AN EXPERIMENTAL STUDY FOR THE PREDICTION OF PRESSURE LAG INHERENT IN BALLISTIC MISSILE PLUMBING SYSTEMS

PART I

A THESIS

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PART I

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SUMMARY

This experimental study was conducted to determine the pressure lag characteristics of constant I.D. (0.0625 inch) tubing of varying lengths (30, 45, 60 and 75 inches) subjected to ambient pressure variations representative of those encountered in the ascent phase of missile flight. Throughout this experimentation one fixed upstream volume (28 cc) was used.

The experimental apparatus consisted of a test tube section, containing atmospheric air separated from a vacuum source by a Polyesther Mylar diaphragm and a trajectory orifice plate. The ambient pressure variations were simulated by opening each of the four orifices at predetermined times. A gasket "O" ring arrangement was used so that each orifice could be opened independently of the others. To rupture the diaphragm in front of the orifices, an electrical current was passed through filaments which were sandwiched between two mylar sheets. Upon application of this current the thin platinum wire across the ends of the filament would become incandescent and sear the diaphragm, thereby introducing the orifice to the two pressure realms. A Resistance-Capacitance unit containing four circuits was used to rupture each of the four diaphragm sections at the proper time. The circuitry was designed so that the first circuit discharged immediately and remained active until the next circuit became operative and so on. For each of the four trajectories, the timing sequence was devised experimentally. To measure the desired pressures, two absolute pressure transducers were tapped into a

volume just forward of the input end of the test tube. In order to obtain the pressure lag across the tubes a sensitive differential transducer was used to measure the pressure difference between the input and response end of the tubes. Two Brown potentiometer recorders were used to record the absolute pressure input and the pressure lag throughout the trajectory.

Curves are provided for the following:

1. Average trajectories simulated by this experimentation.

2. Pressure lags of tubes of different lengths for the same trajectory.

3. Pressure lag variation with tube length.

The conclusions reached within the limits of this experimentaion are as follows:

1. The variation of the pressure lag, at any pressure level, with length is linear for constant rates of change of pressure.

2. The magnitude of the pressure lag across a tube is a function of both the absolute pressure level and the rate of change of pressure.

3. From atmospheric pressure to at least 200 mm absolute pressure, the pressure lag will remain nearly constant if the rate of change of pressure remains almost constant.

4. The use of the tubing tested would result in large pressure lags in static pressure sensing systems in missiles.

CHAPTER I

INTRODUCTION

Different types of barometric sensing systems have found application in many of the present day missiles and test vehicles. As these test vehicles and missiles probe higher and faster, many problems which a few years ago were considered of little consequence have been encountered. One is the question of pressure lag. How long after a certain pressure is applied to a system does the actual sensing element realize this pressure? In the use of the barometric sensing system for providing the ambient pressure along a missile's trajectory, small errors in this information at large rates of ascent can create a considerable error in altitude determination if the altitude is such that the ambient pressure is also small.

A considerable amount of work has been done concerning pressure lag of the different sizes of tubing which might find application in these systems. Nearly all of this information, however, has been obtained by using individual pressure step function inputs.

The purpose of this experimentation is to determine the pressure lag of constant I.D. tubing under the influence of pressure inputs which might represent the ambient pressure variation along a missile trajectory. Four trajectories are applied to the different lengths of tubes taken into consideration. Ball (reference 1) has extended this research to take into account the effect of changing the internal tube diameter. Both experimentations were performed using a constant upstream volume (28 cc).

CHAPTER II

APPARATUS

The experimental tests presented in this paper were conducted in the Aeronautical Engineering Annex at the Georgia Institute of Technology. The apparatus consisted of four main sections exclusive of the instrumentation. The sections will be referred to as the tank section, gage section, diaphragm section and pressure manifold. A schematic diagram of the apparatus is contained in Figure 1. Valves (Hills-McCanna Model 500-A) were installed so that each section could be isolated. This measure was taken to make the setup flexible in regard to leak checking and also to facilitate transducer calibration.

Tank Section.--Two 8,000 cu.in. and one 2,000 cu.in. storage tanks, when evacuated, provided the vacuum source. Three valves were built into this section. Two of these valves were for removing the tanks from the system, and the third was installed so that the vacuum pumps could be taken out during the experimental tests. Three Cenco Hy-Vac vacuum pumps were used to evacuate the storage tanks and the entire system. Each pump was rated as being able to pump down a closed system to within 0.0003 millimeters of Hg absolute pressure. A Welch Duo Seal vacuum pump was installed for calibration purposes and also to assist the other pumps in the before run evacuation. In order to prevent any damaging matter from entering the vacuum pumps, two filters (Sporlan Catch All filter Type C-1645) were included between the pumps and the system. The sections were made up using one-half inch type K copper tubing. All tubing joints were soldered and then sealed with Glyptal (General Electric Glyptal No. 1247 Batch 254).

Gage Section.--The gage section was separated from the tank section and diaphragm section by two Hills-McCanna valves and connected to the pressure manifold by flexible vacuum hose. Four Wallace and Tiernan Absolute Pressure Gages (type FA-160) with ranges of 0-20 mm, 0-100 mm, 0-400 mm and 400-800 mm were used in the system for calibration of the absolute pressure transducers and determination of the initial source pressure and the run equalization pressure.

Pressure Manifold.--The pressure manifold (see Fig. 2) was connected to both the gage section and diaphragm section by means of flexible vacuum hose. The manifold was fabricated to accept the two absolute pressure transducers and 3/8 inch copper tubing was provided for the hose connections.

Diaphragm Section.--Figure 3 contains an exploded pictorial of the diaphragm section. Both face plates of this section were grooved to accept four rubber "O" rings (Victor 72716, 13/16" x 1-1/16" x 1/8"). In order to seal this section to prevent leakage, three pieces of rubber inner tube were used as gaskets. These gaskets also provided the insulation that prevented the electrical leads of the diaphragm from short circuiting on the metal orifice plate. The diaphragm consisted of four filaments sandwiched between two half-mil Polyesther Mylar sheets. Each filament contained two 1/8 inch wide, 0.005 inch thick copper leads with a 0.010 inch platinum wire corrugated between the ends.

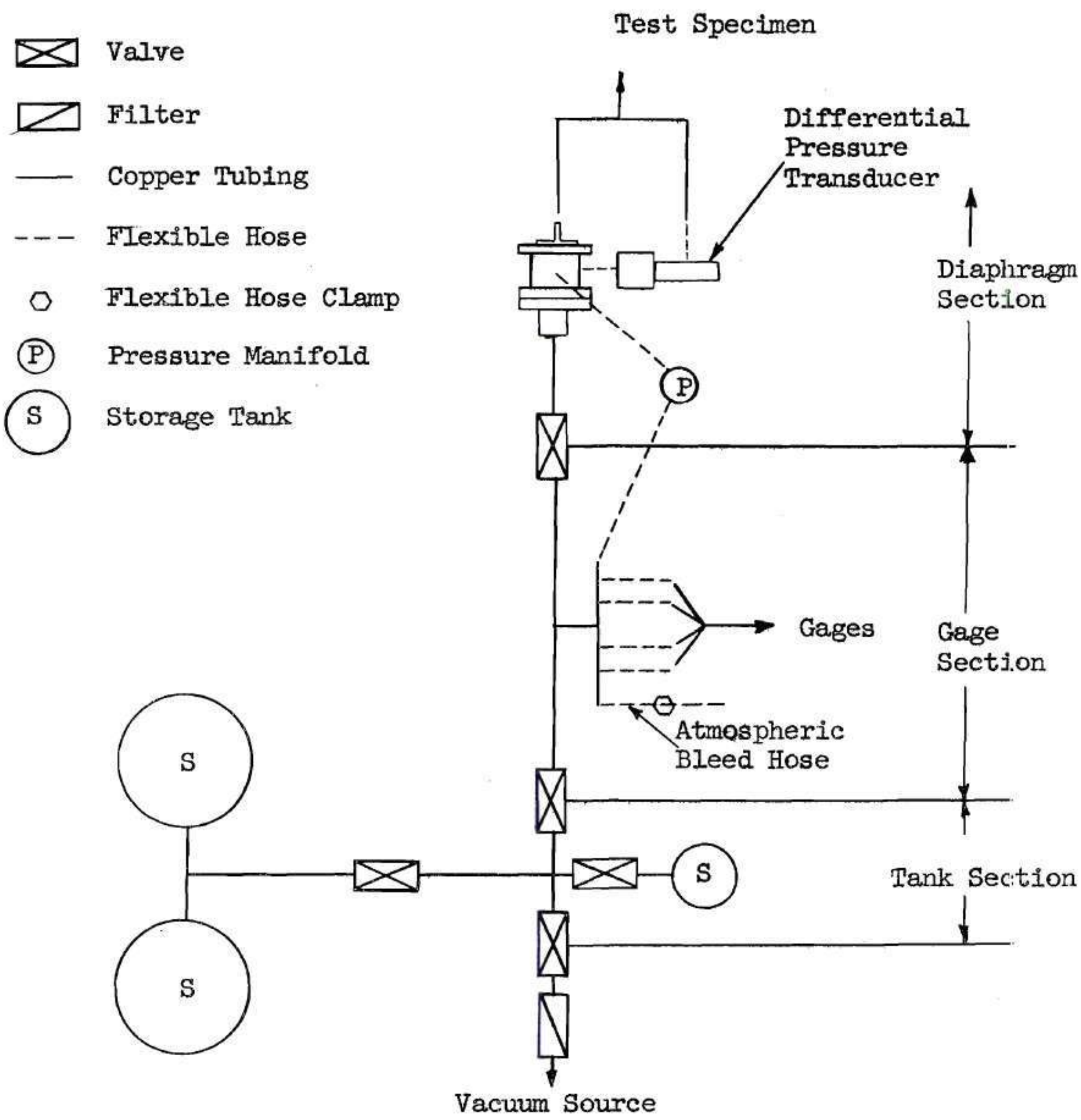

Fig. 1 System Schematic

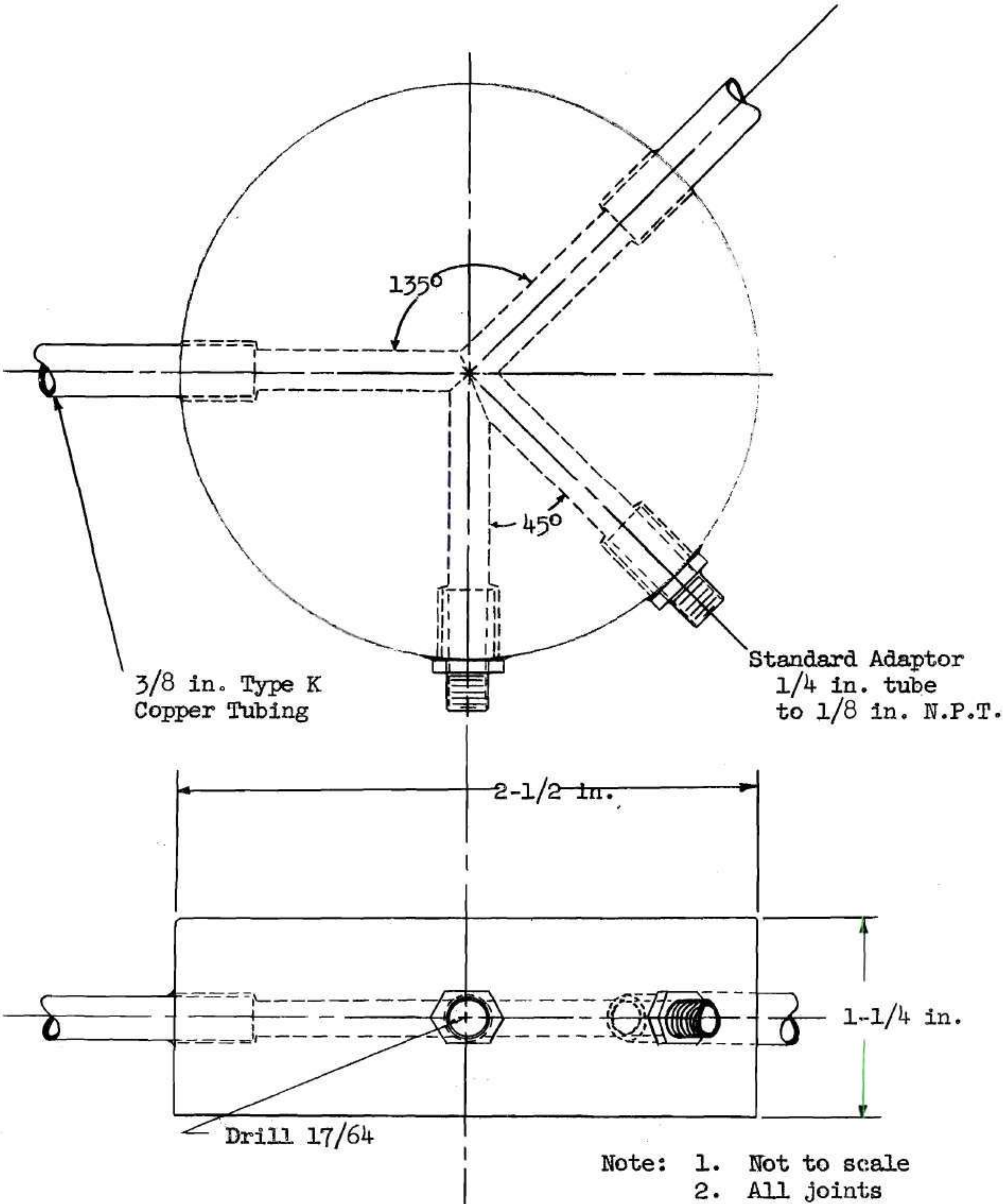

Fig. 2 Pressure Manifold

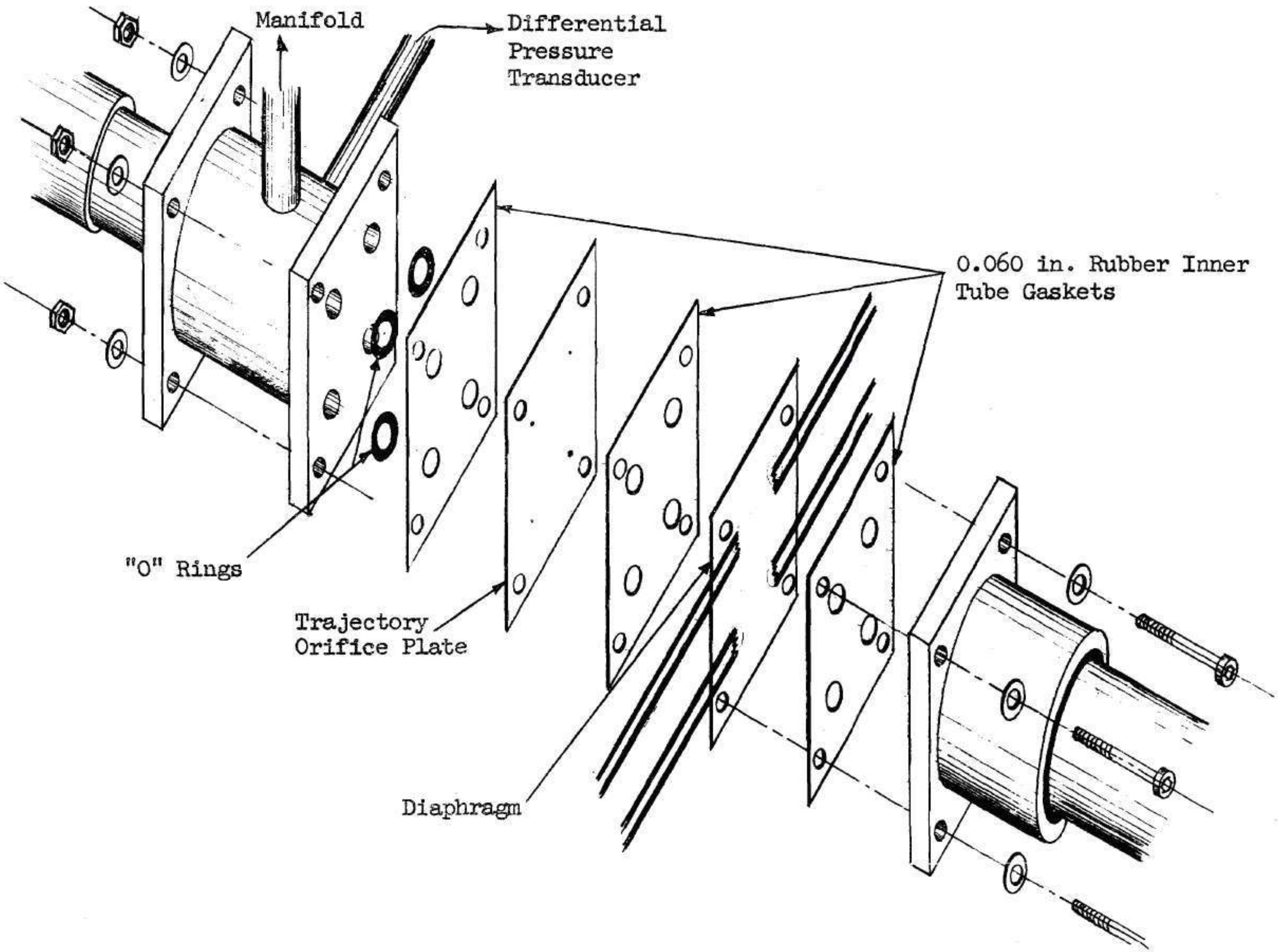

Fig. 3 Exploded Pictorial of Diaphragm Assembly

<u>Orifice Plates</u>.-- The trajectories for this experimentation were produced by a 1/32 inch orifice plate with orifices ranging from approximately 0.005 to 0.020 inches in diameter. Due to the lack of sufficiently small drills, the holes were obtained by puncturing the plate and then peening the orifice until the size that produced the desired pressure-time variation was obtained. A trial and error process was used in building up each trajectory. Four socket head cap screws with nuts were used to assemble the diaphragm section.

<u>Oil Bath</u>.--The necessity of extending the copper leads out of the diaphragm section presented a leak problem that was overcome only by resorting to the use of an oil bath for this entire section. The bath was fabricated from 1/16 inch galvanized tin into a rectangular box 24 inches long, 18 inches wide and six inches deep. Drainage was provided by a 3/4 inch metal tube soldered into the corner of the bath. Attached over this tube was a flexible piece of rubber tubing that could be hooked over the edge of the bath when not in use. Three holes were drilled in the bath; one to accept the tubing from the gage section and the other two for the test tubes. Welch Duo-Seal vacuum oil was used for the bath fluid.

<u>Firing System</u>.--In order to open the orifices at a specified time, a set of four Resistance-Capacitance circuits was used. A Lionel transformer boosted the voltage output of these circuits to a level (12 volts) that insured the platinum wire of becoming incandescent and searing the diaphragm. The first circuit of the R-C system discharged immediately and remained active until the second circuit became operative, and so forth.

All circuits except the first were equipped with coarse and fine time increment control knobs. Table 1 contains pertinent information concerning this unit.

Tubing Tested.--Table 2 contains the steel tubing tested. The ends of the test tubes were built up with cyclindrical metal bushings. Installation of the tubes was accomplished by slipping the end of the tube into a cyclindrical receptacle mounted on the rear plate of the diaphragm section. The entire end assembly was sheathed snugly in a flexible hose and sealed with Glyptal. Each tube was bent in the form of a "U" with approximately a three and one-half inch radius.

Instrumentation.--Two absolute pressure transducers, (0-15 psia Type 4312 Consolidated Electro Dynamics and a 0-5 psia PA 208TC-5-350 Statham Instrument Co.), and a differential pressure transducer ($\pm$ 0.5 psia PM5TC d $\pm$ 0.5 - 350 Statham) were used in this experimentation. Both absolute cells were screw mounted on the pressure manifold. The reference port of the differential transducer was connected to the upstream end (volume end) of the test tube while the pressure port was tapped into a volume to the rear of the diaphragm and just forward of the downstream end of the tube. Attachment was accomplished by means of flexible vacuum hose. Slight changes in absolute pressure transducer input voltage proved to be critical and therefore a twelve volt storage battery and a slide wire resistor were used to provide a stable 7.3 volts. The differential transducer's sensitivity was apparently independent of voltage fluctuations as long as it remained between five and six volts. To record the electrical outputs of the transducers, two Brown Potentiometer recorders (Model no. 153 x 12V - X - 30T Range 0-50 mv) were employed. Both absolute pressure transducer signals were fed into one recorder. A three pole toggle switch was installed on this recorder to permit changing from the fifteen psia signal to the five psia. The recording paper (Brown chart no. 5401 N Range 0-100 evenly graduated) speed for this experimentation was eight inches per minute.

Calibration System (Absolute Pressure Transducers).--The calibration system (see Fig. 4) for the absolute pressure transducers utilized the gage section, pressure manifold (manifold diaphragm hose clamped off), atmospheric bleed hose, an additional 2,000 cu.in. calibration tank, sporlan filter and the fourth vacuum pump. A storage tank was needed for calibration to cut down the time for pressure equalization at each calibration point. For the calibration of the differential transducer, a micromanometer containing alcohol was used.

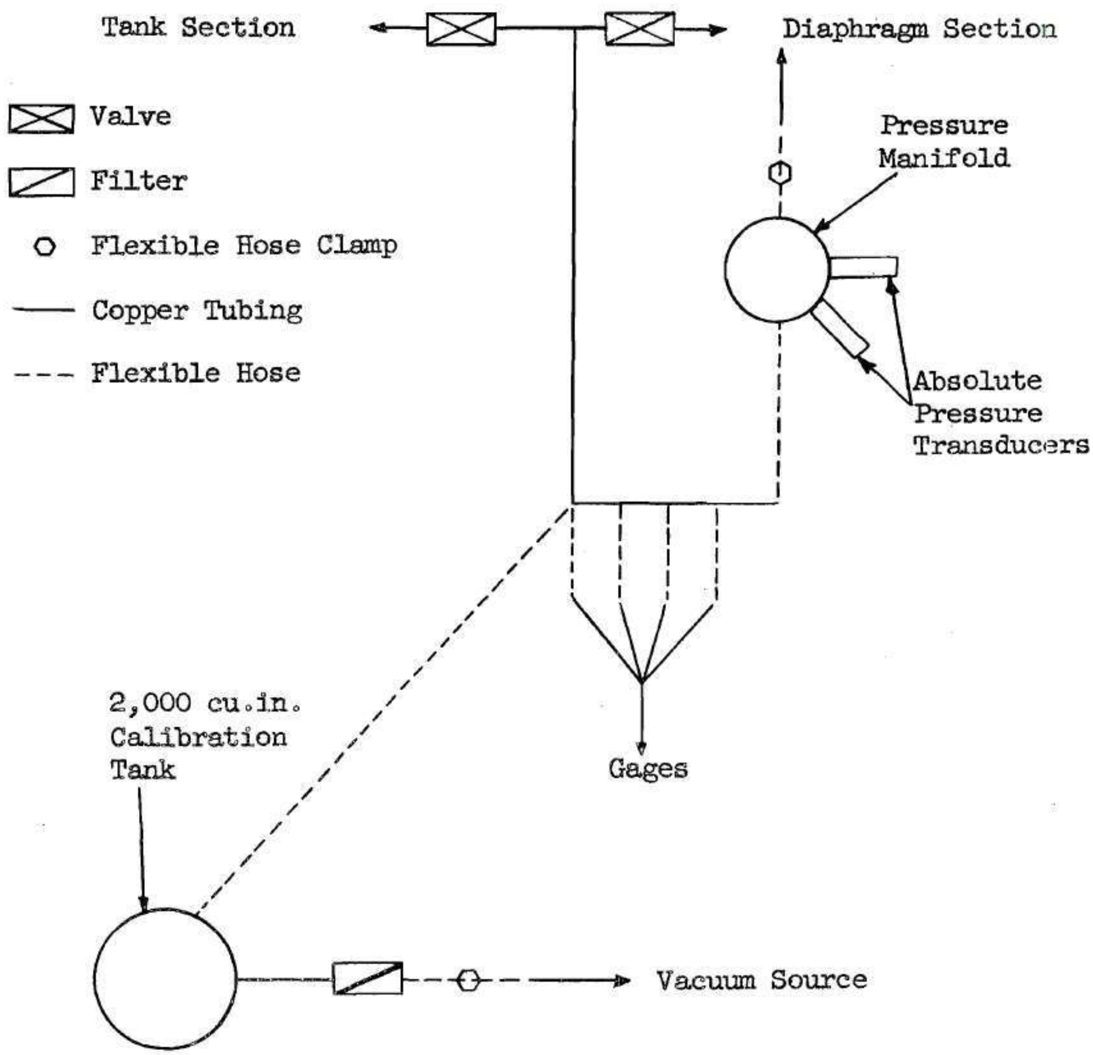

Fig. 4 Schematic of Calibration Setup

(Absolute Pressure Transducer)

CHAPTER III

PROCEDURE

Calibration (Absolute Pressure Transducers).--Each day prior to making experimental runs, the absolute pressure transducers were calibrated. All absolute transducer calibrations were initiated at atmospheric pressure and completed at approximately 0.1 mm Hg. When the calibration system was at atmospheric pressure a trace for the 0-15 transducer was recorded on the Brown recorder. The system was then evacuated to a new lower pressure and after sufficient time was allowed for the system to equalize another trace was recorded. For each trace the corresponding pressure level was obtained from the Wallace and Tiernan absolute pressure gages. This procedure was followed until the range (atmospheric pressure to essentially vacuum) was covered. When the absolute pressure level reached approximately 22 mm, the recorder was switched so that the five psia transducer provided the signal. As a matter of consistency for each reading from the five psia, the transducer selector switch was flipped to the fifteen psia "on", then to the off position where it remained momentarily and then back to the five psia "on" position. The necessity for this was noticed before experimental runs were initiated. When the pressure near the end of a run was near the equalization pressure, the pen of the recorder due to its internal friction would not provide the correct trace for the pressure level. This effect was eliminated by removing the five psia signal in the manner described previously.

After calibration atmospheric air was bled in.

Calibration (Differential Pressure Transducer).--The differential transducer was calibrated every third day. Initially, calibrations were made near vacuum to determine if the transducer was pressure level sensitive. Near vacuum or at any pressure level from atmospheric down, the transducer functioned equally well and therefore all calibrations were conducted with atmospheric pressure as a reference. Ten millimeters of the range of the differential transducer was used during this experimentation. The reference side of the cell was left open to the atmosphere while the pressure side was evacuated, in steps, down to ten millimeters below atmospheric pressure. For each pressure step a trace was recorded on the Brown recorder and the micro-manometer reading corrected from inches of alcohol to millimeters of mercury pressure.

The results of the absolute and differential calibrations were then plotted and the results compared to previous calibrations.

Experimental Test Preparations.--During the transducer calibrations, the storage tanks were being evacuated in preparation for the experiment. Next the diaphragm section was assembled. Figure 3 provides an exploded pictorial of the assembly of this section. When this section was assembled, the electrical leads were connected to the filaments of the diaphragm and the differential transducer reinstalled. Then depending upon which orifice plate was in the system, the proper timing sequence was set in the timing circuit.

The screw clamp was then tightened down on the flexible hose connecting the manifold to the gage section and oil added to the bath. With the diaphragm section under oil and the tanks removed from the system, the valves between the tank and gage section and the gage and diaphragm section were opened and the setup evacuated. When the sections were pumped down, the tanks were reopened and the entire system allowed to be evacuated to approximately 0.2 mm of Hg absolute pressure. The diaphragm section, test tube and pressure manifold comprised a closed system containing air at atmospheric pressure while downstream of the diaphragm a pressure source close to vacuum existed. If the diaphragm was at all damaged so that air leaked from the upstream system, the absolute transducer would indicate a change in pressure level. This served as a before run leak check.

Test Procedure.--Immediately before running, the traces on each Brown recorder were set on corresponding one inch lines. The two recorders were then started simultaneously and the timing circuit manually triggered so that the opening of the first orifice coincided with the trace passing over a one inch line. During the run when the pressure level was approximately twenty-eight millimeters, the fifteen psia transducer was switched out of the recorder and the five psia transducer switched in. Due to the fact that a four second time period was required for the pen to sweep the paper, the switching took place before the five psia trace position was actually on the recording paper. When the pressure level reached 2.2 millimeters, the procedure used for recording the trace of the 0-5 psia transducer during calibration was employed.

The run was considered complete when the absolute trace recorded a pressure level agreeing with the reading from the Wallace and Tiernan gages.

At this point it was necessary to obtain the trace positions for zero differential pressure and approximately zero absolute pressure. The zero differential pressure was obtained by isolating the differential transducer and test tube and allowing the pressure to equalize. To obtain approximately zero pressure for the absolute cells, the pressure manifold and gage section were isolated and then evacuated. Traces for the conditions were recorded.

Next the valve between the tanks and the gage section was closed and the tanks then pumped down during preparation for the next run. The screw clamp between the manifold and diaphragm was then removed and atmospheric air bled in.

After the test section was at atmospheric pressure, a trace for the fifteen psia transducer was recorded and the oil was drained from the bath. Next the diaphragm section was disassembled and the cycle started over except for the calibrations. The only difference was the changing of orifice plates and the firing sequences. Four different trajectories were run on each tube before a tube change was required.

Data Reduction.--For each run, records of the absolute pressure and the corresponding pressure differential (ΔP) across the tube versus time were obtained. The reduction procedure was as follows. From the differential record, count readings were selected for the pressure lag for time zero and at arbitrary time increments after time zero. Next referring to the absolute pressure record, the count readings corresponding to the times from the differential trace were recorded. The count readings from the traces were then converted to pressures by means of the calibration data. Throughout all calibrations, the differential slope remained constant within ± 0.25 per cent of full scale. In order to convert the absolute pressure counts, the zero traces and the atmospheric trace were utilized. If a shift was indicated a new calibration curve was drawn using the new extremes. It was assumed that the calibration remained linear and the entire range was shifted. The absolute pressure counts were then converted to pressure by reading directly from the new calibration.

Frequent leak checks were performed during the experimentation. The tanks over a sixteen hour period indicated no leaks while the system exclusive of the tanks had a pressure increase of about 0.22 mm per hour.

CHAPTER IV

RESULTS

Trajectories simulated in this experimentation were generalized missile trajectories received under contract from the Army Ballistic Missile Agency. The trajectories supplied possessed slope discontinuities. A multi-stage missiles trajectory would necessarily have slope discontinuities where each discontinuity would represent the ignition of a new stage.

Figure 5 contains an average for each trajectory. The poor repeatability of the timing circuit produced variations in the same trajectory and introduced changes in the trajectory for a given orifice plate and timing sequence. Thus only qualitative comparisons on the effect of trajectory can be made.

Figure 6 contains the absolute pressure and tube pressure lags, for the various test lengths, under the influence of trajectory number four. The effect of length is easily discernible from this figure.

Arbitrary absolute pressure levels were selected for each trajectory and the corresponding pressure lag variation with length presented in Figures 7-10. Due to the method of simulating the trajectories, it was impossible to select pressure levels that would permit a comparison between the different trajectories. A linear fairing of the pressure lag versus length curves represented the experimental data well within the accuracy of the measurements. Overall accuracy for the differential measurement was $\pm$ 0.1 mm. The results indicate that the pressure lag is dependent upon the length of tubing, the absolute pressure level and also the rate of change of the absolute pressure level. Also, for a range of pressures at least from atmospheric to 200 mm, the pressure lag will remain nearly constant if the rate of change of pressure remains almost constant.

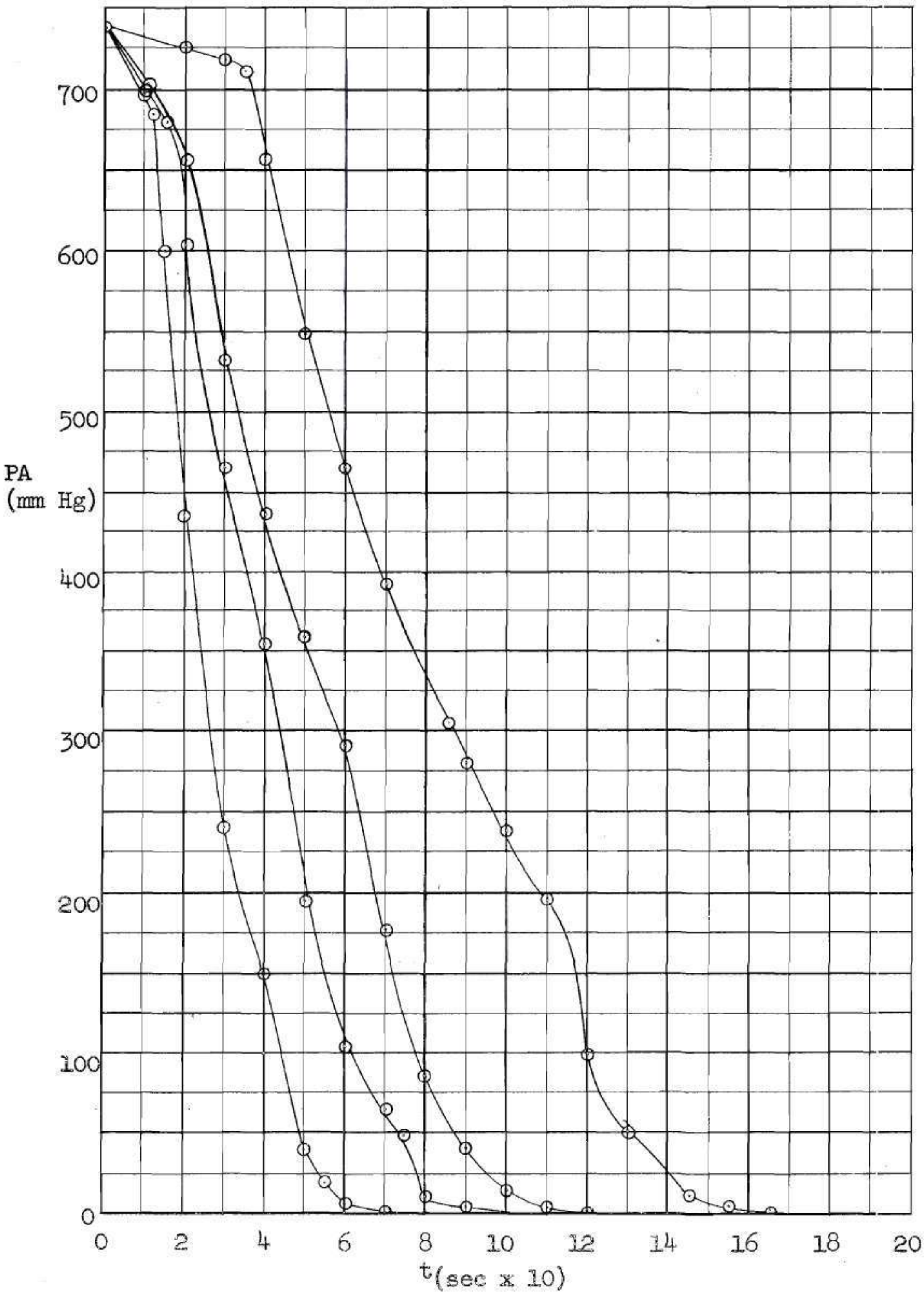

Fig. 5 Averages of Trajectories

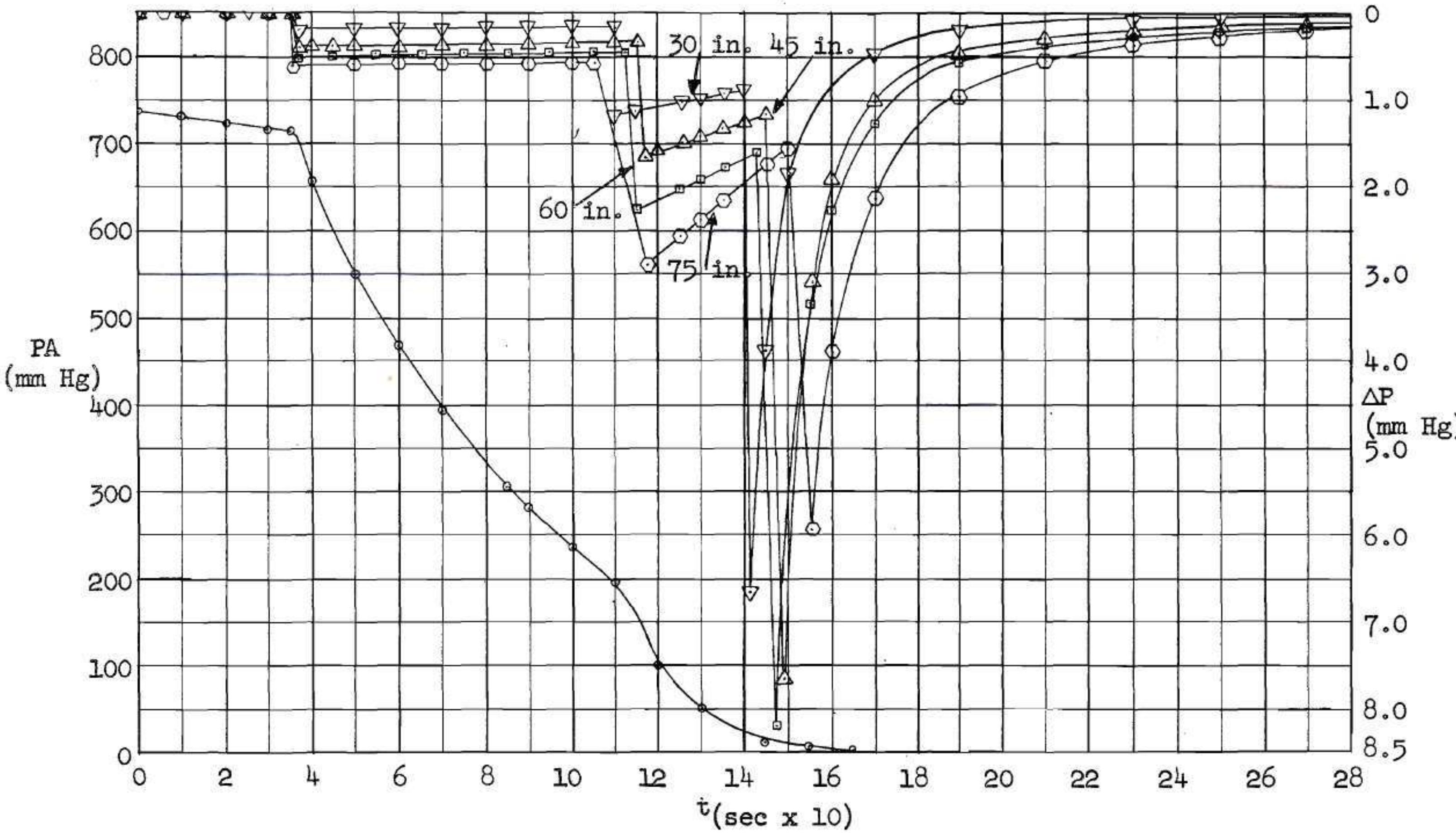

Fig. 6 Effect of Length on Pressure Lag

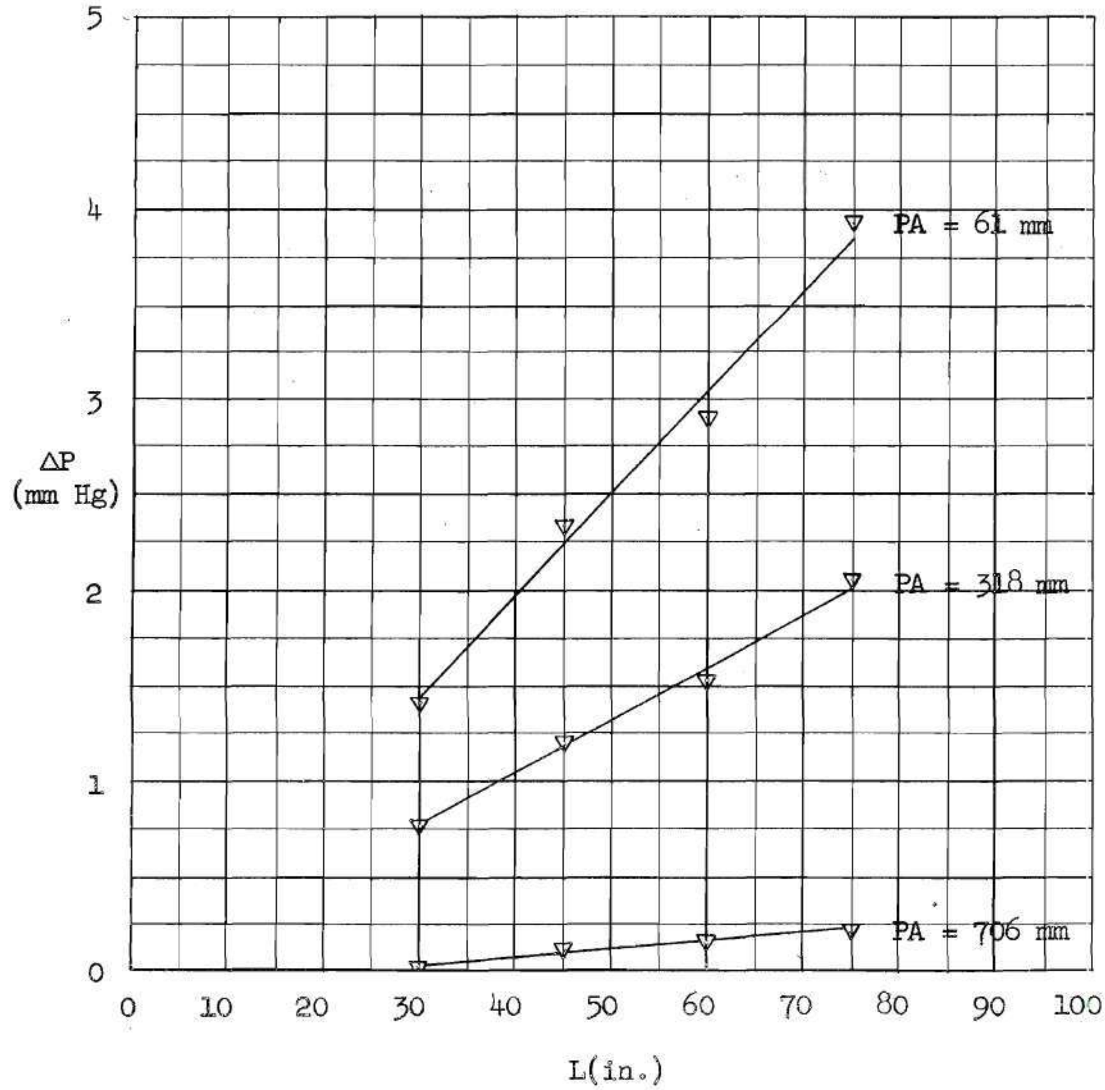

Fig. 7 Pressure Lag vs. Length for

Constant Absolute Pressure (PA)

Trajectory 1

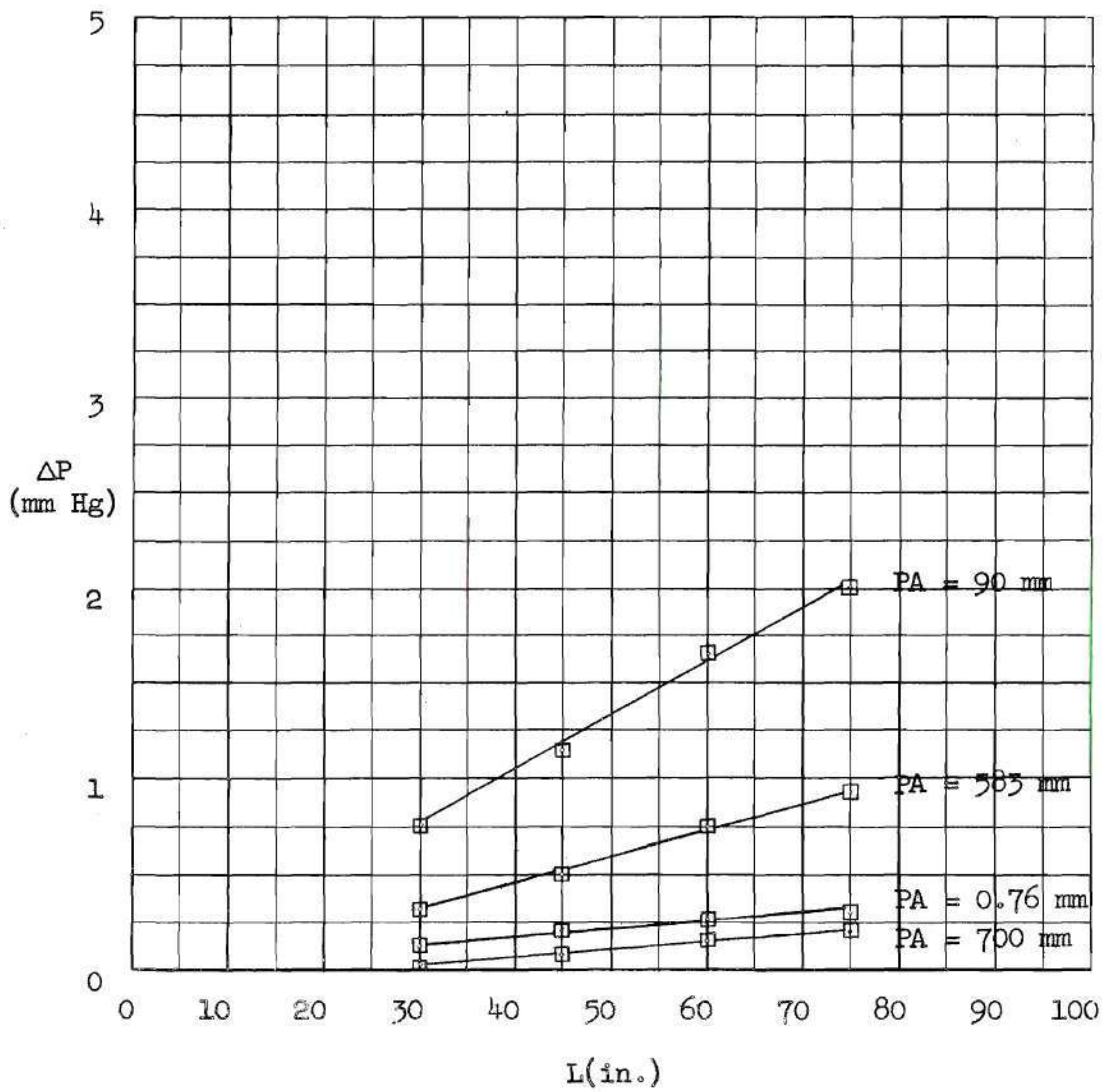

Fig. 8 Pressure Lag vs. Length for

Constant Absolute Pressure (PA)

Trajectory 2

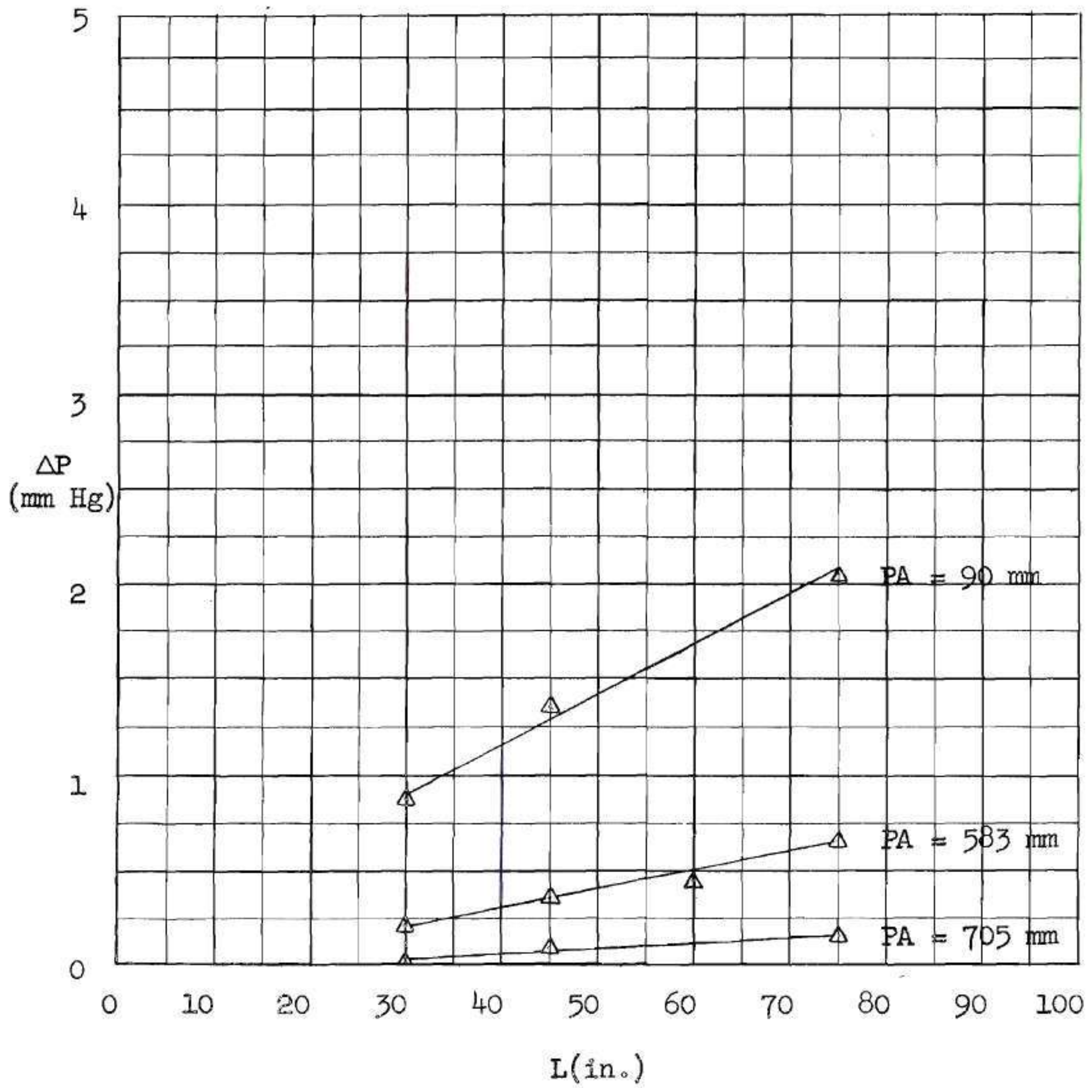

Fig. 9 Pressure Lag vs. Length for

Constant Absolute Pressure (PA)

Trajectory 3

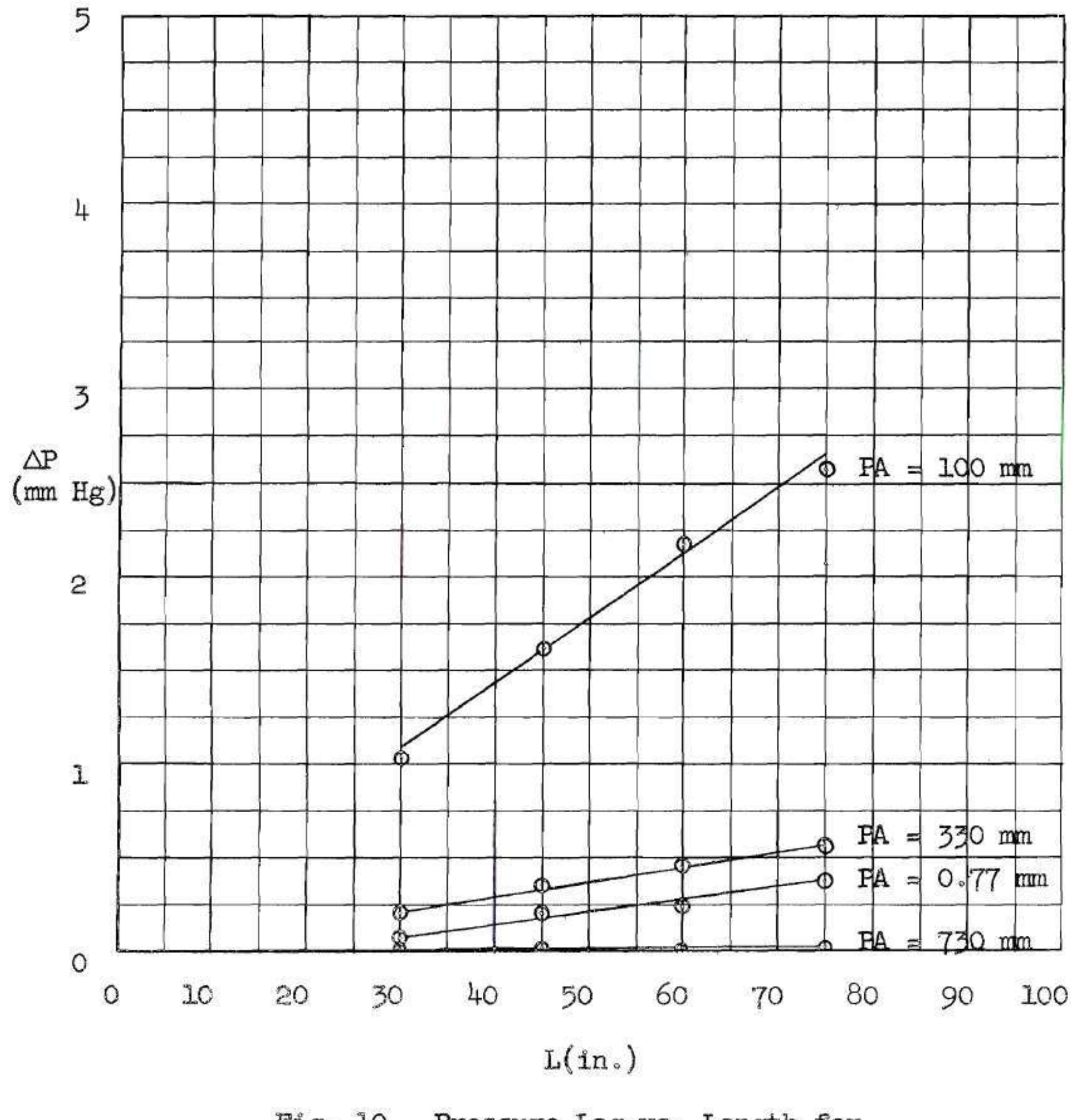

Fig. 10 Pressure Lag vs. Length for Constant Absolute Pressure (PA) Trajectory 4

CHAPTER V

CONCLUSIONS

All conclusions drawn from this experimentation are necessarily restricted to the tubes tested, the upstream volume (28.0 c.c.), the accuracy of the instrumentation, and the poor repeatability of the timing circuit. The conclusions drawn are:

1. The variation of the tube pressure lag, at any pressure level, with length is linear for constant rates of change of pressure.

2. The magnitude of the pressure lag across a tube is a function of both the absolute pressure level and the rate of change of absolute pressure. If a given rate of change of pressure is applied at two different pressure levels, the pressure lag at the lower level would be greater. If at a certain pressure level, two rates of change of pressure are applied, the pressure lag would be greater for the larger rate of change.

3. For a range of pressures at least from atmospheric to 200 mm Hg, the pressure lag will remain nearly constant if the rate of change of pressure remains almost constant.

4. In pressure sensing systems in missiles, the use of tubing with the I.D. tested would result in large pressure lags.

CHAPTER VI

RECOMMENDATIONS

1. A program should be initiated to study the effects of different upstream volumes and standard elbows, tees and straight-through fittings.

2. Information should be obtained for larger internal diameters.

3. Since the data obtained in this experimentation is applicable only to the ascent phase of a missile's flight, a similar program should be performed for the descent phase.

4. Future tests should be run using a firing circuit with better repeatability than a wide-range R-C circuit.

5. A theoretical analysis of the pressure lags encountered due to different trajectories should be made.

A P P E N D I X

Table 1. Resistance - Capacitance Circuitry

Circuit No.	Minimum Time	Maximum Time	Coarse	Fine
1	0	0	-	-
2	0.5 sec	55.5 sec	5 sec	0.5 sec
3	35 sec	167 sec	12 sec	1.2 sec
4	35 sec	230 sec	15 sec	1.5 sec

Table 2. Tubing Tested

Length (in.)	Inside diameter (in.)
30	0.0625
45	0.0625
60	0.0625
75	0.0625

REFERENCES

1. Ball, K. O. W., An Experimental Study for the Prediction of Pressure Lag Inherent in Ballistic Missile Plumbing Systems--Part II. Unpublished Master's Thesis, Georgia Institute of Technology, 1958.