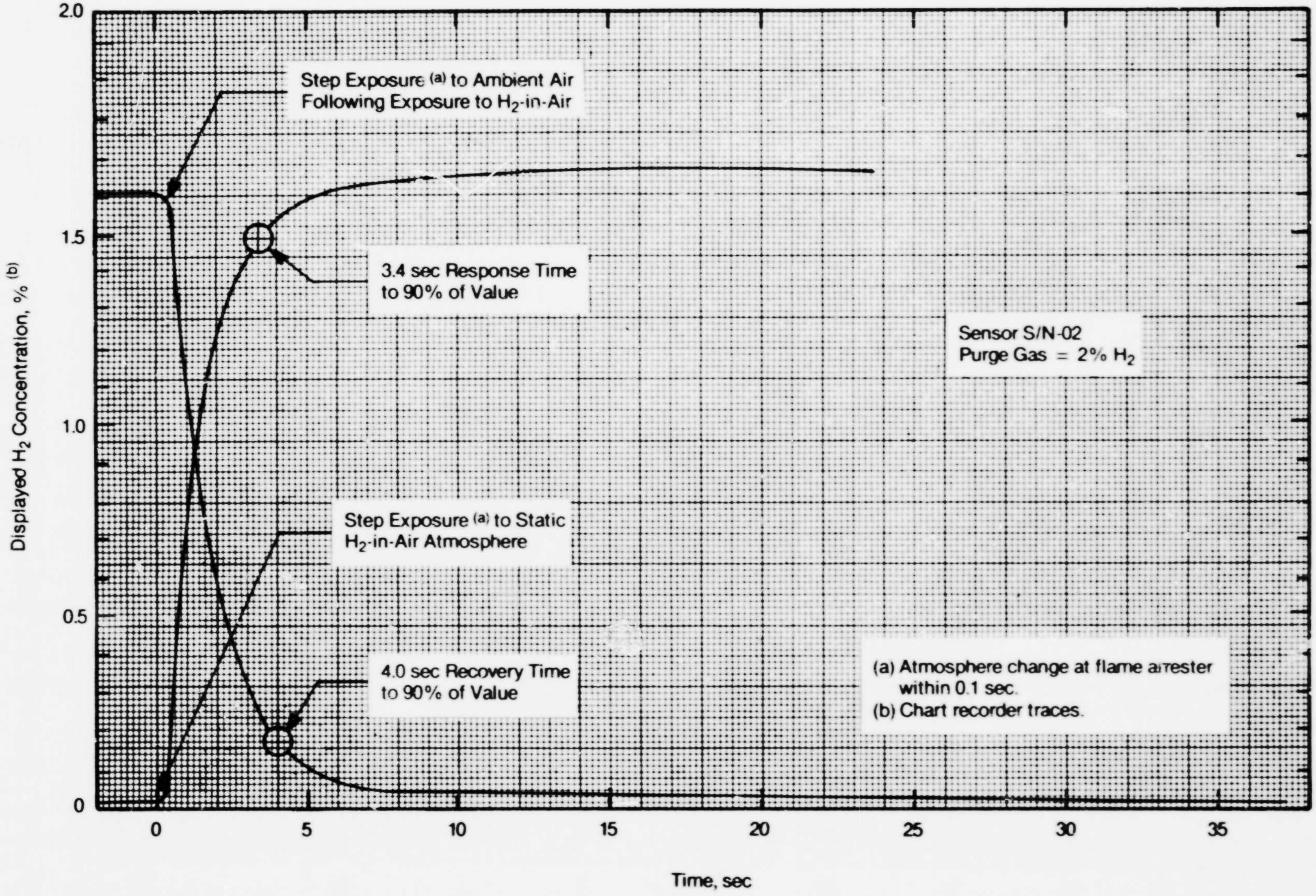


FIGURE A2-4 TRHS RADIAL POSITION SENSITIVITY



(a) Atmosphere change at flame arrester within 0.1 sec.
(b) Chart recorder traces.

FIGURE A2-5 TRHS RESPONSE AND RECOVERY TIMES

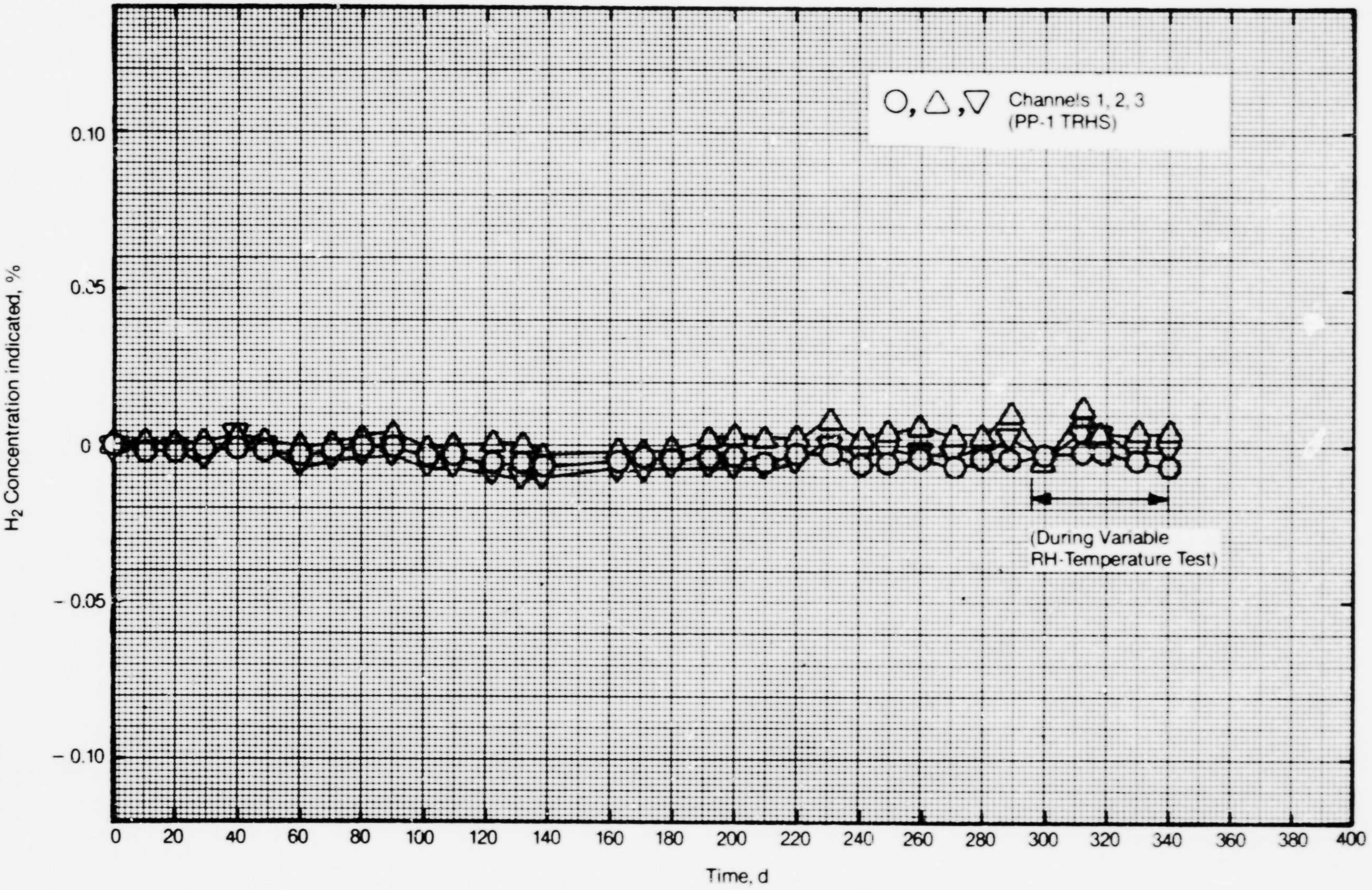


FIGURE A2-6 TRHS ZERO STABILITY

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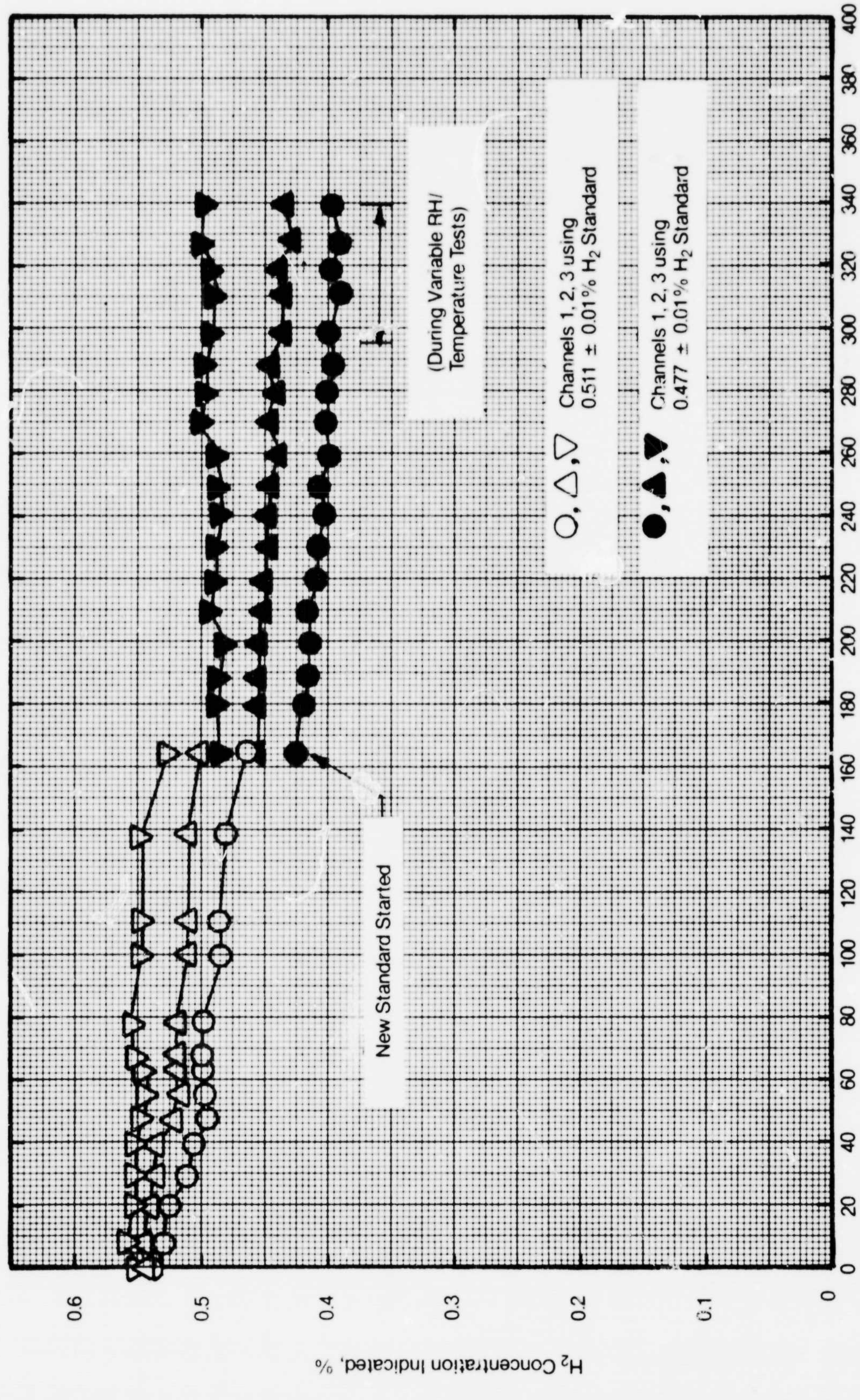

FIGURE A2-7 TRHS SPAN CALIBRATION STABILITY (PP-1 SENSOR)

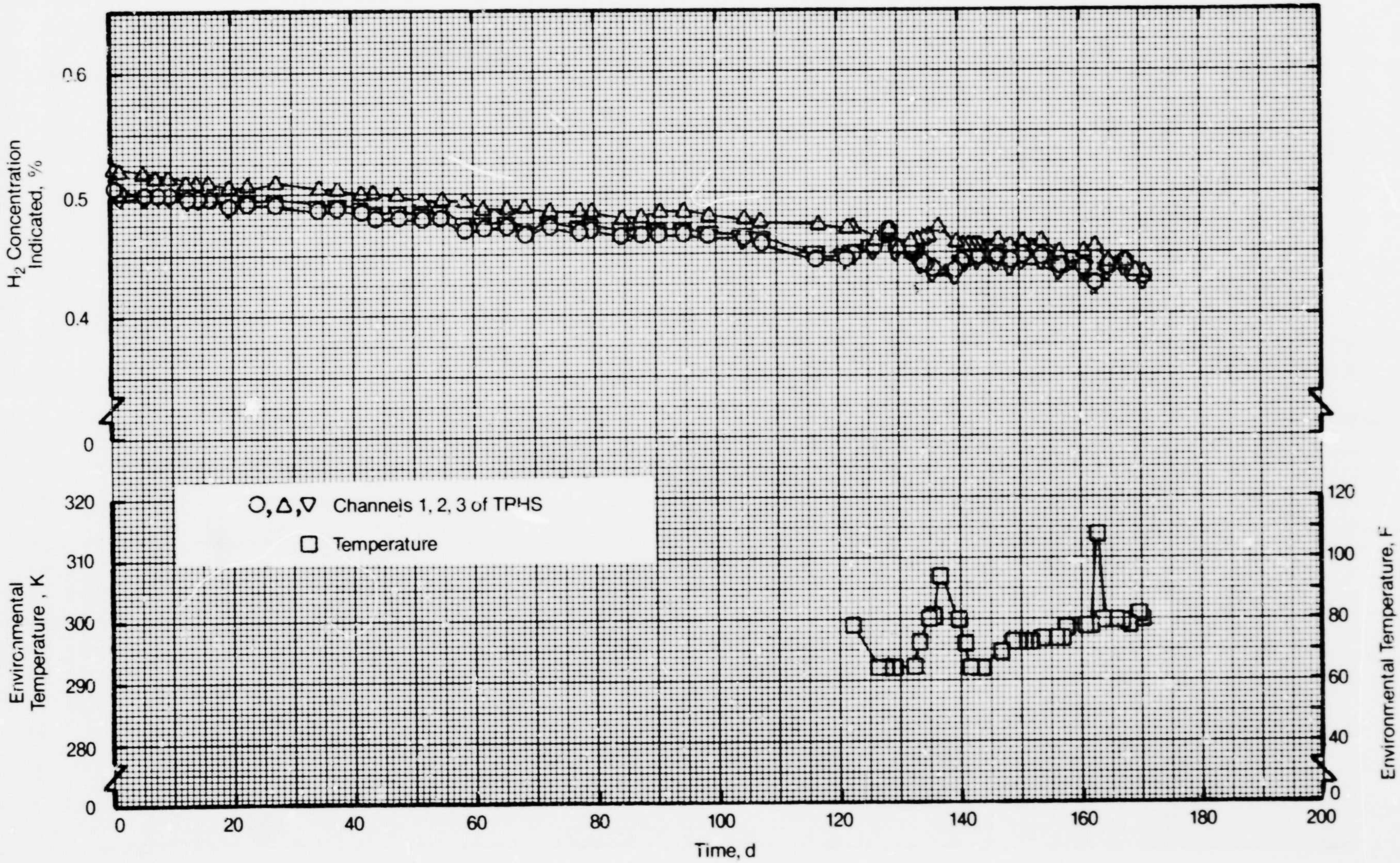

FIGURE A2-8 TPHS SPAN CALIBRATION STABILITY (PP-2 SENSOR)

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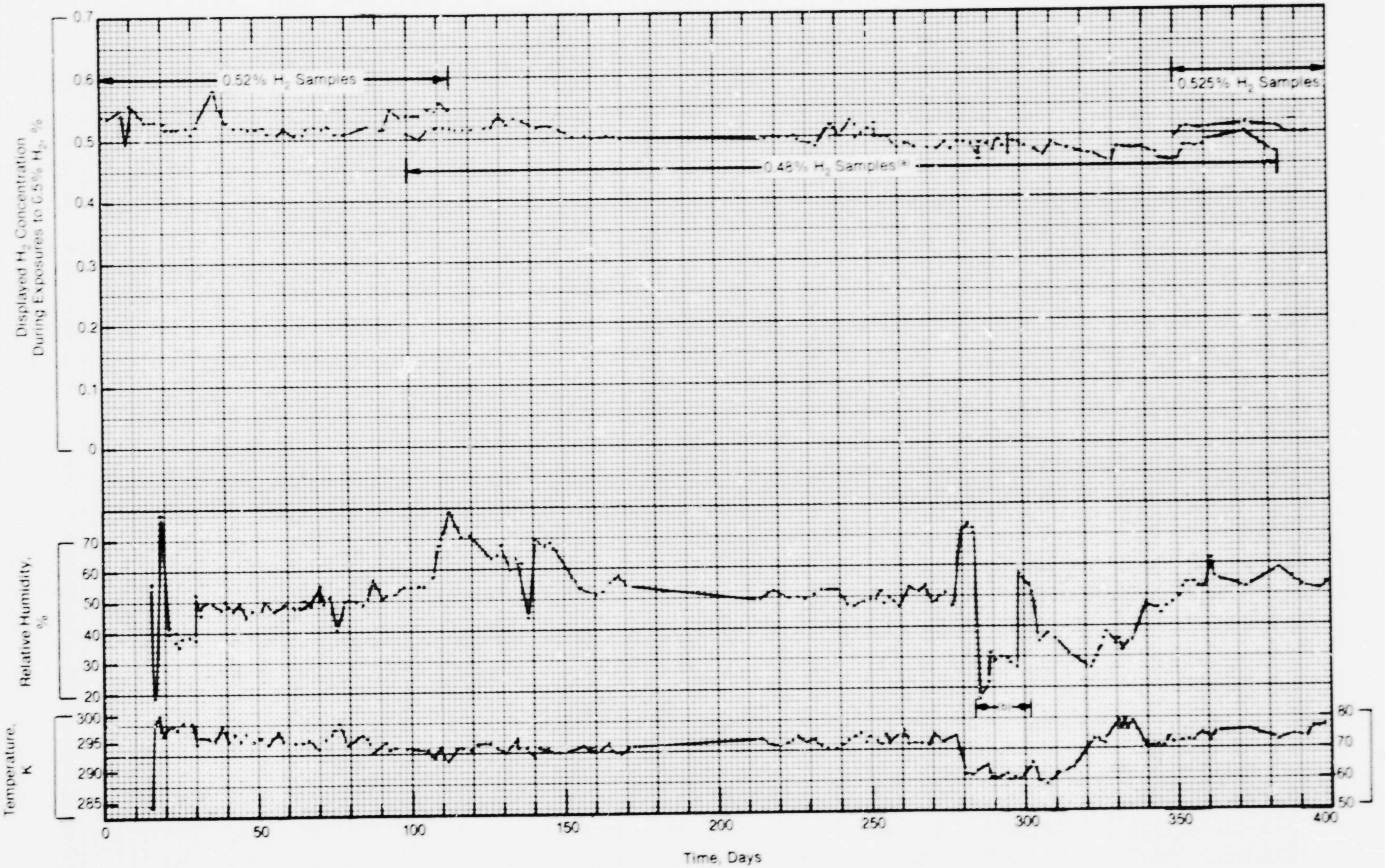

(a) Run in parallel with 0.52% samples, days 100-114, and in parallel with 0.525% H_2 samples, days 351-383.
(b) RH values in question due to dew point sensor malfunction.
(c) Without in situ calibration; channel 1 manually selected.

FIGURE A2-9 TRHS SPAN STABILITY (SENSOR S/N-04[c]) DURING VARIABLE HUMIDITY AND TEMPERATURE CONDITIONS

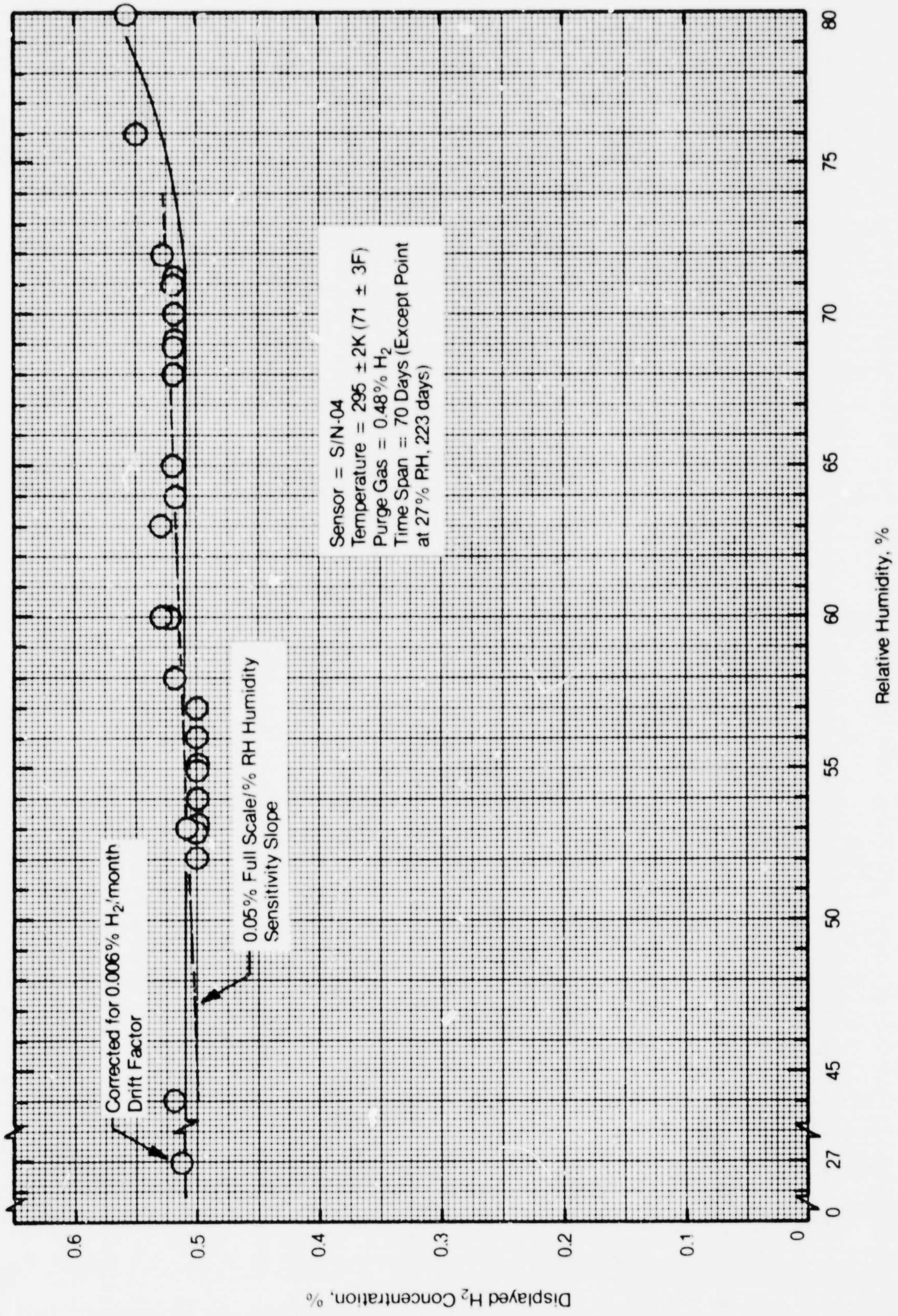

FIGURE A2-10 TRHS RELATIVE HUMIDITY SENSITIVITY

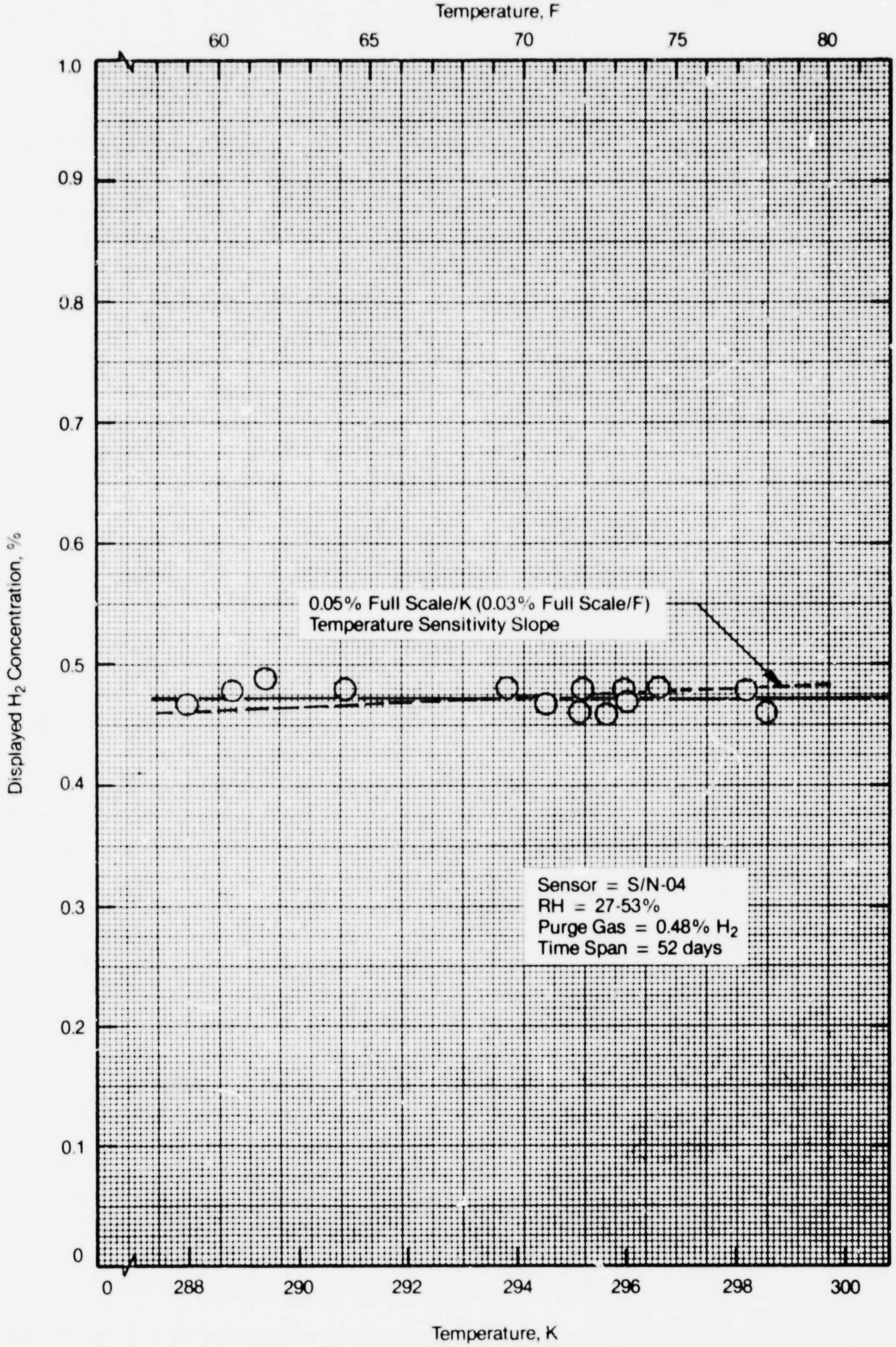

FIGURE A2-11 TRHS TEMPERATURE SENSITIVITY

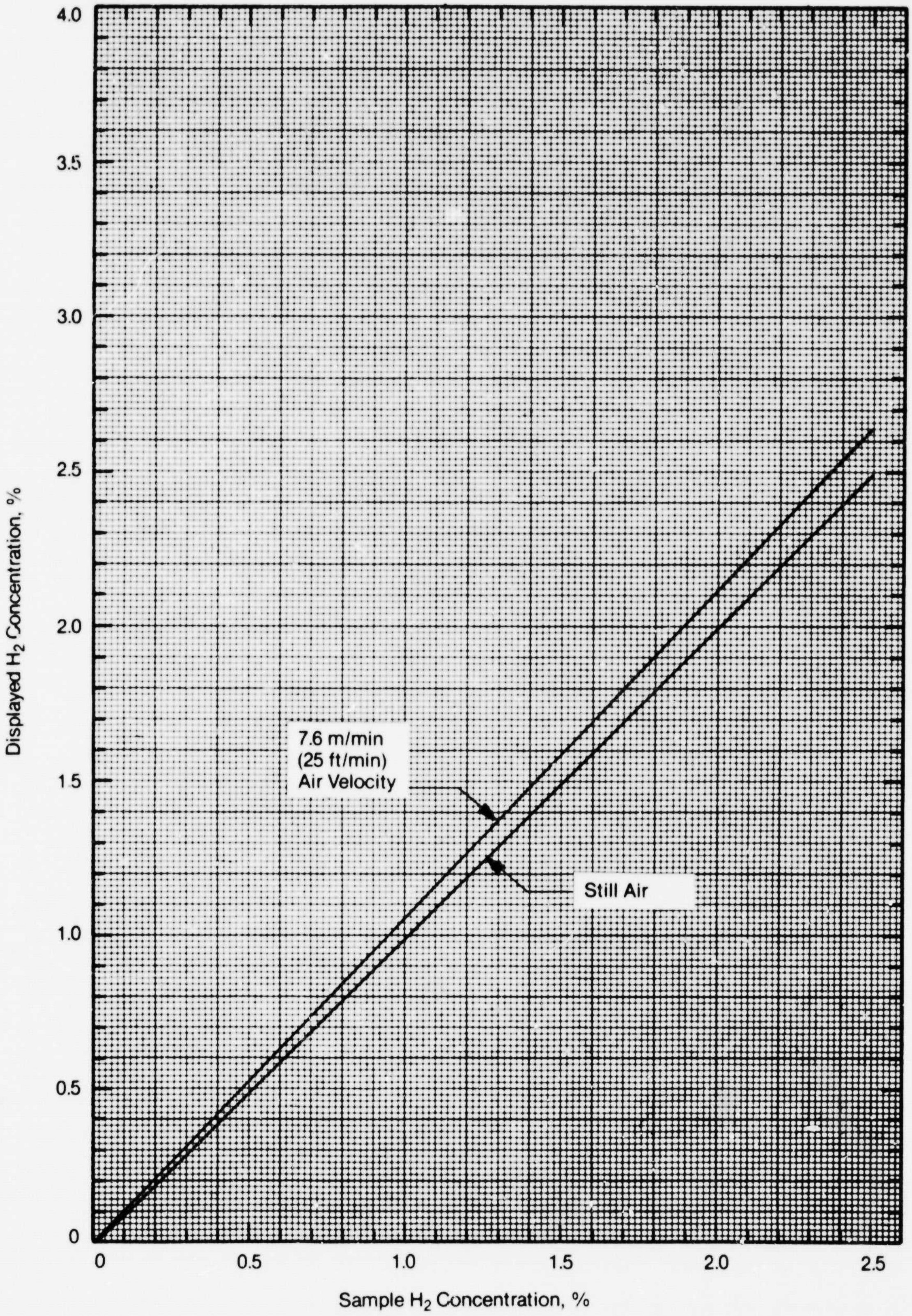

FIGURE A2-12 PROJECTED TRHS DRAFT SENSITIVITY