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PERFORMANCE CHARACTERISTICS OF LIQUID-VAPOR SENSORS OPERATING IN A REDUCED GRAVITY ENVIRONMENT

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An experimental investigation was conducted to observe the liquid retention characteristics of certain liquid-vapor sensors operating in low gravity environments. The complicated nature of these characteristics prevented analytical predictions, hence, all results were derived from Marshall Space Flight Center (MSFC) drop tower data. The results indicated that sensor liquid containment was sufficient in most cases to cause improper operation in low gravity fields. Liquid trapped on the sensing elements produced sensor measurements corresponding to uniform liquid mediums, although the sensors were actually in a vapor environment.

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PERFORMANCE CHARACTERISTICS OF LIQUID-VAPOR SENSORS OPERATING IN A REDUCED GRAVITY ENVIRONMENT

SUMMARY

The applicability of seven liquid vapor sensors for use in low gravity environments has been experimentally investigated. All investigations were conducted in the MSFC drop tower facility which provides test durations of approximately four seconds and gravity levels ranging from 5×10^{-4} to 0.03 of standard earth gravity (g_e). The experiments were executed by initially locating the sensor unit below the liquid level in a transparent container of petroleum ether, then during the test slowly pulling the sensor above the liquid level. Sensor reaction to this process was recorded by a motion picture camera which provided data for visual analysis. Electrical signals from the sensor were also obtained by utilization of a telemetry unit.

The results of the study definitely demonstrated that most of the sensors were unreliable in low gravity environments. In general, during the low gravity test periods the probe sensing elements retained sufficient liquid to prevent sensor identification of the true environment. The quantity of liquid trapped by each sensor was dependent on gravity level and probe geometry.

Some of the sensors did indicate the correct environment when placed in certain orientations relative to the applied gravity force. However, a sensor must properly operate independent of orientation to be considered reliable. Also, successful operation of the sensors at the gravity levels used in this investigation does not insure successful operation at lower gravity levels.

A 16 mm film entitled "Liquid-Vapor Sensor Tests, MSFC Drop Tower Facility" presents typical results from the drop tower tests discussed herein. The film can be obtained on loan by ordering Film Number 9-07307 from:

George C. Marshall Space Flight Center
Photographic Branch
Marshall Space Flight Center, Alabama 35812

INTRODUCTION

The liquid-vapor sensor can be a valuable aid in evaluating propellant behavior during space vehicle flights. In relatively high gravity fields (acceleration $\geqq \frac{1}{4}\ g_e$) these devices operate effectively and offer a high degree of reliability because the gravity forces overcome surface tension effects which act to contain liquid around the sensor. Boost stage flight and powered flight of orbital stages supply sufficient thrust levels for adequate sensor operation.

At reduced gravity levels, however, the surface tension forces dominate gravity forces and allow the entrapment of liquid by the sensor. The quantity of liquid retained is a function of device geometry, acceleration level, and acceleration direction. It is important to note that only a thin film of liquid in a critical location can cause the sensor to indicate a liquid environment instead of the actual vapor environment.

Preceding the AS-203 LH_2 Low Gravity Flight Experiment*, an experimental study was initiated to study the effect of low gravity on the performance of the flight vehicle sensors. The complex geometric characteristics of the sensors prevented analytical predictions of the quantity of liquid that would adhere to the sensors in low gravity. Consequently, the probes were subjected to actual low gravity environments in the MSFC drop tower. Although support of the AS-203 mission was the initial objective of the study, its scope was later broadened to support design of sensors for future vehicles.

TEST APPARATUS AND PROCEDURES

The experimental results were obtained utilizing the MSFC drop tower facility. Major components of the facility** (Figure 1) are the drag shield, test package, and deceleration tube. During a drop the test package floats freely within the drag shield (Figure 2) which provides protection from drag and atmospheric disturbances. The drag shield

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*This was a full-scale flight experiment designed to simulate the earth orbital phase of the S-IVB/Saturn V lunar mission. The experiment and results are described in Reference 1.

**Refer to Reference 2 for details on the construction and operation of this facility.

descends along guide rails into a pneumatic tube which decelerates the drag shield/package combination at structurally acceptable levels.

Figure 3 depicts the experimental package with the primary constituents labeled. A nitrogen gas thruster system was used to provide a controlled thrust on the test package during a drop. The package acceleration could be varied from one drop to another by adjusting the pressure regulator. The small electric motor located above the transparent "Lucite" tank was used to raise the sensor from the liquid during the low gravity period. As illustrated in Figure 4, the sensor was connected to a graduated rod which meshed with the electric motor driving gear. A timer was programmed to actuate the electric motor at the instant of drag shield release. The motor speed was pre-selected to assure that the sensor would be above the liquid level before drop termination.

Prior to each drop the sensor was stationed approximately $\frac{1}{4}$ in. below the fluid level; then, during the low gravity period, the sensor was slowly lifted from the liquid. A motion picture camera viewed the sensor as it rose through the liquid, and a small sensing light darkened as the sensor indicated vapor.

Petroleum ether was chosen for the test fluid because it possesses certain physical properties similar to liquid hydrogen. Both fluids have a contact angle of zero degrees and nearly equal kinematic surface tensions. The density, surface tension, and viscosity of petroleum ether were measured at three different temperatures by the Materials Division of the MSFC Astronautics Laboratory. The following table lists these measurements.

TEST RESULTS

A summary of all tests is presented in Table 1. Seven different sensors were tested at gravity levels ranging from 5×10^{-4} to 0.03 of standard earth gravity. The transonics and concentric ring sensors were flight vehicle instrumentation for the AS-203 vehicle. The remaining sensors were tested to support design for future vehicles.

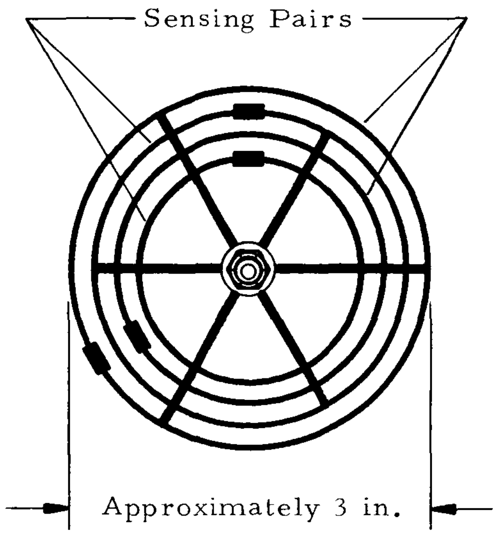
All tests were performed under conditions less severe than would be encountered during actual flight. Gravity levels on orbital flight vehicles are an order of magnitude less than the lowest gravity field used in the drop tower testing. Thus, successful performance in the drop tower does not necessarily insure proper operation on flight stages.

Another factor contributing to proper sensor functioning during the tests was the sensor lifting velocity of approximately 1.5 in./sec. The Weber Number (ratio of inertia to surface tension forces) was calculated for each sensor. These ratios, using maximum characteristic lengths, were found to possess magnitudes near unity. Consequently, inertia effects should not be ignored.

In the forthcoming discussions individual sensors are described briefly and their performance evaluated on the basis of test results.

Concentric Ring Sensor

The concentric ring sensor (manufactured by Minneapolis-Honeywell Corporation) has been used extensively on the S-IV and S-IVB stages and has been established to be reliable in near normal gravity fields (acceleration $\geqq \frac{1}{4}\, g_e$). This liquid-vapor indicator, illustrated in Figure 5A utilizes the capacitance difference between liquid and vapor for its basis of operation. It requires at least one paired set of elements for operation, but possesses two for increased reliability. The capacitance level is measured between the paired elements, and consequently, the environment is identified by capacitance magnitude. The geometric arrangement of the sensing elements is illustrated as follows:

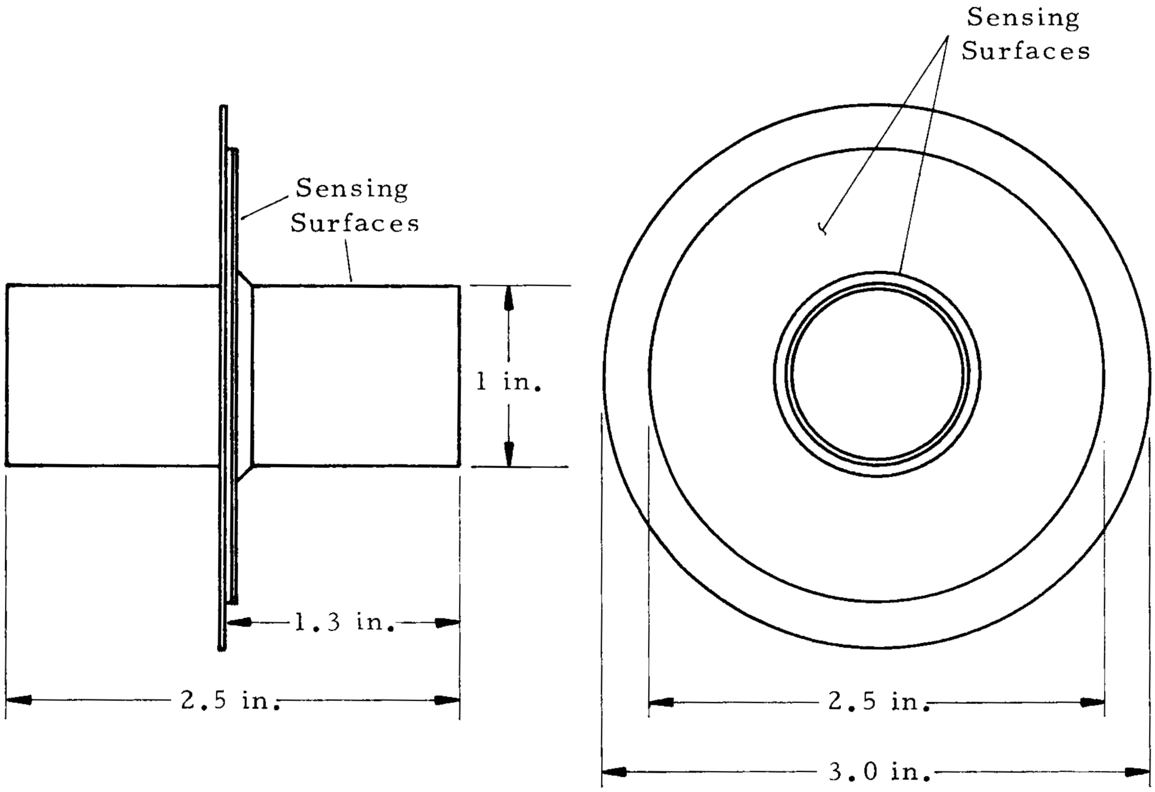


Results obtained from the drop tower tests revealed the inadequacy of this sensor for use in low gravity environments. Three tests were performed at 0.01 g_e with the sensor axis oriented parallel to the acceleration direction, and failure resulted. The gravity level was then increased to 0.03 g_e for an additional test, but sensor performance was not improved. The unsuccessful operation of the sensor can be mainly attributed to its geometric design, that is, the concentric ring elements serve as excellent surface tension liquid retention devices. These rings stabilize surface tension forces and decrease the effectiveness of gravity forces which tend to pull liquid from the sensor. Figure 6 provides visual evidence of the liquid retention capability of this type of sensor at gravity levels of 0.01 g_e and 0.03 g_e. It can be seen that the sensor traps a large quantity of fluid including a cone clinging from the sensor to the liquid surface. The liquid cone remains connected to the sensor until the bulk liquid weight destabilizes the surface tension forces and breaks the cone. Liquid remaining on the sensor then seeks a minimum energy stable configuration (Figure 7).

In all tests the sensing elements were completely enveloped in liquid, thus, the sensor erroneously indicated a liquid medium during the tests. Although no tests were performed with the sensor axis perpendicular to the acceleration direction (horizontal position), it is believed that the sensor would have exhibited similar characteristics. On the basis of test results it has been established that the concentric ring sensor is not suitable for use in low gravity environments.

Trans-Sonics Sensor

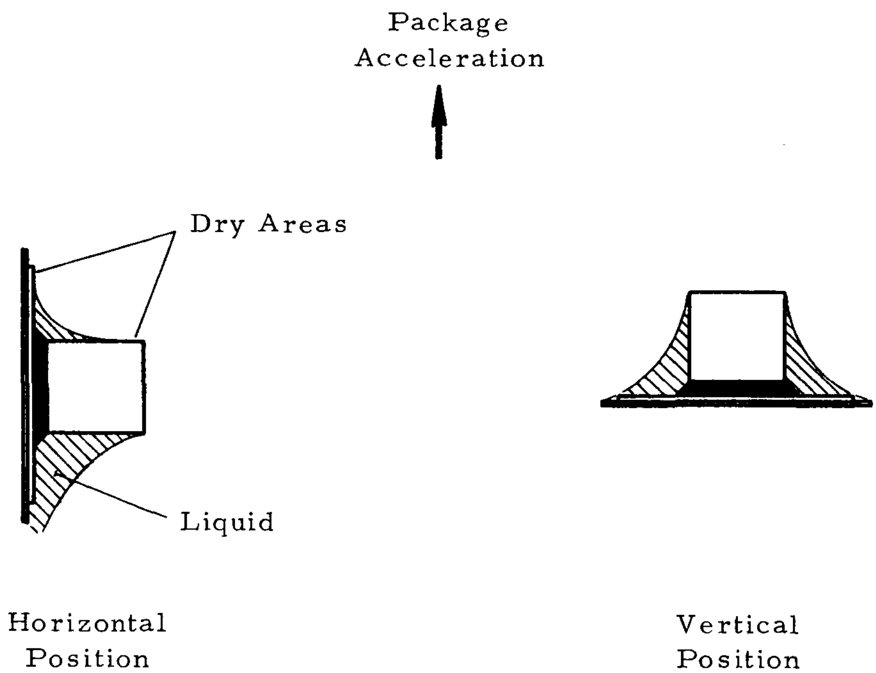
Another capacitance sensor tested was manufactured by Trans-Sonics Incorporated and is shown in Figure 5B. Like the concentric ring sensor, this type requires two sensing surfaces and measures the capacitance level between them. The following sketch illustrates its geometric design:



Two tests were conducted at 0.01 g_e in a vertical position with the cup oriented upward. In this position the disc shaped element supported sufficient liquid to completely cover the sensing surfaces as shown in Figure 8. The sensor operated unsuccessfully during both tests.

Two tests were then performed at 0.01 g_e with the sensor in a horizontal orientation (axis perpendicular to acceleration direction), and success was achieved. This success prompted the execution of two additional tests at the lower acceleration level of 0.001 g_e; the sensor again performed properly.

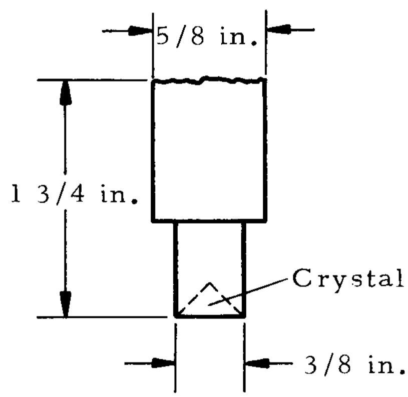
The liquid retained in the horizontal position was much less than in the vertical orientation. As illustrated in Figure 9, some liquid still adhered to the sensor and covered a major portion of the sensing elements, but the uppermost points on the elements were free of liquid. The curvature of the sensor enabled the gravity force to pull much of the liquid away and left only a small quantity on the top surface. The liquid remaining on the top surface then formed a minimum energy configuration. Since the contact angle of the test fluid is essentially zero, the liquid moved until it mated with the upper surfaces at this angle. A typical low gravity fluid configuration is shown below for horizontal and vertical sensor orientations.



It is quite possible that this sensor would not perform successfully in a near zero gravity ($a \leqq 10^{-5} g_e$) environment. The near zero gravity condition could allow liquid to cover all surfaces while seeking a minimum energy position.

Acoustic Probe

The acoustic probe (produced by Acoustica Corporation) operates on an entirely different principle than the capacitance type. This sensor, illustrated in Figure 5C, contains a vibrating crystal located at the small end of the probe. The crystal possesses a certain impedence in liquid environments and changes impedence when placed in vapor surroundings. Thus, the measured impedence provides the basis of operation for the device.

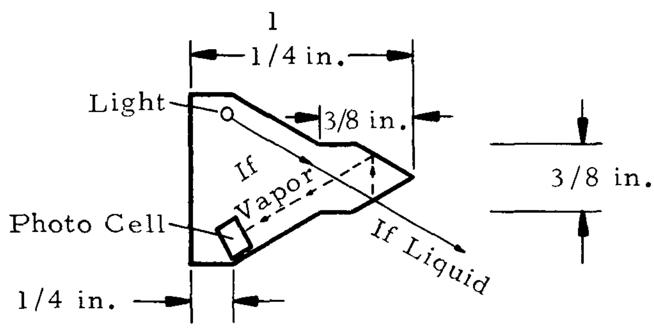


The acoustic probe cannot be considered an improvement over devices described previously. It failed to operate successfully during all drop tower tests. Three tests were conducted at 0.001 g_e with the axis parallel to the acceleration direction. A film of liquid adhered to the body of the sensor in addition to the large cone extending down into the liquid bulk. The low gravity test duration was never sufficient during this test series to allow the liquid cone to separate from the bulk liquid. However, if the cone had broken under controlled conditions, test results would not have been altered.

It is concluded that the geometry of this sensor is not suitable for operation in low gravity. If the sensor axis is parallel to the acceleration direction, a stable semi-spherical globule of liquid can very easily orient itself over the flat surface surrounding the crystal. If the axis is positioned perpendicular to the acceleration direction, the meniscus would be less stable, but it is believed that liquid sufficient to cause an erroneous signal would remain on the sensor. Noting the affinity possessed by the sensor for liquid domination, it seems unlikely that the probe would be successful in any position.

Optical Sensor

The optical probe, devised by Bendix Corporation and illustrated in Figure 5D, utilizes reflection of light to detect liquid and vapor environments. A ray of light directed toward a clear crystal will pass through if the crystal exterior is surrounded by liquid. A vapor exterior will cause the ray to reflect and strike a small photo cell. The reaction from the solar cell produces a signal identifying the medium as vapor. The following sketch illustrates the crystal design:



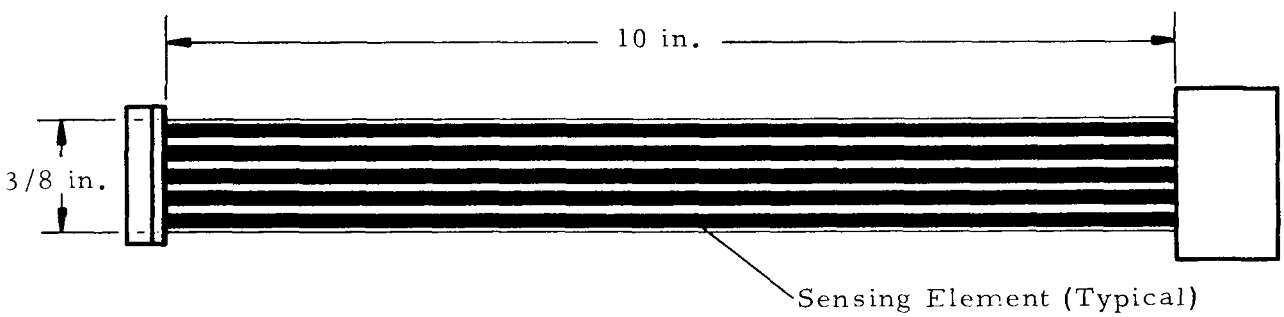
Three tests were performed at 0.001 g_e with the sensor axis perpendicular to the acceleration direction. All three tests indicated sensor failure, but not necessarily due to liquid retention problems. Figure 10 demonstrates that a large quantity of liquid adhered to the sensor base, but the presence of liquid on the crystal could not be definitely detected. Hence, two additional tests were conducted to investigate the effect of the photographic light on sensor operation. The fourth test was performed with a photographic light of low intensity; very marginal visual data resulted, but the sensor functioned properly. The fifth test was conducted with no camera light, thus no visual data was obtained, but the sensor signal was correct.

On the basis of test results it is probable that successful functioning of the sensor will occur in the horizontal position. However, if the sensor was positioned with the crystal oriented downward, success may not occur. It was observed from the motion picture film with the sensor oriented horizontally that a relatively large liquid quantity remained with the sensor base after the cone had separated; this phenomenon could cause failure.

Consequently, the sensor must be tested in the downward position before any positive conclusions can be made. This is scheduled in future tests.

Flat Cable Probe

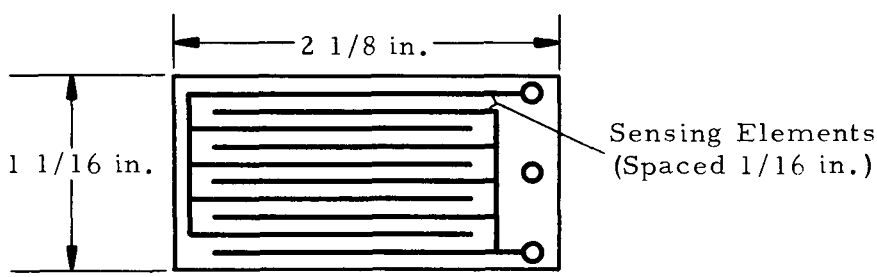
The flat cable probe, manufactured at MSFC, is another capacitance type sensor. In contrast to the point level sensors described previously, this device (Figure 5E) is designed to sense liquid level continuously. This is accomplished by measuring the capacitance magnitude which increases as the device acquires additional liquid. The sensing occurs between any two strips as shown in the following diagram.



Three tests were performed at 0.001 g_e with the probe placed vertically in the tank. Unlike previous tests the sensor was not moved during the drop. It was tested by allowing the liquid to seek its low gravity equilibrium shape and observing the probe response. Figure 11 illustrates the liquid behavior during a typical test. Note that the liquid moves up the tank wall and probe due to surface tension. The liquid climbed vertically along the sensor until an equilibrium state was reached. Thereafter, the probe indicated a liquid level at the equilibrium position which does not necessarily correspond to the nominal liquid level. Once wetted, the probe never became dry, establishing its inadequacy for low gravity applications. Thus, surface tension phenomenon was again the factor producing sensor malfunction.

Printed Circuit Probe

The printed circuit probe (Figure 5F) was devised by Trans-Sonics Inc, and is geometrically similar to the flat cable sensor. It is a capacitance type with the sensing elements placed on a thin flat plate. This probe was designed for local liquid detection; the length not being sufficient to serve as a continuous liquid level probe. The sensing element arrangement differs slightly from the flat cable type as shown by the sketch below.



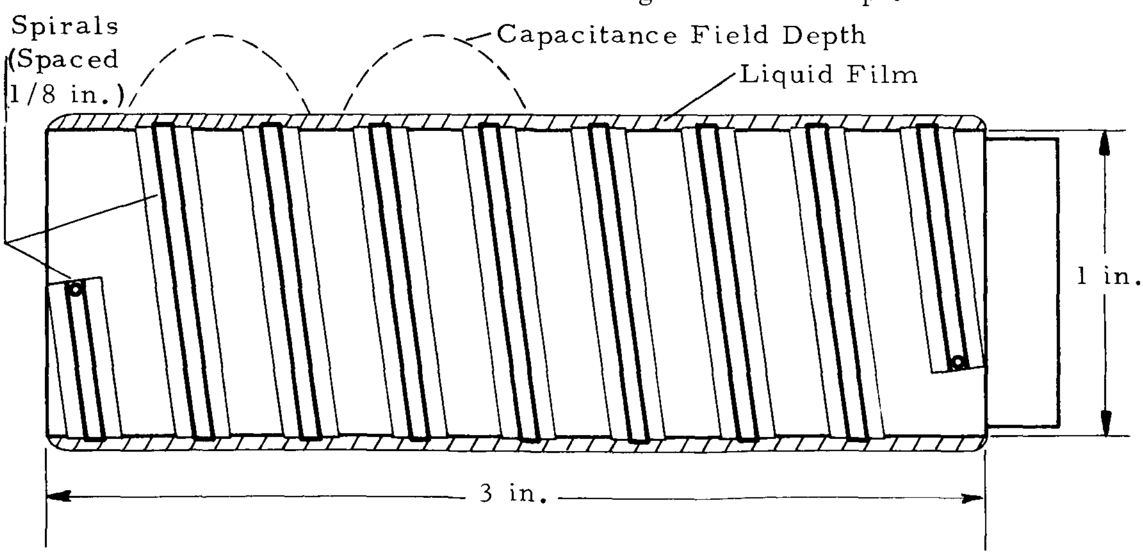
A major disadvantage of this sensor is its sensitivity to liquid presence. Although the major portion of the sensor may be dry, a small fluid globule will produce measurements indicating total liquid domination.

Test results verified the sensor's shortcomings. Two tests were conducted at $5 \times 10^{-4}\ g_e$ with the sensing elements in a vertical position (plane of sensor parallel to tank walls) to gain maximum advantage of the gravity forces.* The photographic data did not contribute to the understanding of the sensor's liquid retention characteristics. Because the sensor plate was oriented perpendicular to the camera view axis, visualization of liquid clinging to the probe could not be accomplished excluding the familiar cone extending into the bulk liquid (Figure 12). However, it was discerned that a fluid film covered the sensor during the test by noting a sizable quantity of liquid was expelled from the probe when the test package was decelerated at the end of the test.

This sensor was proven to be unsatisfactory for low gravity environments. Its inherent lack of sensitivity for vapor presence contributed largely toward failure. Low gravity conditions practically assure some liquid containment and, therefore, reduce the probability of sensor success to a minimum. In addition, the geometric design demonstrated no unique characteristics since liquid retention was not prevented.

Spiral Probe

The spiral probe, shown in Figure 5G, was another sensor devised by MSFC and is composed of a hollow cylinder with two spirals embedded along its length. Capacitance is measured between the two spiral sensing elements. Like most previous capacitance probes discussed, this sensor will indicate vapor if any portion of the sensing elements becomes dry. Also, it possesses the ability to sense vapor although covered by a thin film of liquid. The following sketch and discussion will facilitate the understanding of this concept.



*A horizontal orientation (sensor plane perpendicular to acceleration direction) would have assured failure due to the excellent liquid support provided by the flat surface.

The maximum capacitance is measured when the field depth is completely immersed in liquid. The capacitance level decreases as the field depth becomes exposed to vapor. Since uniform liquid mediums assure maximum capacitance, any reading less than maximum would denote a vapor environment.

Two tests were conducted at $5 \times 10^{-4}\ g_e$ with the cylindrical axis oriented perpendicular to the acceleration direction. Figure 14 illustrates the familiar liquid cone clinging to the probe. It should be noted that no liquid appears to be dominating the top surface, or at most only a small film is present. Resembling the tests of the transonic sensor in a horizontal position, the curvature of the spiral probe enabled much of the liquid to be pulled away.

Both tests performed under these conditions were successful; liquid containment did not prevent proper sensor operation. The test results appear promising but further testing is needed including tests with the cylindrical axis oriented parallel to the acceleration direction. These tests are scheduled in the near future.

Comparison With AS-203 Flight Results

As mentioned previously, the Tran-Sonics and concentric ring sensors were flight instrumentation aboard the S-IVB/203 vehicle. Since the propellant behavior during orbital coast was monitored by television inside the S-IVB liquid hydrogen tank, it was possible to determine the actual sensor environments. Also, the test sensors employed in the drop tower were full scale, thus, the use of scaling parameters was unnecessary. This permitted direct correlation between flight results and drop tower tests.

The flight data substantiated the drop tower results. Once wetted, the vehicle sensors indicated liquid throughout a major portion of the flight, whereas, the television data indicated vapor during certain phases of this time period. Thus, the combined flight and drop tower results provide strong evidence in support of the inadequacy of these liquid-vapor sensing devices.

CONCLUSIONS

It was concluded from the experimental investigations that all sensors, excluding the optical and spiral types, were inadequate for use in low gravity. The rejection of these sensors was based on the following guidelines.

(1) Since gravity levels used in the drop tower are an order of magnitude greater than acceleration levels encountered during orbital coast, drop tower test failure establishes inadequacy for low gravity applications.

(2) The sensor must properly operate independent of orientation relative to the acceleration direction, thus, any failure due to orientation also establishes inadequacy.

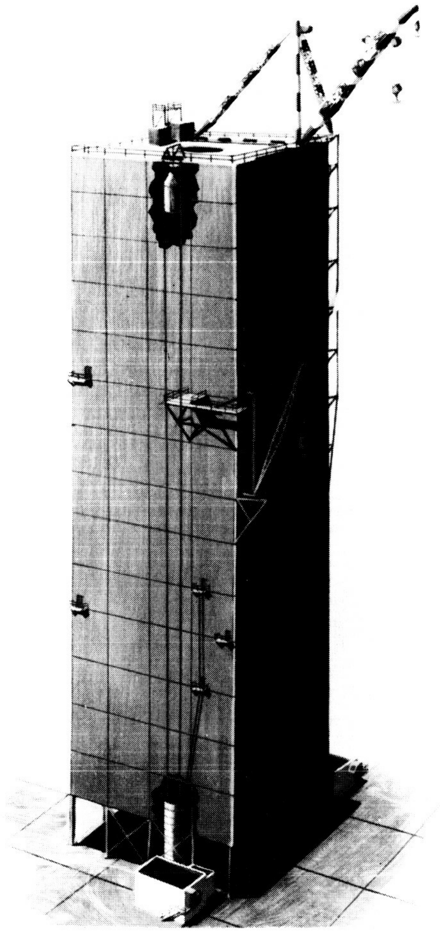
The spiral and optical probes were successful in the positions tested, however, these devices cannot be considered reliable until further qualification is accomplished.

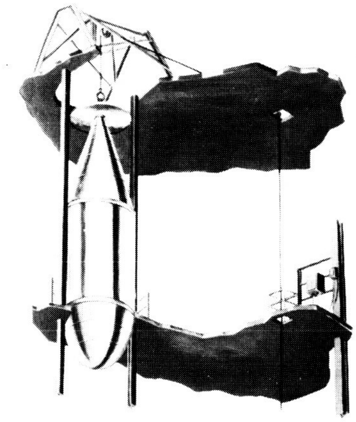
TABLE 1
SUMMARIZATION OF TEST RESULTS

Test No.	Acceleration Level, a/g_e	Sensor Type	Sensor Orientation	Sensor Performance
7F-1	0.01	Concentric Ring	Vertical	Unsuccessful
7F-2	0.01	Concentric Ring	Vertical	Unsuccessful
7F-4	0.01	Concentric Ring	Vertical	Unsuccessful
7F-6	0.03	Concentric Ring	Vertical	Unsuccessful
7F-7	0.01	Trans-Sonics	Vertical	Unsuccessful
7F-8	0.01	Trans-Sonics	Vertical	Unsuccessful
7F-9	0.01	Trans-Sonics	Horizontal	Successful
7F-10	0.01	Trans-Sonics	Horizontal	Successful
7F-11	0.001	Trans-Sonics	Horizontal	Successful
7F-12	0.001	Trans-Sonics	Horizontal	Successful
7F-15	0.001	Acoustic	Vertical	Unsuccessful
7F-16	0.001	Acoustic	Vertical	Unsuccessful
7F-17	0.001	Acoustic	Vertical	Unsuccessful
7G-1	0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
7G-2	0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
7G-3	0.001	Bendix (Light Prism)	Horizontal	Unsuccessful
7G-4	0.001	Bendix (Light Prism)	Horizontal	Successful
7G-5	0.001	Bendix (Light Prism)	Horizontal	Successful
7H-1	0.001	Flat Cable	Vertical	Unsuccessful
7H-2	0.001	Flat Cable	Vertical	Unsuccessful
7H-3	0.001	Flat Cable	Vertical	Unsuccessful

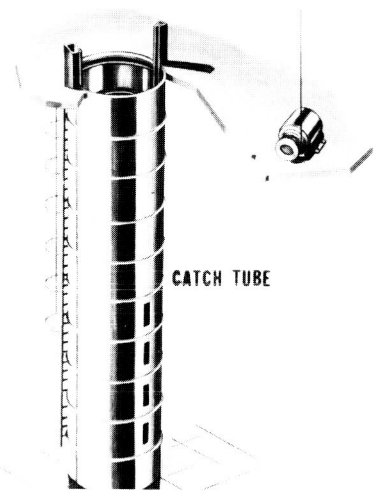
TABLE 1
SUMMARIZATION OF TEST RESULTS (CONT.)

Test No.	Acceleration Level, a/g_e	Sensor Type	Sensor Orientation	Sensor Performance
7J-1	0.0005	Printed Circuit	Vertical	Unsuccessful
7J-2	0.0005	Printed Circuit	Vertical	Unsuccessful
7K-1	0.0005	Spiral Probe	Horizontal	Successful
7K-2	0.0005	Spiral Probe	Horizontal	Successful





DRAG SHIELD



CAPABILITIES

PAYLOAD	
PRESENT	450 lbs.
FUTURE	1000 lbs.
LOW GRAVITY TEST RANGE	
MINIMUM	$10^{-5} g_o$
MAXIMUM	$4 \times 10^{-2} g_o$
DROP TIME (294')	4.135 sec.
TOTAL DROP WEIGHT	4000 lbs.
DECELERATION	less than 25 g's
INSTRUMENTATION TELEMETRY	20 channels
NON-DESTRUCTIVE TESTING	
ZERO TURN-AROUND TIME	

FIGURE 1. DROP TOWER FACILITY

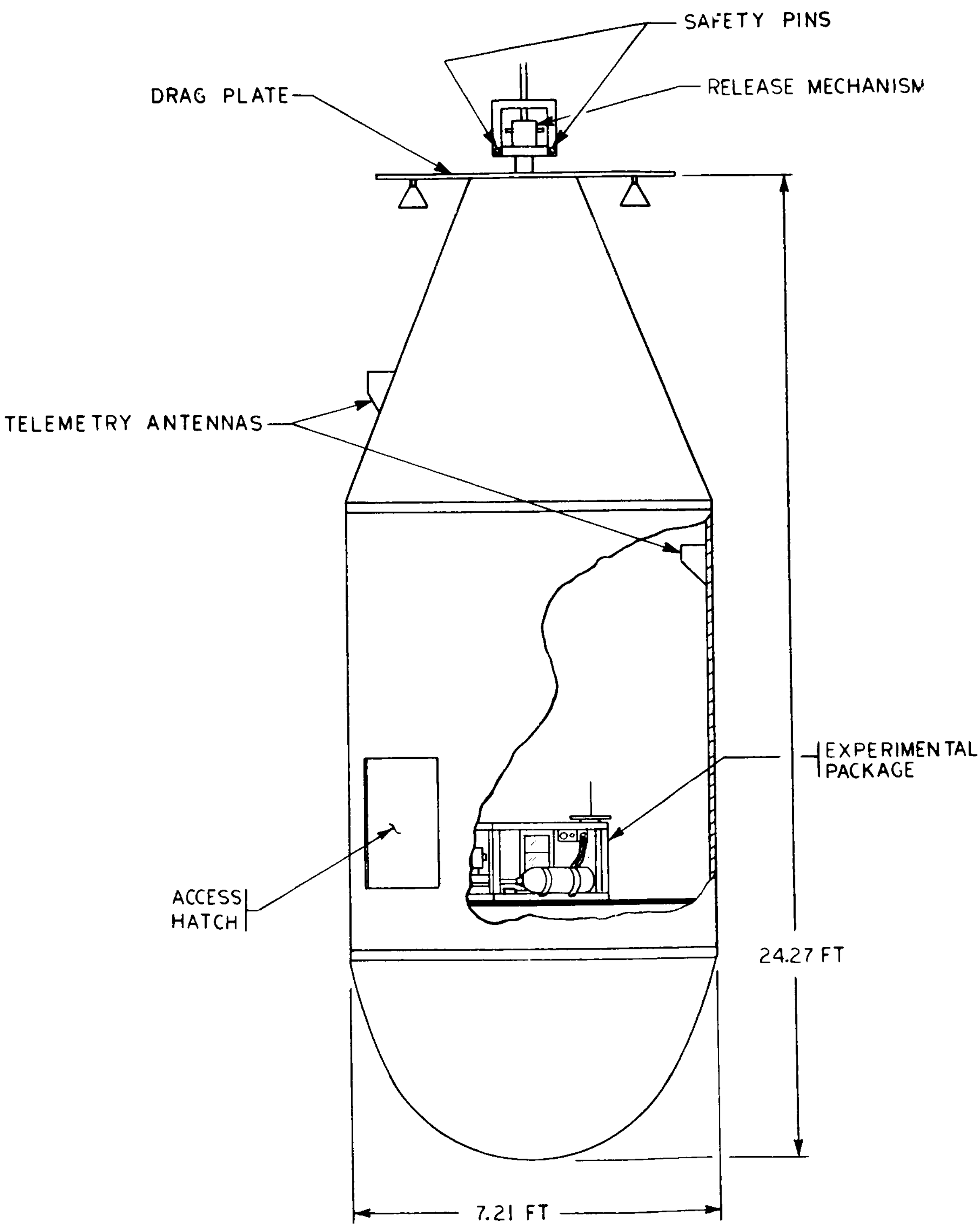


FIGURE 2. DRAG SHIELD

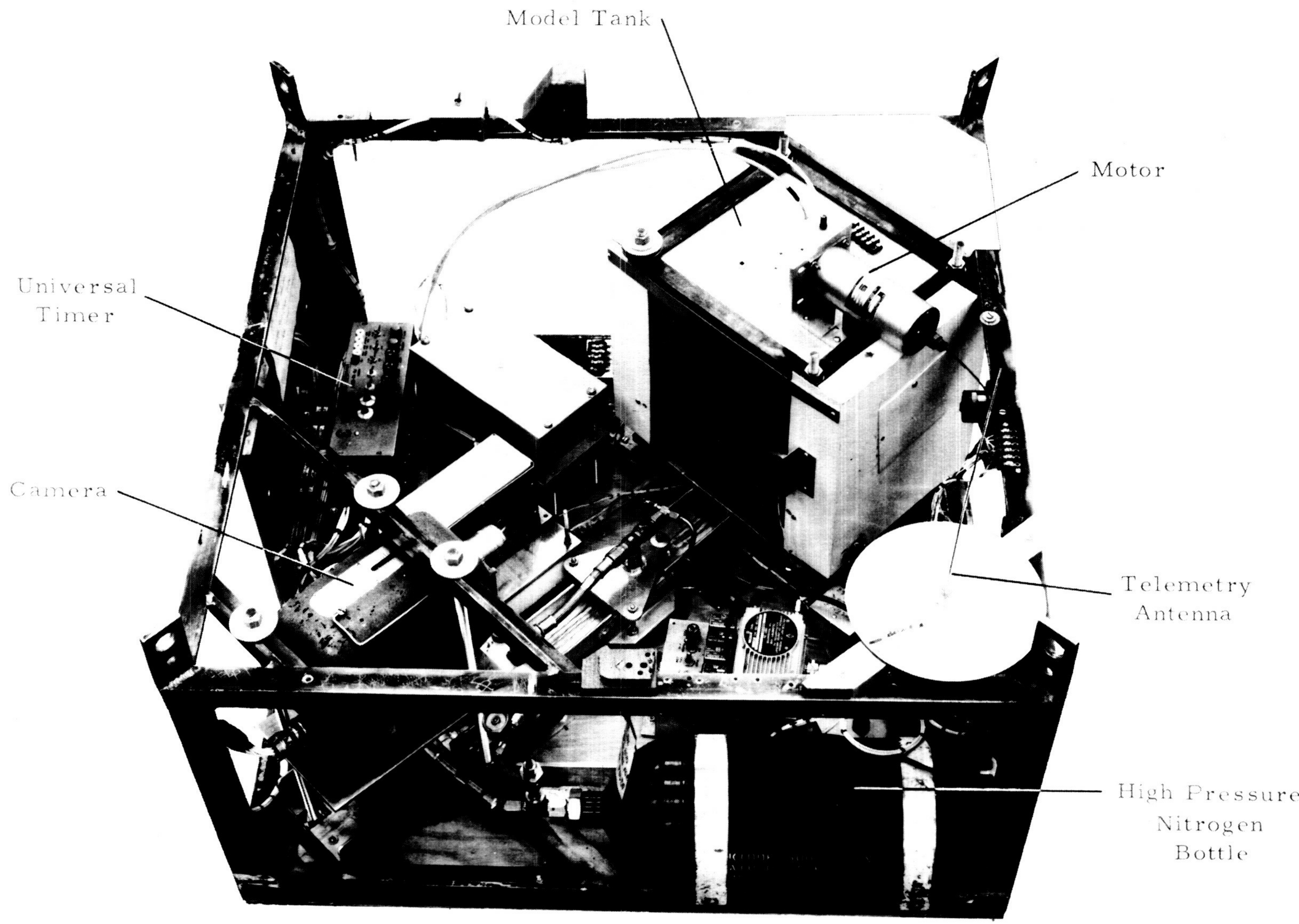


FIGURE 3. LIQUID VAPOR SENSOR EXPERIMENTAL PACKAGE

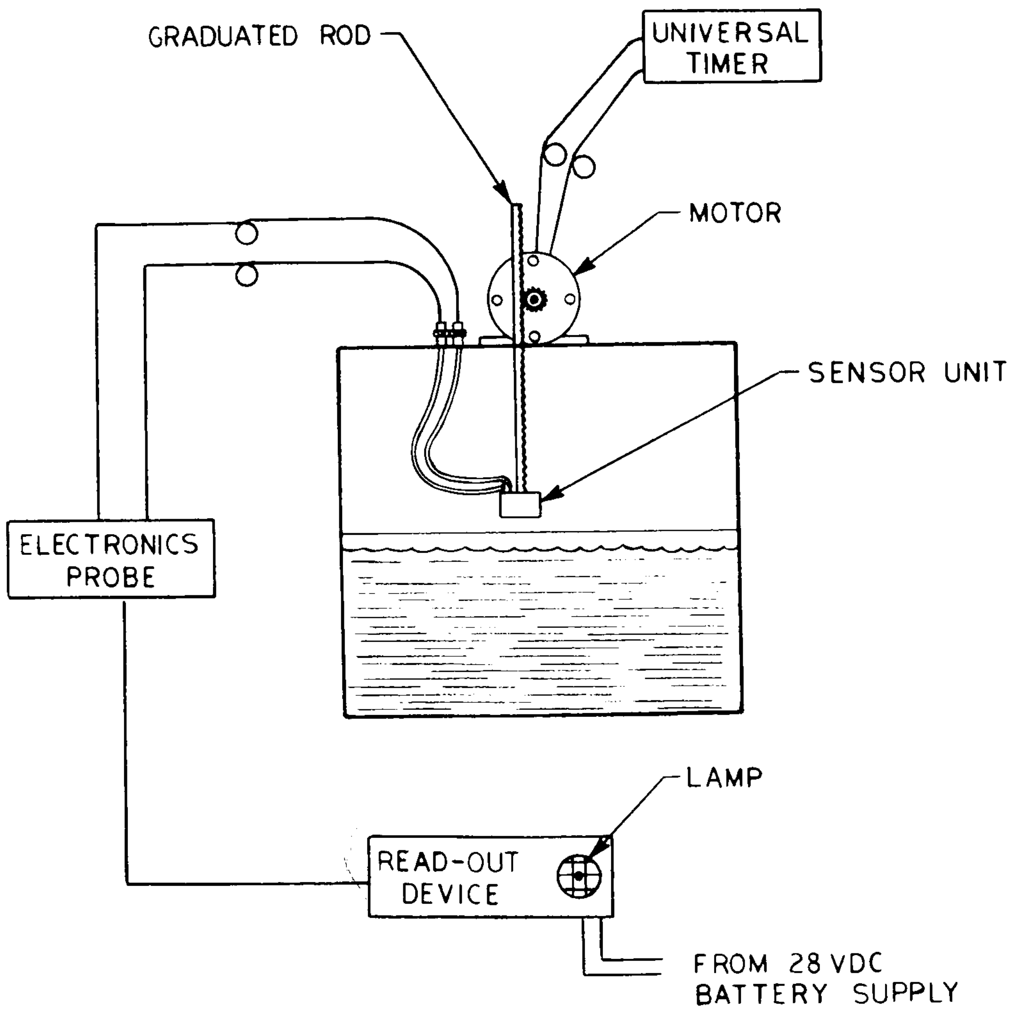


FIGURE 4. LIQUID VAPOR SENSOR SCHEMATIC

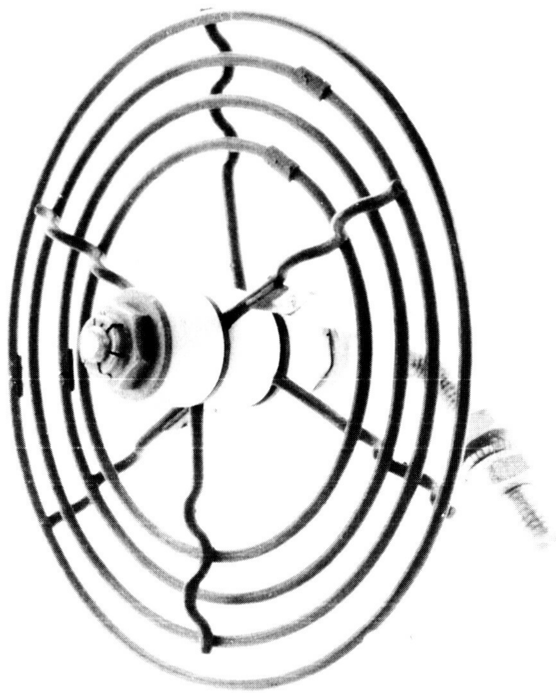


FIGURE 5A. MINNEAPOLIS-HONEYWELL CAPACITANCE SENSOR

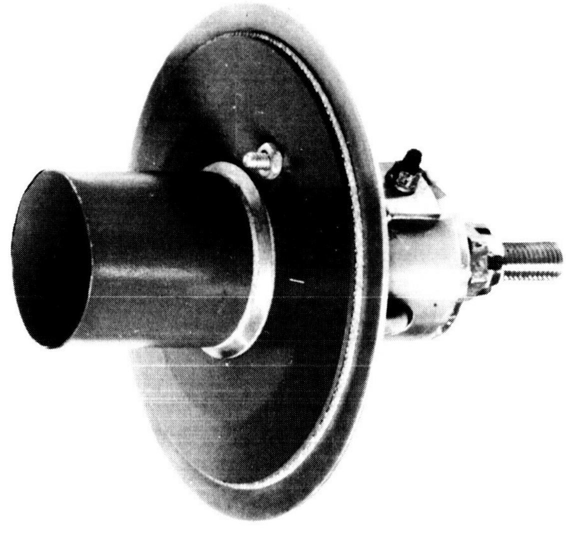


FIGURE 5B. TRANS-SONICS INC. CAPACITANCE SENSOR

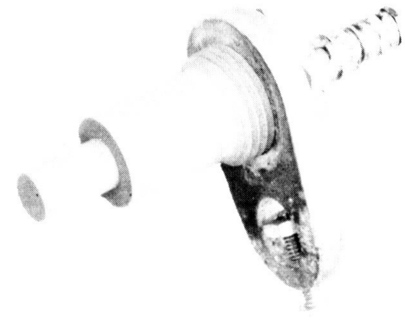


FIGURE 5C. ACOUSTICS PROBE

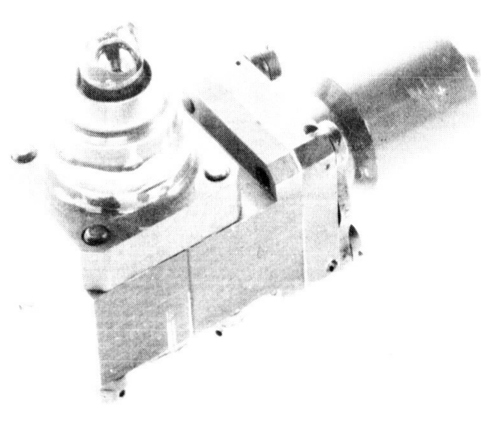


FIGURE 5D. BENDIX CORP. OPTICAL PROBE

FIGURE 5. LIQUID VAPOR SENSORS TESTED

FIGURE 5E. FLAT CABLE CAPACITANCE SENSOR

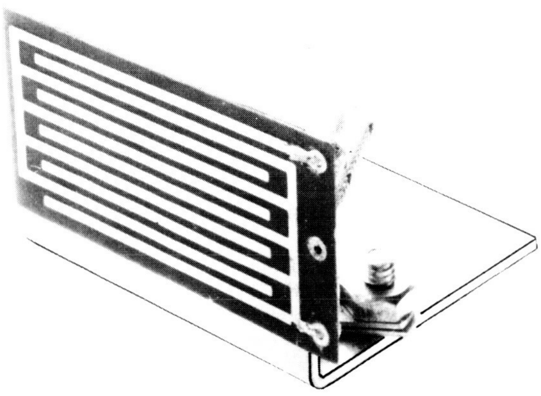


FIGURE 5F. PRINTED CIRCUIT BOARD CAPACITANCE

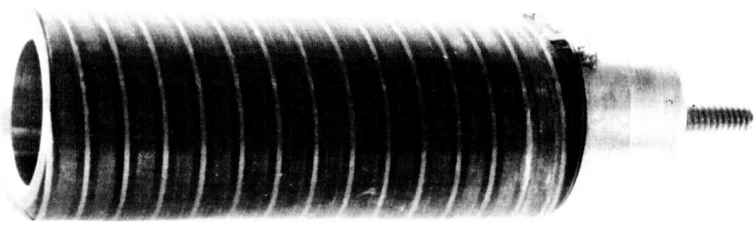
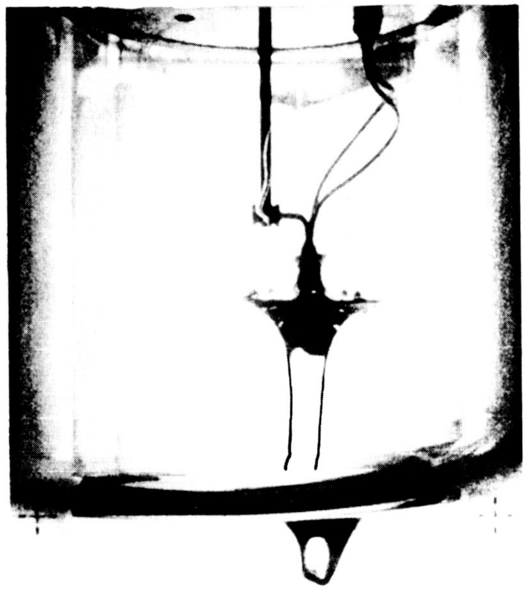
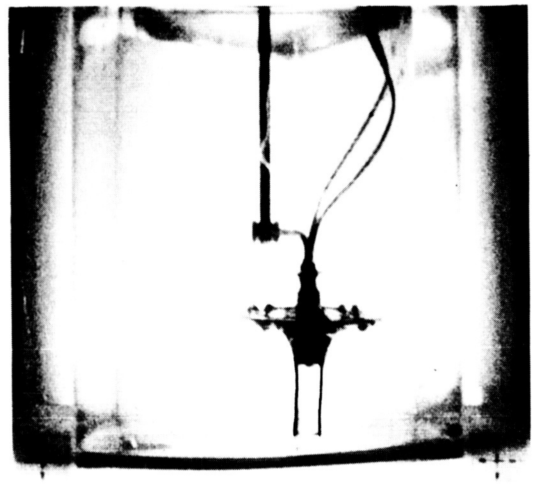


FIGURE 5G. SPIRAL PROBE CAPACITANCE SENSOR

FIGURE 5. LIQUID VAPOR SENSORS TESTED (CONT.)

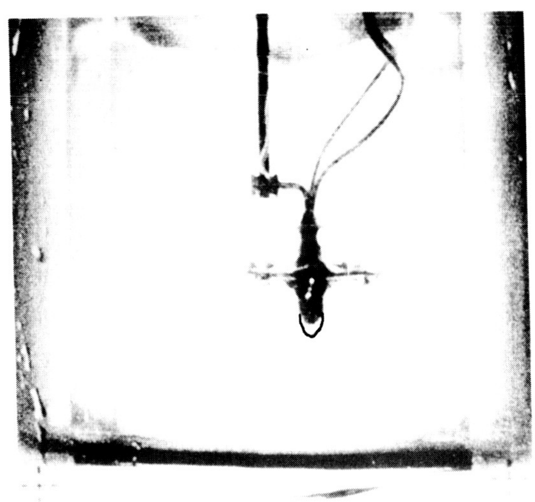


$a/g_e = 0.01$



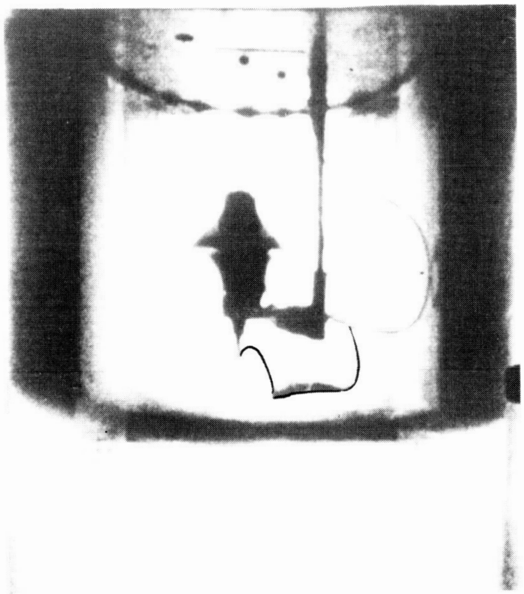
$a/g_e = 0.03$

FIGURE 6. THE EFFECT OF GRAVITY LEVEL ON LIQUID RETENTION CHARACTERISTICS OF THE CONCENTRIC RING SENSOR



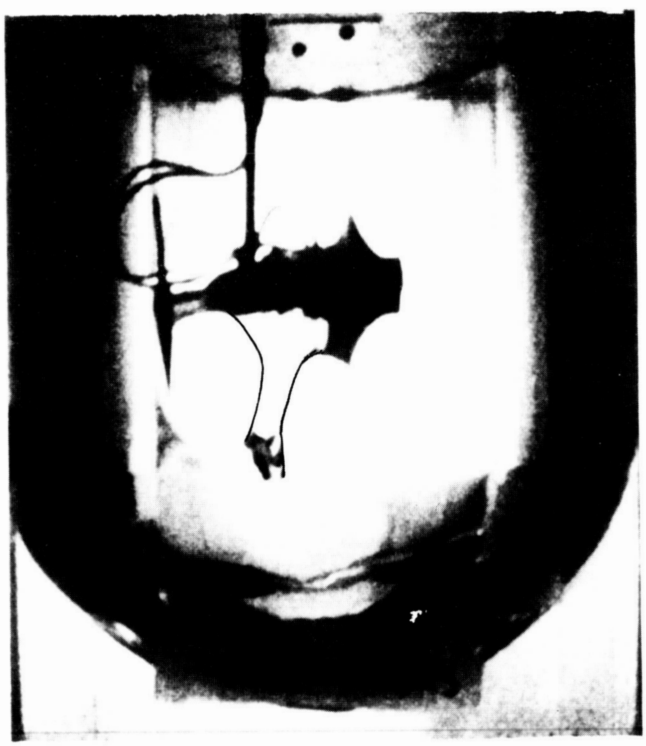
$a/g_e = 0.03$

FIGURE 7. LOW GRAVITY EQUILIBRIUM CONFIGURATION OCCURRING AFTER CONE SEPARATION



$a/g_e = 0.01$

FIGURE 8. LIQUID RETENTION CHARACTERISTICS OF THE TRANS-SONICS SENSOR IN A VERTICAL POSITION

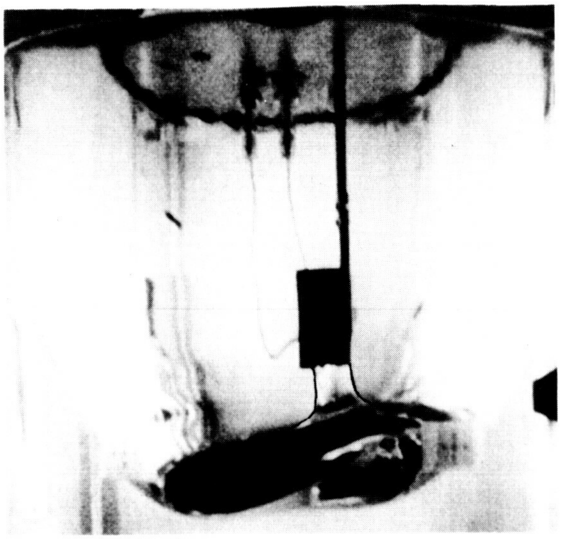


$a/g_e = 0.001$

FIGURE 9 . LIQUID RETENTION CHARACTERISTICS OF THE TRANS-SONICS SENSOR IN A HORIZONTAL POSITION

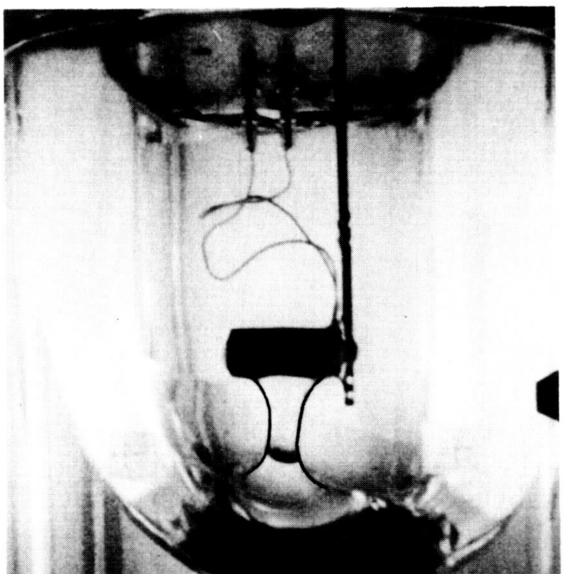
$a/g_e = 0.001$

FIGURE 10. LIQUID RETENTION CHARACTERISTICS OF OPTICAL PROBE



$a/g_e = 5 \times 10^{-4}$

FIGURE 11. LIQUID RETENTION CHARACTERISTICS OF THE PRINTED CIRCUIT PROBE



$a/g_e = 5 \times 10^{-4}$

FIGURE 12. LIQUID RETENTION CHARACTERISTICS OF THE SPIRAL PROBE

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1. Evaluation Of AS-203 Low Gravity Orbital Experiment, Chrysler Corporation Technical Report HSM-R421-67, January 13, 1967.

2. McAnelly, W. B. and Covington, S. S.: Low Gravity Fluid Mechanics Drop Tower Facility, NASA TMX-53765.

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PERFORMANCE CHARACTERISTICS OF LIQUID-VAPOR SENSORS OPERATING IN A REDUCED GRAVITY ENVIRONMENT

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