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EXPERIMENTAL AND ANALYTICAL STUDY OF THERMAL ACOUSTIC OSCILLATIONS

FINAL REPORT

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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, Marshall Space Flight Center, by personnel of Lockheed Missiles & Space Company, Huntsville Research & Engineering Center. Presented herein are the results of a study of thermal acoustic oscillations performed under Contract NAS8-31625. The MSFC Contracting Officer's Representative for this contract was Mr. E.H. Hyde, EP43.

ABSTRACT

Efficient transfer and storage of cryogens has always been plagued by the phenomena known as thermal acoustic oscillations (TAO). This is a gas-dynamic phenomenon that occurs when a tube, closed on one end such as a transfer line or vent tube, is inserted into a cryogenic container. The heat transfer resulting from TAO alone can increase the boiloff/loss rates by factors of 100 to 1000 over that due to conduction alone. This phenomenon has been studied previously, both experimentally and analytically, by various investigators. Two of the better known investigators are Bannister and Rott. However, these previous investigations were generally limited in boiloff data.

The primary purpose of the present study was to expand the TAO data base by running a large number of tubes over a wide range of parameters known to affect the TAO phenomenon. These parameters include tube length, wall thickness, diameter, material, insertion length and length-to-diameter ratio. Emphasis was placed on getting good boiloff data.

During the study a large quantity of data was obtained, reduced, correlated and analyzed and is presented herein. Also presented are comparisons with previous types of correlations. These comparisons showed that our boiloff data did not correlate with intensity. (This was the method Bannister used to correlate his data.) Our data did correlate in the form used by Rott, that is boiloff versus TAO pressure squared times frequency to the one-half power. However, this latter correlation required a different set of correlation constants, slope and intercept, for each tube tested. No explanation of this was found.

Another interesting observation was that there seemed to be some type of coupling or resonance effect between the tube geometry and the liquid level in the dewar, i.e., ullage volume.

Additional efforts are now needed to:

- Further analyze and correlate these data and make additional comparisons with theory and other data correlation.
- Further determine the effects of additional parameters not adequately covered in these measurements, such as liquid level, ullage pressure, temperature distribution in the tube, and time/transient effects. (Attempts were made to study the TAO as a steady-state phenomenon; however, it was difficult to determine when and if "steady-state" occurred. Tests are needed where real time, continuous and simultaneous recording of all parameters is done.)
- Study coupling/resonance effects between tube geometry and ullage space, natural frequencies, etc.
- Convert these results to design applicable forms which can be used to predict and minimize TAO boiloff rates in "real life" situations such as propellant storage in space.
- Study design fixes for the TAO phenomenon such as a "jumper" tube between the TAO tube and storage vessel ullage space, accumulators, trip wires inside the tube, etc.

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1. INTRODUCTION AND SUMMARY

1.1 BACKGROUND

The term "thermal acoustic oscillations" is used to describe the phenomena of thermally induced acoustic pressure waves in a compressible gas. The first observation of the phenomena is generally credited to Sondhauss in 1850. He observed that audible sound was produced from the tubes used by glass blowers. A gas flame applied to a bulb-end caused the air in the tube to oscillate and produce a clear sound which was characteristic of the dimensions of the tube. This observation is known as the Sondhauss thermal acoustic oscillations phenomenon. Lord Rayleigh in 1878 provided an explanation for the spontaneous occurrence of these heat driven sound waves. He explained that the oscillations occur if heat is added to the air at the point of greatest compression and heat is taken out at the point of greatest expansion. This explanation has become known as the "Rayleigh criterion." He further explained that this criterion is fulfilled in the Sondhauss tube because the moment of greatest compression occurs when the gas is compressed into the hot end where it becomes heated and expands, thus encouraging the oscillation; in addition, the moment of greatest rarefaction occurs when the gas expands into the cool end of the tube where heat is removed which also encourages ocillations.

The occurrence of thermal acoustic oscillations in low temperature apparatus has been observed by investigators since 1940. A tube which penetrates a cryogenic storage vessel can become filled with vapor due to normal boiloff of the cold liquid. Figure 1-1 shows schematically a tube open on the end which penetrates the vessel and is closed on the end exposed to ambient conditions.

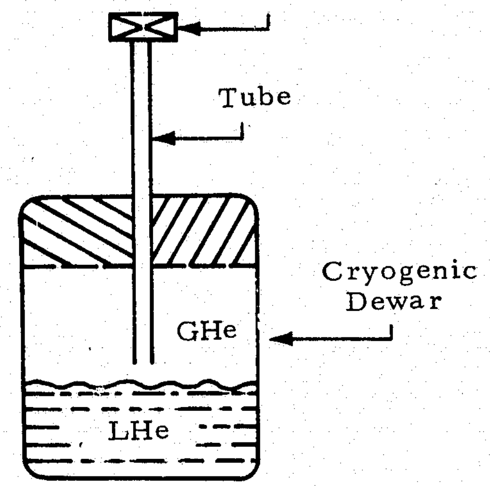


Fig. 1-1 - Schematic of Configuration

The purpose of the tube is for filling the tank, for venting the dewar, for stirring the liquid, etc. The upper closed end of the tube is exposed to ambient temperature and the open end is exposed to the cold environment. As heat leaks into the storage vessel, the liquid starts to boil off, filling the tube with vapor. The gas-filled tube thus has one end at near-ambient temperature and the other end at near-cryogenic temperature. The Rayleigh criterion is thus fulfilled for the cryogenic apparatus and provides an explanation for the spontaneous occurrence of acoustic oscillations. Pressure oscillations are initiated by expansion of the fluid as it is heated at the closed end. These oscillations in turn force vapor from the tube at the open end into the storage vessel. Cool vapor is withdrawn from the ullage space into the tube to replace the ejected mass.

Figure 1-2 is a schematic which illustrates the sequence of events for thermal acoustic oscillations in a liquid helium storage vessel. At the initial "time" $t = 0$, the tube is filled with helium gas at some initial uniform temperature. The upper closed end of the tube is always exposed to the hot (ambient) temperature. An instant of time later (t_1), the gas in the pipe heats

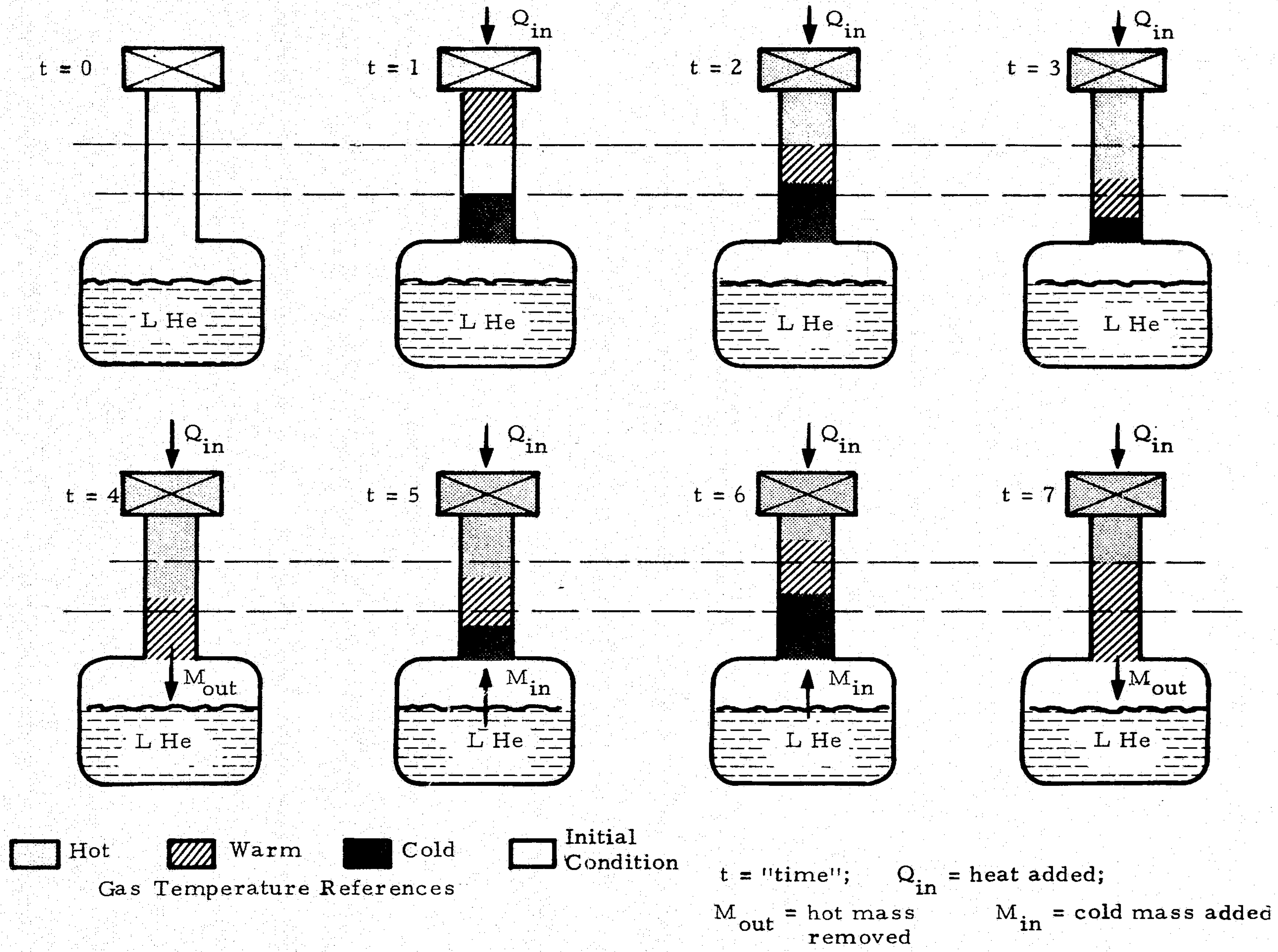


Fig. 1-2 - Illustration of Thermal Acoustic Oscillations Phenomenon up at the top and cools down at the bottom due to conduction heat transfer. The gas column has some temperature distribution at $t=2$ as shown. As heat is continually added from the top, the cold gas is moved down the tube at $t=3$ since the hot gas expands from the closed end. The expansion continues at $t=4$ forcing the warm gas out the end of the tube. This convective heat transfer then increases to the boil-off of the liquid. At time $t=5$, cold gas is drawn back into the tube since the pressure at open end is now lower than the internal gas pressure in the dewar. This "suction" continues at $t=6$, but the gas which was drawn in now warms up due to continued heat addition at the top. The time $t=7$ shows the process being repeated as the oscillations sustain themselves purely by thermal means. This simple illustration was presented to clarify the mechanism by which the oscillations are started (thermal expansion), the mechanism by which heat is transferred (mass transfer), and the mechanism by which the oscillations are sustained (heat addition and removal). This process is sufficient to sustain the oscillations for long periods of time. The mass transfer process at the open end of the tube produces an additional heat leak which has been reported to be a factor of 10 to 200 larger than the no-oscillation values. This large amount of heat "pumped" into a cryogenic storage vessel can cause such large boiloff that long term storage on space missions is impossible.

1.2 PREVIOUS WORK

The thermal acoustic oscillations phenomena has been the subject of many investigations, both analytically and experimentally. Most of the early experimental work was concerned with characterizing the oscillations rather than measuring the boiloff rate (i.e., heat leak) for different tubes and parametric values. The corresponding analytical efforts were confined to studies of linearized hydrodynamic equations. These attempts failed to predict sustained oscillations due to the neglect of the nonlinear driving mechanisms. A literature survey of both analytical and experimental work on thermal acoustic oscillations is given in Ref. 30. The following is a summary of this previous work.

Apparently the first observation of thermal acoustic oscillations in low temperature apparatus was made by Taconis, 1949 (Ref. 32). He observed spontaneous acoustic oscillations in a hollow tube which was used for stirring liquid helium. The upper end of the tube was closed (at room temperature) while the lower end was immersed in the liquid helium. Taconis' explanation of how the large thermal gradient along the tube caused the oscillations was essentially a restatement of the Rayleigh criterion. He noted, however, that the oscillations caused an effective "stirring" such that heat transferred to the fluid was so great that large boiling occurred. The net effect of the "stirring" was to significantly increase the heat transfer and result in the boiling.

Kramers, 1949 (Ref. 16), was credited as the first to attempt a theoretical analysis of the Sondhauss oscillation problem, but had limited success. He attacked the problem by considering small amplitude waves which could be described by the linearized hydrodynamic equations of mass, momentum and energy. He attributed the failure of his theory to the fact that the terms he neglected in linearizing were probably not negligible. Wexler, 1959 (Ref. 38), observed oscillations during a study to design storage containers for liquid helium. When the end of a vent tube was restricted by a rubber tube the oscillations could be felt by holding the rubber tube. He makes the statement, without supporting data, that the influx of heat due to the oscillations may be 1000 times the normal heat leak.

Clement and Gaffney, 1954 (Ref. 4), experimentally studied spontaneous thermal oscillations, which occurred in small diameter tubes having one end at room temperature and the other end at liquid helium temperature. They observed that the optimum conditions for oscillations occurred when the end at room temperature was completely closed and the end immersed in the liquid helium was open. Other important facts discovered by Clement and Gaffney are that oscillations occurred in a tube when the cold end was withdrawn above the liquid surface and that step-like changes occur in the oscillation frequency as the tube is withdrawn from the liquid. Trilling, 1955 (Ref. 36), conducted an analytical study of heat generated pressure waves.

He showed that sharp increases in boundary temperature can cause pressure waves to propagate in much the same manner as pushing a piston through a gas-filled pipe.

Chu (Ref. 3), presents a complex theoretical treatment of heat generated pressure waves. Ditmars and Furukawa, 1964 (Ref. 6), have noted that in certain low temperature experiments, the presence of thermal acoustic oscillations often causes the calorimetric measurements to be difficult or even impossible due to the large additional heat leaks. Feldman, 1966 (Refs. 8, 9), conducted an extensive experimental and theoretical study of the Sondhauss oscillation. A physical analysis of the driving mechanism was presented.

J.D. Bannister, 1966 (Ref. 1), conducted experiments for measuring spontaneous pressure oscillations in tubes connecting liquid helium reservoirs to room temperature environments. He measured oscillation pressure amplitudes and frequencies together with longitudinal temperature profiles and heat pumping rates for a range of tubes. His experimental results indicate that: (1) spontaneous pressure oscillations occurring in tubes, which connect liquid helium reservoirs to their 300°K environments, have an amplitude directly proportional to the slenderness ratio of the gas column, and (2) the heat pumped by spontaneous oscillations is proportional to the product of pressure amplitude times frequency. Larkin, 1967 (Ref. 17), was apparently the first to solve the nonlinear conservation equations for simulating thermally induced wave motion. Results of this analysis indicate that: (1) the heat transfer can be greatly increased over pure conduction due to acoustic pressure waves and (2) numerical methods can be used successfully to calculate thermal acoustic oscillations.

Thullen and Smith, 1968 (Ref. 33), present an analysis for determining the parameters and operating region for oscillations associated with liquid helium. Comparison of the results with some experimental measurements taken from a complex configuration show that the general behavior trend is correct. Rott, 1969 (Refs. 22, 23), presents a complex mathematical formulation of the linearized equations for small amplitude motion. His purpose was to determine the stability limit for thermal acoustic oscillations. This paper presents no results, only the formulation of the problem. However, he presents some very useful results in a later paper. Mortell, 1971 (Ref. 19), also gives the detailed mathematics for description of small amplitude resonant motions of a gas in a tube. Collier, 1972 (Ref. 5), investigated thermally induced oscillations in cryogenic systems. In an experimental study, he found that the surface temperature of a steadily heated cylinder oscillates when immersed in slush hydrogen. The author claims that the experimental results were consistent with a theoretical model which was developed. Since the important effects of viscosity were neglected in Collier's model, his results can be considered as approximate qualitative solutions.

Rott, 1973 (Ref. 24), presents an extension of his previous work aimed at determining the oscillation stability limit for helium. He used a "second-order" linear theory to produce, for a range of dimensionless parameters, a curve indicating the range where oscillations can be expected to occur. The governing parameters were determined to be the ratio of the hot end temperature to cold end temperature, the aspect ratio of the tube, the length of the "cold" part of the tube and the acoustic Reynold's number. Von Hoffmann, Lienert and Quack, 1973 (Ref. 37), present results of an experimental study to verify the stability limit of Rott. Tubes of various sizes were inserted into a double glass dewar. Von Hoffman claims qualitative agreement and explains the lack of quantitative agreement on his experimental inaccuracies.

The most recent work was done at Lockheed-Huntsville under MSFC Contract NAS8-26642. This study identified and quantified many aspects of thermal acoustic oscillations. The results of this study are documented in Ref. 30. Criteria for the spontaneous occurrence of oscillations, amplitude and frequency characteristics, and boiloff rates due to oscillations were determined both analytically and experimentally for a range of system storage parameters. This study showed that: (1) thermal acoustic oscillations are easily initiated in liquid helium apparatus; (2) heat leaks at least two orders of magnitude larger than the normal conduction values can be produced which results in orders of magnitude reduction in storage life; and (3) the oscillations disturb the liquid itself causing stirring and turbulent-like flow in the liquid cryogen.

This previous study at Lockheed-Huntsville identified conditions which favor the occurrence of thermal acoustic oscillations. Comparison of theory and experiment was generally good for most of the system parameters. There was considerable disagreement, however, on the effects of ullage pressure and distance of the tube from the liquid surface.

In addition, the study identified aspects of the thermal acoustic oscillations problem which had not received attention. Among these are: (1) the influence of the tube proximity to the liquid surface; (2) the occurrence of a secondary wave superimposed on the primary oscillation; (3) a disagreement between theory and experiment for oscillation existence criteria; and (4) the effects of vessel ullage pressure on the oscillation characteristics and boiloff rates. These and other aspects of the problem can strongly influence the oscillation characteristics and boiloff rates in cryogenic storage vessels. The current study, which is the subject of this report, was initiated as an extension to the previous work at Lockheed to clarify and quantify some of these aspects of the thermal acoustic oscillations problem.

This current study differs from other work that has been done previously. Specifically, the following items are unique to this investigation:

- A large volume of boiloff data was taken for a wide range of tube sizes and distances from the liquid surface. Previously, only a limited amount of actual boil-off data was available to study trends and magnitudes. We now have these data.
- The first measurements of ullage pressure during oscillation were taken in this study. This phenomenon has not been reported in the literature to date.

- Temperature profiles along the tube were measured at both the warm end and the cold end of the tubes.
- Analytical correlation equations were derived and compared with laboratory data. No previous attempts were successful in even obtaining such equations. Our predictions do not reproduce the data for all cases but do correctly predict the trends of boiloff rate versus oscillation characteristics.
- In summary, this investigation has resulted in the most comprehensive and quantitative laboratory and analytical study to date on thermal acoustic oscillations in cryogenic apparatus.

1.3 STUDY OBJECTIVES AND APPROACH

This study consisted of an experimental and analytical investigation of thermal acoustic oscillations in a cryogenic storage dewar. A major concern aboard space vehicles is the loss of liquid hydrogen due to increased heat leak caused by thermal acoustic oscillations. In this experimental program, liquid helium was substituted because: (1) oscillations are easily initiated due to the low (4.2 K) boiling point; (2) previous data exist on liquid helium oscillations; and (3) safety considerations prohibited use of liquid hydrogen. The study constitutes an extension of the work reported in Ref. 30. Specific objectives of this work were to:

- Quantify by experimental mesurement the previously obtained data on oscillation characteristics and boiloff rate as a function of the tube length/diameter ratio and wall thickness.
- Determine the effects of the tube proximity to the liquid surface on the frequency and amplitude of oscillations.
- Measure boiloff rates for a matrix of tube sizes to determine the magnitude of the heat leak induced by thermal acoustic oscillations.
- Derive and formulate engineering correlation equations based on theoretical means for predicting frequency, amplitude and boiloff rate due to oscillations.
- Compare theory and experiment to provide a definition of system parameters which may be used to suppress oscillations for long term storage of cryogens.

The experimental program was carried out in the Lockheed-Huntsville Cryogenics Laboratory using both a "research dewar" and the commercial "shipping dewars" of liquid helium. A matrix of stainless steel tubes with length-to-diameter ratios L/d = 100 to L/d = 300 were used as the test specimens. The tubes range in length from 66 to 197 cm inside diameters from 0.627 to 0.975 cm and wall thickness of 0.048 to 0.162 cm. Pressure oscillations were measured at the "top" closed end of the tube with a Kistler Piezotron dynami pressure transducer. Recordings were made on a dual trace oscilloscope, a true root-mean-square meter and a frequency counter. Boiloff measurements were taken from a vent port on the dewars using Hastings-Raydist flowmeters. In addition, some of the tubes were instrumented with cryoresistors, carbon resistors and thermocouples to monitor temperature profiles. Ullage pressures were checked with a simple manometer, and liquid level data were taken in the research dewar using the sensor supplied with the dewar. Liquid level was monitored in the shipping dewars by cryoresistors before and after the tests. Pressure responses, boiloff rates and some temperature data were recorded on strip chart devices.

Parameters that were measured are:

- Liquid helium level
- Tube length above top of dewar
- Temperature distributions
- Ullage gas pressure
- Oscillation frequency
- Oscillation amplitude (rms)
- Boiloff rates

Each tube in the matrix was tested at least once with several being repeated for redundancy checks. The data were compiled, reduced using calibration curves for the instrumentation, and plotted versus the test parameters. Section 2 contains the details of the test configuration and summarizes the data in curve form.

The analytical portion of the study consisted of deriving simplified correlation-type equations for a model of the real system. The work of Rott (Ref. 24) was used as a basis of the investigation. Equations were derived for oscillation frequency, amplitude and boiloff rate as a function of the length-to-diameter ratio of the tube, wall thickness, material properties, temperature ratio of "hot" to "cold" end values, and distance of the tube from the liquid surface. The equations contain some unspecified parameters that were not derivable from theory alone. The experimental data were used to semi-empirically derive these unspecified constants. This approach was necessary because the nonlinear nature of the differential equations precludes any closed form solution and a linearized analysis will not predict the correct nature of the oscillations. The previous study at Lockheed-Huntsville (Ref. 30) used a numerical solution which gives good results, but it is not readily adaptable for use by engineering designers. It was decided that a semi-empirical correlation equation approach would provide a more practical means of predicting oscillation effects. The analytical predictions are then compared to the data and conclusions drawn as to the influence of each of the previously defined parameters on the oscillation characteristics.

Section 3 contains the details of the correlation equations and shows the comparison between theory and data for representative cases.

1.4 SUMMARY OF RESULTS

The study has resulted in a number of significant results and an equal number of new problem areas which will require further investigation. The following is a summary of the findings of this study.

General

- The onset of oscillations is a strong function of the liquid helium level and the distance of the tube from the liquid surface.
- The effects of ullage pressure on oscillation characteristics is significant. The exact nature of effects on each parameter

was not determined as it appeared to be coupled to the many other parameters in the system.

- Due to the coupling of many parameters in the system, problems were encountered in getting repeatability in some of the tests. The oscillation characteristics for a given tube would change drastically with liquid volume and ullage pressure.

Oscillation Characteristics

- The frequency measurements ranged from 10 Hz for the longer tubes to about 90 Hz for the shortest one.
- Maximum pressure amplitudes measured were of the order of 0.5 kg/cm^2, with a mean of $\sim$0.1 kg/cm^2.
- The frequency of oscillations decreases as the tube is moved closer to the liquid surface. The amplitude, however, shows a general increase as the tube is moved closed to the liquid surface.
- The temperature of the cold part of the tube remains virtually constant at $\sim$4 to 5 K regardless of the cold length value.
- The analytical correlation equation for oscillation frequency predicts accurate to $\sim$ 5% for a major portion of the data taken.
- The amplitude correlation equation predicts accurate to $\sim$ 25% for approximately one half of the data and misses the other half of the measurements by as much as a factor of 2.

Boiloff Rate

- The largest boiloff rate measured was 2×10^4 sccm due to oscillations. The static no-oscillation value was $\sim 10^2$ sccm. The boiloff rate can thus be increased 200 fold by the oscillations.
- The boiloff rate trend was found to correlate with the product of amplitude squared and the square root of frequency.
- The correlation equation for boiloff rate correctly predicts the slope of the curve versus amplitude squared times the square root of frequency. However, the magnitude of the prediction is inaccurate. Some data correlate to within 20% of the prediction, while most of the boiloff measurements are overpredicted by as much as a factor of 3.

Example Data

Figure 1-3 is a plot of data taken in laboratory for a representative stainless steel tube which is 197 cm in length, inside diameter = 0.657 cm and wall thickness = 0.147 cm. The figure shows oscillation frequency, peak-to-peak pressure amplitude and boiloff rate ratio as a function of distance from the liquid surface. The frequency shows a characteristic drop as the tube approaches the liquid and then remains virtually constant as it is submerged lower into the liquid. The pressure amplitude shows a corresponding rise as the tube approaches the liquid. The boiloff curve is plotted as total measured boiloff rate in standard cubic centimeters per second divided by the boiloff rate without oscillations occurring. This quantity then represents the factor by which the boiloff is increased due to oscillations themselves. At a distance of ~ 9 cm above the liquid, the oscillations started but did not significantly affect the boiloff rate. There is, however, a sharp rise to about 45 times the static value with the tube at the liquid surface. The boiloff ratio continues to rise with the tube below the liquid with a maximum of ~200 fold increase at ~20 cm below the liquid. These curves are typical of the data taken and represent the first comprehensive measurements of boiloff rate and oscillation characteristics known to the authors.

Figure 1-4 was prepared from typical data taken in this study to illustrate the potential impact of such large boiloff due to thermal acoustic oscillations. Shown on this figure is the percent of cryogen remaining versus time in days. The upper curve represents boiloff due to normal heat leak through insulation, struts etc. A maximum boiloff of 1% per day was used as an upper limit of this "static" value. The lower curve represents boiloff due to static heat leak plus thermal acoustic oscillations. A conservative factor of 25 was used as the increase due to oscillations. In many cases (Fig. 1-3), this factor can be much higher. The curve shows emphatically that such oscillations can potentially decrease the storage life to such a degree that a space mission could be rendered impossible.

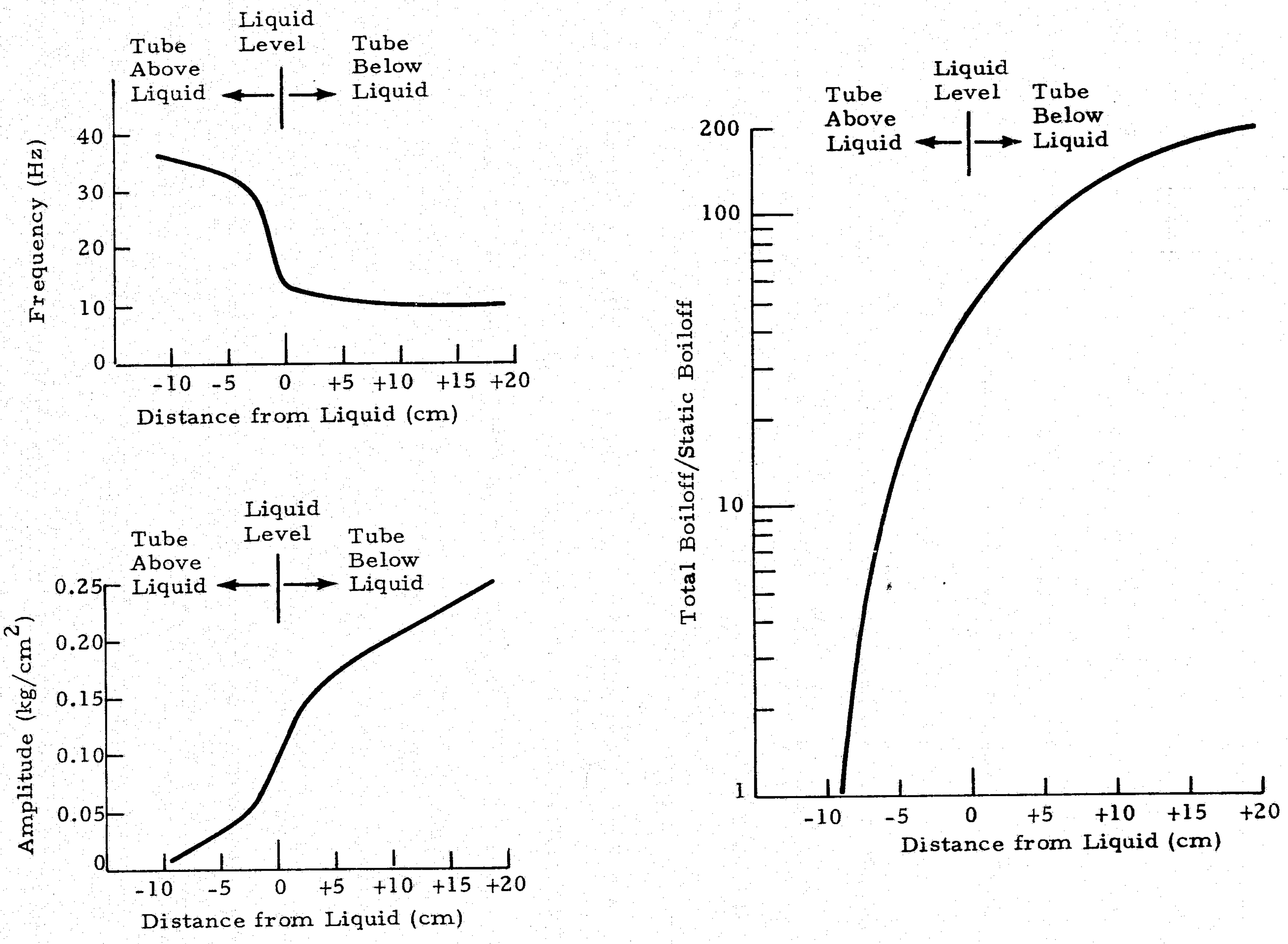


Fig. 1-3 - Frequency, Amplitude and Boiloff Rate Measurements for a Representative Tube vs Distance from Liquid Surface (Tube 1a, see page 2-8)

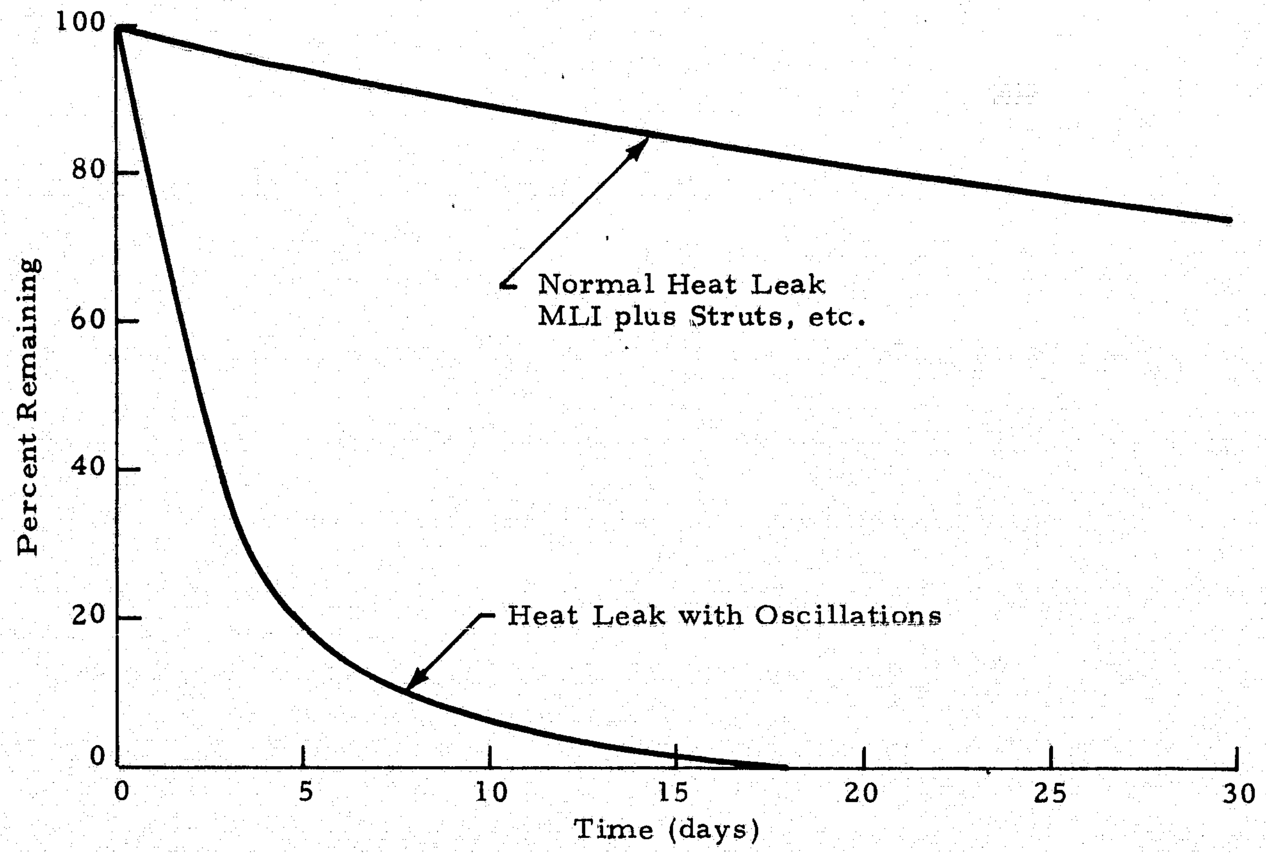


Fig. 1-4 - Illustration of the Effects of Thermal Acoustic Oscillation on Storage Life of Liquid Helium (Using data of this study)

1.5 PROBLEM AREAS AND RECOMMENDATIONS

The study has provided a large volume of data showing effects of thermal acoustic oscillations never before reported. The fact that additional problem areas were found is also significant. Even though we have solved a number of problems associated with this phenomenon, we have not explained all of the data or all of the effects which were observed. The conclusions reached from this study suggest that additional work is definitely needed to clarify and quantify a number of problems. An experimental and analytical study program should be conducted with the following objectives:

- Experimentally investigate and verify parametric and mechanical techniques for suppressing thermal acoustic oscillations,
- Quantify the vapor/liquid interface disturbance phenomena by flow visualization,
- Refine the engineering correlation equations and analytical prediction procedures for use by designers in analyzing storage systems for the possibility of thermal acoustic oscillations occurring and the resultant leaks they cause,
- Conduct experimental verification tests of the influence of oscillations when the tube is below the liquid surface,
- Quantify the effects of ullage pressure variations, and
- Measure oscillation characteristics in tubes with curved or coiled configurations.

Specifically, the following tasks are recommended.

Task 1

Experiments should be conducted using the existing hardware to determine effective and practical means of suppressing thermal acoustic oscillations. Mechanical techniques to be investigated should include the following: (1) tube surface roughness methods such as screw threads, taps and random identations; (2) Helmholtz resonator or equivalent procedures; (3) venting methods; (4) valve connection/accumulator expansion regions; and (5) trap door techniques. Parametric methods to be tested should include distance of the tube above the liquid surface, distance below the liquid surface and length/diameter ratios. The results of this task will provide data for making recommendations on suppression techniques which can be used for long-term storage systems on space vehicles.

Task 2

The vapor/liquid interface disturbance caused by thermal acoustic oscillations should be experimentally quantified by experiments using flow visualization techniques. The existing hardware can be used to obtain data for constructing an empirical model of the flow and mixing at the liquid surface. Schlieren-type movies, "smoke" observation techniques, and tracer particle methods in glass tubes, can be used to obtain the data. Previous data on this phenomenon can be used for comparison and to verify the mpirical model. The results of this task will be an assessment of the potential influence of turbulent flow and mixing in long-term storage system due to thermal acoustic oscillations.

Task 3

Oscillation characteristics measurements can be made using the existing hardware but with new tube penetrations which have curved and coiled geometries. Both U-tube and S-tube configurations could be tested to obtain data for application to space storage systems with large length/diameter ratio penetrations. The results of this task will be a systematic procedure whereby designers can use known system parameters to accurately evaluate thermal acoustic oscillations in specific storage systems.

Task 4

This task would provide a refined engineering analysis and simplified analytical prediction procedure for thermal acoustic oscillations. The procedure should incorporate a systematic dimensional analysis with semi-empirical data correlations which can be used by designers in performing a thermal acoustic oscillations evaluation of a specific configuration. The effects of ullage pressure need to be taken into account in the analytical correlation equations. This appears to be the major inaccuracy in the analytical equations.

1.6 REPORT CONTENTS

Section	Page	Description
2.1	2-1	The overall procedure that was followed in obtaining the experimental data is given.
2.2	2-1	The test apparatus and instrumentation that were used are described. Photographs and drawings of the hardware are given and calibration curves for the instruments are discussed.
2.3	2-5	A discussion of the parameters that were measured and a list of those system parameters that were varied is given. The procedure for measuring each parameter is also described.
2.4	2-19	This section contains a summary of the data reduction procedures.
2.5	2-19	A summary of the data for oscillation frequency, amplitude and boiloff rate is given in curve form. Experimental problems and anomalies which arose are also presented.
3.1	3-1	The approach for obtaining analytical correlation equations is discussed with the model parameters and assumptions being defined.
3.2	3-3	This section presents a derivation of the engineering correlation equations.
3.3	3-9	Comparisons of theory versus data are made for oscillation frequency, amplitude and boiloff rate. Limitations on the model are discussed and reasons for discrepancies are speculated.
3.4	3-15	A list of improvements that could and should be made to the analytical model is given.
4	4-1	A summary of conclusions resulting from the study constitutes Section 4.
5	5-1	This section contains a recommended list of items that should be pursued to provide a more complete understanding of the problem. Methods for suppressing the oscillations should receive primary emphasis.

6	6-1	A bibliography of literature on the subject of thermal acoustic oscillations.
Appendix		
A	A-1	A thermal acoustic oscillations data book is given that contains plots of all of the data taken in this study.

2. EXPERIMENTAL PROGRAM

2.1 TEST PROCEDURES

The general testing procedure used in this study was to insert test tubes of various sizes into liquid helium dewars and measure the effects on thermal acoustic oscillations (TAO) caused by varying the insertion depth. The tubes were initially inserted to a depth that would be just deep enough to cause oscillations and then backed up until the oscillation stopped. At this point data were taken to establish baseline, "no TAO," values of boil-off rates. (Static, no-tube values were also usually obtained.) Then the tube was lowered into the dewar in steps and data were taken at each step until the tube was well into the liquid helium.

In general, the following parameters were measured:

- TAO pressure amplitude
- TAO frequency
- Boiloff rates
- Dewar ullage space pressure
- TAO wave forms
- LHe liquid level

In addition, temperatures along the length of the tubes were measured in some cases. These measurements were not made on all tests, depending on the test purpose and availability of instrumentation. In general, the measurements were improved and added as the program progressed.

2.2 APPARATUS

Figures 2-1, 2-2 and 2-3 show the general laboratory setup used for these tests. Each of the individual pieces of equipment are pointed out on

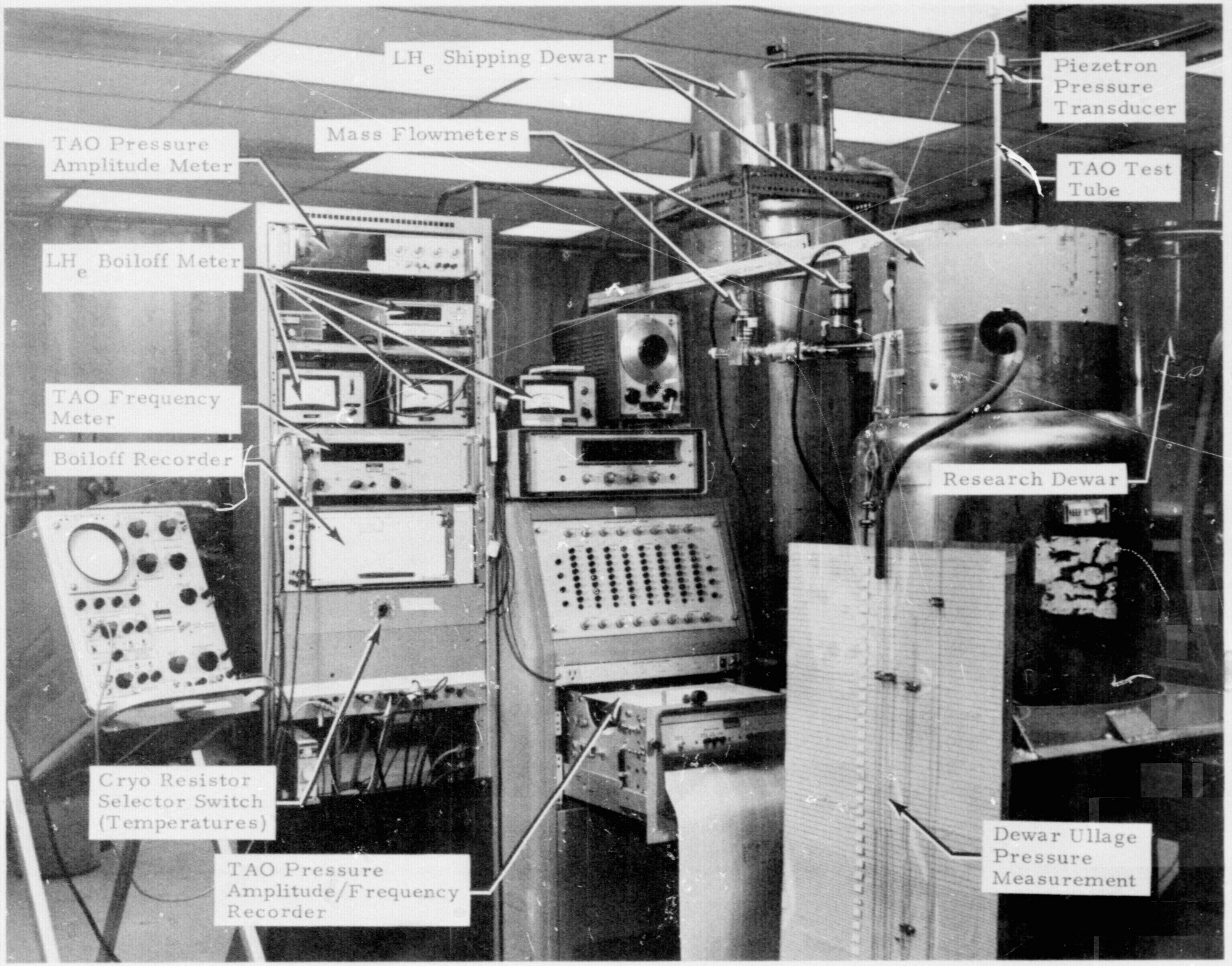


Fig. 2-1 - Thermal Acoustics Oscillations Laboratory Instrumentation Setup (View 1)

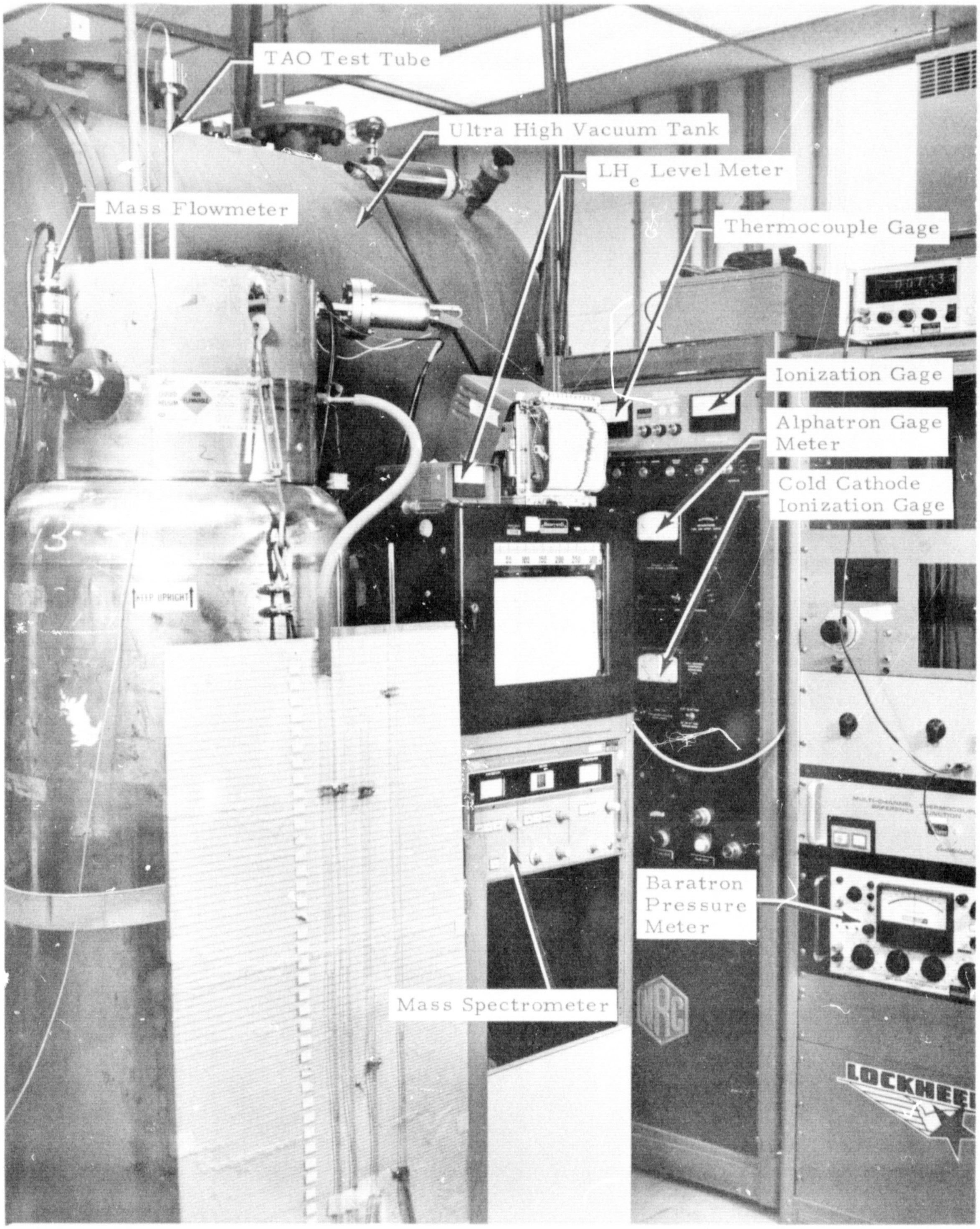


Fig. 2-2 - Thermal Acoustics Operation Laboratory Instrumentation Setup (View 2)

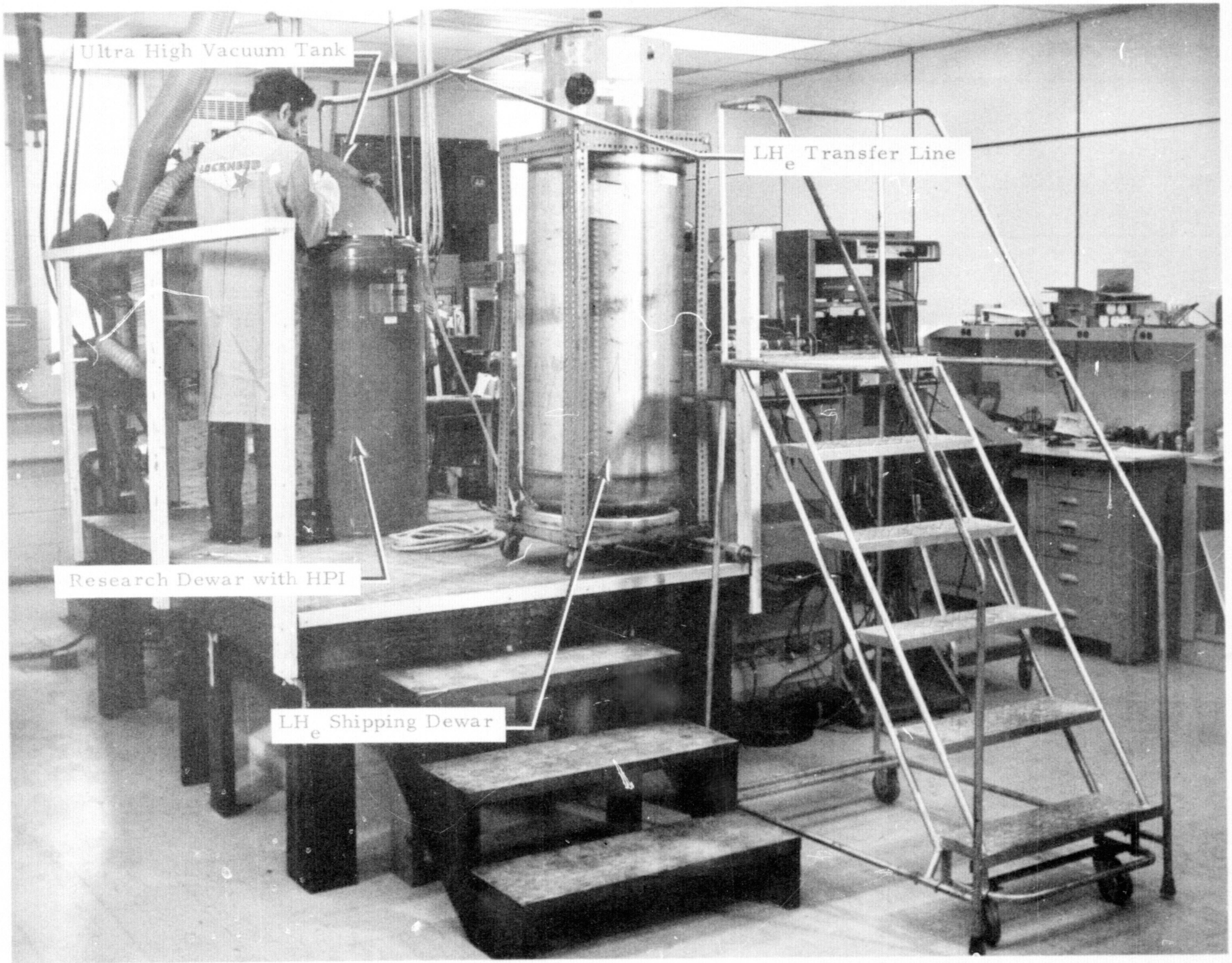


Fig. 2-3 - Thermal Acoustics Oscillations Laboratory Setup Showing Liquid Helium Transfer these figures. Tests were conducted in two types of LHe dewars. The first used was a model SD-10 research dewar made by Cryogenics Associates, Inc. Some problems were encountered with this dewar in the test program, in that the static boiloff rate of the dewar went up drastically. This was apparently due to loss of hard vacuum in the superinsulation jacket of the dewar. Attempts were made to pump the pressure down but were not successful. Therefore, the last part of the test program was conducted using the shipping dewars in which the LHe was received from Linde. Special fittings were made to allow various tube diameters to be tested up to 0.5 in. Continuous liquid level measurements were not possible on the shipping dewar as with the research dewar. These level measurements had to be made before and after the tests which proved to be satisfactory. These dewars are shown on the photos of Figs. 2-1 and 2-3. Figure 2-4 shows an approximate scale sketch of the research dewar with dimensions, specifications, etc. Figure 2-5 shows a similar sketch for the shipping dewar. Also shown are the measurements defining L_c and L_H, the "cold" and "hot" length of the test tubes.

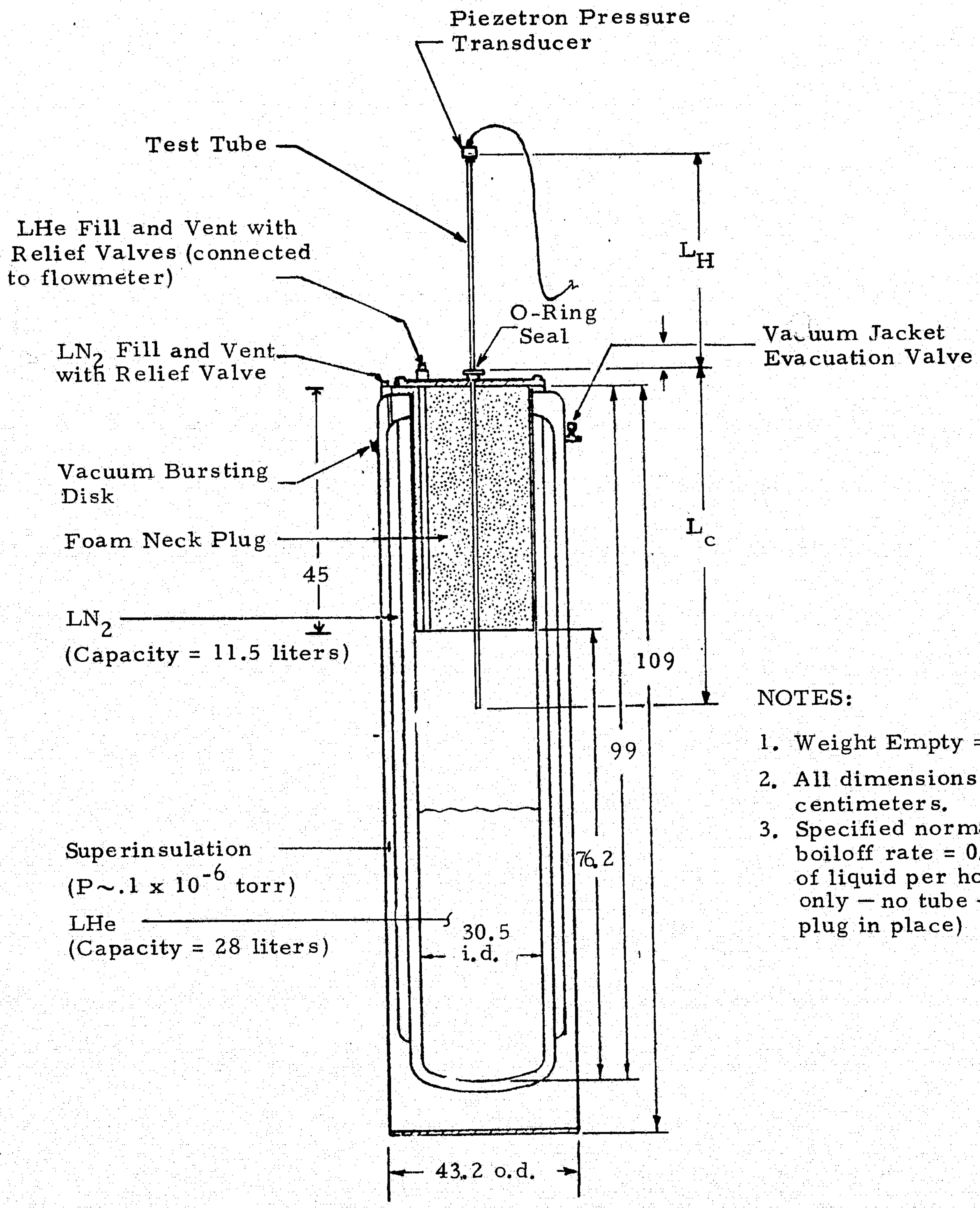
A number of tubes were tested. The details of these tubes are all given in Table 2-1. All tubes tested were type 304 stainless steel. Some tubes were instrumented for temperature measurements as shown in Table 2-1 and are discussed later.

2.3 PARAMETER MEASUREMENT

The following sections discuss the details of how the various parameters were measured.

2.3.1 Tube Temperature Measurement

Chromel/alumel thermocouples were used to measure tube temperatures in the "warm" regions. Carbon resistors were used for temperature measurements in the "cold" regions. Lead wires to these were potted in place inside slots which were milled in the tube walls. This was required



NOTES:

1. Weight Empty = 115 lb
2. All dimensions are in centimeters.
3. Specified normal static boiloff rate = 0.27 liters of liquid per hour. (dewar only — no tube — with neck plug in place)

Fig. 2-4 - Cryogenics Associates Model SD-10 Liquid Helium Research Dewar

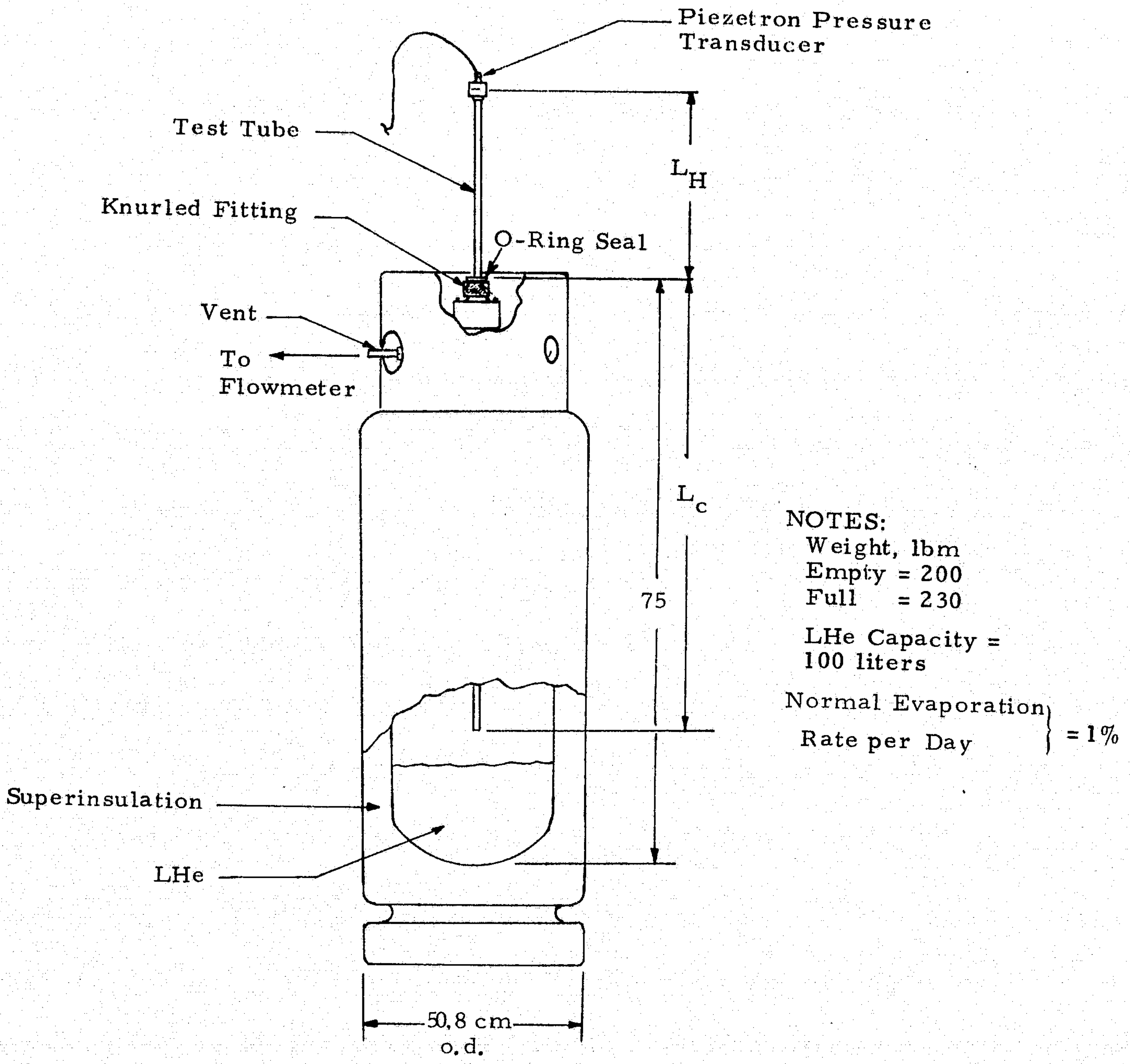


Fig. 2-5 - Linde LSHe-100 Liquid Helium Shipping Dewar

TABLE 2-1. SUMMARY OF ALL TEST TUBES USED

Tube No.	Wall Thickness		Outside Diameter		Inside Diameter		Length		Length to Inside Diameter Ratio	Instrumented for Temperature Measurements
	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)		
1a	.058	.147	.375	0.953	.258	.657	77.6	197.0	300	No
1b	.028	.071	.315	0.800	.258	.657	77.6	197.0	300	No
1c	.064	.162	.375	0.953	.247	.627	77.6	197.0	314	No
2a	.058	.147	.375	0.953	.258	.657	39.0	99.0	150	Yes
2b	.058	.147	.375	0.953	.258	.657	39.0	99.0	150	No
3a	.058	.147	.375	0.953	.258	.657	26.0	66.0	100	Yes
3b	.058	.147	.375	0.953	.258	.657	26.0	66.0	100	No
4	.019	.048	.125	0.318	.280	.711	43.3	110.0	155	No
5a	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	Yes
5b	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	No
5c	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	No
6a	.058	.147	.375	0.953	.258	.657	58.3	148.0	225	Yes
6b	.058	.147	.375	0.953	.258	.657	58.3	148.0	225	No
6c	.064	.162	.375	0.953	.247	.627	58.3	148.0	236	No

Note: All tubes are type 304 stainless steel.

to get the leads out of the dewar and still maintain a seal at the top O-ring fitting so that boiloff would not escape through the flow meters.

The carbon resistors were calibrated to liquid helium temperature by dipping them into the dewar together with two germanium "standard" cryoresistors. The mounting arrangements of some of these carbon resistors in the calibration fixture are shown on Fig. 2-6. These carbon resistors are standard 100 ohm, Ohmite brand of the types used in radio/television circuits. They are inexpensive and gave sufficient accuracy for the purposes of this test. For a discussion of the use of such resistors for cryogenic temperature measurements, see Ref. 6. A typical calibration curve of one of these resistors is shown in Fig. 2-7. Figure 2-8 shows a calibration curve for one of the germanium cryoresistors. Table 2-2 shows the location of thermocouples and carbon resistors for each tube that was instrumented.

2.3.2 TAO Pressure Amplitude and Frequency Measurement

Piezotron dynamic pressure transducers were used for measuring TAO pressure amplitude and frequency. These were made by the Kistler Company (Model 206). They were calibrated by Kistler and checked by Lockheed inspection when they were purchased from Kistler for the previous study (Ref.30). This calibration was checked again by Kistler before the transducers were used during this study. Table 2-3 gives the specifications for the transducers.

These transducers were mounted on the upper end of each test tube by specially designed adjusters for various diameter tubes. Figure 2-9 shows a typical cross section of one of these adjusters.

The output of these transducers was fed to four sources for recording. These were: (1) Brush recorder; (2) true root-mean-square meter; (3) a frequency counter, and (4) an oscilloscope. The Brush recorder gave the waveform, the true root-mean-square meter gave the rms value of

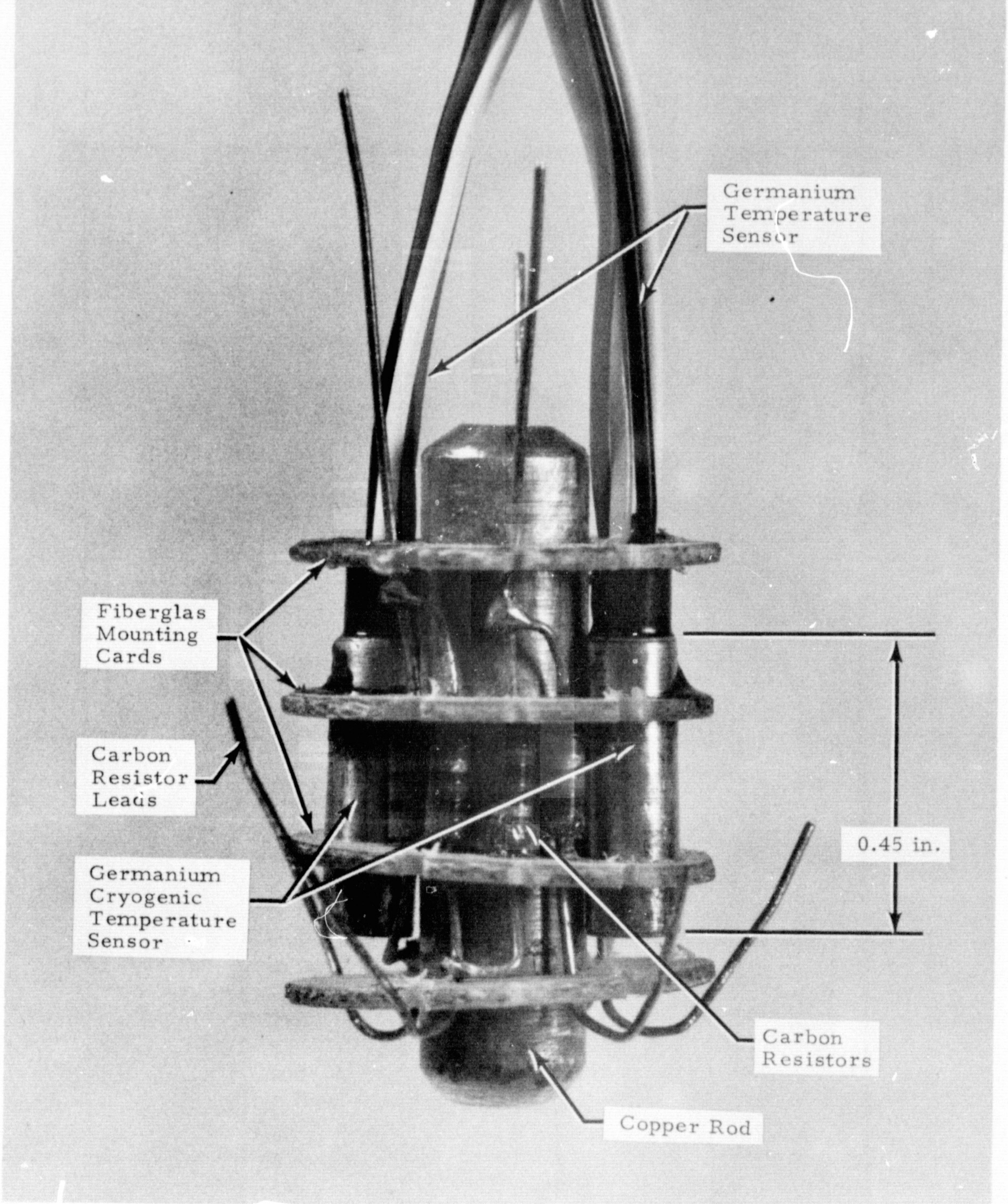


Fig. 2-6 - Mounting Arrangement of Carbon Resistors in Calibration Fixture

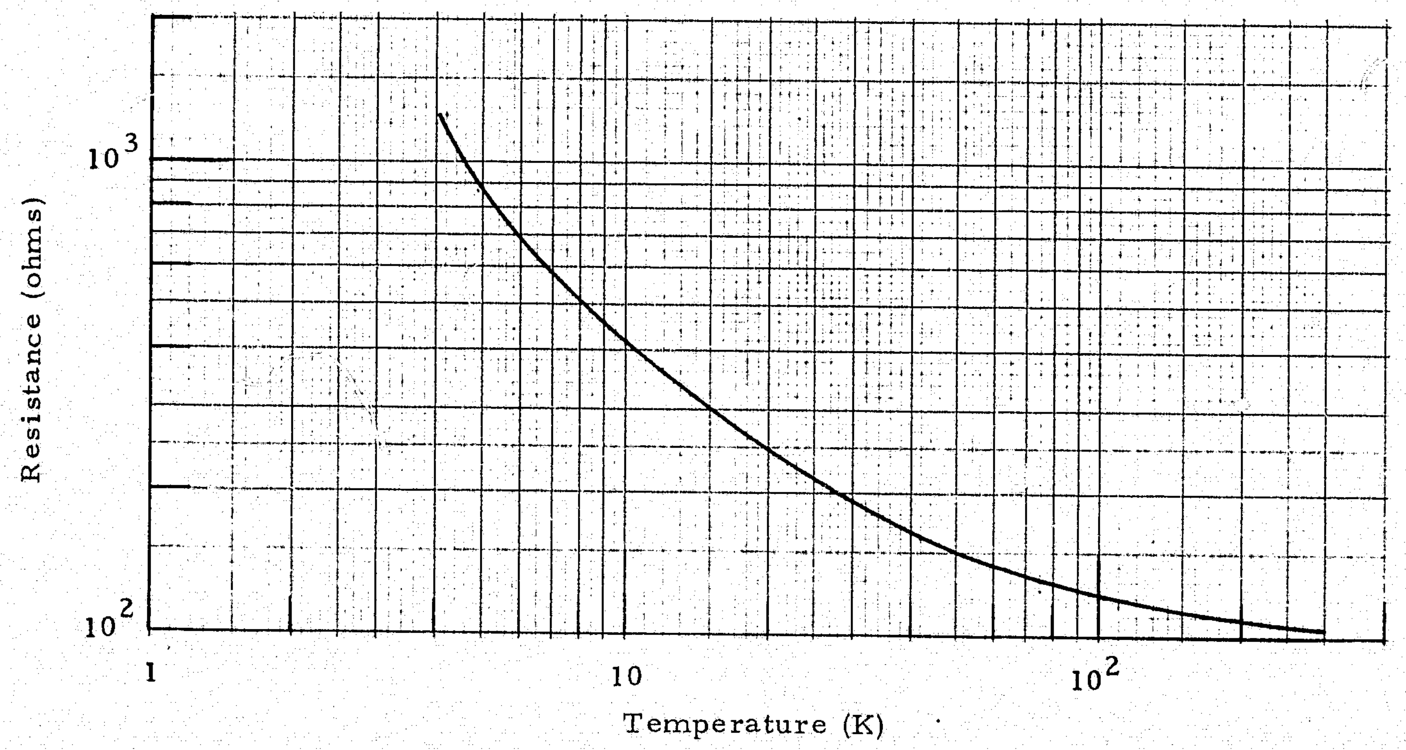


Fig. 2-7 - Typical Calibration Curve for Carbon Resistors

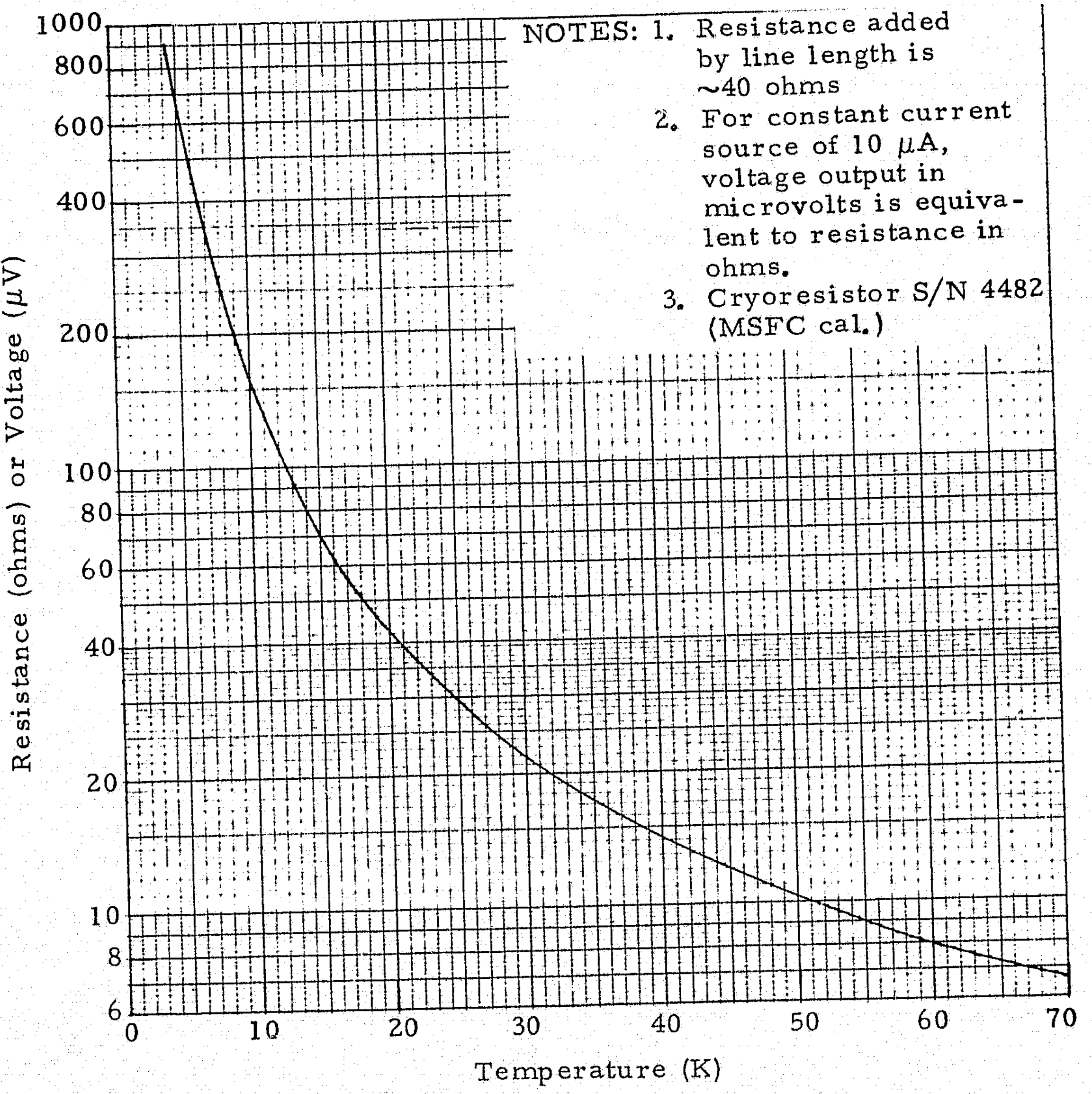
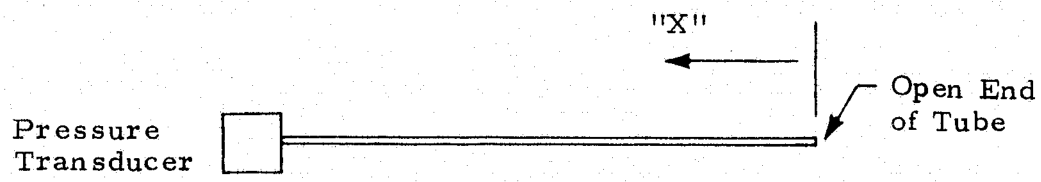


Fig. 2-8 - Calibration Curve for Cryoresistors

TABLE 2-2. LOCATION OF THERMOCOUPLES AND CARBON RESISTORS FOR EACH TUBE



Tube	"X" Inches							
1a, 1b	.25 △	10 △	20 △	27 ●	34 ●	45 ●	55 ●	65 ●
2	.25 △	10 △	20 △	27 ●	34 ●			
3	.25 △	8 △	16 △	23 ●				
4	.25 △	10 △	20 △	26 ●	32 ●	38 ●		
5	.25 △	10 △	20 △	27 ●	34 ●			
6	.25 △	10 △	20 △	27 ●	34 ●	45 ●	55 ●	

△ Location of Carbon Resistor

● Location of Thermocouple

TABLE 2-3. PIEZOTRON TRANSDUCER SPECIFICATIONS

Pressure Range	5.62 kg/cm^2
Resolution	5.62 x 10^{-5} kg/cm^2
Sensitivity	1715 mV/kg/cm^2
Linearity	$\pm$1% full scale
Rise Time	3 μsec
Low Frequency Time Constant	2.5 sec
Full Scale Output Voltage	8.0 V
Low Frequency Response	0.05 Hz
High Frequency Response	20 kHz

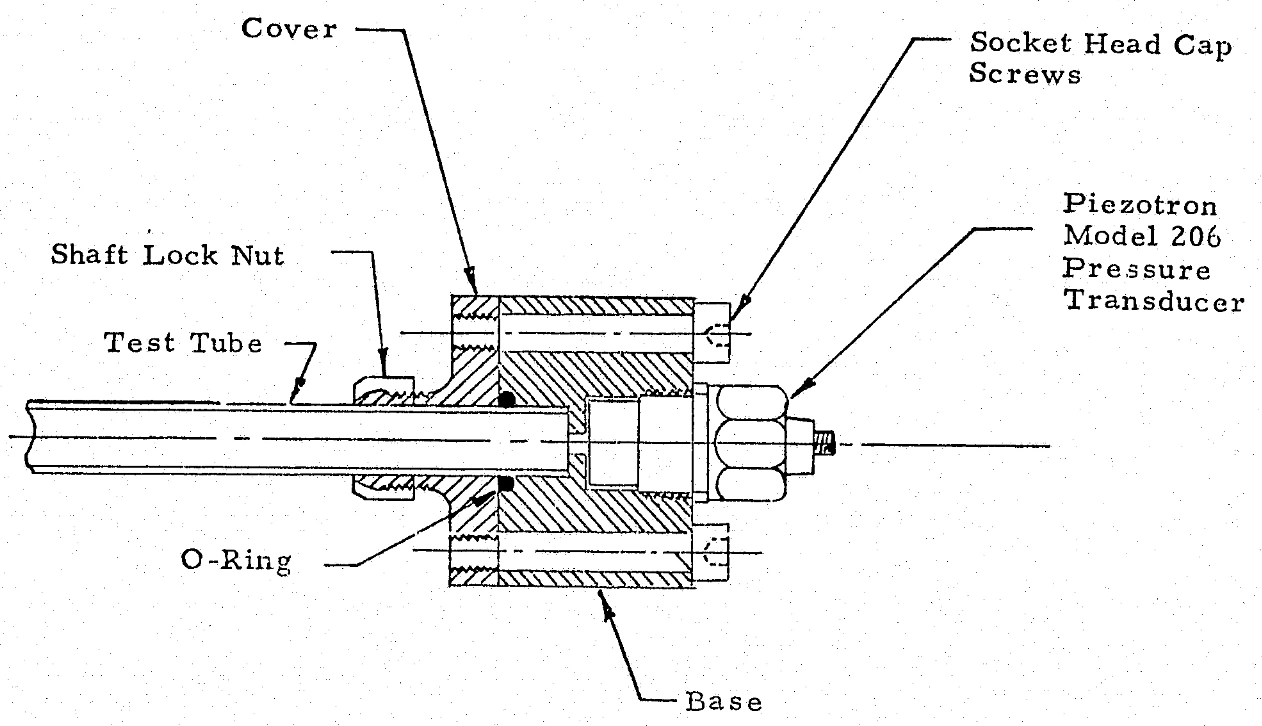


Fig. 2-9 - Schematic of Modified Ballistic Mount for Piezotron Model 206 Pressure Transducer the pressure amplitude (in volts) and the frequency meter gave a digital readout of the TAO frequency in Hertz. The oscilloscope gave a continuous monitoring of TAO amplitude and waveform, and was used for detecting onset of oscillations, etc.

2.3.3 Boiloff Measurement

Three different flowmeters were used for measuring gaseous helium boiloff rates. Three were required to cover the large range of boiloff rates encountered, which cover a range from 100 to 60,000 sccm of GHe. These flowmeters were all Hastings-Raydist (linear mass meter type), and were calibrated by personnel at the NASA-MSFC Calibration Laboratory. Model numbers and calibration curves are shown in Figs. 2-10, 2-11 and 2-12. Output of these meters was read on their dial-face meters, on a digital voltmeter, and recorded on a stripchart recorder.

2.3.4 Liquid Level Measurements

The LHe level in the research dewar was monitored using an NbTi filament snesor which gave a continuous reading of percent liquid level throughout the tests. For the shipping dewar, however, test measurements could be made only before and after the tests. This was done using a cryoresistor mounted on the end of a small fiberglass probe.

2.3.5 Dewar Ullage Pressure Measurements

These measurements were made using a simple water-filled "U-tube" manometer.

2.3.6 Schematic of Setup

Figure 2-13 shows a line schematic of the integrated test setup data system.

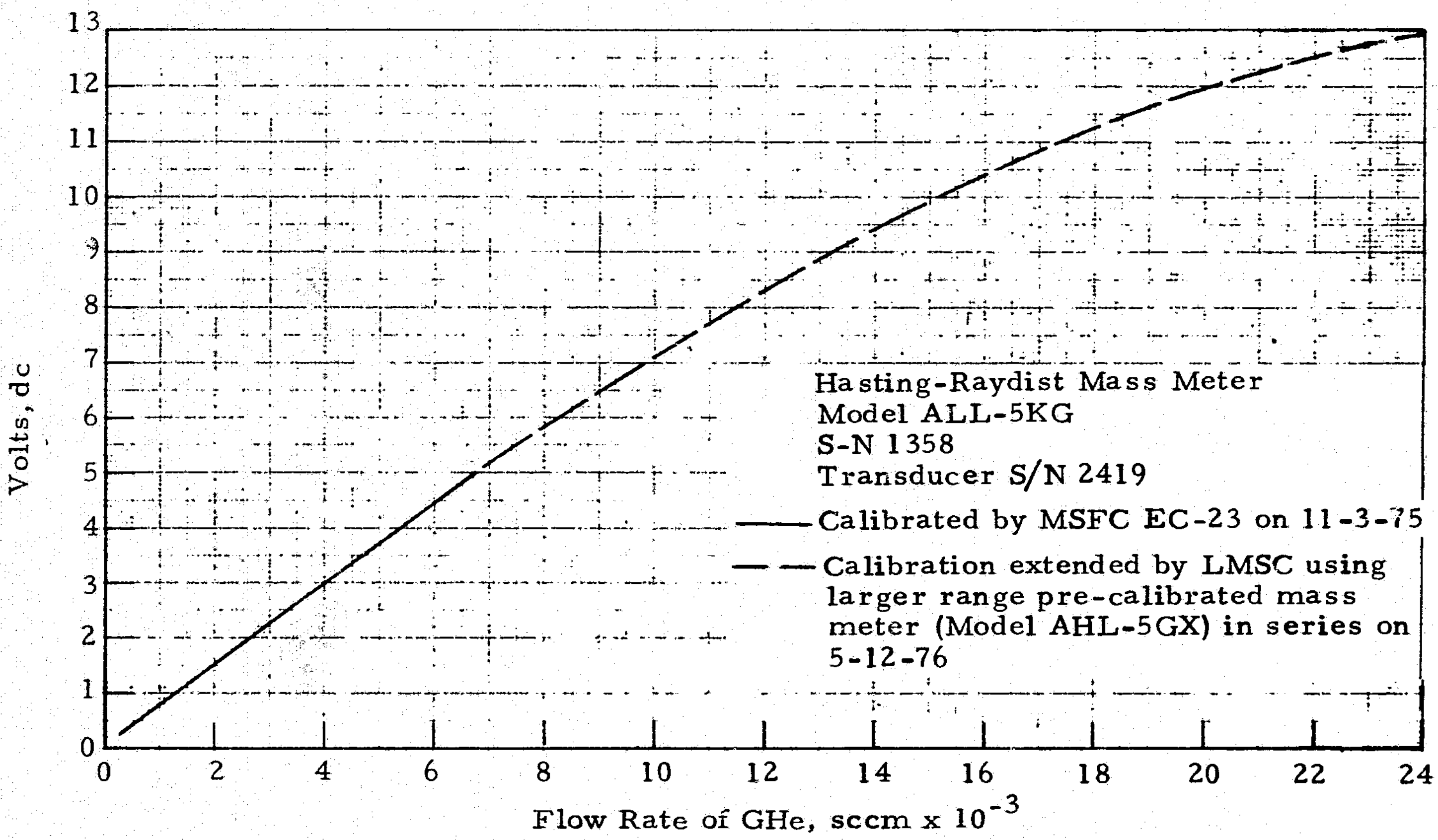


Fig. 2-10 - Flowmeter Calibration Curve

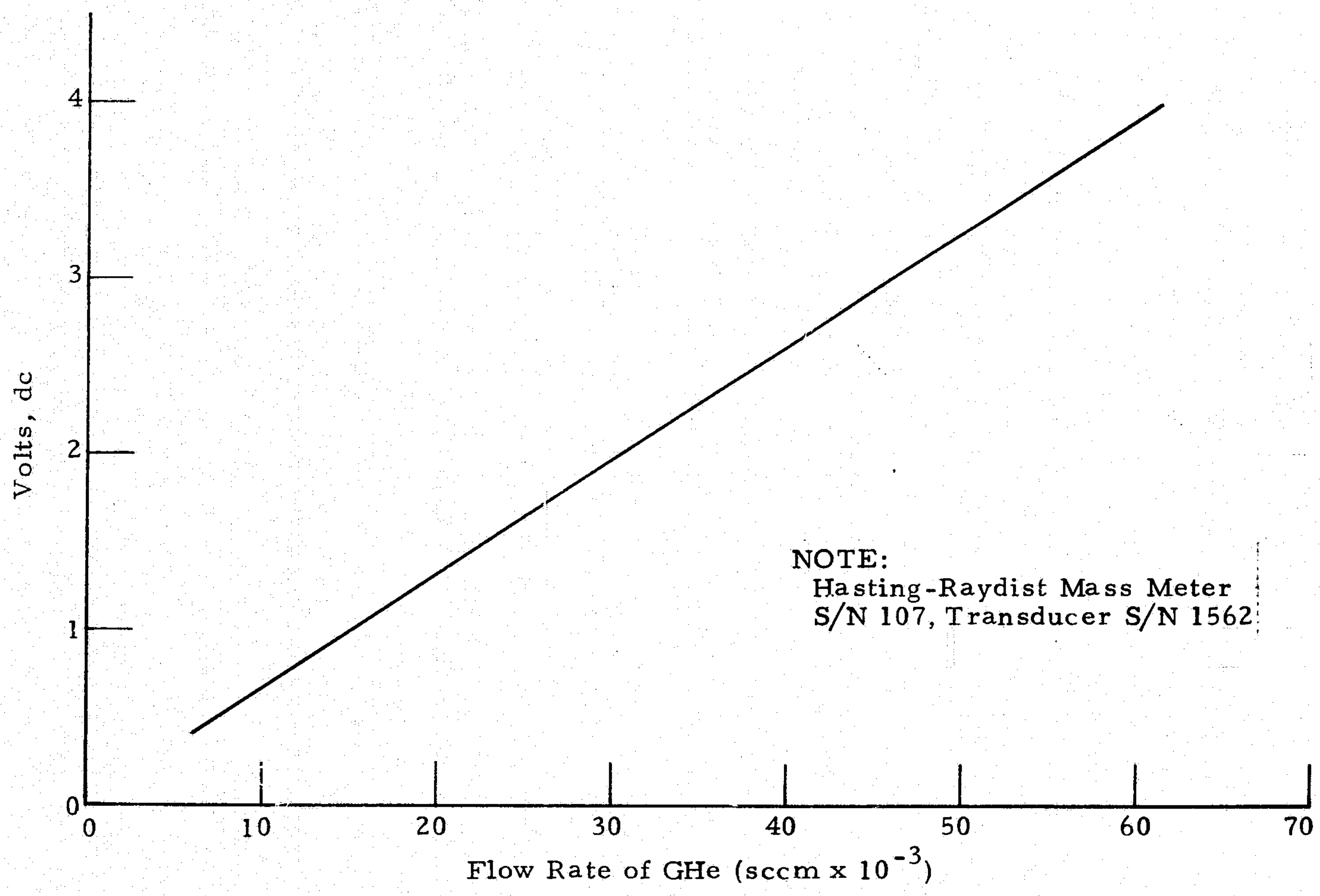


Fig. 2-11 - Flowmeter Calibration Curve (Model AHL 56X)

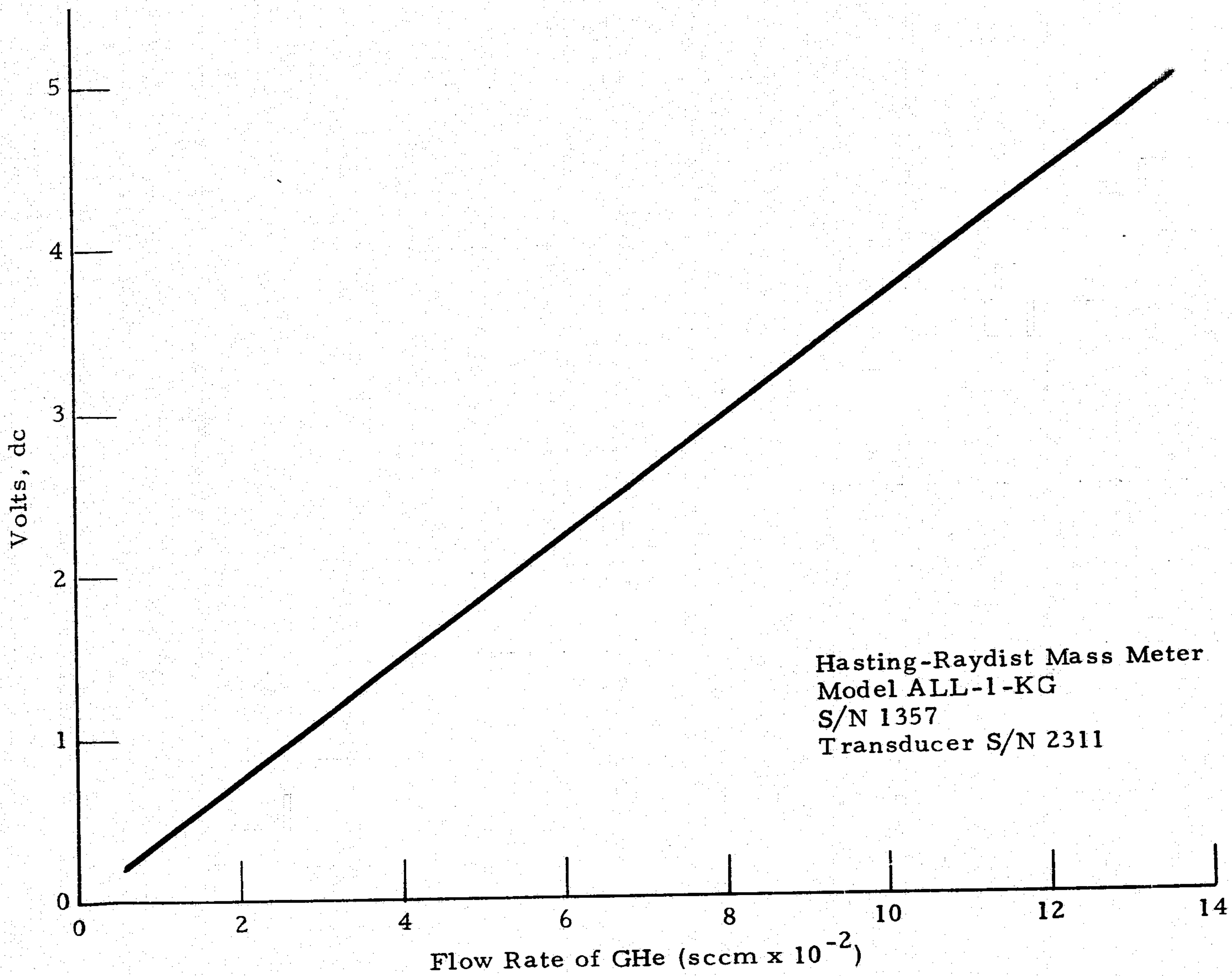


Fig. 2-12 - Flowmeter Calibration Curve

2.4 DATA REDUCTION METHODS

2.4.1 TAO Frequency and Amplitude

Frequency was read in Hertz directly off the digital voltmeter and plotted. Amplitude was measured primarily by the true rms digital voltmeter and converted to peak-to-peak amplitudes for plotting. This was done using the following relationship:

$$\text{rms} = \frac{\text{peak-to-peak}}{2} (.707)$$

This assumes a sine wave form of the TAO that was checked on the oscilloscope and Brush recorder and found to be a good assumption.

2.4.2 Boiloff Data Reduction

The boiloff data were read in volts and converted to standard cubic centimeters per minute of GHe by the calibration curves. Net boiloff rates due to TAO only were obtained by subtracting the boiloff rate with the tube inserted into the dewar but with no oscillations.

2.4.3 Temperature Data Reduction

Standard thermocouple tables and the carbon resistor calibration curves were used for temperature data reduction.

2.5 DATA SUMMARY

Typical TAO waveform data from the Brush recorder are shown in Fig. 2-14. Almost all the data showed very regular waveforms such as these

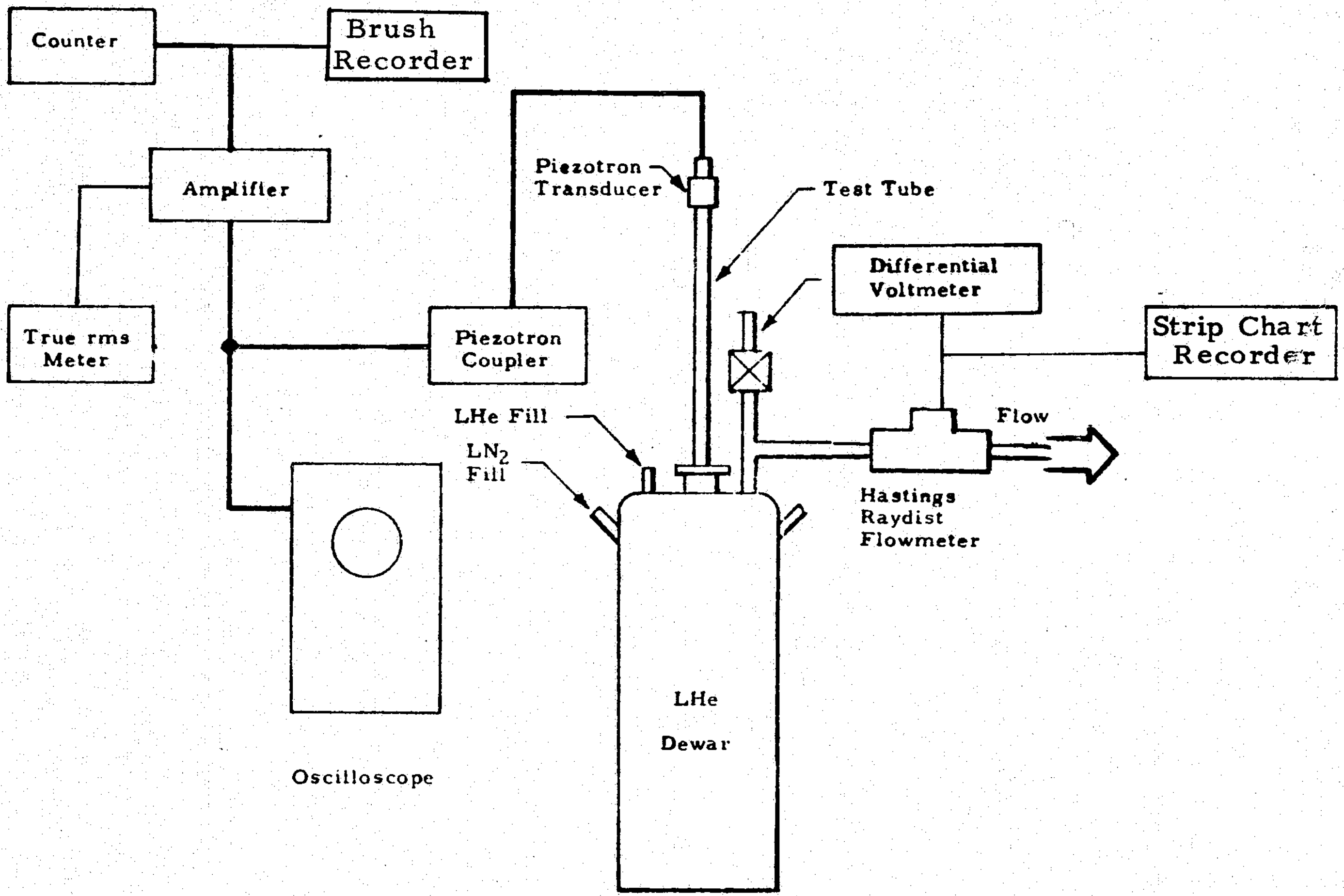


Fig. 2-13 - Schematic of TAO Test Hardware

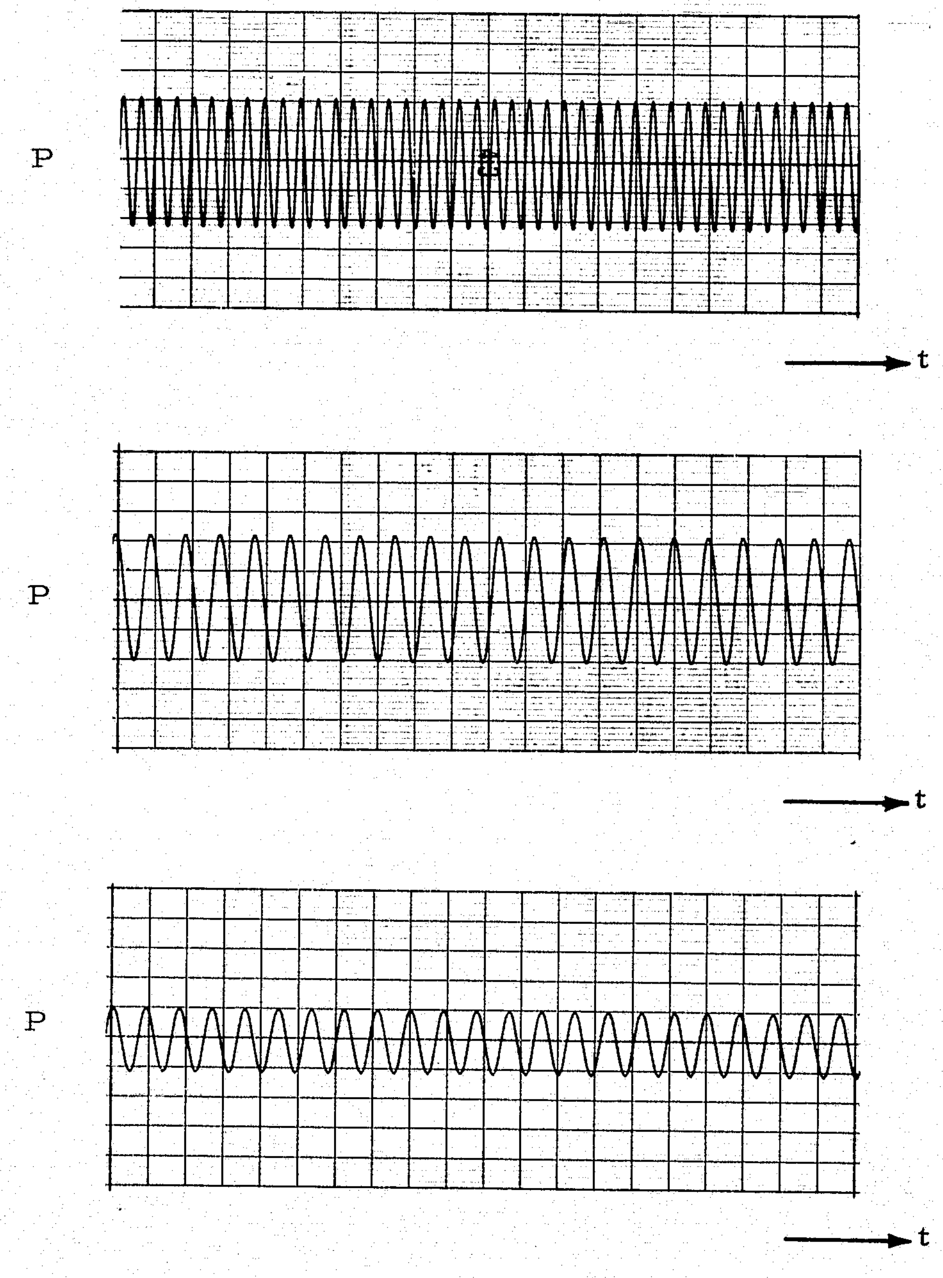


Fig. 2-14 - Raw Pressure Data Readout on BRUSH Recorder (Three different L_c values for L/D = 225, Stainless Steel tube) except in unstable regions when tubes were just being lowered into the dewar and oscillations were just beginning.

Figures 2-15 and 2-16 show typical TAO pressure amplitude and frequency results. These are plotted versus L_c, cold length of the tube. As these figures show, it is obvious that the data did not repeat when the same tube was run on a different day. This indicates that other variables in addition to L_c affect the TAO results. It was not determined during the phase of the testing precisely what these variables are or their effect on oscillations. However, candidate variables are: (1) ullage pressure; (2) liquid level; (3) ullage volume; and (4) time since the tests were initiated.

Typical boiloff results are shown in Fig. 2-17 where boiloff rate is plotted versus $P_A^2\ f^{1/2}$. Considerable scatter is evident in these data, which is typical of the data taken. The scatter is believed to be due more to some unknown coupling than to data accuracy problems, because great care was taken to get the data to repeat and it just did not come out this way. Because of this, it was concluded that other variables affect the results in addition to P_A and f. Also it is noted that the TAO phenomena seem to be a transient, time dependent phenomena, whereas attempts were made to study it as a "steady state" and this state was sometimes difficult to establish or define. Also there appears to be some possibility of "coupling" or resonance between the tube and ullage volume. This was especially true of tube 4.

Attempts were made also to correlate boiloff rate versus oscillation intensity but this did not correlate well at all.

Intensity versus L_c correlations were attempted also, and typical data of this type are shown in Fig. 2-18.

Typical temperature data are shown on Figs. 2-19 and 2-20. Figure 2-19 is a temperature distribution down a tube for various positions of the tube in the research dewar (with neckplug inserted). Figure 2-20 shows the variation of

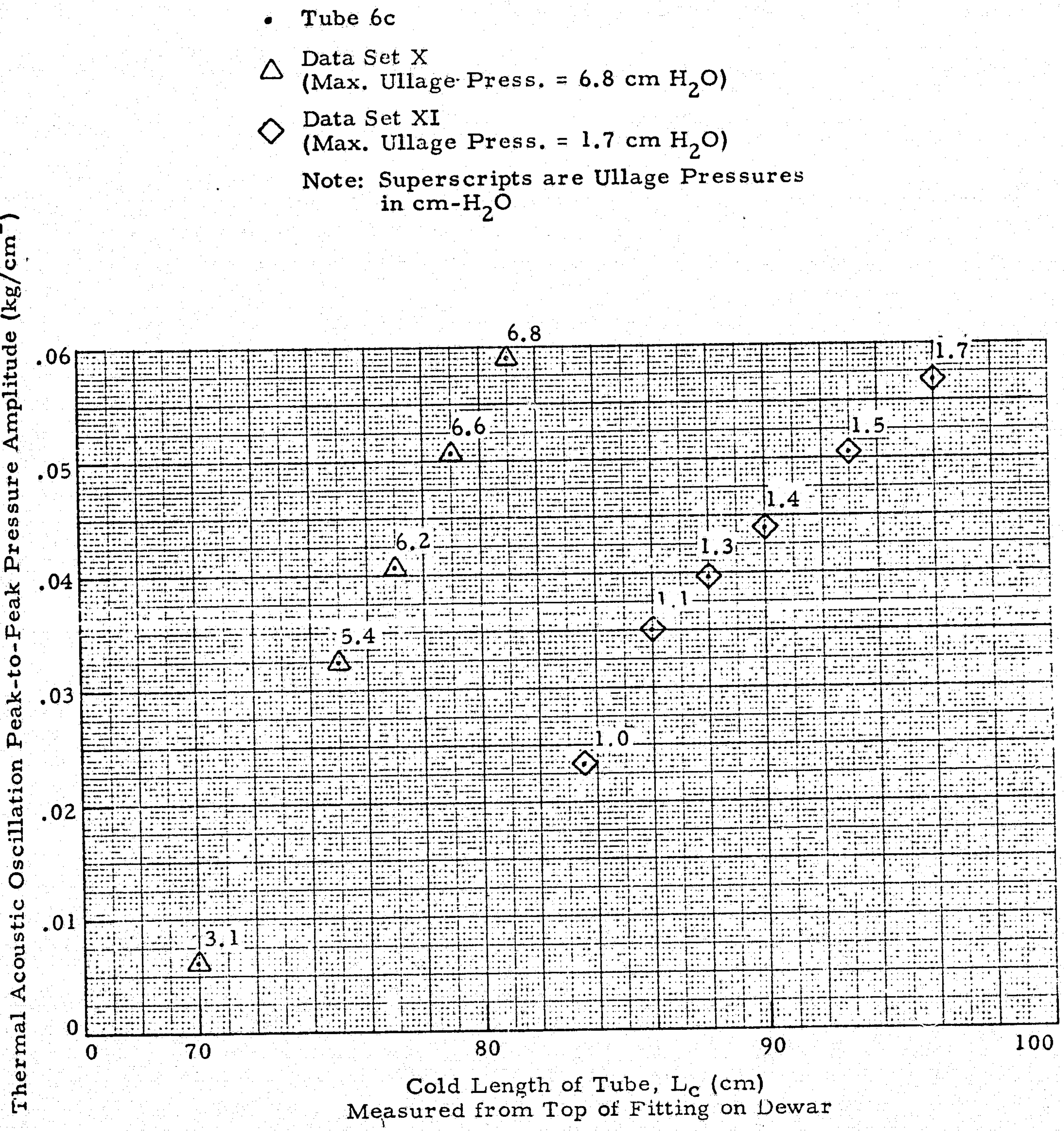


Fig. 2-15 - Pressure Amplitude vs Cold Length of Tube for Tube 1c at Two Different Ullage Pressure Ranges

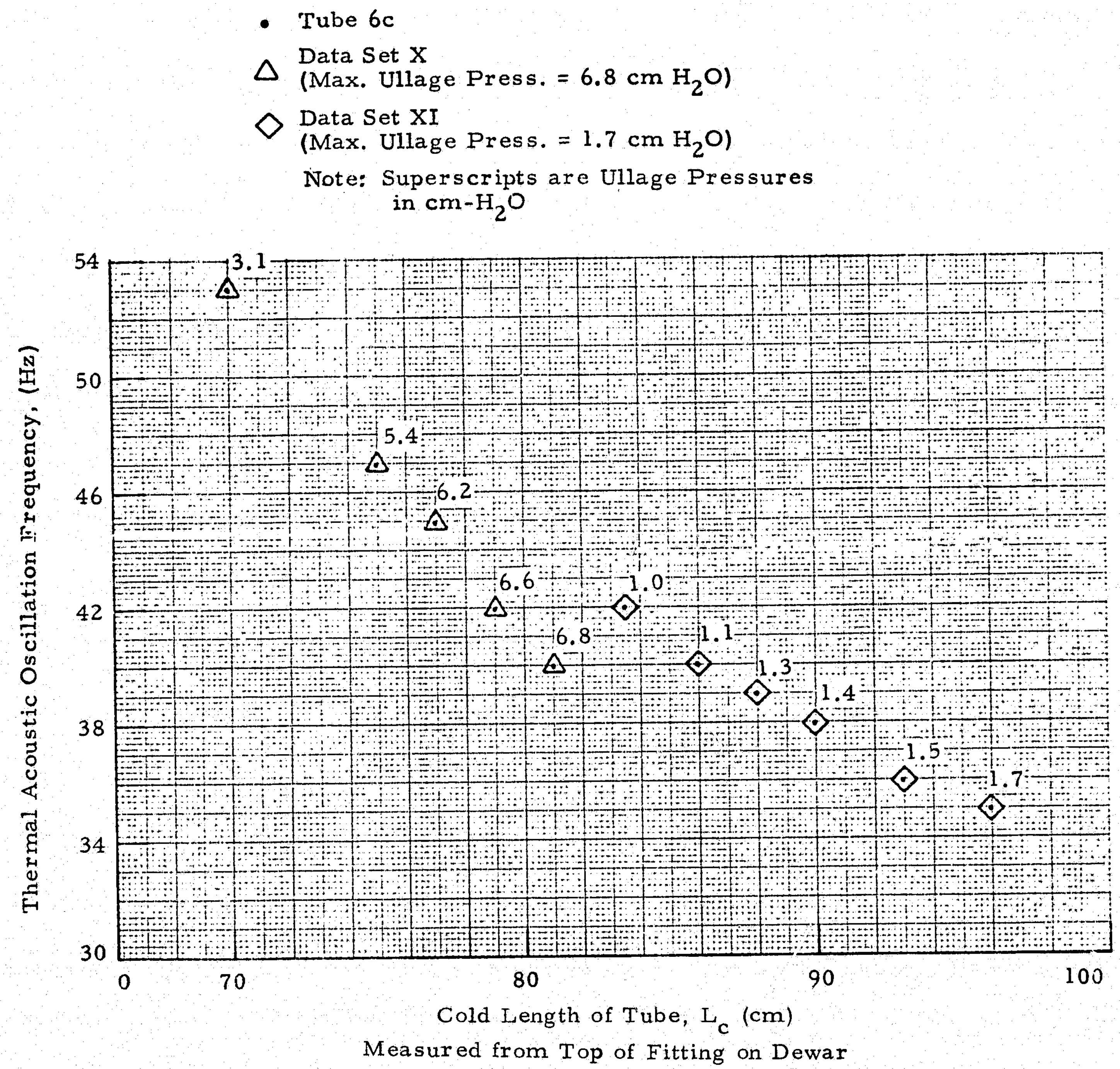


Fig. 2-16 - Frequency vs Cold Length of Tube, for Tube 1c at Two Different Ullage Pressures

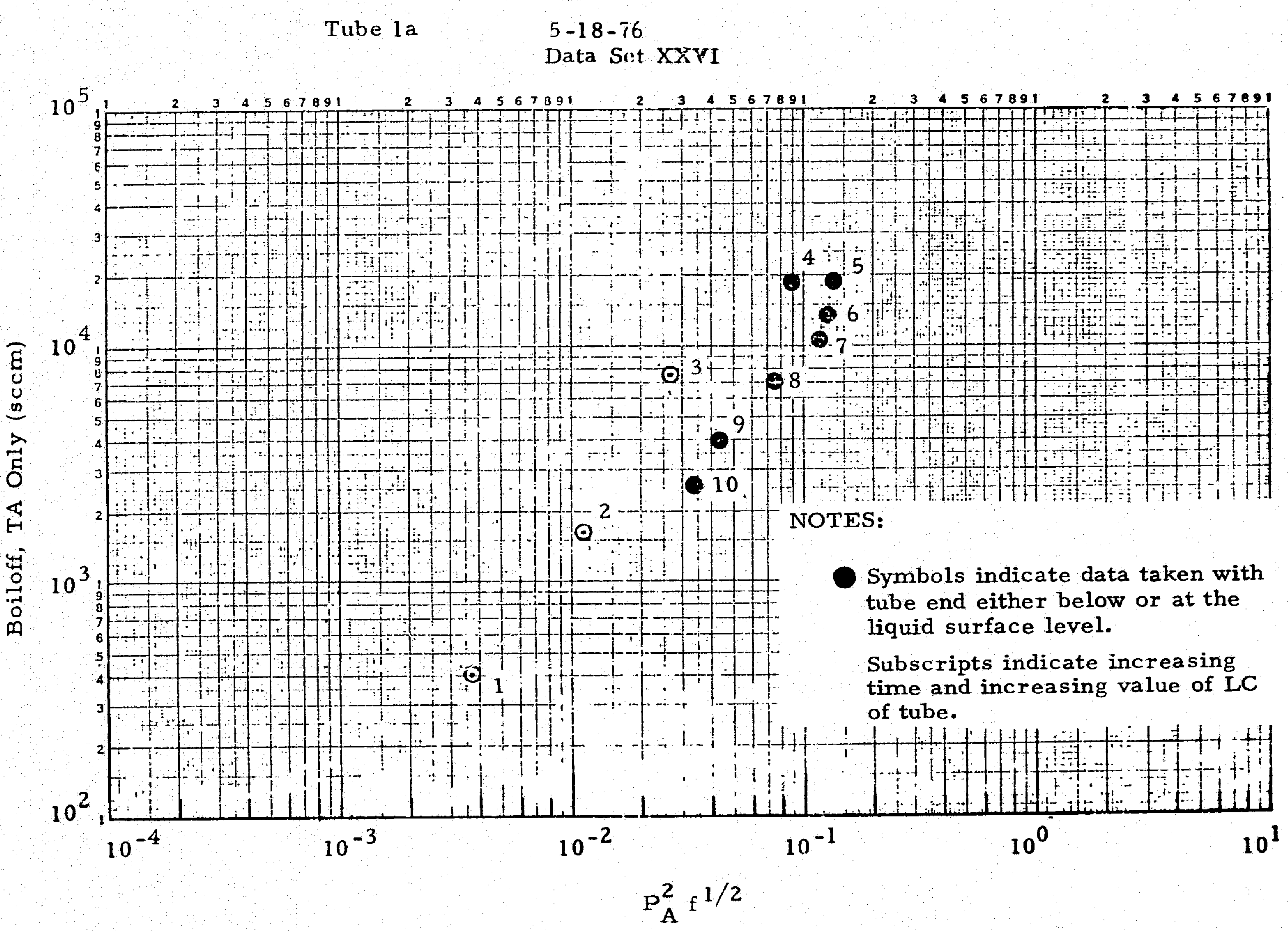


Fig. 2-17 - Boiloff Data vs $P_A^2\ f^{1/2}$

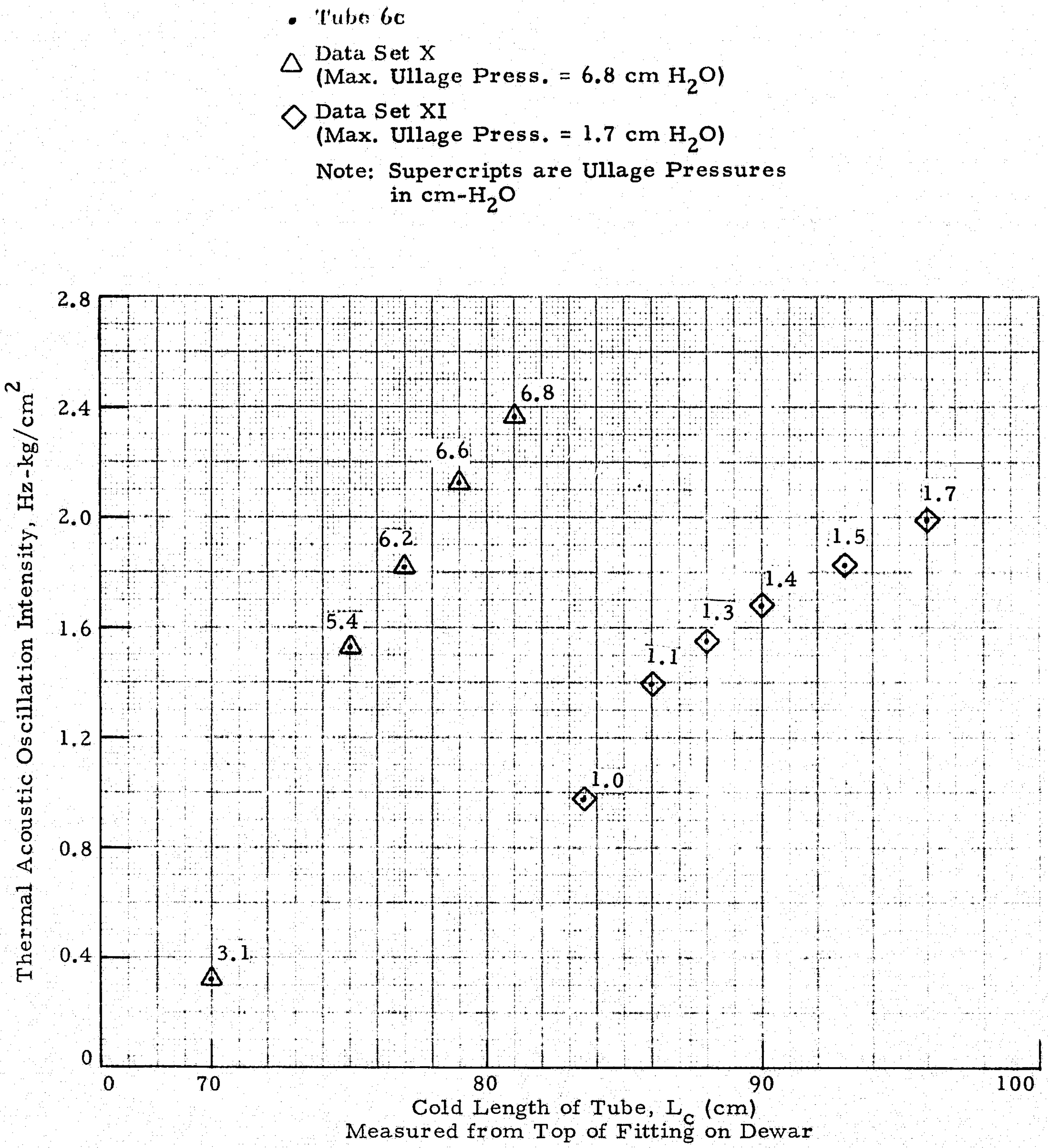


Fig. 2-18 - Intensity vs Cold Length of Tube for Tube 1c at Two Different Ullage Pressures

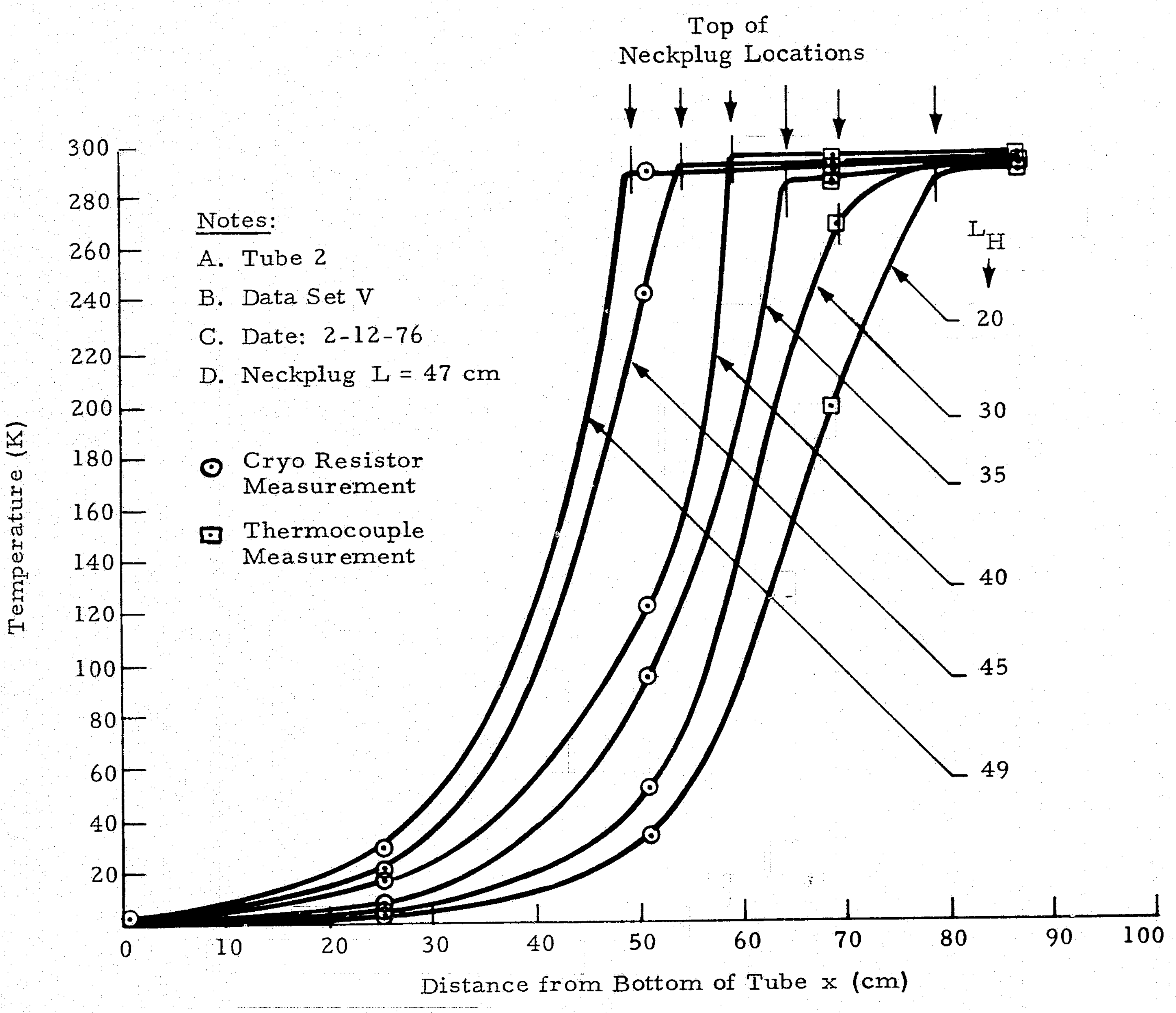


Fig. 2-19 - Tube Temperature vs Distance from Cold End for Tube 2

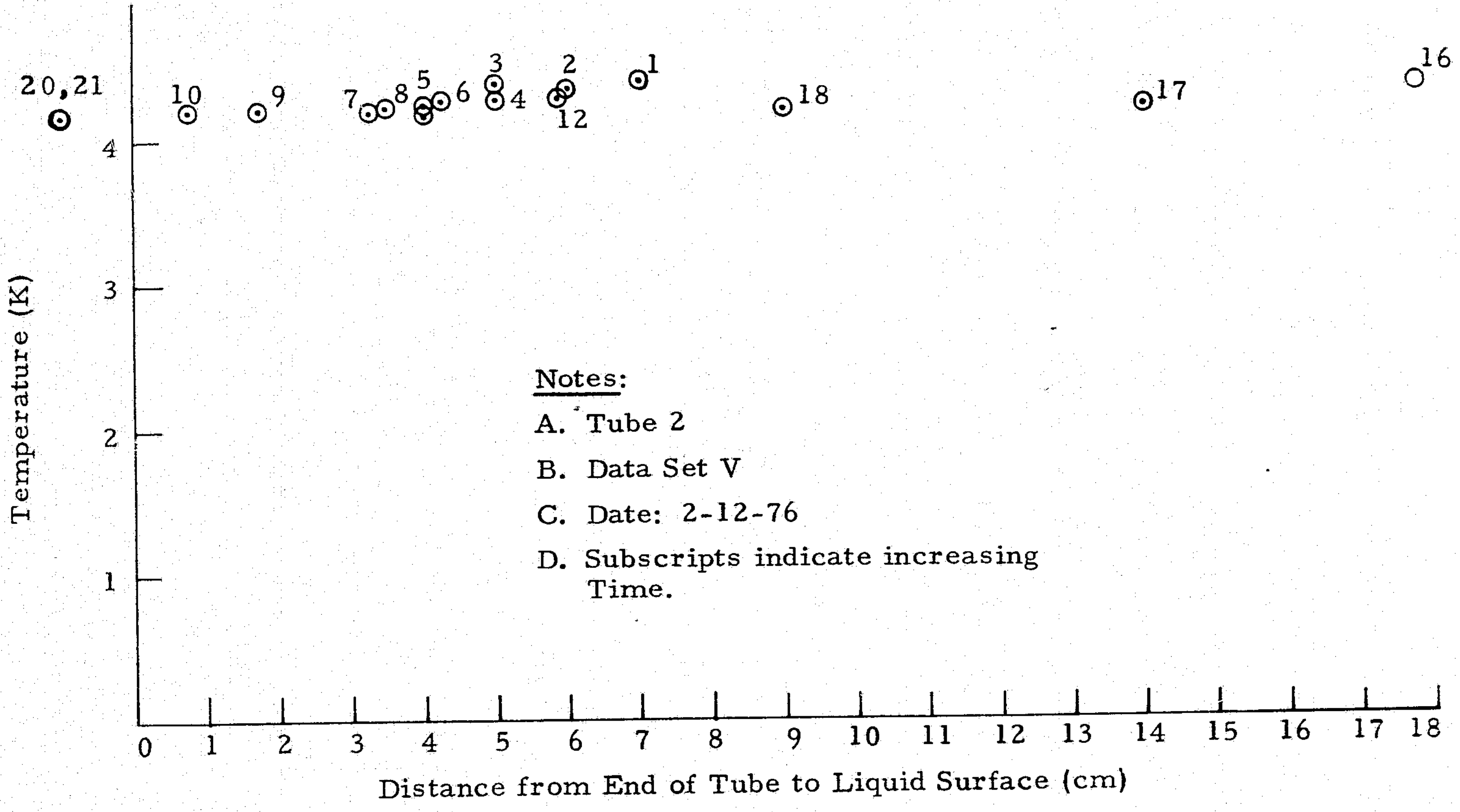


Fig. 2-20 - Temperature of Tube at Resistor D_1 Location vs its Distance from Liquid for Tube 2. (Resistor D_1 was located .25 inches from end of tube).

the temperature of the end of a tube as it is moved up and down inside the ullage space. This being virtually constant is a surprising result since earlier correlations had shown a greater variation of tube temperature versus distance from the liquid surface.

A complete set of all data taken is given in Appendix A.

Since there appeared to be an effect of ullage pressure on TAO, an attempt was made to determine this effect. The following procedures were used:

- The vent on the dewar was plugged and a tube was inserted in the dewar to cause boiloff of liquid and to increase ullage pressure.
- Ullage static pressure and true rms TAO amplitude were monitored until ullage pressure came up to ~35 cm H_2O. (Try 1).
- The plug on the dewar vent was removed and pressure was released rapidly. Both pressure and amplitude were recorded during this depressurization time.
- The above process was repeated but this time the ullage pressure was released at a slower rate. (Try 2).
- Ullage pressure was built up again to a much higher value – 110 cm of H_2O – and ullage pressure was again released at yet another rate approximately between that of tries 1 and 2. At about 40 cm of H_2O ullage pressure, the ullage pressure was released a little faster. (Try 3).

Results of these effects are shown in Fig. 2-21 where the arrows show the direction of increasing time. The results are interesting but inconclusive. This effort was made at the conclusion of the contract and no further efforts were allowed for additional data or explanation of the results.

A summary plot of all boiloff data is presented as Fig. 2-22.

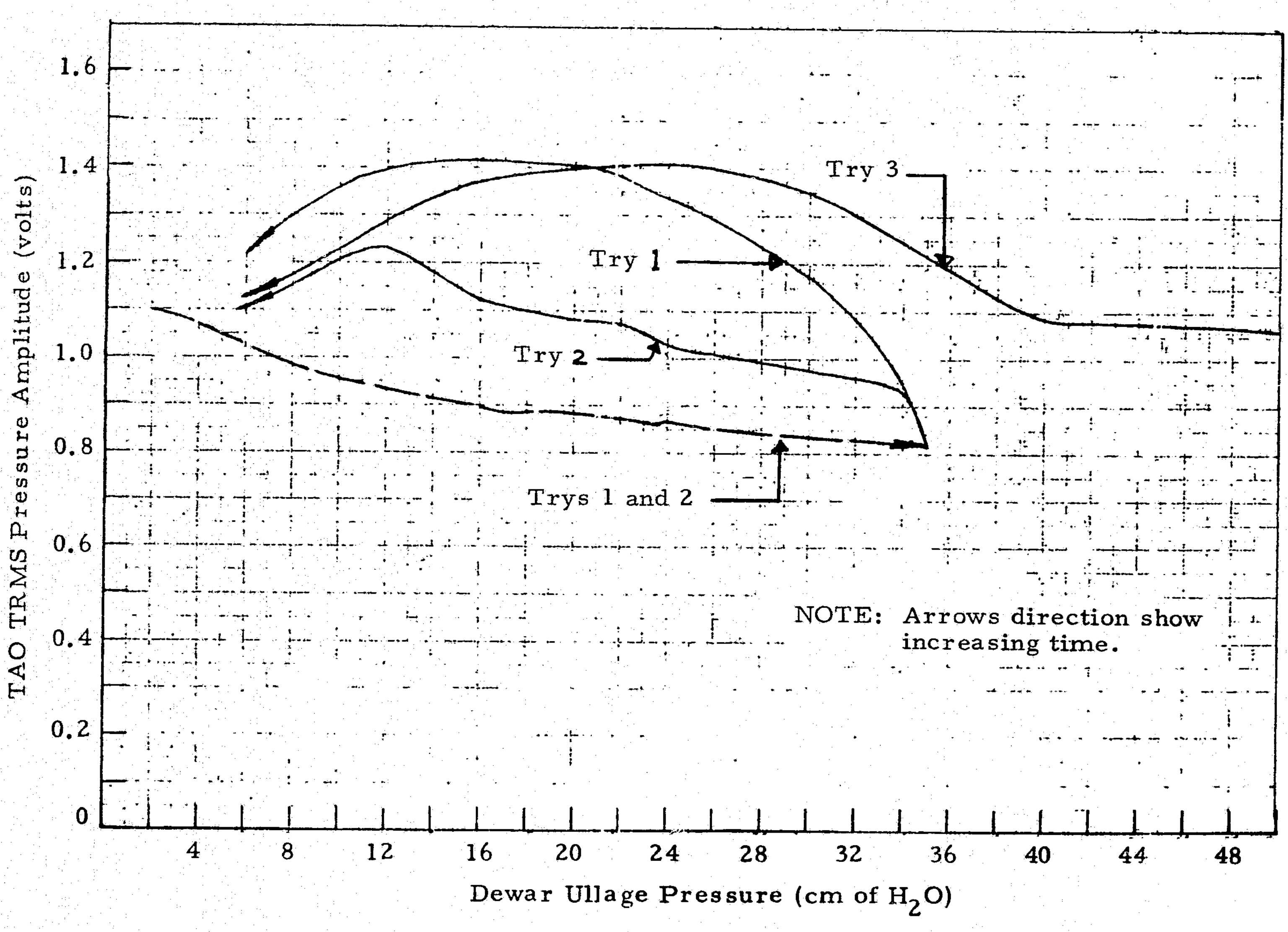
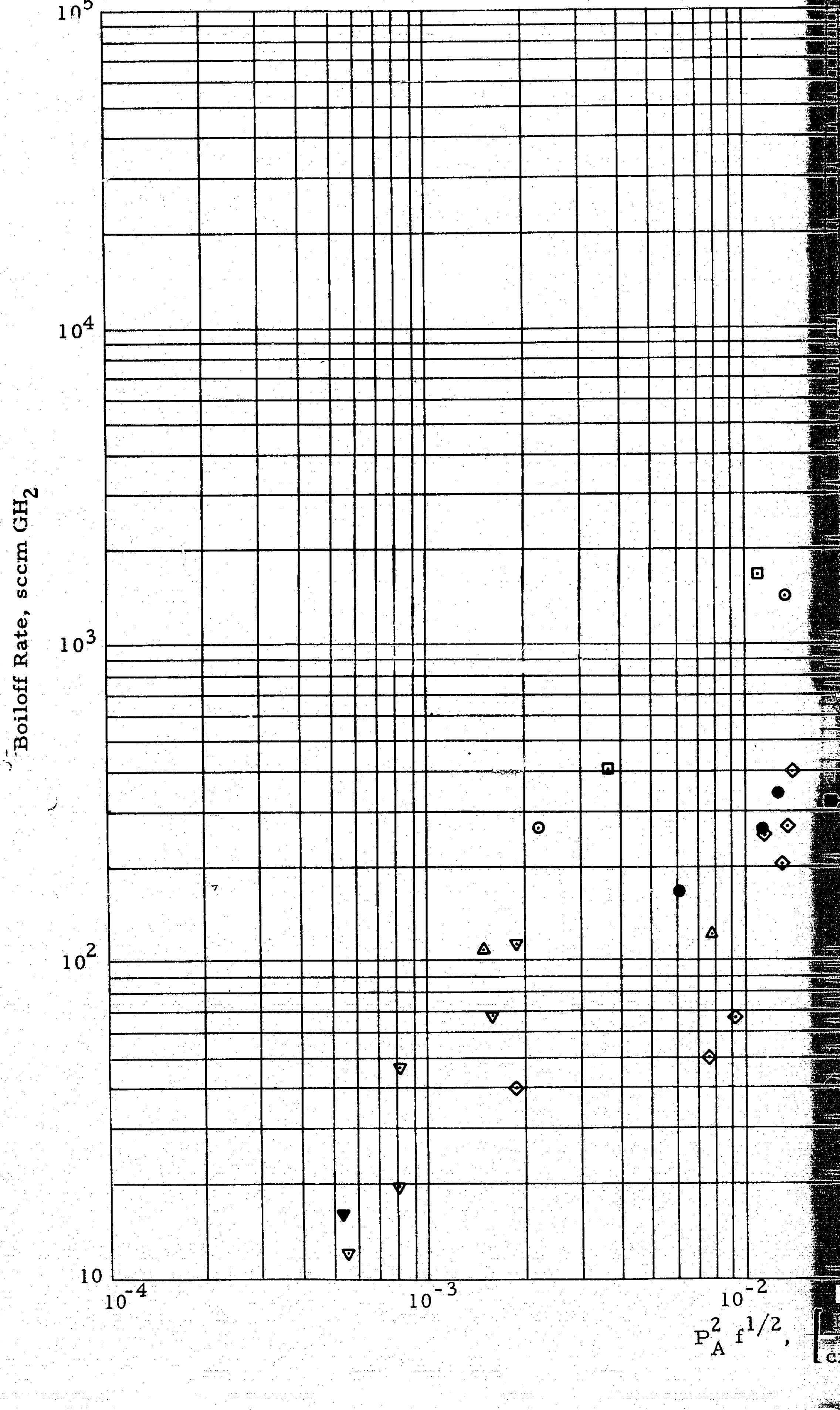


Fig. 2-21 - Effect of Ullage Pressure on TAO Pressure Amplitudes



FOLDOUT FRAME

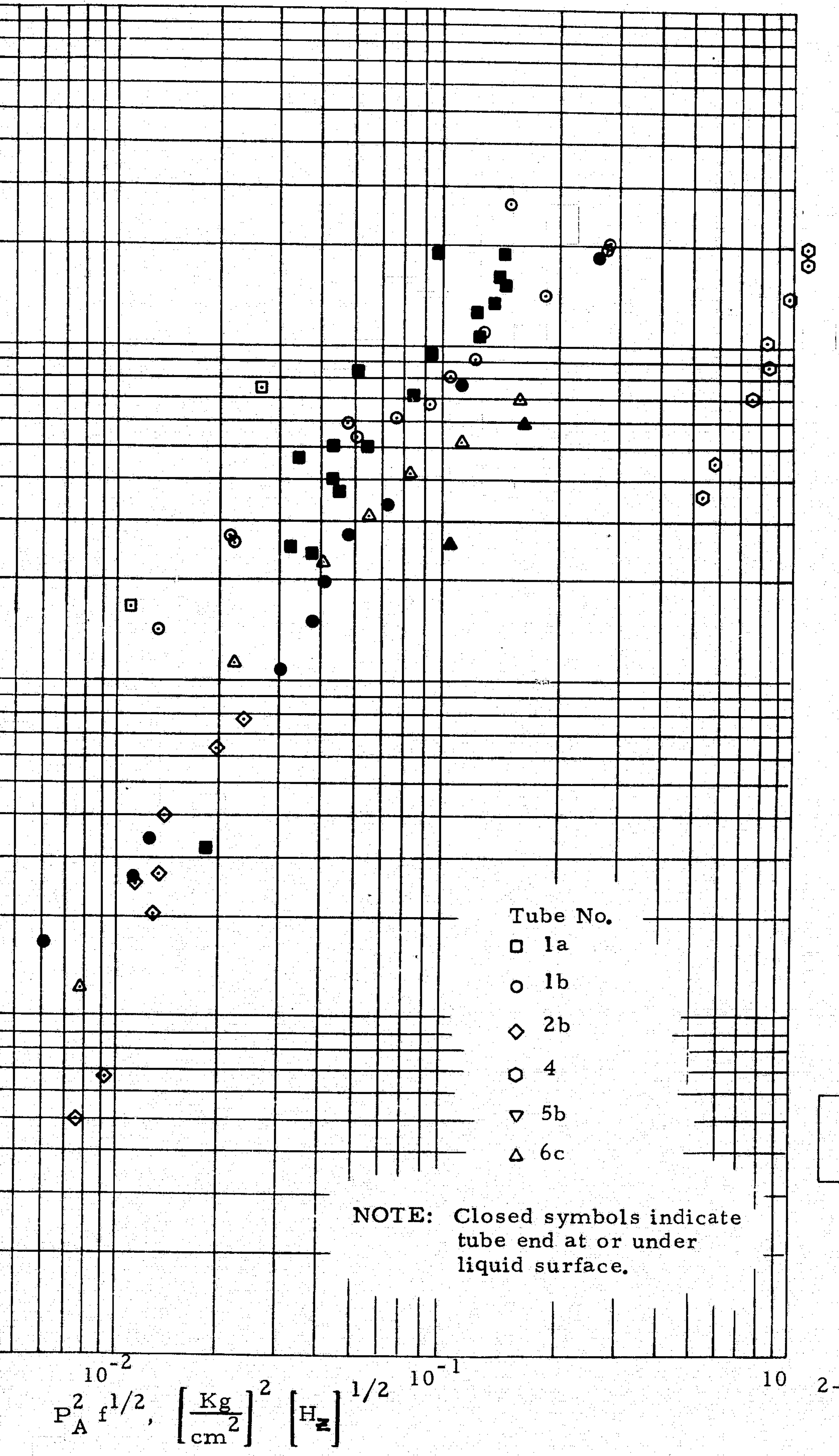


Fig. 22 - Composite Plot of All Boiloff Data Taken in This Study

FOLDOUT FRAME 2

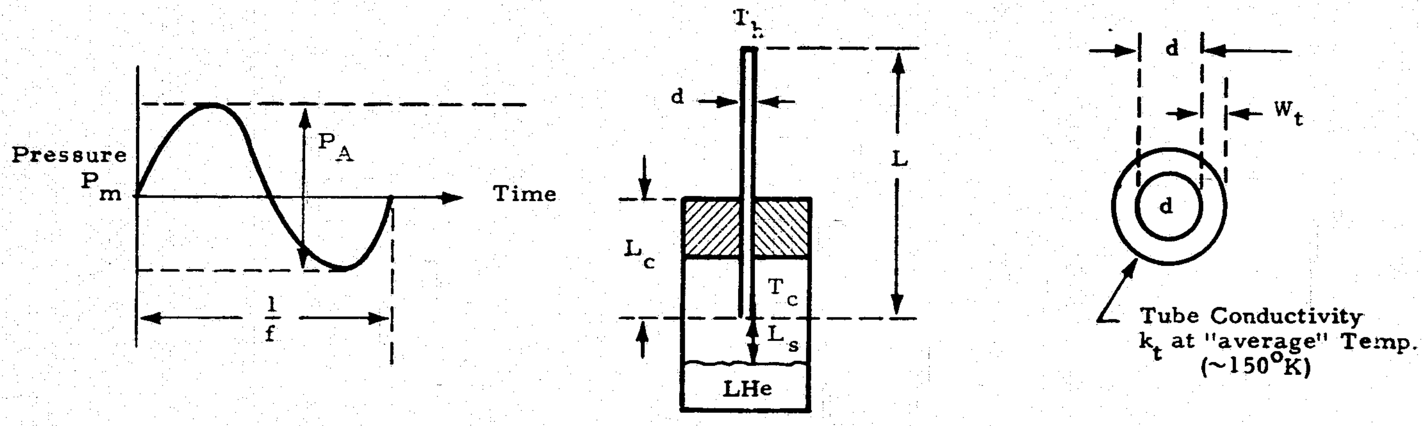
3. ANALYTICAL STUDY

3.1 APPROACH

The approach used in the model development of Ref. 30 was to obtain a system of differential equations and boundary conditions which represent the physical problem. The most general equations describing the thermal acoustic oscillations phenomena are the Navier-Stokes equations. These are very complex in their general form, and no solution for general cases have been reported. The approach which was taken applied certain assumptions, which are justified, to obtain equations which can be solved. Even in their simplest form for thermal acoustic oscillations, these cannot be solved in "closed form." However, numerical methods using a digital computer were successful in obtaining solutions. The Thermal Acoustic Oscillations (TAO) program (Ref. 30) is based on a numerical solution of the Navier-Stokes equations.

It is highly desirable, however, to have simplified equations which can be used by designers in estimating the additional heat leak when oscillations are occurring. The development presented here is directed toward this goal. Rott (Ref. 24) and Von Hoffman et al. (Ref. 37) have developed models of thermal acoustic oscillations. Recently, Rott (Ref. 24) published a paper on the heat transfer enhancement aspects. The correlation equations presented here were derived using his ideas and the governing parameters derived in the Lockheed work (Ref. 30).

Figure 3-1 summarizes the parameters derived in Ref. 30 for analytically modeling thermal acoustic oscillations. The correlation equations will be written in terms of dimensionless ratios of these parameters. The ratios used are the following:



Oscillation Parameters | Configuration | Tube Parameters

d	=	tube inside diameter (cm)
L	=	tube length (cm)
L_c	=	length of cold part of tube (cm)
W_t	=	wall thickness of tube (cm)
k_t	=	thermal conductivity of tube material at the "average" temperature (~150K) (cal/cm-sec/K)
L_s	=	distance of tube from liquid surface (cm)
f	=	oscillation frequency (Hz)
P_A	=	peak-to-peak pressure amplitude (kg/cm^2)
P_M	=	mean pressure (usually atmospheric) (kg/cm^2)
q_T	=	total heat transfer (with oscillations)
q_c	=	conduction heat transfer (no oscillations)
T_M	=	mean temperature of gas (K)
T_h	=	"hot" end temperature (K)
T_c	=	"cold" end temperature (K)
γ	=	ratio of specific heats of gas at T_M
ν	=	kinematic viscosity of gas (cm^2/sec)

Fig. 3-1 - Parameter Definitions for Analytical Model

- L/d – The length-to-diameter ratio of the tube determines to great extent whether or not oscillations will occur. If they do occur, the length of the tube influences the frequency and hence boiloff.
- T_h/T_c – The ratio of the "hot" temperature at the closed end to the "cold" temperature at the open end is the driving mechanism for initiating and sustaining oscillations.
- L_c/L – The ratio of the length of tube exposed to the cold environment, L_c to the total length, L. This parameter also strongly influences the intensity of the oscillations and, in the physical situation, the disturbance of the liquid surface.
- Re – The acoustic Reynolds number,

$$Re = \frac{\rho La}{\mu}$$

  where a, the local acoustic velocity (speed of sound), strongly governs the stability of the system to perturbations, i.e., whether or not the oscillations are sustained.
- q_T/q_c – The ratio of the total heat leak (oscillations plus conduction) to the normal heat leak in the tube walls is a measure of the effect of oscillations on boiloff rates and hence efficiency of storage of the cryogen.

Equations for determining the frequency and amplitude of the oscillations were derived from semi-empirical considerations. The form of the equations was determined by examining the output of the TAO computer program (Ref. 30) with unspecified constants being obtained from the experimental data.

3.2 CORRELATION EQUATIONS

The basis of the correlation equation for heat transfer is the definition of an effective coefficient of heat transfer such that

$$\frac{k_{eff}}{k} \tag{3.1}$$

relates the total heat transfer (with oscillations) to the heat transfer without oscillations. This can be expressed as

$$\frac{q_T}{q_c} = \frac{q_{cond} + q_{osc}}{q_{cond}} \tag{3.2}$$

or equivalently

$$\frac{q_T}{q_c} = 1.0 + \frac{q_{osc}}{q_{cond}} \tag{3.3}$$

where q_{cond} = heat transfer in tube wall, q_{osc} = heat transfer in the gas column. The conduction down the tube wall is simply

$$q_{cond} = k_t A_t \left.\frac{\partial T}{\partial X}\right|_t \tag{3.4}$$

where k_t = conductivity of tube material, A_t = cross-sectional area of tube wall, $\left.\frac{\partial T}{\partial X}\right|_t$ = temperature gradient in tube.

The gas column heat transfer can be given in terms of the effective conductivity coefficient as

$$q_{osc} = k_{eff} A_g \left.\frac{\partial T}{\partial X}\right|_g \tag{3.5}$$

where A_g = cross-sectional area of gas column, $\left.\frac{\partial T}{\partial X}\right|_g$ = temperature gradient in gas column and k_{eff} is the heat conductivity relation to be defined in terms of the oscillation characteristics.

On the basis of experimental data, we now make the assumption that oscillations do not drastically affect the temperature distributions in the gas column or the tube wall. Combining Eqs. (3.5), (3.4) and (3.2) we get

$$\frac{q_T}{q_c} = 1 + \frac{A_g}{A_t} \frac{k_{eff}}{k_t} \tag{3.6}$$

or

$$\frac{q_T}{q_c} = 1 + \left[\frac{\frac{1}{4} d^2}{k_t \left(w_t^2 + d w_t\right)} \right] k_{eff} \tag{3.7}$$

Rott's expression (Ref. 4) for k_{eff}/k is given in terms of the square of the oscillation amplitude times the square root of the frequency, i.e.,

$$\frac{k_{eff}}{k} = \sqrt{f} \left(\frac{P_A}{P_M} \right)^2 C \tag{3.8}$$

where the constant C is determined from the gas Prandtl number, Stokes layer thickness and viscosity of the gas. (C was computed on a theoretical basis alone and from a fit of the experimental data.) Substituting Eq. (3.8) into (3.7) and combining constants we get

$$\frac{q_T}{q_c} = 1 + C \left[\frac{d^2}{k_t \left(w_t^2 + d w_t\right)} \right] \sqrt{f} \left(\frac{P_A}{P_M} \right)^2 \tag{3.9}$$

From theory alone we should get C = 0.0023. In the next subsection we compare this equation model with data and show that C = 0.000425 better fits the data. The discrepancy has not been explained specifically but is most likely due to assumptions made in obtaining a simplified model equation. The assumptions are analyzed in this regard in Section 3.3.

The correlation for oscillation frequency was obtained from a modified form of the quarter wave formula

$$f = \frac{A_o}{4L} \tag{3.10}$$

where A_o is an "acoustic" velocity at some mean temperature of the gas;

$$A_o = \sqrt{\gamma R T_M}$$

In C.G.S. units we can evaluate the constants and get

$$f = \frac{1475 \sqrt{T_M}}{L} \tag{3.11}$$

In addition, the TAO computer program output suggests that the frequency is reduced by about one-half if the tube is in the liquid. We thus modified Eq. (3.11) as follows;

$$f = \frac{1475 \sqrt{T_M}}{NL} \tag{3.12}$$

where N = 1 if tube is out of liquid
= 2 if tube is in the liquid.

The value of T_M can only be determined from examination of the experimental data. The expression used in this analysis is

$$T_M = 4.2 + 15.8 \exp \left[\frac{-3.33\, L_c/L}{0.5 - L_c/L} \right] \tag{3.13}$$

The correlation for pressure amplitude was obtained by considering formulas of the form

$$\frac{P_A}{P_M} = C \left(\frac{L}{d}\right)^M \left(\frac{T_h}{T_c}\right)^N \left(\frac{L_c}{L}\right)^\ell \tag{3.14}$$

Again, experimental measurements and the TAO computer program suggest values

$$M = 0.75, \; N = 2, \; \ell = 3.25, \; C = 3.2 \times 10^{-6}.$$

Figure 3-2 summarizes the correlation equations for quick reference.

An attempt was made to derive a simplified prediction equation for oscillation existence criteria. The computer solutions from the TAO program were plotted on a stability diagram (Fig. 31 of Ref. 30) and compared to experimental findings. This figure shows considerable disagreement between analytical and experimental data. Nevertheless, this stability diagram was put into equation form as follows:

$$S_p = \frac{T_h}{T_c} + \frac{21.2\, d\, (\gamma T)_m^{\frac{1}{2}}}{\nu_c\, (L_c/L)^{\frac{1}{2}}} \tag{3.15}$$

$S_p > 6$ Yes (oscillations should occur)

$S_p < 5$ No (oscillations should not occur)

$5 < S_p < 6$ Marginal

where T_h/T_c is the temperature ratio, d is the tube inside diameter, γ is the ratio of specific heats, ν_c is the kinematic viscosity of the gas at a mean temperature T_M and L_c/L is the ratio of cold length to total tube length.

$$T_M = 4.2 + 15.8 \exp\left[\frac{-3.33\, L_c/L}{0.5 - L_c/L}\right]$$

Frequency:

$$f = \frac{1475\sqrt{T_M}}{nL} \qquad \begin{array}{l} n = 1 \text{ tube out of liquid} \\ n = 2 \text{ tube in liquid} \end{array}$$

Amplitude:

$$\frac{P_A}{P_M} = 3.2\left(10^{-6}\right)\left(\frac{L}{d}\right)^{.75}\left(\frac{T_h}{T_c}\right)^{2}\left(\frac{L_c}{L}\right)^{3.25}$$

Heat Transfer:

$$\frac{q_T}{q_c} = 1.0 + C\left[\frac{d^2}{k_t\,(W_t^2 + d\,W_t)}\right](f)^{\frac{1}{2}}\left(\frac{P_A}{P_M}\right)^2$$

[C = .0023 from theory, C = .000425 from data fit]

Fig. 3-2 - Summary of Correlation Equations

According to the TAO computer solutions, the Sp modulus should be an indication of the onset of oscillations. Comparison of this Eq. (3.15) with experimental observations indicates that the Sp module is not a reliable indicator. The comparisons were made for a limited number of cases and no quantitative conclusions could be reached. Equation (3.15) is thus not recommended until further work can be done.

3.3 COMPARISON WITH EXPERIMENTAL DATA

Figures 3-3 through 3-6 present comparisons of analytical predictions with experimental data for four cases:

- Figure 3-3 shows oscillation frequency versus L_c/L for tube 1a. The analytical prediction is compared to previous data (Ref. 1) and to the current measurements.
- Figure 3-4 is a plot of oscillation amplitude versus temperature ratio, T_h/T_c for the data of Ref. 1.
- Figure 3-5 presents a comparison of data and theory for oscillation amplitude versus L_c/L. Data taken at two different ullage pressures are shown.
- Figure 3-6 shows boiloff rate (sccm) due to oscillations as a function of the parameter $P_A^2 \sqrt{f}$. Two analytical predictions are shown for different values of the correlation constant.

These curves are shown to summarize the findings of the analytical study. Numerous others could be shown but they demonstrate the same basic behavior as these four.

Figure 3-3 serves two purposes: (1) it gives a comparison of the "old" data from Ref. 30 with the current data, and (2) it shows the effects of the tube being above or below the liquid surface. The figure shows that oscillation frequency can be predicted with reasonable accuracy by Eq. (3.12). There is some disagreement, at lower values of L_c/L,

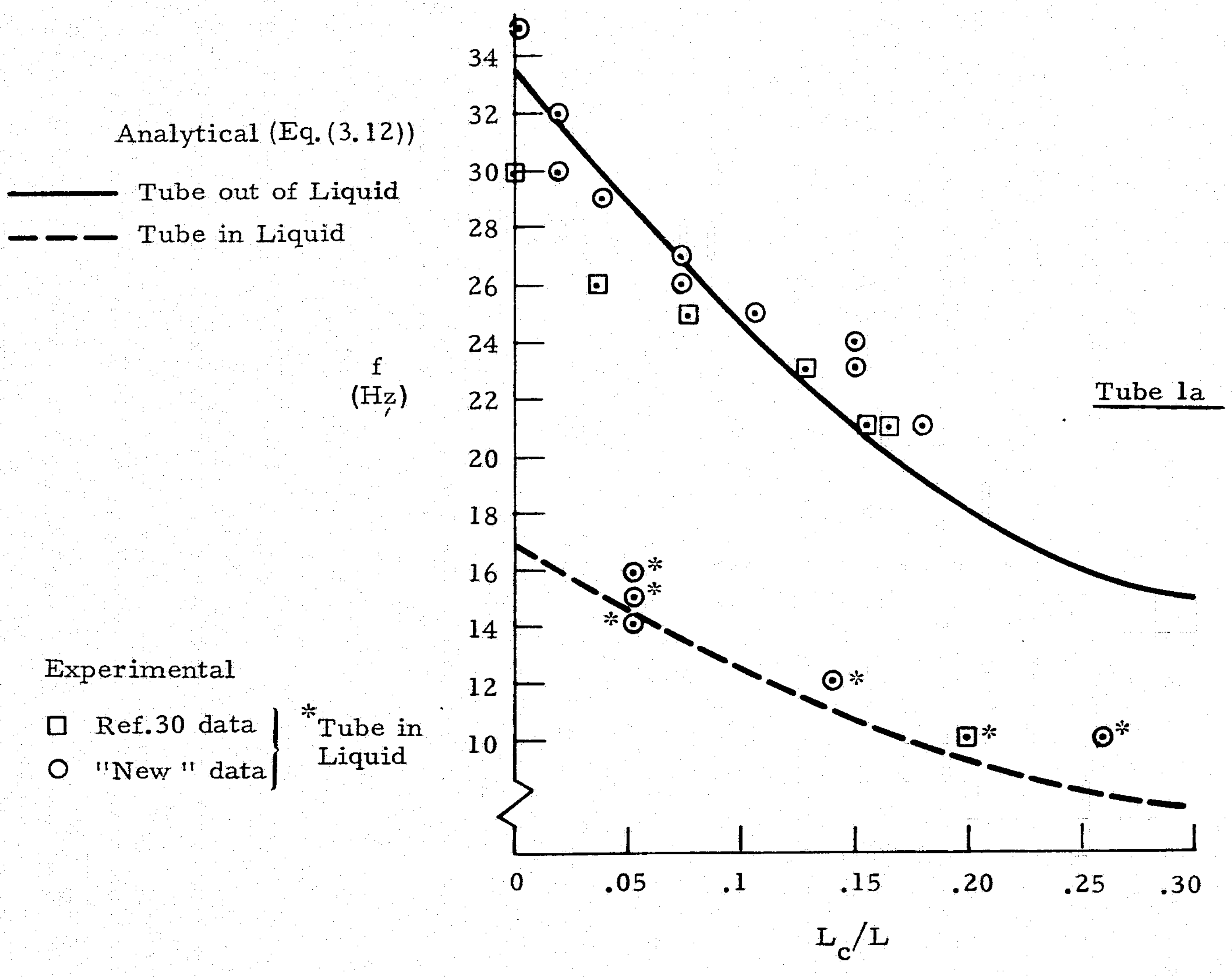


Fig. 3-3 - Comparison of Analytical Prediction with Experiment Data for Oscillation Frequency

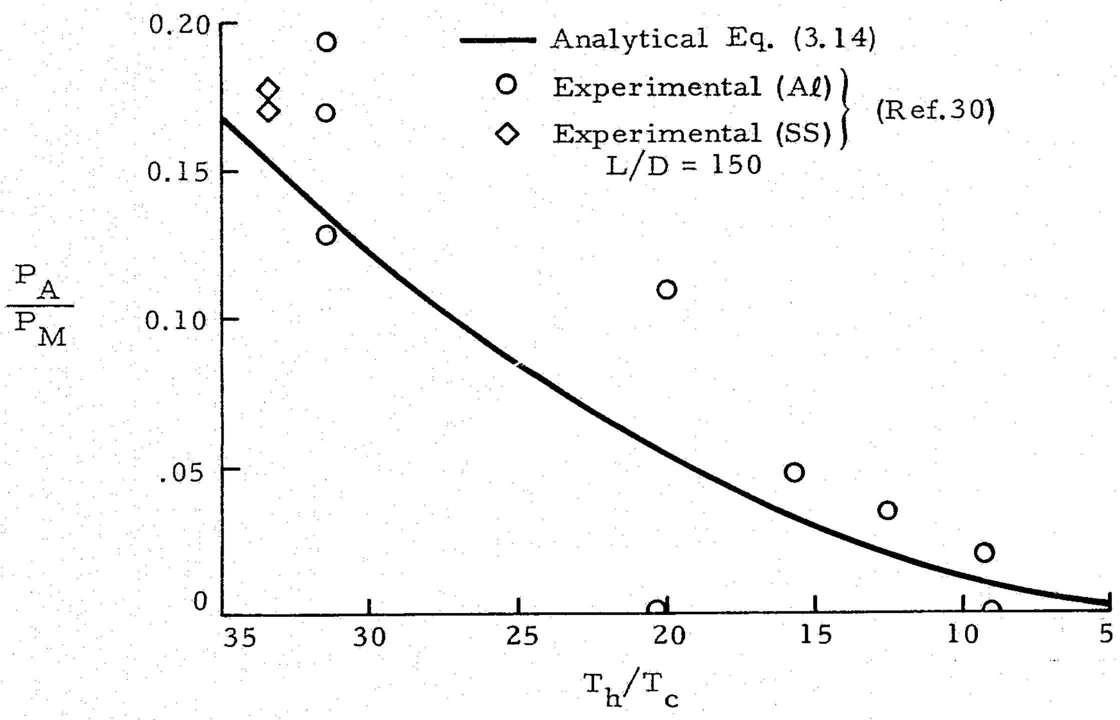


Fig. 3-4 - Comparison of Analytical Prediction with Experimental Data for Oscillation Amplitude vs Temperature Ratio

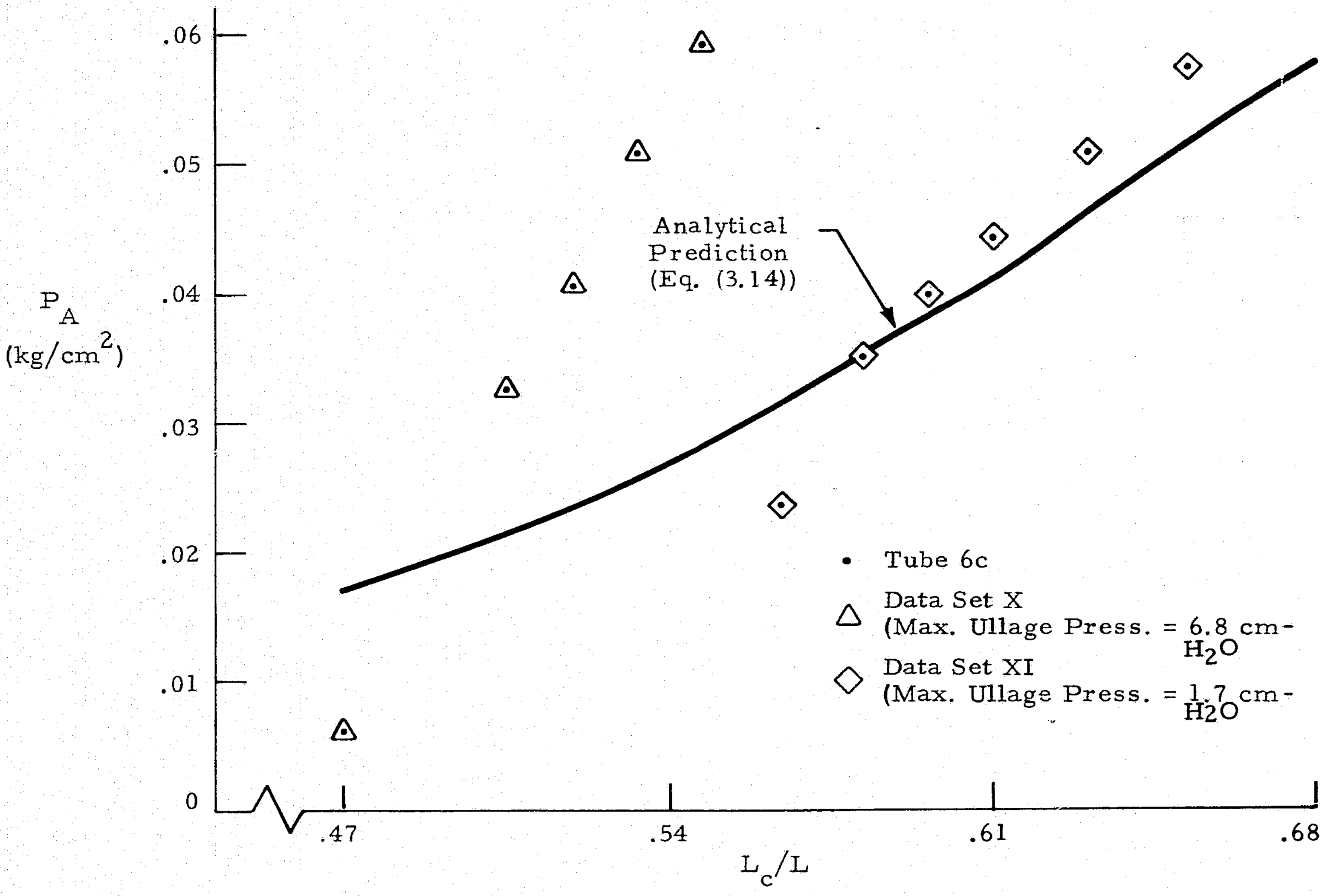


Fig. 3-5 - Comparison of Analytical Prediction with Experimental Data for Oscillation Amplitude vs L_c/L

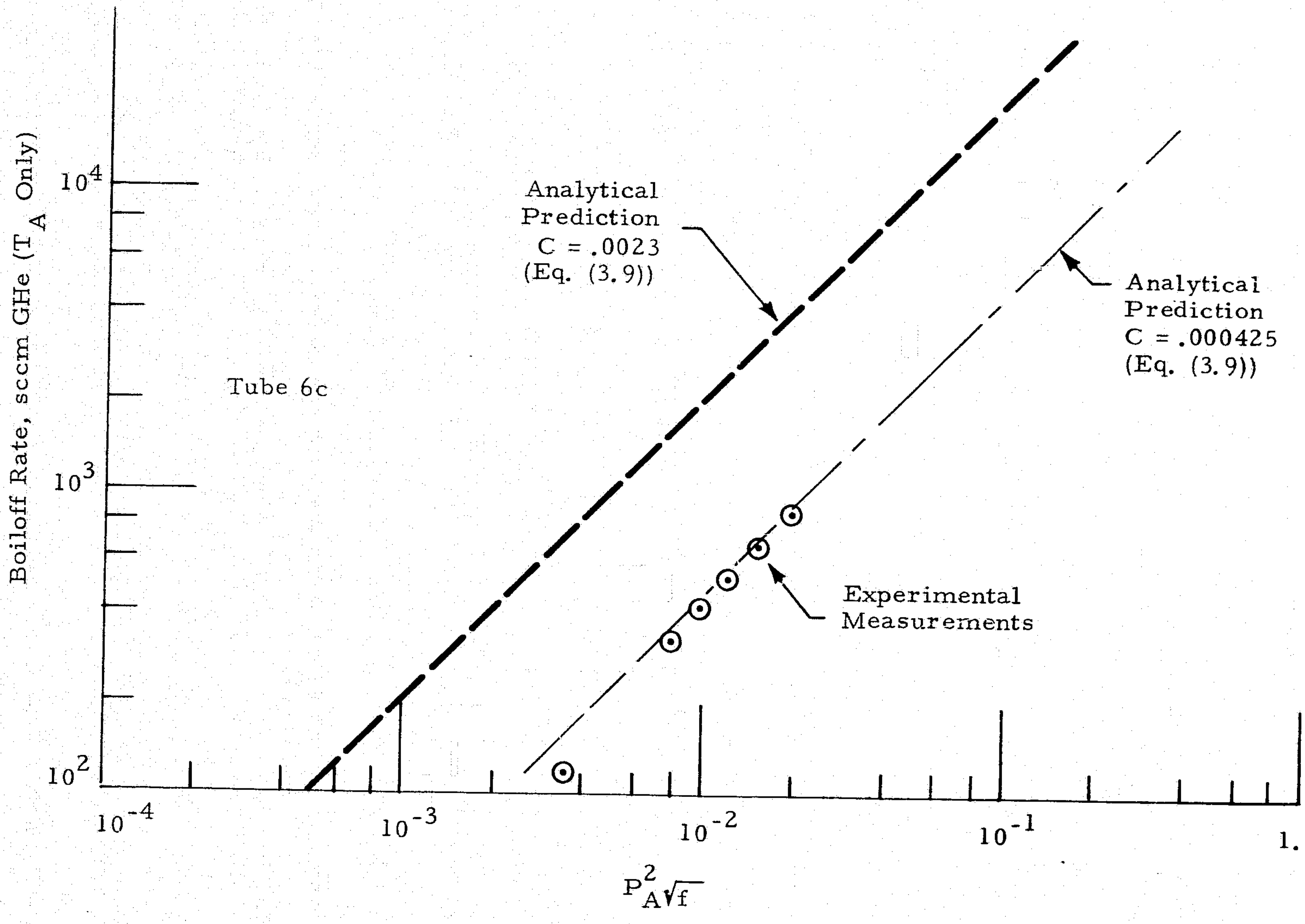


Fig. 3-6 - Comparison of Analytical Prediction with Experimental Data for Boiloff Rate between the correlation equation and data of Ref. 30. The factor of two reduction in frequency for a tube below the liquid surface appears to be good. The behavior of frequency versus L_c/L also appears to be correct.

The plots of oscillation amplitude shown in Figs. 3-4 and 3-5, however, do not agree as well as the frequency plots. Figure 3-4 shows amplitude predictions versus T_h/T_c compared with the data of Ref.30. The theory underpredicts the data by ~80% in some cases. The value of T_h/T_c at which oscillations cease is shown to be ~9 according to the data and ~5 according to the analytical predictions. The comparison shown in Fig. 3-5 illustrates the uncertainty in the analytical predictions due to ullage pressure variations. The correlation Eq. (3.14) does not contain an ullage pressure influence and this is clearly illustrated in the figure. The correlation is reasonably good compared to the 1.7 cm - H_2O data but completely misses the trend and magnitude for the 6.8 cm - H_2O data. This finding was totally unexpected since a "relatively" small change in ullage pressure was not anticipated to have any effect of oscillation amplitude. Equation (3.14) must, therefore, be restricted to systems of relatively low pressures with the definition of low not being quantified at this time.

Figure 3-6 shows boiloff rate in sccm of GHe due to oscillations only (the static boiloff has been subtracted out). This curve shows two important facts:

- The theory predicts that boiloff rate should correlate with the parameter $P_A^2 \sqrt{f}$, and the data show this trend to be correct.
- Equation (3.9) with the constant C = 0.0023 overpredicts boiloff rate by as much as a factor 3. With the constant adjusted to 0.000425 by empirical analysis, we can predict very accurately the oscillation boiloff rate.

Similar comparisons of boiloff were made for other tubes and all showed the same basic behavior. Approximately one-half of the cases could be predicted to ~20% accuracy using Eq. (3.9), while about one-third of the remaining cases were overpredicted by 100% or more. These discrepancies have not been fully explained at this time; however, on the basis of our experience with this problem, the following speculations are offered:

- The boiloff rate is probably a strong function of the pressure in the ullage space of the shipping dewar. The correlation equation does not account for this phenomenon.
- The volume of liquid present in the dewar, i.e., liquid level also has an influence on the boiloff rate. For the large (10^4 sccm) boiloff rates, the liquid level may also be changing relatively fast.
- The temperature distribution in the gas column may have been altered enough to render our assumption invalid in deriving the correlation equation.
- The experimental measurements show a type of hysteresis in that we could not get repeatability in all of the cases. Some presently unknown phenomena must have been affecting the oscillation characteristics.

The analytical study was directed toward obtaining simplified equations for predicting characteristics of thermal acoustic oscillations. Equation (3.12) for frequency prediction appears to be excellent. Equation (3.14) gives reasonable predictions of oscillation amplitudes for conditions of relatively ambient ullage pressure but should not be applied to cases much higher than ambient. Equation (3.9) correctly predicts the trend of boiloff rate versus $P_A^2 \sqrt{f}$ but overpredicts the magnitude by as much as a factor of 3. The semi-empirical version of Eq. (3.9) predicts boiloff accurate to ~20% for about half of the cases studied.

3.4 MODEL IMPROVEMENTS

On the basis of these comparisons and from an examination of the assumptions made in constructing the analytical models, the following suggestions are made for improving the models:

- The general differential energy equation with second order heat flux could be examined for removing the restriction on the temperature profile $\partial T/\partial X$ in the heat transfer correlation.

- The gas thermal properties could be evaluated at a temperature other than the mean gas column temperature.
- The effect of ullage pressure on boiloff rate must be included in the correlation equation. This may render the energy equation too complex for analytical solution. Perhaps a curve fit of a numerical solution could be used.
- Equation (3.14) for predicting oscillation amplitude must also be modified to include ullage pressure as a parameter. A form such as

$$\frac{P_A}{P_M} = C\left(\frac{L}{d}\right)^M \left(\frac{T_h}{T_c}\right)^N \left(\frac{L_c}{L}\right)^\ell \left(\frac{P_u}{P_M}\right)^k$$

could be used with k being defined by the data fits.

- The influence of the liquid volume present in the dewar should be included in some manner in all of the equations. A suitable way may be to define an effective L_c/L ratio which is determined from a given volume of liquid.
- A further search should be made for an existence criteria equation. The equation (dimensionless group) should consist of products, quotients and sums of these parameters:

$$S_p = f\left(\frac{L}{D}, \frac{T_h}{T_c}, \text{Re}, \frac{L_c}{L}, \frac{L_c - L_\ell}{L}, \text{constant}\right)$$

It is desired then to determine a "critical" value of S_p where oscillations will exist. This is analogous to a critical Reynolds number for laminar to turbulent transition or a critical Grashoff number for occurrence of natural convection flow. This approach will allow a simple analysis such as

if $S_p > 1$ Oscillations will occur.

$S_p < 1$ Oscillations will <u>not</u> occur.

To date no such expression has been presented in the literature.

4. CONCLUSIONS

The study has resulted in a number of significant results and an equal number of new problem areas which will require further investigation. The following is a summary of the findings of this study.

- The onset of oscillations is a strong function of the liquid helium level and the distance of the tube from the liquid surface.
- A large volume of data was taken on frequency, amplitude and boiloff rate for a matrix of parametric conditions.
- The effects of ullage pressure on oscillation characteristics is significant. The exact nature of effects on each parameter was not determined as it appeared to be coupled to the many other parameters in the system.
- Due to the coupling of many parameters in the system, we had problems getting repeatability in some of the tests. The oscillation characteristic for a given tube would change drastically with liquid volume and ullage pressure.
- The boiloff rate was found to correlate with the product of amplitude squared and the square root of frequency.
- The largest boiloff rate measured was 2×10^4 sccm due to oscillations. The static no-oscillation value was $\sim 10^2$ sccm. The boiloff rate is thus increased 200 fold by the oscillations.
- The frequency measurements ranged from 10 Hz for the longer tubes to about 90 Hz for the shortest one.
- Maximum pressure amplitudes measured were of the order of 0.5 kg/cm^2 with a mean of ~ 0.1 kg/cm^2.
- The frequency of oscillations decreases as the tube is moved closer to the liquid surface. The amplitude, however, shows a general increase as the tube is moved closer to the liquid surface.
- The temperature of the cold part of the tube remains virtually constant at ~ 4 to 5 K regardless of the cold length value.

- The analytical correlation equation for oscillation frequency predicts accurate to ~5% for a major portion of the data taken. The amplitude correlation equation predicts accurate to ~25% for approximately one half of the data and misses the other half of the measurements by as much as a factor of 2.
- The correlation equation for boiloff rate correctly predicts the slope of the curve versus amplitude squared times the square root of frequency. However, the magnitude of the prediction is inaccurate. Some data correlate to within 20% of the prediction, while most of the boiloff measurements are overpredicted by as much as a factor of 3.
- More experimental work is needed to clarify the effects of ullage pressure on oscillation characteristics.
- The transient nature of the oscillations needs to be studied by recording time histories of the wave characteristics as opposed to studying psuedo-steady oscillations.
- The effects of ullage pressure needs to be taken into account in the analytical correlation equations. This appears to be the major inaccuracy in the analytical equations.

The study has provided a large volume of data showing effects of thermal acoustic oscillations never before reported. The fact that additional problem areas were found is also significant. Even though we have solved a number of problems associated with this phenomenon, we have not explained all of the data or all of the effects which were observed.

5. RECOMMENDATIONS

The conclusions reached from this study suggest that additional work is definitely needed to clarify and quantify a number of problems. An experimental and analytical study program should be conducted with the following objectives: (1) experimentally investigate and verify parametric and mechanical techniques for suppressing thermal acoustic oscillations; (2) quantify the vapor/liquid interface disturbance phenomena by flow visualization; (3) provide engineering correlation equations and analytical prediction procedures for use by designers in analyzing storage systems for the possibility of thermal acoustic oscillations occurring and the resultant leaks they cause; (4) conduct experimental verification tests of the influence of oscillations when the tube is below the liquid surface; (5) quantify the effects of ullage pressure variations; and (6) measure oscillation characteristics in tubes with curved or coiled configurations. The results of the study will yield quantitative design criteria and effective and practical methods of suppressing thermal acoustic oscillations in cryogenic storage systems for space vehicle application.

The following tasks should be performed to accomplish the objectives of the recommended program.

Task 1 – Methods of Suppressing Oscillations

Experiments should be conducted using the existing hardware to determine effective and practical means of suppressing thermal acoustic oscillations. Mechanical techniques to be investigated should include the following: (1) tube surface roughness methods such as screw threads, taps and random identations; (2) Helmholtz resonator or equivalent procedures; (3) venting methods; (4) valve connection/accumulator expansion regions; and (5) trap door techniques. Parametric methods to be tested should include distance of the tube above the liquid surface, distance below the liquid surface and length/diameter ratios. The results of this task will provide data for making recommendations on suppression techniques which can be used for long-term storage systems on space vehicles.

Task 2 – Liquid Surface Disturbance

The vapor/liquid interface disturbance caused by thermal acoustic oscillations should be experimentally quantified by experiments using flow visualization techniques. The existing hardware can be used to obtain data for constructing an empirical model of the flow and mixing at the liquid surface. Schlieren-type movies, "smoke" observation techniques, and tracer particle methods in glass tubes, can be used to obtain the data. Previous data on this phenomenon can be used for comparison and to verify the empirical model. The results of this task will be an assessment of the potential influence of turbulent flow and mixing in long-term storage systems due to thermal acoustic oscillations.

Task 3 – Oscillations in Curved Penetrations

This task would provide an engineering analysis and simplified analytical prediction procedure for thermal acoustic oscillations. The procedure should incorporate a systematic dimensional analysis with semi-empirical data correlations which can be used by designers in performing a thermal acoustic oscillations evaluation of a specific configuration. In addition, experimental tests should be conducted to obtain data on the influence of oscillations for the situation of a tube deeply immersed in the liquid cryogen. Oscillation characteristics measurements can be made using the existing hardware but with tube penetrations with curved and coiled geometries. Both U-tube and S-tube configurations could be tested to obtain data for application to space storage systems with large length/diameter ratio penetrations. The results of this task will be a systematic procedure whereby designers can use known system parameters to accurately evaluate thermal acoustic oscillations in specific storage systems.

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Appendix A

THERMAL ACOUSTIC OSCILLATIONS DATA BOOK

Appendix A

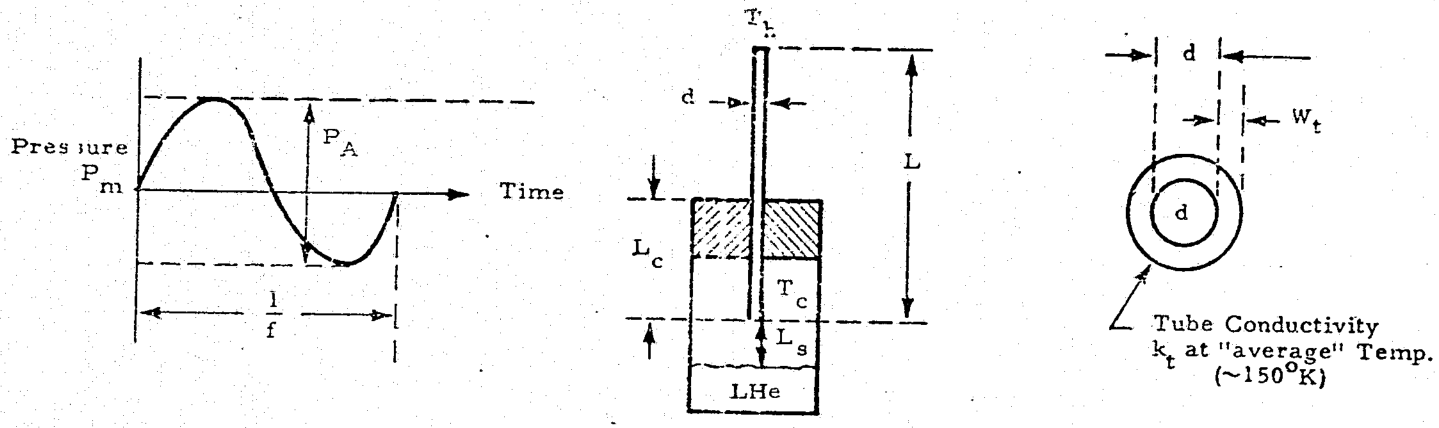
This appendix presents plots of all the data which were taken in the experimental program. The data are arranged by tube number from tubes 1 through 6. Within each tube number section, the plots are given as frequency and amplitude versus cold length, L_c, and boiloff rate versus ampliutude squared times the square root of frequency. Data taken at different ullage pressures are indicated by the different symbols on the curves. Each plot is labeled with tube number, a data set number, the calendar date on which the data were taken and a comments section. This "data book" format provides a complete documentation of all thermal acoustic oscillations data that were taken in this study.

Figure A-1 presents a definition of each parameter used in the test program. Table A-1 presents a summary of each tube that was tested in this study.

TABLE A-1. SUMMARY OF ALL TEST TUBES USED

Tube No.	Wall Thickness		Outside Diameter		Inside Diameter		Length		Length to Inside Diameter Ratio	Instrumented for Temperature Measurements
	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)		
1a	.058	.147	.375	0.953	.258	.657	77.6	197.0	300	No
1b	.028	.071	.315	0.800	.258	.657	77.6	197.0	300	No
1c	.064	.162	.375	0.953	.247	.627	77.6	197.0	314	No
2a	.058	.147	.375	0.953	.258	.657	39.0	99.0	150	Yes
2b	.058	.147	.375	0.953	.258	.657	39.0	99.0	150	No
3a	.058	.147	.375	0.953	.258	.657	26.0	66.0	100	Yes
3b	.058	.147	.375	0.953	.258	.657	26.0	66.0	100	No
4	.019	.048	.125	0.318	.280	.711	43.3	110.0	155	No
5a	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	Yes
5b	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	No
5c	.058	.147	.500	1.27	.384	.975	38.2	97.0	100	No
6a	.058	.147	.375	0.953	.258	.657	58.3	148.0	225	Yes
6b	.058	.147	.375	0.953	.258	.657	58.3	148.0	225	No
6c	.064	.162	.375	0.953	.247	.627	58.3	148.0	236	No

Note: All tubes are type 304 stainless steel.



Oscillation Parameters — Configuration — Tube Parameters

- d = tube inside diameter (cm)
- L = tube length (cm)
- L_c = length of cold part of tube (cm)
- W_t = wall thickness of tube (cm)
- k_t = thermal conductivity of tube material at the "average" temperature (~150K) (cal/cm-sec/K)
- L_s = distance of tube from liquid surface (cm)
- f = oscillation frequency (Hz)
- P_A = peak-to-peak pressure amplitude (kg/cm^2)
- P_M = mean pressure (usually atmospheric) (kg/cm^2)
- q_T = total heat transfer (with oscillations)
- q_c = conduction heat transfer (no oscillations)
- T_M = mean temperature of gas (K)
- T_h = "hot" end temperature (K)
- T_c = "cold" end temperature (K)
- γ = ratio of specific heats of gas at T_M
- ν = kinematic viscosity of gas (cm^2/sec)

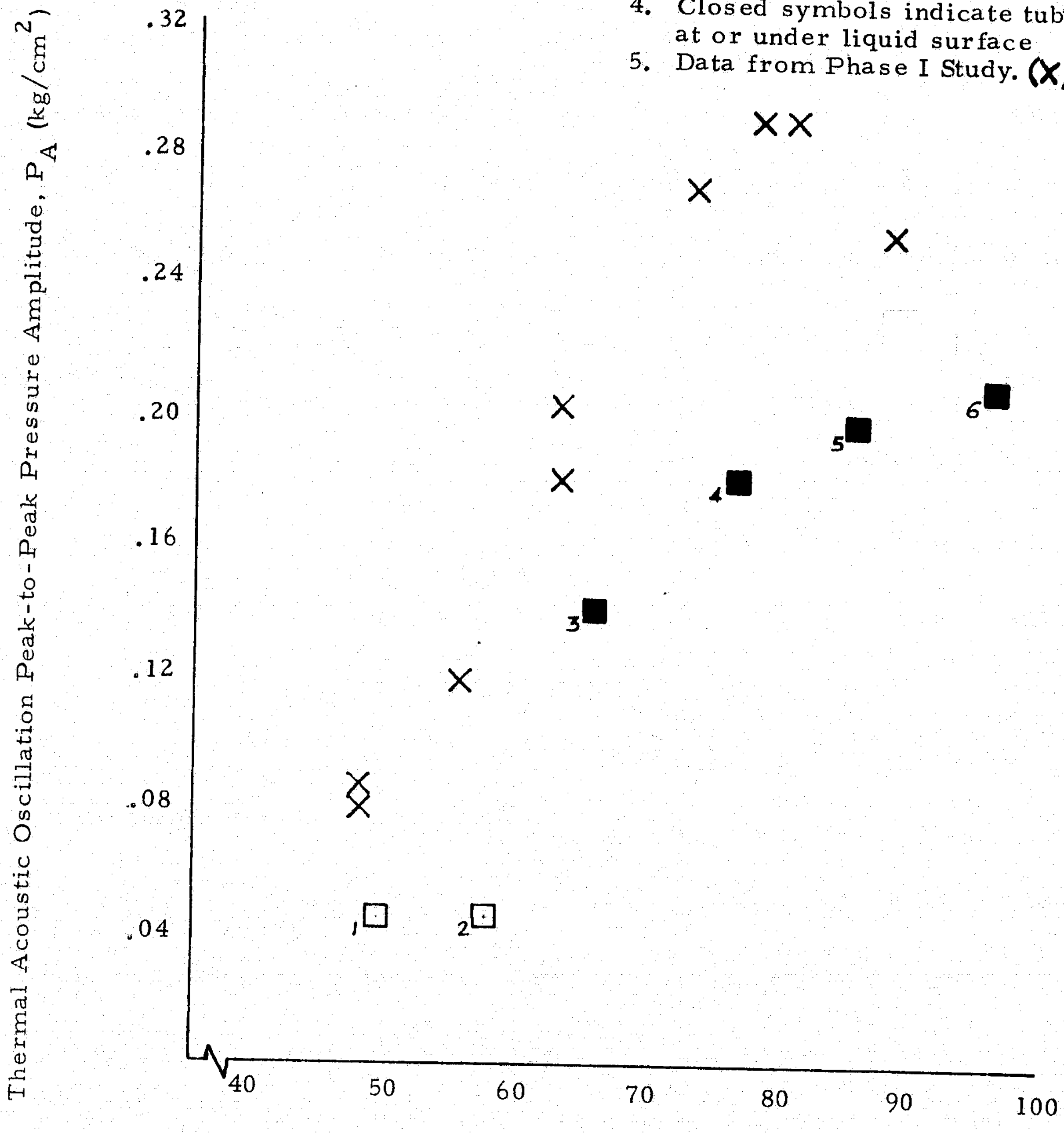
Fig. A-1 - Parameter Definitions for Thermal Acoustic Oscillations

A.1 TUBE 1, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
1a	197	.657	.147	300
1b	197	.657	.071	300
1c	197	.627	.162	314

Tube: 1a
Data Set: II
Date: 1-13-76

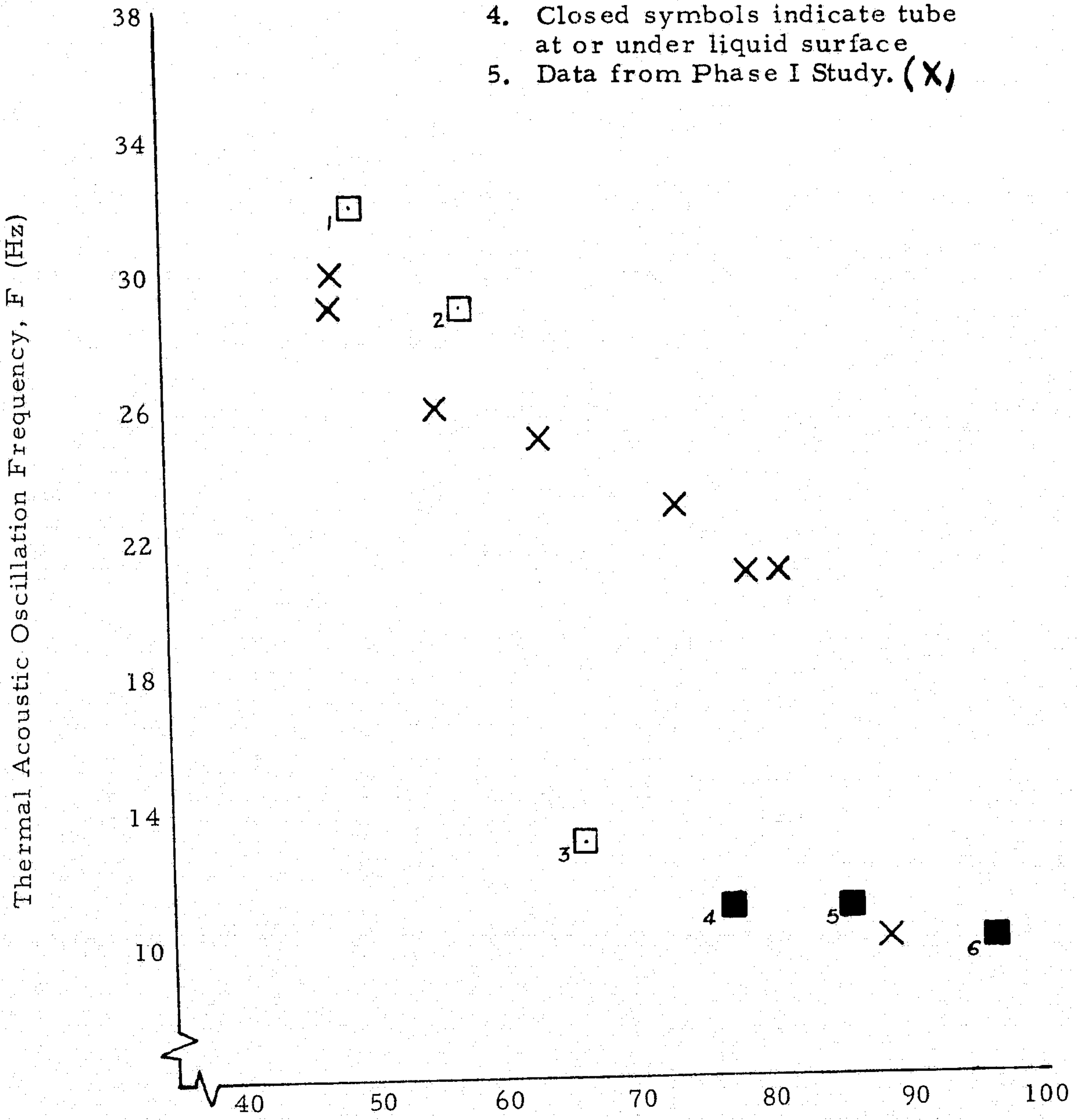
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface
5. Data from Phase I Study. (X)



Cold Length of Tube, L_c, (cm) (Measured from top of Dewar)

Tube: 1a
Data Set: II
Date: 1-13-76

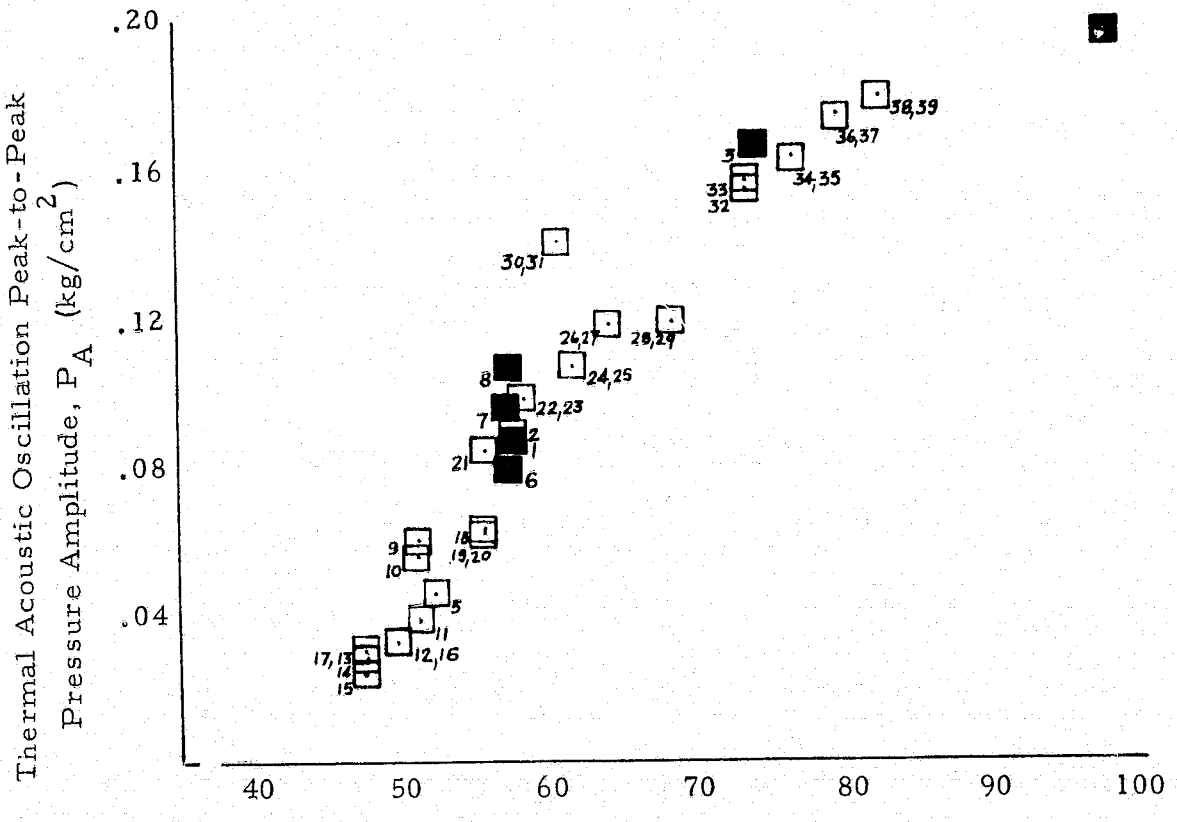
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface
5. Data from Phase I Study. (X)



Cold Length of Tube, L_c, (cm) (Measured from top of Dewar)

Tube: 1a
Data Set: IV
Date: 2-11-76

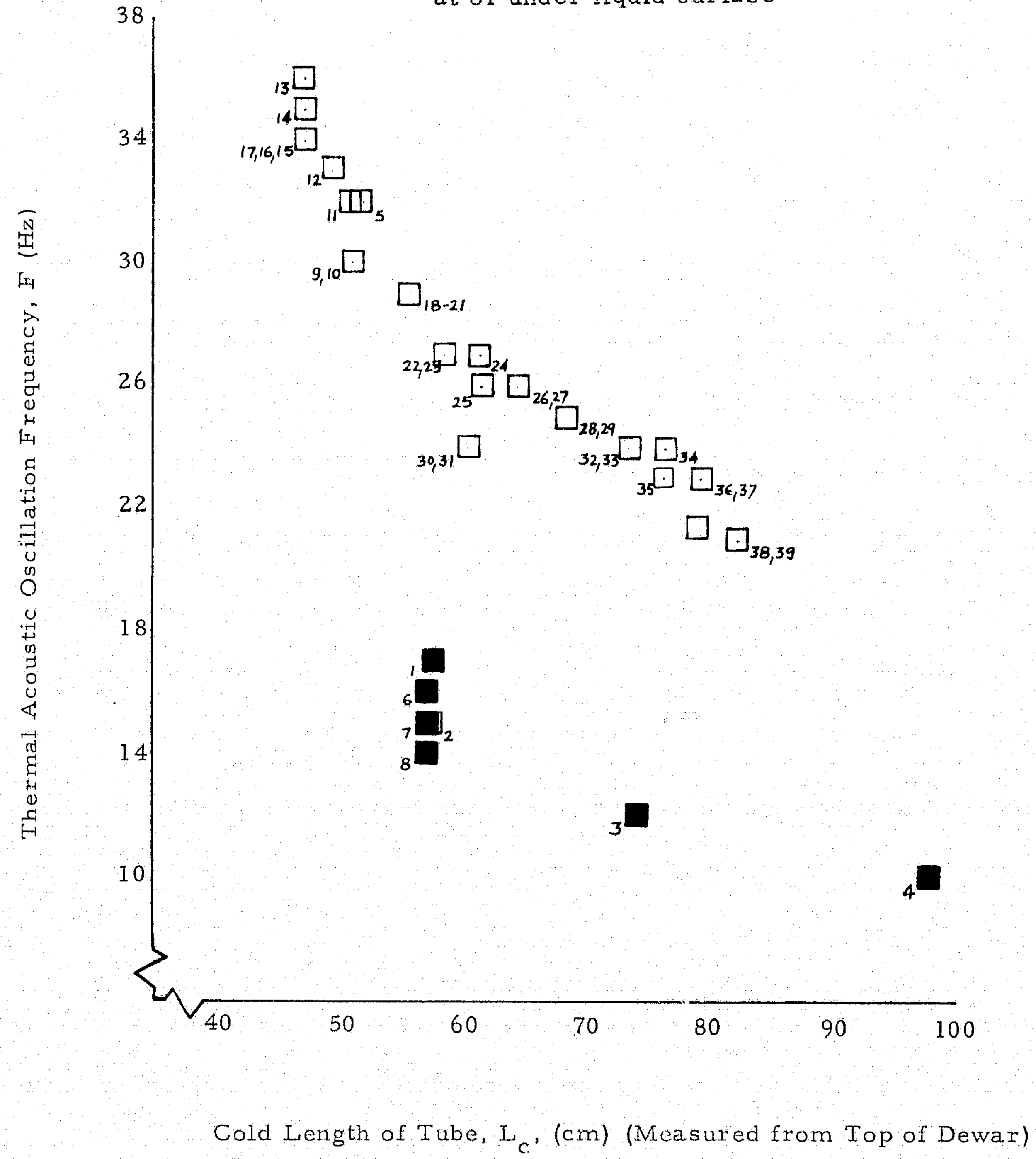
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface

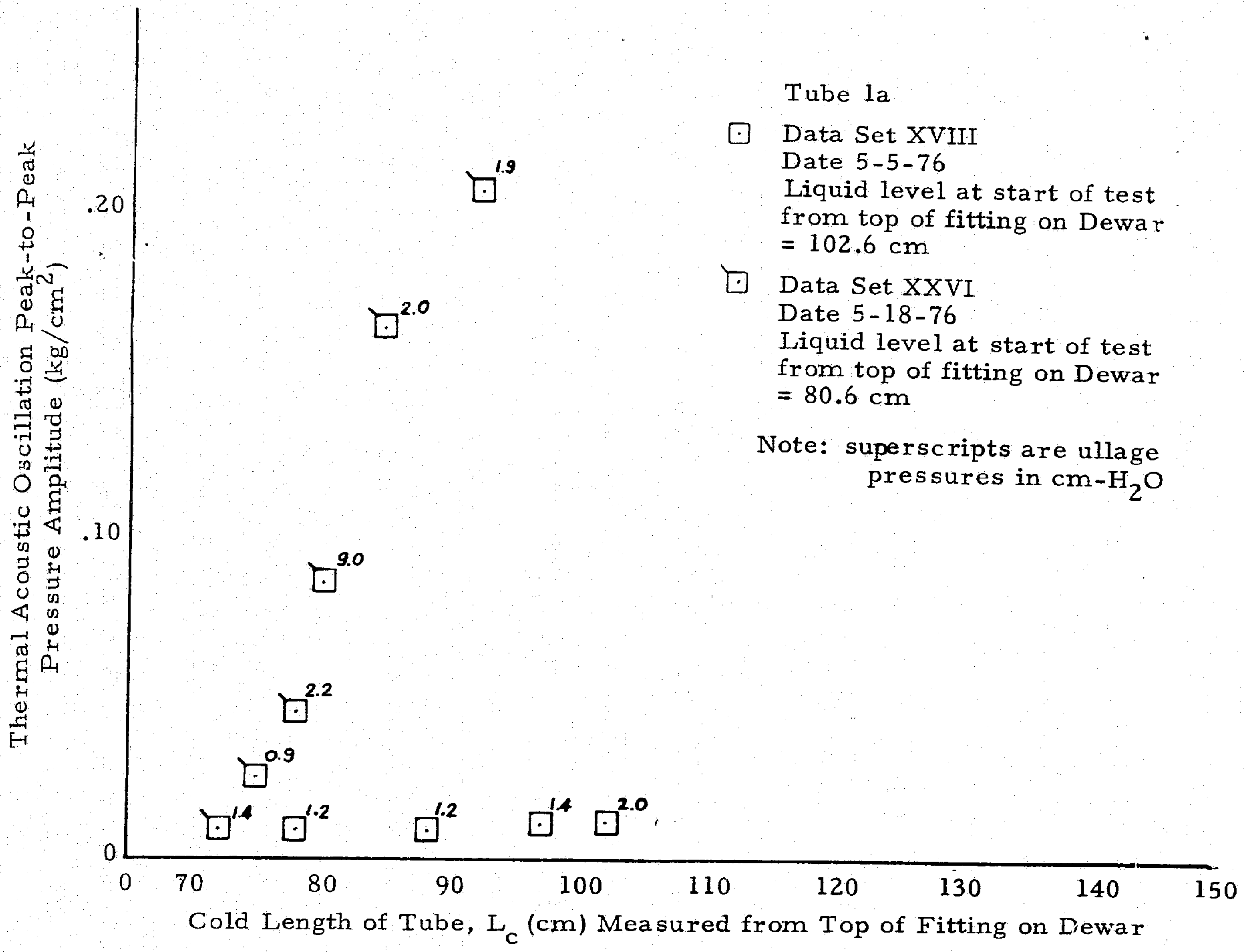


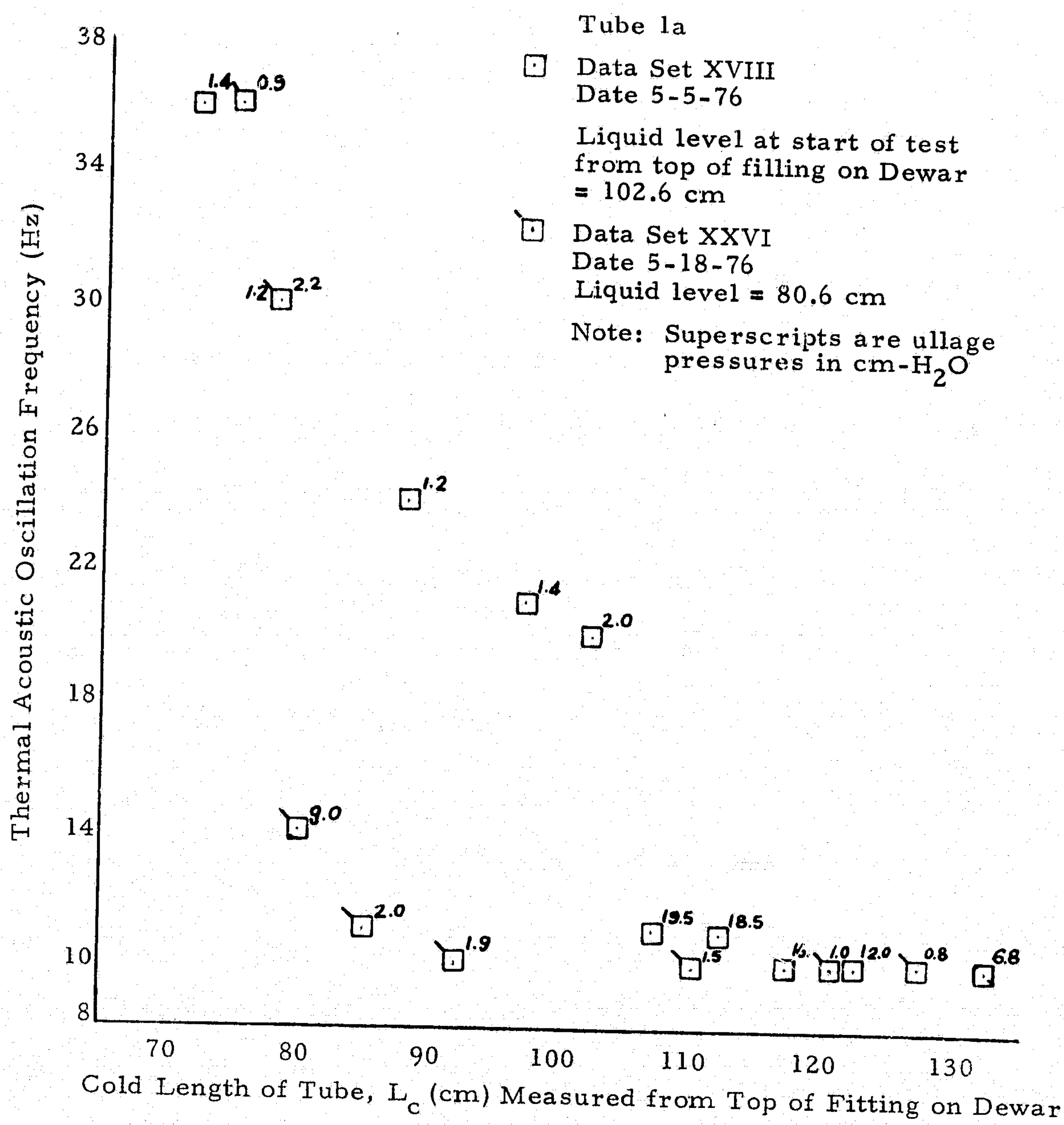
Cold Length of Tube, L_c, (cm) (Measured from Top of Dewar)

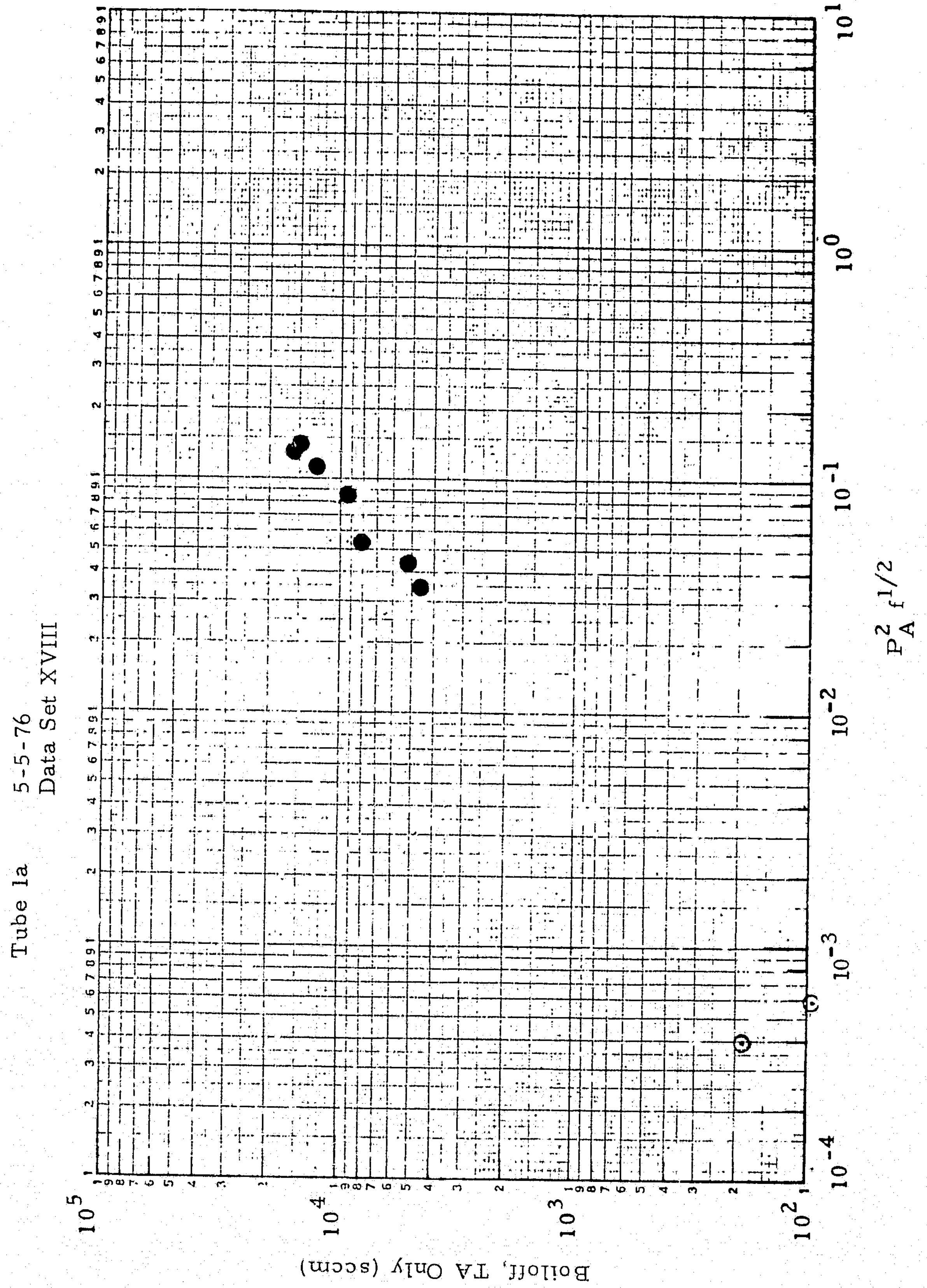
Tube: 1a
Data Set: IV
Date: 2-11-76

NOTES:
1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface



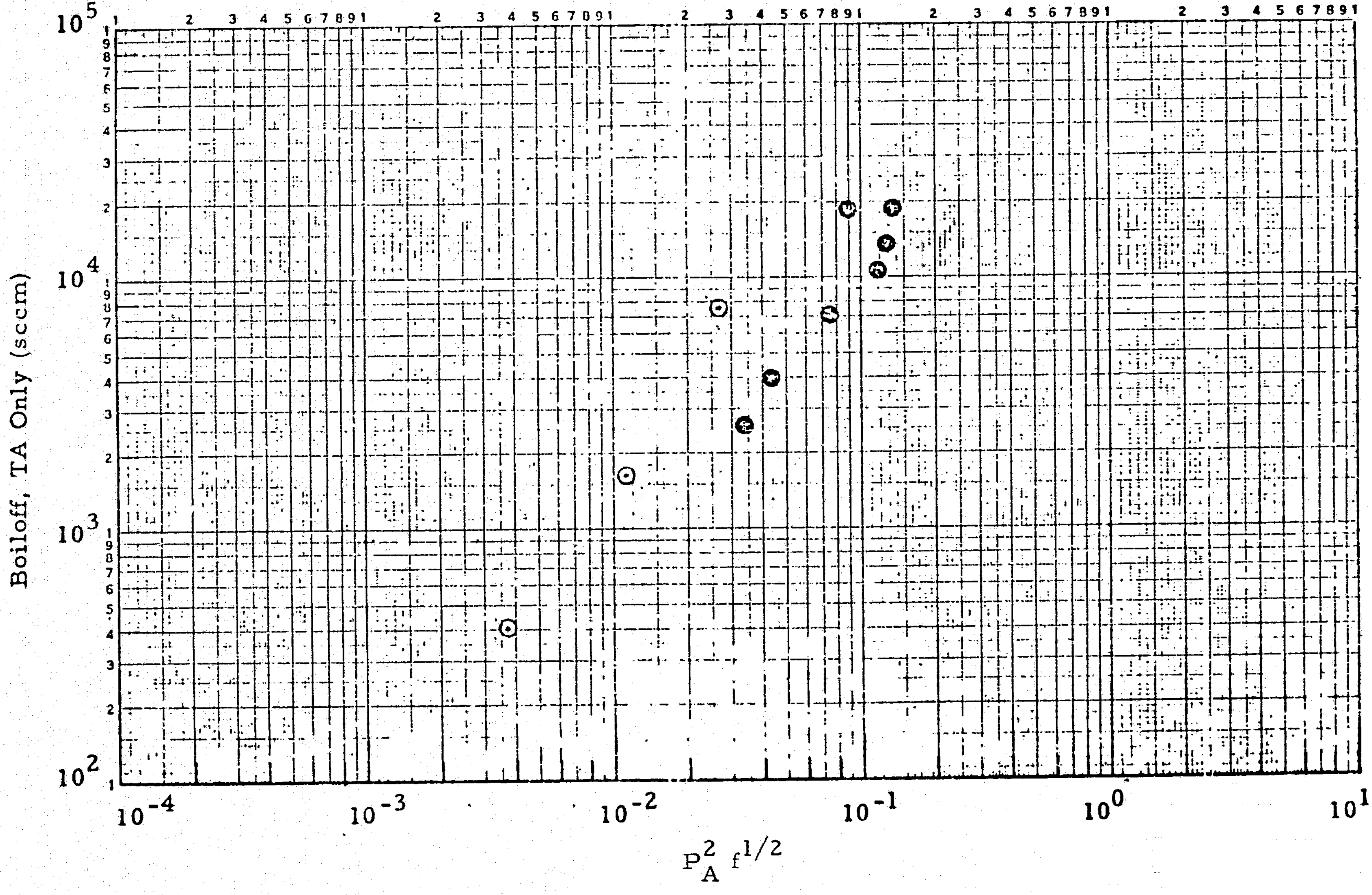

Tube 1a
Data Set XVIII
Date 5-5-76
Liquid level at start of test from top of fitting on Dewar = 102.6 cm
Data Set XXVI
Date 5-18-76
Liquid level at start of test from top of fitting on Dewar = 80.6 cm
Note: superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude (kg/cm^2)
.20
.10
0
0
70
80
90
100
110
120
130
140
150
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar
1.9
2.0
9.0
2.2
0.9
1.4
1.2
1.2
1.4
2.0

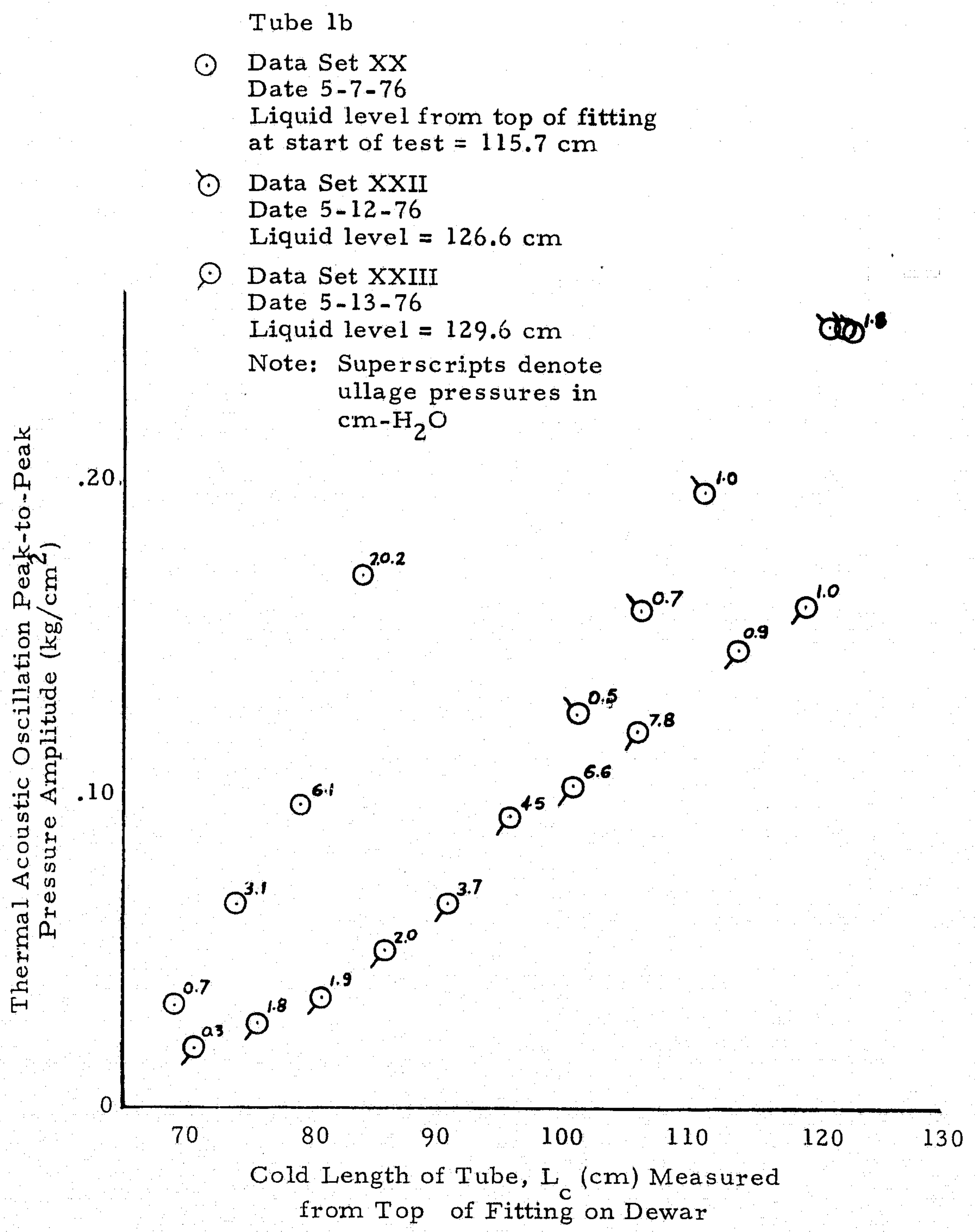

Tube 1a
Data Set XVIII
Date 5-5-76
Liquid level at start of test from top of filling on Dewar = 102.6 cm
Data Set XXVI
Date 5-18-76
Liquid level = 80.6 cm
Note: Superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Frequency (Hz)
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar
38
34
30
26
22
18
14
10
8
70
80
90
100
110
120
130



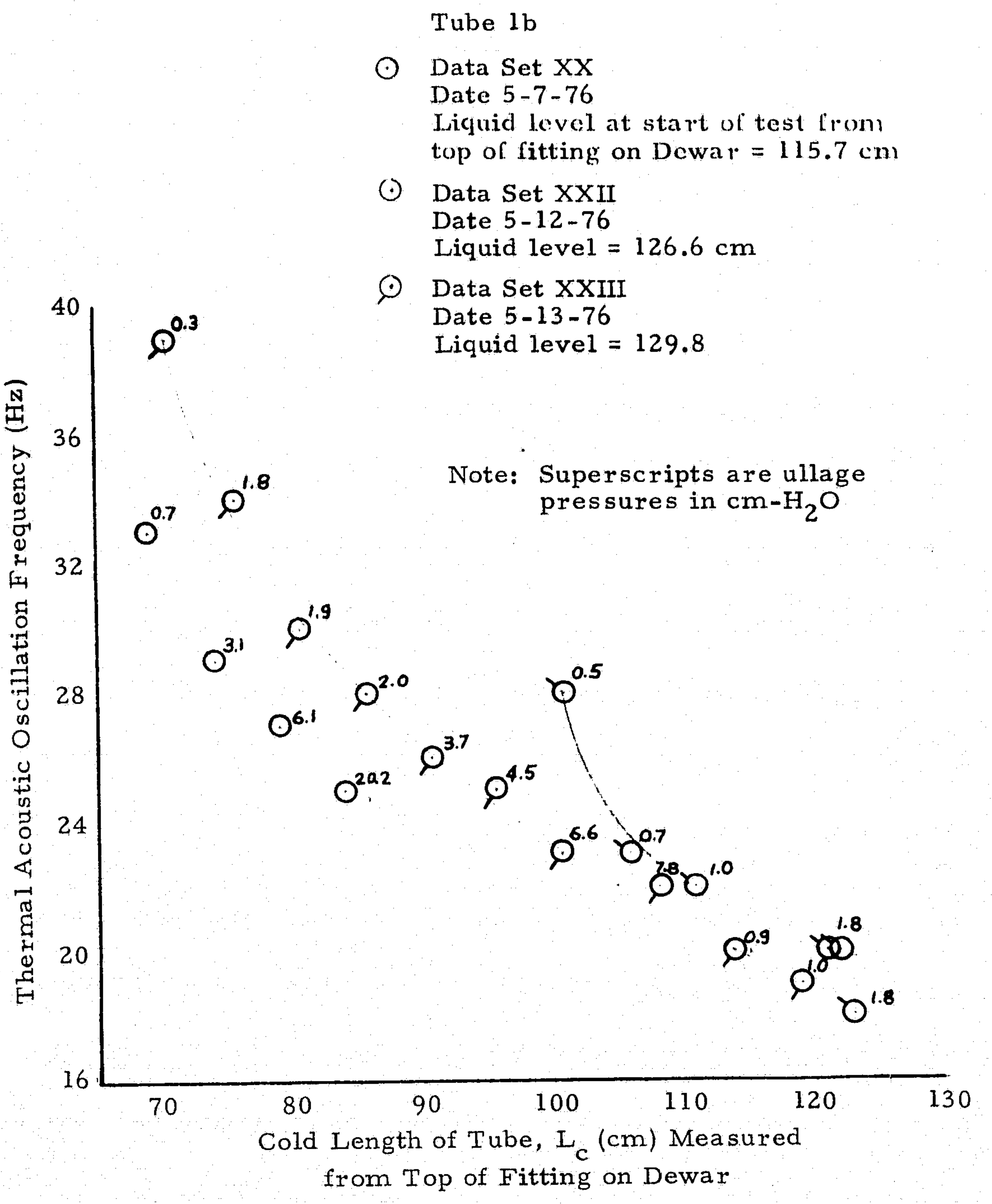
Tube 1a
5-5-76
Data Set XVIII
$P_A^2 f^{1/2}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Boiloff, TA Only (sccm)
10^5
10^4
10^3
10^2

Tube 1a 5-18-76
Data Set XXVI



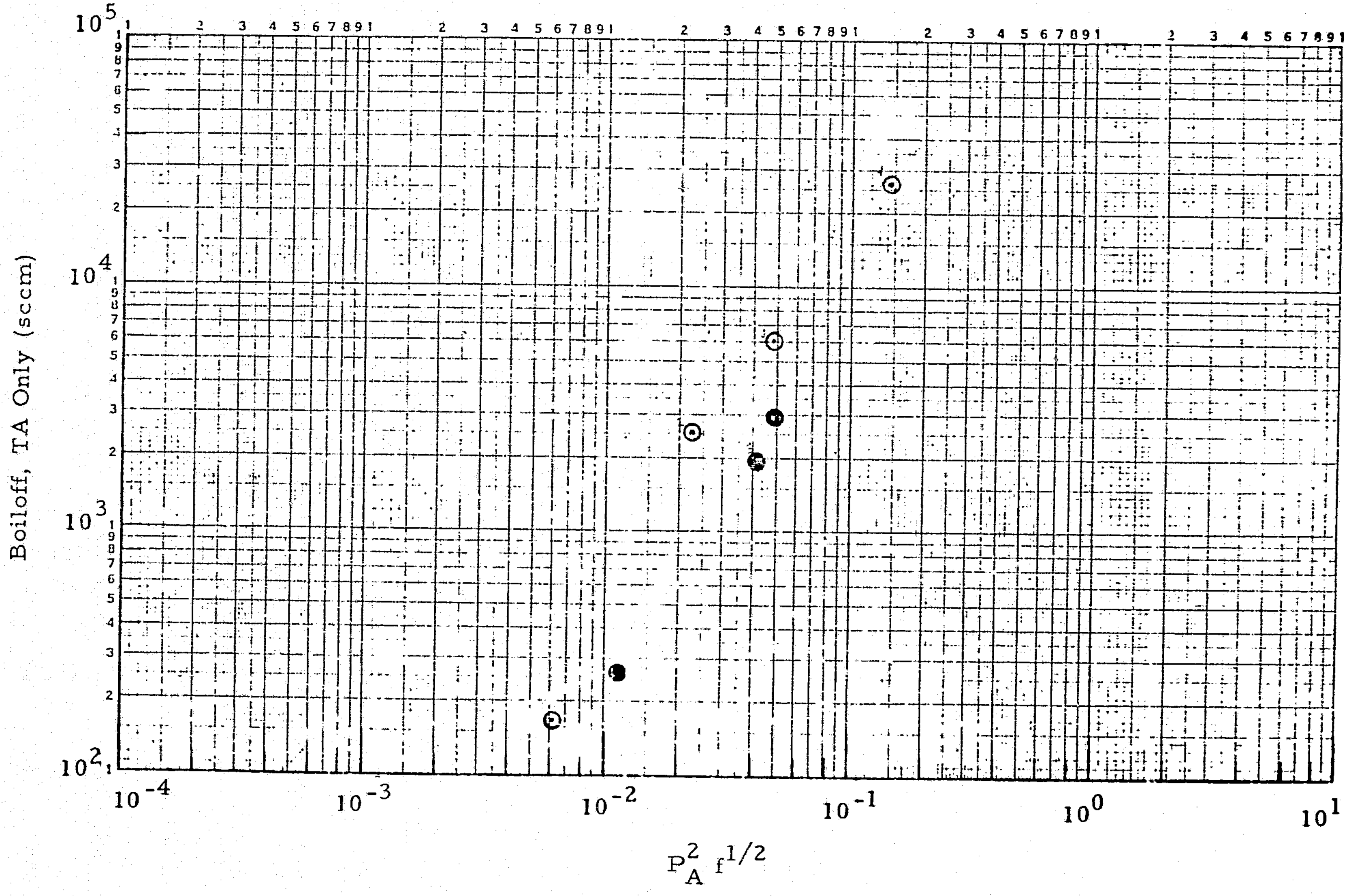


Tube 1b
Data Set XX
Date 5-7-76
Liquid level from top of fitting at start of test = 115.7 cm
Data Set XXII
Date 5-12-76
Liquid level = 126.6 cm
Data Set XXIII
Date 5-13-76
Liquid level = 129.6 cm
Note: Superscripts denote ullage pressures in cm-H2O
Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude (kg/cm2)
.20
.10
0
70
80
90
100
110
120
130
Cold Length of Tube, Lc (cm) Measured from Top of Fitting on Dewar



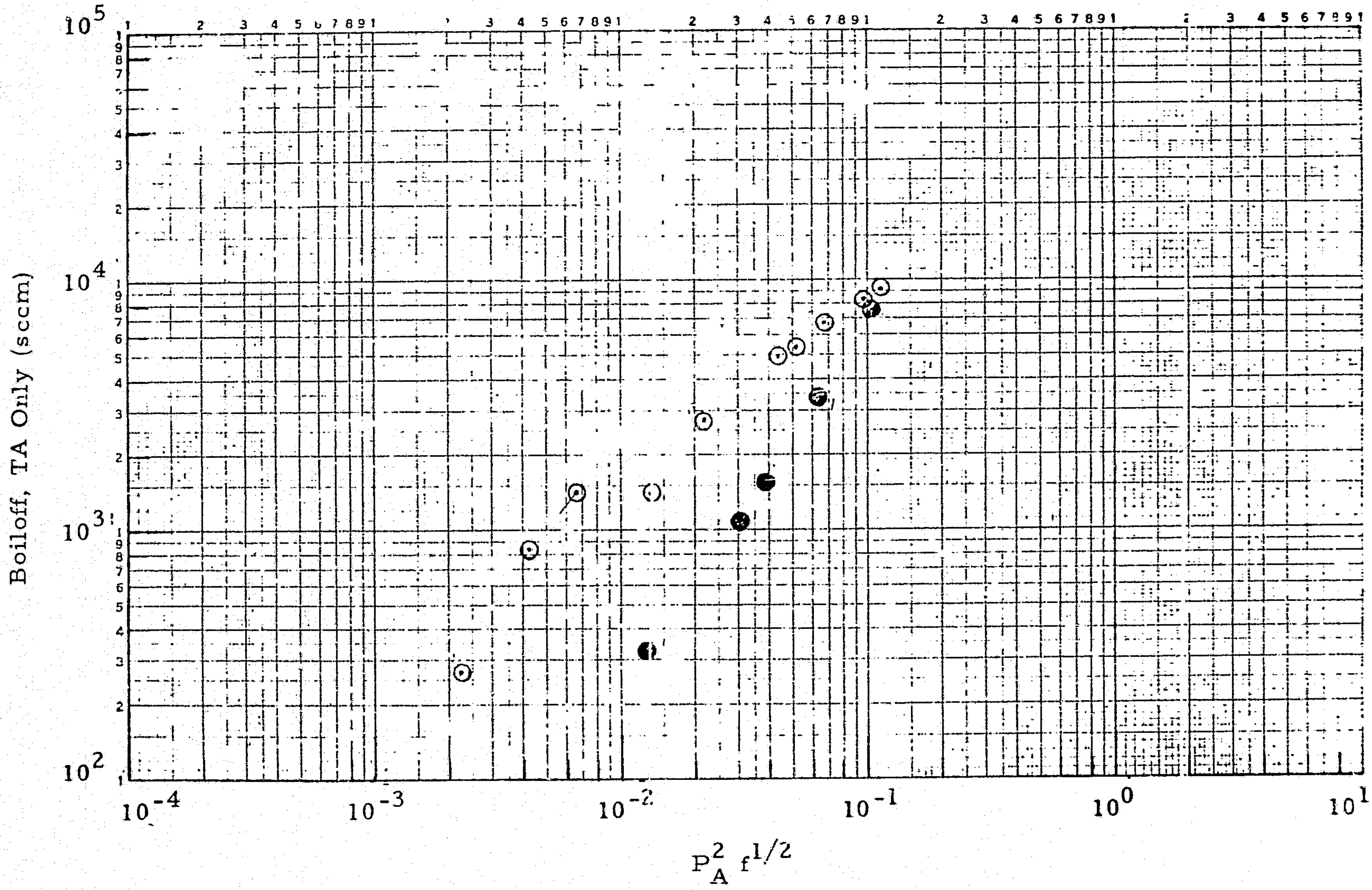
Tube 1b
Data Set XX
Date 5-7-76
Liquid level at start of test from top of fitting on Dewar = 115.7 cm
Data Set XXII
Date 5-12-76
Liquid level = 126.6 cm
Data Set XXIII
Date 5-13-76
Liquid level = 129.8
Note: Superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Frequency (Hz)
40
36
32
28
24
20
16
70
80
90
100
110
120
130
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar

Tube 1b 5-7-76
Data Set XX



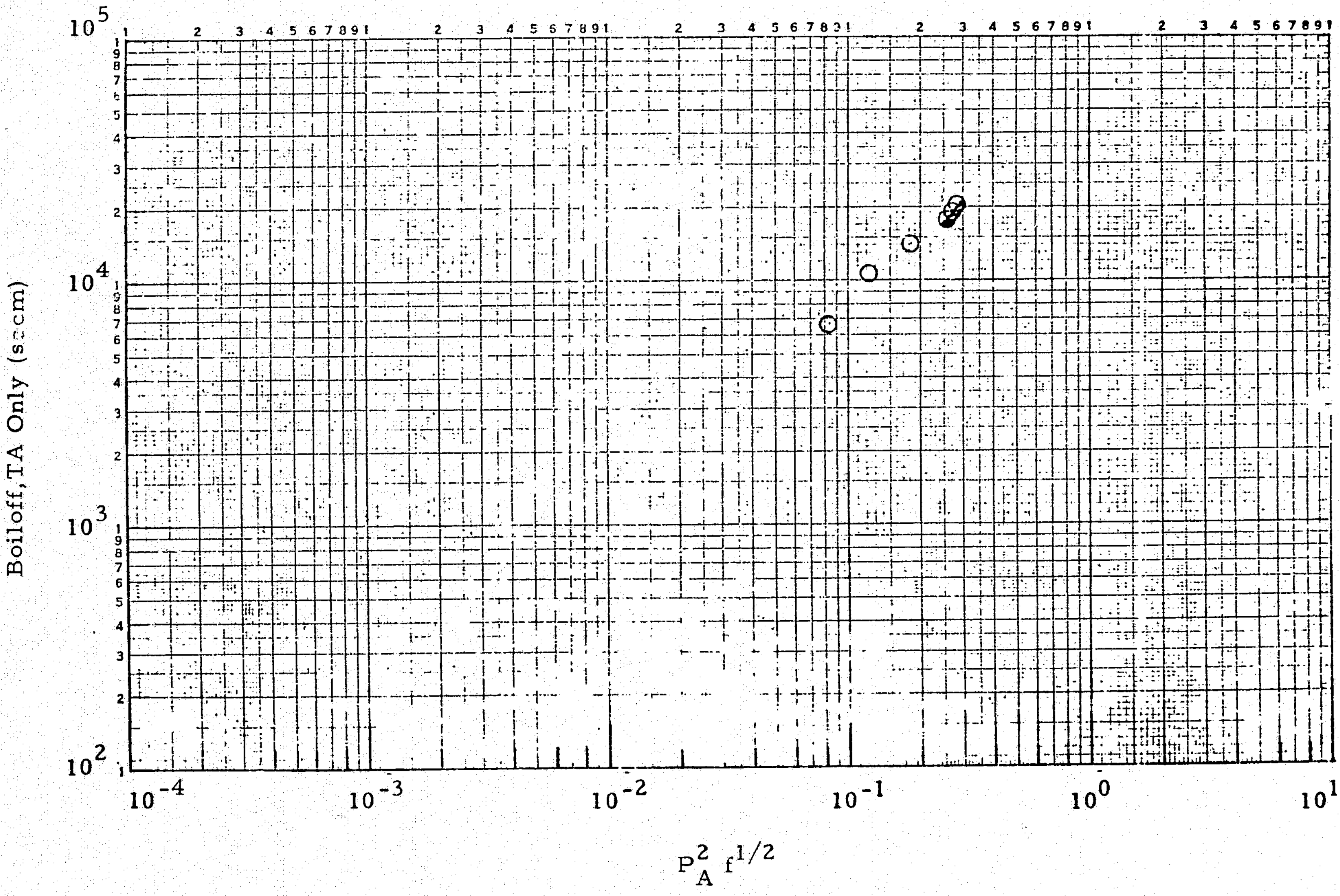
Tube 1 5-13-76

Data Set XXIII



C-2

Tube 1b   5-12-76
Data Set XXII



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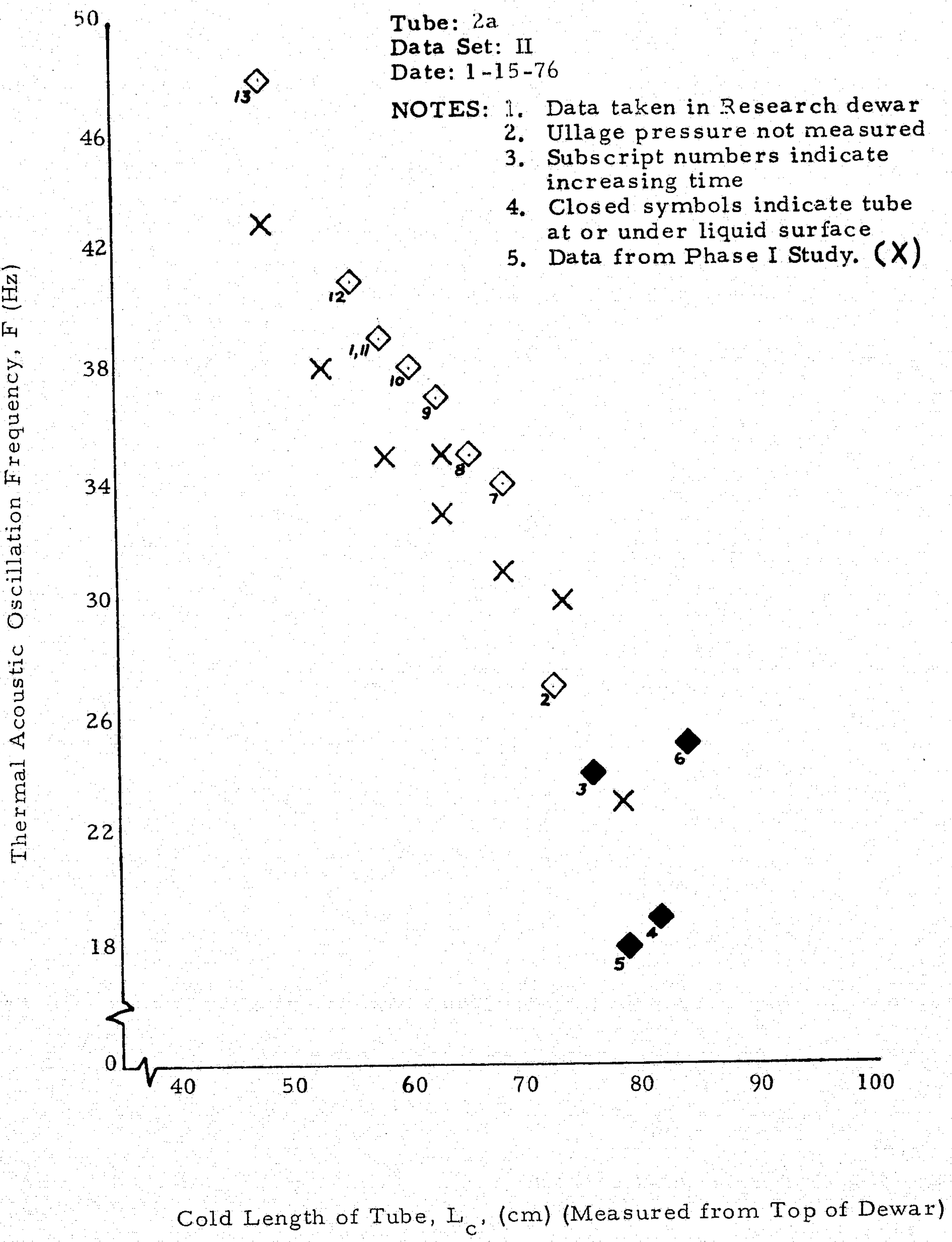
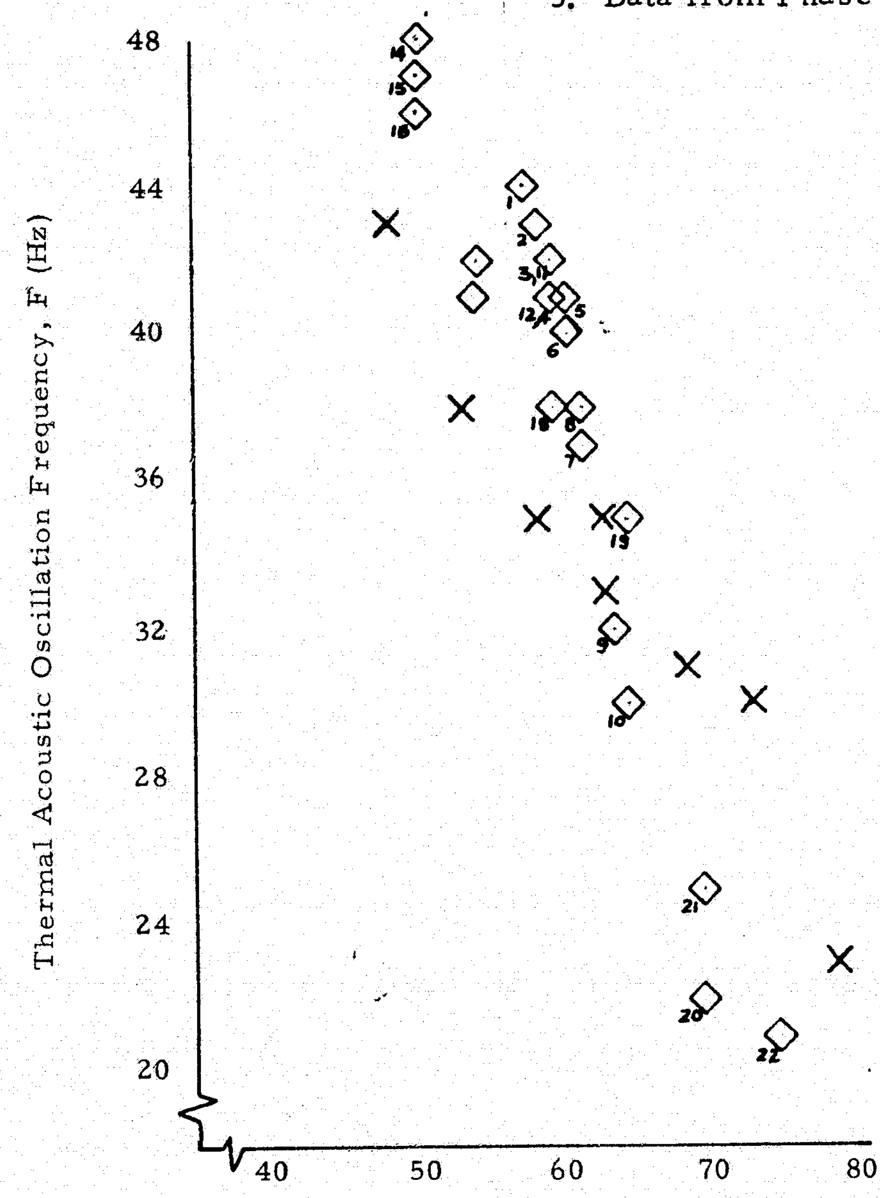
A.2 TUBE 2, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
2a	99	.657	.147	150
2b	99	.657	.147	150

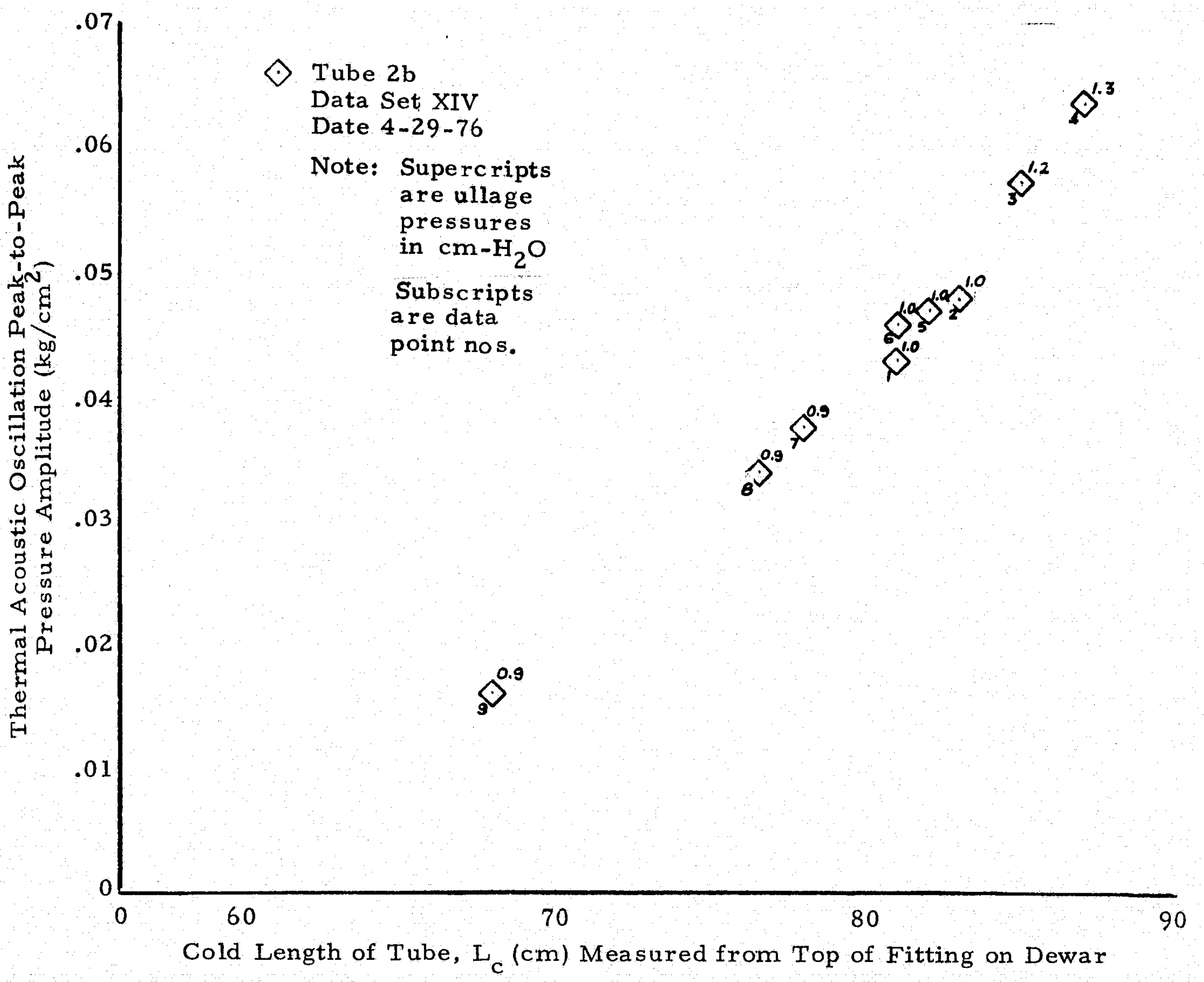

Tube: 2a
Data Set: II
Date: 1-15-76
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface
5. Data from Phase I Study. (X)
Thermal Acoustic Oscillation Frequency, F (Hz)
50
46
42
38
34
30
26
22
18
0
40
50
60
70
80
90
100
13
12
1,11
10
9
8
7
2
3
6
4
5
Cold Length of Tube, L_c, (cm) (Measured from Top of Dewar)

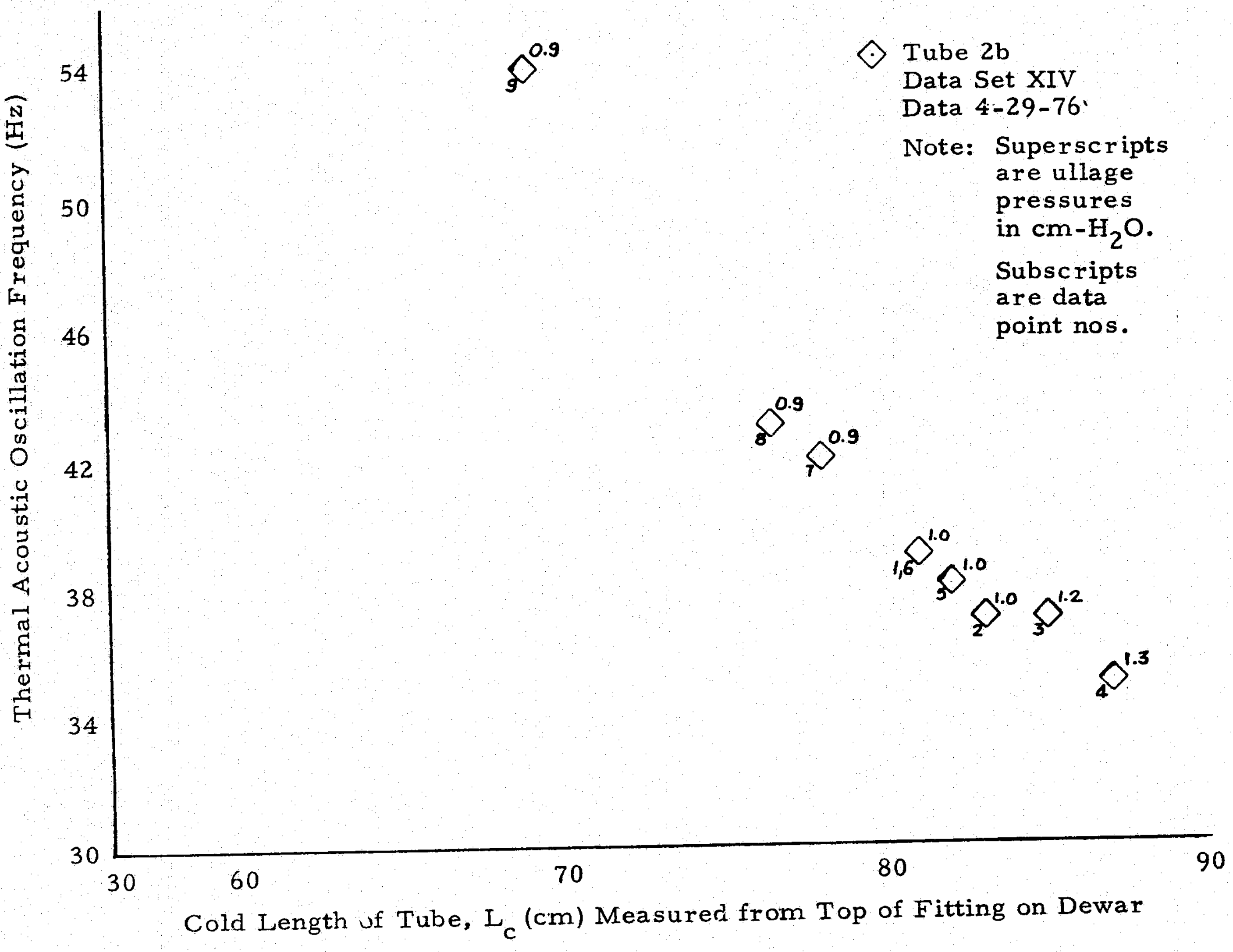
Tube: 2a
Data Set: V
Date: 2-12-76

NOTES:
1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface
5. Data from Phase I Study. (X)



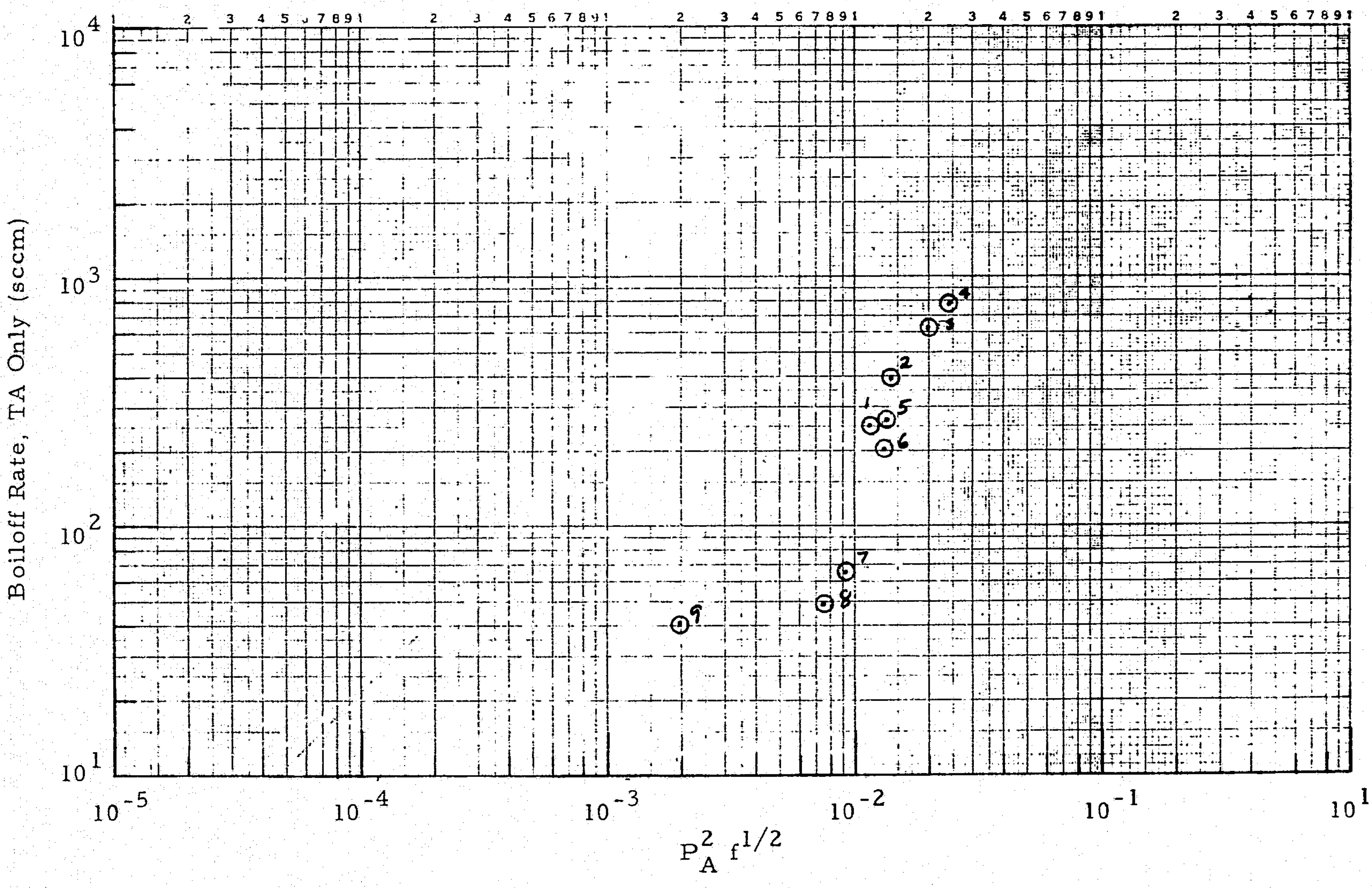
Cold Length of Tube, L_c, (cm)
(Measured from Top of Dewar)


Tube 2b
Data Set XIV
Date 4-29-76
Note: Superscripts are ullage pressures in cm-H_2O
Subscripts are data point nos.
Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude (kg/cm^2)
.07
.06
.05
.04
.03
.02
.01
0
0
60
70
80
90
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar


Tube 2b
Data Set XIV
Data 4-29-76
Note: Superscripts are ullage pressures in cm-H_2O.
Subscripts are data point nos.
Thermal Acoustic Oscillation Frequency (Hz)
54
50
46
42
38
34
30
30
60
70
80
90
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar
0.9
9
0.9
8
0.9
7
1.0
1,6
1.0
5
1.0
2
1.2
3
1.3
4

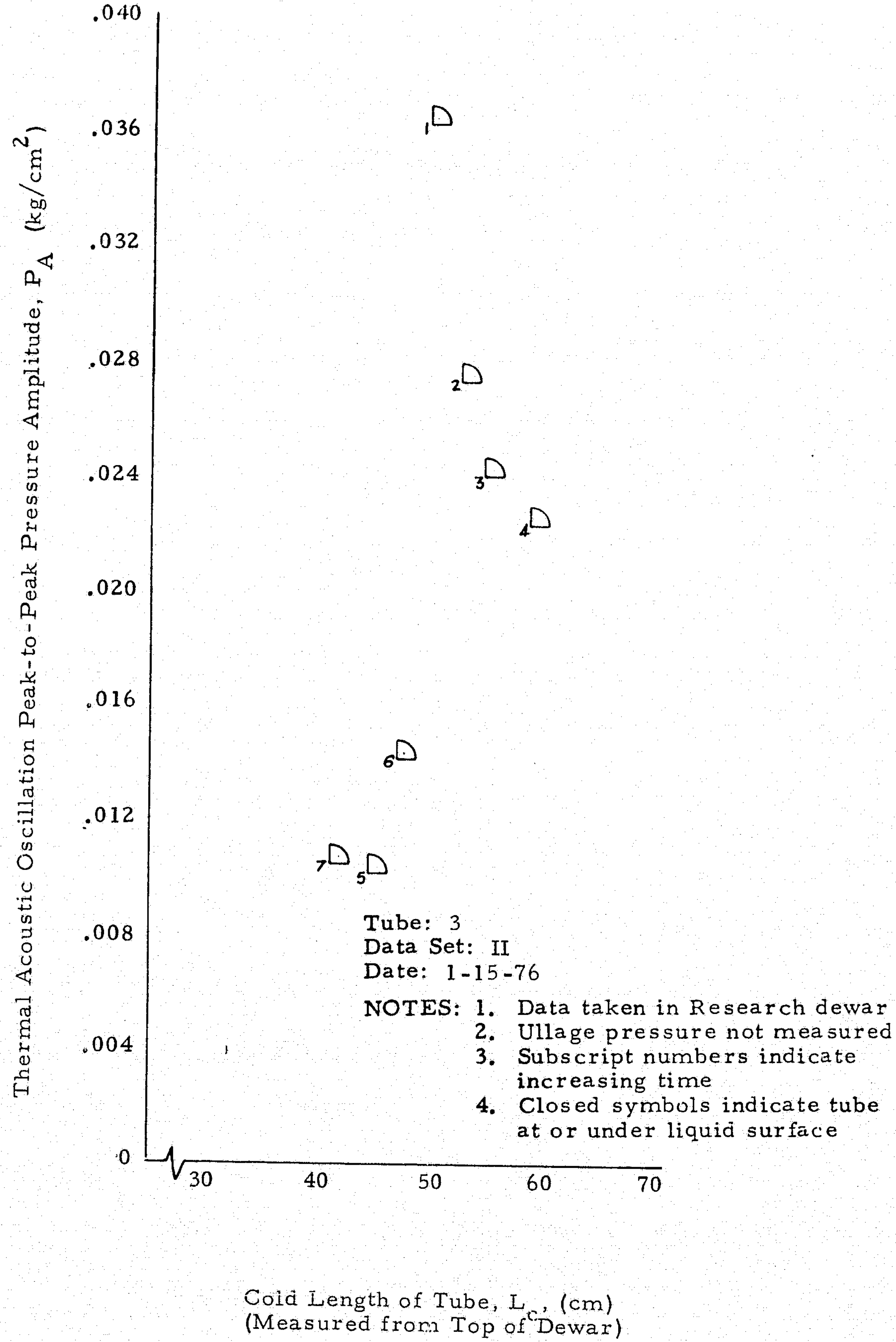
Tube 2b
Data Set XIV
Date: 4-29-76

NOTE: Superscripts are data point numbers: 1-4 = increasing L_{cold}; 5-9 = decreasing L_{cold}; liquid level not known.



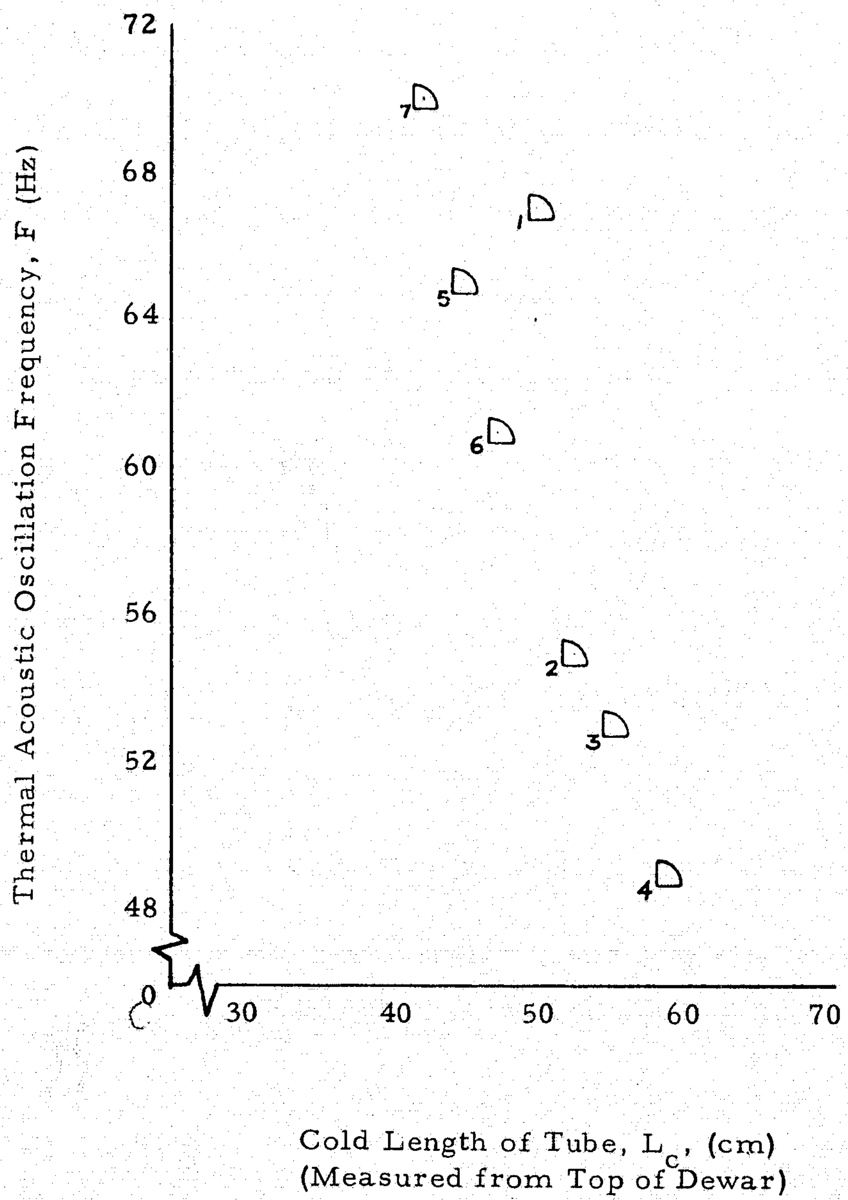
A.3 TUBE 3, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
3	66	.657	.147	100


Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude, P_A (kg/cm^2)
.040
.036
.032
.028
.024
.020
.016
.012
.008
.004
0
30
40
50
60
70
1
2
3
4
5
6
7
Tube: 3
Data Set: II
Date: 1-15-76
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface
Cold Length of Tube, L_c, (cm)
(Measured from Top of Dewar)

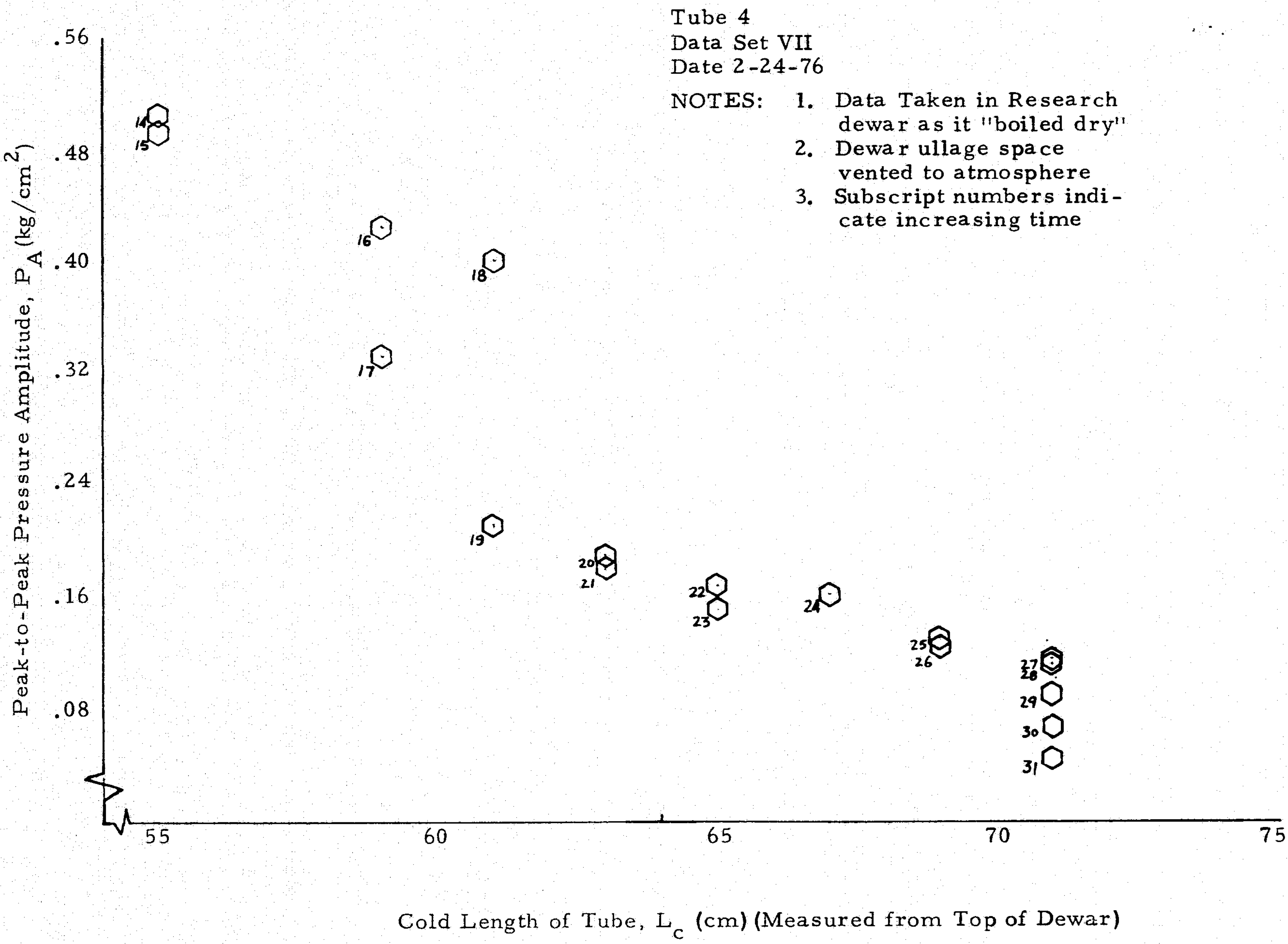
Tube: 3
Data Set: II
Date: 1-15-76

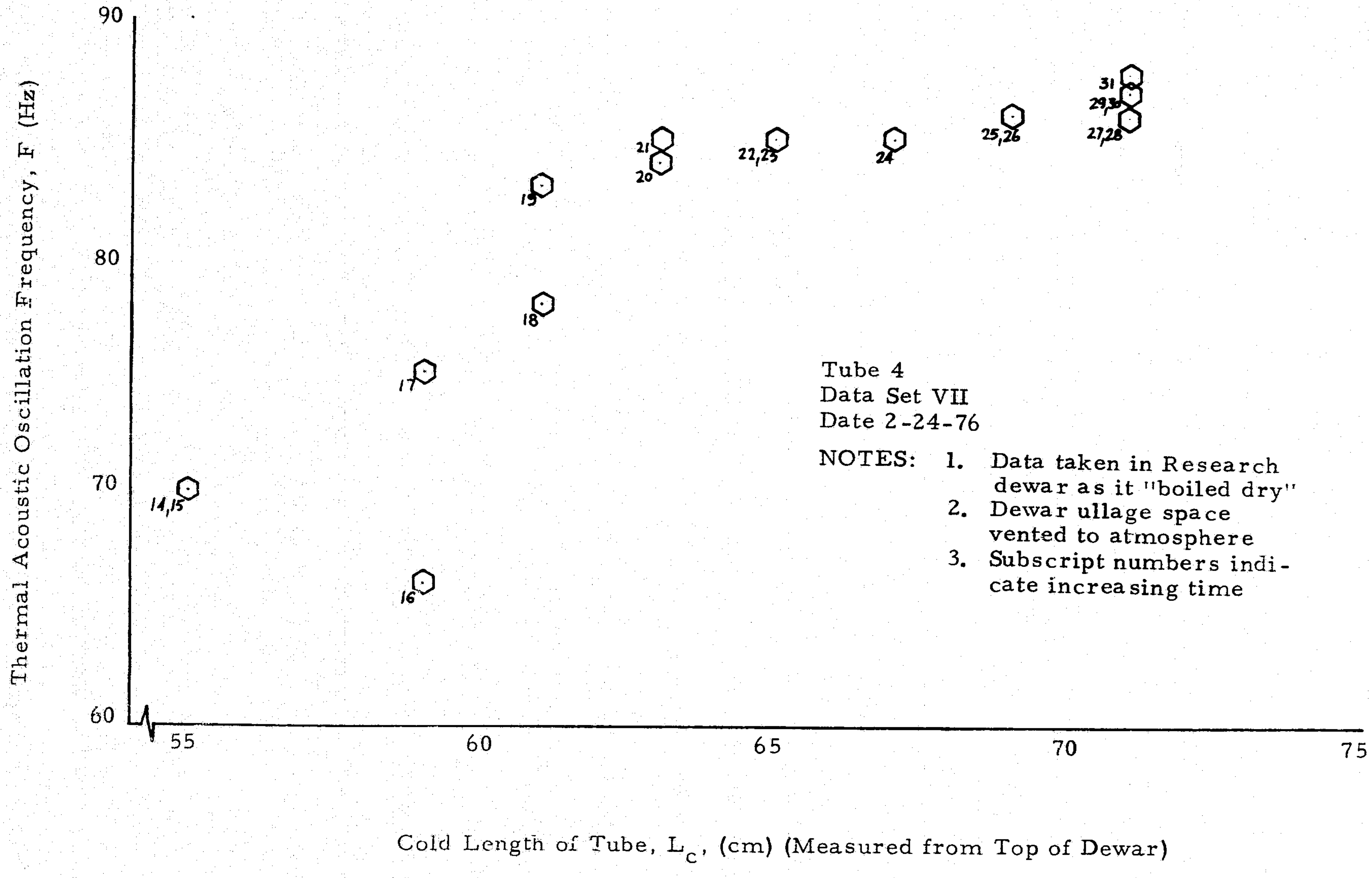
NOTES: 1. Data taken in Research dewar
2. Ullage pressure not measured
3. Subscript numbers indicate increasing time
4. Closed symbols indicate tube at or under liquid surface

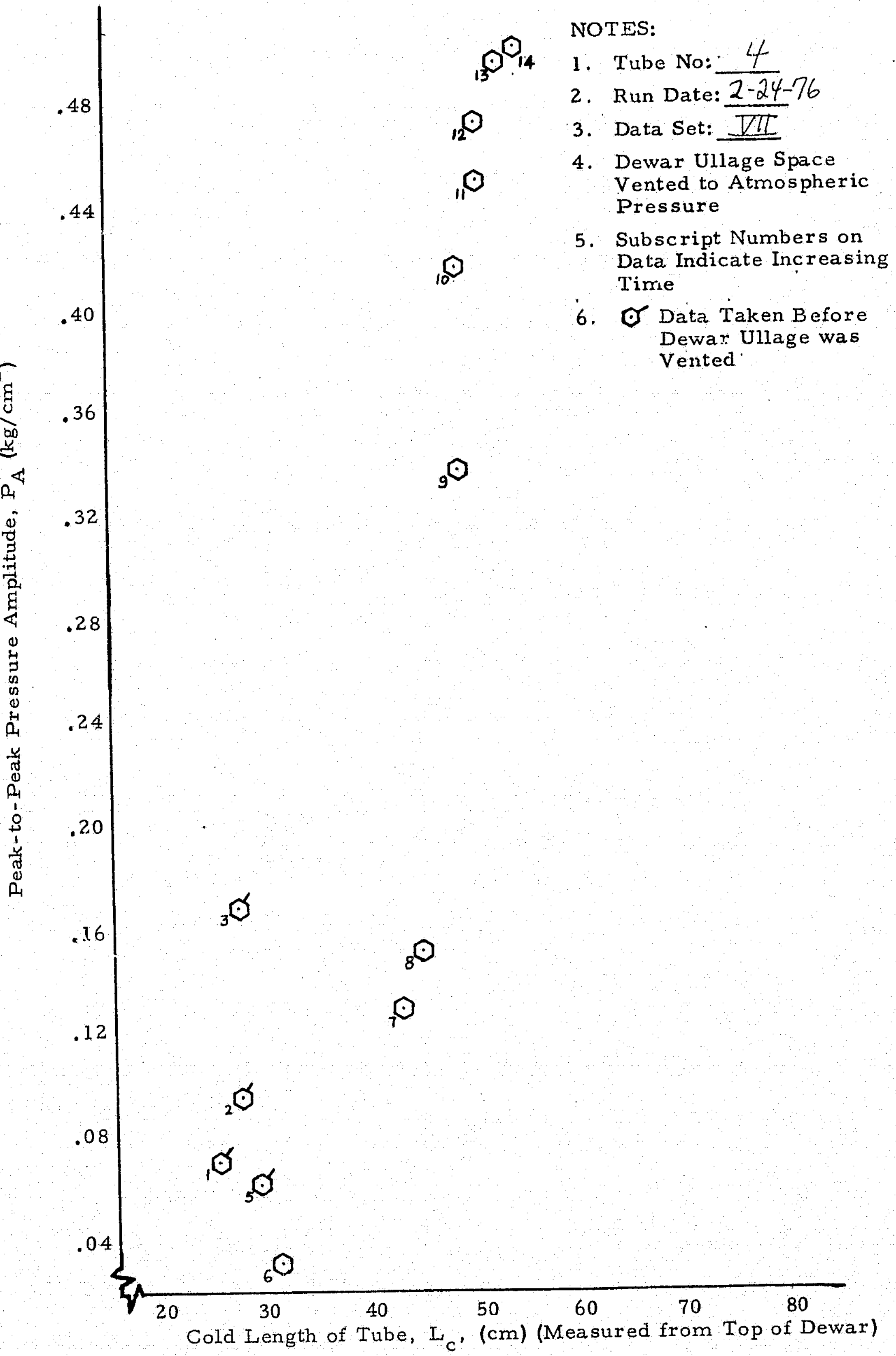


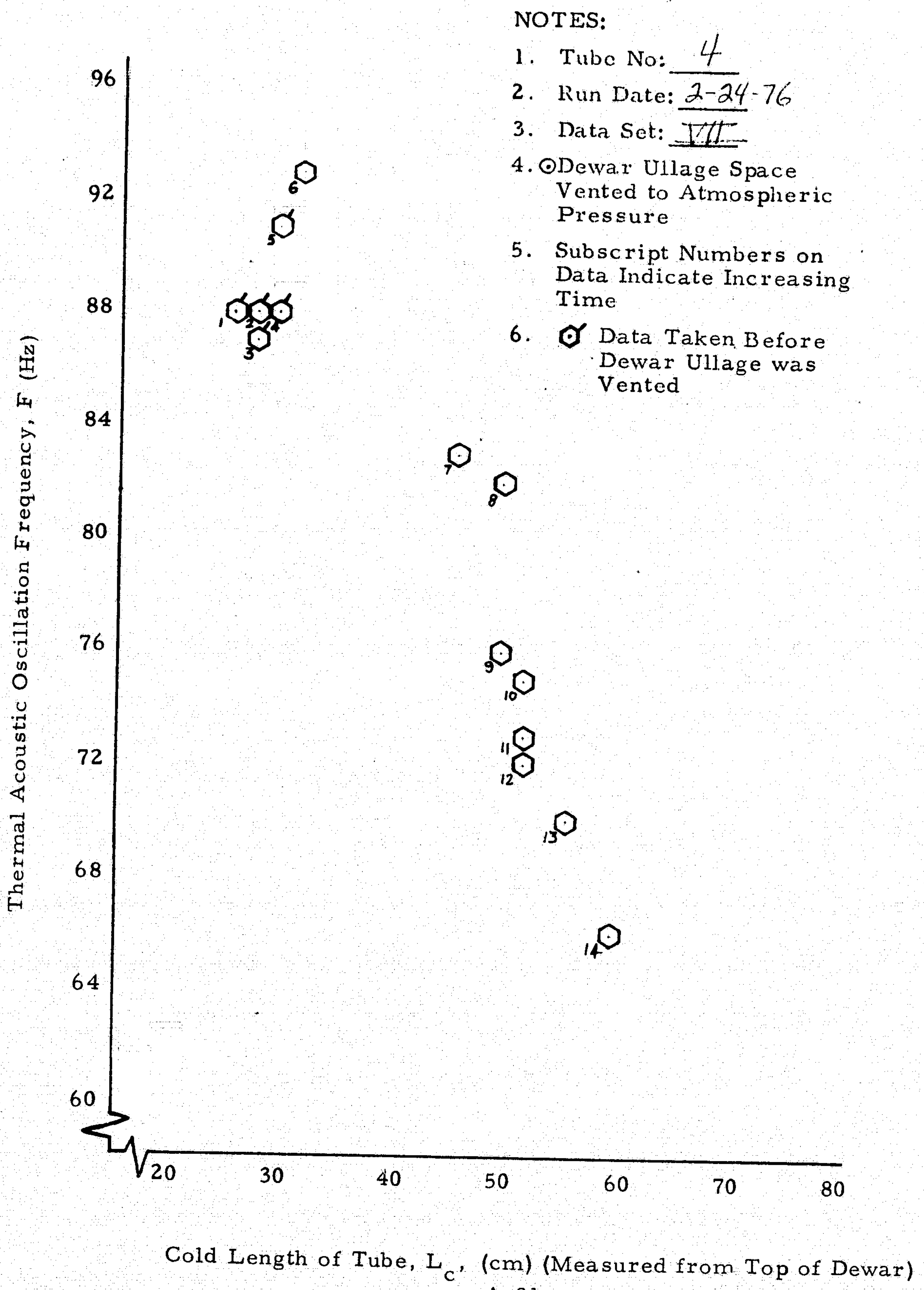
A.4 TUBE 4, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
4	110	.711	.048	155

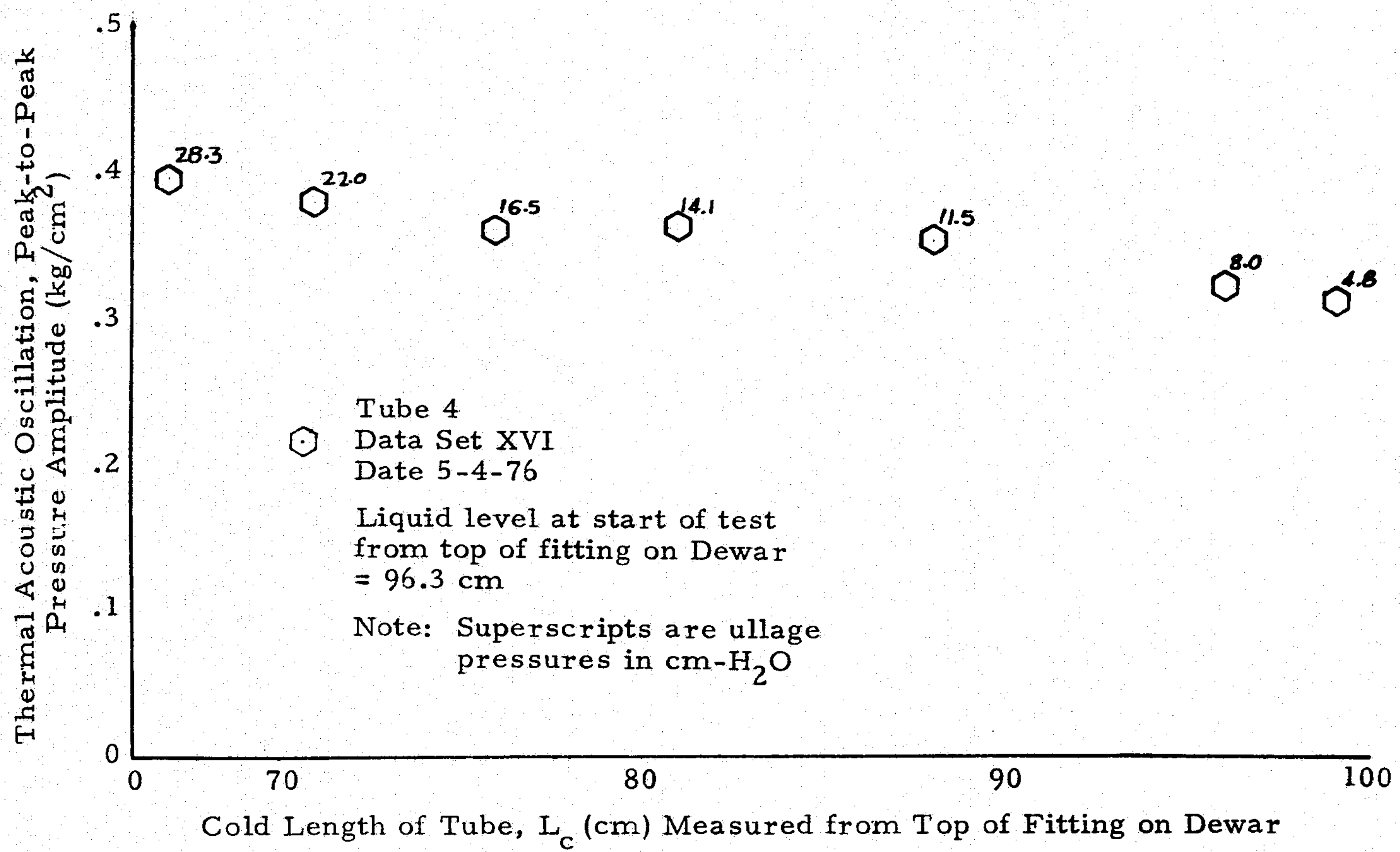

Tube 4
Data Set VII
Date 2-24-76
NOTES: 1. Data Taken in Research dewar as it "boiled dry"
2. Dewar ullage space vented to atmosphere
3. Subscript numbers indicate increasing time
Peak-to-Peak Pressure Amplitude, P_A (kg/cm^2)
.56
.48
.40
.32
.24
.16
.08
55
60
65
70
75
Cold Length of Tube, L_c (cm) (Measured from Top of Dewar)
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

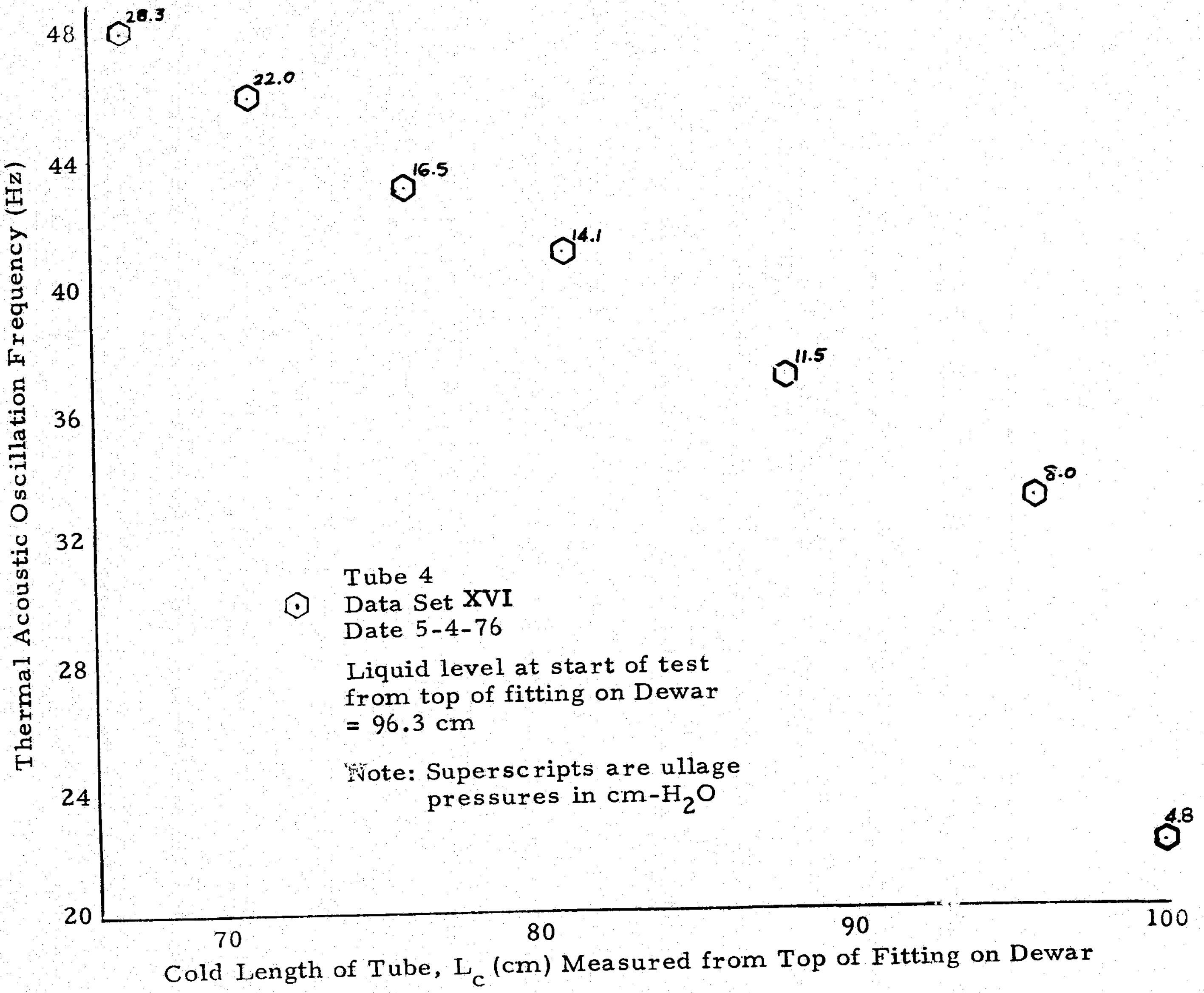

Thermal Acoustic Oscillation Frequency, F (Hz)
90
80
70
60
55
60
65
70
75
Cold Length of Tube, L_c, (cm) (Measured from Top of Dewar)
14,15
16
17
18
19
20
21
22,23
24
25,26
27,28
29,30
31
Tube 4
Data Set VII
Date 2-24-76
NOTES: 1. Data taken in Research dewar as it "boiled dry"
2. Dewar ullage space vented to atmosphere
3. Subscript numbers indicate increasing time

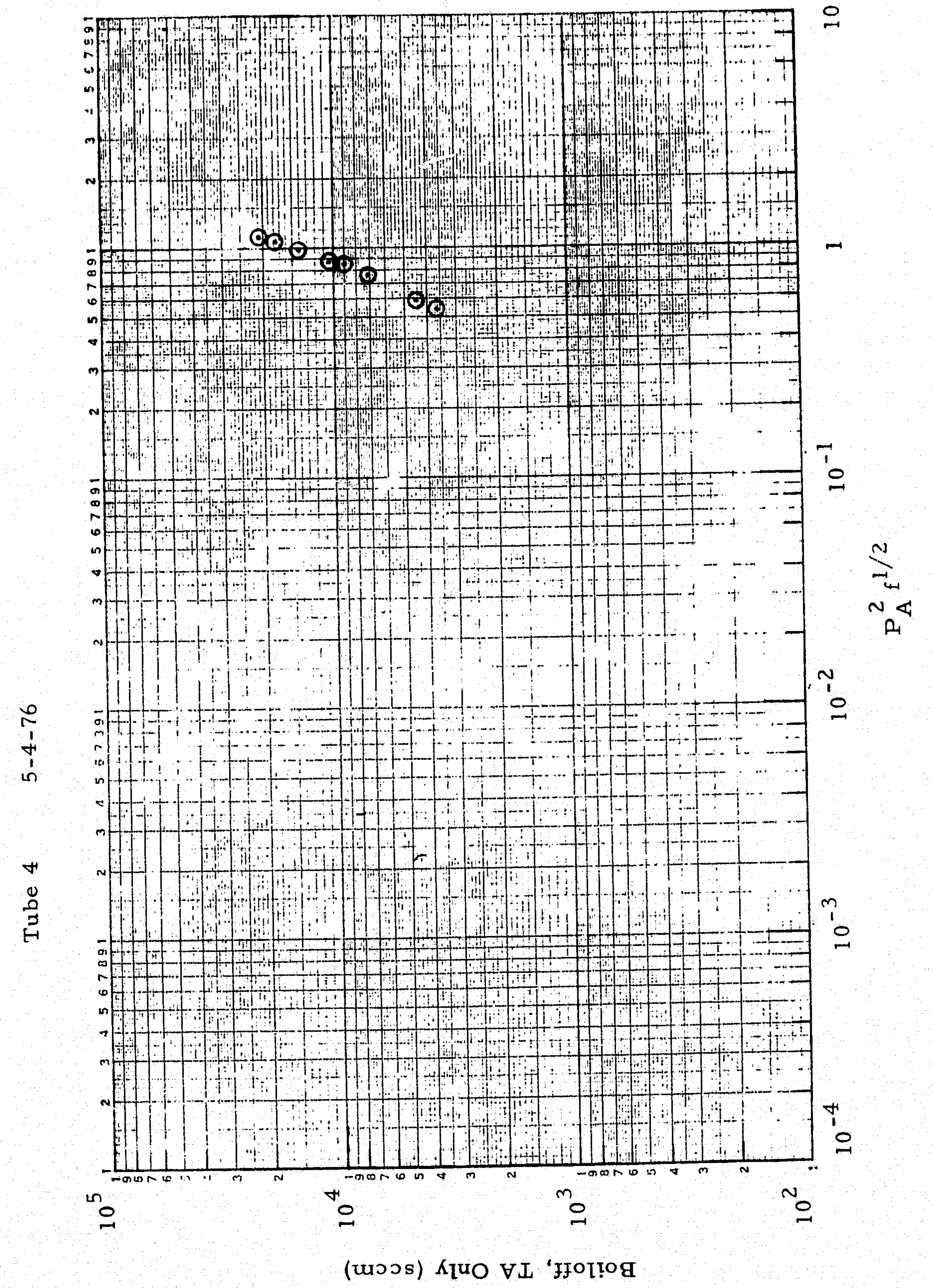

NOTES:
1. Tube No: 4
2. Run Date: 2-24-76
3. Data Set: VII
4. Dewar Ullage Space Vented to Atmospheric Pressure
5. Subscript Numbers on Data Indicate Increasing Time
6. Data Taken Before Dewar Ullage was Vented
Peak-to-Peak Pressure Amplitude, P_A (kg/cm^2)
.48
.44
.40
.36
.32
.28
.24
.20
.16
.12
.08
.04
20
30
40
50
60
70
80
Cold Length of Tube, L_c, (cm) (Measured from Top of Dewar)
1
2
3
5
6
7
8
9
10
11
12
13
14



NOTES:
1. Tube No: 4
2. Run Date: 2-24-76
3. Data Set: VII
4. ⊙ Dewar Ullage Space Vented to Atmospheric Pressure
5. Subscript Numbers on Data Indicate Increasing Time
6. Data Taken Before Dewar Ullage was Vented
Thermal Acoustic Oscillation Frequency, F (Hz)
96
92
88
84
80
76
72
68
64
60
20
30
40
50
60
70
80
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Cold Length of Tube, L_c, (cm) (Measured from Top of Dewar)

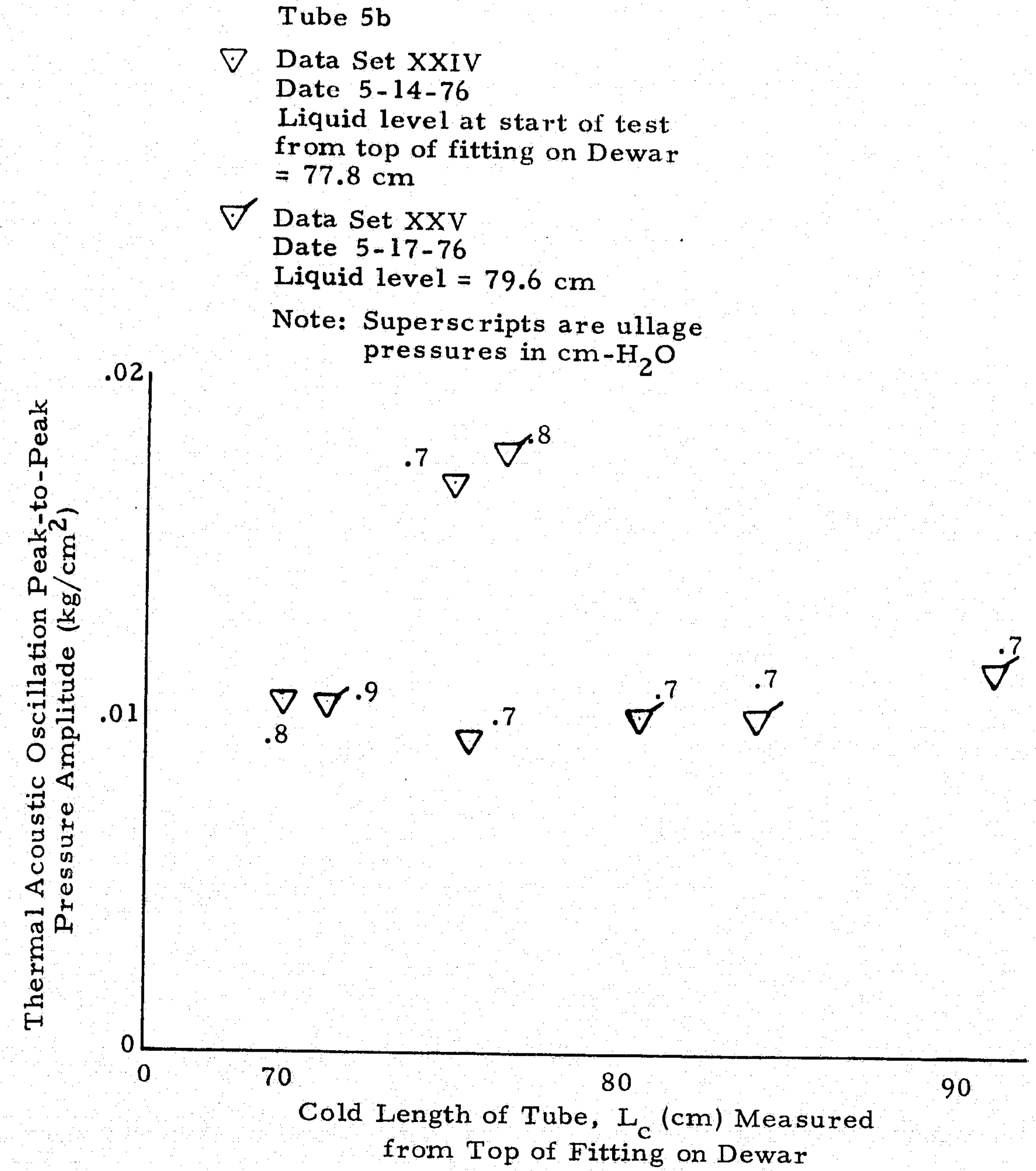

Thermal Acoustic Oscillation, Peak-to-Peak Pressure Amplitude (kg/cm^2)
.5
.4
.3
.2
.1
0
0
70
80
90
100
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar
28.3
22.0
16.5
14.1
11.5
8.0
4.8
Tube 4
Data Set XVI
Date 5-4-76
Liquid level at start of test from top of fitting on Dewar = 96.3 cm
Note: Superscripts are ullage pressures in cm-H_2O

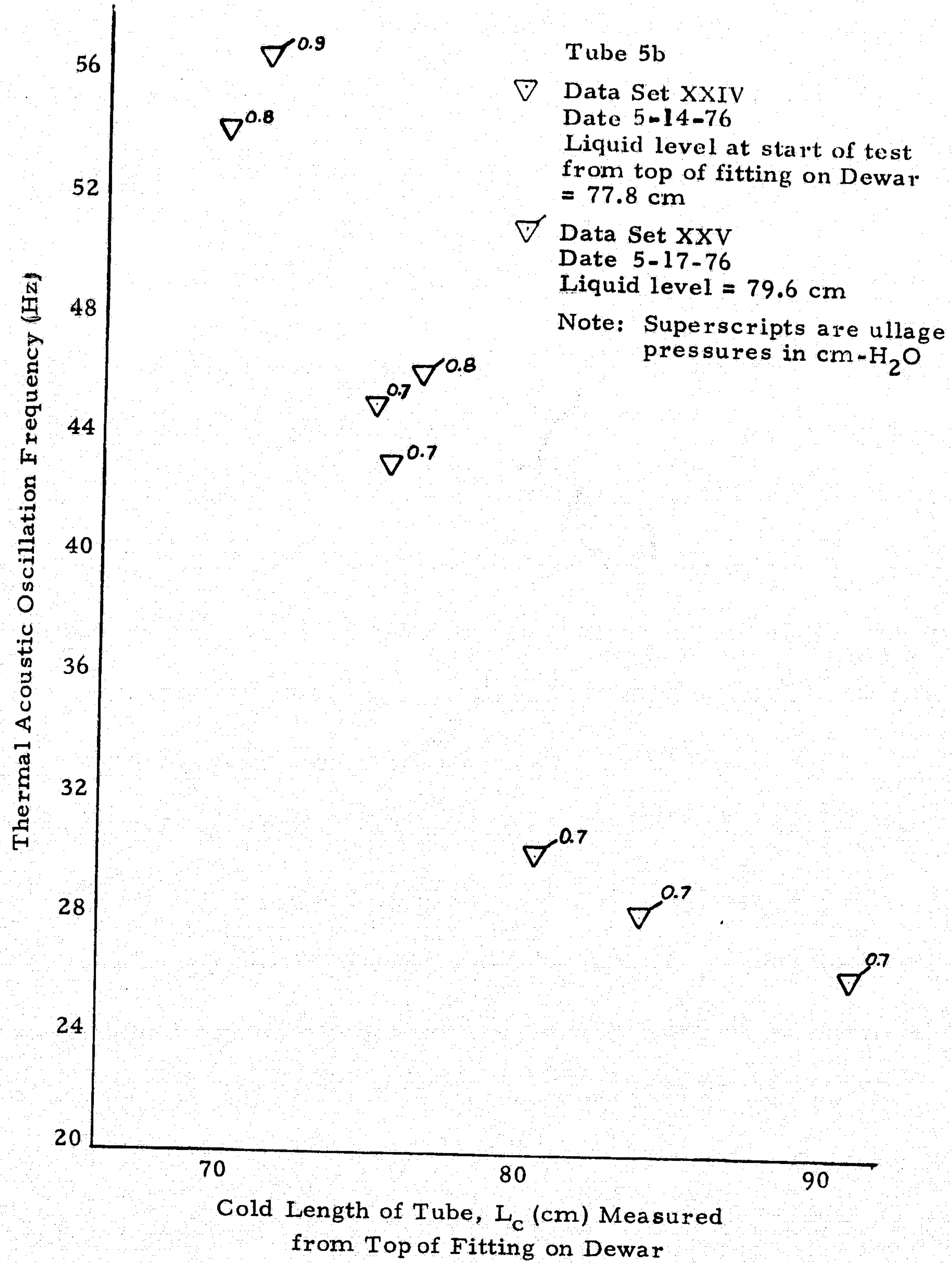

Thermal Acoustic Oscillation Frequency (Hz)
48
44
40
36
32
28
24
20
28.3
22.0
16.5
14.1
11.5
8.0
4.8
Tube 4
Data Set XVI
Date 5-4-76
Liquid level at start of test
from top of fitting on Dewar
= 96.3 cm
Note: Superscripts are ullage
pressures in cm-H_2O
70
80
90
100
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar

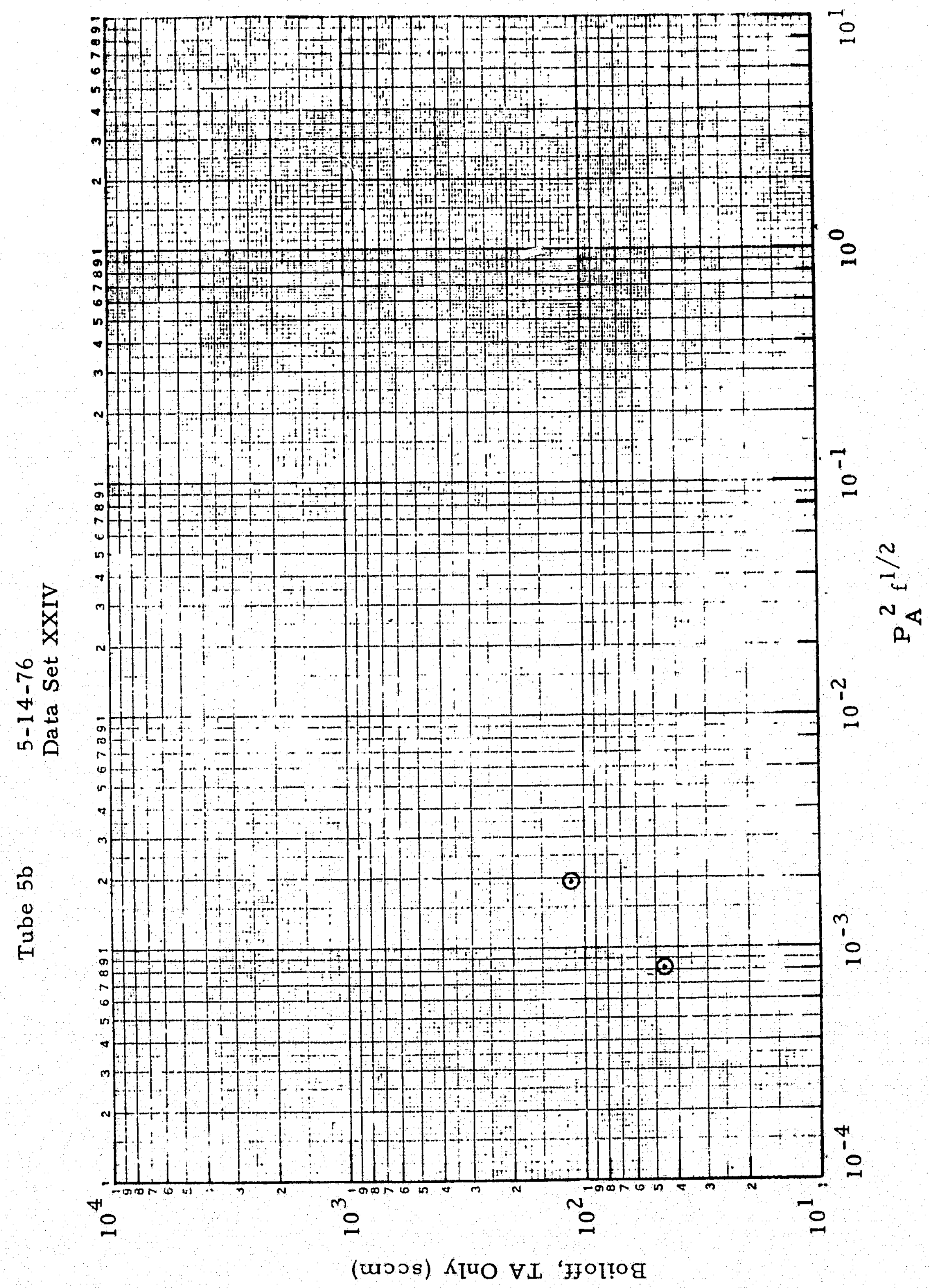

Tube 4 5-4-76
$P_A^2 f^{1/2}$
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^5
10^4
10^3
10^2
Boiloff, TA Only (sccm)

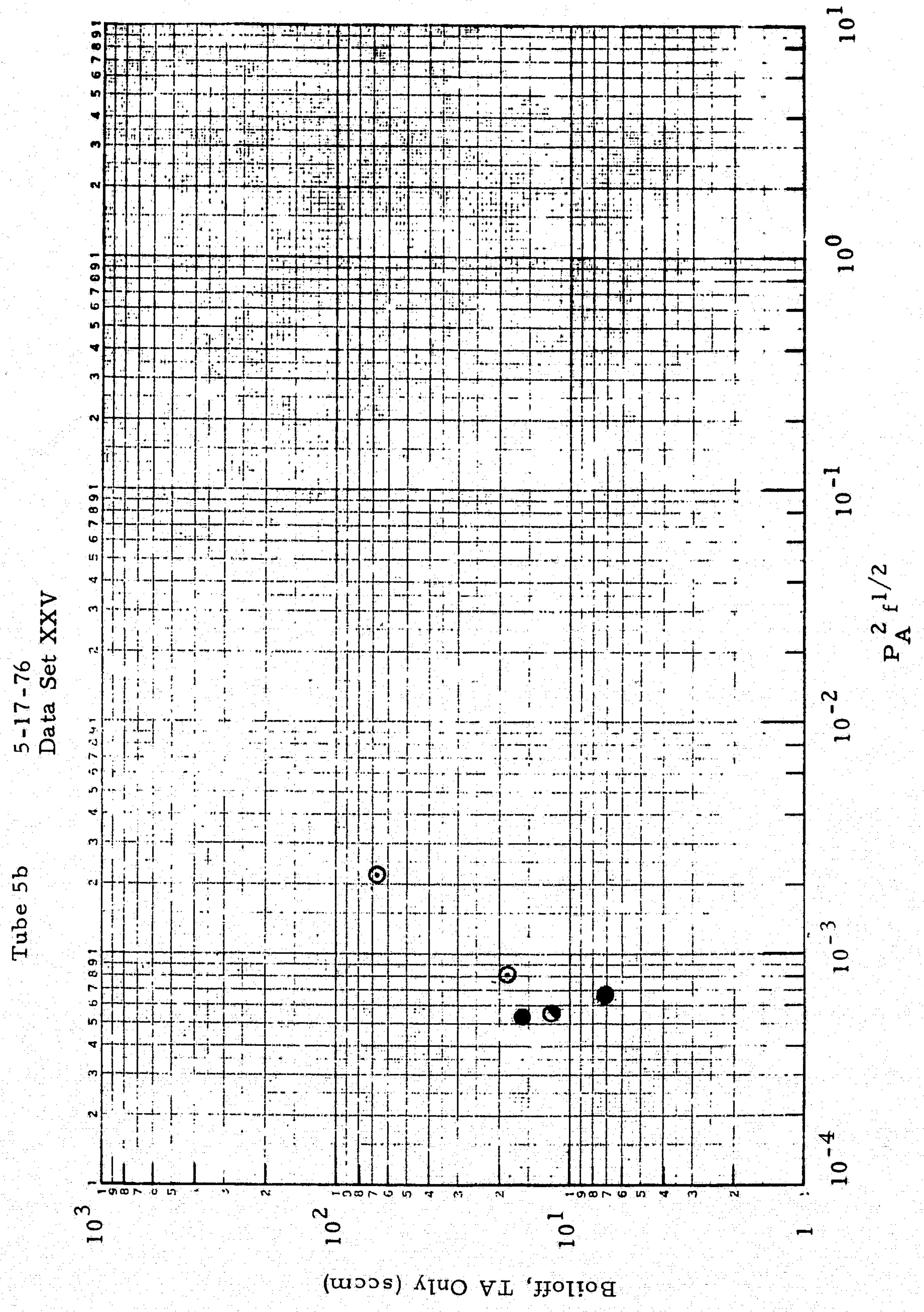
A.5 TUBE 5, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
5a	97	.975	.147	100
5b	97	.975	.147	100
5c	97	.975	.147	100


Tube 5b
Data Set XXIV
Date 5-14-76
Liquid level at start of test from top of fitting on Dewar = 77.8 cm
Data Set XXV
Date 5-17-76
Liquid level = 79.6 cm
Note: Superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude (kg/cm^2)
.02
.01
0
0
70
80
90
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar


Tube 5b
Data Set XXIV
Date 5-14-76
Liquid level at start of test from top of fitting on Dewar = 77.8 cm
Data Set XXV
Date 5-17-76
Liquid level = 79.6 cm
Note: Superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Frequency (Hz)
56
52
48
44
40
36
32
28
24
20
70
80
90
0.9
0.8
0.8
0.7
0.7
0.7
0.7
0.7
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar


Tube 5b
5-14-76
Data Set XXIV
$P_A^2 f^{1/2}$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Boiloff, TA Only (sccm)
10^4
10^3
10^2
10^1


Tube 5b
5-17-76
Data Set XXV
$P_A^2 f^{1/2}$
Boiloff, TA Only (sccm)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{3}
10^{2}
10^{1}
1

A.6 TUBE 6, STAINLESS STEEL 304

Tube	Length (cm)	Inside Diameter (cm)	Wall Thickness	Length to Inside Diameter Ratio
6a	148	.657	.147	225
6b	148	.657	.147	225
6c	148	.627	.162	236

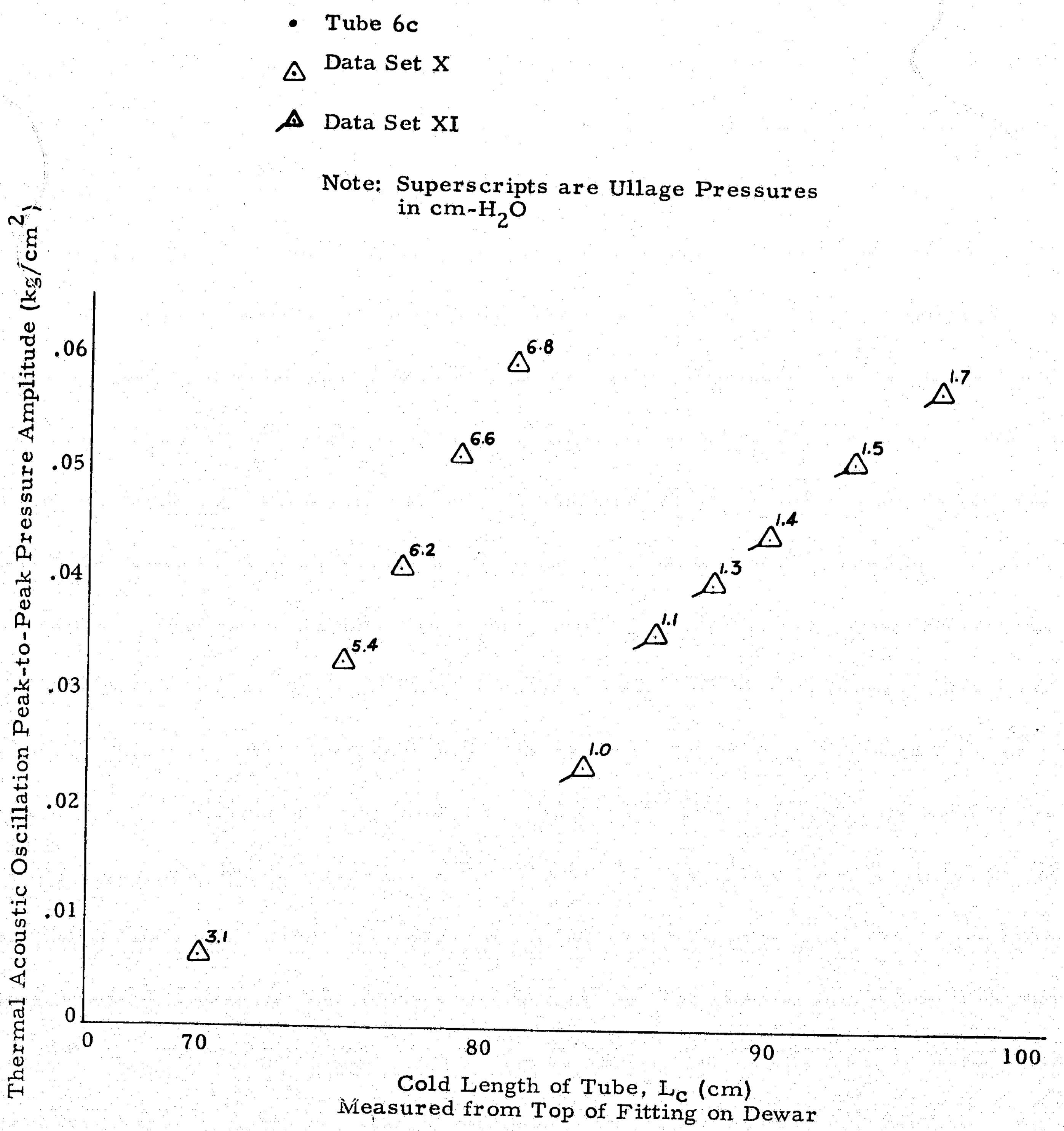


Fig. 1 - Pressure Amplitude vs Cold Length of Tube for Tube 1c at Two Different Ullage Pressure Ranges

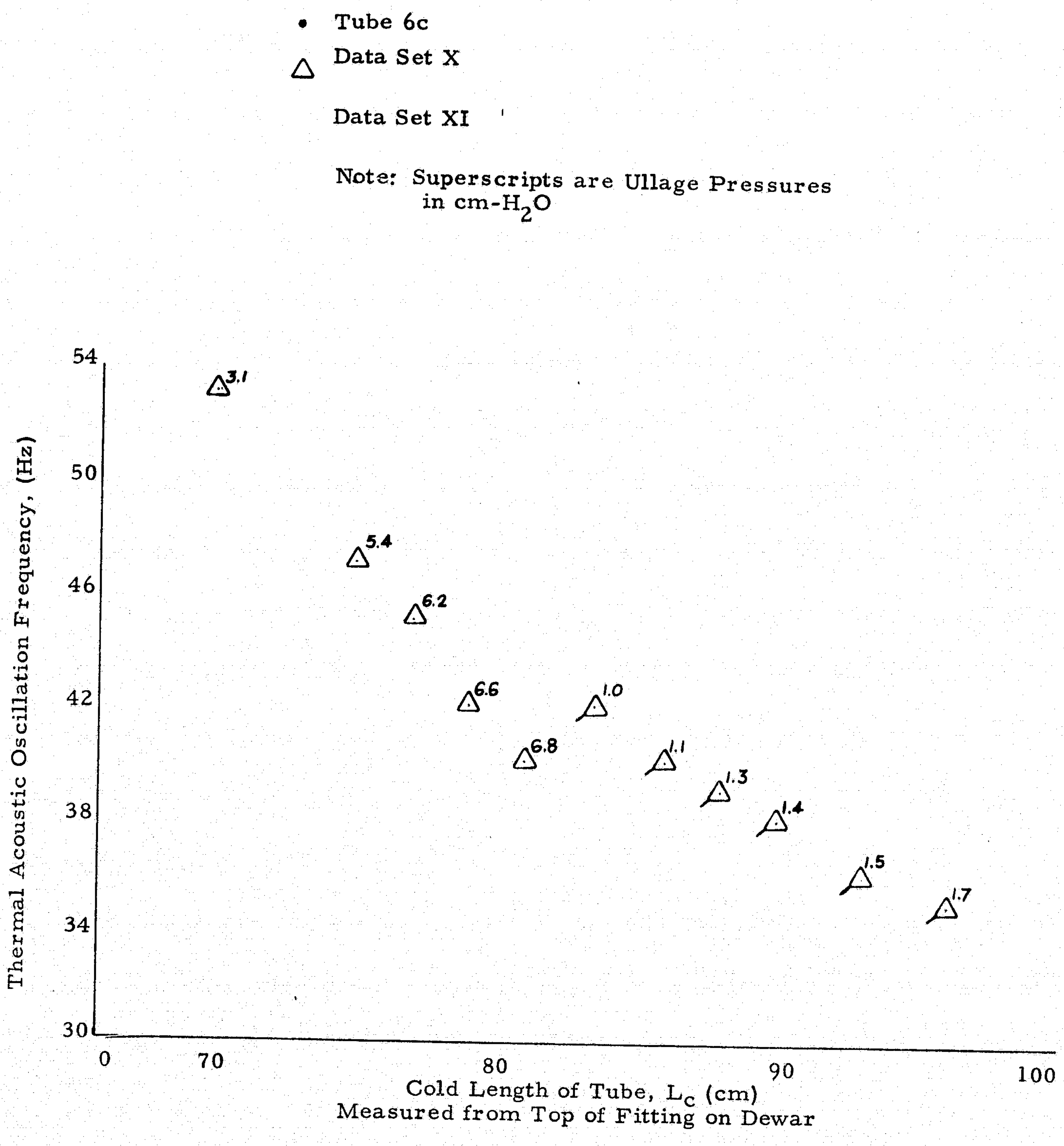
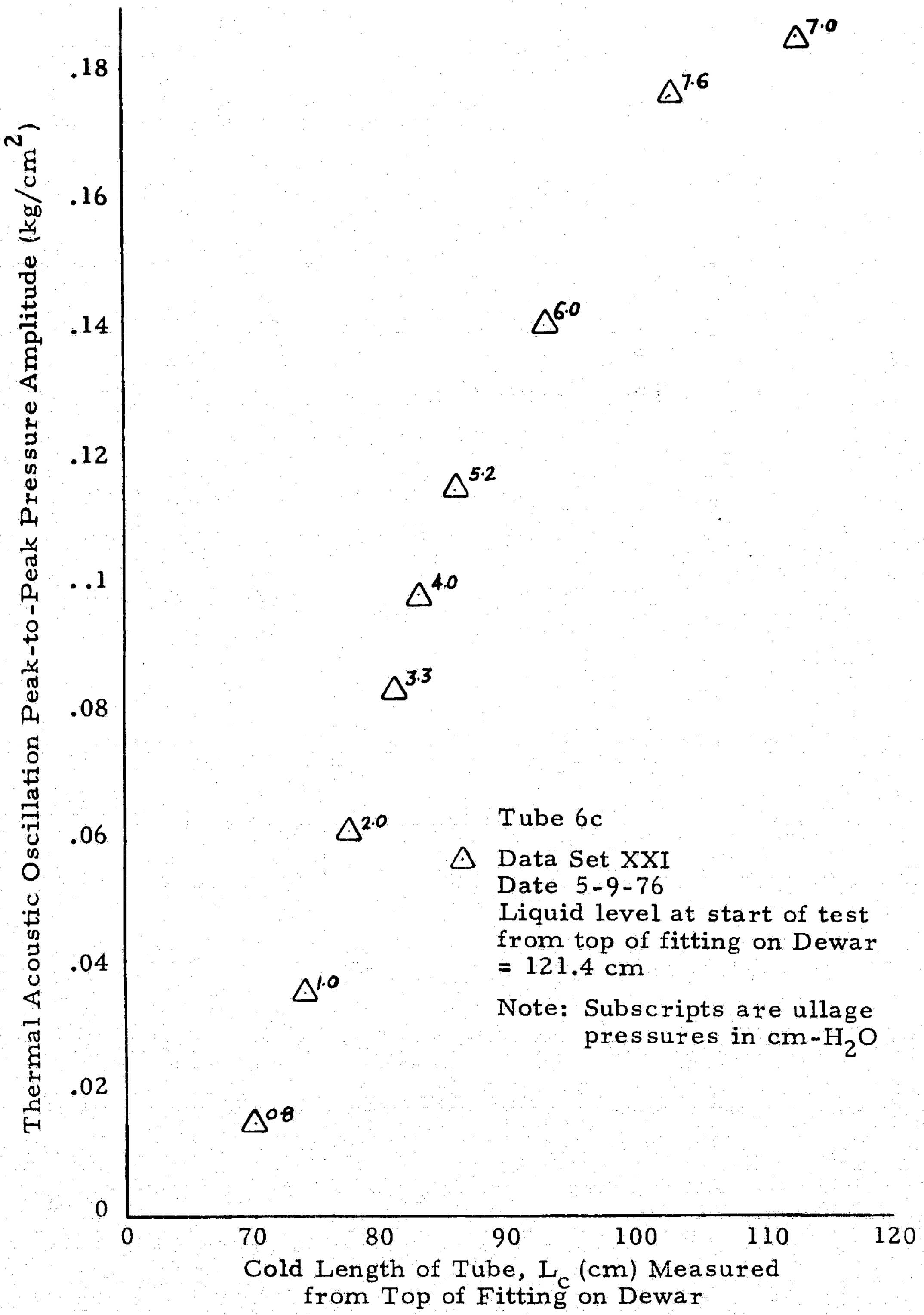
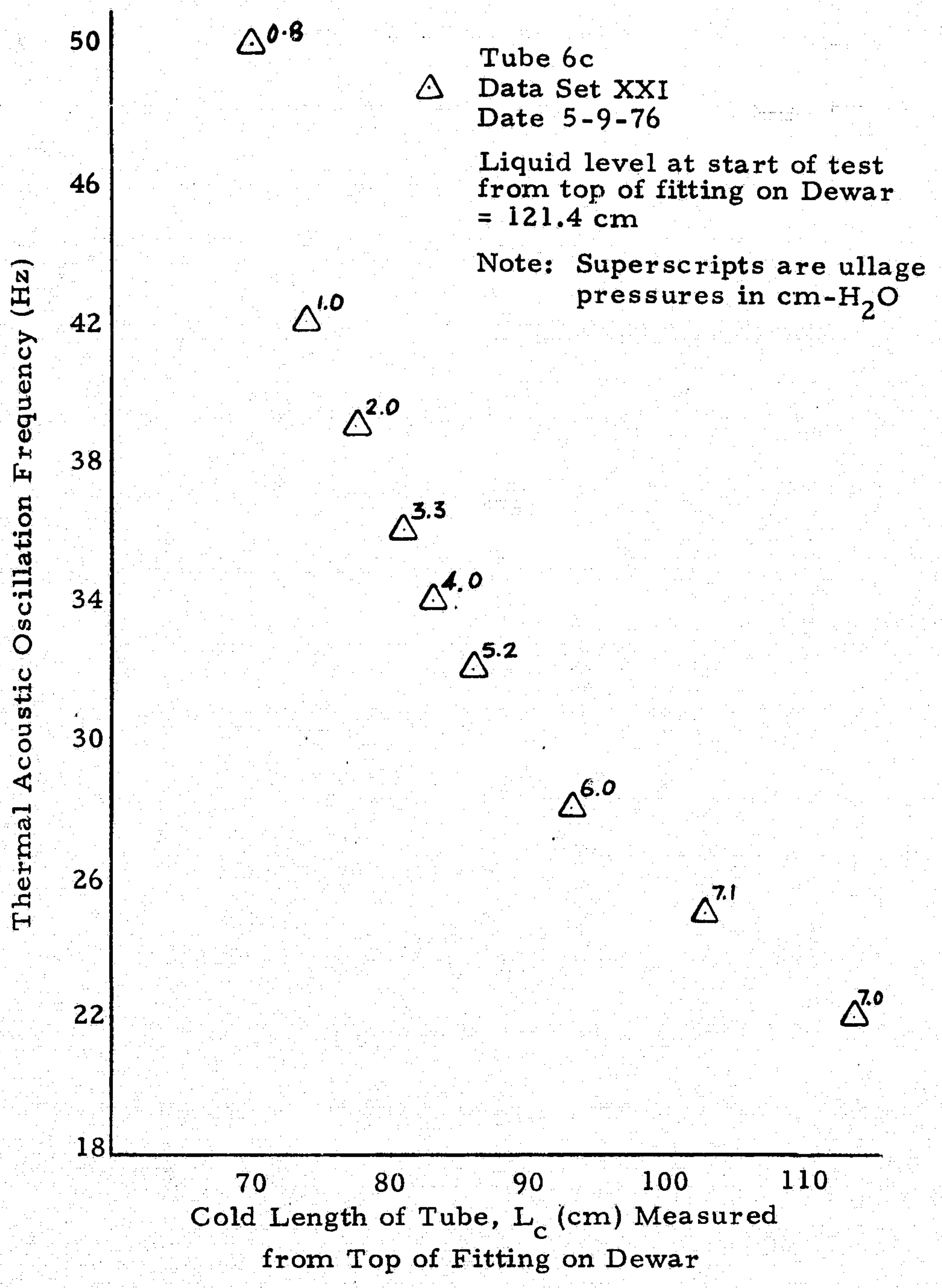
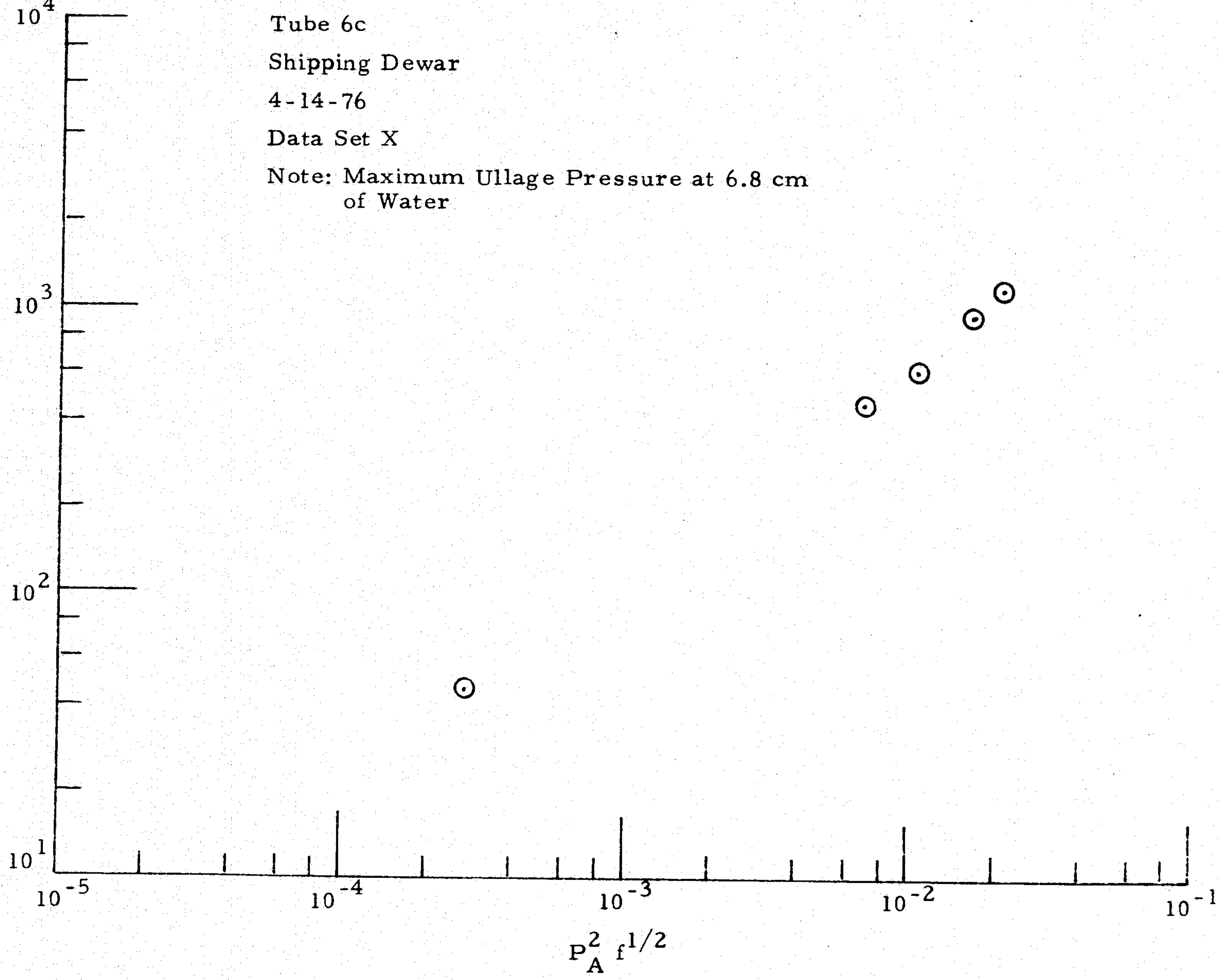
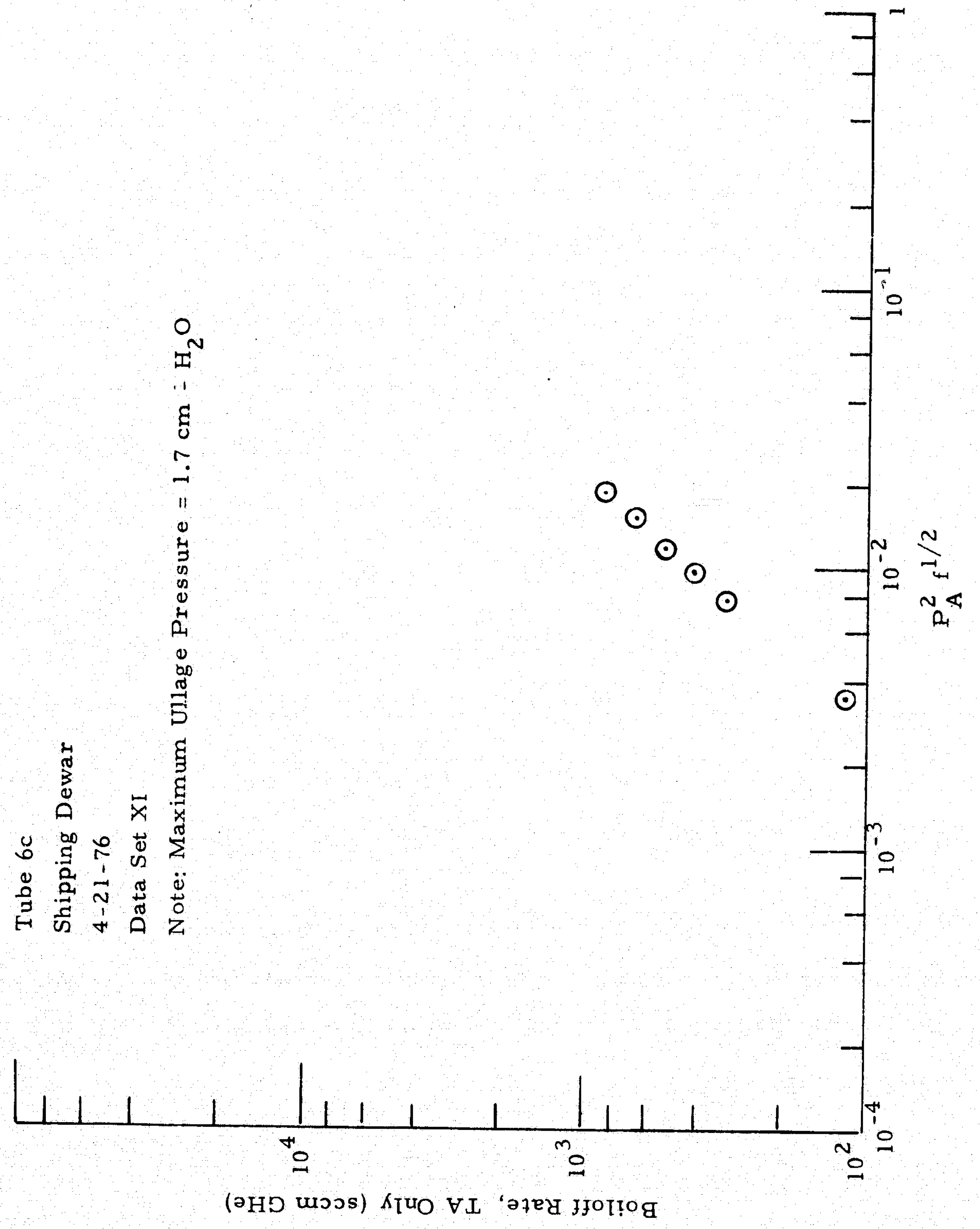


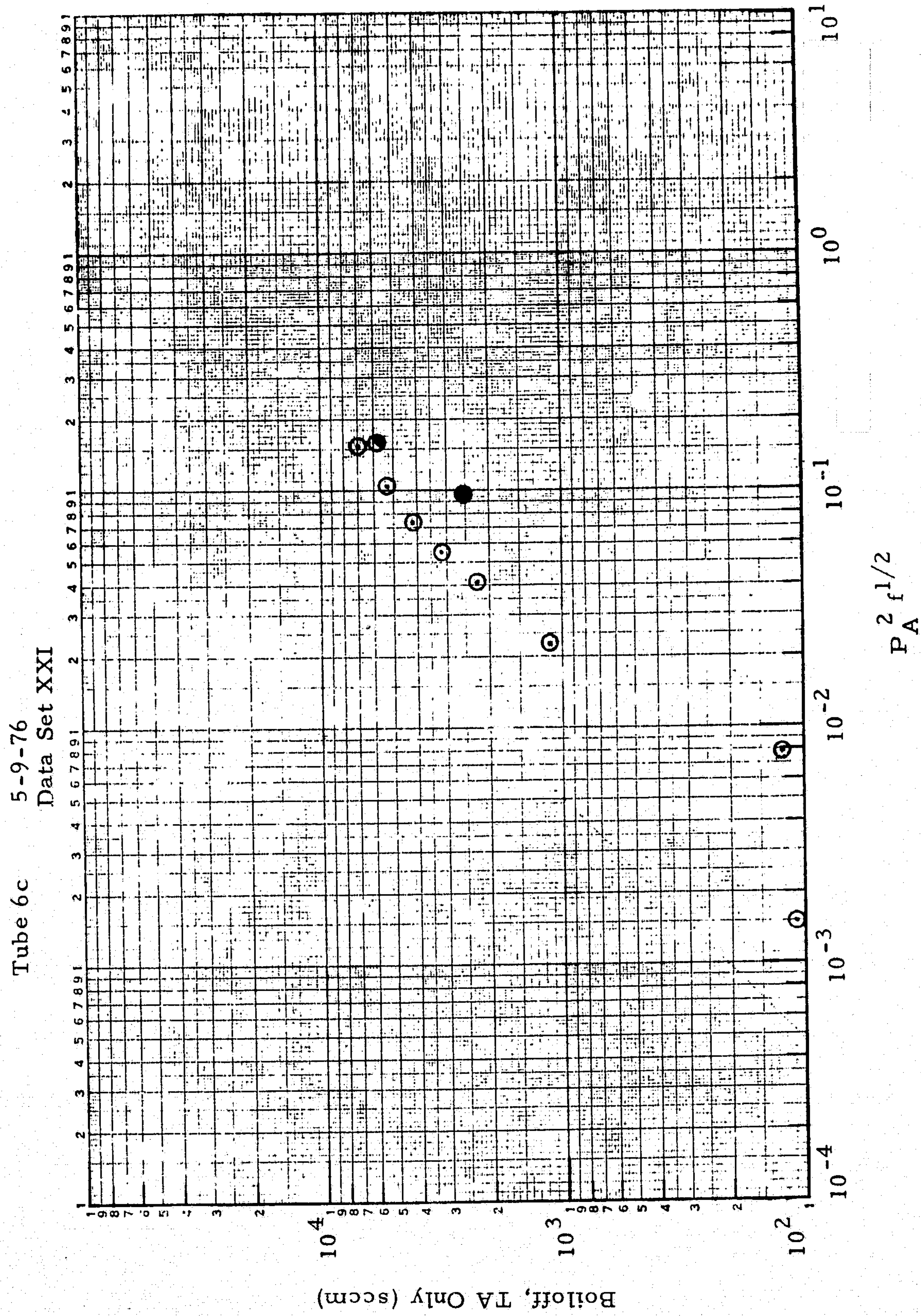
Fig. 2 - Frequency vs Cold Length of Tube, for Tube 1c at Two Different Ullage Pressures


Thermal Acoustic Oscillation Peak-to-Peak Pressure Amplitude (kg/cm²)
.18
.16
.14
.12
..1
.08
.06
.04
.02
0
7.0
7.6
6.0
5.2
4.0
3.3
2.0
1.0
0.8
Tube 6c
Data Set XXI
Date 5-9-76
Liquid level at start of test
from top of fitting on Dewar
= 121.4 cm
Note: Subscripts are ullage
pressures in cm-H₂O
0
70
80
90
100
110
120
Cold Length of Tube, Lc (cm) Measured
from Top of Fitting on Dewar


Tube 6c
Data Set XXI
Date 5-9-76
Liquid level at start of test from top of fitting on Dewar = 121.4 cm
Note: Superscripts are ullage pressures in cm-H_2O
Thermal Acoustic Oscillation Frequency (Hz)
50
46
42
38
34
30
26
22
18
70
80
90
100
110
0.8
1.0
2.0
3.3
4.0
5.2
6.0
7.1
7.0
Cold Length of Tube, L_c (cm) Measured from Top of Fitting on Dewar


Tube 6c
Shipping Dewar
4-14-76
Data Set X
Note: Maximum Ullage Pressure at 6.8 cm of Water
Boiloff, TA Only (sccm)
10^4
10^3
10^2
10^1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$P_A^2\ f^{1/2}$


Tube 6c
Shipping Dewar
4-21-76
Data Set XI
Note: Maximum Ullage Pressure = 1.7 cm - H_2O
10^2
10^3
10^4
Boiloff Rate, TA Only (sccm GHe)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$P_A^2 f^{1/2}$


Tube 6c
5-9-76
Data Set XXI
Boiloff, TA Only (sccm)
$P_A^2 f^{1/2}$
10^4
10^3
10^2
10^-4
10^-3
10^-2
10^-1
10^0
10^1