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Temperature and Pressure Effects on Capacitance Probe Cryogenic Liquid Level Measurement Accuracy

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TEMPERATURE AND PRESSURE EFFECTS ON CAPACITANCE PROBE CRYOGENIC LIQUID LEVEL MEASUREMENT ACCURACY

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SUMMARY

The inaccuracies of liquid nitrogen and liquid hydrogen level measurements by use of a coaxial capacitance probe were investigated as a function of fluid temperatures and pressures. Significant liquid level measurement errors were found to occur due to the changes in the fluids dielectric constants which develop over the operating temperature and pressure ranges of the cryogenic storage tanks. The level measurement inaccuracies can be reduced by using fluid dielectric correction factors based on measured fluid temperatures and pressures. The errors in the corrected liquid level measurements were estimated based on the reported calibration errors of the temperature and pressure measurement systems. Experimental liquid nitrogen (LN_2) and liquid hydrogen (LH_2) level measurements were obtained using the calibrated capacitance probe equations and also by the dielectric constant correction factor method. The liquid levels obtained by the capacitance probe for the two methods were compared with the liquid level estimated from the fluid temperature profiles. Results show that the dielectric constant corrected liquid levels agreed within 0.5% of the temperature profile estimated liquid level. The uncorrected dielectric constant capacitance liquid level measurements deviated from the temperature profile level by more than 5%. This paper identifies the magnitude of liquid level measurement error that can occur for LN_2 and LH_2 fluids due to temperature and pressure effects on the dielectric constants over the tank storage conditions from 5 to 40 psia. A method of reducing the level measurement errors by using dielectric constant correction factors based on fluid temperature and pressure measurements is derived. The improved accuracy by use of the correction factors is experimentally verified by comparing liquid levels derived from fluid temperature profiles.

INTRODUCTION

The Cryogenic Fluids Systems Branch of the Space Propulsion Technology Division located at NASA Lewis Research Center is involved in conducting research in the areas of storage, acquisition and transfer of cryogenic fluids. Precise determination of liquid level during tank fill and boil off tests is often required to determine the mass of fluid within a container and the rate of liquid level change as a function of time and heat input.

The measurement of liquid level generally utilizes the difference in physical properties between the vapor and liquid fluids[1]. Differences in gaseous and liquid fluid properties such as thermal conductivity (thermal level sensors), fluid density (hydraulic head pressure transducers), and dielectric constants (capacitance probes) are commonly used for liquid level determination for cryogenic liquids.

Capacitance probes are used at NASA Lewis Research Center to measure the levels of liquid nitrogen (LN_2) and liquid hydrogen (LH_2) in the various testing tanks[2]. The probes can operate at the required cryogenic temperatures, have no moving parts, and are specified to have reasonable inaccuracy (±1%) of span over a wide operating temperature range. The capacitance probe principle of operation is based on the change in capacitance that occurs as liquid displaces the vapor in the annulus of the probe.

Liquid level point sensors are installed on a rake which is attached to the capacitance probe and facilitate the probe calibration. The point sensors are carefully positioned on the rake at the desired distances and are used to indicate when the fluid is at the desired zero and 100% levels. The capacitance probe is calibrated by filling the tank liquid level to the desired zero level and adjusting the probes signal conditioner for a 4 mA output. The liquid level is raised to the desired 100% fill level and the signal conditioner is set for a 20 mA output. The current output of the capacitance probe signal conditioner will then output a current level proportional to the liquid level over the calibrated range. The inaccuracy of the liquid level measurement is dependant on the signal conditioner error, data acquisition error, and the error in setting the initial zero and full scale levels. The largest and most important errors will occur if the fluids temperatures and pressures change from their values that existed when the probe was initially calibrated.

Theoretical analysis of the change in dielectric constants and probe capacitance due to temperature and pressure changes that could occur over the operational range of cryogenic tanks showed that significant liquid level measurement errors would occur. Correcting for the dielectric constant change by monitoring the temperature and pressure of the fluid would minimize the error in the level measurement. Uncertainty in the dielectric corrected capacitance liquid level measurement will still exist due to the uncertainty in the temperature and pressure measurements. The magnitude of the level measurement uncertainty for LH_2 and LN_2 fluids was investigated using the specified inaccuracy ratings of the temperature and pressure measurement systems. Actual liquid level measurement results were obtained using uncorrected and dielectric constant corrected capacitance probe data. The indicated liquid levels were compared with temperature/liquid level profiles obtained from a rake of silicon diode temperature sensors which were spaced approximately 0.3 inches apart. The liquid level location was estimated to be between the temperature sensor locations which indicated temperatures below and above the theoretical saturation temperature of the fluid. The capacitance probe dielectric constant corrected liquid level results correlated with the temperature profile results and confirmed the importance of temperature and pressure corrections for accurate liquid level measurements.

NOMENCLATURE

a = inner tube radius of coaxial capacitance probe (11/32 inch).
b = outer tube radius of coaxial capacitance probe (1/2 inch).
B_c = bias error limit of capacitance measurement circuitry.
$B_{\epsilon l}$ = bias error limit of relative permittivity of liquid.
$B_{\epsilon v}$ = bias error limit of relative permittivity of vapor.
B_{HL} = bias error limit of liquid level height.
B_T = bias error limit of temperature measurement.
B_P = bias error limit of pressure measurement.
C = capacitance
cal = subscript denoting a calibration condition.
F = farad, unit of measure of capacitance equal to one coulomb per volt.
pF = 10^{-12} farads.
G_f = gain factor.

GH_2 = gaseous hydrogen.
GN_2 = gaseous nitrogen.
H_l = height of liquid in capacitance probe (inch).
H_t = total height of liquid and vapor in capacitance probe (inch).
H_v = height of vapor in capacitance probe (inch).
$K = 2\pi\epsilon_o/\ln(b/a) = 3.77$ pF/inch.
LH_2 = liquid hydrogen.
LN_2 = liquid nitrogen.
P = pressure (psia).
P_s = saturation pressure (psia).
T = temperature (rankine, R).
T_s = saturation temperature (R).
Z_f = Zero correction factor.
ϵ_l = dielectric constant or relative permittivity of liquid.
ϵ_o = Permittivity of free space ($2.249*10^{-13}$ farads/inch).
ϵ_v = dielectric constant or relative permittivity of vapor.
U = uncertainty, example UH_l = uncertainty in liquid height.
$\partial H_l/\partial C$ = change in liquid height with respect to change in capacitance.
$\partial H_l/\partial \epsilon_L$ = change in liquid height with respect to liquid relative permittivity.
$\partial H_l/\partial \epsilon_V$ = change in liquid height with respect to vapor relative permittivity change.

BACKGROUND

CAPACITANCE PROBE PRINCIPLE OF OPERATION: The liquid level is determined from the change in capacitance of a coaxial capacitor probe as the dielectric in the probes annulus changes from a vapor to a liquid. Equation (1a) describes the capacitance to liquid - vapor relationship of a coaxial capacitor with a flat horizontal liquid - vapor interface[3].

$$C_{cal} = H_{lcal}\frac{(2\pi e_0 e_l)_{cal}}{\ln(b/a)} + H_{vcal}\frac{(2\pi e_0 e_v)_{cal}}{\ln(b/a)} \tag{1a}$$

$$K = \frac{2\pi e_0}{\ln(b/a)} = 3.77 pF/inch \tag{1b}$$

$$C_{cal} = K\, H_{lcal}(e_l - e_v)_{cal} + K\, H_t e_{vcal} \tag{1c}$$

Equation (1c), obtained by substituting equation (1b) and the relationship $H_V = (H_T - H_L)$ into equation (1a), shows that the capacitance change is linearly proportional to the liquid level height. The proportionality constant is dependant on the difference in dielectric constants or relative permittivities between the liquid and vapor fluids. The zero (liquid level) value of equation (1c) is proportional to the product of the vapors relative permittivity and the total probe length.

Solving equation (1c) for liquid level height yields equation (2).

$$H_{lcal} = \frac{C_{cal}}{K(\epsilon_l-\epsilon_v)_{cal}} - \frac{H_t \epsilon_{vcal}}{(\epsilon_l-\epsilon_v)_{cal}} \tag{2}$$

Calibration of the capacitance probe consists of ensuring that the tank liquid level is completely below the probe or at the desired probe zero level. The capacitance probe signal conditioner is adjusted for a zero level output of 4 mA. The tank is next filled to the desired 100% liquid level and the signal conditioner is adjusted for a 100% span output of 20 mA. Liquid level point sensors are mounted along side the capacitance probe at the desired levels to facilitate the calibration operation.

ANALYSIS

VARIABLE DETERMINISTIC ERRORS: During the course of an experiment the fluid temperature and pressure will often vary from the initial calibration conditions. The fluid densities and relative permittivities will change from their calibration values and liquid level measurement errors will occur in addition to the bias and random errors that exist. This type of error that changes in a non-random manner during the coarse of an experiment was described by Moffat as a "variable but deterministic" error[4].

The mathematical relationship between the liquid height indicated by the capacitance probes calibration equation and the actual liquid level height was investigated. Equation (3) represents the capacitance of the probe that occurs at conditions different from calibration and is denoted by the subscript "a" for actual. Substituting the right side of equation (3) for C_{cal} in calibration equation (2) results in the capacitance to liquid height interpolation equation (4a). The actual liquid height is acquired by rearranging (4a) to yield (4b). The difference between the calibration equation output liquid height and the actual correct liquid height is the variable deterministic error.

$$C_a = K\, H_{la}(\epsilon_l-\epsilon_v)_a + K\, H_t \epsilon_{va} \tag{3}$$

$$H_{lcal} = H_{la}\frac{(\epsilon_l-\epsilon_v)_a}{(\epsilon_l-\epsilon_v)_{cal}} + H_t\frac{(\epsilon_{va}-\epsilon_{vcal})}{(\epsilon_l-\epsilon_v)_{cal}} \tag{4a}$$

$$H_{la} = H_{lcal}\frac{(\epsilon_l-\epsilon_v)_{cal}}{(\epsilon_l-\epsilon_v)_a} - H_t\frac{(\epsilon_{va}-\epsilon_{vcal})}{(\epsilon_l-\epsilon_v)_a} \tag{4b}$$

CALIBRATION EQUATION CORRECTION FACTORS: The liquid height can be expressed as a ratio (R_a) of total probe length by dividing both sides of (4b) by the total probe height (H_t) as shown in equation (5). The ratio of liquid height indicated by the calibration equation to total probe length is designated R_{cal}.

$$R_a = R_{cal}\frac{(e_l - e_v)_{cal}}{(e_l - e_v)_a} - \frac{(e_{va} - e_{vcal})}{(e_l - e_v)_a} \qquad (5)$$

Equation (5) reveals the necessary correction factors required to convert the indicated liquid level height into the actual liquid level. The ratio $(\epsilon_l - \epsilon_v)_{cal}/(\epsilon_l - \epsilon_v)_a$ represents the gain factor and is denoted G_f. This factor represents the amount by which the calibration equation result must be attenuated or amplified. The ratio $(\epsilon_{va} - \epsilon_{vcal})/(\epsilon_l - \epsilon_v)_a$ represents the zero shift factor and represents the length (ratio times full scale height) that the probe output would be in error at an actual zero level. The zero factor will be denoted as Z_f. The corrected liquid level would be determined from the indicated liquid level by equation (6).

$$H_{la} = (R_{cal}G_F - Z_F)H_t \qquad (6)$$

THEORETICAL VARIABLE ERROR RANGE FOR LH_2 AND LN_2 TEST TANKS: Tables 1a and 1b list the saturation state relative permittivity values for LH_2 and LN_2 fluids at 5 psia, 14.7 psia, and 40 psia. This pressure range represents the operational range of the ground based cryogen testing tanks. The relative permittivity values were acquired from thermodynamic fluid property tables[5,6]. The liquid level errors that could occur over the tank operational ranges were estimated by substituting the permittivity values of the fluids for the tank operating limits of temperature and pressure along with assumed values of actual liquid height ratios (R_a) into equation (5) and solving for R_{cal}. R_{cal} represents the theoretical liquid height ratio that would be indicated by the capacitance liquid level measurement system previously calibrated at 14.7 psia saturated conditions. Tables 2a and 2b list the ratio results for the fluids. Figure 1 is a graph of the LH_2 and LN_2 level measurement variable errors for the theoretical capacitance probe calibrated at 14.7 psia when operated at 5 psia or 40 psia saturation conditions. The indicated errors are due to the relative permittivity changes and do not include the bias and random errors of measurement that would also exist.

The analysis show that significant liquid level measurement errors would occur due to changes in the liquid and gaseous relative permittivities. Correcting for the relative permittivity changes by monitoring the temperature and pressure of the fluid should minimize the error in the level measurement. Uncertainty in the permittivity corrected capacitance liquid level measurement will still exist due to the uncertainty in the temperature, pressure, and capacitance measurement systems. The uncertainty of the relative permittivity corrected liquid level measurement system was investigated based on the existing temperature, pressure, and capacitance liquid level measurement systems.

CAPACITANCE LIQUID LEVEL MEASUREMENT UNCERTAINTY ANALYSIS: The partial derivative sensitivity coefficients of the relative permittivity corrected liquid level height (H_{la}) were computed with respect to the variables of equation (4b). The sensitivity coefficients were used along with the individual component bias error limit (B_x) to compute the root-sum-square (RSS) measurement uncertainty according to equation (7)[7]. Random error components were considered insignificant and were not included is this study.

$$UH_{la} = \pm\sqrt{(\frac{\partial H_{la}}{\partial \epsilon_{lc}}B\epsilon_l)^2 + (\frac{\partial H_{la}}{\partial \epsilon_{vc}}B\epsilon_v)^2 + (\frac{\partial H_{la}}{\partial \epsilon_{la}}B\epsilon_l)^2 + (\frac{\partial H_{la}}{\partial \epsilon_{va}}B\epsilon_v)^2 + (\frac{\partial H_{la}}{\partial H_{lc}}BH_{lc})^2 + (\frac{\partial H_{la}}{\partial H_t}BH_t)^2} \qquad (7)$$

RELATIVE PERMITTIVITY BIAS ERROR LIMIT ESTIMATES: The bias error limit of the vapor ($B\epsilon_v$) and liquid ($B\epsilon_l$) relative permittivity values were estimated using equations (8a) and (8b).

The sensitivity coefficients were estimated by preparing graphs in which the reported values of dielectric constants were plotted as functions of temperature for constant pressure conditions and as functions of pressure at constant temperature conditions. Linear regression analysis of the data was performed and first order equations were found which mathematically described the functions. The partial derivatives or sensitivity coefficients of the equations were determined over the operating range of the cryogenic tank for both LH_2 and LN_2 fluids. The third uncertainty term in equations 8a and 8b accounts for the bias error limit of the dielectric constants listed in the thermodynamic fluid property tables[5,6].

$$B\epsilon_l = \sqrt{(\frac{\partial \epsilon_l}{\partial T}B_T)^2 + (\frac{\partial \epsilon_l}{\partial P}B_P)^2 + (B(\epsilon_l - 1))^2} \qquad (8a)$$

$$B\epsilon_v = \sqrt{(\frac{\partial \epsilon_v}{\partial T}B_T)^2 + (\frac{\partial \epsilon_v}{\partial P}B_P)^2 + (B(\epsilon_v - 1))^2} \qquad (8b)$$

INFLUENCE OF TEMPERATURE AND PRESSURE ON ϵ_{lH2} AND ϵ_{lN2}: Figures 2 and 3 are graphs of the constant temperature LH_2 (36 R) and LN_2 (135 R) relative permittivity values as functions of pressure. The linear equations describing the functions are listed on the figures. The liquid relative permittivity values increased slightly with pressure. The small slopes (sensitivity coefficients) indicate the near incompressibility of the liquids.

Graphs of ϵ_{lH2} and ϵ_{lN2} relative permittivities as functions of temperature for fixed pressures of 14.696 psia and 40 psia are shown in figures 4 and 5. The values tended to be inversely proportional to temperature.

INFLUENCE OF TEMPERATURE AND PRESSURE ON ϵ_{vH2} AND ϵ_{vN2}: Figures 6 and 7 show graphs of the constant temperature ϵ_{vH2} and ϵ_{vN2} constants as a function of pressure for the listed temperatures. The (ϵ_{vH2} -1) and (ϵ_{vN2} - 1) constants as a function of (1/Temp) for fixed pressures of 5.0 psia, 14.696 psia and 40 psia are shown in figures #8 and #9. The temperature range evaluated covers the possible temperature gradient found in the cryogenic test tanks.

Table 3 is a summary listing of the linear regression analysis results for the various operating conditions. The maximum derivative values (sensitivity factors) for the range of pressure and temperature evaluated are indicated.

The liquid relative permittivities were far more sensitive to temperature change than pressure change as indicated by the variable temperature slopes values being 100 times greater than the variable pressure results.

The vapor relative permittivity values increased linearly with pressure and inversely with temperature. The H_2 vapor temperature and pressure sensitivity factors were of similar magnitude so both would have about equal influence on their error contributions. The GN_2 vapor relative permittivity was more sensitive to pressure change (factor of 4) than temperature change.

MAXIMUM RELATIVE PERMITTIVITY BIAS ERROR LIMITS: The inaccuracy in the silicon diode temperature and 350 ohm strain gage pressure measurement systems used on the experiment cryogenic tank were reported to be ±0.9 R and ± 0.2 psia and were assumed to be bias errors. The product of the temperature and pressure errors and the maximum relative permittivity sensitivity factors were used in (8a) and (8b) to determine the RSS bias error limits $B\epsilon_l$ and $B\epsilon_v$ of the liquid and vapor relative permittivities for H_2 (9a) & (10a) and N_2 (9b) & (10b). The uncertainty in the NIST table values of $(\epsilon - 1)$ were assumed to be accurate within ±0.1%. The worse case values of $(\epsilon - 1)$ used were $4.5*10^{-4}$ and $2.4*10^{-4}$ for LN_2 and LH_2, $6*10^{-6}$ and $1*10^{-5}$ were used for GN_2 and GH_2.

$$B\epsilon_l = \sqrt{\left(\frac{\partial\epsilon_l}{\partial T}B_T\right)^2 + \left(\frac{\partial\epsilon_l}{\partial P}B_P\right)^2 + \left(B(\epsilon_l - 1)\right)^2} \qquad \textbf{(8a)}$$

$$B\epsilon_{lH_2} = \sqrt{((2.1x10^{-3})0.9)^2 + ((3.2x10^{-5})0.2)^2 + (2.4x10^{-4})^2} = 1.9x10^{-3} \qquad \textbf{(9a)}$$

$$B\epsilon_{lN_2} = \sqrt{((1.5x10^{-3})0.9)^2 + ((8.6x10^{-5})0.2)^2 + (4.5x10^{-4})^2} = 1.4x10^{-3} \qquad \textbf{(9b)}$$

$$B\epsilon_v = \sqrt{\left(\frac{\partial\epsilon_v}{\partial T}B_T\right)^2 + \left(\frac{\partial\epsilon_v}{\partial P}B_P\right)^2 + \left(B(\epsilon_v - 1)\right)^2} \qquad \textbf{(8b)}$$

$$B\epsilon_{vH_2} = \sqrt{((2.4x10^{-4})0.9)^2 + ((2.6x10^{-4})0.2)^2 + (1.0x10^{-5})^2} = 2.2x10^{-4} \qquad \textbf{(10a)}$$

$$B\epsilon_{vN_2} = \sqrt{((3.6x10^{-5})0.9)^2 + ((1.5x10^{-4})0.2)^2 + (6.0x10^{-6})^2} = 4.4x10^{-5} \qquad \textbf{(10b)}$$

CAPACITANCE PROBE AND DATA ACQUISITION BIAS ERROR ESTIMATES: The manufacturer listed inaccuracy of the calibrated capacitance probe signal conditioning system was 1% of span. This error translates directly into an error of 0.2 inches for a 20 inch fluid level span. This error component was denoted as B_{HLc}. The data acquisition system used to record the capacitance probe output had a listed inaccuracy rating of 0.05% of range which was considered insignificant.

BIAS ERROR ESTIMATE OF THE 100% LIQUID FILL LEVEL HEIGHT (H_t): During the capacitance probe calibration, the liquid level of the tank would be raised to the desired 100% fill level. This height was determined by the position and response of a silicon diode temperature sensor. The estimated error in the position of the sensor was assumed to be ± 0.15 inch. This bias error was identified as B_{Ht}.

LIQUID LEVEL MEASUREMENT UNCERTAINTY ANALYSIS SENSITIVITY COEFFICIENTS: The partial derivative of the relative permittivity corrected liquid level measurement with respect to the variables of equation (4b) are listed as equations (11) through (16). These equations are required to determine the influence of the variables bias error limits on the overall liquid level measurement inaccuracy.

$$\frac{\partial H_{la}}{\partial \epsilon_{la}} = \frac{-H_{lc}(\epsilon_{lc}-\epsilon_{vc})+H_t(\epsilon_{va}-\epsilon_{vc})}{(\epsilon_{la}-\epsilon_{va})^2} \qquad 11$$

$$\frac{\partial H_{la}}{\partial \epsilon_{lc}} = \frac{H_{lc}}{(\epsilon_{la}-\epsilon_{va})} \qquad (12)$$

$$\frac{\partial H_{la}}{\partial \epsilon_{va}} = \frac{H_{lc}(\epsilon_{lc}-\epsilon_{vc})-H_t(\epsilon_{va}-\epsilon_{vc})}{(\epsilon_{la}-\epsilon_{va})^2} - \frac{H_t}{(\epsilon_{la}-\epsilon_{va})} \qquad (13)$$

$$\frac{\partial H_{la}}{\partial \epsilon_{vc}} = \frac{-H_{lc}+H_t}{(\epsilon_{la}-\epsilon_{va})} \qquad (14)$$

$$\frac{\partial H_{la}}{\partial H_{lc}} = \frac{(\epsilon_{lc}-\epsilon_{vc})}{(\epsilon_{la}-\epsilon_{va})} \qquad (15)$$

$$\frac{\partial H_{la}}{\partial H_t} = \frac{(\epsilon_{va}-\epsilon_{vc})}{(\epsilon_{la}-\epsilon_{va})} \qquad (16)$$

EXPERIMENTAL TEST PROCEDURES AND MEASUREMENT UNCERTAINTIES

CALIBRATION CONDITIONS AND CAPACITANCE UNCERTAINTY: Capacitance values for a 20 inch coaxial capacitance probe used in cryogenic tank pressurization experiments at NASA Lewis Research Center were estimated using equation (1) with the measured fluid properties listed in Table 4. Large temperature gradients existed in the vapor region of the tank (ullage). The effective relative permittivity of the vapor was estimated using the average vapor temperature and the tank pressure. The average vapor temperature was obtained by integrating the vapor temperature profile over the height of the vapor region (ullage) using equation (17). The relative permittivity was acquired using GASPLUS[8]. Situations in which significant temperature gradients exist through the liquid would also require a similar analysis.

$$T_{avg}=\frac{1}{H}\int T(h)dh \qquad (17)$$

Table 5 and Table 6 are summary tables which list the theoretical magnitude of the various sensitivity coefficients and their bias error products as a function of capacitance probe indicated liquid level. The total root sum square (RSS) uncertainty of the individual bias error limits is also listed and represents the uncertainty in the liquid level measurement after correcting for temperature and pressure effects on the relative permittivities. Figure 10a and 10b show the magnitude of the liquid level bias error components expressed as a percentage of full scale reading due to the relative permittivity and capacitance signal conditioning errors for LH_2 and LN_2 fluids. The RSS combination of the individual errors is also indicated on the figures. The results show that the error components due to the temperature and pressure estimated relative permittivities is insignificant for LN_2 and contributes less than 0.1 inch to the RSS error for LH_2.

EXPERIMENTAL VS THEORETICAL LIQUID LEVEL MEASUREMENT ERROR RESULTS: Experimental data showing the inaccuracies of uncorrected liquid level measurements were obtained from cryogenic tank pressurization experiments[9]. The capacitance probe was originally calibrated at the conditions listed in Table 4. A rake of silicon diode temperature sensors was attached to the capacitance probe. The temperature sensors were spaced every 0.3 inches along the length of the capacitance probe. Figure (11) and figure (12) show the temperature profiles obtained with saturated LN_2 and LH_2 fluids. Test results showed that the temperature indicated by the sensors immersed in liquid would be nearly constant while the temperatures of the sensors in vapor would increase rapidly with distance from the liquid-vapor interface. Theoretically the interface exists at the saturation temperature (T_s) of the tank ullage pressure. Temperatures above T_s are in the vapor while temperatures below T_s are in the liquid. The liquid level interface was estimated to be located at the average height value of the two temperature sensors which indicated temperatures above and below the saturation temperature. Since the temperature sensors were spaced approximately 0.3 inches apart, the uncertainty of this liquid level measurement was assumed to be ± 0.15 inches. The capacitance probe liquid level was also recorded and a relative permittivity corrected level was calculated based on the measured temperatures and pressures.

RESULTS

Table 7 lists the measured experimental conditions for the tests along with the dielectric correction factors. The liquid levels indicated by the capacitance probe calibration equation, the relative permittivity corrected equations, and the temperature profile methods are listed in Table 8. The experimental results showed that the uncorrected capacitance probe liquid level measurements deviated from the temperature profile derived liquid levels by approximately 5 times the uncertainty band of the temperature profile liquid level measurement system. Correcting for the relative permittivity of the fluids based on the measured fluids temperatures and pressures significantly improved the agreement between the capacitance probe and temperature profile liquid level measurements. The deviation between the temperature profile indicated levels and the relative permittivity corrected capacitance probe levels were less than 0.1 inches which is within the uncertainty bands of the measurement and calibration systems.

SUMMARY AND CONCLUSIONS

Significant errors can result in the liquid level measurement of LH_2 and LN_2 due to changes in the fluids relative permittivity from their initial calibration condition values. The liquid level inaccuracy can be improved by measuring the fluids temperature and pressure and compensating for the dielectric constant changes. Correction factors for span and zero can be derived which allow the output of the capacitance probe to be corrected for the permittivity changes.

A liquid level measurement error analysis was performed over the cryogenic fluid tanks operating ranges of pressure and temperature. First order linear equations were found which described the temperature and pressure effects on the cryogenic fluids liquid and vapor dielectric constants. The slopes of the equations were used along with the estimated errors in the pressure and temperature measurements to determine the overall liquid level measurement uncertainty. The analysis showed that liquid level measurements theoretically could be made with an uncertainty of less than 1.5% full scale (FS) for LH_2 and 1.1% FS for LN_2 with existing capacitance measurement systems. This error magnitude is based on making corrections to the capacitance probe calibration equation based on temperature and pressure effects on the dielectric constants of both the liquid and vapor phases. The analysis was based on temperature measurement accuracy of ± 0.9 R and pressure measurement accuracy of ± 0.2 psia. The primary error limitation is reduced to the inaccuracy of the capacitance signal conditioning system which was listed as 1% of span.

Actual experimental liquid level results measured by the capacitance probe were compared with the liquid level height estimated from the tanks fluid temperature profile. The difference between the calibrated capacitance probe liquid level measurement and the liquid level determined from the temperature profiles agreed favorably with the theoretical dielectric constant corrected error value based on the measured temperature and pressure changes from calibration conditions.

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TABLE 1A
SATURATED LH2 DIELECTRIC CONSTANTS AND RELATIONSHIPS FOR GROUND BASED TESTING OPERATIONAL LIMITS

psia	ϵ_l	ϵ_v	G_f	Z_f
5.0	1.24121	1.00154	.94188	-.01043
14.7	1.22978	1.00404	1.0	0.0
40.0	1.2123	1.01024	1.11719	0.030684

TABLE 1B
SATURATED LN2 DIELECTRIC CONSTANTS AND RELATIONSHIPS FOR GROUND BASED TESTING OPERATIONAL LIMITS

psia	ϵ_l	ϵ_v	G_f	Z_f
5.0	1.45263	1.0008	.95049	-.00303
14.7	1.43163	1.00217	1.0	0.0
40.0	1.40405	1.00551	1.07758	0.008381

TABLE 2A
LH_2 CALIBRATION EQUATION LIQUID LEVEL RATIO ERRORS

R_a	R_c 5psia	Error %FS	R_c 40psia	Error %FS
0	-0.011	-1.10	0.027	2.7
0.1	0.095	-0.50	0.117	1.7
0.2	0.2013	0.13	0.2065	-0.65
0.3	0.3074	0.74	0.296	-0.40
0.4	0.4136	1.36	0.3855	-1.45
0.5	0.5198	1.98	0.4750	-2.50
0.6	0.6260	2.60	0.5645	-3.55
0.7	0.7321	3.21	0.6540	-4.60
0.8	0.8383	3.83	0.7435	-5.65
0.9	0.9445	4.45	0.8331	-6.69
1.0	1.0506	5.06	0.9226	-7.74

TABLE 2B
LN_2 CALIBRATION EQUATION LIQUID LEVEL RATIO ERRORS

R_a	R_c 5psia	Error %FS	R_c 40psia	Error %FS
0	-.0032	-0.32	0.0078	0.78
0.1	0.1020	-0.20	0.1006	0.06
0.2	0.2072	0.72	0.1934	-0.66
0.3	0.3124	1.24	0.2862	-1.38
0.4	0.4176	1.76	0.3790	-2.10
0.5	0.5229	2.29	0.4718	-2.82
0.6	0.6281	2.81	0.5646	-3.54
0.7	0.7333	3.33	0.6574	-4.26
0.8	0.8385	3.85	0.7502	-4.98
0.9	0.9437	4.37	0.8430	-5.70
1.0	1.0489	4.89	0.9358	-6.42

TABLE 3
Dielectric Constant vs Temp. and Press. Analysis Results

Fixed Parameter	Variable Parameter	Partial Derivative	Derivative Value	WorstCase Value
LH_2 T = 36 R	Pres.(psia)	$\partial \epsilon_{lH2}/\partial P$	$3.2*10^{-5}$/psia	$3.2*10^{-5}$
LN_2 T = 135R	Pres.(psia)	$\partial \epsilon_{lN2}/\partial P$	$8.6*10^{-6}$/psia	$8.6*10^{-6}$
LH_2 40 psia	Temp. (R)	$\partial \epsilon_{lH2}/\partial T$	$-2.1*10^{-5}$/R	$-2.1*10^{-5}$
LN_2 40 psia	Temp. (R)	$\partial \epsilon_{lN2}/\partial T$	$-1.5*10^{-3}$/R	$-1.5*10^{-3}$
GH_2 T = 44 R	Pres.(psia)	$\partial \epsilon_{vH2}/\partial P$	$2.6*10^{-4}$/psia	$2.6*10^{-4}$
GN_2 T = 140 R	Pres.(psia)	$\partial \epsilon_{vN2}/\partial P$	$1.5*10^{-4}$/psia	$1.5*10^{-4}$
GH_2 40 psia	Temp. (R)	$\partial \epsilon_{vH2}/\partial T$	$-4.5*10^{-1}R/T^2$	*$-2.4*10^{-4}$
GN_2 40 psia	Temp. (R)	$\partial \epsilon_{vN2}/\partial T$	$-8.9*10^{-1}R/T^2$	**$-3.6*10^{-5}$

* Evaluated at worst case T = 43.5 R
** Evaluated at worst case T = 156.5 R

TABLE 4
Estimated Capacitance Readings For Calibration Conditions

	Temp	Pres.	Dielectric Constants		C(20 in)	C(0 in)	Span
Fluid	(R)	Psia	ϵ_v	ϵ_l	pF	pF	pF
LH_2	37.5	17.4		1.225054	92.369		
GH_2	194	16.9	1.000783			75.459	16.91
LN_2	142	19.1	1.424793		107.429		
GN_2	175	18.1		1.00209		75.558	31.871

TABLE 5
Liquid Hydrogen Level RSS Uncertainty Analysis Results

Liquid Level inch	$BH_{Lc}*\frac{\partial H_{La}}{\partial H_{Lc}}$ inch	$B\epsilon_{L}*\frac{\partial H_{La}}{\partial \epsilon_{Lc}}$ inch	$B\epsilon_{L}*\frac{\partial H_{La}}{\partial \epsilon_{La}}$ inch	$B\epsilon_{V}*\frac{\partial H_{La}}{\partial \epsilon_{vc}}$ inch	$B\epsilon_{V}*\frac{\partial H_{La}}{\partial \epsilon_{va}}$ inch	$BH_{T}*\frac{\partial H_{La}}{\partial H_{T}}$ inch	UH_{L} ±inch	Error ±% FS
21	0.187	0.166	-0.156	-0.001	0.000	0.000	0.295	1.47
20	0.187	0.159	-0.148	0.000	-0.001	0.000	0.287	1.43
19	0.187	0.151	-0.141	0.001	-0.002	0.000	0.278	1.39
18	0.187	0.143	-0.133	0.002	-0.003	0.000	0.271	1.35
17	0.187	0.135	-0.126	0.003	-0.004	0.000	0.263	1.31
16	0.187	0.127	-0.119	0.004	-0.005	0.000	0.255	1.28
15	0.187	0.119	-0.111	0.005	-0.005	0.000	0.248	1.24
14	0.187	0.111	-0.104	0.006	-0.006	0.000	0.241	1.21
13	0.187	0.103	-0.096	0.006	-0.007	0.000	0.235	1.17
12	0.187	0.095	-0.089	0.007	-0.008	0.000	0.228	1.14
11	0.187	0.087	-0.082	0.008	-0.009	0.000	0.222	1.11
10	0.187	0.079	-0.074	0.009	-0.010	0.000	0.217	1.08
9	0.187	0.071	-0.067	0.010	-0.011	0.000	0.212	1.06
8	0.187	0.063	-0.059	0.011	-0.011	0.000	0.207	1.03
7	0.187	0.055	-0.052	0.012	-0.012	0.000	0.203	1.01
6	0.187	0.048	-0.045	0.013	-0.013	0.000	0.199	0.99
5	0.187	0.040	-0.037	0.014	-0.014	0.000	0.196	0.98
4	0.187	0.032	-0.030	0.015	-0.015	0.000	0.193	0.97
3	0.187	0.024	-0.022	0.016	-0.016	0.000	0.191	0.96
2	0.187	0.016	-0.015	0.017	-0.017	0.000	0.190	0.95
1	0.187	0.008	-0.007	0.017	-0.017	0.000	0.189	0.95
0	0.187	0.000	0.000	0.018	-0.018	0.000	0.189	0.95
-1	0.187	-0.008	0.007	0.019	-0.019	0.000	0.189	0.95

TABLE 6
Liquid Nitrogen Level RSS Uncertainty Analysis Results

Liquid Level inch	$BH_{Lc}*\frac{\partial H_{La}}{\partial H_{Lc}}$ inch	$B\epsilon_L*\frac{\partial H_{La}}{\partial \epsilon_{Lc}}$ inch	$B\epsilon_L*\frac{\partial H_{La}}{\partial \epsilon_{La}}$ inch	$B\epsilon_V*\frac{\partial H_{La}}{\partial \epsilon_{vc}}$ inch	$B\epsilon_V*\frac{\partial H_{La}}{\partial \epsilon_{va}}$ inch	$BH_T*\frac{\partial H_{La}}{\partial H_T}$ inch	UH_L ±inch	Error ±% FS
21	0.189	0.066	-0.062	0.000	0.000	0.000	0.209	1.05
20	0.189	0.063	-0.059	0.000	0.000	0.000	0.207	1.04
19	0.189	0.059	-0.056	0.000	0.000	0.000	0.206	1.03
18	0.189	0.056	-0.053	0.000	0.000	0.000	0.204	1.02
17	0.189	0.053	-0.050	0.000	0.000	0.000	0.202	1.01
16	0.189	0.050	-0.047	0.000	0.000	0.000	0.201	1.00
15	0.189	0.047	-0.044	0.000	-0.001	0.000	0.200	1.00
14	0.189	0.044	-0.042	0.001	-0.001	0.000	0.198	0.99
13	0.189	0.041	-0.039	0.001	-0.001	0.000	0.197	0.98
12	0.189	0.038	-0.036	0.001	-0.001	0.000	0.196	0.98
11	0.189	0.034	-0.033	0.001	-0.001	0.000	0.195	0.97
10	0.189	0.031	-0.030	0.001	-0.001	0.000	0.194	0.97
9	0.189	0.028	-0.027	0.001	-0.001	0.000	0.193	0.96
8	0.189	0.025	-0.024	0.001	-0.001	0.000	0.192	0.96
7	0.189	0.022	-0.021	0.001	-0.001	0.000	0.191	0.96
6	0.189	0.019	-0.018	0.001	-0.001	0.000	0.191	0.95
5	0.189	0.016	-0.015	0.001	-0.001	0.000	0.190	0.95
4	0.189	0.013	-0.012	0.002	-0.002	0.000	0.190	0.95
3	0.189	0.009	-0.009	0.002	-0.002	0.000	0.189	0.95
2	0.189	0.006	-0.006	0.002	-0.002	0.000	0.189	0.95
1	0.189	0.003	-0.003	0.002	-0.002	0.000	0.189	0.94
0	0.189	0.000	0.000	0.002	-0.002	0.000	0.189	0.94
-1	0.189	-0.003	0.003	0.002	-0.002	0.000	0.189	0.94

TABLE 7
Experimental Liquid Level Measurement Conditions and Dielectric Correction Factors

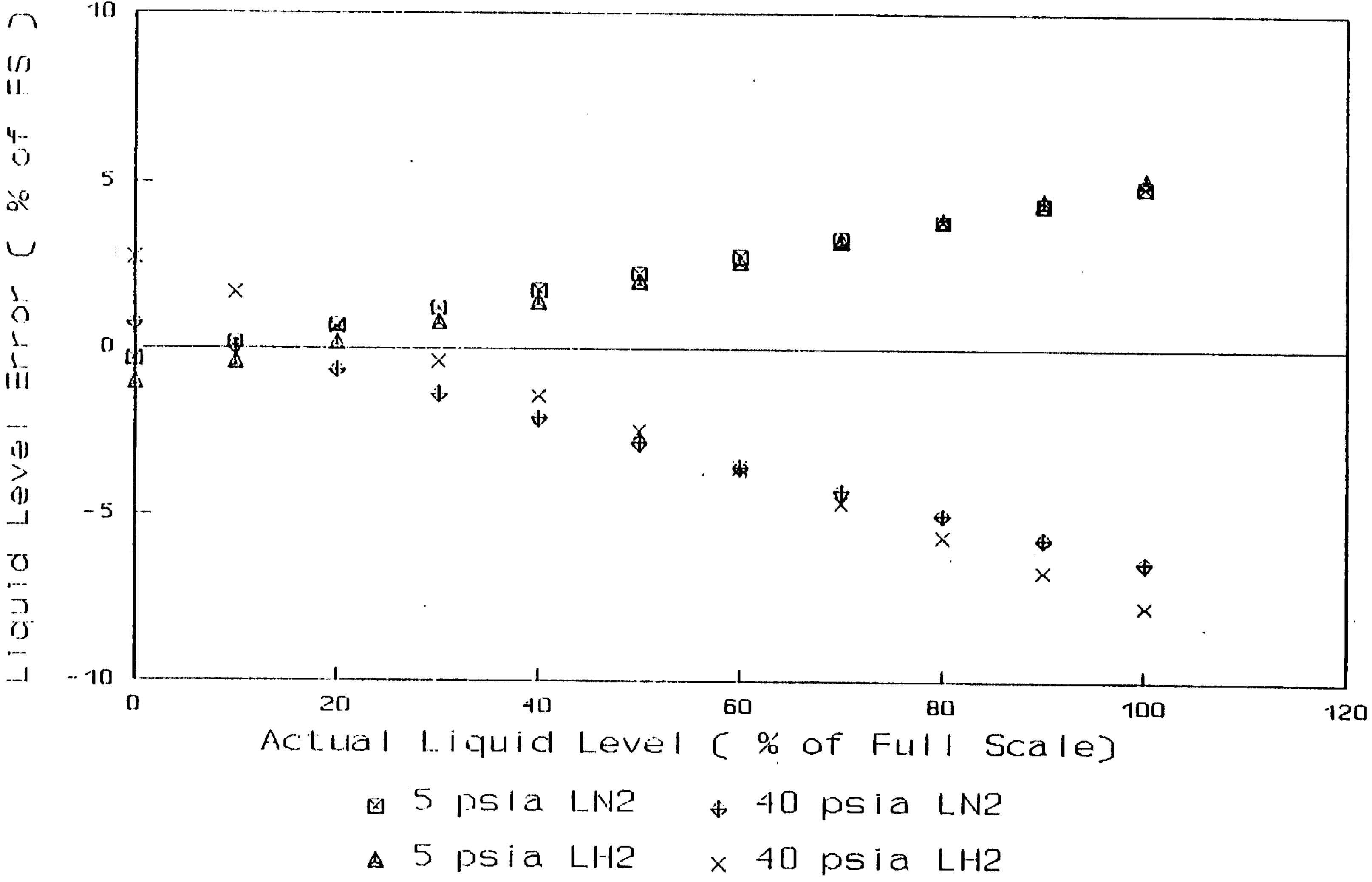
Test	Fluid	Temp	psia	ϵ_l	ϵ_v	ϵ_l-ϵ_v	G_f	Z_f
cal	LN_2	141.9	19.1	1.424793				
cal	GN_2	175.1	18.1		1.00209	.422703	1.0	1.0
1	LN_2	125.6	7.1	1.448508				
1	GN_2	203	7.1		1.0007	.447818	.9439169	-.00310
cal	LH_2	37.5	17.4	1.225054				
cal	GH_2	194	16.9		1.000783	.224271	1.0	1.0
2	LH_2	29.9	7.6	1.240476				
2	GH_2	92.3	7.6		1.000743	.239733	.9355032	-.000167

TABLE 8
Temperature Sensor Liquid Level Results and Capacitance Probe
Relative Permittivity Uncorrected and Corrected Results.

Test #	Liquid	Liquid Height Uncorrected (inch)	Liquid Height ϵ corrected (inch)	Temp Profile Liquid Level (inch)
1	(LN_2)	13.66	12.96 ±0.25	12.93 ±0.15
2	(LH_2)	14.40	13.47 ±0.25	13.53 ±0.15

Figure 1

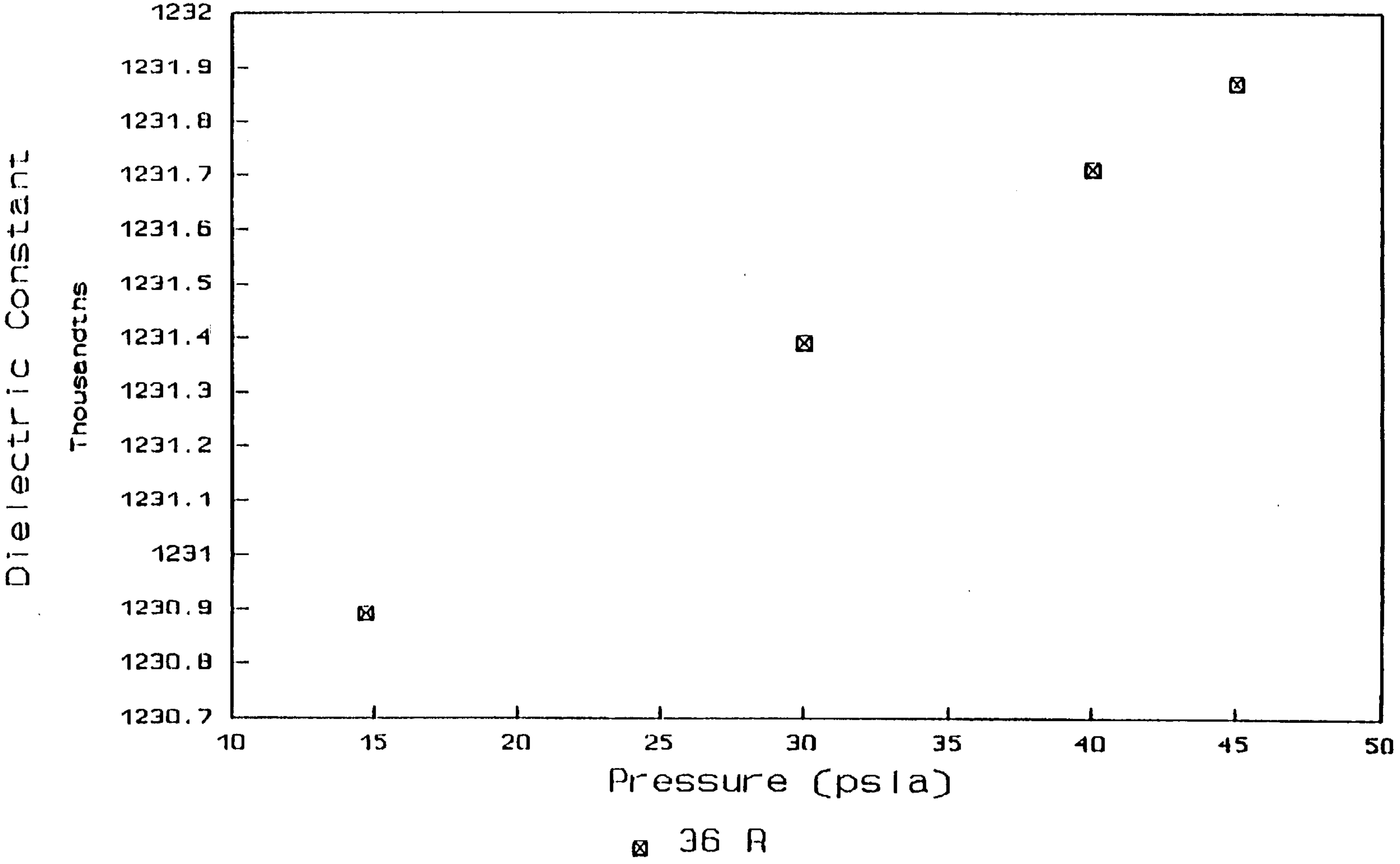
Liquid Level Error Due To Change In Dielectric Constants From 14.7 psia Values.



LLdev.plc

Figure 2

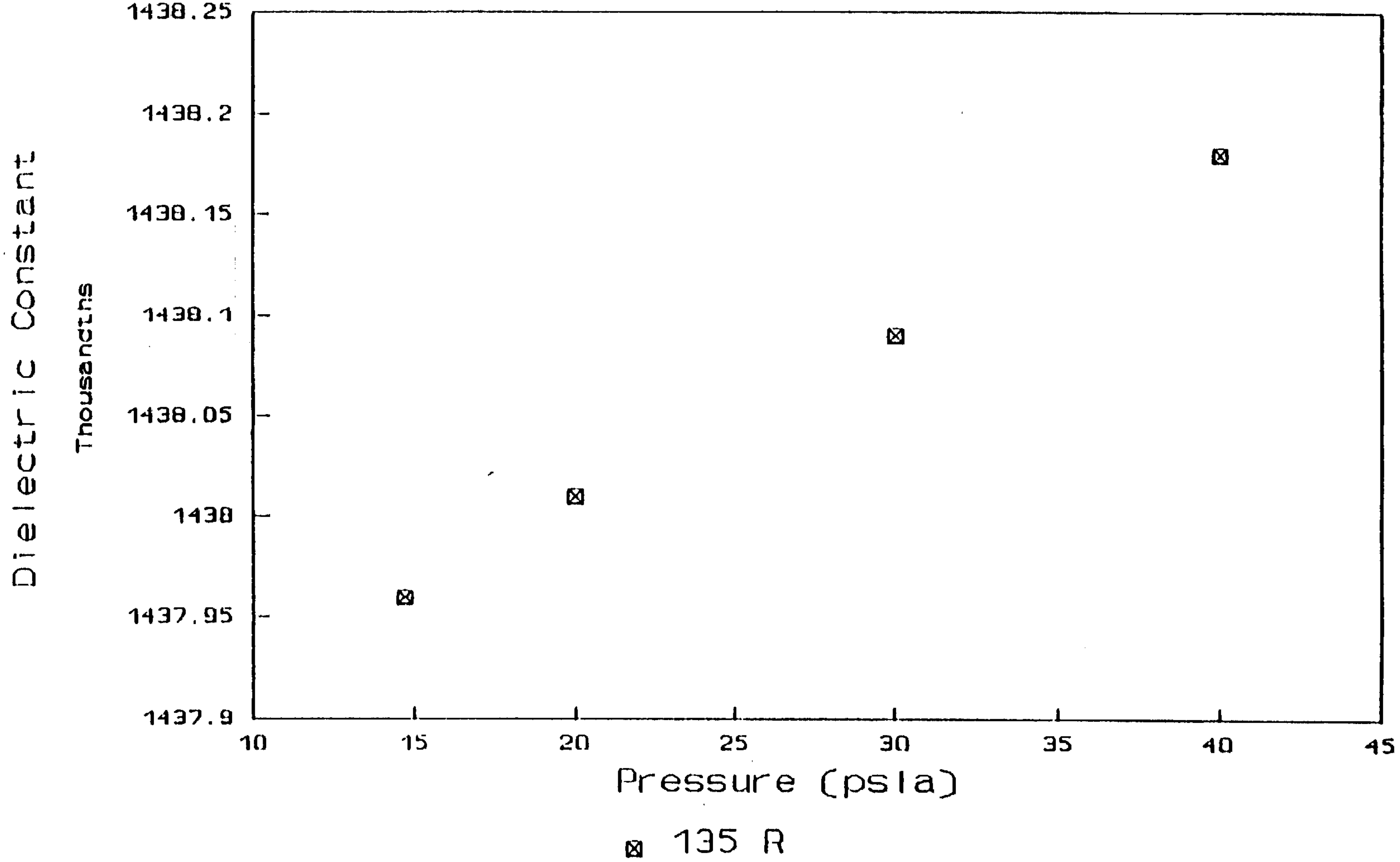
H2 Liquid Dielectric Constant vs Pressure



E(36R) = (3.2*10^-5)*P +1.230416, R^2 = .999
lh2evsp.plc

Figure 3

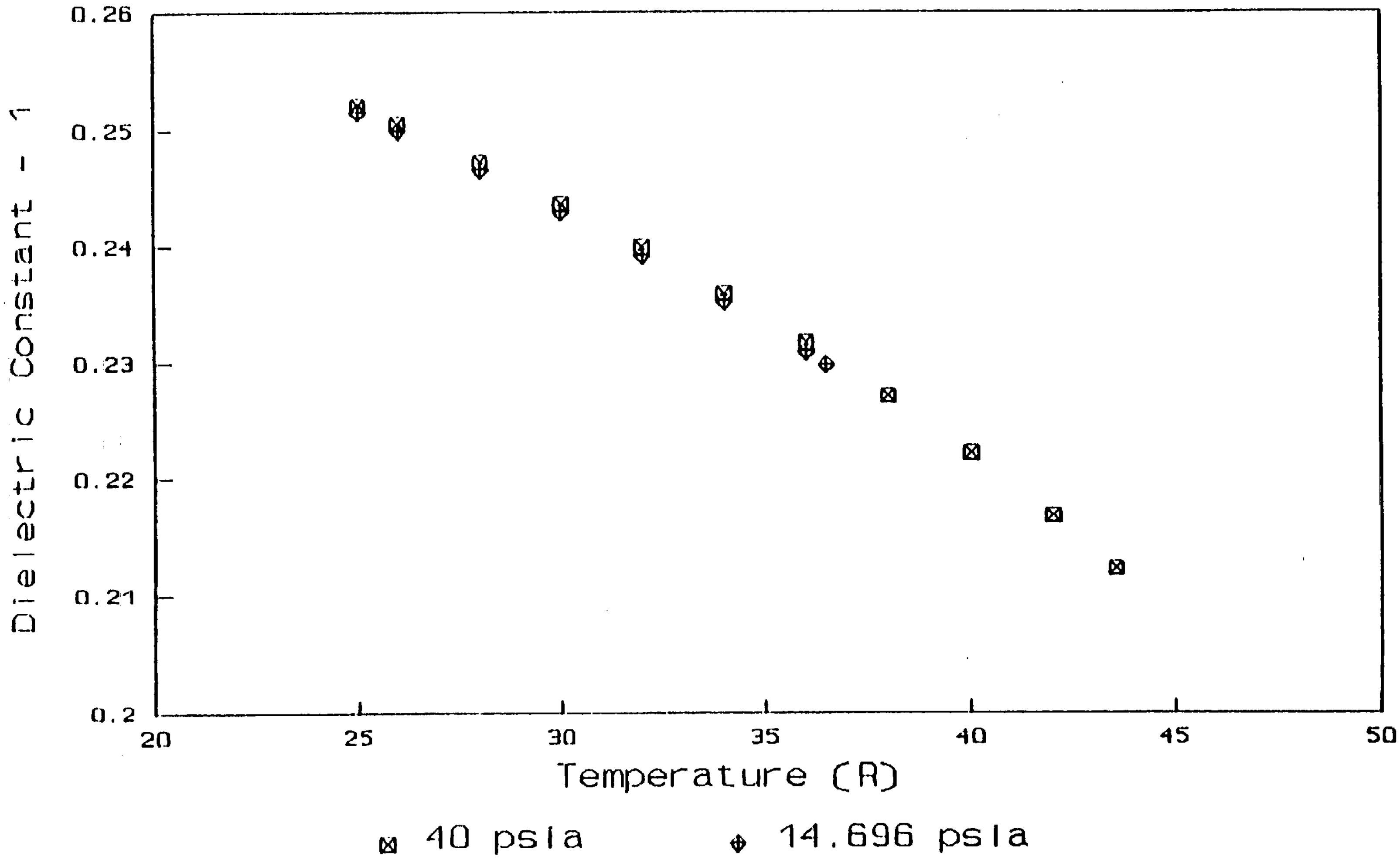
N2 Liquid Dielectric Constant vs Pressure



E(135R) = (8.6*10^-6)*P +1.437835, R^2 = .999
ln2evsp.plc

Figure 4

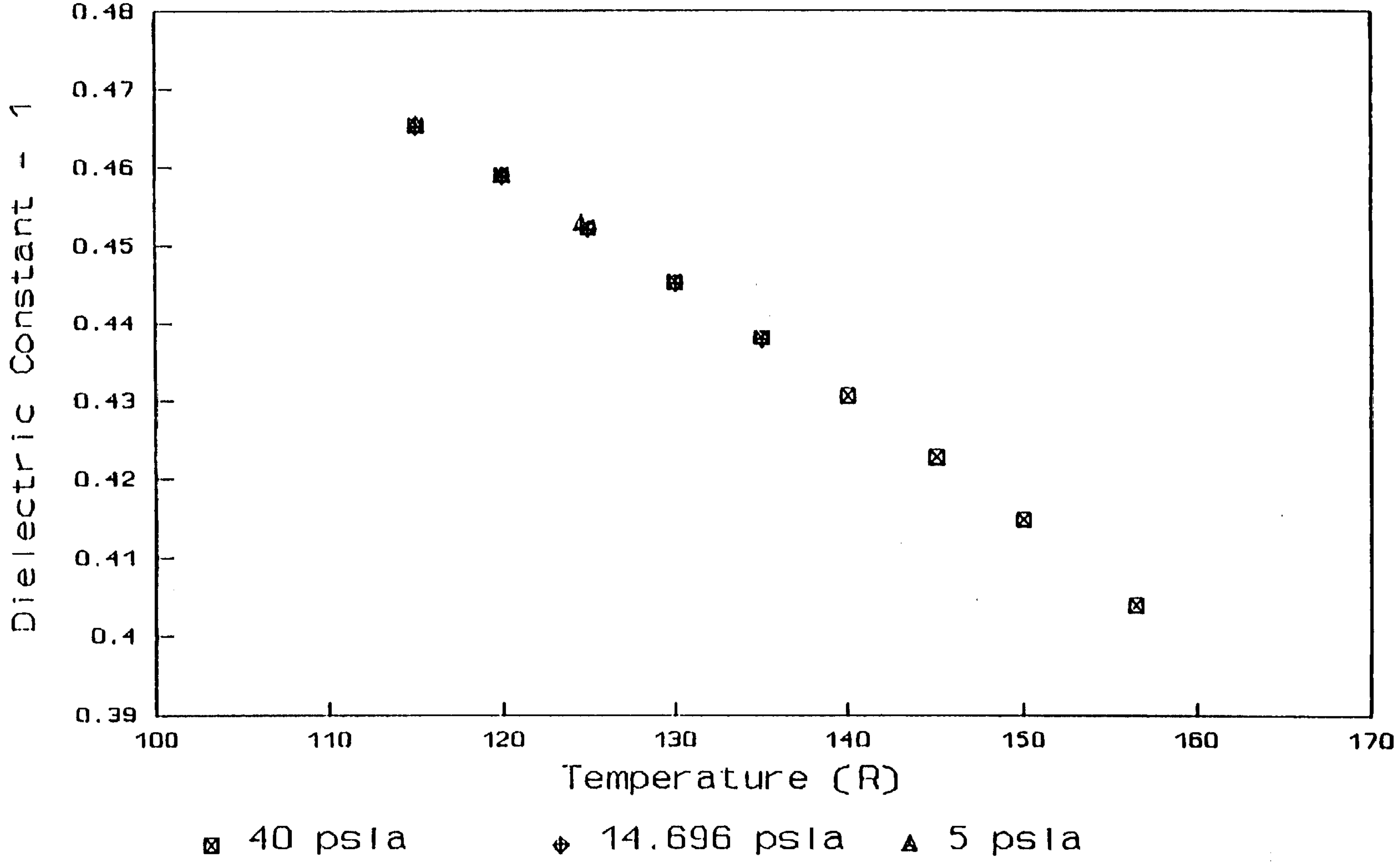
H2 Liquid (Dielectric Constant -1) vs Temperature



E(40psi) = (-2.1*10^-3)*T + 1.306596, R^2 = .992
lh2avst.plc

Figure 5

N2 Liquid (Dielectric Constant -1) vs Temperature



E(40psi) = (-1.5*10^-3)*T + 1.625962, R^2 = .998
ln2evst.plc

Figure 6

H2 Vapor Dielectric Constant vs Pressure

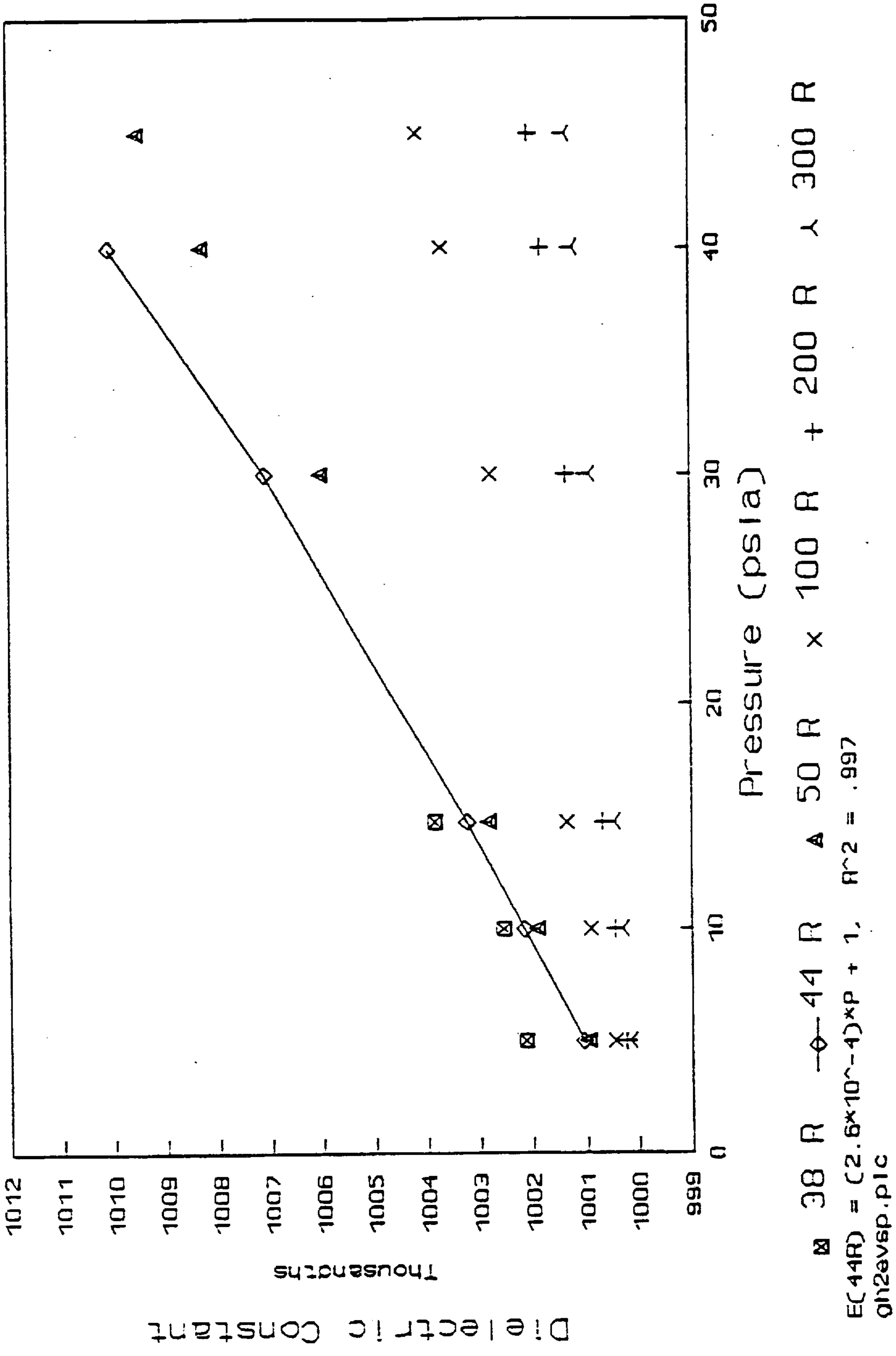
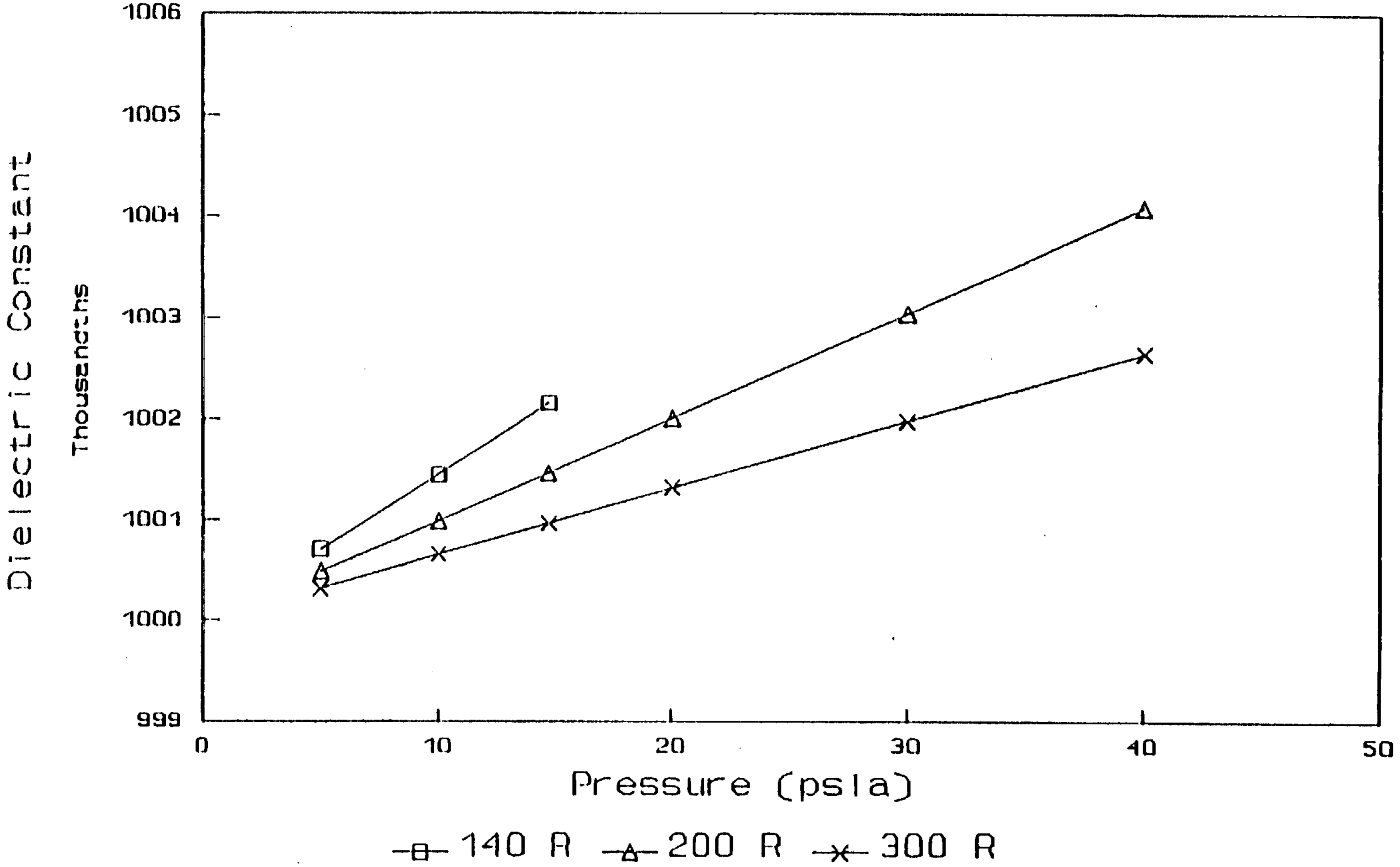


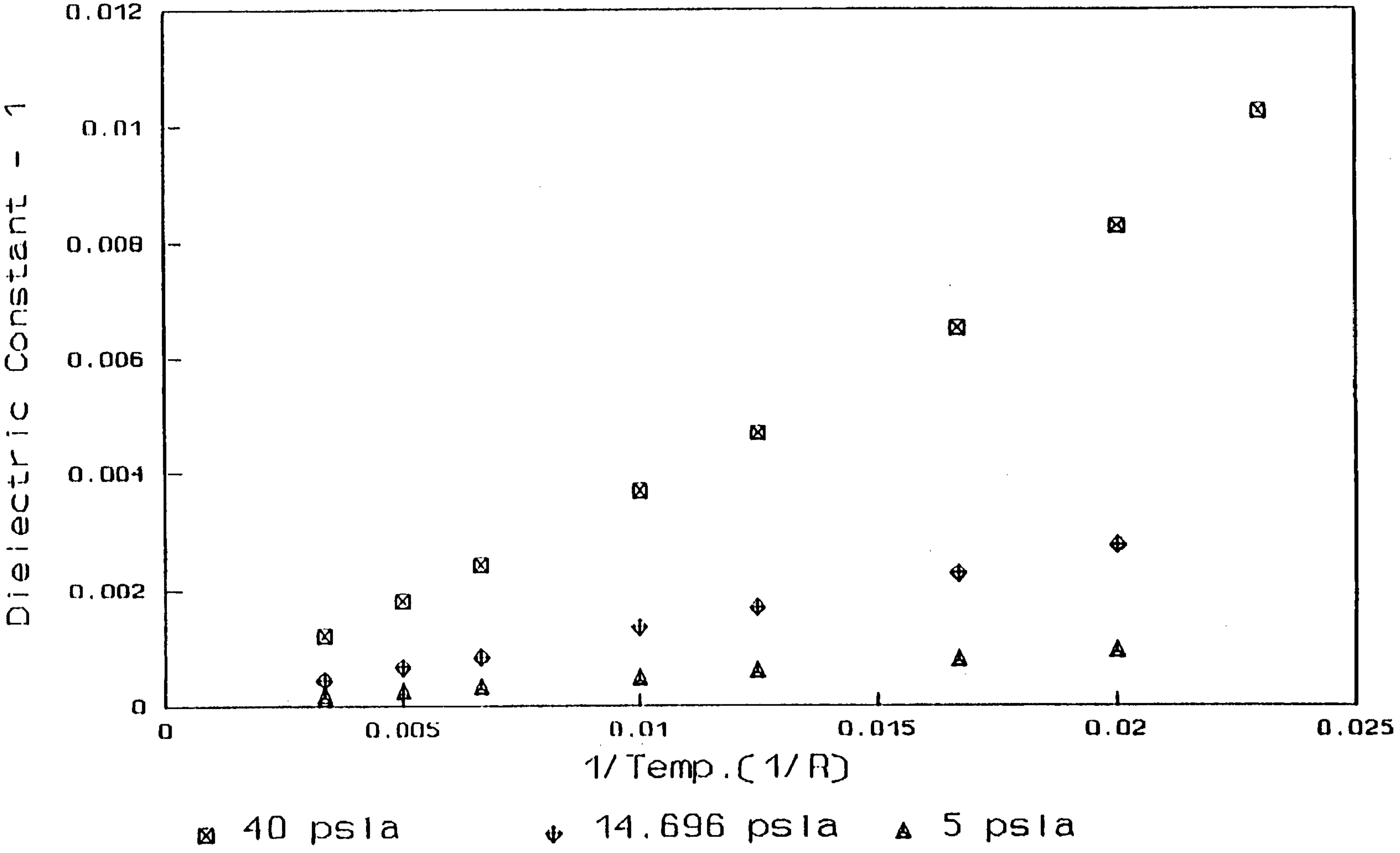
Figure 7
N2 Vapor Dielectric Constant vs Pressure



E(140R) = (1.5*10^-4) * P + 1, R^2 = .999
gn2evsp.plc

Figure 8

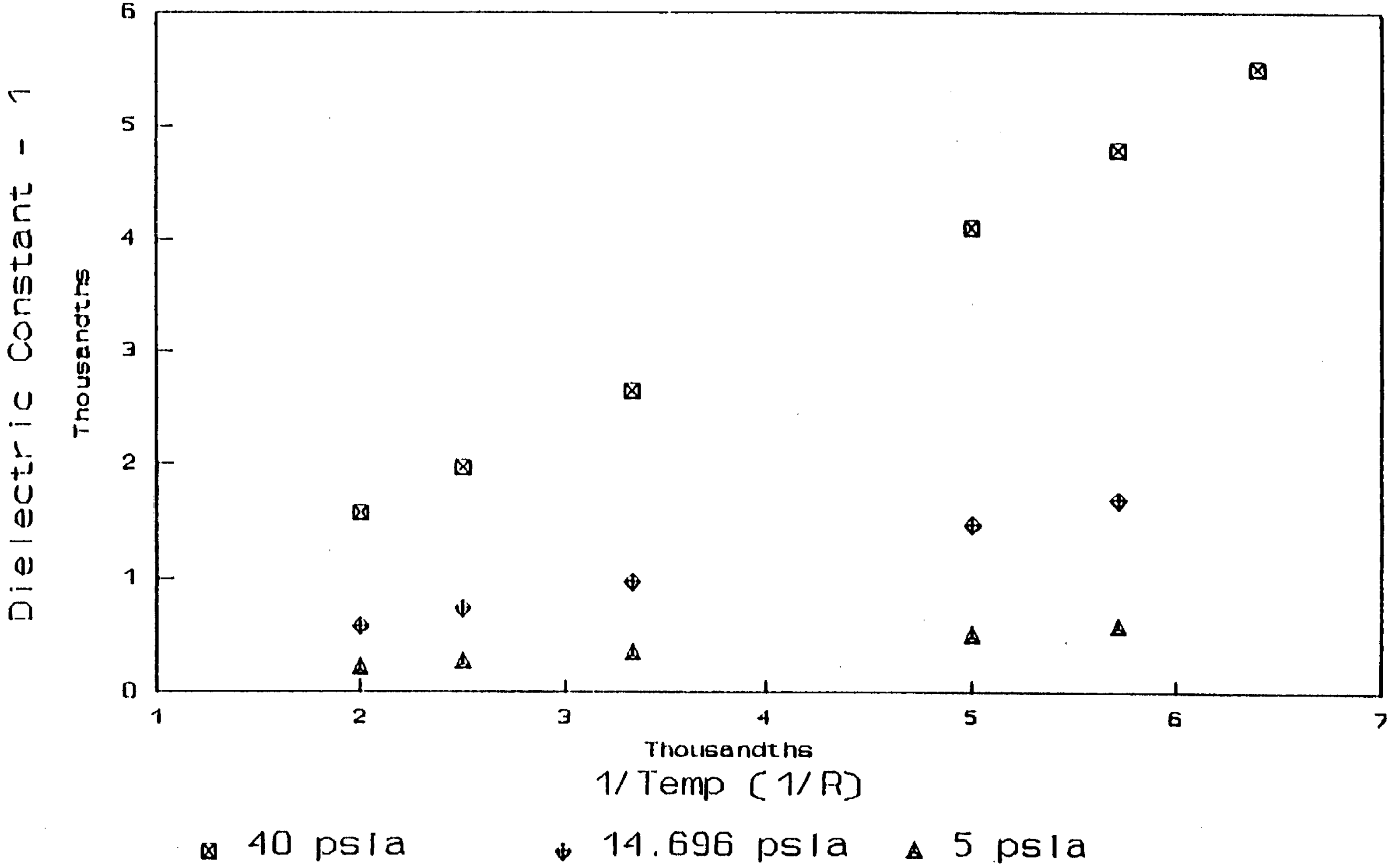
H2 Vapor (Dielectric Constant -1) vs 1/Temperature



E-1 = .45/T, R^2 = .99
gh2evst.plc

FIGURE 9

N2 Vapor (Dielectric Constant -1) vs 1/Temp.



E-1 = .89/T, R^2 = .998
gn2evst.plc

Figure 10A

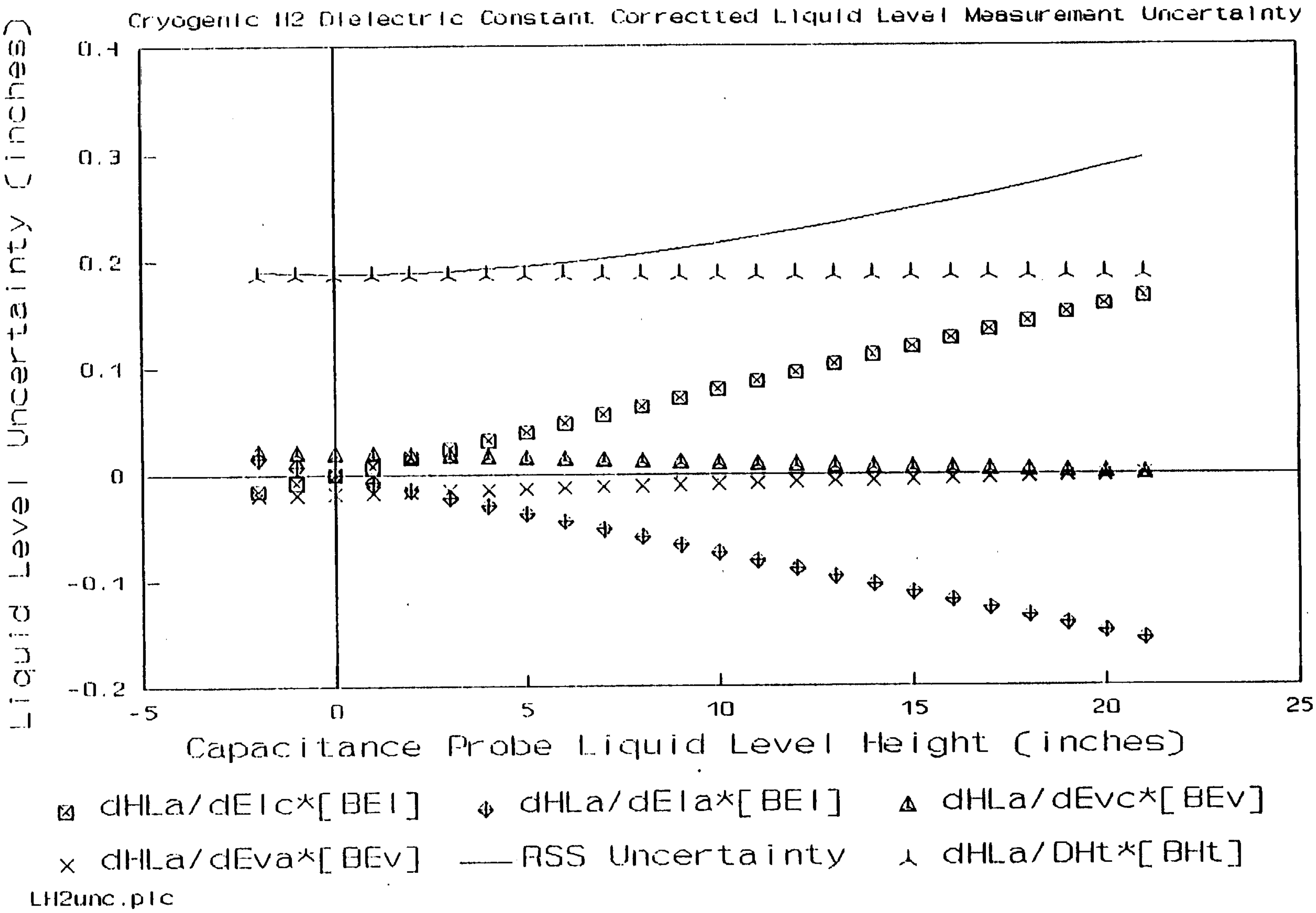

Cryogenic H2 Dielectric Constant Corrected Liquid Level Measurement Uncertainty
Liquid Level Uncertainty (inches)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-5
0
5
10
15
20
25
Capacitance Probe Liquid Level Height (inches)
dHLa/dElc*[BEl]
dHLa/dEla*[BEl]
dHLa/dEvc*[BEv]
dHLa/dEva*[BEv]
RSS Uncertainty
dHLa/DHt*[BHt]
LH2unc.plc

Figure 10B

Cryogenic N2 Dielectric Constant Correctted Liquid Level Measurement Uncertainty

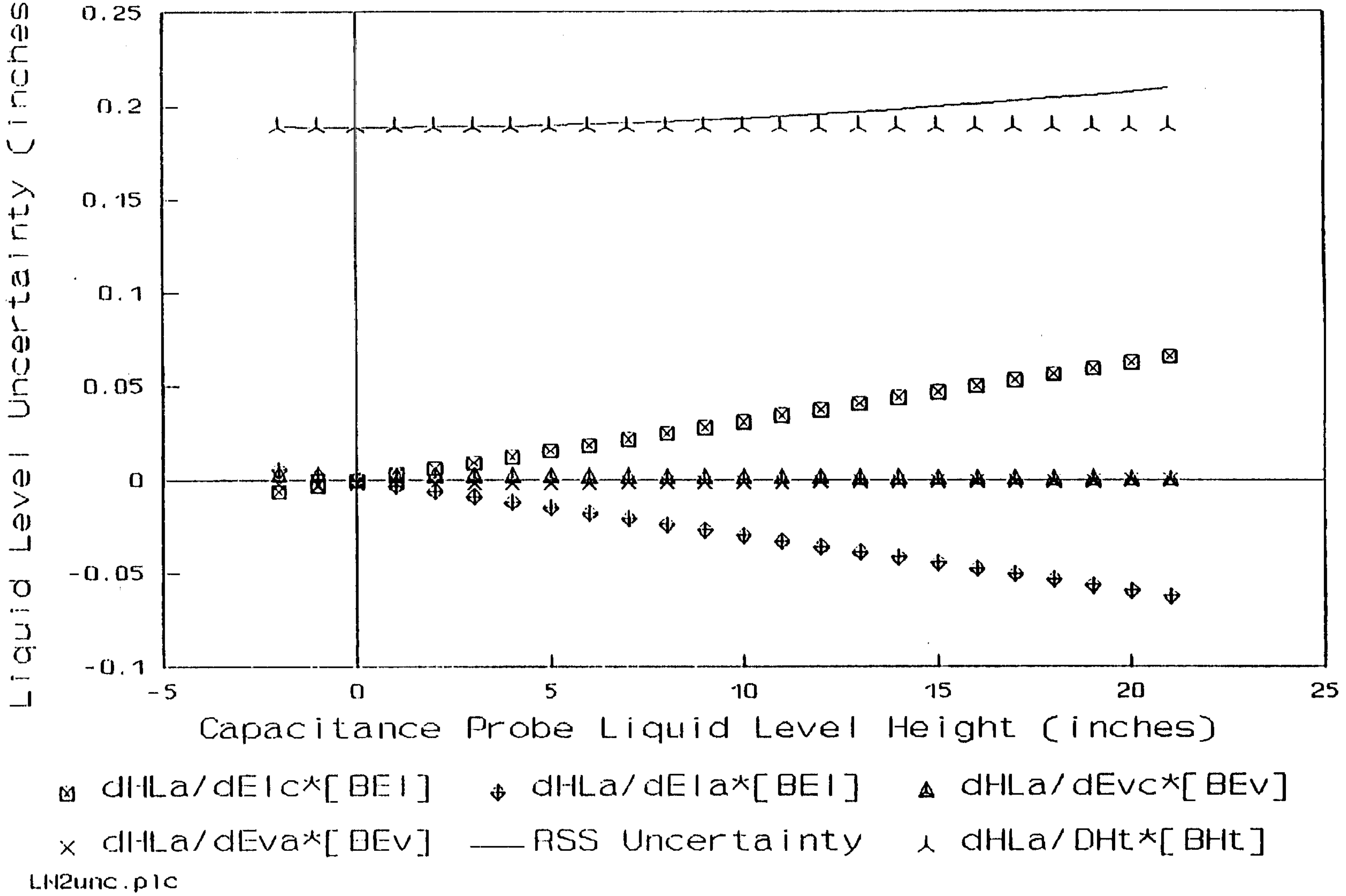


FIGURE 11

LN2 LIQUID/VAPOR INTERFACE
TEMPERATURE PROFILE

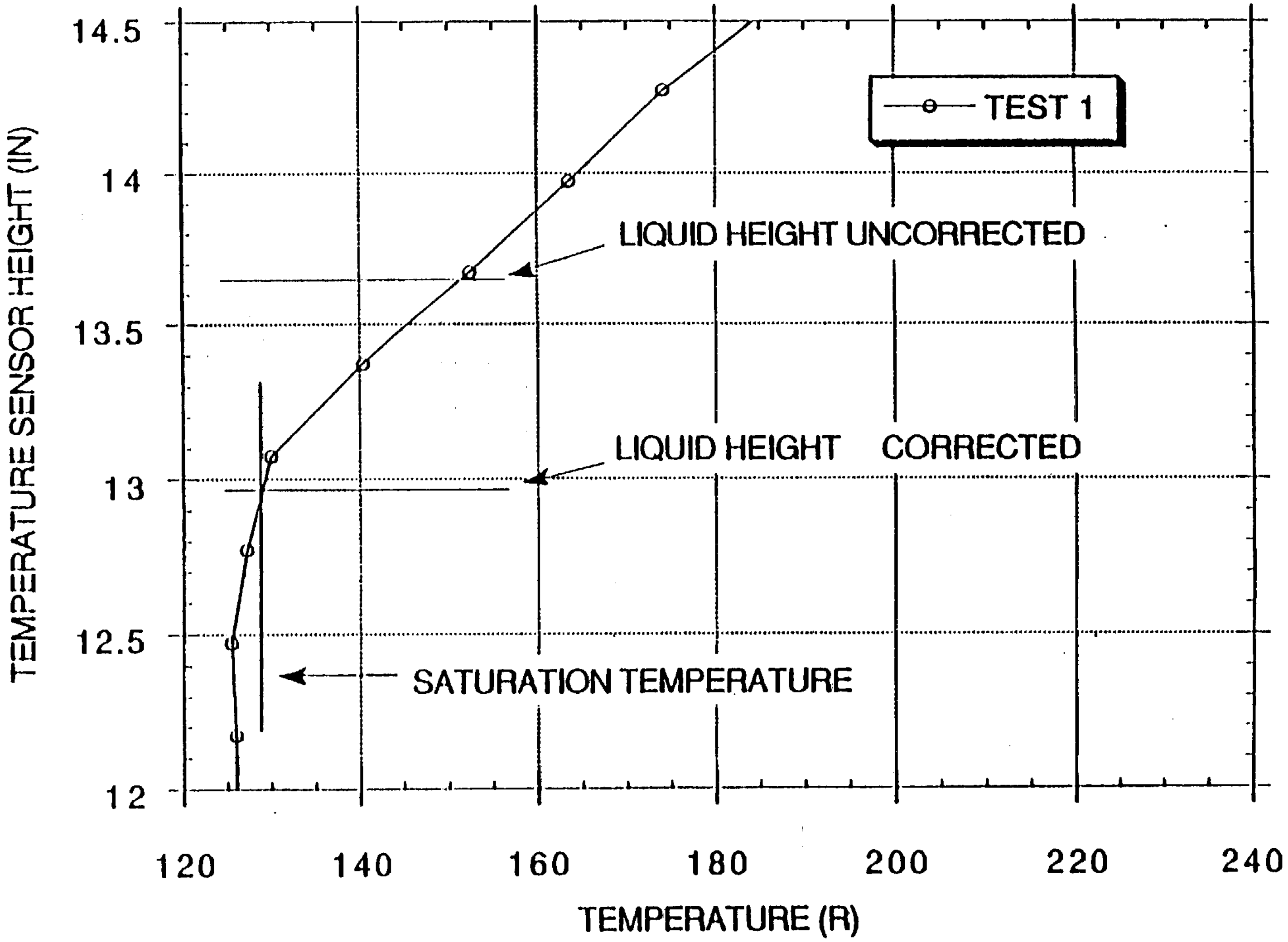
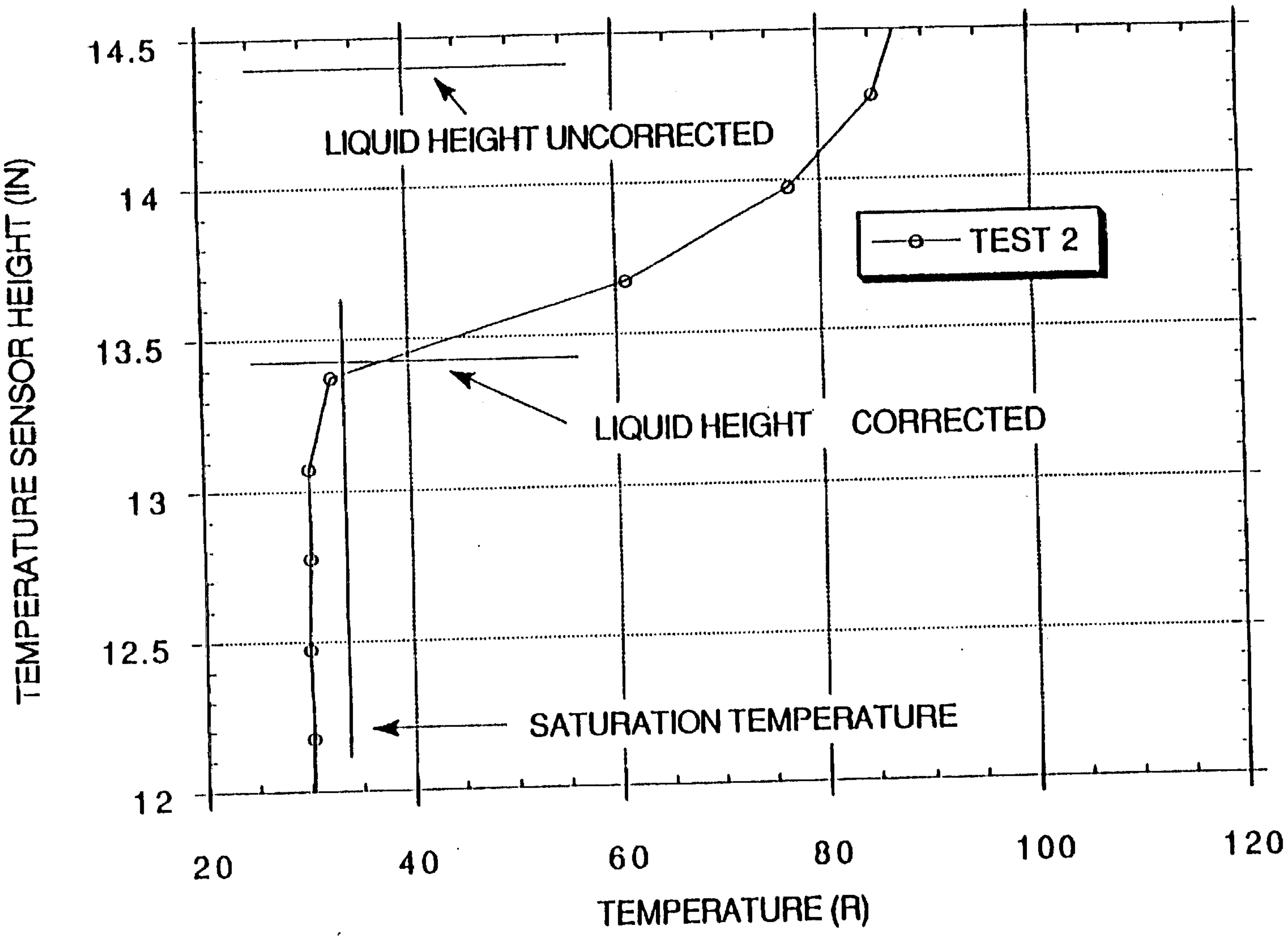


FIGURE 12

LH2 LIQUID/VAPOR INTERFACE TEMPERATURE PROFILE



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13. ABSTRACT ***(Maximum 200 words)***

The inaccuracies of liquid nitrogen and liquid hydrogen level measurements by use of a coaxial capacitance probe were investigated as a function of fluid temperatures and pressures. Significant liquid level measurement errors were found to occur due to the changes in the fluids dielectric constants which develop over the operating temperature and pressure ranges of the cryogenic storage tanks. The level measurement inaccuracies can be reduced by using fluid dielectric correction factors based on measured fluid temperatures and pressures. The errors in the corrected liquid level measurements were estimated based on the reported calibration errors of the temperature and pressure measurement systems. Experimental liquid nitrogen (LN_2) and liquid hydrogen (LH_2) level measurements were obtained using the calibrated capacitance probe equations and also by the dielectric constant correction factor method. The liquid levels obtained by the capacitance probe for the two methods were compared with the liquid level estimated from the fluid temperature profiles. Results show that the dielectric constant corrected liquid levels agreed within 0.5% of the temperature profile estimated liquid level. The uncorrected dielectric constant capacitance liquid level measurements deviated from the temperature profile level by more than 5%. This paper identifies the magnitude of liquid level measurement error that can occur for LN_2 and LH_2 fluids due to temperature and pressure effects on the dielectric constants over the tank storage conditions from 5 to 40 psia. A method of reducing the level measurement errors by using dielectric constant correction factors based on fluid temperature and pressure measurements is derived. The improved accuracy by use of the correction factors is experimentally verified by comparing liquid levels derived from fluid temperature profiles.

14. SUBJECT TERMS

Bias error; Coaxial capacitance liquid level probe; Cryogenic fluids; Dielectric constants; Liquid hydrogen; Liquid nitrogen; Measurement uncertainty; Pressure/temperature effects; Relative premittivity

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