GPO PRICE $ ____________

CSFTI PRICE(S) $ ____________

Hard copy (HC) $3.00

Microfiche (MF) .75

ff 653 July 65

N65-35352

(ACCESSION NUMBER)	(THRU)
71	1
(PAGES)	(CODE)
CR-62313	14
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

FACILITY FORM 602

Enclosure to
LMSC/A734537

INVESTIGATION AND DEVELOPMENT OF AN RF LIQUID LEVEL SENSING TECHNIQUE

Summary of Laboratory Investigation

15 February 1965

Prepared Under Contract NAS 8-11476

J. D. Lockhart
J. D. Lockhart
LSVP Engineering

LOCKHEED MISSILES AND SPACE COMPANY
Sunnyvale, California

INTRODUCTION

This technical note summarizes the Laboratory Investigation, requirements of Contract NAS 8-11476 between Lockheed Missiles & Space Company and NASA's Marshall Space Flight Center and covers a period from July 1964 through February 15, 1965. The investigation included experiments with liquid hydrogen, liquid oxygen, and liquid rocket fuel (RP-1) to determine the feasibility of using an RF resonant-cavity technique for detecting the liquid level. The effects of filling rates, internal tank insulation, slosh baffles, surface conditions, and suction lines on accuracy and mode jumping were studied. In accordance with contract requirements, the next or second phase is to demonstrate the use of this technique in conjunction with large-scale tanks.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SUMMARY

The basic principle of the RF resonant-cavity, liquid-sensing technique is that the dielectric property of a fluid contained in a tank (cavity) with conducting walls causes the resonant frequency to change in proportion to the amount of that fluid in the cavity. The cavity is excited by radio frequency (RF) electrical energy and a change is detected in the resonant frequency when it is compared to that of the empty tank. By applying a scaling factor, the level or volume of the fluid in the tank is determined.

An aluminum cryogenic tank, 24 in. diameter and 24 in. high, and a copper tank, 22.5 in. wide and 22.5 in. high and having a 0.020-in.-thick wall were used for the investigation. The testing of the liquid hydrogen and liquid oxygen was conducted at the cryogenic facility at the Lockheed Santa Cruz Test Base. The RP-1 testing was conducted at the Lockheed facility in the Moffett Field Hangar No. 1. Simulated testing for proving system designs was conducted in the development laboratory of Lockheed's Research and Development facilities in Building 151 at Sunnyvale, California.

Two types of RF instrumentation systems were employed. The first type was a sweep generator that required manual tracking of the resonant frequency. The second type used a self-excited oscillator technique in which the tank was the frequency-determining element. Supporting instrumentation for the cryogenic testing consisted of three types that were

mounted inside the tank. One set of four resistance temperature probes (RTB's). Two of these were mounted at the same height and, therefore, only three discrete elvels could be detected. A series of 10 carbon resistors provided continuous level monitoring with a discrete level point at each of the 10 resistor location. The third type consisted of 12 independent carbon resistors. Each of these resistors provided a positive indication of being in or out of the cryogenic liquid. Liquid measure and scales for weighing were used for determining the amounts or levels of RP-1.

The various internal tank configurations included a simulated slosh baffle, a simulated metallic suction line, and internal cryogenic insulation. For simulating zero "g," an internal tank void was provided by a hollow non-metallic tube.

Tank measurements were made to determine all modes, phase and impedance characteristics, and to determine the effect of the internal tank configurations.

The influence of surface effects on system accuracy and mode jumping was investigated. During the cryogenic tests, the vent valve was closed. This caused the tank pressure to increase and thus stop surface boiling. With several different liquid levels of RP-1, the tank was tilted up to 60 degrees from the vertical and the change in resonant frequency was recorded. Also, with RP-1, the tank was mechanically oscillated until violent sloshing occurred.

Tables, illustrations, data plots, and diagrams are included with the discussion.

Some of the more important results of the laboratory investigation are as follows:

- The radio-frequency, resonant-cavity sensing technique is suitable for liquid-level determination.
- The technique offers a high degree of accuracy with good resolution.
- The technique offers fast response with excell[illegible] repeatability.
- Installation of a system is simple, weight and power requirements are low, and reliability is high.
- System accuracy remains within acceptable tolerances under changing surface conditions.
- Internal tank configurations and the specific liqui[illegible] must be taken into consideration during the design of the system.
- Test results conform to the theory.
- Zero "g" simulated test results indicate that the technique may prove suitable for determining liquid level (volume) measurements under a zero "g" condition.

DISCUSSION

Background

The use of RF techniques to measure cryogenic or other liquid in a fuel tank is based on the fact that the tank can be made to function as a cavity resonator. The resonant frequencies will be influenced by the shape of the tank and by the amount of the dielectric in the tank. The change in resonant frequency can be calibrated to indicate the change in the quantity of fuel.

For a right circular cylinder cavity, resonant wavelength can be determined by the following formula;*

$$\lambda = \frac{2}{\sqrt{\left(\frac{2\,X_{lm}}{D}\right)^2 + \left(\frac{n}{L}\right)^2}}$$

where

λ = free space wavelength of the resonant frequencies

D = cavity diameter

L = cavity length

x_{lm} = m^{th} root of $J_1^1\,(X) = 0$ for the TE modes

or m^{th} root of $J_1\,(X) = 0$ for the TM modes

n = number of one-half wavelengths along the axis

An extremely large number of field configurations (modes) are possible, and these can be calculated by utilizing the appropriate Bessel function

Carol G. Montgomery, Technique of Microwave Measurements, McGraw_Hill Book Co., N. Y. 1947, pp. 297- 308 root in the above formula. In practice, however, cavity oscillators are usually designed to operate in one of the lower order modes, with the final choice being governed by frequency, tuning, Q, coupling considerations, or a combination of these factors. The table below lists roots of J_1 (X) and J_1^1 (X) for several of the lower order modes.

TE - Mode	Xlm	n/L	TM - Mode	Xlm	n/L
TE_{111}	1.841	1/L	TM_{010}	2.405	0
TE_{112}	1.841	2/L	TM_{011}	2.405	1/L
TE_{011}	3.832	1/L	TM_{110}	3.832	0
TE_{211}	3.054	1/L	TM_{012}	2.405	2/L
			TM_{111}	3.832	1/L

Filling the cavity with dielectric material increases the wavelength over the free-space value in accordance with the following formula:

$$\lambda' = \lambda \sqrt{E_r}$$

where E_r is the relative dielectric constant of the material introduced into the cavity.

Cavity size for the experimental program was determined by cryogenic tank availability. Ideally, to favor the TM modes, the ratio L/D should be less than 1, whereas, to favor TE modes $\frac{L}{D} \geq 1$** should apply. In each case the lowest order mode should be dominant. Loop placement and orientation can also be adjusted to favor a given mode. This was done in the case of the Phase I experimental program, since the L/D ratio was 1.

*For a more complete listing see: Roger F. Harrington, Time-Harmonic Electromagnetic Fields, McGraw-Hill Book Co., N.Y., 1961 p. 205

**Harrington, op cit. pp. 213-16

Two experimental approaches were investigated. One consisted of sweeping the tank with a signal generator and noting the change in resonant frequency as a function of fill. The other approach utilized the tank as the frequency-determining element of an oscillator, and the change in frequency was determined as a function of amount of liquid in the tank.

Instrumentation

A block diagram of the experimental sweep generator RF system is shown in Figure 1. An operator manually tracked the resonant peak depicted on the oscilloscope trace. This was accomplished by tuning the output frequency of the Hewlett-Packard Model 608 signal generator (No. 1) to maintain a frequency marker at the tank resonant frequency as displayed on the oscilloscope. Figure 2 illustrates a typical oscilloscope trace with a frequency marker at the resonant peak. Signal generator No. 2 (H-P Model 608) was set near the empty resonant frequency of the tank. The difference frequency between the two signal generators was detected by the balanced modulator, and the output applied to an H-P Model 524 frequency counter. A digital print-out of the difference frequency was provided at fixed intervals of two (2) seconds for most of the tests.

The experimental self-oscillating RF system is shown in Figure 3. The wide-band UHF amplifier provided positive feedback across the tank, and the combination served as an RF oscillator. The H-P 608 signal generator was set at or near the empty-tank frequency. As the tank filled, f_t decreased in frequency, and $f_o - f_t$ (ΔF) increased as a function of the amount of dielectric in the tank. The 0 - 50 Mc band-pass amplifier

RF SWEEP GENERATOR BLOCK DIAGRAM

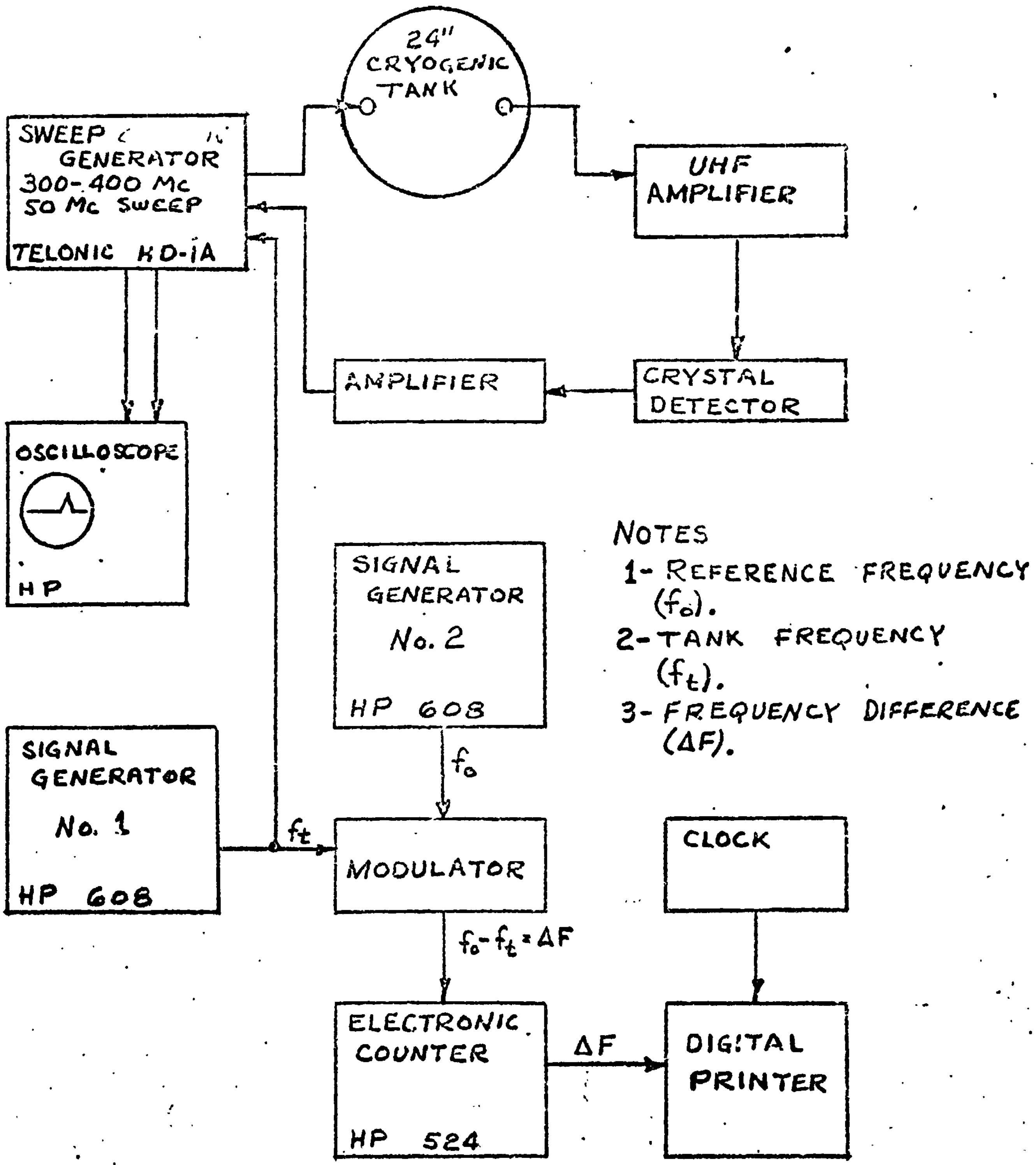


FIGURE No. 1

TYPICAL OSCILLOSCOPE TRACES

SWEEP GENERATOR AND MARKER
LH_2 TEST RUN No. 3
OCTOBER 28, 1964

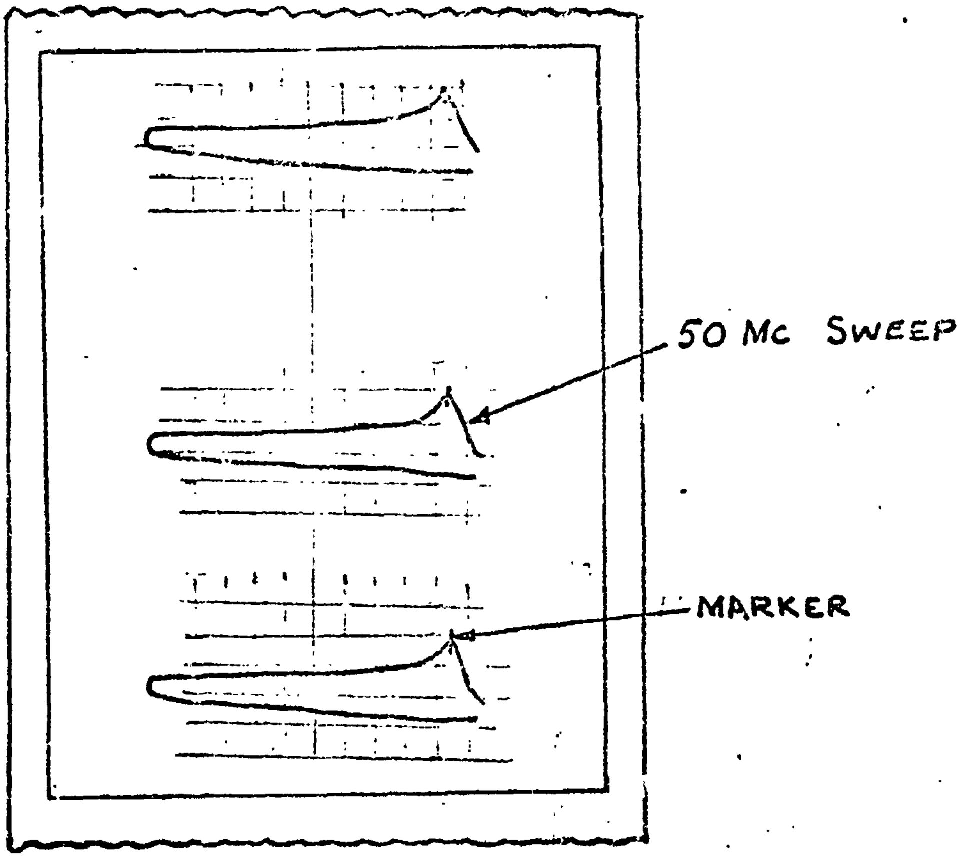


FIGURE NO. 2

SELF-OSCILLATING RF SYSTEM

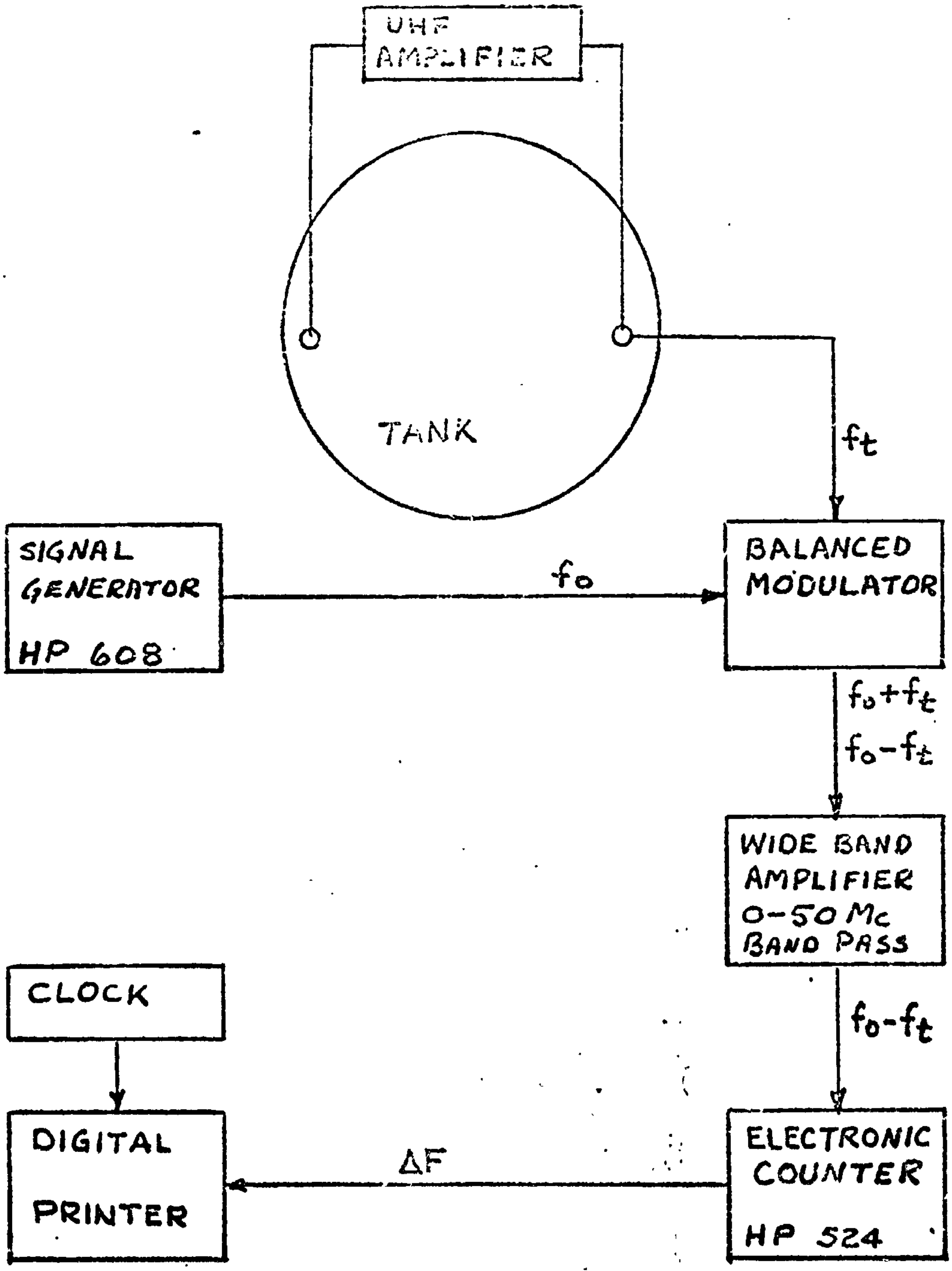


FIGURE No. 3

served as a filter against the sum frequencies and also provided sufficient amplitude to drive the electronic counter. As was the case for the manual system, the Δ F and elapsed time were printed out in digital form.

Cryogenic Testing

Liquid hydrogen (LH_2) and liquid oxygen (LOX) were tested at the Lockheed Santa Cruz Test Base (SCTB) facility.

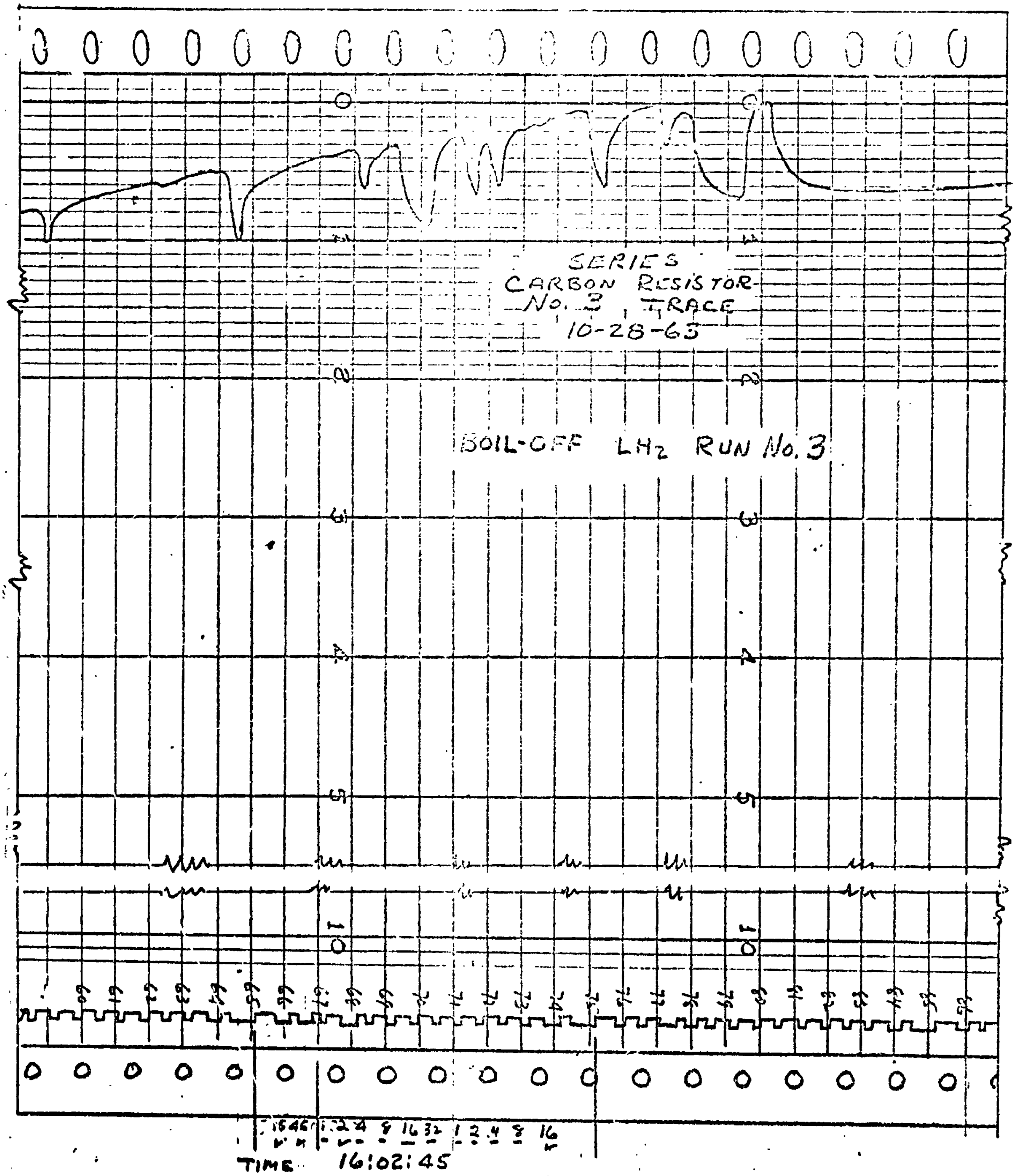
Liquid Hydrogen Tests. Seven separate LH_2 tests were conducted, and the test conditions for each run are provided with the individual summary. The sequence of testing as outlined in the Lockheed Specification No. LMSC TS 6528029, Rev. B was closely followed. The experimental sweep generator RF system (Figure 1) was used for all the LH_2 tests.

Resistance thermometers (RTB's) and carbon resistors were used to determine the level of the LH_2 and thus serve as calibration points for the RF system. Figure 4 is a typical chart recording of one of the series carbon resistors. The internal tank instrumentation without and with the baffles installed is shown in Figures 5 and 6, respectively.

LH_2 Test Run No. 1. The first test, consisting of a single-fill and boil-off cycle, was conducted on 22 October 1964. The 24-inch-diameter aluminum tank was internally insulated, no slosh baffle was used, and a fiberglass fill line extended into the tank.

The empty-tank resonant frequency was approximately 376 Mc. Total RF frequency shift over the fill cycle was about 38 Mc. Figure 7 shows a plot of ΔF versus elapsed time during the test run. Only the three RTB level points were available for comparison on this test; however, the test

TYPICAL CH[illegible] R[illegible]DING.



CARBON RESIST[illegible] [illegible] LH_2

FIGURE No. 4

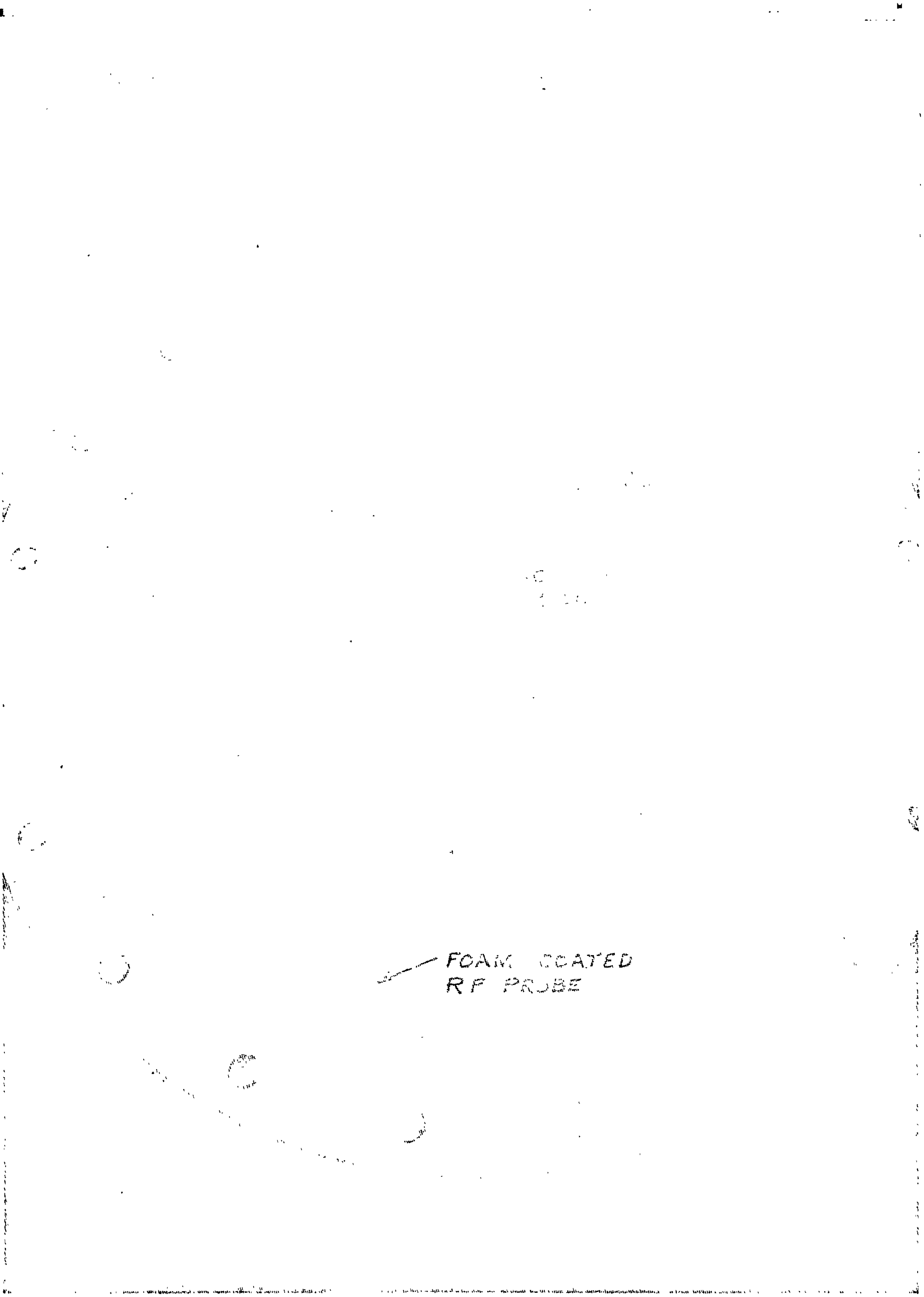


FIGURE No. 5

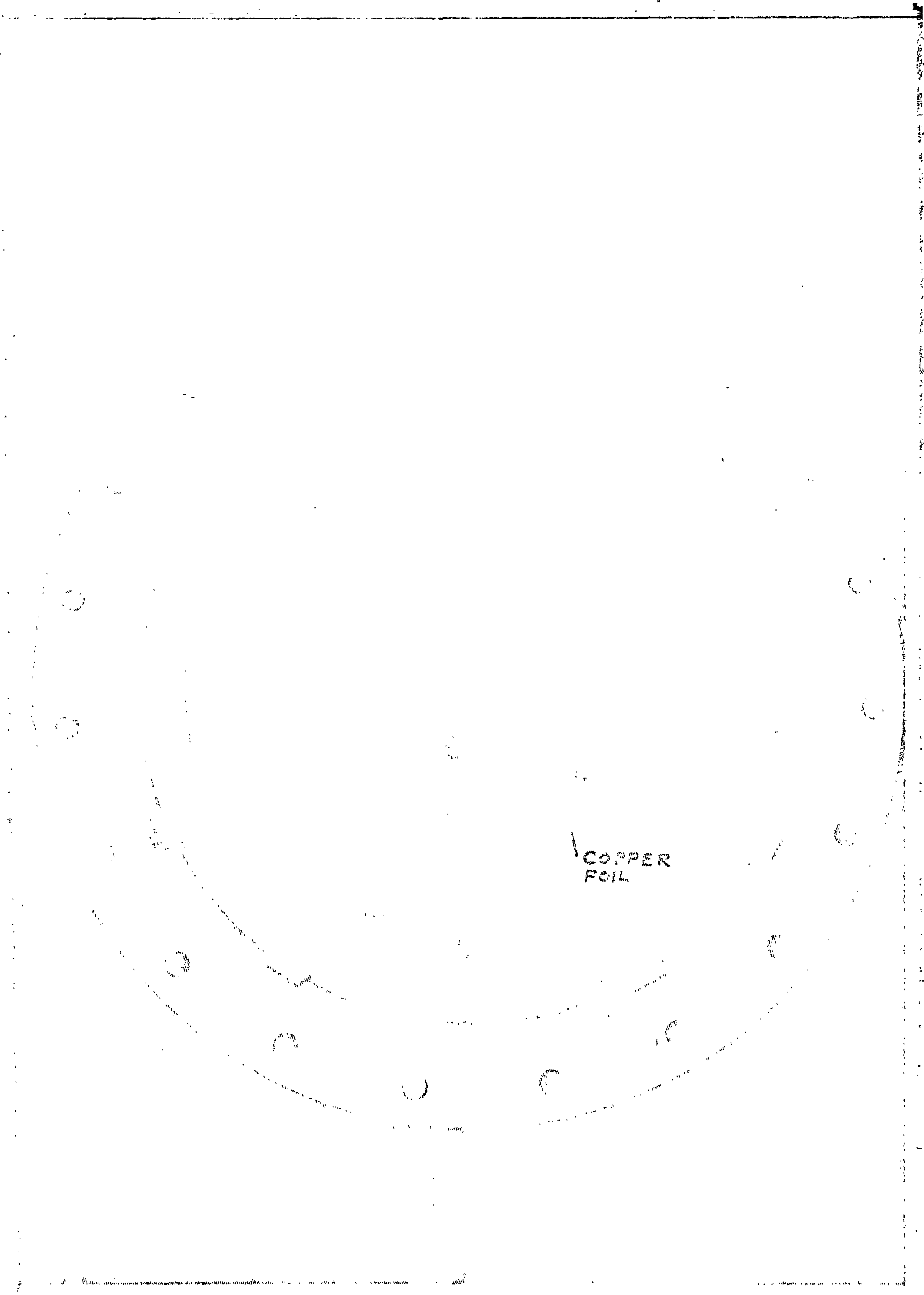


FIGURE NO. 6

RESONANT FREQUENCY DIFFERENCE vs ELAPSED TIME

LIQUID HYDROGEN TEST RUN NO. 1

OCTOBER 22, 1964

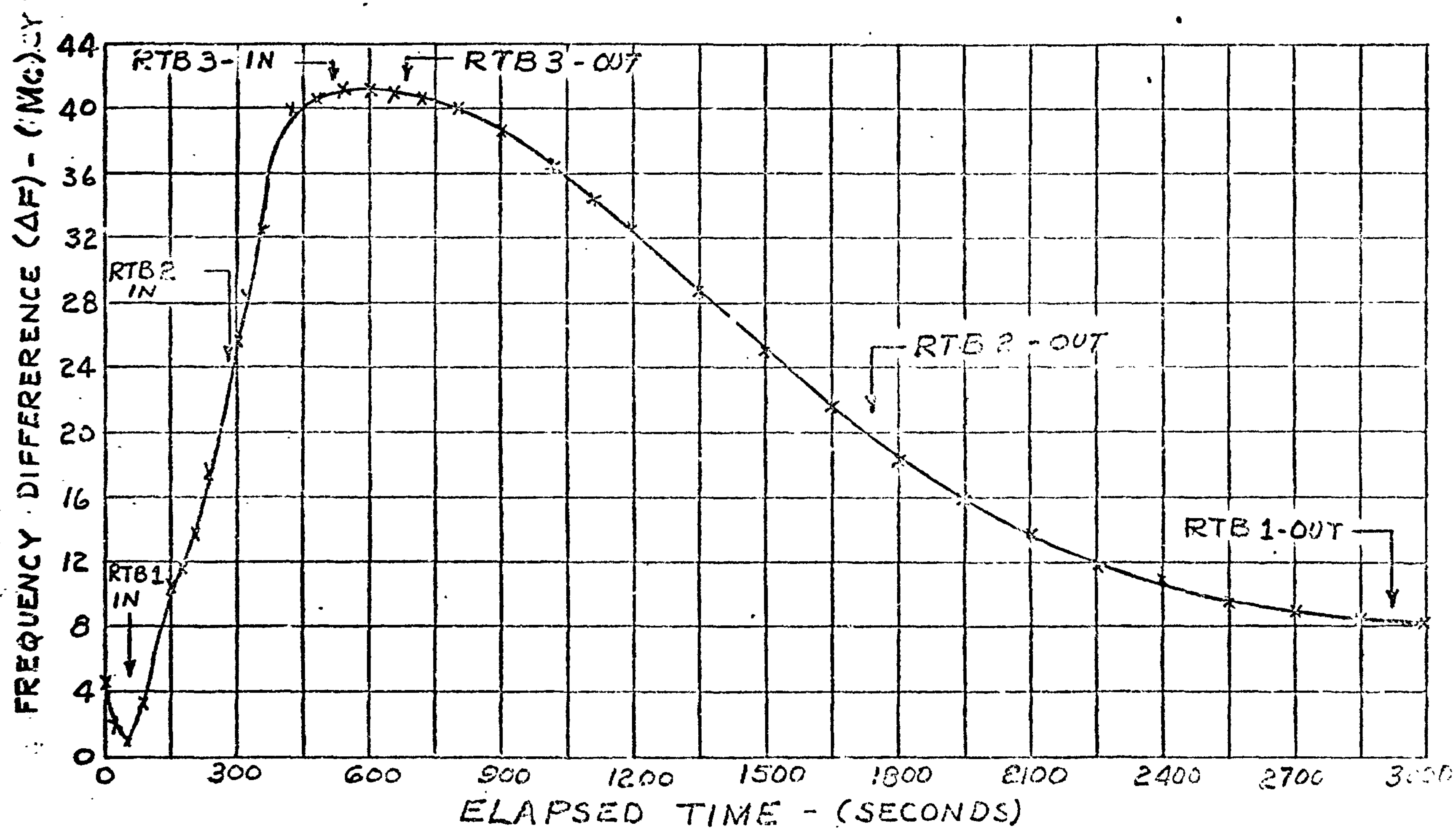


FIGURE NO. 7

did prove valuable as a system check and as a qualitative indicator of the feasibility of the RF method of liquid-level sensing. The experimental data also indicated that a time delay was required for the RTB sensors to reach the LH_2 temperature. This delay probably accounted for the frequency discrepancy at a given check point between fill and boil-off cycles.

LH_2 Test Run No. 2. The test was conducted on 23 October with conditions identical to those established for Test Run No. 1. The test procedure was modified slightly in that the fill was accomplished in three steps with a ten-minute boil-off between steps 1-2 and 3-4 as noted on the ΔF versus time plot of Figure 8. On the final boil-off cycle, back pressure was allowed to increase from 2 psig to 20 psig in order to quiet the surface of the liquid. The output of the continuous-resistor-level sensor was not properly ranged and the pen was driven off the chart as soon as the resistors were exposed to the cold gas; therefore, only the three RTB sensors provided an output for calibration checkpoints.

It may be noted from Figure 8 that the resonant frequency of the tank remained essentially constant during the increased back-pressure periods, indicating that surface disturbances, such as those caused by normal boiling, apparently do not introduce measurement errors.

LH_2 Test Run No. 3. This test was conducted 28 October 1964. The test conditions were identical to those for Run Nos. 1 and 2 except that a piece of 0.003-in.-thick copper foil 1½ in. wide was wrapped around the portion of the fill line extending into the tank. The foil was internally grounded and provided a realistic simulation of a metal fill line.

RESONANT FREQUENCY DIFFERENCE Vs ELAPSED TIME
LIQUID HYDROGEN TEST RUN NUMBER 2
OCTOBER 23, 1964

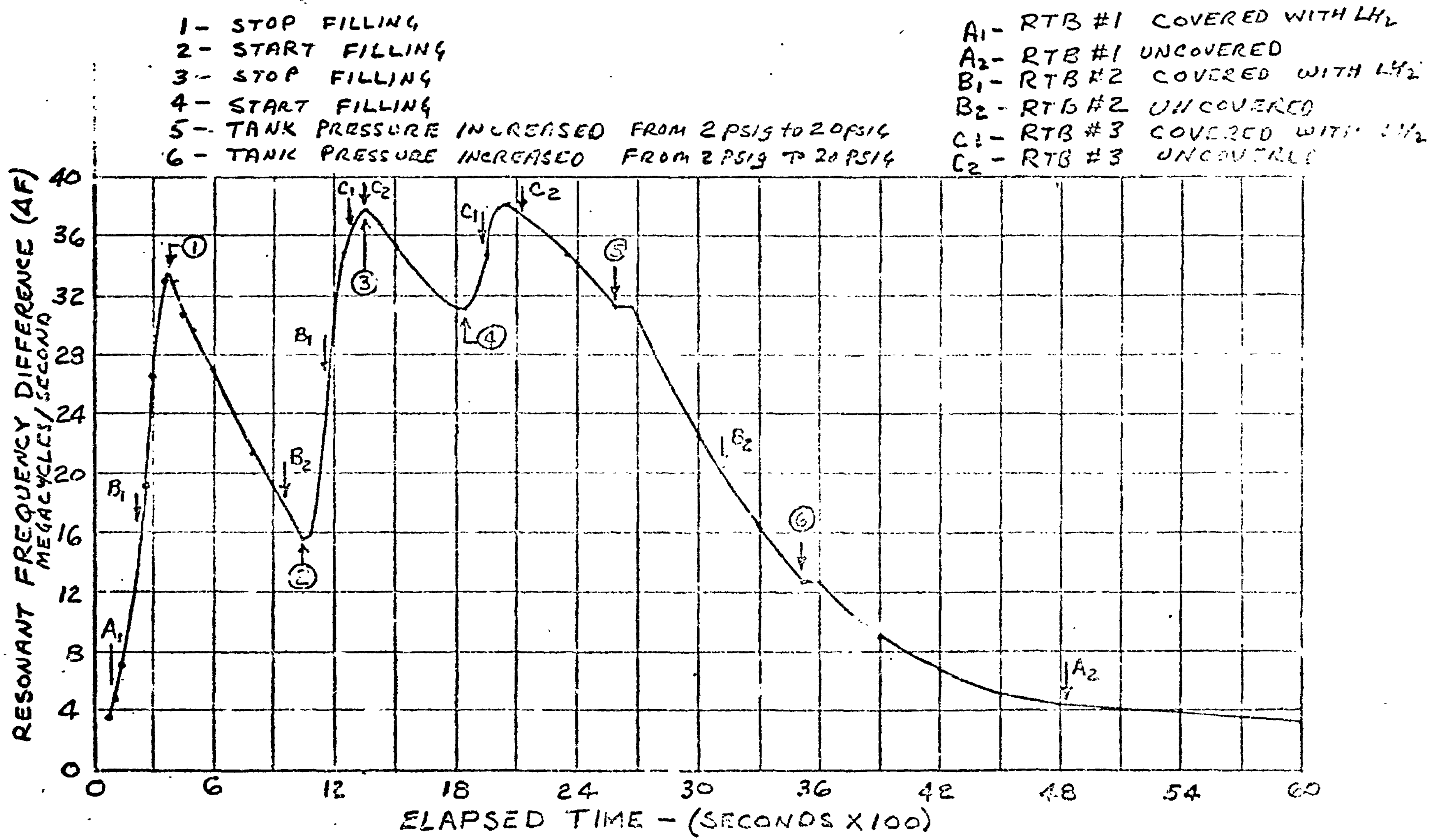


FIGURE NO. 8

Empty resonant frequency shifted from approximately 376 Mc to approximately 373 Mc and the total ΔF was about 32 Mc as compared with 38 Mc for Run Nos. 1 and 2.

This test provided data considerably improved over that obtained from Runs Nos. 1 and 2 because a substantial number of calibration points was available. The uncovering of each of the 10 carbon resistors was discernible from the continuous-liquid-level chart recording during the boil-off cycle.

A plot of liquid level versus ΔF is shown in Figure 9. The fill portion of the test run is plotted against the three RTB points. The difference between these three points and corresponding resistor sensor points obtained during the boil-off cycle was probably due to the thermal lag of the RTB sensors. The response of an RTB is good; however, the total mass of the probe and splashing of the LH_2 caused uncertainty in the readings.

<u>LH_2 Test Run No. 4.</u> Run No. 4 was made on 29 October 1964. Physical parameters of the tank were identical to those of run 3. The fill was accomplished in 3 steps, with boil-off cycles in between as for Run No. 2. The back pressure was permitted to build up to 20 psig twice during the boil-off. Figure 10 shows a plot tank fill versus change in resonant frequency. Again, limited calibration points were available during fill; however, the data obtained were generally consistent with those of Run No. 3. The boil-off provided good comparative data. The two pressure cycles during boil-off caused no appreciable shift in ΔF, thus corroborating the results of Run No. 2 The RTB data were quite widely dispersed as was noted during the preceding tests.

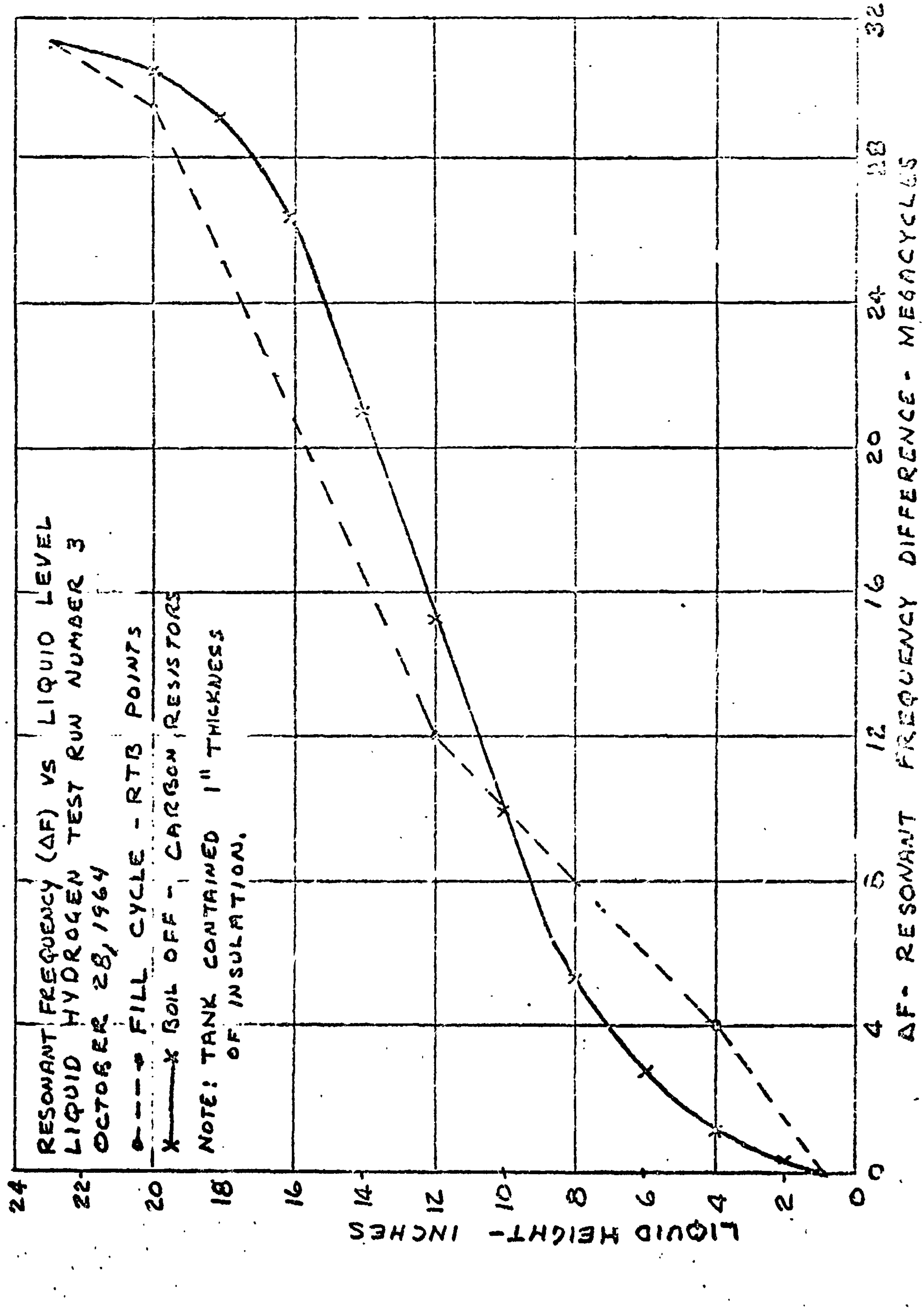

RESONANT FREQUENCY (ΔF) VS LIQUID LEVEL
LIQUID HYDROGEN TEST RUN NUMBER 3
OCTOBER 28, 1964
FILL CYCLE - RTB POINTS
BOIL OFF - CARBON RESISTORS
NOTE: TANK CONTAINED 1" THICKNESS OF INSULATION.
LIQUID HEIGHT - INCHES
ΔF - RESONANT FREQUENCY DIFFERENCE - MEGACYCLES
0
2
4
6
8
10
12
14
16
18
20
22
24
0
4
8
12
16
20
24
28
32

FIGURE NO. 9

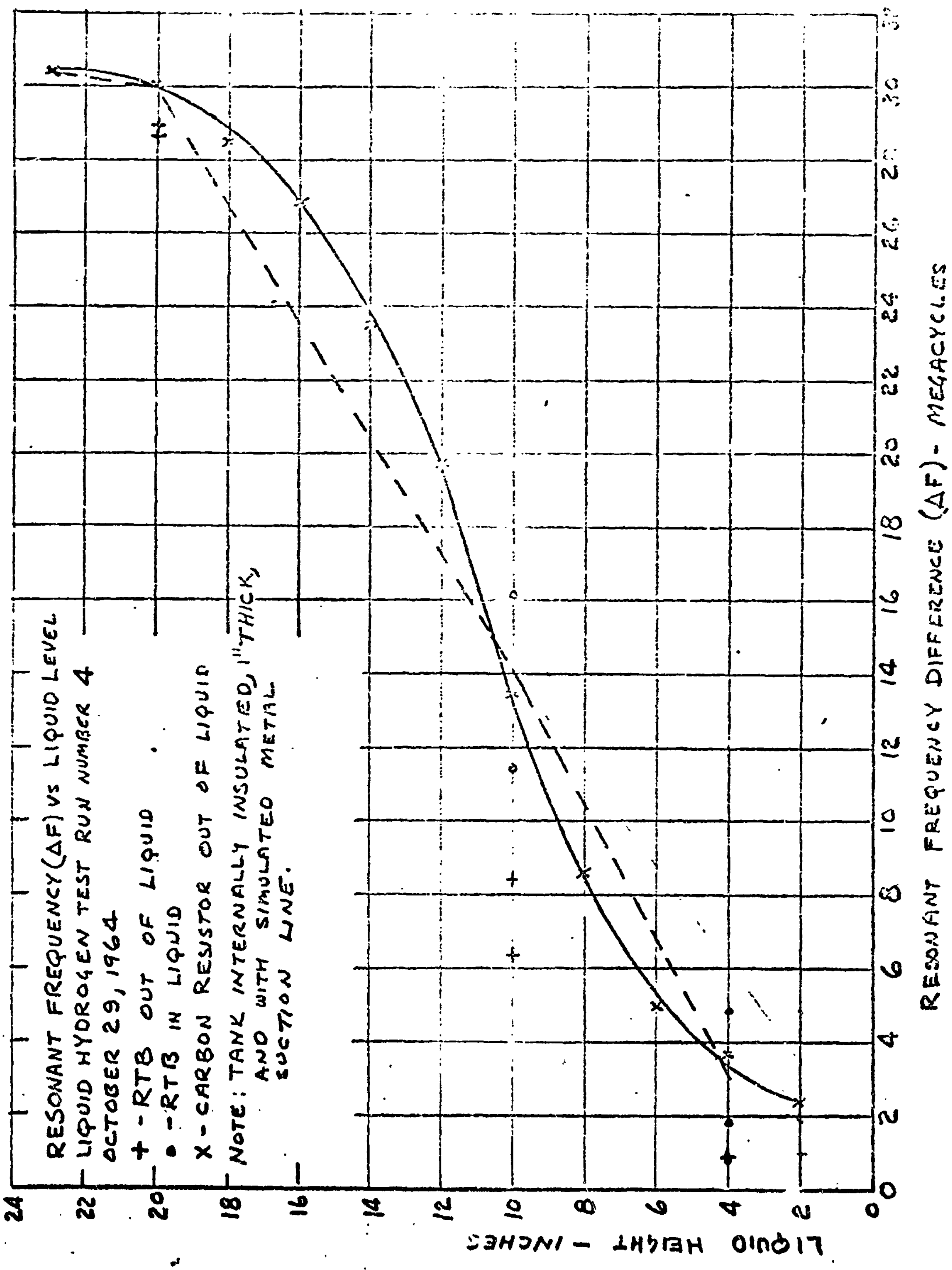

RESONANT FREQUENCY (ΔF) VS LIQUID LEVEL
LIQUID HYDROGEN TEST RUN NUMBER 4
OCTOBER 29, 1964
+ - RTB OUT OF LIQUID
• - RTB IN LIQUID
X - CARBON RESISTOR OUT OF LIQUID
NOTE: TANK INTERNALLY INSULATED, 1" THICK, AND WITH SIMULATED METAL SUCTION LINE.
RESONANT FREQUENCY DIFFERENCE (ΔF) - MEGACYCLES
LIQUID HEIGHT - INCHES

FIGURE No. 10

LH_2 Test Run No. 5. This test run was conducted on 17 November 1964. The internal insulation was removed from the tank, approximately 2-1/2 inches of fiberglas insulation was wrapped around the tank, and solid foam insulation was placed externally on the top and bottom of the tank. The tank and insulation were placed in a plastic bag which was purged with helium during the test run. Twelve 2.4 K ohm carbon resistors were added to the internal instrumentation. Each resistor was connected to a separate recording channel.

The outputs from the continuous-liquid-level carbon resistor lines, the RTB's, and the 12 separate carbon resistors were recorded and compared with the ΔF.

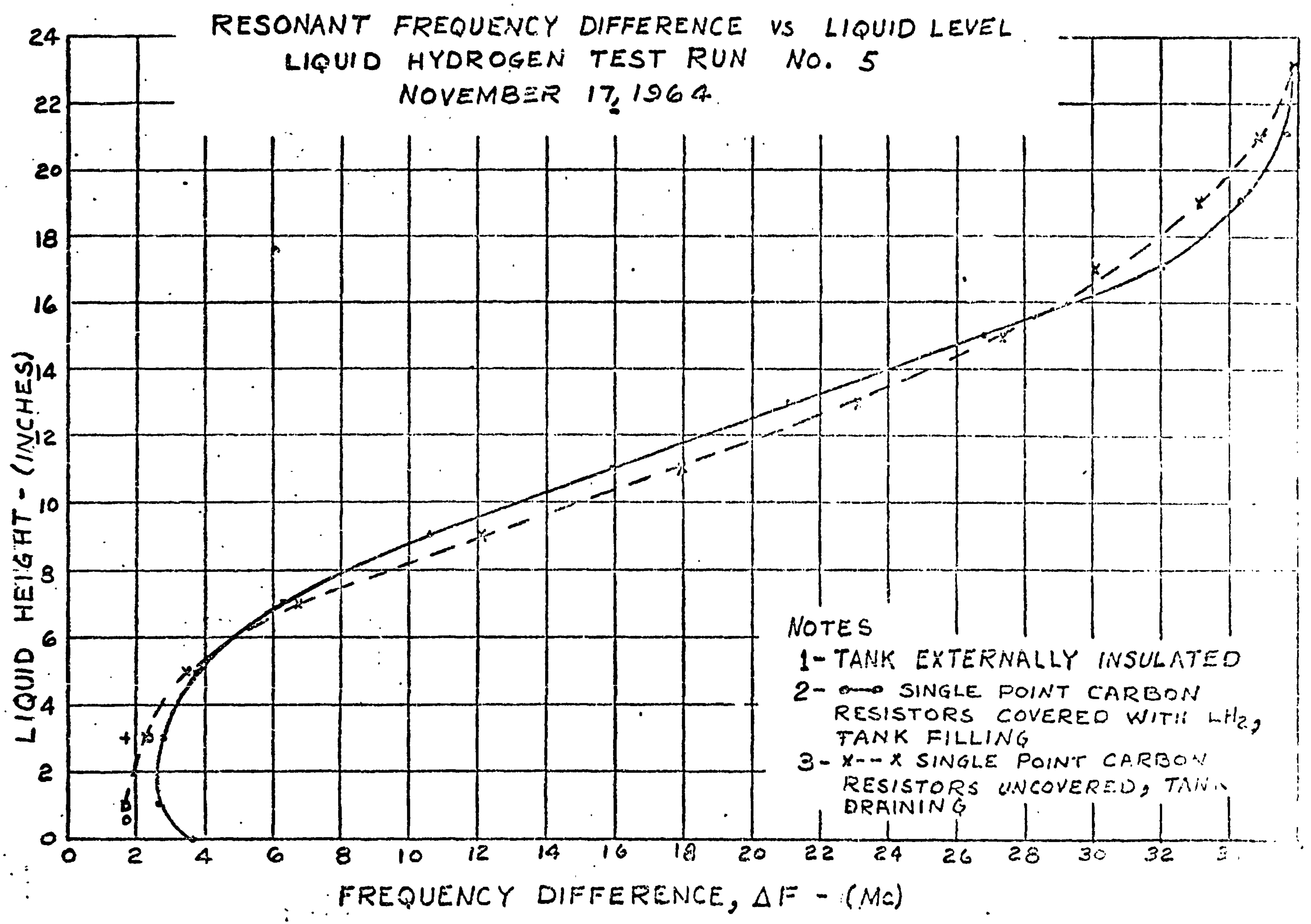
Figure 11 illustrates liquid height as determined by the single-resistor sensors and the corresponding frequency difference for each calibration point. The discrepancies between fill and drain cycles were much less than when RTB's were used for comparison purposes. Note also that when starting with a warm tank, the resonant frequency shifted upward before starting the normally downward shift. This can be adequately explained by tank contraction during the cooling process. If the tank had cooled from 294°K down to 0°K, frequency would have shifted upward by about 1.74 Mc due to the decrease in cavity diameter.*

For the TM_{010} mode, the formula for wavelength at resonance given in a preceding section simplifies to

$$\lambda = \frac{\pi D}{Xlm} = 1.3056 \ D$$

where D = cavity diameter and Xlm = appropriate root of Bessel Function = 2.405.

*Goldsmith, Waterman, and Hirschorn, Handbook of Thermophysical Properties of Solid Materials, The Macmillan Co., 1961, Vols. 1 and 2.



RESONANT FREQUENCY DIFFERENCE vs LIQUID LEVEL
LIQUID HYDROGEN TEST RUN No. 5
NOVEMBER 17, 1964
NOTES
1- TANK EXTERNALLY INSULATED
2- o—o SINGLE POINT CARBON RESISTORS COVERED WITH LH2, TANK FILLING
3- x--x SINGLE POINT CARBON RESISTORS UNCOVERED, TANK DRAINING
LIQUID HEIGHT - (INCHES)
FREQUENCY DIFFERENCE, ΔF - (Mc)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

FIGURE No. 11

The resonant wavelength of the tank can be calculated by placing the value of D in the above formula for a given temperature. Conversely, if resonant frequency is known at ambient and after the tank has cooled, the temperature change of the tank can be estimated. Actually, the frequency change was about 1.3 Mc, indicating that the tank cooled to approximately 123°K, which seems reasonable. Figure 12 is a plot of linear thermal expansion versus temperature for aluminum. As nearly as could be determined from the reference material, the expansion characteristics of the common aluminum alloys are practically identical to that of pure aluminum.

During the boil-off cycle of this test, the fill valve accidently opened. This was detected with the RF system, and operators monitoring the other sensor systems were alerted. However, several minutes had elapsed before confirmation from the fill-line pressure and valves position sensing devices was apparent. Cyclical variations over small frequency ranges were noted just prior to the decrease of resonant frequency which indicated fill. It is postulated that the fill valve opened in an erratic manner and the liquid was introduced in spurts, with boil-off in between. It was further assumed that finally the valve remained open, thus resulting in a normal refilling.

<u>LH_2 Test Run No. 6</u>. This run was conducted on 18 November 1964, and the same test conditions applied here as for Run No. 5. Two power failures were experienced during the course of the test, and the digital printer failed toward the end of the boil-off cycle. These detracted very little from the value of the test which fact can be ascertained from the plot of liquid height versus frequency difference shown in Figure 13. The frequency shift near the empty condition was not as great as that for the previous run in which tests were started with a warm tank. Ice from test

LINEAR THERMAL EXPANSION VS TEMPERATURE
FOR ALUMINUM

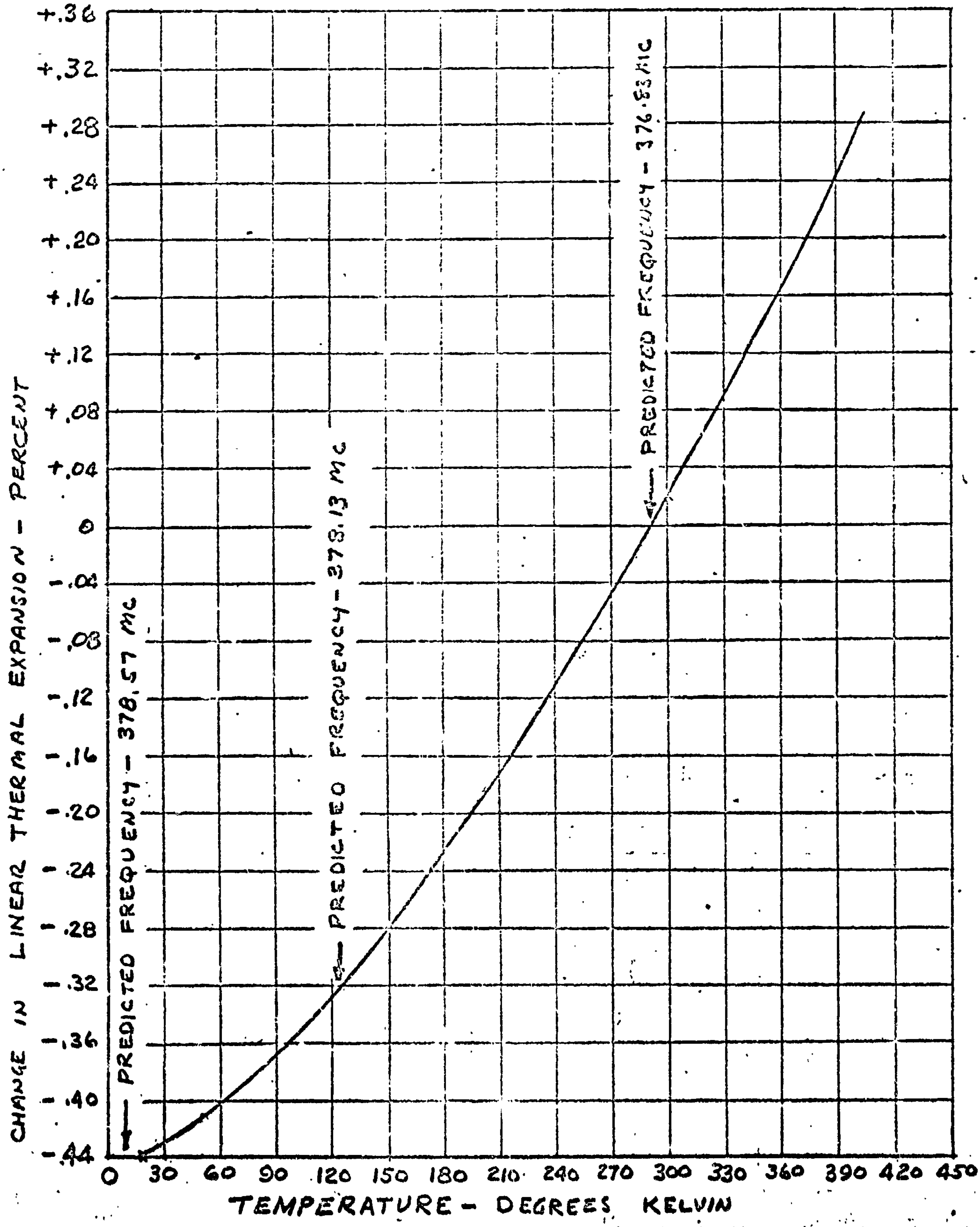


FIGURE NO. 12

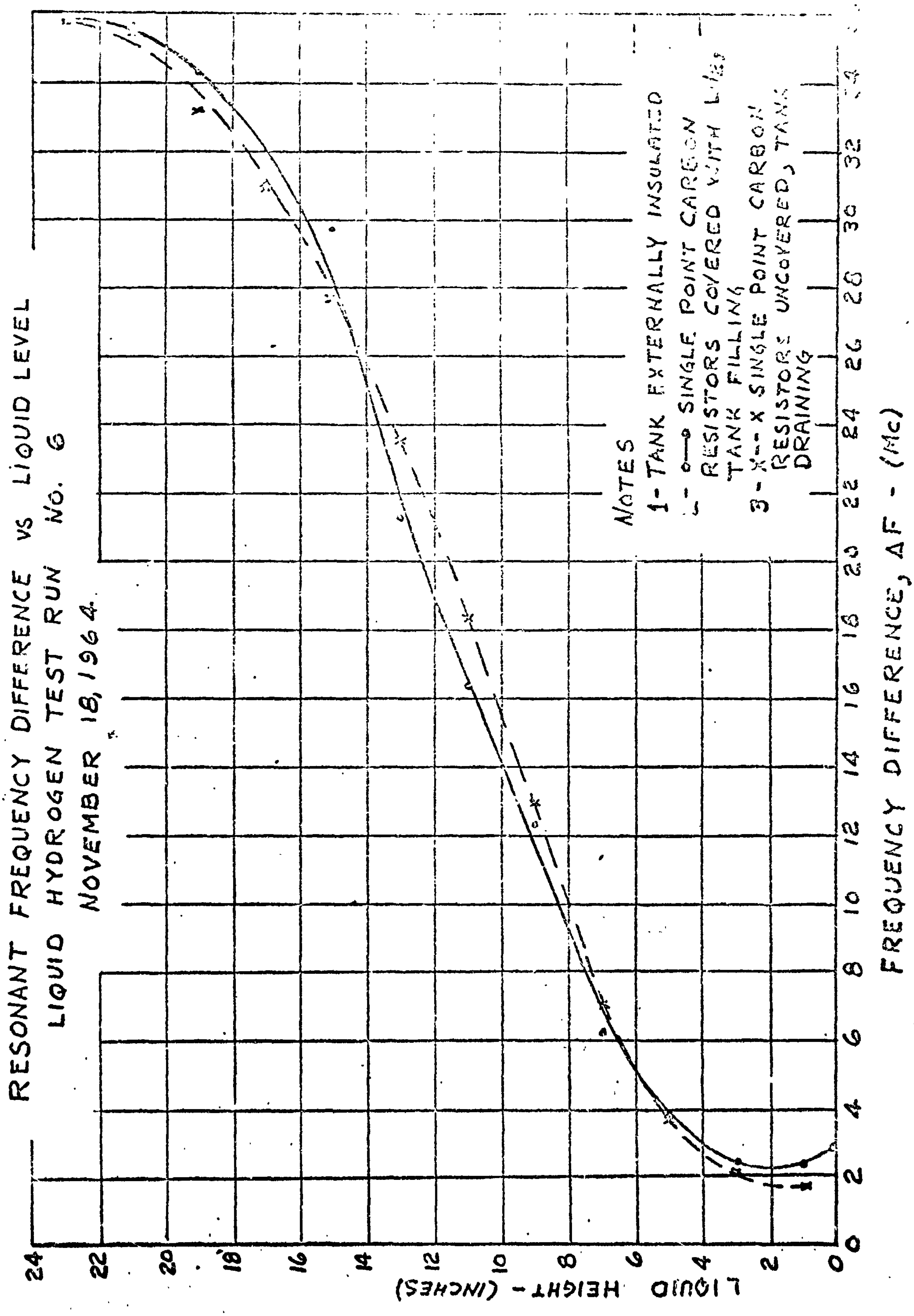

RESONANT FREQUENCY DIFFERENCE VS LIQUID LEVEL
LIQUID HYDROGEN TEST RUN NO. 6
NOVEMBER 18, 1964
NOTES
1 - TANK EXTERNALLY INSULATED
2 - o—o SINGLE POINT CARBON RESISTORS COVERED WITH LH2 TANK FILLING
3 - X--X SINGLE POINT CARBON RESISTORS UNCOVERED, TANK DRAINING
FREQUENCY DIFFERENCE, ΔF - (Mc)
LIQUID HEIGHT - (INCHES)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
0 2 4 6 8 10 12 14 16 18 20 22 24

FIGURE No. 13

Run No. 5 coated the tank external insulation. The frequency shifted about 0.7 Mc when the LH_2 was introduced. This would indicate that the tank walls were at a temperature of about 213°K and then cooled to 122°K. The data agreed quite well over most of the fill and drain cycle with the data for Run No. 5.

<u>LH_2 Test Run No. 7.</u> This test run was conducted on 25 November 1964. Simulated metal slosh baffles and a fill line were placed in the tank, causing the empty resonant frequency to be raised to about 396 Mc. Data for the test are plotted in Figure 14. Note that when nearly empty the resonant frequency increased by approximately 1.6 Mc before turning and behaving normally. The resonant frequency was essentially determined by the inside diameter of the baffles. Since the baffles were not attached to the tank walls, they reached equilibrium much more rapidly with the introduction of LH_2 than was the case for the bare tank wall. Hence, there was greater contraction and a correspondingly larger shift in the resonant frequency. The flattening of the curve near full, was not observed in tests with noncryogenic materials. Presumably, the contraction of the upper rings of the baffle more than offset the normal frequency change effects due to the LH_2 fill. Near the empty tank condition, other resonant modes were observed, which were probably caused by contraction of the baffles. This resulted in poor electrical contact with the tank walls.

For this run, the series resistor liquid-level sensor provided calibration checkpoints on both the fill and drain cycles. A plot of liquid height versus ΔF appears on Figure 15. Note that up through resistor 10 agreement

RESONANT FREQUENCY DIFFERENCE vs LIQUID LEVEL
LIQUID HYDROGEN TEST RUN No. 7
NOVEMBER 25, 1964

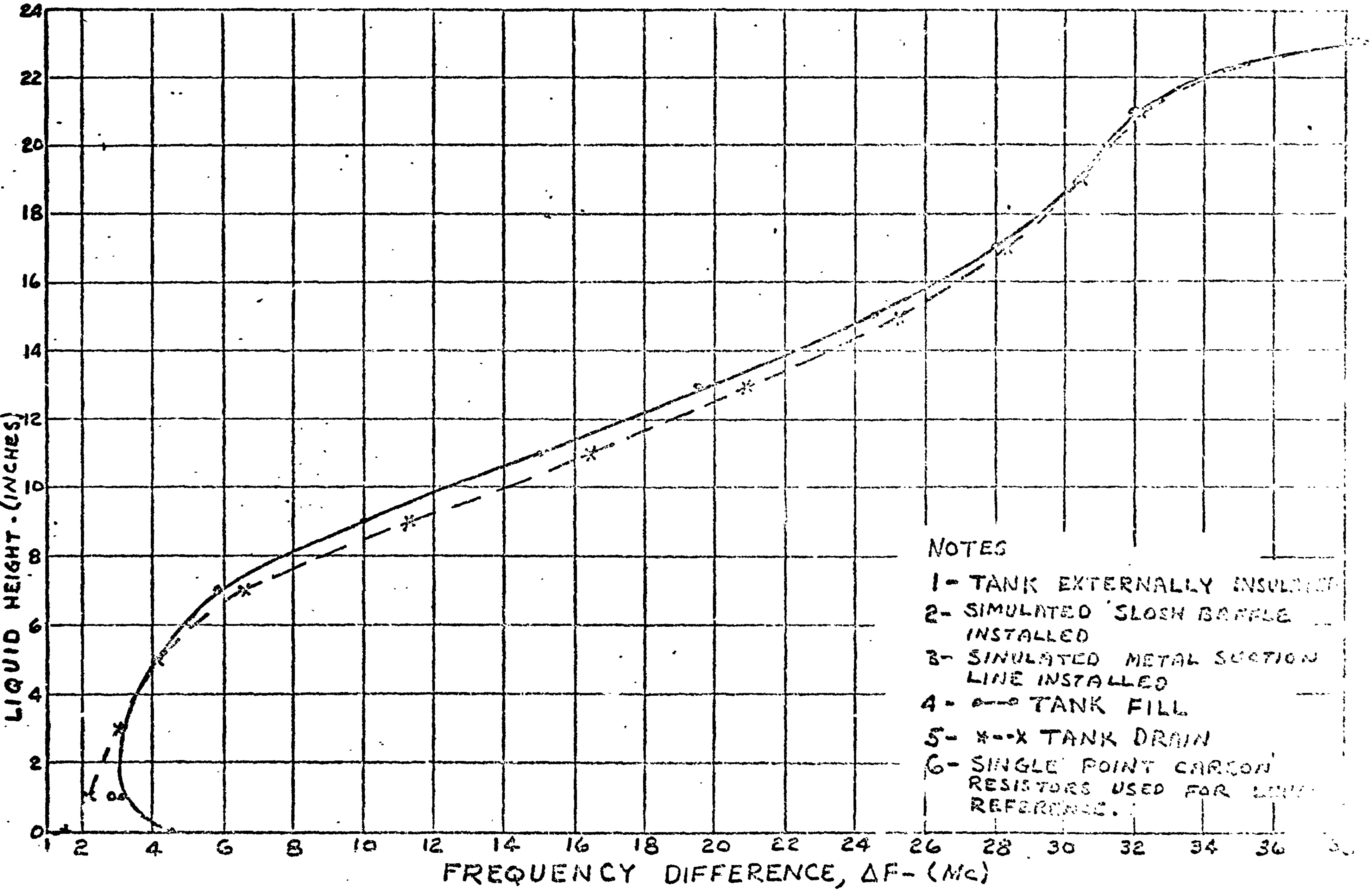


FIGURE 14

RESONANT FREQUENCY DIFFERENCE VS LIQUID LEVEL
LIQUID HYDROGEN TEST RUN No. 7
NOVEMBER 25, 1964

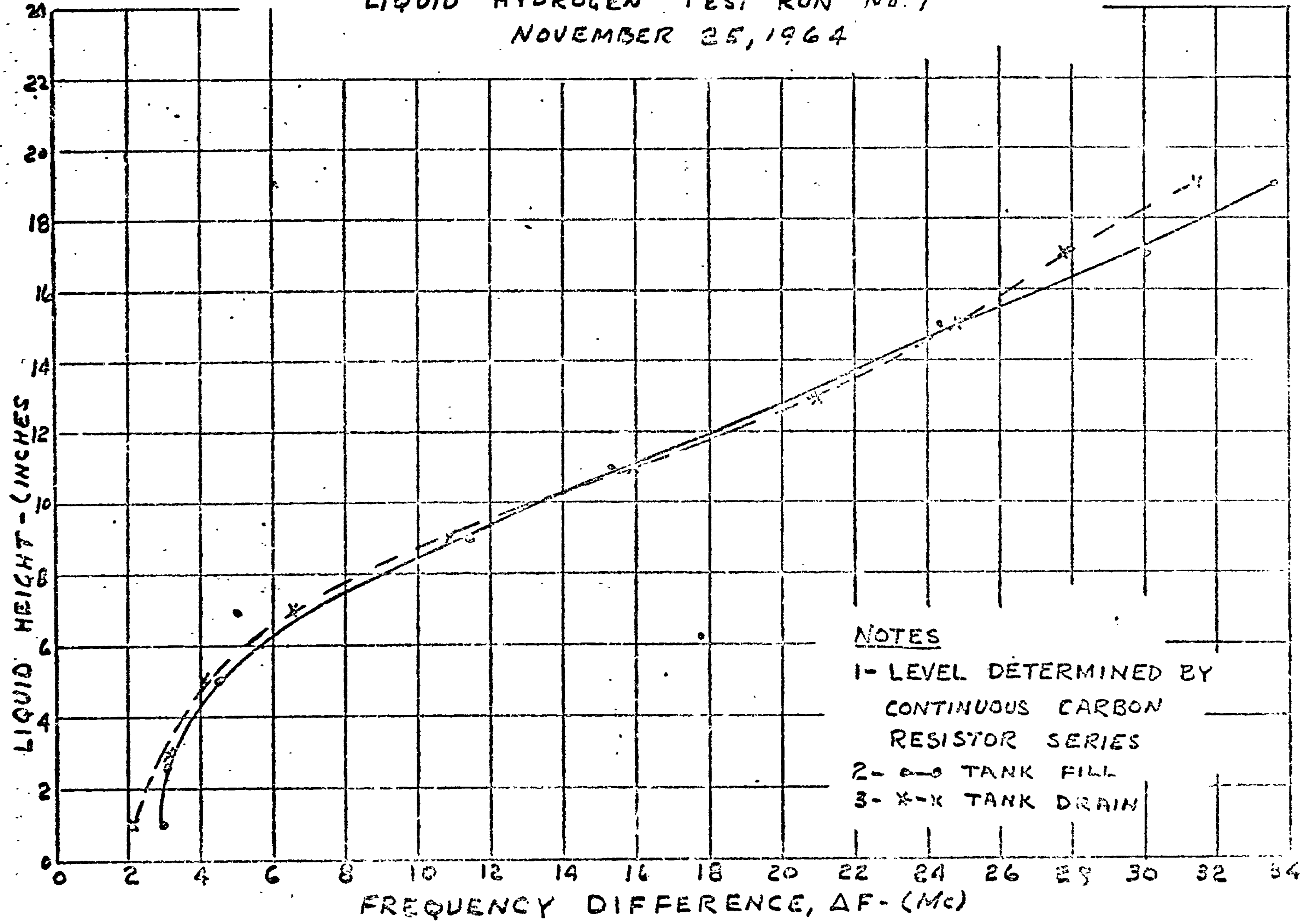


FIGURE No. 15

is quite good with Figure 14 in which individual carbon resistors were the sensing elements.

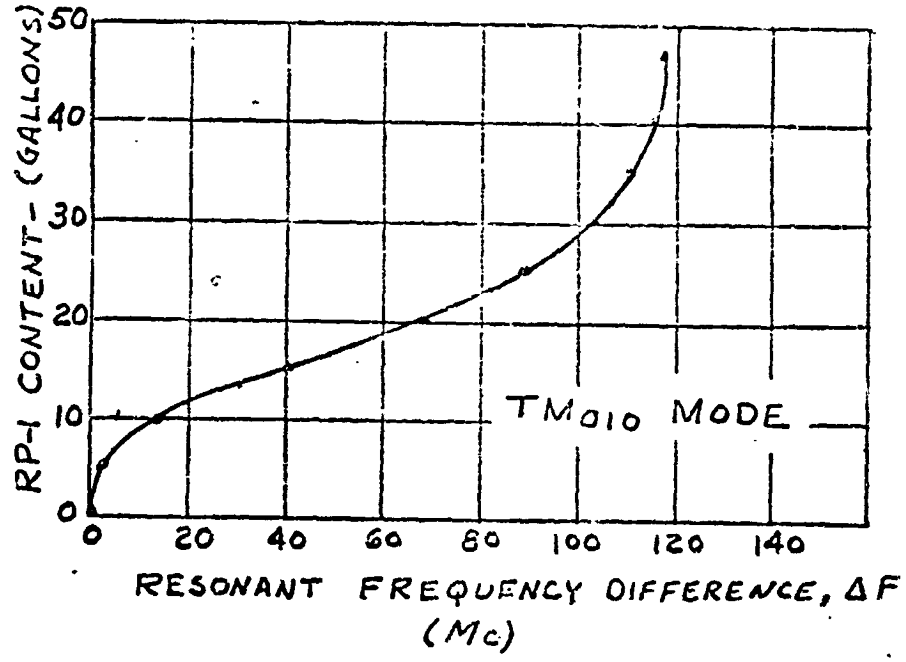
Liquid Oxygen Tests. Tests were conducted at the SCTB facility on 25-27 January 1965. The tank contained a teflon fill line, and the 12 individual level-sensing carbon resistors mounted on a teflon tube that extended the length of the tank midway between the center axis and the sidewall. The tank and instrumentation are shown in Figures 16 and 17. Because of possible incompatibility with LOX, the fiberglass for the fill line and instrumentation boards removed from the tank. A plot of the test results is shown in Figure 18. Note the similarity between the liquid height versus ΔF curve for LOX and those for LH_2. Empty resonant frequency was 377 Mc for the TM_{010} mode, and the frequency decreased to about 314 Mc when the tank was full. Empty tank Q was about 300.

On the basis of RP-1 test results described in the following section, it was anticipated that the TM_{011} mode would be used for the LOX testing. However, this mode was suppressed with the carbon resistor instrumentation and associated wiring in the tank. Consequently, a fill and drain was conducted, using the sweep generator RF system in the TM_{010} mode.

Also depicted in Figure 18 are results for the self-excited RF system. The instrumentation was taken out of the tank, and the TM_{011} mode was operative from empty to about 1/6 full. In the TM_{010} mode, self-excited operation was possible continuously from a 10 in. liquid level to a completely full tank. This covered approximately 60 percent of the range. In addition, oscillation in this mode occurred at two other points during the fill as indicated on Figure 18.

COMPARISON OF TM_{010} AND TM_{011} MODES

RP-1 IN 24" CRYOGENIC TANK



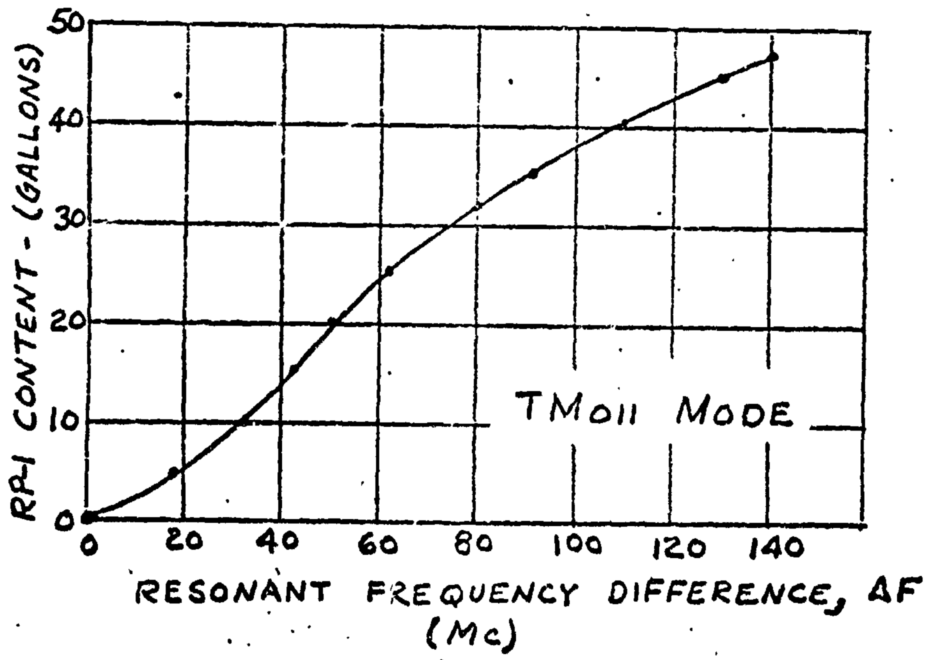
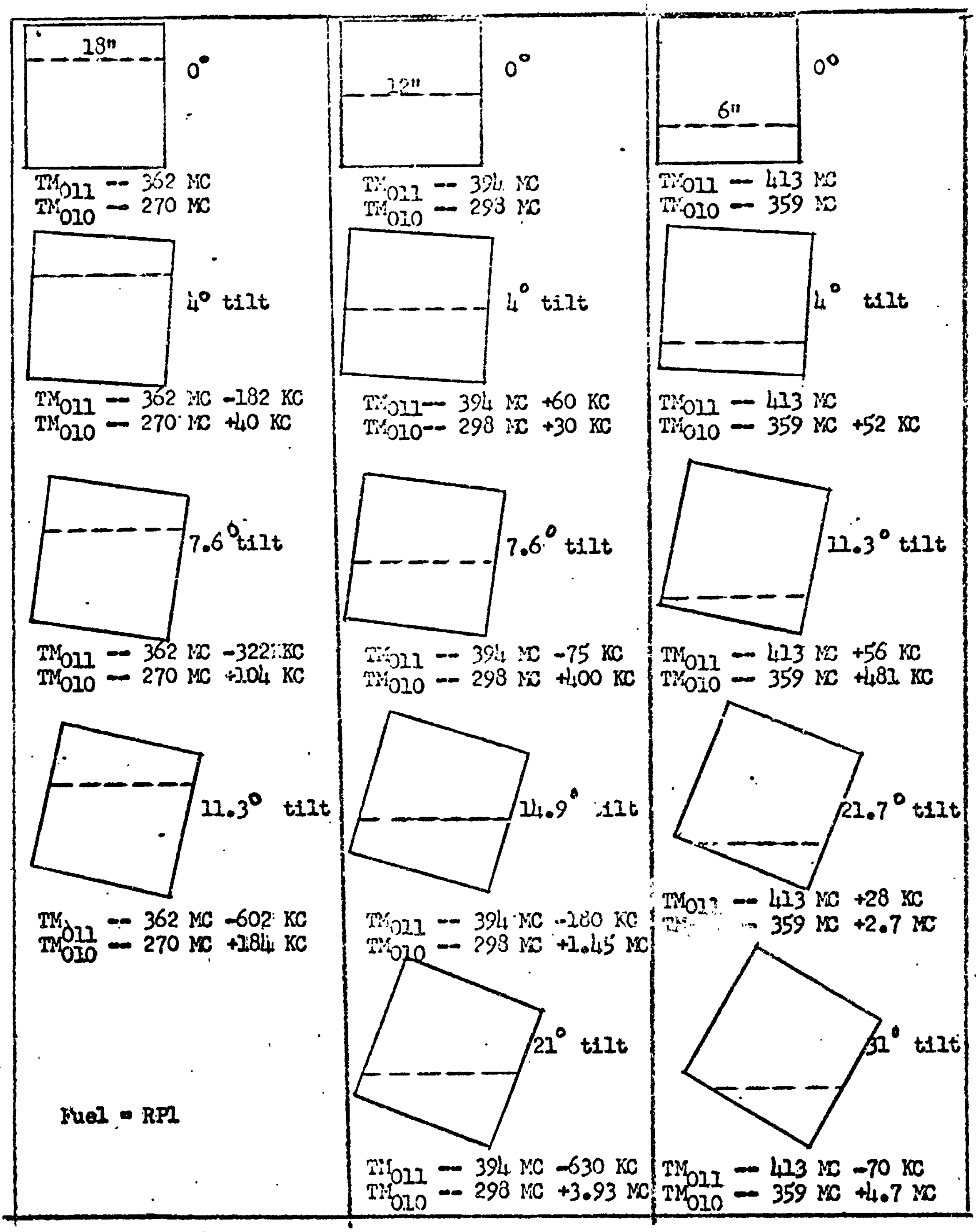


FIGURE No. 20



RESONANT FREQUENCY CHARACTERISTICS AS A FUNCTION OF TILT ANGLE AND MODE FOR 24" ALUMINUM TANK.

FIGURE NO. 21

resonant frequency for the TM_{011} mode at the 12-in. level would represent a measurement error of about 0.15 of a gallon out of about 24 gallons or about 0.6 percent. On the other hand, the 4.7-Mc shift in the TM_{010} mode at the 6-in. level (~15 gallons) represented a measurement error of 1 gallon or 6.6 percent.

Fill tests were also made with baffles placed in the tank, and results are shown in Figure 22. For the TM_{011} mode, the empty resonant frequency shifted downward to about 4.3 Mc. The resonant frequency of the TM_{010} mode shifted upward to about 400 Mc, as was the case for the LH_2 tests with baffles. The TE_{111} resonance was not observed over the fill cycle. There was considerable instability in resonance as the tank was filled with double or triple resonance peaks occurring at irregular intervals. It is likely that the RP-1 covering the baffle caused the conducting path between the baffle and tank wall to vary. If the baffle were an integral part of the tank structure, such spurious resonances would probably disappear.

Severe tilting of the tank, when about half full of RP-1, caused shifting of the resonant frequencies as indicated in Figure 23. The frequency shift did not follow the same pattern as was observed without the use of baffles. It was about the same for the two observed modes. Here, again, variation in conductivity between baffles and tank walls probably influenced resonance characteristics. Severe sloshing caused the resonant frequency to shift ±2 Mc (±4 percent measurement error) about the center frequency in the TM_{011} mode. Placing a metal fill line in the tank, whether baffles were present or not, caused rather extensive shifts in resonant peaks. These resonances were a function of fill-line axial position and penetration

RESONANT FREQUENCY vs LIQUID LEVEL
RP-1 MEASUREMENT
JANUARY 7, 1965

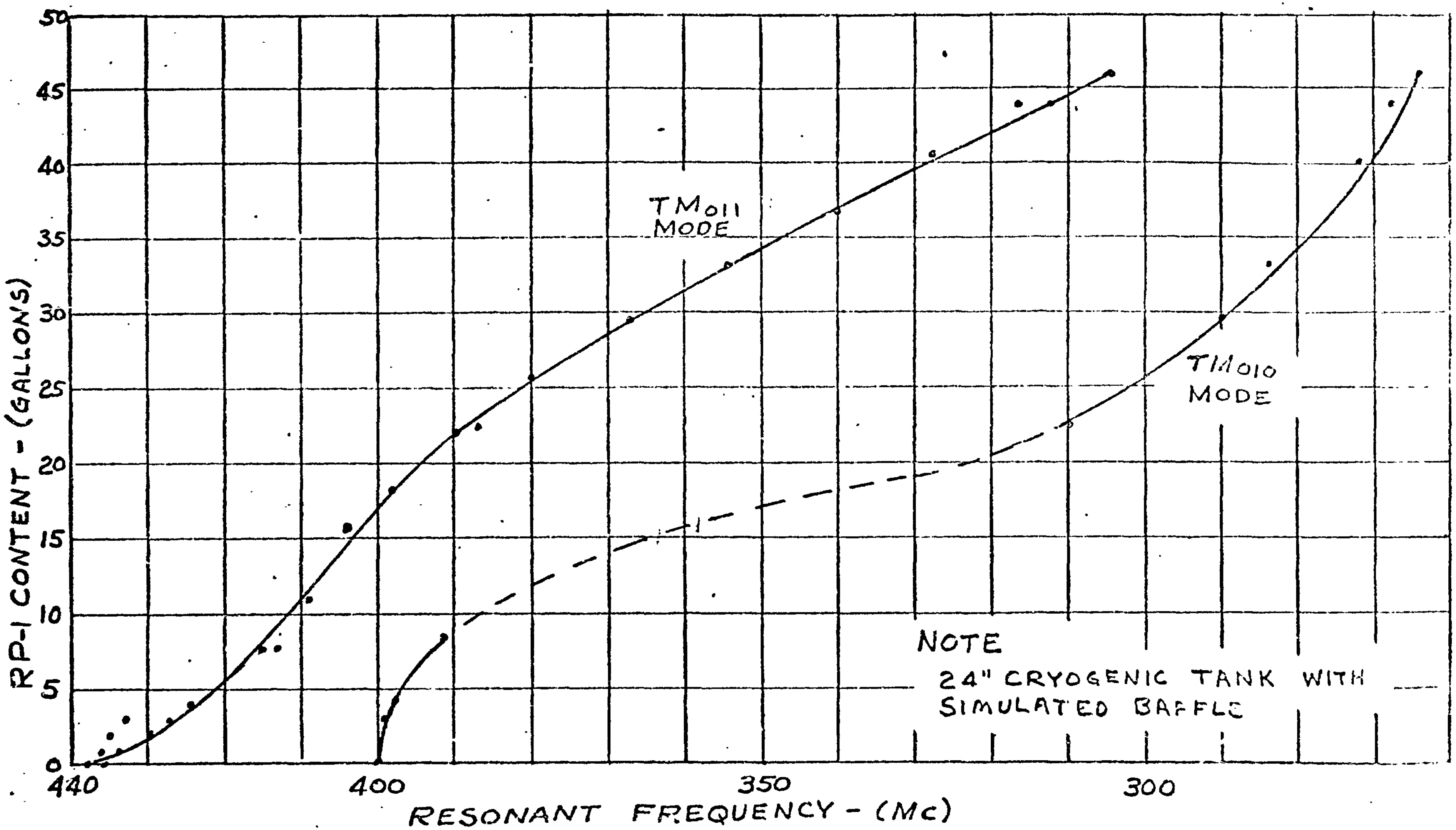
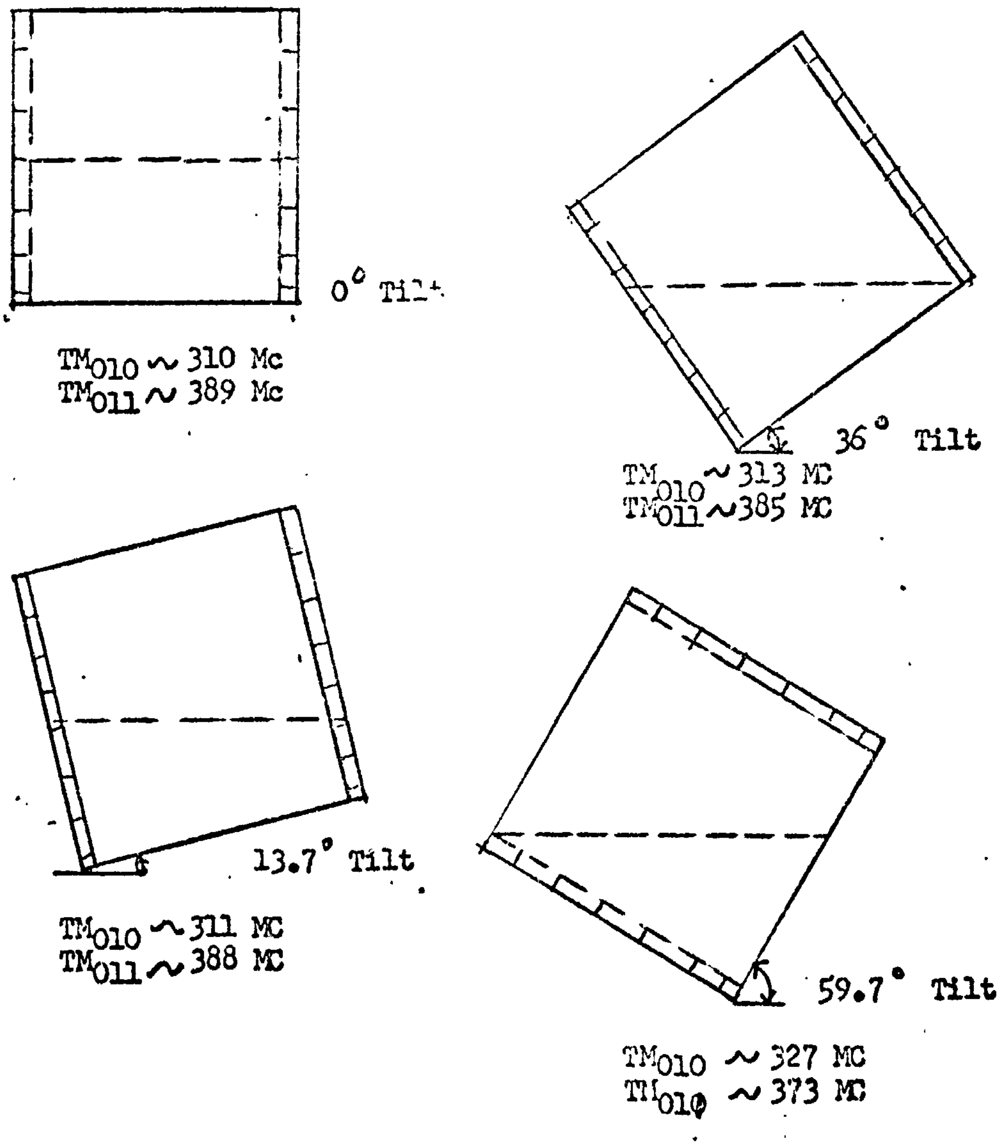


FIGURE NO. 22



Resonant Frequency Characteristics as a Function of Tilt Angle and Mode for 24" Aluminum Tank with Baffles

FIGURE No. 23

into the tank. As a typical example, with the tank full of RP-1 (46 gallons with the baffles in place), a fill line in the center caused the TM_{011} resonance to shift from 304 Mc to approximately 326 Mc.

Measurement Accuracy. A calibration run was made for the TM_{011} mode in which resonant frequency was determined at 42 points over the fill cycle. The RP-1 fuel was either measured prior to transfering it to the tank or weighed as it was removed.

Without reference to the calibration curve, and starting with some liquid in the tank, another complete fill cycle was run. Resonant frequency difference (ΔF) at four additional check points was also noted as the liquid was pumped from the tank. The results of these tests are shown in Table 1, and a plot of the test results is shown in Figure 24. Note that the check run follows calibrated values extremely well. This is further illustrated by Figure 25 which is a plot of percent of full scale of the measurement error. Measurements were repeatable, and it is believed that the larger errors were due to (1) weighing and measuring errors, and (2) the fuel that remained in the tank at the near-empty condition. Actually, near the empty-tank condition, accuracy with the TM_{011} mode would be somewhat better, since the frequency changes are more than 500 Kc with each pound of RP-1 added to the tank in this portion of the fill cycle.

Zero "g" Simulation Measurements

The schedule permitted an investigation of the effects of zero "g" on the RF resonant cavity sensing technique. To simulate zero "g" conditions for LH_2, a void was created in the tank. A hollow 4 5/8-in. outside diameter

CALIBRATION TESTS

RESONANT FREQUENCY DIFFERENCE VS LIQUID LEVEL

24" CRYOGENIC TANK

JANUARY 4, 5, AND 8, 1965

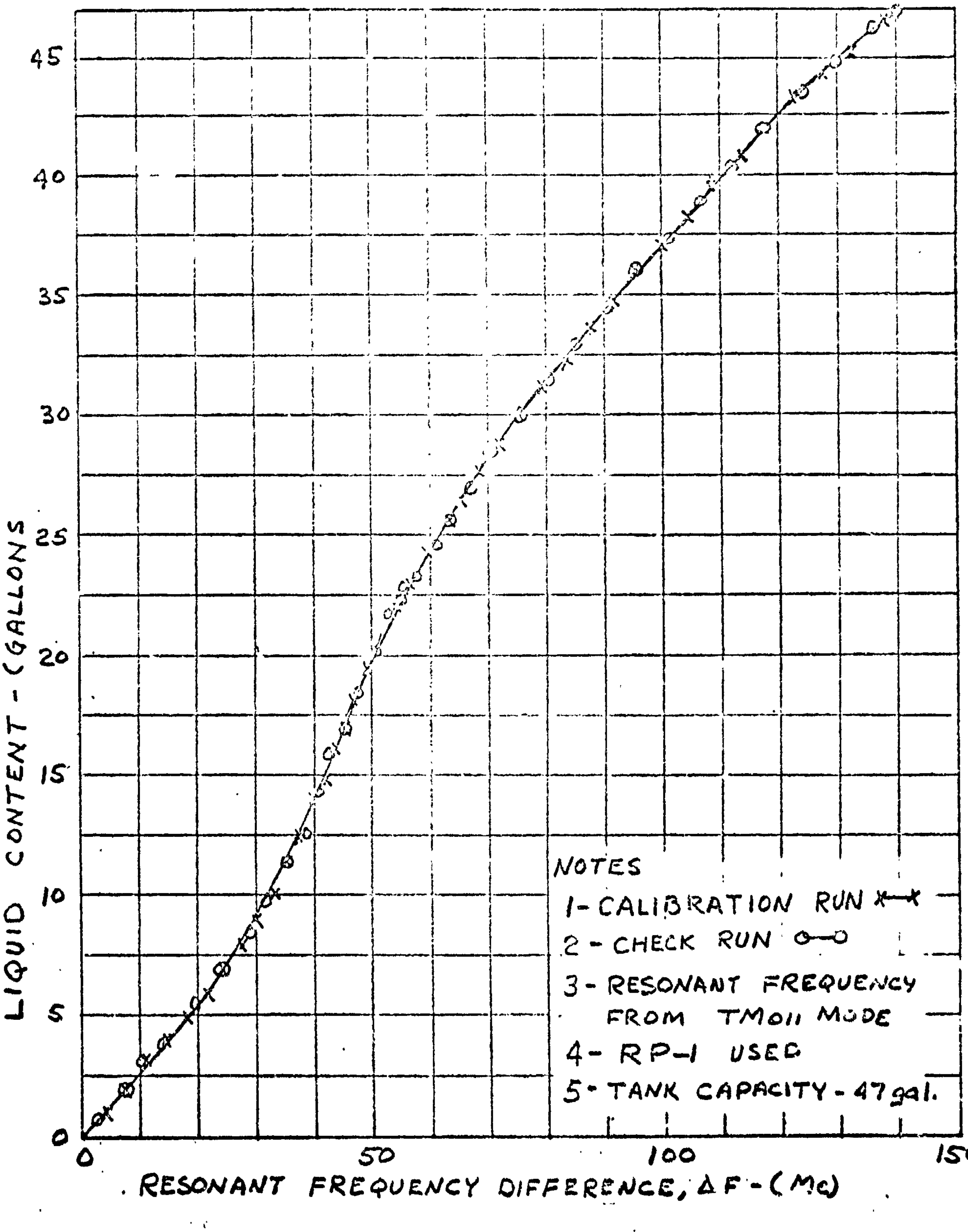


FIGURE No. 24

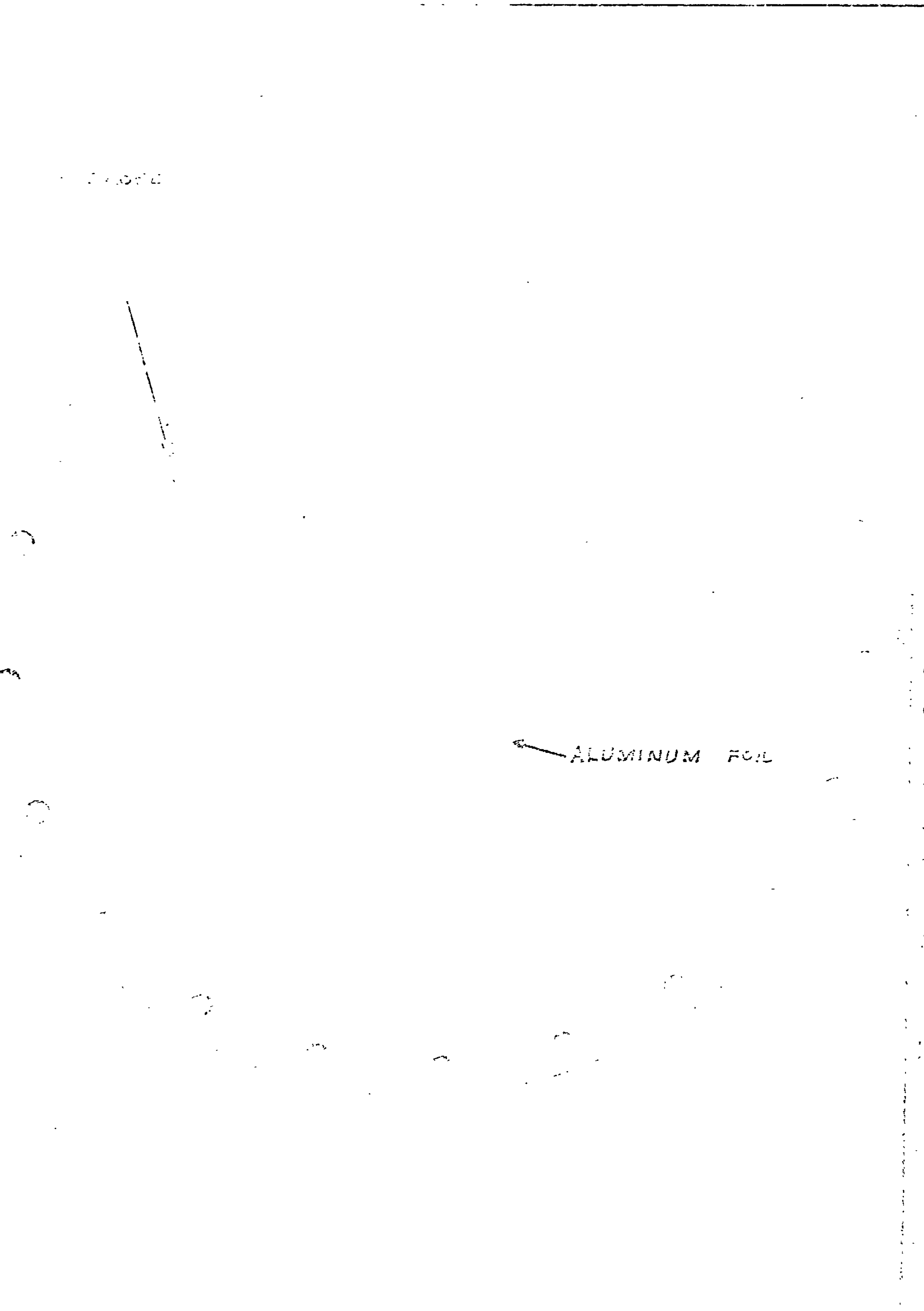


FIGURE No.16

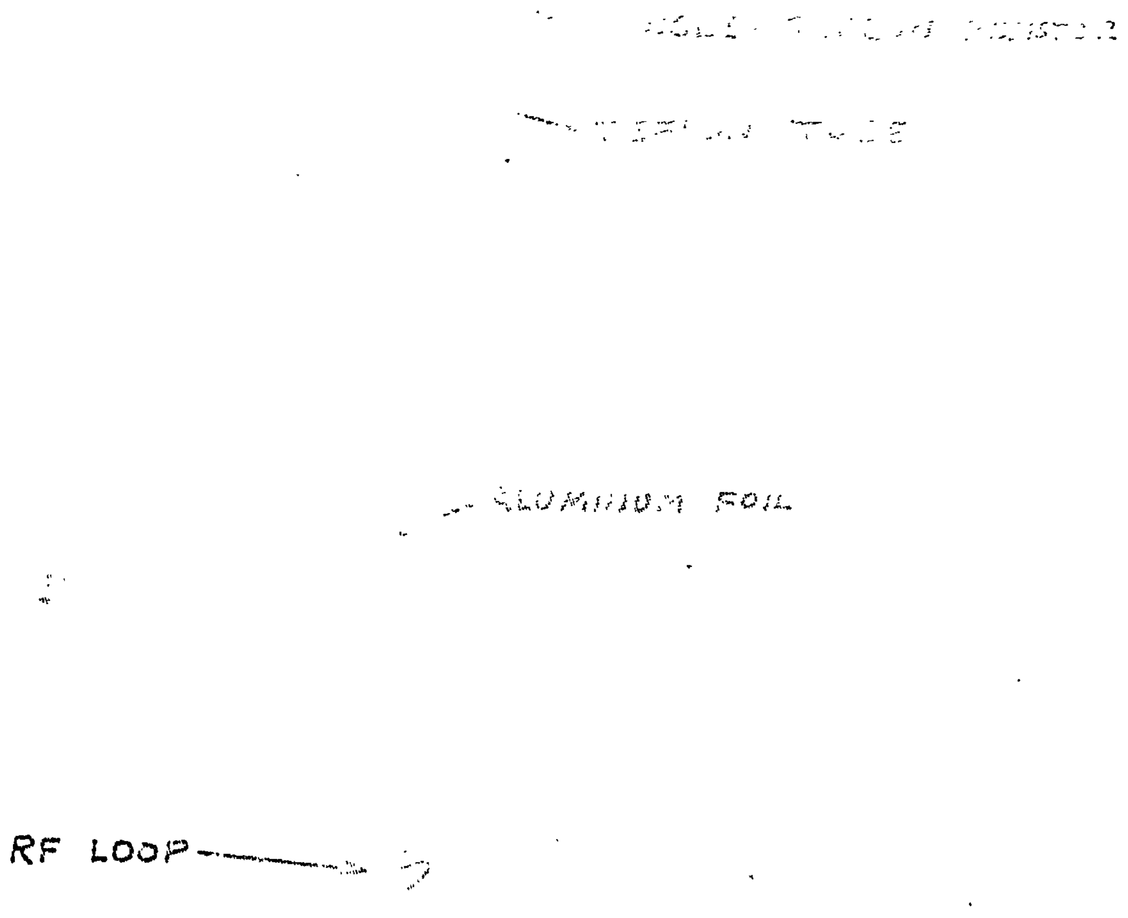


FIGURE No. 17

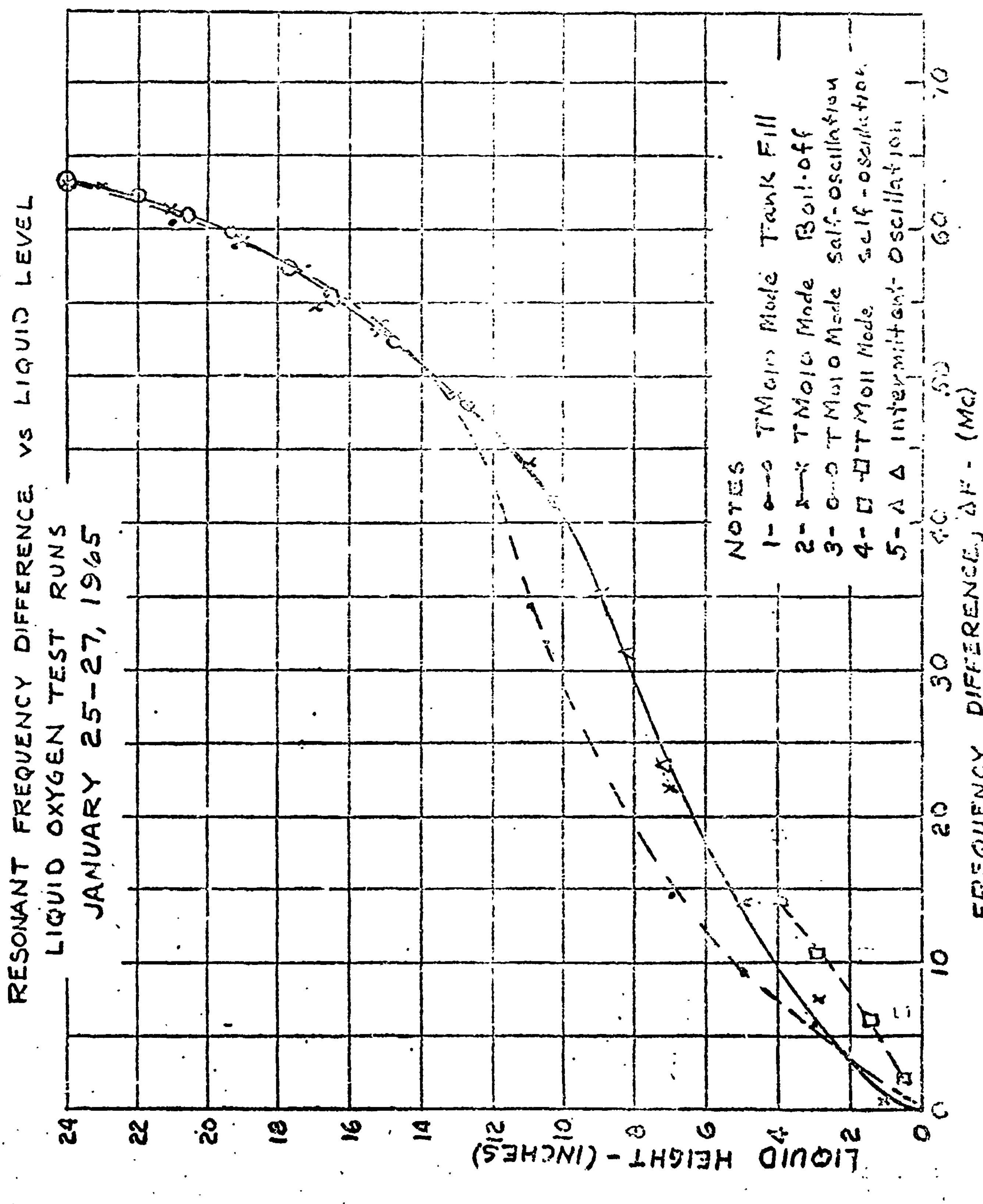

RESONANT FREQUENCY DIFFERENCE vs LIQUID LEVEL
LIQUID OXYGEN TEST RUNS
JANUARY 25-27, 1965
NOTES
1- TMolo Mode Tank Fill
2- TMolo Mode Boil-off
3- TMolo Mode Self-oscillation
4- TMoll Mode self-oscillation
5- Intermittent Oscillation
LIQUID HEIGHT - (INCHES)
FREQUENCY DIFFERENCE, ΔF - (Mc)

FIGURE No. 18

Rocket Fuel, RP-1, Tests

These tests were run at Lockheed facilities in the hangar area at Moffett Field between 14 December 1964 and 8 January 1965. Several different types of tests were conducted and are discussed separately.

Resonant Characteristics of the Tank. A series of fills was made to accurately determine the resonant characteristics of the 24 in. aluminum tank utilizing RP-1 fuel. Tests results for the tank without baffles or fill lines are shown in Figure 19. The TM_{010} mode has the same characteristic shape exhibited for LH_2 and LOX tests. The TM_{011} mode, while somewhat higher in frequency, did show much improved ΔF, particularly when nearly empty. The TE_{111} mode also had good frequency resolution with fill near empty but was considerably lower in amplitude than the other modes. The TM_{010} mode exhibited a double resonance over the entire fill cycle, with the solid line always being several decibels greater in amplitude. To further illustrate the improved characteristics of the TM_{011} mode over the TM_{010} mode for the tank used in the tests, both curves appear in Figure 20. The TM_{010} mode changed from 379 Mc down to 262 Mc, whereas the TM_{011} mode had a frequency range from 448 Mc to 310 Mc. In addition, amplitude of the TM_{011} mode was 6-20 db greater over the fill cycle. The Q was approximately 1000.

Tests were taken at several different fuel levels to determine resonant-frequency shifts as a function of tilt angle and mode. The results of these tests are shown in Figure 21. Note particularly that the TM_{011} mode exhibited less shift in resonant frequency at the more severe tilt angles than did the TM_{010} mode. At the smaller tilt angles, a 600-kc shift in

RESONANT FREQUENCY CHARACTERISTICS
RP-1 MEASUREMENTS
DECEMBER 16 & 17, 1964

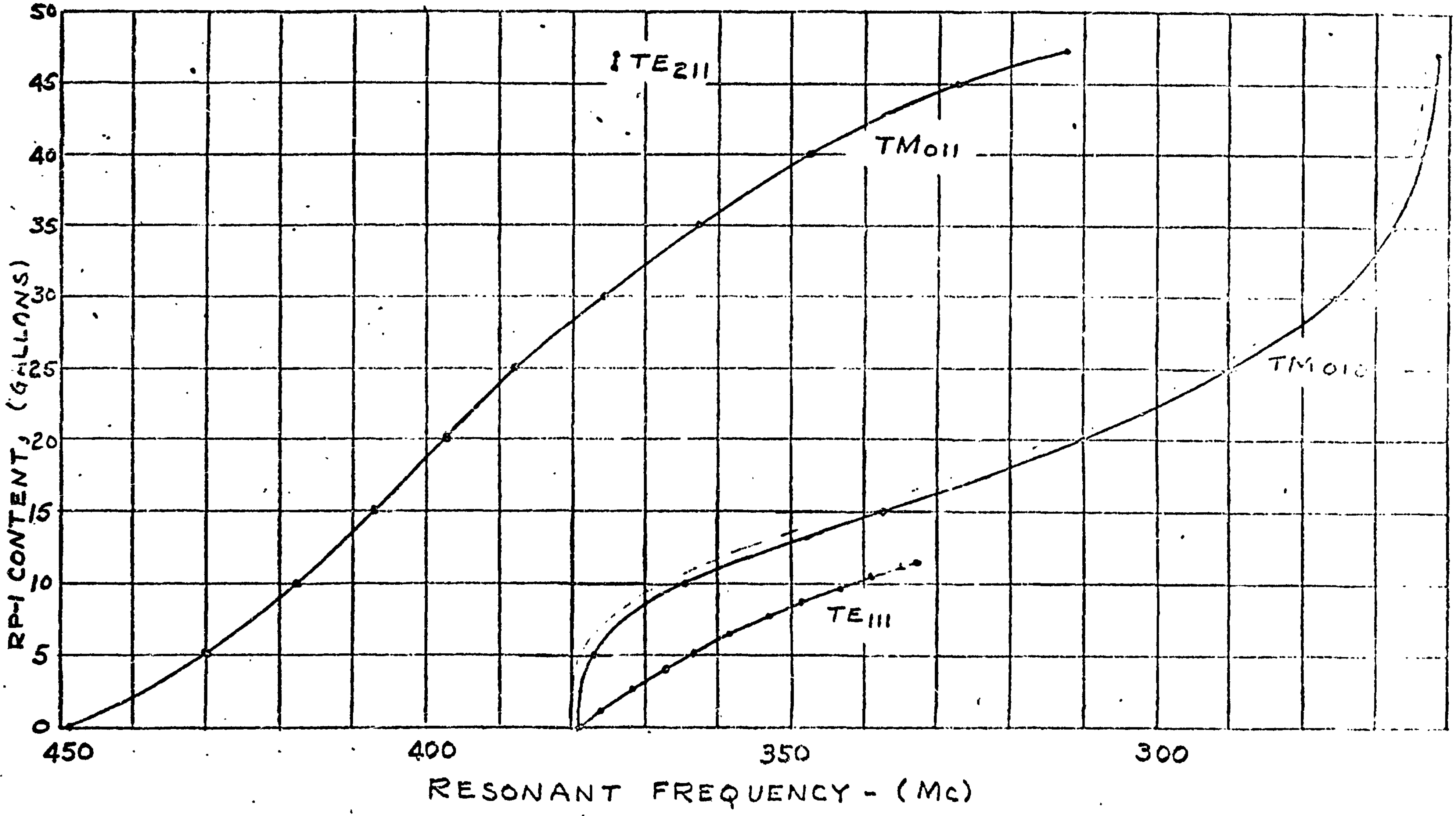
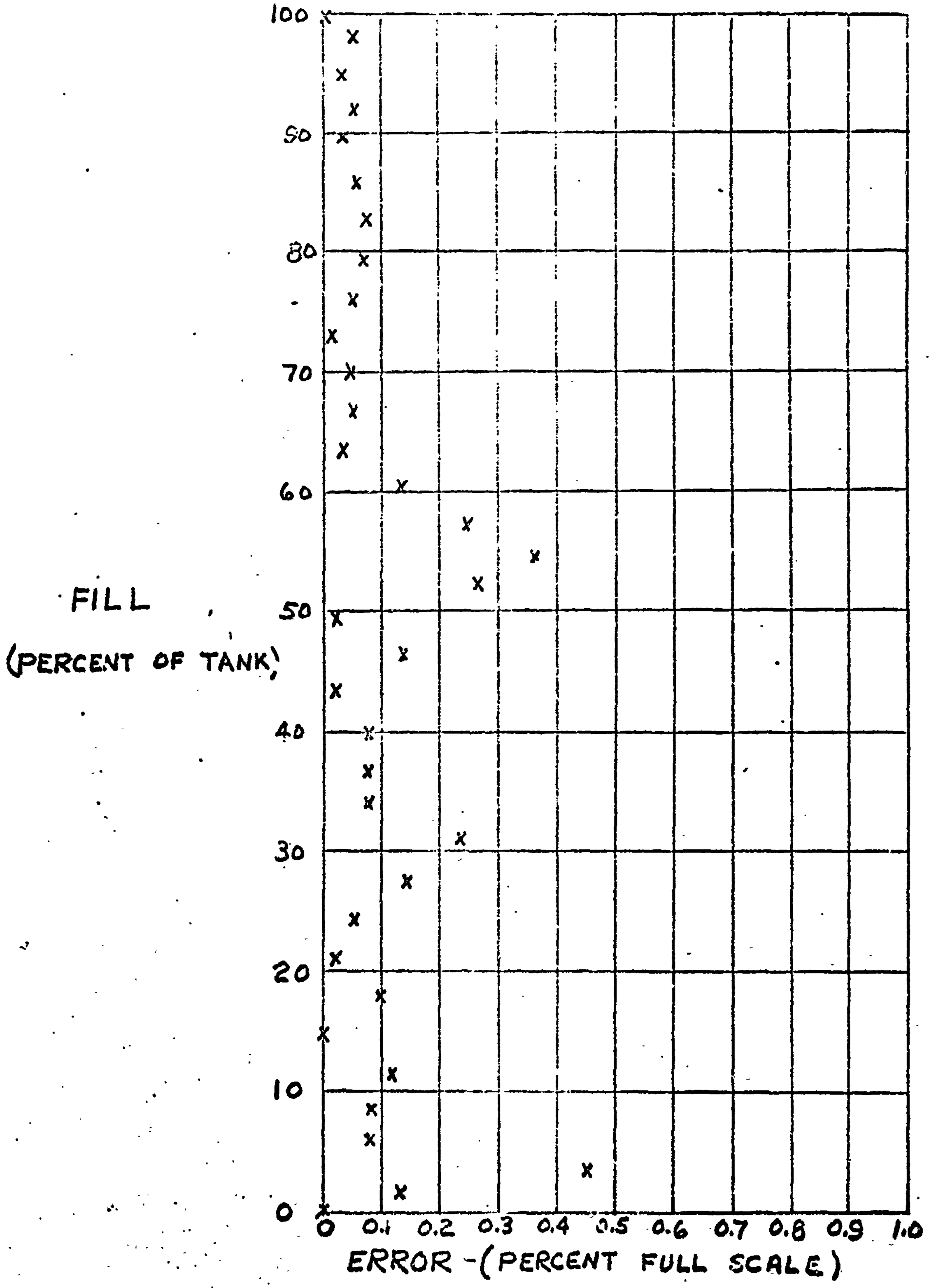


FIGURE No. 19

MEASUREMENT ACCURACY TEST

TABLE 1

RP-1 LBS.	Δ F Check Run	Δ F Calib. Run	Indicated Error - Lbs.	Percent Error	Percent Tank Fill
0	0	0	—	—	0
5.9	3 MC	3.23 MC	- .42	.13	1.86
12.65	7.628	6.858	+1.43	.45	3.99
19.4	10.37	10.531	- .29	.09	6.12
26.9	14.398	14.554	-.31	.09	8.49
36.9	19.55	19.722	- .35	.11	11.64
47.0	24.486	24.486	0	0	14.83
56.9	28.480	28.601	- .32	.10	17.95
67.1	32.201	32.172	+ .09	.02	21.17
76.9	35.247	35.192	+ .18	.05	24.26
87.0	38.037	37 934	+ .40	.13	27.44
97.9	40.710	40.937	- .75	.24	30.88
107.1	42.897	42.942	- .25	.08	33.79
116.9	45.185	45.2[illegible]	- .27	.08	36.88
126.9	47.71	47.781	- .27	.08	40.03
136.9	50.414	50.403	+ .04	.01	43.19
146.9	53.438	53.319	+ .42	.13	46.34
156.9	56.581	56.574	+ .02	.01	49.50
165.9	60.348	59.905	+0.88	.28	52.33
174.2	63.510	63.857	-1.16	.36	54.50
182	66.699	6[illegible].395	+0.79	.25	57.41
192	70.98	70.816	+0.39	.12	60.57
202	75.5	75.546	-0.10	.03	63.72
212	80.176	80.264	- .18	.05	66.86
222	85.062	85.232	- .14	.04	70.03
232	90.201	90.203	- .04	.01	73.19
241.9	95.359	95.430	.13	.04	76.31
251.9	100.593	100.702	- .20	.06	79.46
261.9	105.990	106.113	- .23	.07	82.62
271.9	111.715	111.619	+ .17	.05	85.77
281.8	117.202	117.271	- .10	.03	89.90
2[illegible]1.2	122.856	122.766	+ .14	.04	91.86
301.2	129.262	129.220	+ .06	.02	95.02
311.2	135.838	135.948	- .16	.05	98.17
317	140.019	140.019	0	—	100.00



RF SYSTEM ACCURACY

FIGURE NO. 25

cardboard tube extending the entire length of the tank provided the void. A second series of experiments was conducted by containing 3.5 quarts of a dielectric (polystyrene pellets) material in a plastic bag. The bag was positioned in several locations in the copper tank.

Figure 26 illustrates the results of the center void simulation. The tube was very lossy and caused the output to drop by approximately 44 db and the Q to decrease from 1800 to less than 100. The curve shows that ΔF curves with and without the void were nearly parallel indicating that the only change was due to the difference in the amount of dielectric in the tank.

For the reverse condition, i.e. with the dielectric contained in a plastic bag, various positioning of the dielectric resulted in an error of approximately 2.5 percent. Table II is a tabulation of the data obtained during the experiment. The empty tank frequency was 474.6 Mc.

Table II

RESONANT FREQUENCY AS A FUNCTION
OF DIELECTRIC LOCATION WITHIN COPPER TANK

Position of Dielectic	TM_{011}	TM_{010}	TE_{111}
Uniformly on Bottom	471.6 Mc	403.7 Mc	3[illegible]5.2 Mc
Top Along Axis	469.0 Mc	398 Mc	[illegible] Mc
Center Axis	472.6 Mc	394.7 Mc	386.2 Mc
Bottom Axis	465 Mc	400 Mc	385 Mc
Top, Parallel to Axis	469.5 Mc	402 Mc	392 Mc
Center, Parallel to Axis	471.5 Mc	399 Mc	392.5 Mc
Bottom, Parallel to Axis	468.5 Mc	402 Mc	390 Mc

Impedance Measurements. After determining that the TM_{011} mode showed greatly improved resonant-frequency characteristics near the empty-tank conditions the spurious resonance near the TM_{010} mode could not be easily eliminated, the decision was made to utilize the TM_{011} mode for the self-excited system in tests with RP-1 fuel. Prior to this decision, however,

SIMULATED ZERO "G" TEST
COPPER TANK
JANUARY 21, 1965

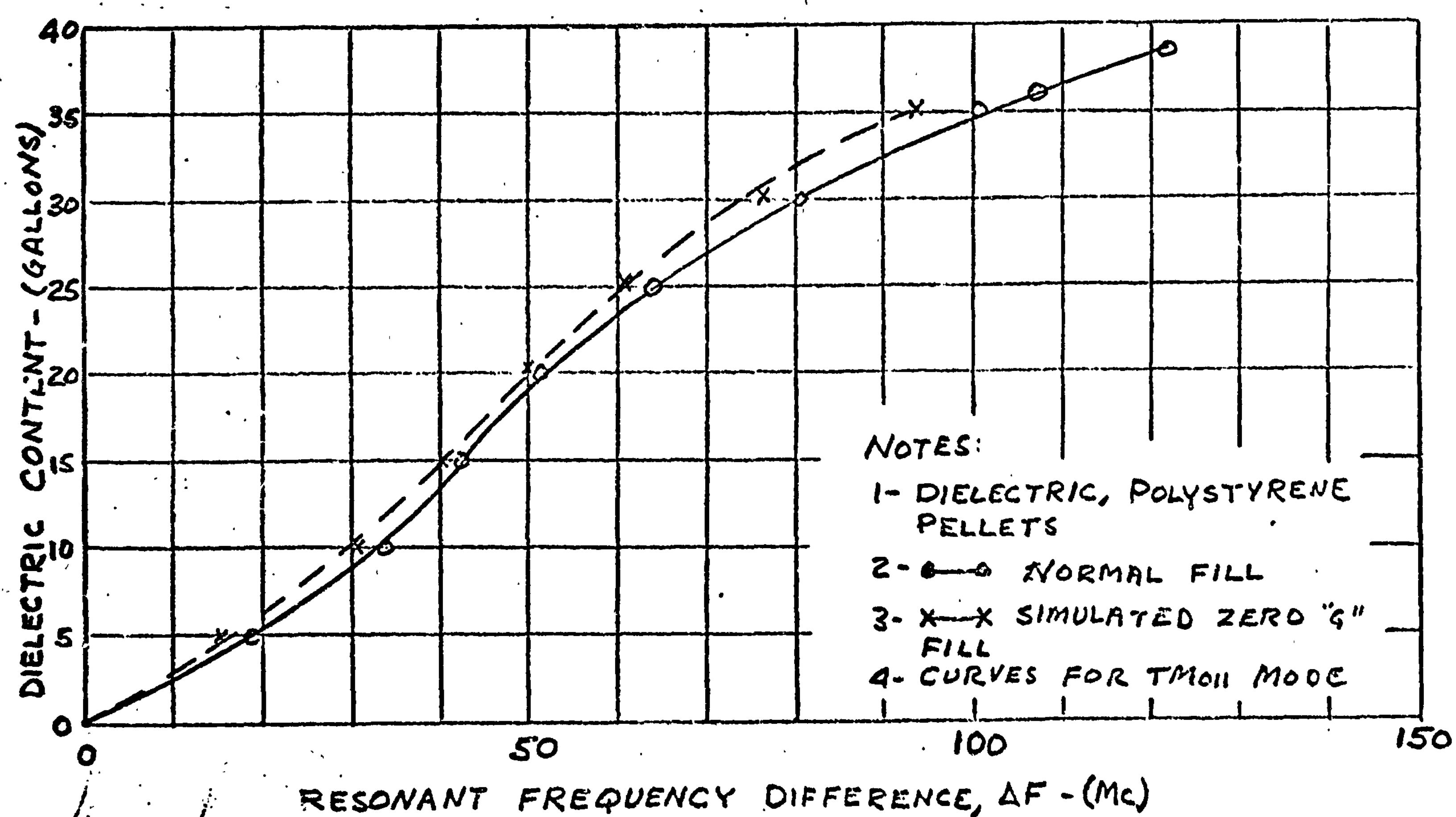


FIGURE No. 26

a brief investigation of the TM_{011} mode was made to determine resonance characteristics over the entire fill cycle. The following factors were determined in the course of these tests:

- For the empty tank, the TM_{011} resonance occurred at 450 Mc and was free of any spurious resonances. Q was about 1000 and voltage amplitude was 16 times that of the TM_{010} mode.
- The TM_{011} peak remained stronger than for any other mode over the entire fill range.
- The amplitude of the peak decreased, at most, by a factor of 15 over the range.
- Q remained near 1000 throughout the fill.
- The TM_{011} response remained clean and undistorted without spurious peaks over the fill range.
- The amplitude of the TM_{010} decreased much more severely as a function of fill.
- A higher mode (TE_{211}) appeared, but it remained negligible until the tank was nearly full, where amplitude was 6 db less than the TM_{011} mode. Full resonant frequency for this mode was about 445 Mc.

To utilize the TM_{011} mode in the self-excited RF system, the input and output impedances of the tank and the wide-band amplifier were determined, and the frequency response of the amplifier was tailored to favor this mode. A plot of the amplifier gain characteristics after retuning is shown in Figure 27. Note that gain is good to 450 Mc and then decreases quite rapidly. A gain of better than 20 db down to 180 Mc is available.

WIDE BAND AMPLIFIER
GAIN CHACTERISTICS
DECEMBER 31, 1964

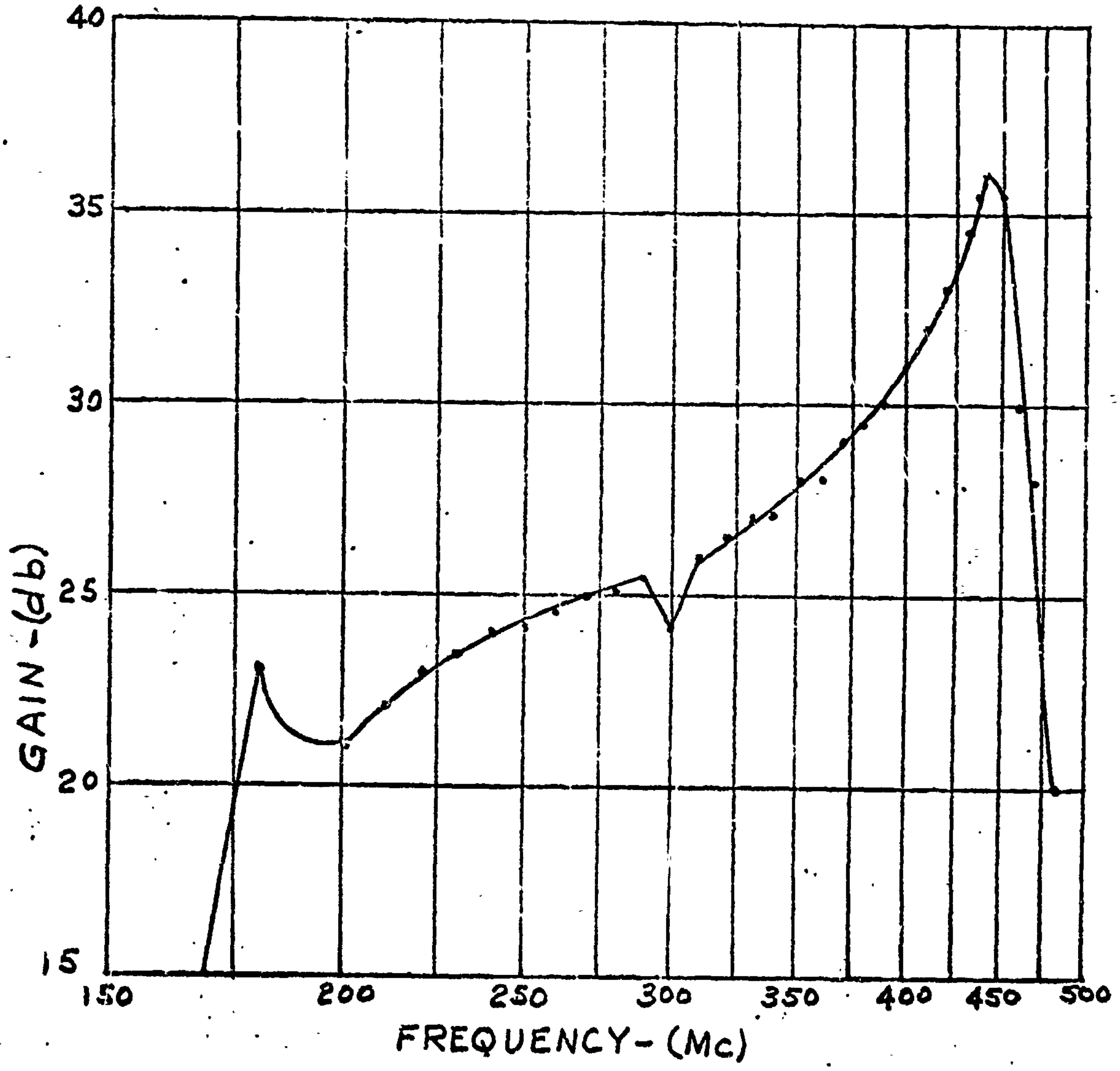


FIGURE No. 27

The input impedance of the tank, with the output terminated with 50 ohms, was measured with a VHF bridge. The input admittance as a function of liquid content is presented in Table III and plotted in Figure 28. Admittance rather than impedance was presented because of more precise readings from a Smith chart calculator. It may be observed from Figure 28 that susceptance starts at zero for the empty tank and then rises linearly to constant value for increasing fill level. The conductance remained constant until roughly half full and then dropped to another constant until roughly half full and then dropped to another constant value for the remainder of the fill cycle.

The tank output feeds into a wide-band amplifier, with an input impedance that varies with frequency. In order to compensate for this changing impedance, it needs to be known over the frequency range of the fill cycle. Accordingly, measurements were taken with the VHF bridge in increments of 10 Mc from 450 Mc down to 300 Mc. The results are tabulated in Table IV and plotted in Figure 29. The input impedance was referenced to the top of the input connector.

The reactive component of this impedance was capacitive for all frequencies except 450 Mc and 440 Mc. The amplifier circuit as shown in Figure 30 has coupling capacitors at the input to the base of the first transistor. One would expect, therefore, that the impedance be capacitive at all frequencies. The inductive reactance observed was quite small and could have been due to the length of lead from the top of the input connector to the capacitor terminal. This inductive reactance could have been slightly greater than the capacitive reactance at the frequencies involved. The error in the phase-angle reading from the bridge is also enough to account for this inductance.

TABLE III

TANK IMPEDANCE*

RP-1 Level, (In.)	Normalized Input** Conductance	Normalized Input** Conductance
0	.24	+.01
3	.22	-.18
6	.25	-.16
9	.26	-.12
12	.22	-.08
15	.18	-.12
18	.08	-.125
20	.10	-.10
22	.11	-.12
23	.10	-.15
23 1/2	.11	-.08
24	.16	-.09
RP-1 Content (gal.)		
0	.15	+.01
1	.155	+.005
2	.180	+.005
3	.160	-.025
4	.130	-.125
5	.160	-.066
6	.160	-.100
7	.175	-.08
8	.175	-.08
9	.175	-.07
10	.200	-.07
11	.185	-.07

*50 ohm load on output
**Characteristic impedance Zo = 50 ohms

INPUT ADMITTANCE
24" CRYOGENIC TANK
LIQUID - RP-1

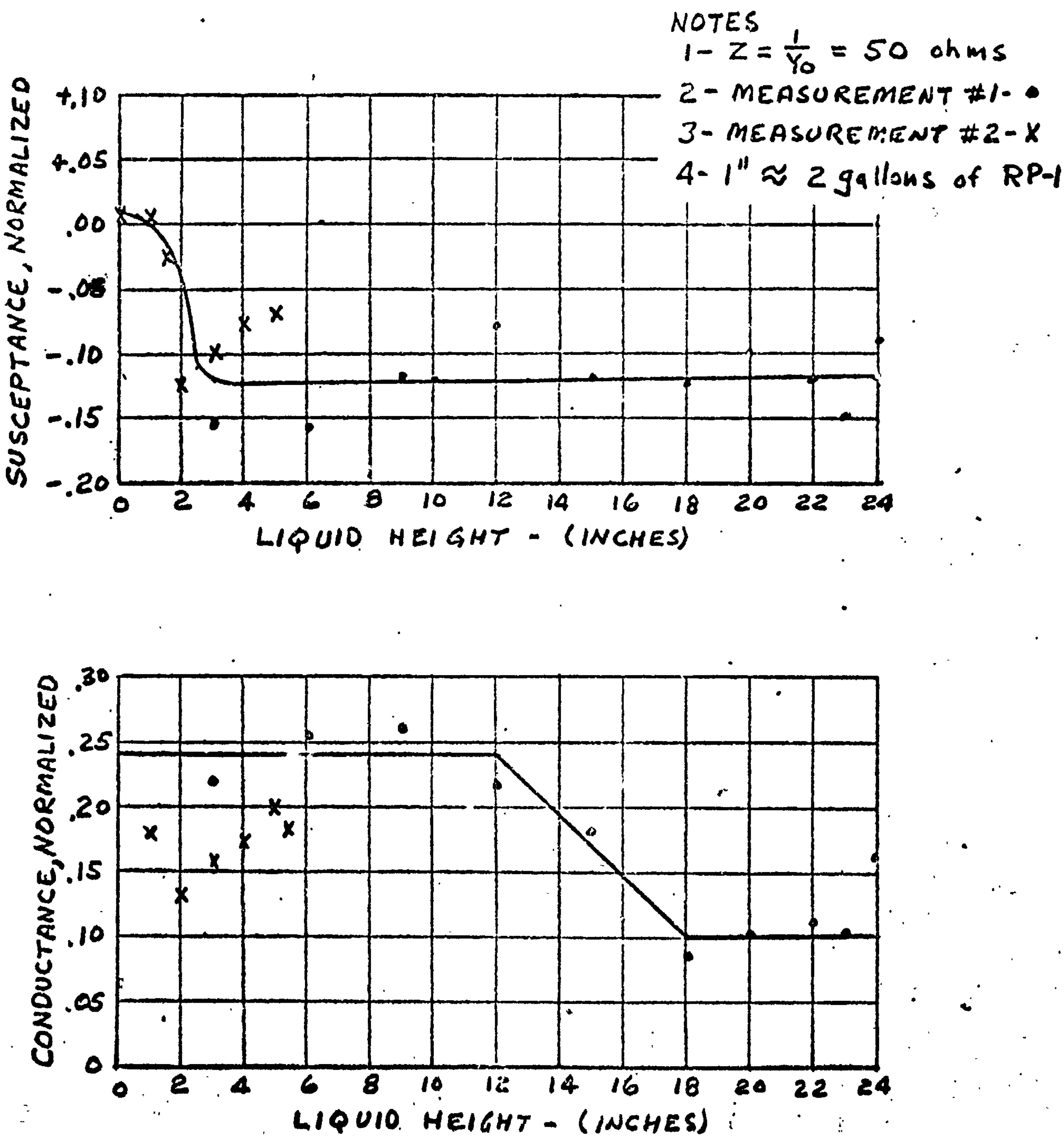


FIGURE No. 28

TABLE IV

AMPLIFIER IMPEDANCE*

Frequency (Mc/S)	Normalized Input** Resistance	Normalized Input** Reactance
450	.43	+.04
440	.41	+.05
430	.47	-.05
420	.46	-.10
410	.52	-.21
400	.50	-.25
390	.53	-.27
380	.53	-.34
370	.55	-.37
360	.55	-.43
350	.52	-.47
340	.67	-.62
330	.57	-.63
320	.58	-.70
310	.61	-.75
300	.57	-.91

*50 ohm load on the amplifier output
**Characteristic impedance Z_o = 50 ohms

WIDE BAND AMPLIFIER

INPUT IMPEDANCE

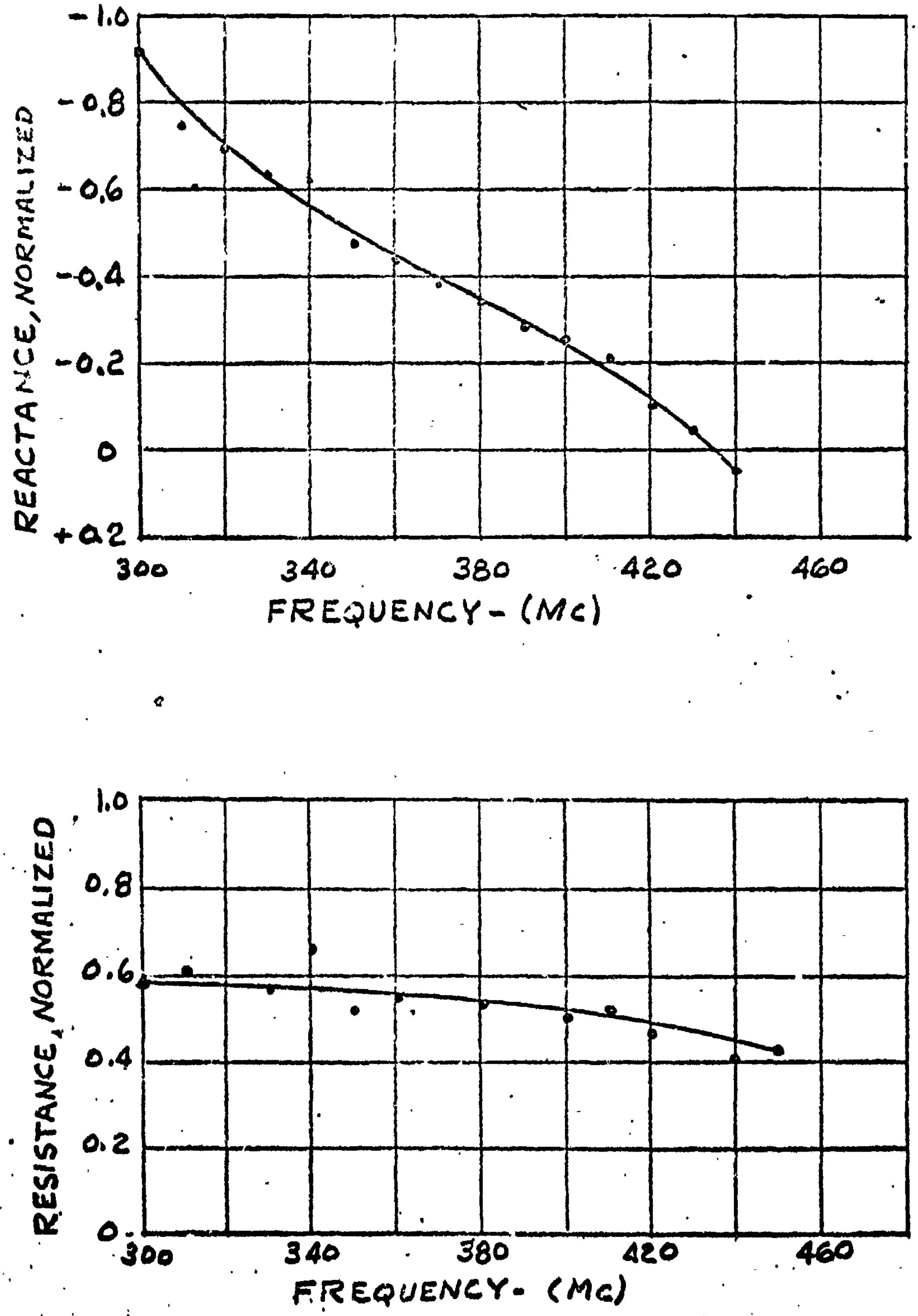
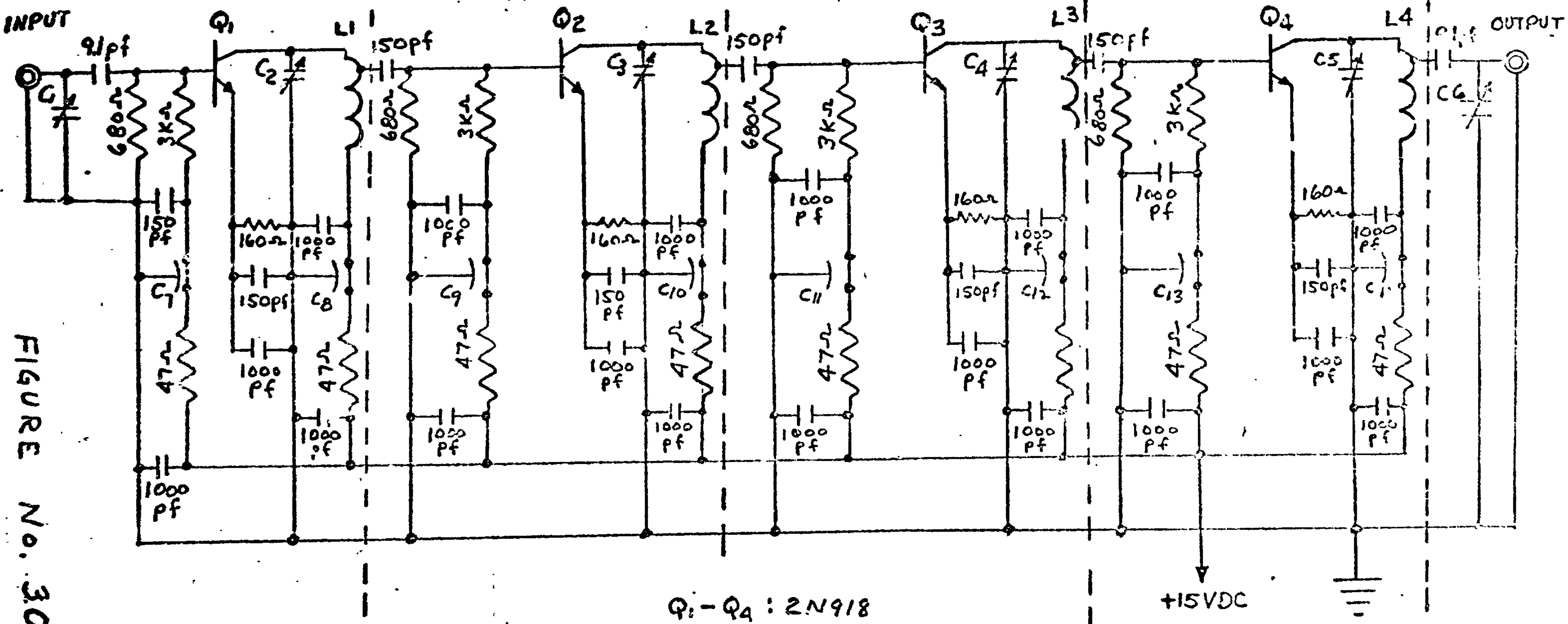


FIGURE No. 29

4 STAGE AMPLIFIER CIRCUIT



$Q_1 - Q_4$: 2N918

$C_1 - C_6$: 1 to 10 pf

$C_7 - C_{14}$: 1000 pf feed thru

FIGURE No. 30

The purpose of the admittance and impedance measurements was to determine circuit characteristics in sufficient detail to determine requirements as to phase shift and isolation for the amplifier in an experimental, self-excited RF system.

Self Excited System. The technique of measuring dielectric (fuel) content using the self-oscillating system requires that the total-phase shift around the feedback loop be zero. The lengths of cable leading from the tank to the amplifier input and from the amplifier output to the tank can be adjusted so that the input impedance of the tank and the amplifier be pure real at a single frequency. Because the system must operate over a range of frequencies, the optimum choice of cable lengths should be for the middle frequency in the range. Then subsequent phase shifts at other frequencies, would remain small enough to keep the loop in oscillation. Attenuators at the input and output of the amplifier can help by providing isolation, but only if the open loop gain does not fall below unity. Isolators and matching devices would also be useful, but are not available as stock items at these frequencies. Size, cost, and delivery schedules were such as to preclude use of custom-built devices for this application.

In accordance with the impedance measurements, the cables were tailored to be 0.520, 0.770, and 0.557 wavelengths at 380 Mc (the middle frequency of the RP-1 fill range). The first two cables differed by $\lambda/4$ and were used between the amplifier output and the tank. The third cable connected the tank to the amplifier input (See Figure 3). The first two were used separately to determine which worked best when the balanced modular was placed on the amplifier input or output.

The test was started with the tank approximately half full with the 0.520 λo (λo = wavelength at 380 Mc) cable on the amplifier output. Operation from 393 Mc down to 332 Mc was possible by changing to the 0.770 cable on amplifier output around 380 Mc. The tank was then emptied until approximately 2 gallons of fuel remained. The system oscillated at 441 Mc with the 0.567 λo cable on the amplifier input and the 0.770 λo. cable on the output. No other available cable combination was satisfactory. When the balanced modulator was placed on the input, the loop oscillated, with slight waveform distortion. With the balanced modulator on the output, the waveform was clean and undistorted. Upon adding RP-1, the feedback loop maintained strong oscillations up to 410 Mc at which point the power supply lead to the amplifier broke. Other cables were tried during this run from 441 Mc, but oscillation could not be sustained. The waveform continued to be best with the balanced modulator on the amplifier output rather than the input.

Results of the tests indicate that self-oscillation can be maintained with proper cable adjustment. However, it is apparent that, with available instrumentation, input impedance measurements and properly tailored cable lengths predicted on such measurements are required for each dielectric material utilized. While this is permissible for a custom installation, where only one fuel is utilized, it has serious drawbacks in an experimental setup where tests are conducted on a variety of liquids.

Dry Dielectric Tests

To aid in establishment of instrumentation and test procedure, to confirm RF loop size and placement, and to furnish backup material with other dielectric materials, a thinly walled copper tank was fabricated in dimensions reasonably near those of the 24-inch. aluminum tank. Tests were conducted at various times during Phase I, particularly during the early stages when instrumentation requirements were being investigated. The tank also proved a valuable aid in determining wide-band amplifier requirements and investigating the self-exited oscillator system.

Resonant Characteristics of The Copper Tank. Both the diameter and the height of the copper tank were 22.5 in. Therefore, resonant frequencies for the modes were slightly higher than those for the aluminum tank as indicated in the tabulation below:

TM_{011}	474.6 Mc
TM_{010}	403.8 Mc
TE_{111}	396.8 Mc

The tank Q was extremely high, particularly with the lid securely soldered in place. For example, Q was in excess of 5,000 for the TM_{010} mode. Measurements of Q for the TM_{011} mode were made with the lid placed on the tank (but not soldered) and were about 1800. This value would undoubtedly have been higher had the lid been soldered in place.

The resonant-frequency characteristics of the copper tank as a function of fill are depicted in Figure 31. Note that the TM_{010} mode curve is quite similar to that for the liquids tested in the 24-in. aluminum tank. The TE_{111} mode has better fill characteristics near empty than does the TM_{010} mode. This is in accordance with experimental findings of other investigators.* It is to be noted, however, that for this tank and pickup

*G.A.Bunns and C. J. Meierbacktol, "Propellant Gaging Utilizing Radio Frequency Techniques," (paper presented at the 1964 SAE Convention)

RESONANT FREQUENCY CHARACTERISTICS

COPPER TANK
POLYSTYRENE PELLETS
JANUARY 21, 1965

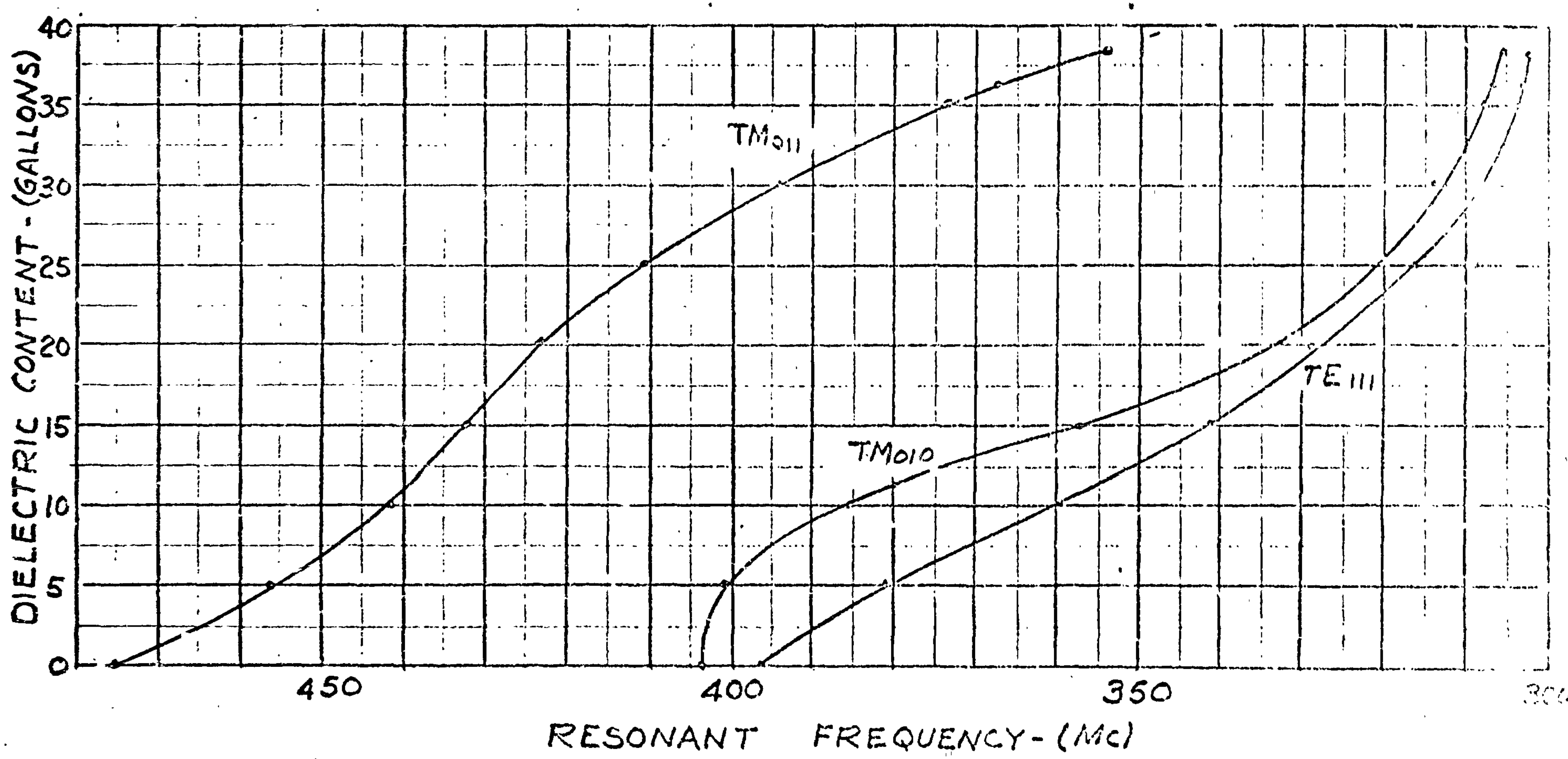


FIGURE No. 31

loop configuration this mode was lower in amplitude by 10 to 22 db than was the TM_{011} mode over the entire fill cycle.

With baffles placed in the tank, the empty resonant frequency for the TM_{010} mode increased 23 Mc to 427 Mc. A fill curve in which the polystyrene pellet dielectric material was used (as above) is shown in Figure 32. With 36 gallons of dielectric material in the tank, the resonant frequency was about 312 Mc. General shape of the fill curve agrees well with that for RP-1. As indicated previously, however, the fill curve for LH_2, with baffles in the tank, was skewed near the full position.

Based on the resonant-frequency change between empty and full conditions, the relative dielectric constant of the polystyrene pellets was slightly higher than 1.7.

Impedance Measurements. In order to use the tank as part of the self-excited oscillator system, it was necessary to determine tank input impedance as a function of dielectric fill. To this end, measurements were taken at 5-gallon increments, using a VHF bridge excited by a signal generator. Resonance was detected by a sharp dip on a meter which measured reflected power from the tank through a directional coupler.

The results of the impedance measurements are shown in Figures 33 and 34. The plane of reference of the input impedance was taken at the top of the input connector. The real part of the impedance varied between a low of 44 ohms and a high of 94 ohms. The imaginary part, as expected, varied over a wider range. The real part reflects the wall and dielectric conductance losses in the tank, which do not vary greatly over the frequency range of the TM_{010} mode. Because the tank inductive and capacitive reactance add to zero at each resonance, the imaginary part of the impedance is only

DIELECTRIC HEIGHT VS RESONANT FREQUENCY DIFFERENCE
LABORATORY THIN WALL COPPER TANK
WITH BAFFLE AND POLYSTYRENE PELLET DIELECTRIC
TEST CONDUCTED OCTOBER 3, 1964

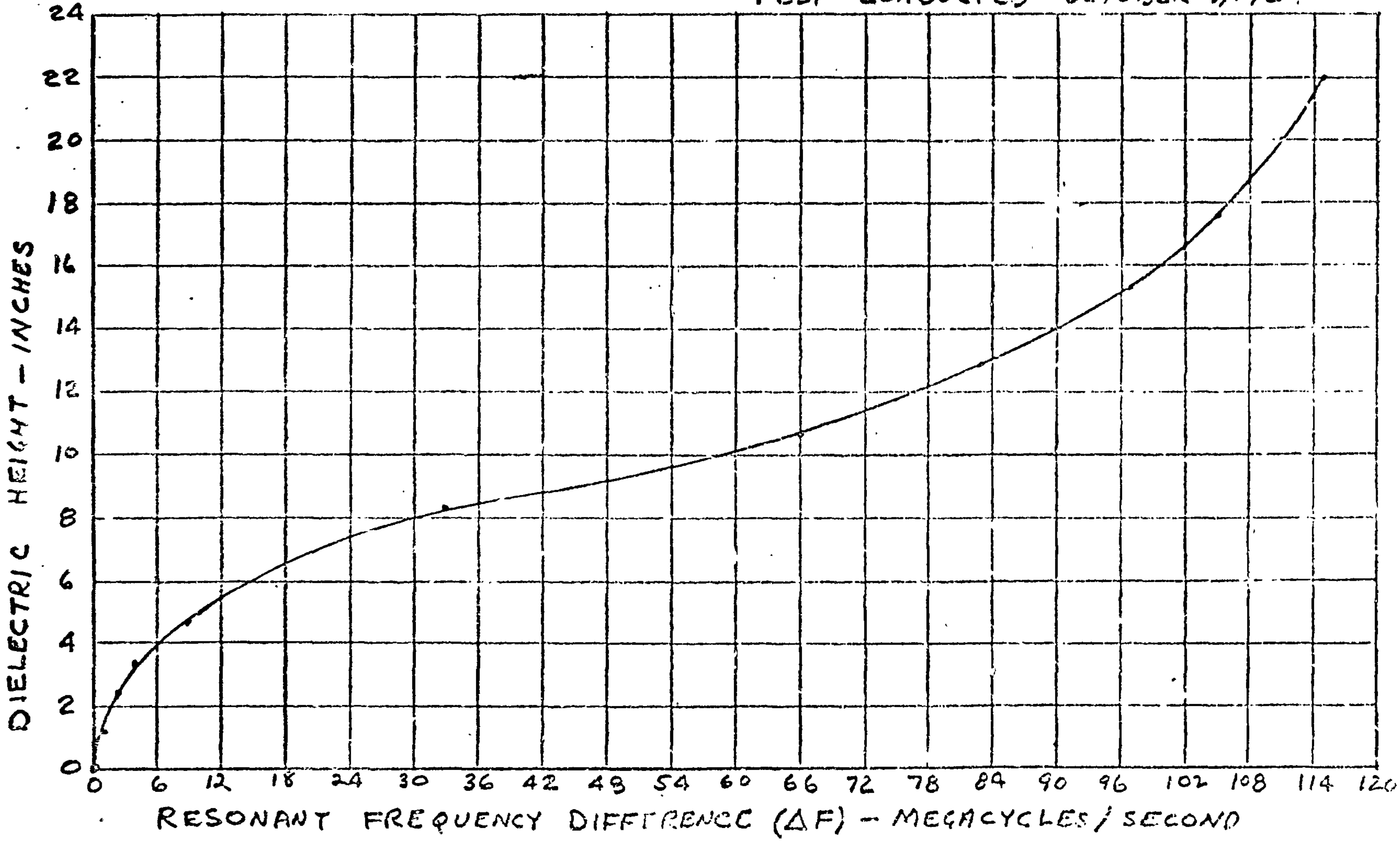
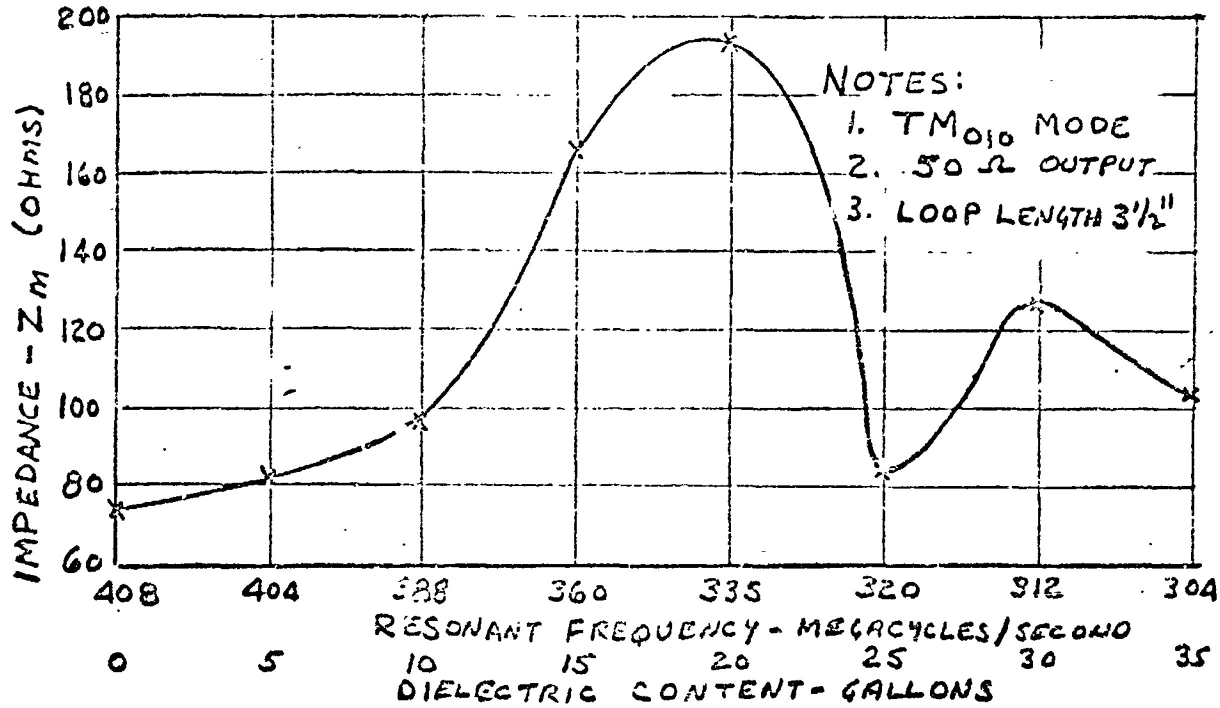


FIGURE NO. 32

INPUT IMPEDANCE OF COPPER TANK



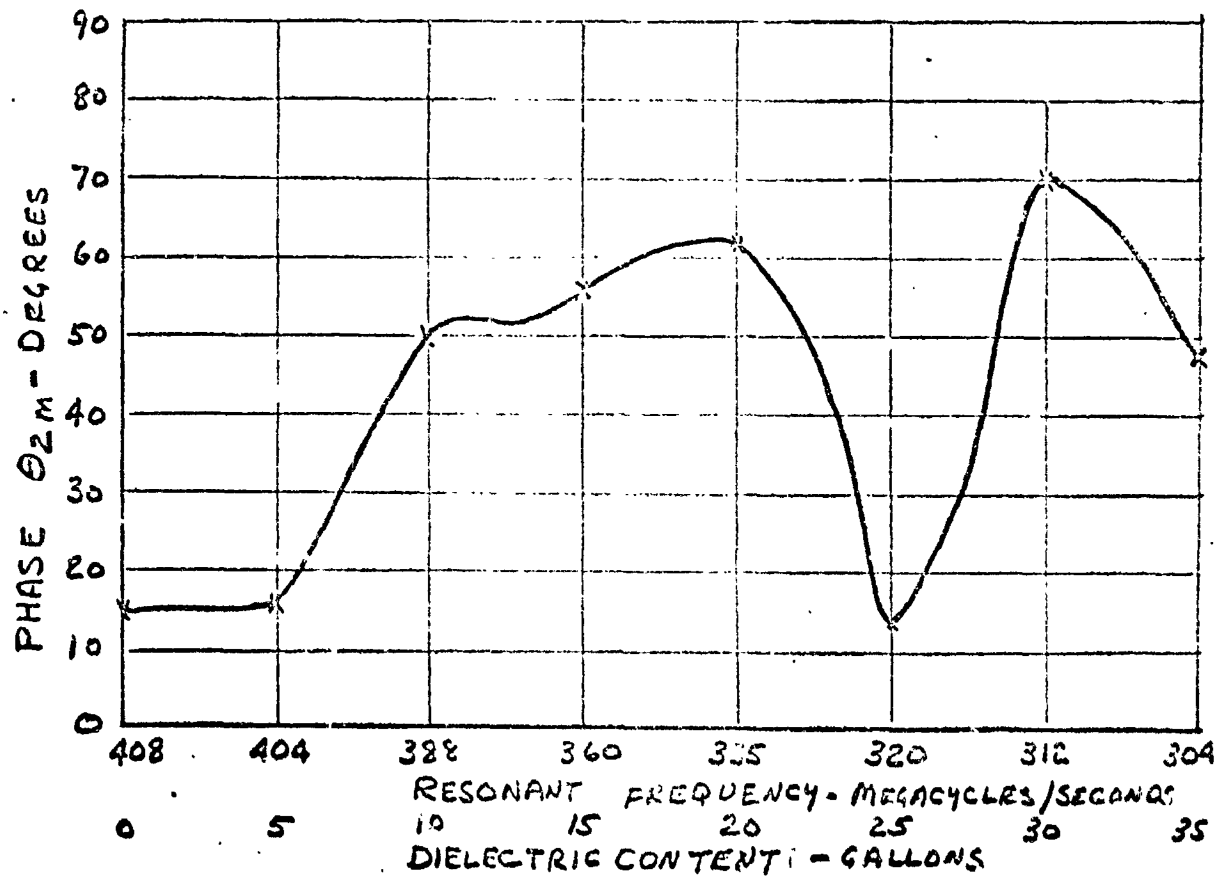
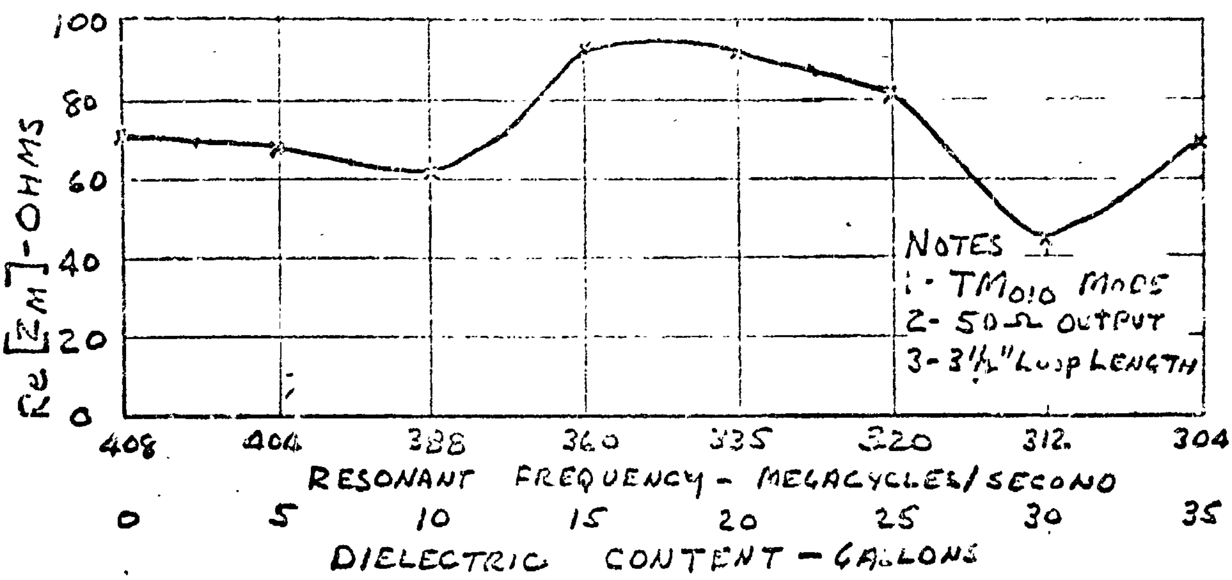


FIGURE No. 33

INPUT IMPEDANCE OF COPPER TANK



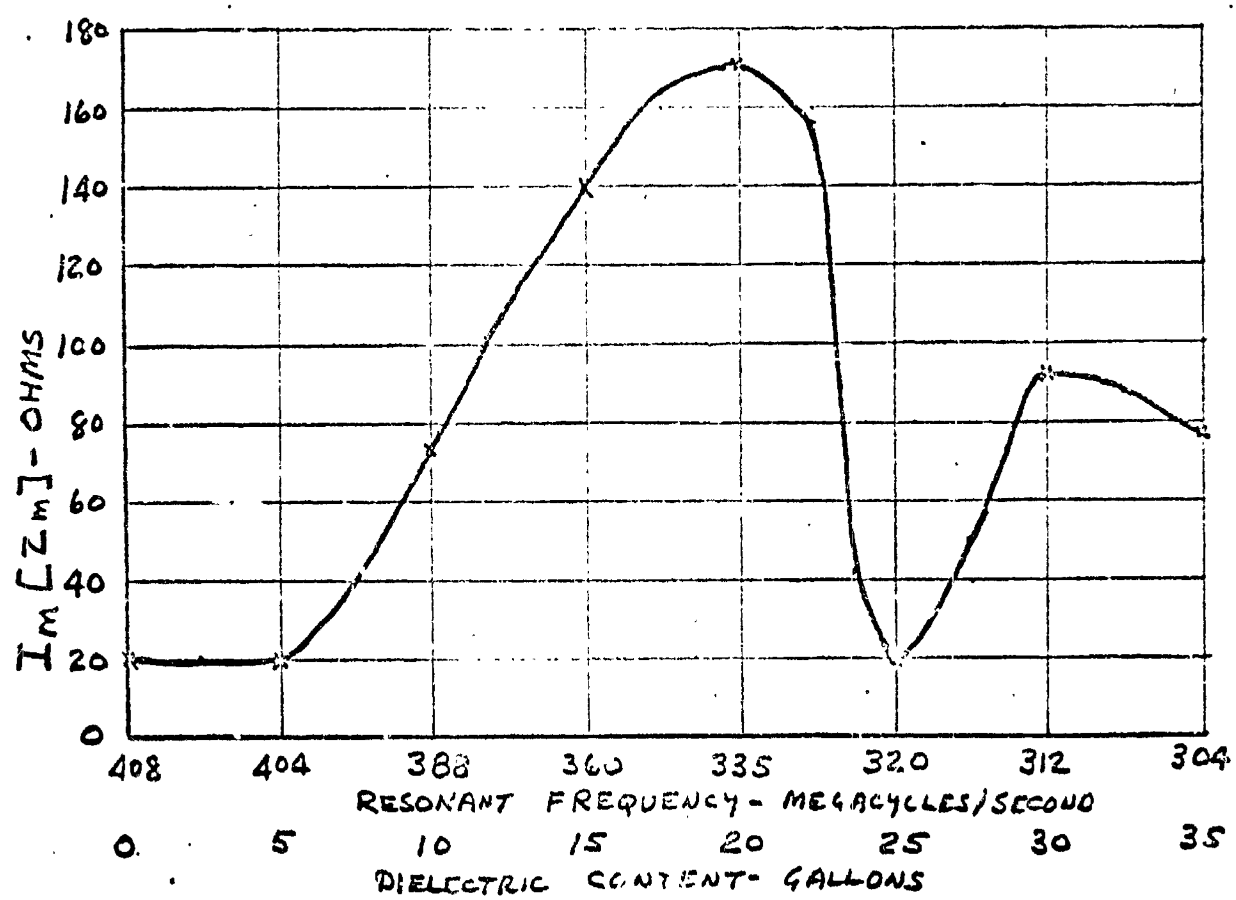


FIGURE No. 34

the loop inductive reactance which can vary rather widely over the frequency range. A subsequent measurement of loop inductive reactance as a function of frequency is shown in Figure 35. It does not vary in a manner similar to the tank inductive reactance. The loop reactance was measured by varying only the signal-generator frequency with an empty tank - the tank being decoupled from the loop when not in resonance. The tank impedance, on the other hand, was determined as a function of dielectric content.

It is suspected that the dielectric produced capacitive effects that did not show up in the loop reactance measurement. It is certain that the changing inductive reactance was due to the change of the loop reactance with frequency because there was no other net reactance in the system at resonance.

Self-Excited System. The problems of maintaining self-oscillation over the fill range of the copper tank were quite similar to those encountered in the RP-1 and LOX tests with the aluminum tank. Cable lengths from the tank to the amplifier input and output can be tailored so that the impedance is pure real at a given frequency. If the required cable lengths correspond to the middle of the frequency range, subsequent phase shifts at other resonant frequencies of the tank would be small enough so that oscillation could still be maintained at a given resonant frequency. Two cable lengths could then be chosen for both input and output, such that the input or output impedance is pure real, referenced from the amplifier terminals (so-called plane of "detuned short" or "detuned open" located $\lambda/4$ away). The two possible resistance values are plotted in Figure 36 at resonant frequencies corresponding to 5-gallon increments of dielectric.

REACTANCE OF COUPLING LOOP
(COPPER TANK)

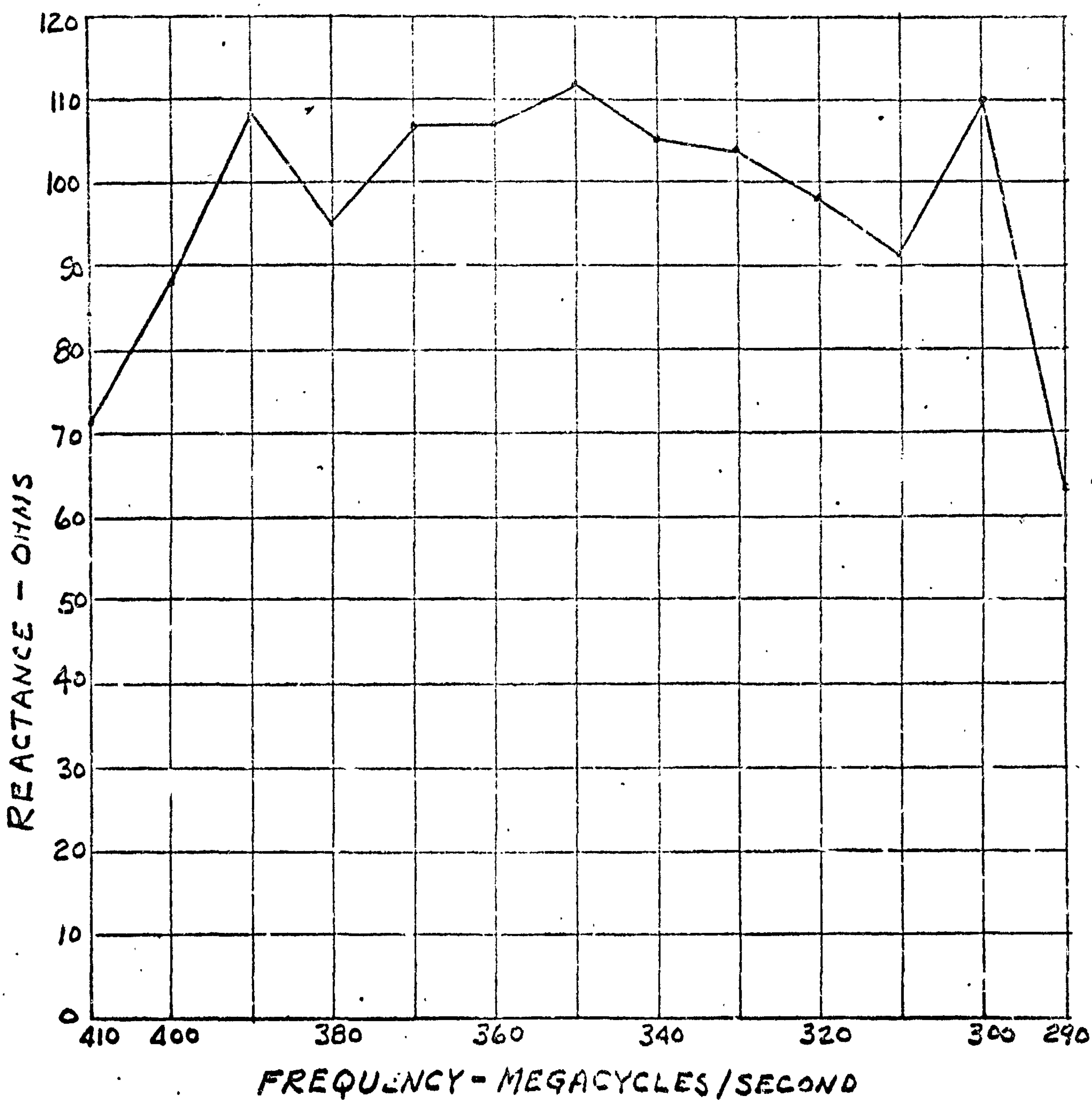


FIGURE NO. 35

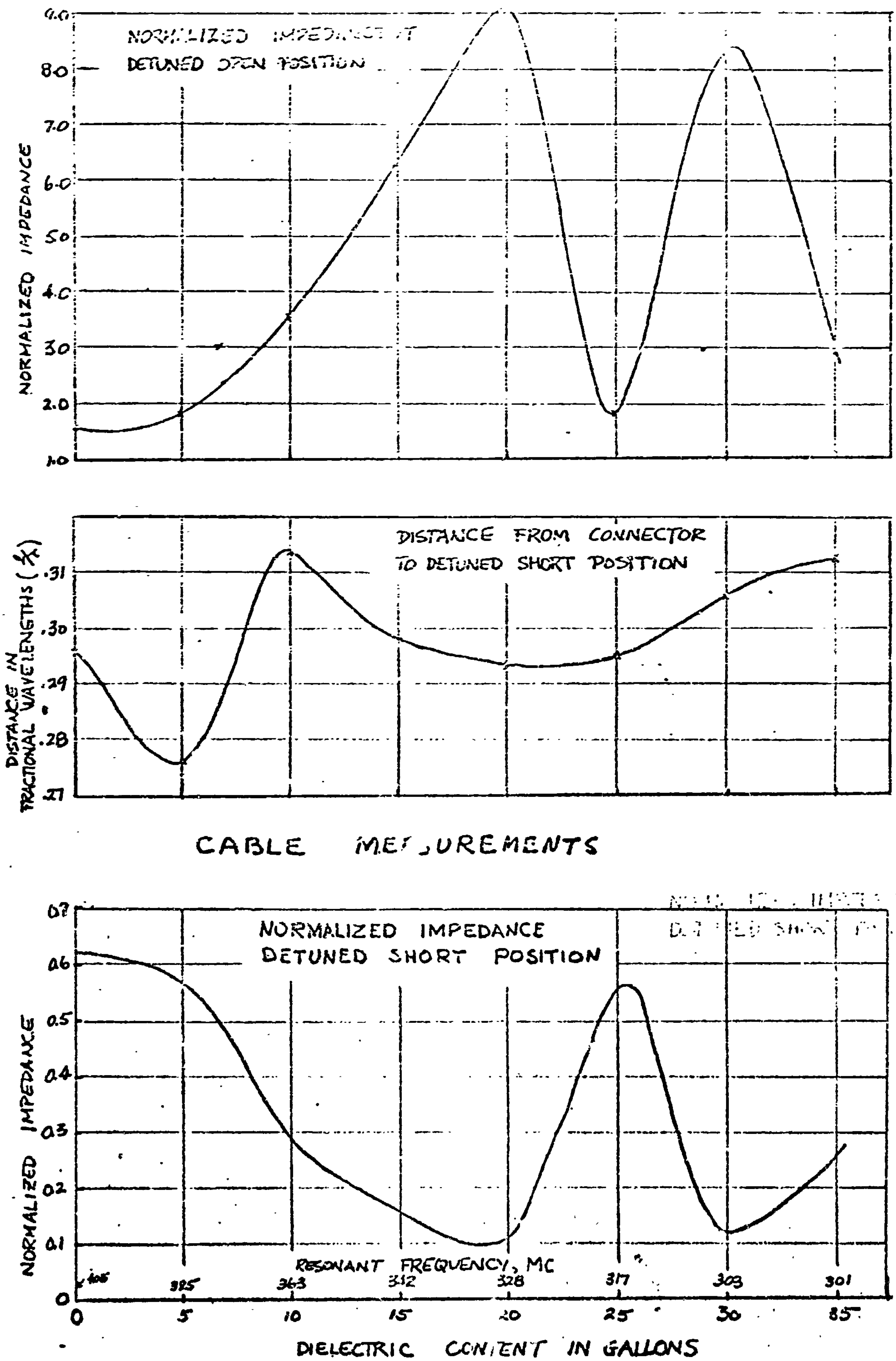

NORMALIZED IMPEDANCE AT
DETUNED OPEN POSITION
NORMALIZED IMPEDANCE
DISTANCE FROM CONNECTOR
TO DETUNED SHORT POSITION
DISTANCE IN FRACTIONAL WAVELENGTHS (λ)
CABLE MEASUREMENTS
NORMALIZED IMPEDANCE
DETUNED SHORT POSITION
NORMALIZED IMPEDANCE
RESONANT FREQUENCY, MC
DIELECTRIC CONTENT IN GALLONS

FIGURE No. 36

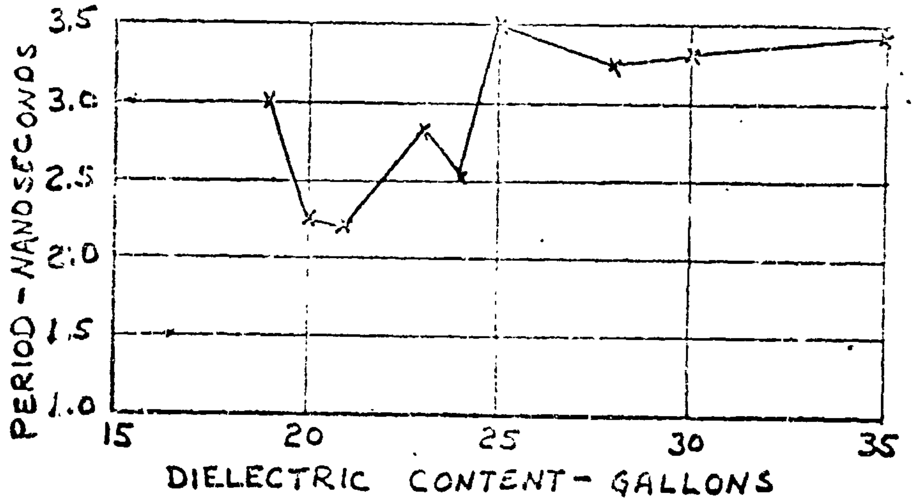
Cable lengths were selected for the 350 Mc frequency, which was midfrequency for the TM_{010} mode. The cable length from the output of the amplifier to the tank was tailored so that the amplifier would operate into an impedance of about 455 ohms. The input cable was tailored so that the amplifier would see a 5.5-ohm source impedance. This was to satisfy the conditions of feeding the amplifier from a low impedance source and loading it with a relatively high impedance. The signal was detected with a sampling oscilloscope on the input or output. Measurements were taken with a balanced modulator both on and off the output of the amplifier. Rough measurements of oscillation frequency were made from the oscilloscope trace.

In the range of 17 to 35 gallons of dielectric, the output of the amplifier was measured as shown in Figure 37. In the range between 17 and 25 gallons, the waveform was distorted and changes in period indicated mode jumping. At this point, dropout occurred over a 4-gallon interval when the balanced modulator was connected to the amplifier output. With the balanced modulator removed, oscillations started again after 2 quarts of dielectric were added to the tank. Strong oscillations with good waveform continued to the 35-gallon level. Additionally, there was no mode jumping over this range.

Starting with an empty tank, the input waveform to the amplifier was monitored with the sampling oscilloscope. From 0 to 9 gallons, the waveform was clean and undistorted and increased gradually as would normally be expected. At 9 gallons, the oscillations ceased, with the balanced modulator on the amplifier output, but only for a range of 1.5 gallons. Without the modulator, good results continued until the fill reached 14 gallons. At this point, the tank jumped to a higher mode of oscillation, with

AMPLIFIER CHARACTERISTICS

COPPER TANK



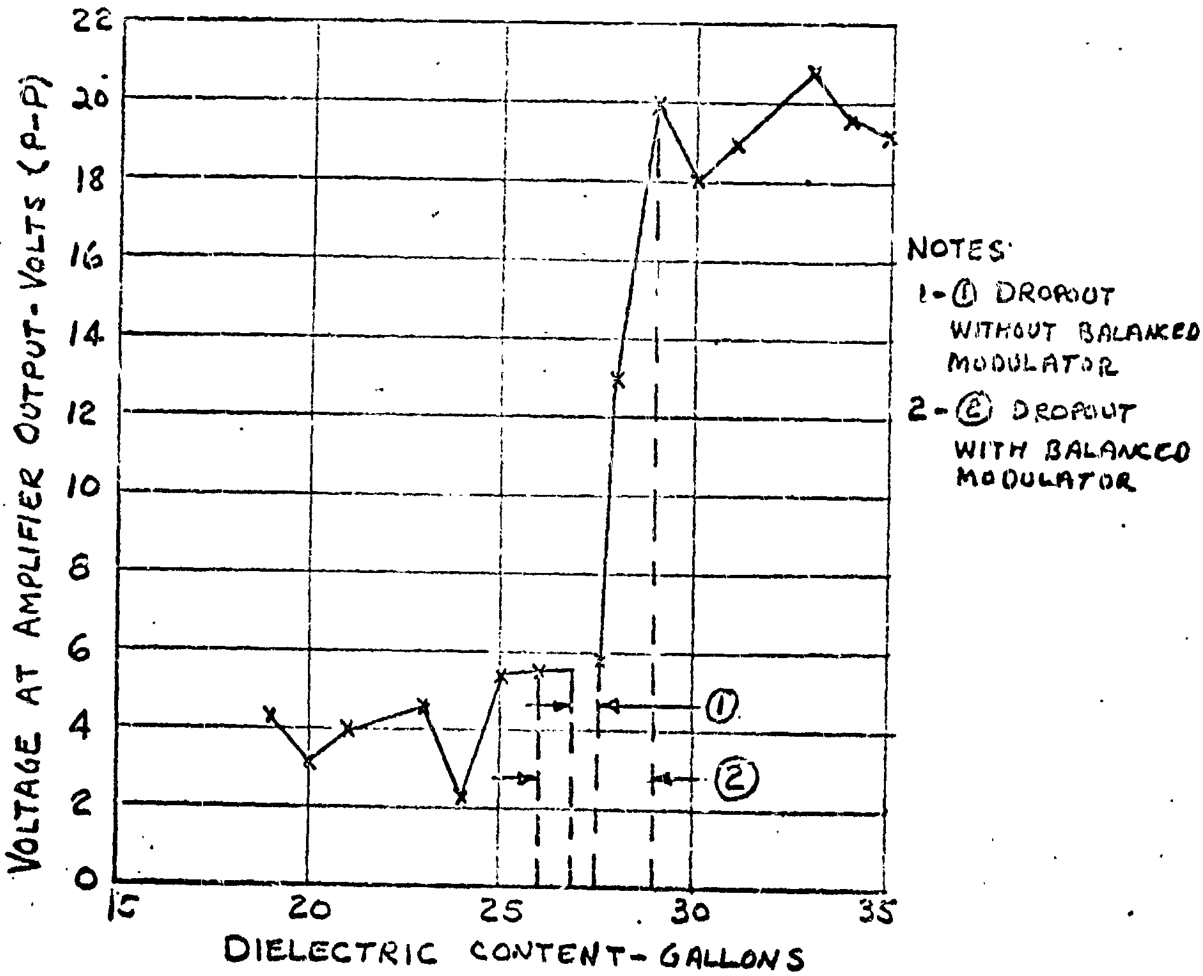


FIGURE No. 37

a period of 2.2 nanoseconds or around 450 Mc. This mode continued to the 17-gallon level. Results described above are shown in Figure 38.

The self-excited operation with polystyrene pellet dielectric material in the copper tank, the following factors were evident:

- o Without the balanced modulator in the circuit, the tank oscillations were sustained over the entire fill range, except for a short interval between 26 and 26.5 gallons of fill. However, a high order mode was sustained between 14 and 26 gallons, rather than the anticipated TM_{010} mode.

- o With the balanced modulator attached to the amplifier output, there were several wide gaps in which oscillations did not occur in any mode. It is evident that the balanced modulator presented a loading problem, with a resulting decrease in loop gain.

The results of the measurements and experience gained throughout the testing show that care must be exercised in the design of an RF liquid level sensing system. However, the requirements are no more demanding then for any other RF system. Considering the wide range of application as far as materials and tank configurations, the investigation has proven that this is a feasible technique. A design for a specific application at a more favorable frequency should varify these observations.

AMPLIFIER CHARACTERISTICS
COPPER TANK

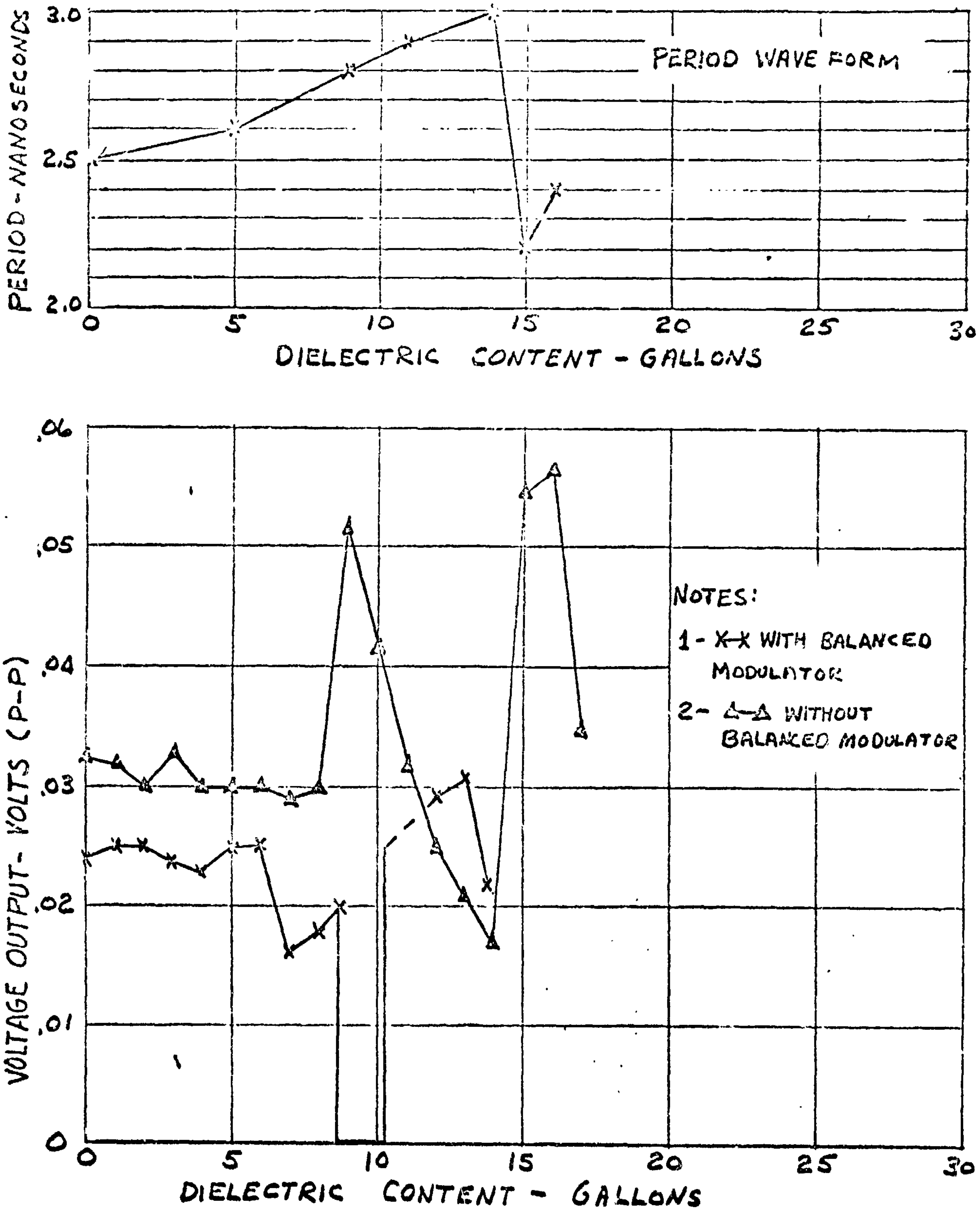


FIGURE NO. 38

CONCLUSIONS

The following conclusions are based on the results of the laboratory investigation:

- o The RF resonant cavity sensing technique for determining liquid level in fuel tanks is feasible.
- o The accuracy of the technique was higher than the accuracy of available measuring systems used for comparison.
- o Proper selection of mode, probe location, and circuitry would result in unwanted mode suppression and prevent mode jumping.
- o The system response time is limited only by readout or printout equipment. It is conceivable that the technique could be used for flow measurements.
- o Surface conditions influence the accuracy; however, neither tank tilt angles up to 60° from the axis, surface boiling nor sloshing introduced serious errors.
- o A self-oscillating system can be designed for most applications. The selection of the 24" cryogenic tank for this investigation imposed demanding circuit loading and matching problems because of the particular resonant frequency band.
- o Internal tank geometry such as baffles, suction lines, internal insulation, must be taken into consideration when designing an RF resonant cavity sensing system.
- o Cursory investigation of operation under zero "g" condition yielded encouraging results.

o The resonant frequency curves resulting from the experimental data are true behavior and differ from the theoretical curves because the theoretical curves are primarily 3 point curves.

RECOMMENDATIONS

Inasmuch as the results of the laboratory investigation have been favorable it is recommended that the program proceed as follows:

- o A larger tank installation be made and cryogenic testing be conducted at the Lockheed Cryogenic Test Facilities at the Santa Cruz Test Base.
- o A similar large scale test be conducted at the Lockheed Moffett Hangar facilities with RP-1.
- o Zero "g" simulated tests be continued within the cost and schedule of the contract.
- o A computer program be prepared so that more points for the theoretical curves may be plotted. The results of this should varify or cause further study to determine the reason for the difference between the straight-line theoretical curves and those obtained from the plots of the experimental data.
- o A study of radiation effects on the performance of the RF cavity be conducted. Levels would be based upon exposures at various orbits and mission durations.

It is further recommended that the last three items be conducted in lieu of the liquid oxygen testing. There would be no resulting impact on the contract cost or schedule.