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LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

PRESSURE OSCILLATIONS INDUCED BY FORCED CONVECTION HEAT TRANSFER TO TWO PHASE AND SUPERCRITICAL HYDROGEN

PRELIMINARY EXPERIMENTS

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PRESSURE OSCILLATIONS INDUCED BY FORCED CONVECTION HEAT TRANSFER TO TWO PHASE AND SUPERCRITICAL HYDROGEN

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by

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ABSTRACT

Pressure oscillations induced by forced convection heat transfer to liquid hydrogen have been probed using a preliminary apparatus which cooled from ambient to LH_2 temperatures during each run. Acoustic modes due to Helmholtz and open-open pipe resonances were observed at sub and supercritical pressures. These oscillations did not develop when the inlet hydrogen was superheated. Pressure fluctuations in the form of sawteeth, negative pulses, and beats were also observed above and below the critical pressure. A mode which primarily occurred above the critical pressure and one associated with subcritical two phase flow were also observed. Experimental evidence also indicated that heat transfer was substantially better in two phase flow than in supercritical flow at low flow rates, that pressure drop increased after the apparatus had cooled near LH_2 temperatures at moderate flow rates, and that greater axial temperature gradients were obtained in the slower cooldowns.

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NOMENCLATURE

A = cross sectional flow area, in^2

c = velocity of sound, in/sec

g = gravitational constant, 386 in/sec^2

L = length, in

ΔL = increment of length used in calculations, in

m = mass of fluid in neck of resonator, slugs/12

p = pressure, psia

V_G = volume of gas in resonator cavity, in^3

V_G^1 = volume of gas in outlet plenum and flow channels, in^3

γ = ratio of specific heats

ρ = weight density of hydrogen, lbs/in^3

w_H = frequency of Helmholtz resonator, cps

w_p = fundamental frequency of open-open pipe resonance, cps

CHAPTER ONE

INTRODUCTION

1.1 PURPOSE

Although heat transfer has been known for over 100 years to be capable of inducing acoustic phenomena, the subject of this investigation was chosen as a result of some relatively recent incidental observations made in what were basically heat transfer experiments. This investigation is concerned with making a study of pressure oscillations accompanying heat transfer to hydrogen, and it is being undertaken in two parts. The one reported here was a preliminary series of experiments designed to probe the fundamental modes of these oscillations, obtain estimates of their amplitudes, and probe the conditions required for their occurrence. The final experiments will be designed to collect data for a more thorough analysis of the phenomena.

1.2 DEFINITIONS

In this report <u>supercritical</u> will mean above the critical pressure but in the vicinity of the critical temperature. The critical point of parahydrogen is 187.7 psia and 59.4° R.

Superheated will mean at a temperature above the saturated vapor temperature at subcritical pressures, or above the temperature at which specific heat is maximized at supercritical pressures.

A *dense state* will mean that which has a temperature below the saturated liquid temperature at subcritical pressures, or below the temperature at which specific heat is maximized at supercritical pressures.

Pipe resonance will mean the resonance associated with the fundamental wave length for an open-open pipe. The fundamental wave length is comparable with the longest dimension of the pipe, and pressure nodes occur at the open ends. For a pipe of length L at uniform temperature, the frequency of the fundamental tone is given by

$$w_p = \frac{c}{2L} \tag{1.1}$$

Helmholtz resonance is that associated with a resonator composed of a cavity connected to an external atmosphere via an orifice or neck. The gas in the cavity is compressed and expanded by the to and fro motion of the fluid in the neck (or vicinity of the orifice), analogous to a spring-mass system. Applying the spring-mass analogy, the frequency of a Helmholtz resonator consisting of a neck attached to a cavity is derived to be

$$w_H = \frac{A}{2\pi}\sqrt{\frac{\gamma P}{m\, V_G}} \tag{1.2}$$

1.3 PREVIOUS EXPERIMENTS

In studies of forced convection heat transfer to gaseous hydrogen and helium, McCarthy and Wolf [1]* observed that under some conditions heat transfer appeared to become independent of Reynolds number while being accompanied by pressure oscillations. The frequencies were on the order of 500 cps, approximately the fundamental acoustic frequency of the test section between two mixing chambers.

Hines and Wolf [2] reported that in heat transfer experiments with supercritical hydrocarbons, severe pressure oscillations, with amplitudes up to 380 psi and frequencies up to 10,000 cps, destroyed their thin walled test sections. They observed these oscillations when the temperature at which specific heat was maximized was crossed in their test sections.

Goldmann [3, 4] has observed the production of acoustic noise, which he described as "heat transfer with a whistle" in forced convection heat transfer to two-phase and supercritical water. He has attributed this phenomenon to large property variations under nonequilibrium conditions.

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*Numbers in brackets refer to similarly numbered references in bibliography.

Geery [5] and Hendricks [6] have also observed the existence of pressure oscillations in heat transfer experiments with hydrogen.

Two series of transient cooldown experiments had previously been performed on heat transfer to liquid hydrogen at Los Alamos. In one series [7], the forcing of two phase hydrogen through an aluminum block containing 18 flow channels in parallel produced pressure oscillations which were simulated in frequency by the concept of a Helmholtz resonator. In the second series [8], supercritical and two phase hydrogen were forced through a single thick walled brass tube with no comparable frequencies of pressure oscillations. The single brass tube experiments raised the following questions about the oscillations observed in the first series: (i) Were they the result of heat transfer or caused by feedback loops in the control system? (ii) If they weren't the result of feedback loops, why should they appear in one apparatus and not in the other? (iii) Was parallel channel flow a necessary condition? (iv) Would the spring-mass concept of a gas and liquid apply at supercritical pressures?

1.4 OBJECTIVES OF PRELIMINARY EXPERIMENTS

A proper apparatus for studying pressure oscillations induced by heat transfer should contain a steady heat source and allow one to choose and maintain operating conditions over a period of time. However, because of the delay introduced by the purchase of a suitable dc generator to electrically heat a test section, it was decided that a number of fundamental questions could be answered by a more quickly prepared transient cooldown apparatus, discussed in the next section. All control loops would be open for most of the run to eliminate oscillations caused by feedbacks in the control system. The objectives of the preliminary experiment therefore became:

(a) Investigate the existence of resonant modes of pressure oscillations in forced convective heat transfer.

(b) Identify the Helmholtz resonance mode by a shift in frequency produced by a change in volume of the resonating chamber and by a comparison of observed and computed frequencies.

(c) Identify the pipe resonance mode by its restriction to flow channels between inlet and outlet plena and by a comparison of observed and computed frequencies.

(d) Investigate the existence of these modes at supercritical pressures.

(e) Establish the necessity for parallel channel flow by performing experiments with all channels but one plugged.

(f) Obtain approximate notions of where threshold conditions for these oscillations may lie.

(g) Test the adequacy of instrumentation techniques for such an investigation at cryogenic temperatures.

CHAPTER TWO

APPARATUS

2.1 OVERALL SYSTEM

The system employed in this investigation is outlined in Figure 1. It basically consists of a 300 litre dewar with a 300 psi maximum working pressure, a Fisher-Porter turbine flow meter, a servo control valve, the test section, and exhaust lines.

Typical operating procedures with a frangible diaphragm separating the test section from the upstream elements of the system included:

(a) Purging the dewar and all upstream elements through vent lines with helium and analyzing a sample of dewar contents with a gas chromatograph.

(b) Evacuating and purging the test section with helium.

(c) Filling the dewar to 40% of capacity with liquid hydrogen.

(d) Chilling vacuum jacketed lines up to the frangible diaphragm to liquid hydrogen temperatures.

(e) Pressurization of dewar with helium until the frangible diaphragm breaks.

(f) Setting the pressure for a run and shutting off the helium supply for dewar pressurization.

(g) Cooldown of the test section with the control valve operating open loop.

(h) Emptying the dewar of liquid hydrogen.

(i) Purging the system with helium.

(j) Allowing the system to warm for at least 24 hours before the next run.

2.2 TEST SECTION

The test section was constructed of duraluminum. It is shown in Figure 2. After rupture of the frangible diaphragm, hydrogen entered the inlet plenum, where part of it could be bled away for quick chilling of the inlet plenum during the initial phases of a run. A section of the vacuum jacket was in contact with the inlet plenum walls, acting like a fin for a heat leak into the plenum.

The central test section piece was a 2-3/4" rod of duraluminum, 52" long, with four holes of 3/16" diameter drilled through on a 1-1/2" circle. During the last four runs, three of the four flow channels were blocked by means of a stainless steel wire on which were mounted a nut, steel washer, and teflon washer on the inlet end. These were pulled tight against a steel washer and nut in the outlet plenum.

The outlet plenum could be either of two sizes depending on whether or not a volume filling plug was used. Flow discharged from the outlet via an orifice plate, which usually operated under sonic flow conditions limiting flow rates through the system.

2.3 INSTRUMENTATION

Hydrogen temperatures were measured in both plena by Rosemount platinum resistance sensors. Static pressures were measured in both plena and in one flow channel 36" from the inlet plenum by Statham "temperature compensated" pressure transducers attached directly to the test section. The differential pressure between inlet and outlet plena was measured directly by a Statham differential pressure transducer. Temperatures in the duraluminum structure were measured by copper-constantan thermocouples located about 1/16" from the flow channels. At distances of 13, 26, and 39 inches from the inlet plenum, a thermocouple was placed, on each of the flow channels, at 45° from a line passing through the centers of the rod and a flow channel. At 27", a thermocouple was placed at 135° on one flow passage to check the strength of angular temperature variation about a flow passage. At 4", a thermocouple was placed near the same flow channel to check against unusual axial temperature variations near the inlet plenum.

The outputs of the Statham static pressure transducers were recorded on a Honeywell Visicorder via amplifiers whose responses were flat to 240 cps. The output of the differential pressure transducer and the Rosemount temperature sensors were also displayed on the Visicorder but through amplifiers whose responses were flat to 24 cps.

The thermocouples' outputs were sampled 20 times per second by a Texas Instrument multiplexer and recorded on magnetic tape. These data were subsequently reduced and plotted by a digital computer.

Flow rate was measured by a Fischer-Porter turbine flow meter and recorded on a Brown strip chart.

2.4 EXPERIMENTAL DIFFICULTIES

Since one of the objectives of the preliminary experiments was to test the adequacy of instrumentation techniques for this type of investigation at cryogenic temperatures, a section under the above subtitle is appropriate.

The first trouble encountered was not in the instrumentation but is still worth mentioning as a practical cryogenic problem. All o-rings with a diameter greater than two inches had to be of teflon coated stainless steel. Neoprene and teflon o-rings leaked at cryogenic temperatures. When using liquid nitrogen, the same o-ring could hold well after its joint was taken apart and put together several times. However the same type of o-rings could withstand only the initial compression without leaking when exposed to liquid hydrogen.

The turbine flow meter was intended to be the sole means of measuring mass flow rate. Unfortunately the control valve was too big for the proper flow meter for this experiment. After destroying a flow meter of an appropriate capacity by overspeeding during purging procedures after the third hydrogen experiment, a unit with a capacity too large for this investigation was installed. It was of little value during the runs, but aided purging and cooldown procedures. Useful flow recordings were only obtained for four runs. Flow rates during the runs were also estimated from sonic flow orifice calculations using outlet plenum data.

Two difficulties were experienced with recording the output of thermocouples measuring wall temperatures. First, all thermocouple pairs were calibrated prior to the runs; but after installation and recording their output on the Texas Instrument Multiplexer, they consistently recorded temperatures of 470° R when the apparatus was sitting at ambient temperatures outdoors in pleasant fall weather. This was observed not only 24 hours after a run, but also when the apparatus had not been used for five days. Thermocouple output looked proper when liquid hydrogen temperatures were achieved, at the end of a run.

Since the Multiplexer did not give rise to such problems in its previous usage, it is assumed that the technique employed in the installations of the thermocouples stressed them and changed their calibration. An arbitrary linear correction of 0° R at 60° R and + 70° R at an output of 470° R was used when analyzing wall temperatures. Wall temperature graphs presented in this report are uncorrected. It is recommended that at least one thermocouple be calibrated before and after its placement in a sample installation to avoid an installation technique which significantly stresses the thermocouple.

The second difficulty in measuring wall temperatures occurred during the last five runs, including all four runs with only one flow passage. The base voltage on the Multiplexer shifted to too high a value to permit machine reduction of the data. Temperatures for these runs were recorded only as normalized voltage outputs from the thermocouples.

The Statham pressure transducers were close mounted on the test section to avoid pressure transmission line response problems. However, their output was temperature dependent even though the units were "temperature compensated". Zero shifts with temperature were observed for the transducers on the flow channel and outlet plenum, but not on the inlet plenum transducer. Recent analytical studies show this problem can be compromised by using a 6 inch long, 0.005 inch I.D. (1/8" O.D.) stainless steel transmission tube. At 250 cps, with hydrogen as the transmitting fluid, the output amplitude was computed to be about 10% high and the phase lag less than a degree. After having its inlet end exposed to liquid hydrogen for 10 minutes, the transmission tube's outlet end temperature was computed to only drop 50° R.

Had good data been the required end product of the experiments, these runs would have had to be repeated with the troubles eliminated. However, these experiments were only a preliminary probing to establish the existence of the phenomena under investigation, and that goal was achieved as explained in the following sections.

CHAPTER THREE

RESULTS

3.1 RESULTS FROM NITROGEN

Since the test sections were proof tested with liquid nitrogen some data were recorded using that fluid and they are presented here even though this report is basically concerned with hydrogen. Figure 3 presents an observation of pipe resonance during a nitrogen run, as traced from the Visicorder record. In all the figures made from tracings of the Visicorder record, pressure is increasing toward the bottom of the graph. Characteristic of pipe resonance, the oscillations appear mainly in the flow channel and only at considerably diminished amplitudes in the plena. The flow channel mode also shows a structure indicating the presence of higher harmonics.

Figure 4 illustrates Helmholtz resonance, characterized by equal amplitudes in the flow channel and plena and by a frequency dependence on the volume of the outlet plenum. Comparison of the two runs with similar fluid conditions but different outlet plena show frequencies differing by a factor of 1.78, which is within 4% of the factor of 1.85

predicted by equation (1.2). Even this small discrepancy can be accounted for if one considers that the compressibility of gas in the flow channels contributes an additional spring effect.

As shown by Figures 3 and 4, pipe and Helmholtz resonant modes appear independently of one another, but as will be shown later with hydrogen data and was also observed with nitrogen they may appear superimposed on one another. At the low flow rates accompanying the use of a 0.07 inch diameter orifice, no pipe resonance was observed in either nitrogen or hydrogen. This is believed to indicate that higher flow rates are required to excite this high frequency resonant mode.

3.2 OBSERVED OSCILLATIONS IN HYDROGEN

Figure 5 presents data showing a superposition of pipe and Helmholtz resonances during an experiment with hydrogen. Both modes retained the characteristics observed in the nitrogen experiments. The Helmholtz mode also appeared on the Rosemont temperature sensor in the outlet plenum. The almost 180° phase shift is what one would anticipate from a pulsating flow with heat transfer independent of Reynolds number, as McCarthy and Wolf observed [1]. In such a case a pressure maximum is associated with a flow maximum and consequently an outlet temperature minimum. This particular section of the record was chosen because it also illustrates the Helmholtz mode ceasing suddenly while the pipe mode continued, which is an additional indication that the two modes are separately excited.

Figure 6 shows sawtooth fluctuations and negative pulses typically observed in the early phases of an experiment. In the experiments performed at supercritical pressures, the negative pressure pulse phenomena was observed to accompany a rise and fall in inlet plenum temperature, as shown on Figure 7. The frequency of these pulses was not as highly regular as the Helmholtz and pipe resonant modes, but on the average the period between pulses lengthened as the system cooled down. Eventually the pulses degenerated into beats when the temperature rise lessened, as shown in Figure 8, and then disappeared.

The accompaniment of the negative pressure pulses by rises in inlet plenum temperature and their amplitude dependence on the magnitude of the inlet temperature rise indicate this phenomenon is caused by a heat flux into the inlet plenum. One may visualize a build up of vapor bubbles at subcritical pressures, or the lower density species at supercritical pressures, until the bubbles are dragged into the flow stream, cooled by the abundant subcooled hydrogen there, and collapsed, producing a sudden decrease in pressure.

An interesting observation of the negative pressure pulse and beat phenomenon at supercritical pressures is the disappearance of the higher frequency modes with a rise in fluid temperature in the inlet plenum. A plot distinguishing oscillatory and nonoscillatory phenomena for pipe, Helmholtz, and supercritical modes on coordinates of inlet fluid pressure versus inlet fluid temperature is shown in Figure 9.

A distinct segregation of oscillatory and nonoscillatory conditions takes place along the saturated vapor pressure-temperature line at subcritical pressures and the locus of specific heat maxima at supercritical pressures. The latter curve appears to have the interesting property of being continuous in magnitude and slope with the vapor pressure line at the critical point.

One can conclude from Figure 9 that pressure oscillations were not generated in the preliminary apparatus when the inlet fluid was superheated, whether at sub- or super-critical pressures. Furthermore, since the oscillations did not take place when the entire tube was filled with superheated hydrogen one may deduce that the mechanism for driving them occurred only in that part of the flow channel where the dense state was present.

3.3 COOLDOWN HISTORIES

The following material will present a brief discussion of the experimental runs in chronological order. The general pattern of presentation of graphs for each run is:

(1) Inlet plenum pressure, outlet plenum fluid temperature, and average pressure drop between plena versus time; at the top of this graph, the peak-peak amplitude of the pressure oscillations is also plotted versus time.

(2) Frequency of pressure oscillations versus time.

(3) Temperatures of duraluminum, in the vicinity of the flow passages at axial locations of 4, 13, 26, and 39 inches from the inlet plenum face.

(4) Duraluminum temperatures close to the four flow channels at the 13 inch location.

(5) Duraluminum temperatures close to the four flow channels at the 26 inch location.

(6) Duraluminum temperatures close to the four flow channels at the 39 inch location.

(7) Volumetric flow rate, in gpm versus time.

Items 4, 5, and 6 were included for only two runs. Item 3 appears on all runs up to October 30, 1963. The remainder of the runs experienced electronic difficulty in the reduction of the wall temperature data, and consequently the remaining wall temperatures exist only in a digitized coded form. Item 7 was obtained for only four runs.

October 11

This experiment was performed at a nearly constant subcritical pressure of 150 psiA. As shown in Figure 10, the outlet temperature and pressure drop decreased during the recorded portion of the experiment. Three kinds of pressure variations are apparent. The sawtooth fluctuation, which eventually became negative pulses, persisted in the first two runs due to a loss of inlet plenum vacuum, which was later corrected by keeping the neoprene o-rings in vacuum jacket warm. The Helmholtz and open-open pipe resonant modes also appear. As shown by Figure 13, the sawtooth and pulse phenomena produced almost full scale fluctuations in recorded flow. These did not accompany Helmholtz and pipe resonance.

The computed outlet temperature and pressure drop obtained using methods discussed in LAMS 2803 [7] are also shown on Figure 10. The numerical simulation, which assumed the fluid at the inlet to the test section to be a saturated liquid, allowed the estimation of a density and sonic velocity distribution in the test section. The sonic velocity distribution was used to calculate an open-open pipe resonance frequency from

$$w_p = \frac{1}{2\,\Sigma\,(\frac{\Delta L}{c})} \tag{3.1}$$

The calculated results appear as triangles on Figure 11.

In computing frequencies for Helmholtz resonance, the mass of all the hydrogen in the flow channel was estimated by integrating the computed density distribution, and the volume of gaseous hydrogen in the flow channel was added to that in the outlet plenum for compressibility considerations. The formula employed for this calculation was

$$w_H = \frac{1}{2\pi}\sqrt{\frac{\gamma\, g\, PA}{(\Sigma\rho\Delta L)\; V_G}\,\frac{}{1}} \tag{3.2}$$

These results appear as circles on Figure 11.

The agreement between the observed and computed frequencies provided the second means of identifying the resonant modes. (The first was by their characteristics, discussed in 3.1 and 3.2.)

A tracing of duraluminum wall temperatures reduced from multiplexer records is shown in Figure 12. The lines shown are an average through scatter, which is very narrow at high temperatures but fairly broad in the cryogenic region.

October 14

Results of this run appear in Figures 14 through 20. The planned difference between this run and the previous one was the use of a smaller outlet plenum, which was expected to produce an increase in Helmholtz frequency, as was observed in nitrogen. The inlet plenum bleed was left open in the early part of the run to chill the inlet plenum quickly. This also had the effect of changing the development of wall temperatures from the preceding run, which in turn probably affected the density distribution. In essence the average density was increased. This is evidenced by lower pipe resonance frequencies in the second experiment for equivalent inlet pressures and outlet temperatures. Consequently, the Helmholtz frequencies are lower than those which may have been obtained had the density distributions been similar.

The wall temperatures along the length of the test section, as shown in Figure 16, exhibit an undulation in their fall which may either be real or a quirk of the multiplexing system. An argument that they may have been real is that at a given axial location all the temperatures showed the same undulation. This can be seen by comparing Figures 17, 18, and 19 which present traces of multiplexer data at the 13, 26, and 39 inch locations. Towards the outlet of the test section, at the 39 inch location, there is little undulation, and it was not discerned in the outlet plenum temperature recording. Figures 17, 18, and 19 also indicate there was no thermal asymmetry during the run. Consequently, it is suspected that flow asymmetry among the channels was also absent.

The sudden cessation of the Helmholtz mode from a 10 psi oscillation at time 312.2 seconds is the event appearing on Figure 5. This seems to indicate that thresholds exist for oscillations induced by forced convection heat transfer.

October 16

Much of this run was performed at supercritical pressures, and results appear on Figures 21, 22, 23, and 24. As shown in Figure 21, pipe resonance, and for the first time, Helmholtz resonance are demonstrated to exist in hydrogen at supercritical pressures.

There are several other interesting aspects to this run. One is the rise in amplitude from 6 psi to 9 psi at 305 seconds, when the pressure dropped from 219 to 181 psia. The pressure excursion at 303 seconds was too rapid and large to provide interpretable data.

Another interesting observation is the abrupt cessation of a 3 psi amplitude Helmholtz oscillation at 315.5 seconds, while the inlet pressure is 161 psiA and rising. There is no Helmholtz mode while the apparatus is at a supercritical pressure and the exit temperature at its minimum, but the mode returns just as the critical pressure is passed while pressure is falling at the end of the run.

During most of the run, pressure drop fell as the system cooled down. After 313 seconds with the outlet temperature at about 55° R, the inlet pressure was increased accompanied by an increase in pressure drop. After 318 seconds, when the pressure was falling again from a supercritical value, the pressure drop continued to rise until at 325 seconds it was six times greater than it had been at 312 seconds. The inlet pressure, flow, and outlet temperature were then about the same as they had been at 312 seconds. This phenomenon may possibly be attributed to a decrease in the average quality of the test section's hydrogen which, in accordance with calculations using a Lockhart-Martinelli model applied to hydrogen by Rogers [9], would cause pressure drop to increase to a maximum with decreasing quality. However the quality dependence of the calculated frictional pressure gradient is small at this pressure, and it may not account for the entire increase in pressure loss.

Another possible cause of the increased pressure drop may be a transition from film to nucleate boiling over an increasingly longer length of the flow channels. This is suggested because the existence of a stable vapor layer on a solid surface in film boiling has been demonstrated to provide a large reduction in friction drag [10]. Wall temperature records, shown in Figure 23, lend credence to this hypothesis because they show only the 4" temperature bottomed out at 312 seconds, but all wall temperatures bottomed out at 325 seconds.

October 18

The intent of this run was to study pressure observations at very low flow rates of the order of 0.2 gpm. Results are shown in Figures

25, 26, 27, 28, 29, and 30. Since pipe resonance was absent during this run it seems that flow rates higher than those encountered are required to excite it. The pressure drop was almost zero during the entire run.

Helmholtz resonance appeared in the latter part of the run and exhibited a sudden cessation at 240 psiA at 760 seconds and made a second appearance later as the pressure was falling towards 200 psiA.

An oscillation, appearing only at supercritical pressures, is shown in Figure 25. As closely as the recordings could be read, this mode started when pressure ascended to the critical value, existed at pressures above it, and stopped when pressure decended to the critical value. As seen in Figure 26, in contrast to the Helmholtz mode, the supercritical frequency remained almost constant during the cooldown.

As pressure fell below the critical value at 788 seconds, the outlet temperature began to rise even though the test section was cooling. From this, one can infer that the intensity of turbulence was greater with two phase flow than with supercritical flow. If that is correct, then it might also be possible that the supercritical mode may arise from a transition such as that between laminar and turbulent flow. The low frequency mode shown in Figure 7 is the supercritical oscillation.

Figures 28, 29, and 30 again demonstrate that no thermal asymmetry occurred during the course of the experiment.

October 22

In this run, pressure was varied several times between values around 240 psiA and the critical pressure. The results appear in Figures 31, 32, and 33. The differential pressure is not given as the associated electronic circuitry failed during the course of the run.

Pulses, pipe resonance, Helmholtz resonance, and the supercritical mode appeared during this run. Figure 31 shows the only apparent existence of what is called the supercritical mode below the critical pressure. Whether this actually occurred or is the result of a drift in the transducer's calibration will be investigated in future experiments.

October 23

This run was made to observe pressure oscillations occurring at comparatively high flow rates. The results are shown in Figures 34, 35, 36, 37, and 38.

The flow record, Figure 37, shows none of the large oscillations that accompanied sawtooth and pulse fluctuations at lower flow rates.

Pipe resonance persisted throughout most of the run, but Helmholtz resonance made only a brief appearance. At 262 seconds, 3 seconds after the outlet temperature bottomed out, a new type of oscillation appeared with an amplitude in the inlet plenum larger than in the flow channel. Either subcooled and two phase or all two phase conditions existed throughout the test section. This new mode herein identified as plug flow, must be associated with such conditions. Traces from a high speed recording of operative pressure channels are shown in the upper half of Figure 38. Plug flow is suggested as a source of these oscillations because a rise in inlet pressure was coincident with a reduction in pressure drop. The formation of a vapor plug in a channel would tend to slow flow and thereby produce a reduction in pressure drop between plena and an increase in inlet pressure due to a relative back up of fluid. Also, the oscillations in the flow channel are smooth while those in the inlet plenum are irregular in form, which very likely could be caused by the non synchronous formation of plugs in all four channels. A single channel experiment did not show the irregular pressure wave form at the inlet plenum. The average pressure drop remained fairly constant during the existence of these oscillations. This differs from phenomena observed at lower flow rates when a rise in pressure drop was usually observed. Finally, it should be recalled that in the CISE experiments [11], plug flow followed a dispersed flow pattern when liquid rates were held constant and gas rates reduced. Since hydrogen has a low surface tension it tends to disperse very easily, and only at high flow rates with the low vapor generation provided by a cold apparatus would plug flow be anticipated.

Comparison of Figure 36 with 27, a record from a low flow rate cooldown, shows that there was a much greater axial wall temperature gradient in a slow cooldown than in a fast one.

October 24

The intent of this run was to reproduce the run of October 18 but with a smaller outlet plenum. Results from the run are shown in Figures 39, 40, and 41. As on October 18, this run contained no pipe resonance modes, but unlike the earlier run, the supercritical mode made only a brief appearance and the amplitude of the Helmholtz mode was much larger. Pressure drop was nearly zero throughout the run.

Comparison of the two runs indicates they were not as similar as had been hoped since the run of October 24 achieved liquid hydrogen temperatures in the outlet plenum nearly 200 seconds before they were reached during the run of October 18. Not only flow rates but hydrogen density distributions were probably different for comparable outlet temperatures. Nevertheless, the experiment performed with the smaller outlet plenum did have higher frequencies for comparable outlet temperatures. These were not as high as anticipated because the higher flow rate in that experiment probably allowed a greater mass of hydrogen to exist in the flow channel of the small plenum experiment than in the large plenum experiment.

October 30

In this experiment, inlet pressure was brought up to almost 280 psiA, dropped to 170 psiA, and again raised into the supercritical region. Results are shown in Figures 42 and 43. The differential pressure circuitry failed during the course of this run but was restored in time to observe a post chill down pressure drop rise at supercritical pressures. This had been observed and anticipated at subcritical pressures, but here was the same phenomenon at supercritical pressures.

Helmholtz and pipe resonance modes were present during this run.

November 6, 7, 8, and 13

These runs are considered in a group because they had the common objective of checking the necessity of parallel channel flow as a requirement for the observed oscillations. Three of the four flow channels were plugged, or at least given an extremely high impedance compared to the open channel, by slipping a stainless steel wire with both ends threaded into the channels; installing a teflon washer, a stainless steel washer, and a nut on the inlet end; and tightening against this with a stainless steel washer and a nut in the outlet plenum. Flow rates were reduced; but the inlet plenum heat leak, which led to the recognition of the inlet state as a necessary condition for Helmholtz, pipe resonance, and supercritical oscillations in this apparatus, now often provided inlet temperatures that were too high for oscillations to occur. As a result there were long periods of these runs in which no oscillations appeared and others in which their appearance was sporadic. Nevertheless, at various times all classes of pressure fluctuations were observed.

The results are shown in Figures 44 through 51. It is interesting to note at 1080 seconds in Figure 45, the Helmholtz frequency is 4.5 cps.

Under roughly similar conditions in a four channel experiment, 295 seconds in Figure 11, the Helmholtz frequency is 9 cps. This dependence on flow area is in accord with equation (3.2).

As in the four channel experiments, Figure 50 shows an increasing pressure drop as outlet temperature bottoms out. It also displays plug flow oscillations, with the inlet plenum amplitudes larger than those in the flow channel. However, unlike the four channel experiment, the inlet plenum oscillations are not irregular in form, as seen in the lower half of Figure 38.

Examination of data from these single channel experiments indicates that all categories of pressure oscillations observed in the four channel experiments should be seen in the single electrically heated tube of the final apparatus.

CHAPTER FOUR

CONCLUSIONS

The conclusions of this investigation can be classified according to three categories: (1) pressure oscillations, (2) cooldown phenomena, and (3) instrumentation.

4.1 PRESSURE OSCILLATIONS

A. Five classes of pressure fluctuations have been recognized in these experiments:

a. Open-open pipe resonance occurs in a resonant system confined to a flow channel, but this mode radiates into plena and its pressure oscillations have been observed there at diminished amplitudes. This mode was identified by this characteristic and by a comparison of observed with computed frequencies. The calculation of these frequencies required a knowledge of the sonic velocity distribution in the flow channel. This mode was observed at sub and supercritical pressures.

b. Helmholtz resonance, the acoustic analogy of a spring-mass system, exhibited equal amplitudes in flow channels and plena. Besides this characteristic, it was also identified by a predictable dependence on outlet plenum volume, flow channel area, and by a comparison of observed with computed frequencies. The frequency computation requires the flow channel density distribution to be known. This mode was observed at sub and supercritical pressures.

c. The supercritical mode is so named because it was observed to start when ascending pressure reached the critical value and to stop when a descending pressure again reached that value. The amplitude of this mode was observed to be equal in the flow channel and plena; and its frequency in many runs seemed almost independent of the cooldown, typically remaining near 9 cps. A possible cause of this mode may be an instability caused by a flow transition such as that between laminar and turbulent flow.

d. Plug flow oscillations were observed only at subcritical pressures, high flow rates, and in an apparatus cold enough to produce a liquid hydrogen temperature in the outlet fluid. Other identifying characteristics of these oscillations were a larger amplitude at the inlet plenum than farther downstream in the flow channel, a phase reversal between inlet plenum pressure oscillations and pressure difference between plena, and a smooth inlet plenum oscillation for single channel flow, while four channel flow produces an irregular pressure wave form in the inlet plenum.

e. Sawtooth and negative pulse fluctuations were attributed to a heat flux from elements upstream of the flow channels, specifically the inlet plenum. Sawtooth fluctuations were usually followed by negative pressure pulses, and the latter degenerated into beats. These fluctuations were accompanied by large scale variations in flow rate. These fluctuations were observed at sub and supercritical pressures. However, at supercritical pressures the magnitude of the flow oscillations were reduced; and in a high flow rate experiment, these fluctuations were not present.

B. Helmholtz, pipe, and supercritical resonant modes were not observed in the test section when the inlet fluid was superheated. From this, one can deduce that the mechanism for driving these modes occurred in only that part of the test section in which a dense state was present.

C. Flow in multiple parallel channels was shown not to be a necessary condition for these pressure oscillations.

D. The pressure oscillations were not caused by feedback loops in the control system, because they occurred when these loops were not operating.

E. The amplitude of the Helmholtz mode generally tended to be higher at lower flow rates. As cooldown progressed and frequency decreased, this amplitude would typically increase to a maximum and then decrease to zero. Sometimes this mode would suddenly cease to exist when the amplitude had previously been increasing.

F. The existence of wall temperature thresholds for pressure oscillations at low temperatures might be inferred from the observed sudden cessations of Helmholtz resonance. The threshold picture at higher temperatures is clouded by the production of superheated inlet hydrogen early in the run. The low flow runs with a 0.07 inch diameter orifice may be interpreted as indicating the existence of a low flow threshold for pipe resonance. They also may be interpreted as indicating that a lower flow threshold exists for the lower frequency Helmholtz mode than for pipe resonance.

G. Since Helmholtz and pipe resonance frequencies were observed to vary continuously during an experiment, the excitation of these modes probably occurs over a spectrum of frequencies.

4.2 COOLDOWN PHENOMENA

A. When cooling of the test section produced no further drop in hydrogen temperature at the outlet plenum, an increase in pressure drop was often observed. This occurred at sub and supercritical pressures but not at very high flow rates when a plug flow pattern was believed to exist. This phenomenon may be caused by a transition from film boiling to nucleate boiling over an increasingly longer length of flow channel, or it may be caused by an increasing internal shear stress as the average hydrogen quality is decreasing. The latter concept tends to agree with two phase flow calculations by a Lockhart-Martinelli method applied at the pressures of these experiments. However the calculated dependence of frictional effects on quality appears to be too small to account for the entire increase in pressure loss. Similar processes might have taken place at supercritical pressures between high and low density regions of hydrogen.

B. Greater axial temperature gradients were observed in the slow cooldowns than in the fast ones.

C. When the test section pressure was lowered across the critical value at low flow rates, a noticeable change occurred in the time derivative of the outlet temperature. The change always indicated an improvement in heat transfer at subcritical pressures. At some times a rise in outlet temperature was observed as the system cooled down when pressure went from super to subcritical. One interpretation of this phenomenon is that there is a higher intensity of turbulence in two phase flow than in supercritical flow.

D. The test section showed no indication of thermal asymmetry either between flow passages or around a flow passage.

E. The inlet end of this test section did not show the unusual elevation of wall temperature observed in the apparatus of Watts, et al., [8].

4.3 INSTRUMENTATION

A. Lengths of pressure transducer transmission lines should be carefully selected to meet the conflicting requirements of a good frequency response and a minimum variation in transducer temperature.

B. Before a method of installing thermocouples is chosen, some thermocouples should be calibrated before and after a sample installation to assure that the installation technique does not affect their calibration.

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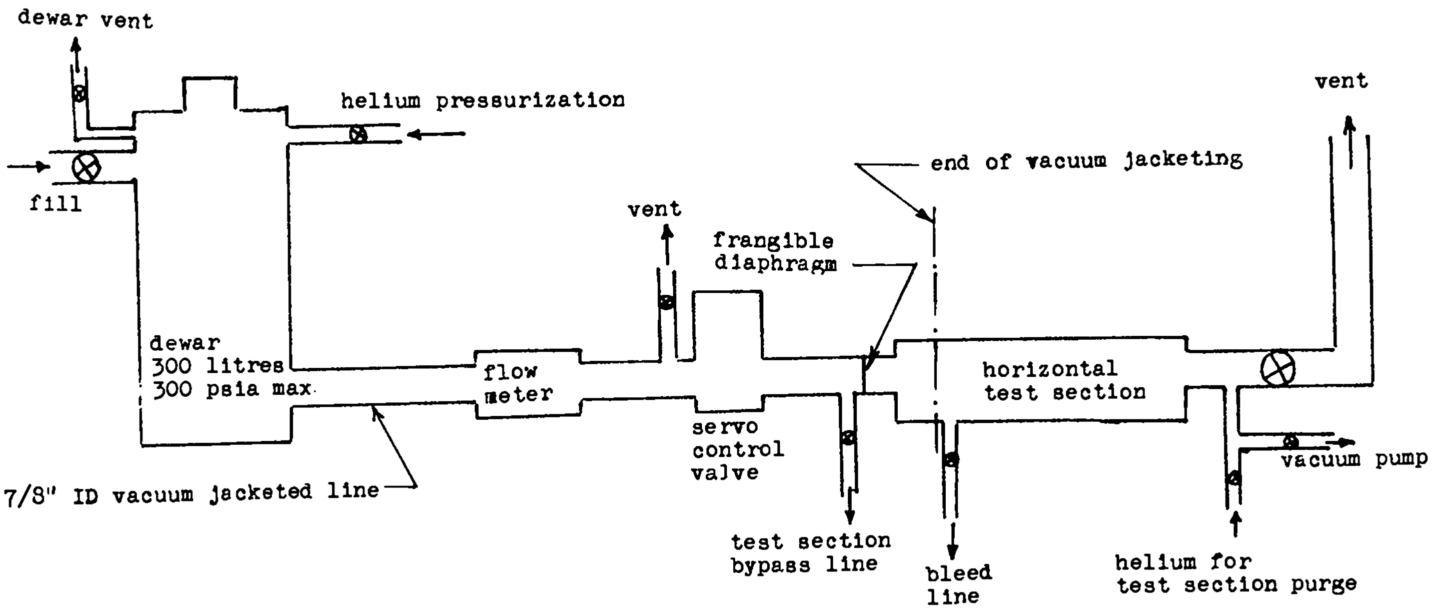


Figure 1. Cryogenic Flow System

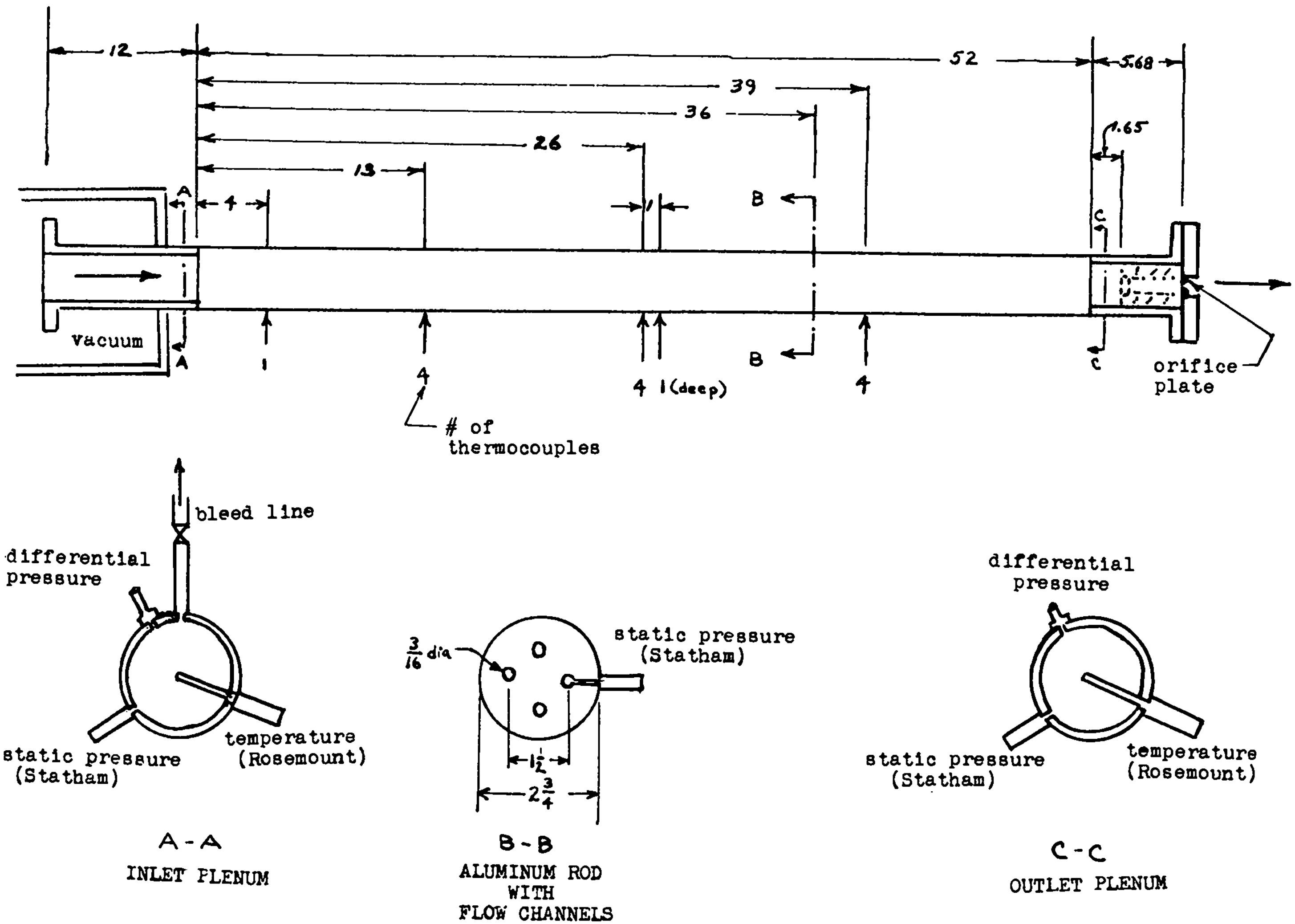
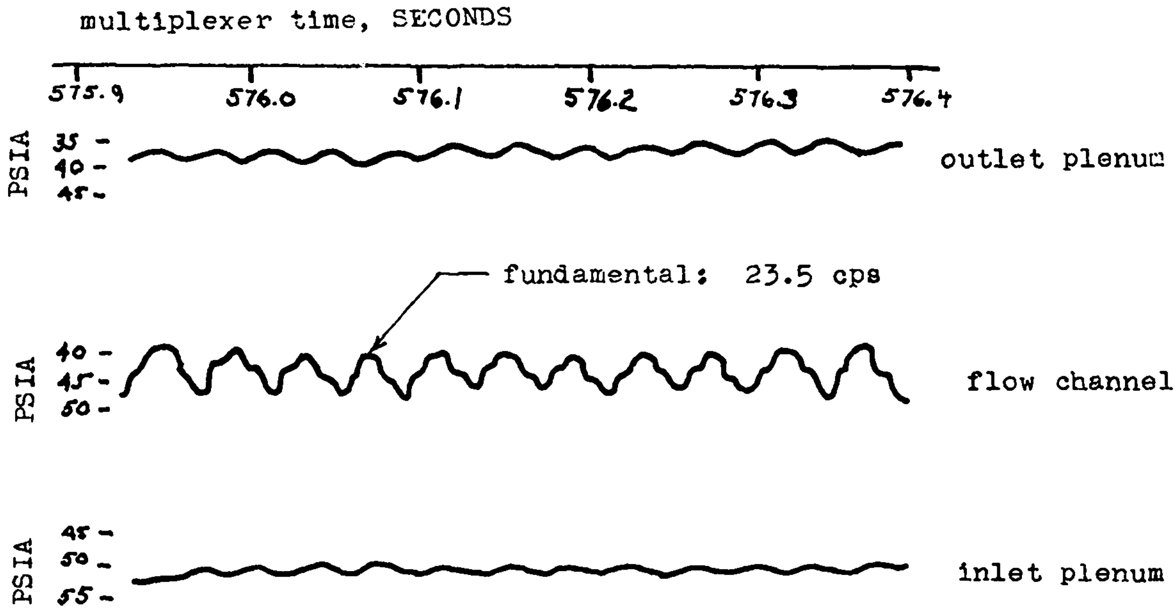


Figure 2. Test Section Details

NITROGEN



130°R at inlet, 160°R at outlet

EXPERIMENT OF SEPTEMBER 30, 1963

8.15 in^3 outlet plenum
0.203 in orifice

Figure 3. Pipe Resonance in Nitrogen

NITROGEN

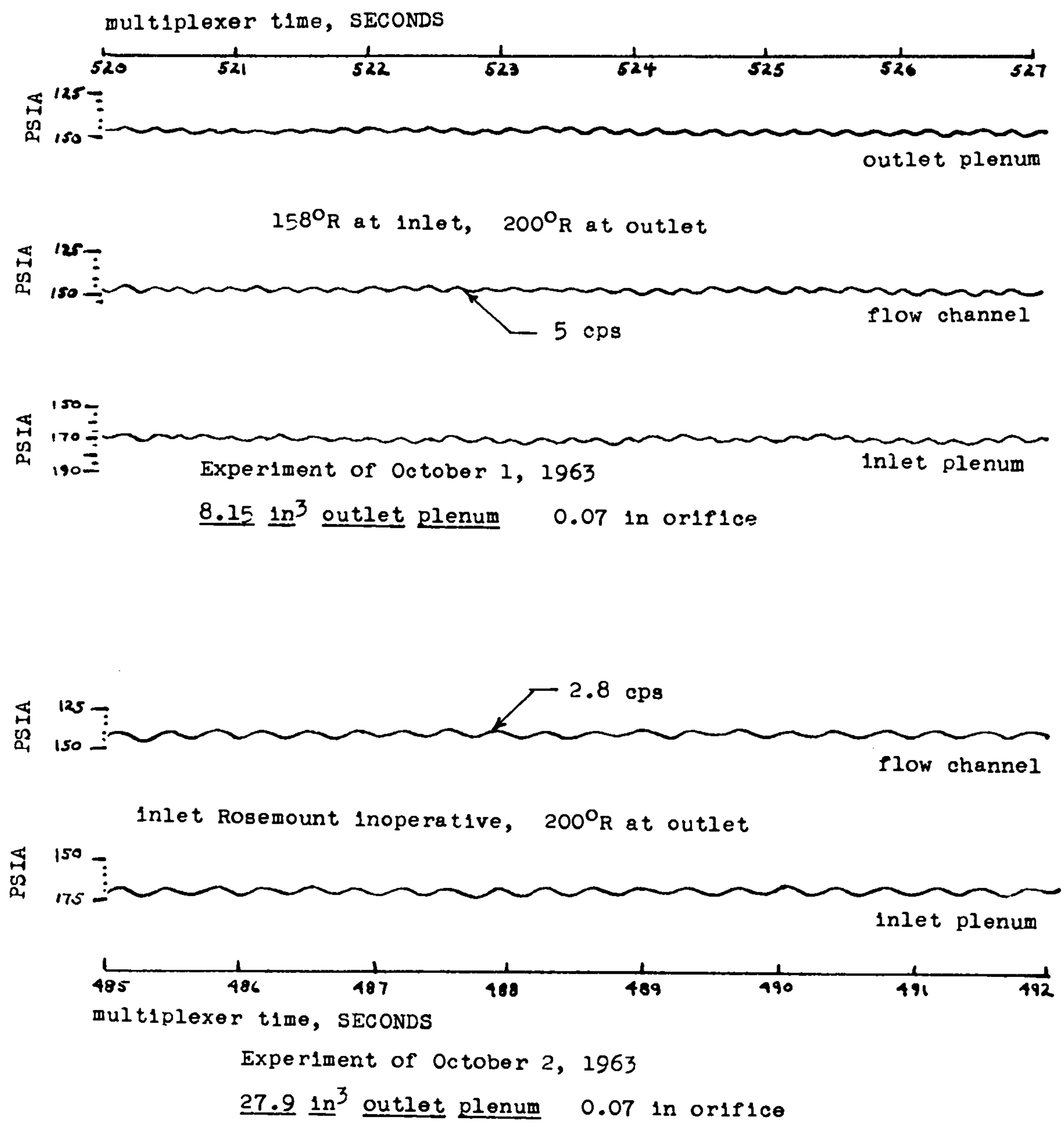
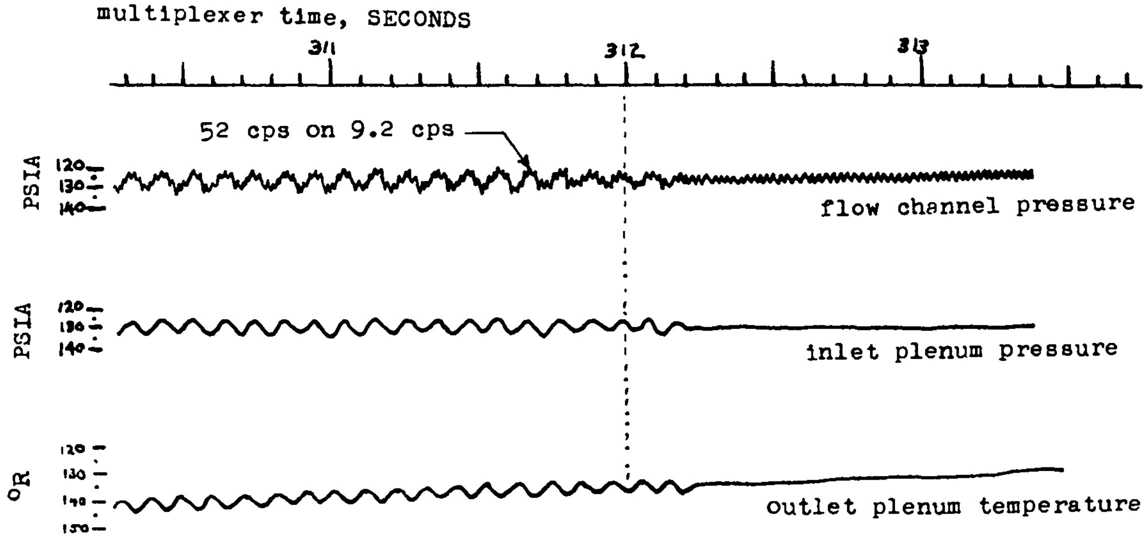


Figure 4. Outlet Plenum Volume Effects on Helmholtz Resonance in Nitrogen

HYDROGEN

Experiment of October 14, 1963



note sudden cessation of Helmholtz oscillation
& phase difference between temperature and pressure

Figure 5. Superposition of Pipe and Helmholtz Resonances in Hydrogen

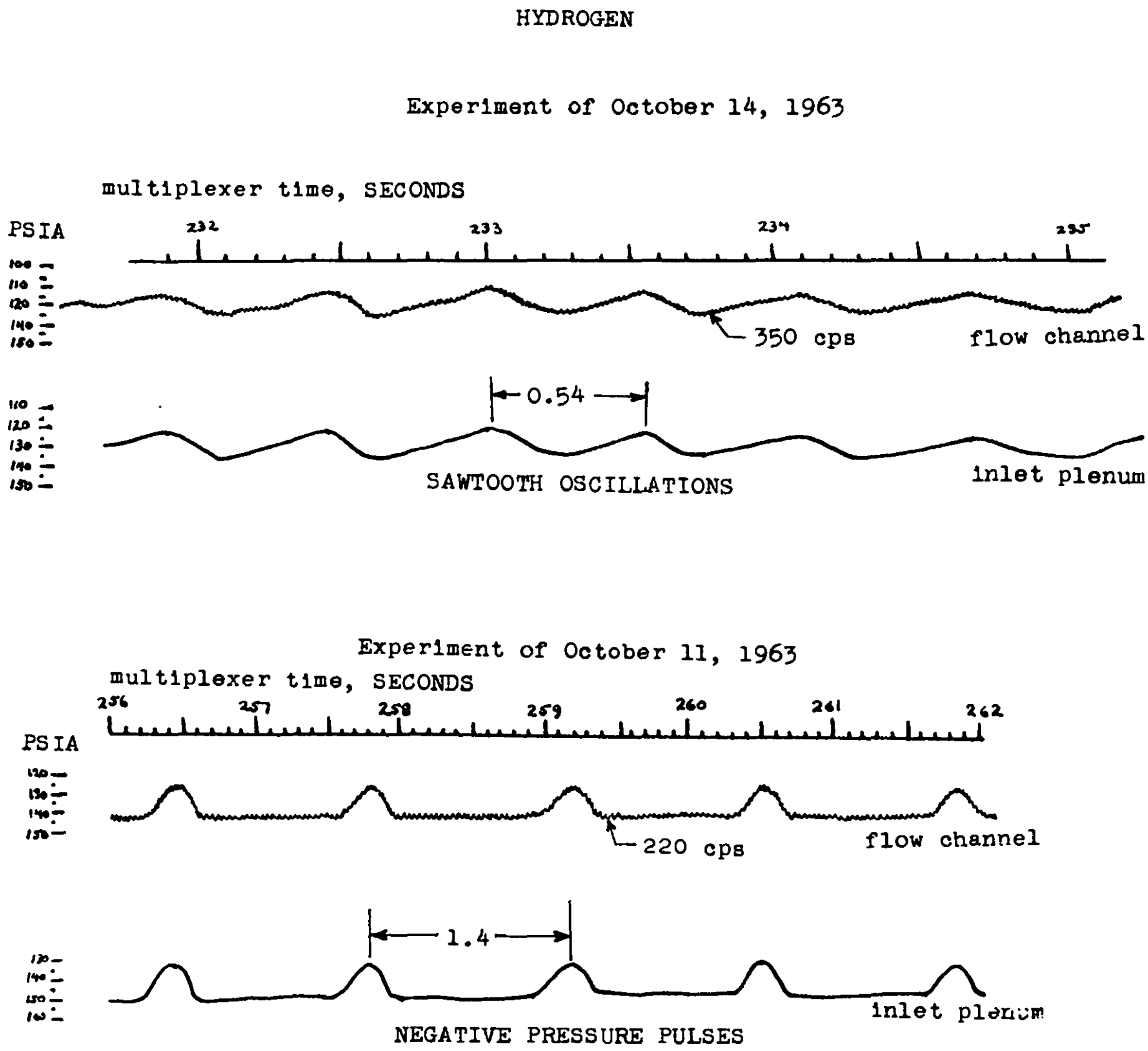


Figure 6. Sawtooth and Negative Pulse Phenomena in Hydrogen

HYDROGEN

Experiment of October 22, 1963

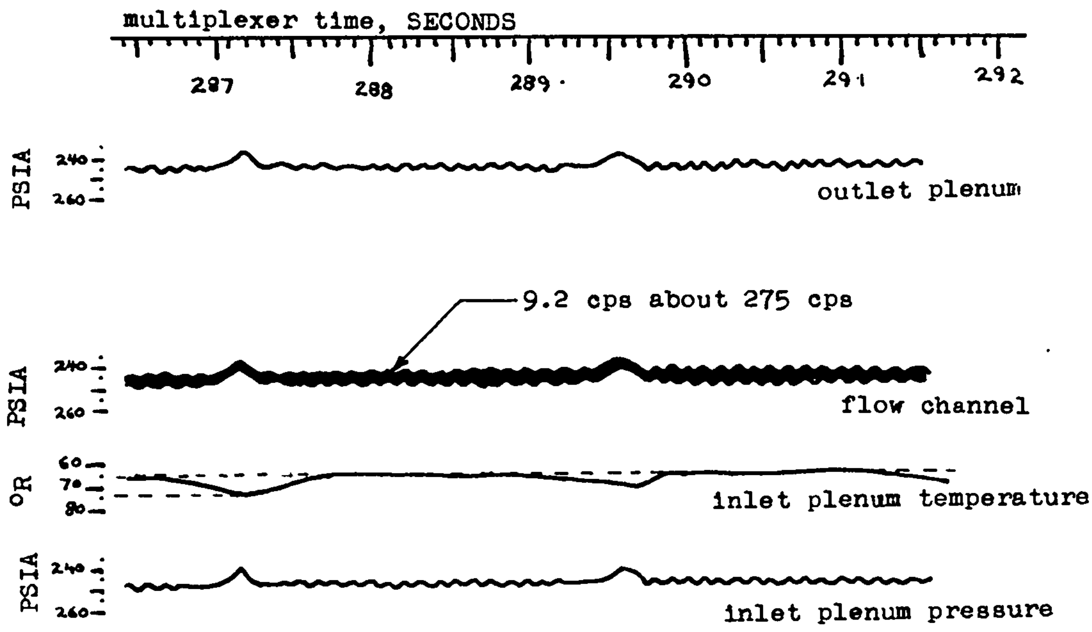


Figure 7. Negative Pressure Pulses Accompanying a Rise in Inlet Temperature at Supercritical Pressures

HYDROGEN

Experiment of October 22, 1963

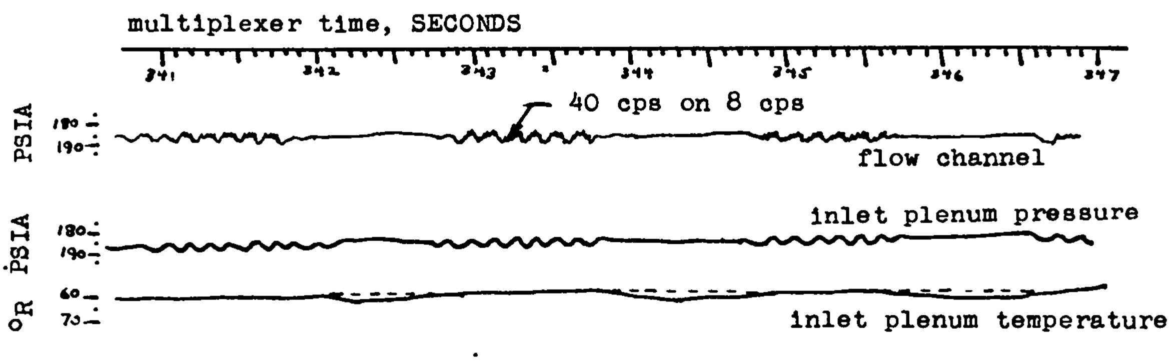


Figure 8. Pressure Beats Accompanying a Two Degree Rise in Inlet Temperature at Supercritical Pressures

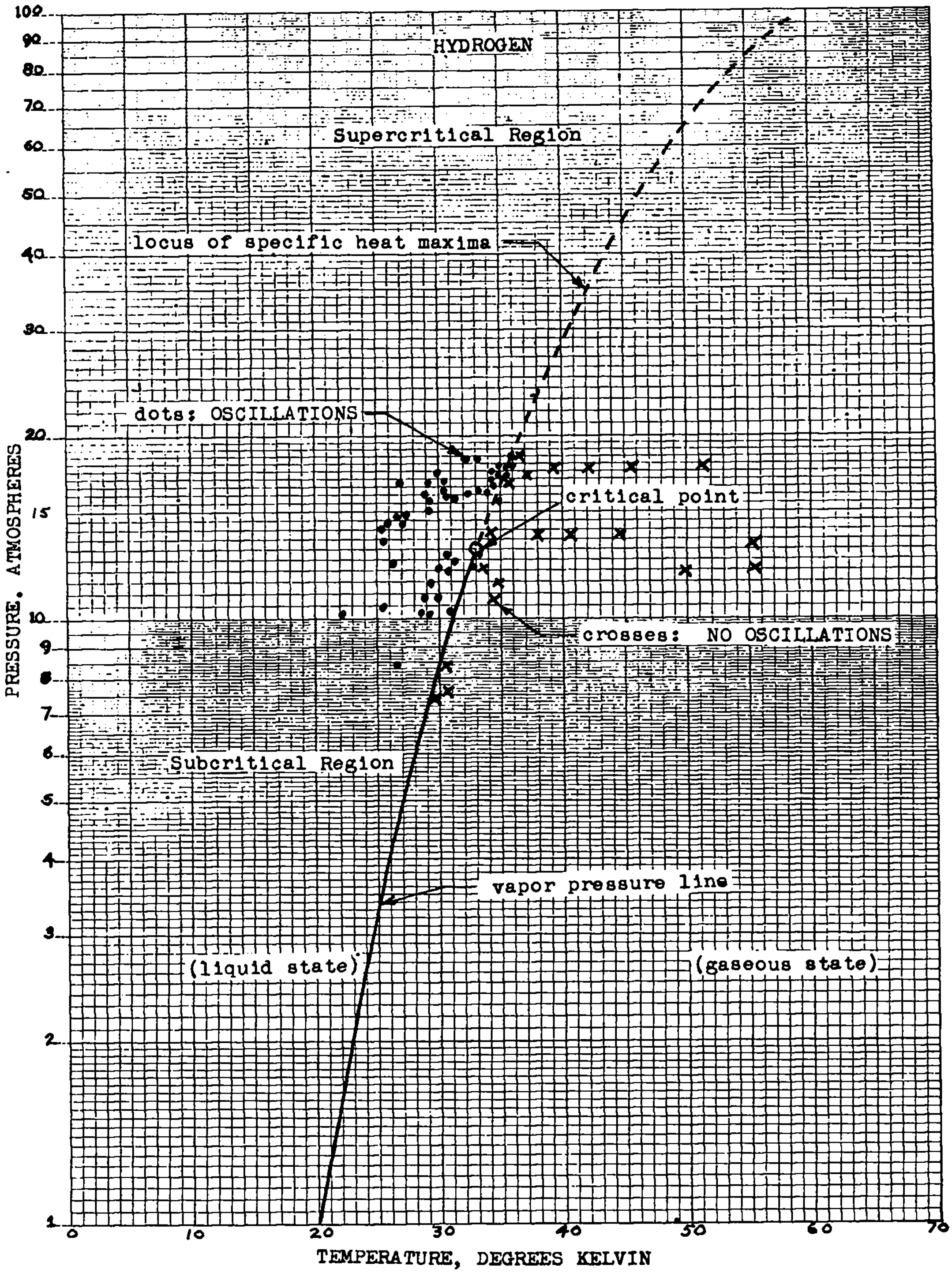


Figure 9. Dependence of Pressure Oscillations on Inlet Conditions

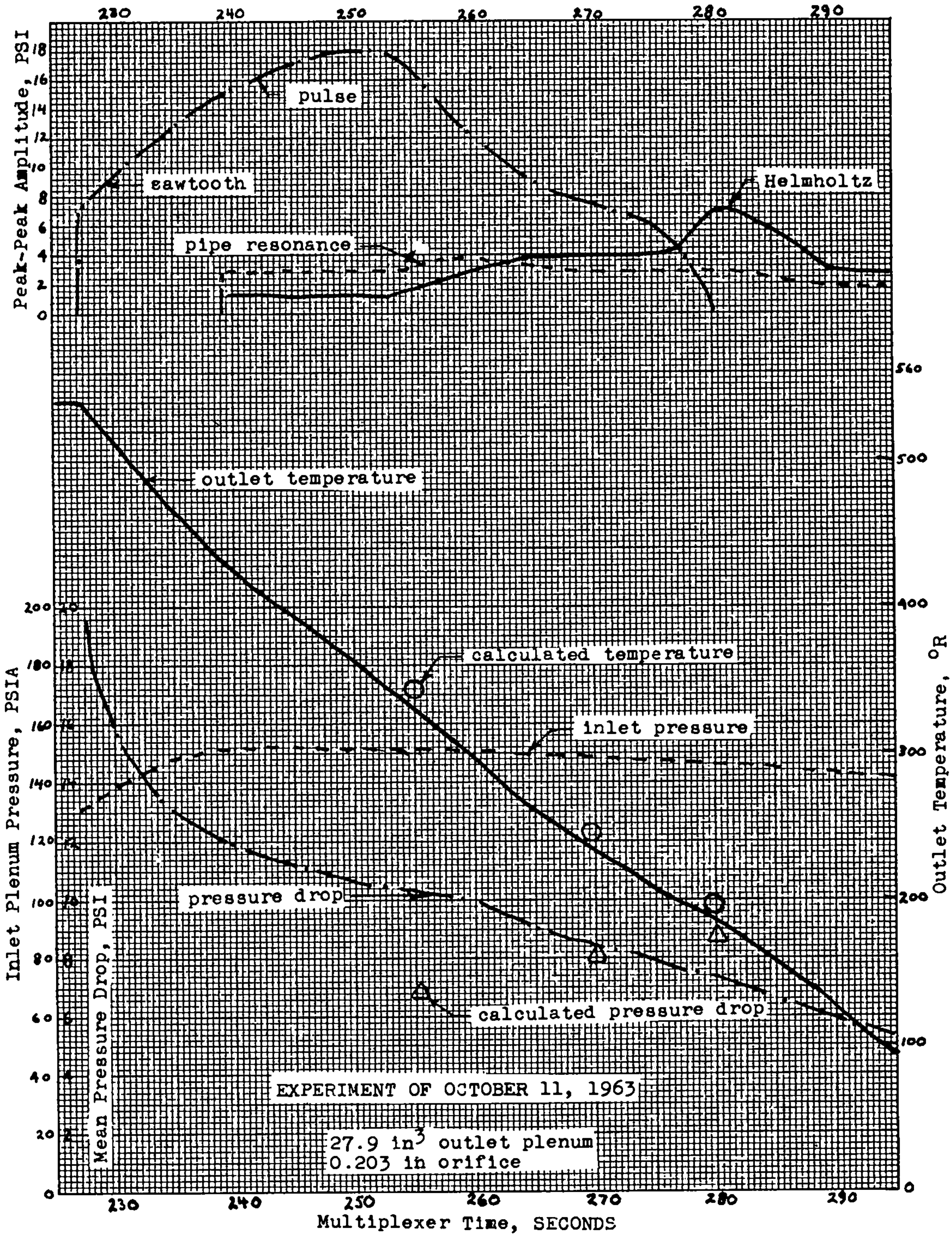


Figure 10. Pressures, Temperatures, Amplitudes - October 11, 1963

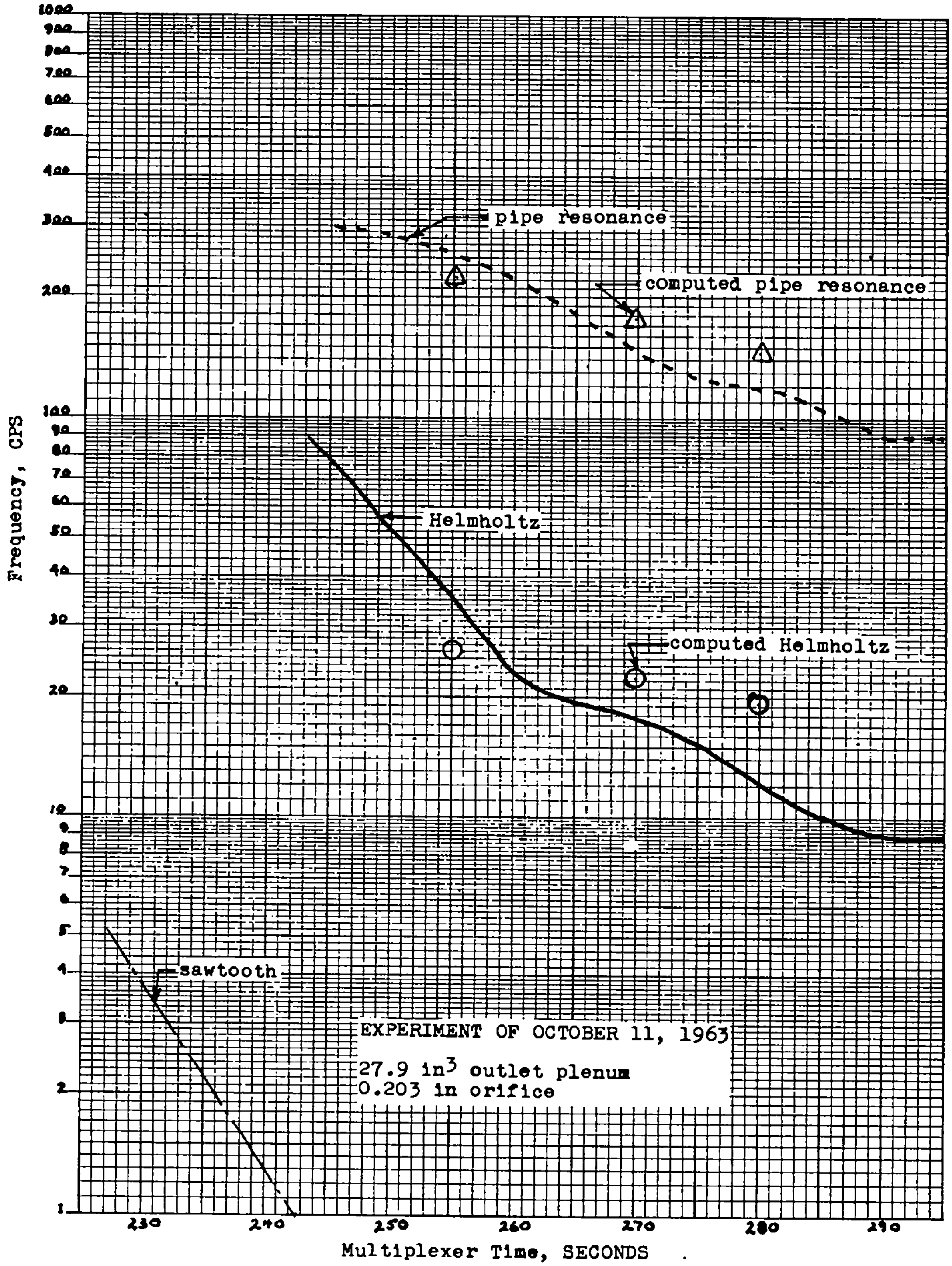


Figure 11. Frequencies - October 11, 1963

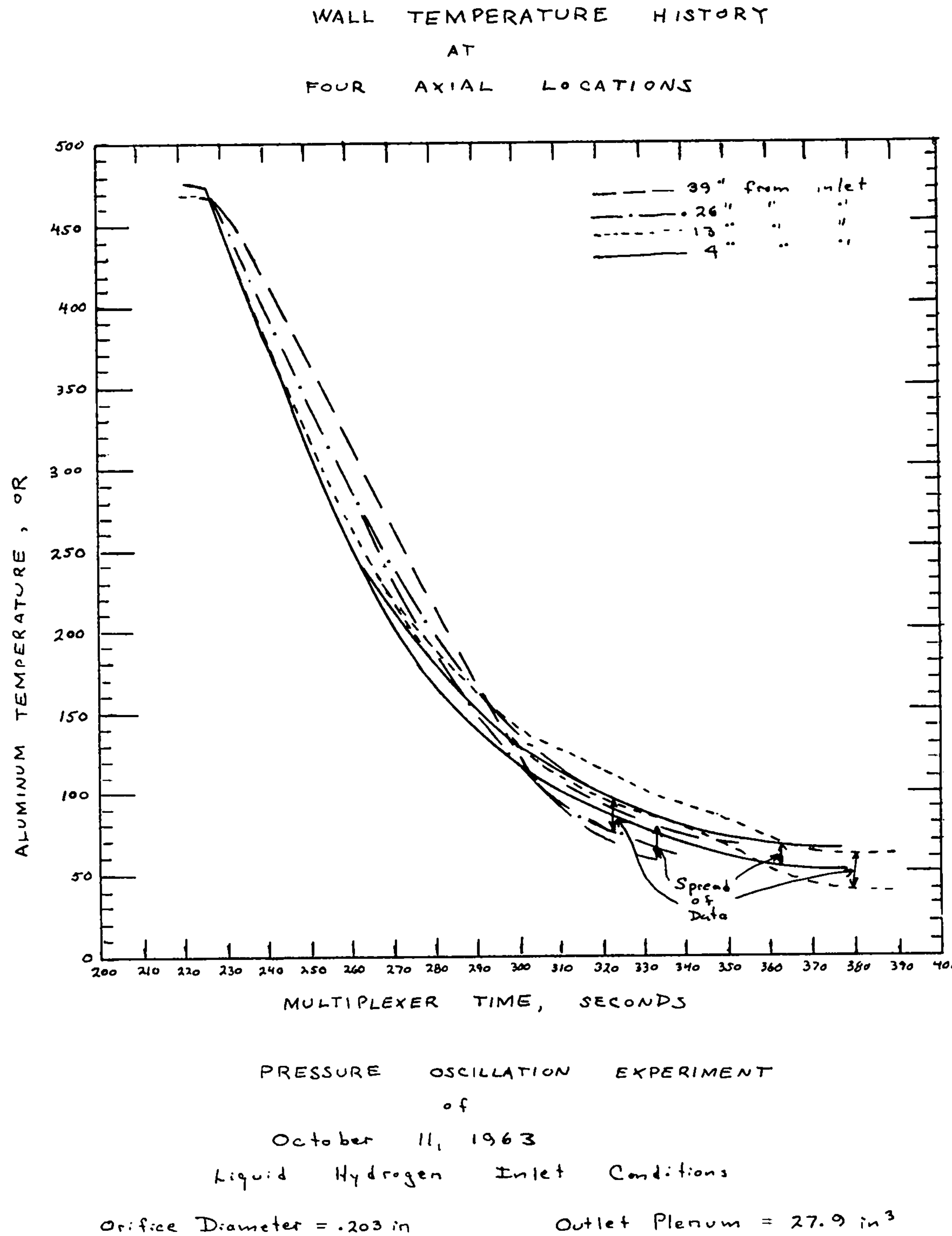


Figure 12. Axial Wall Temperatures - October 11, 1963

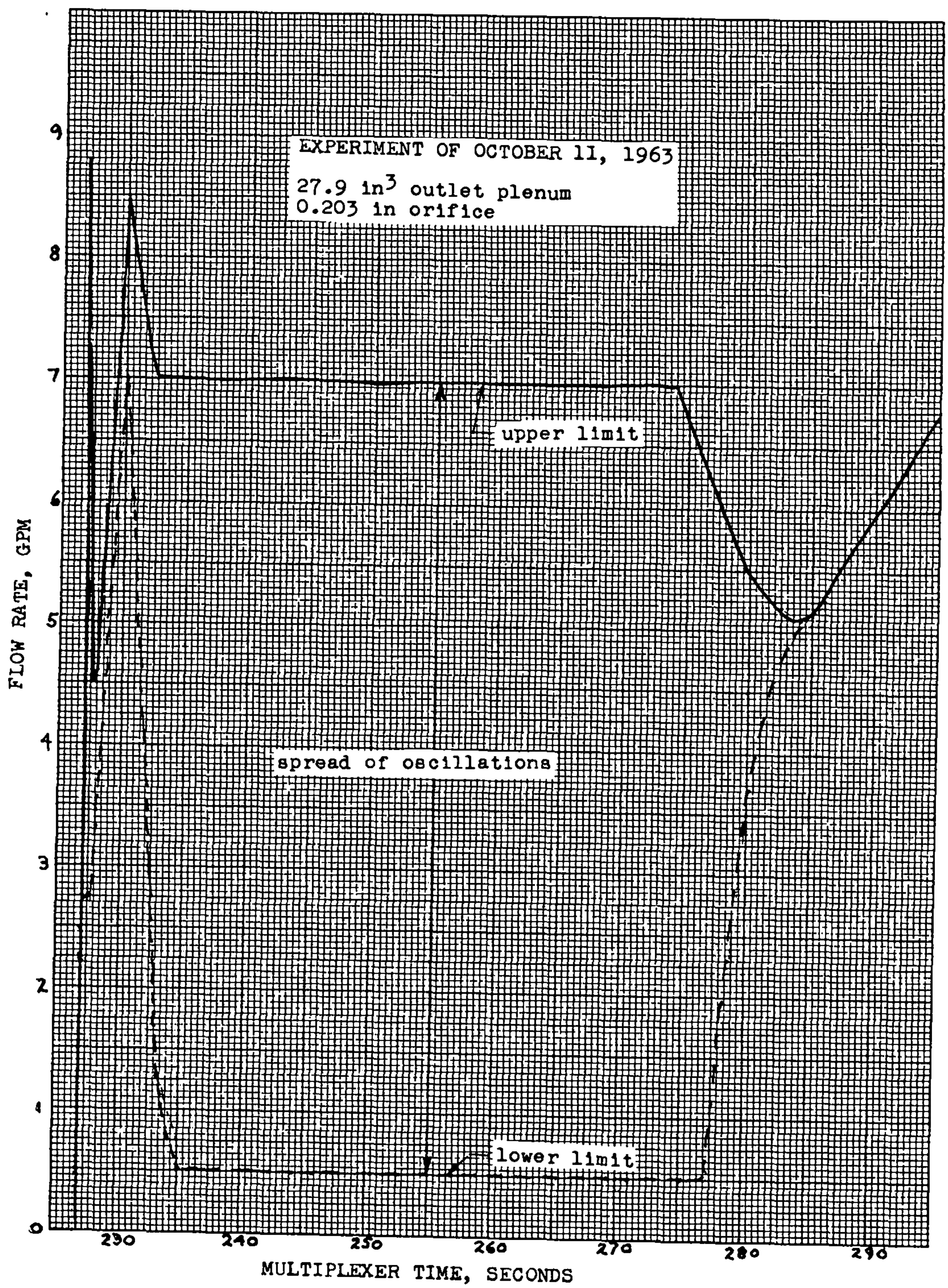


Figure 13. Flow Rate - October 11, 1963

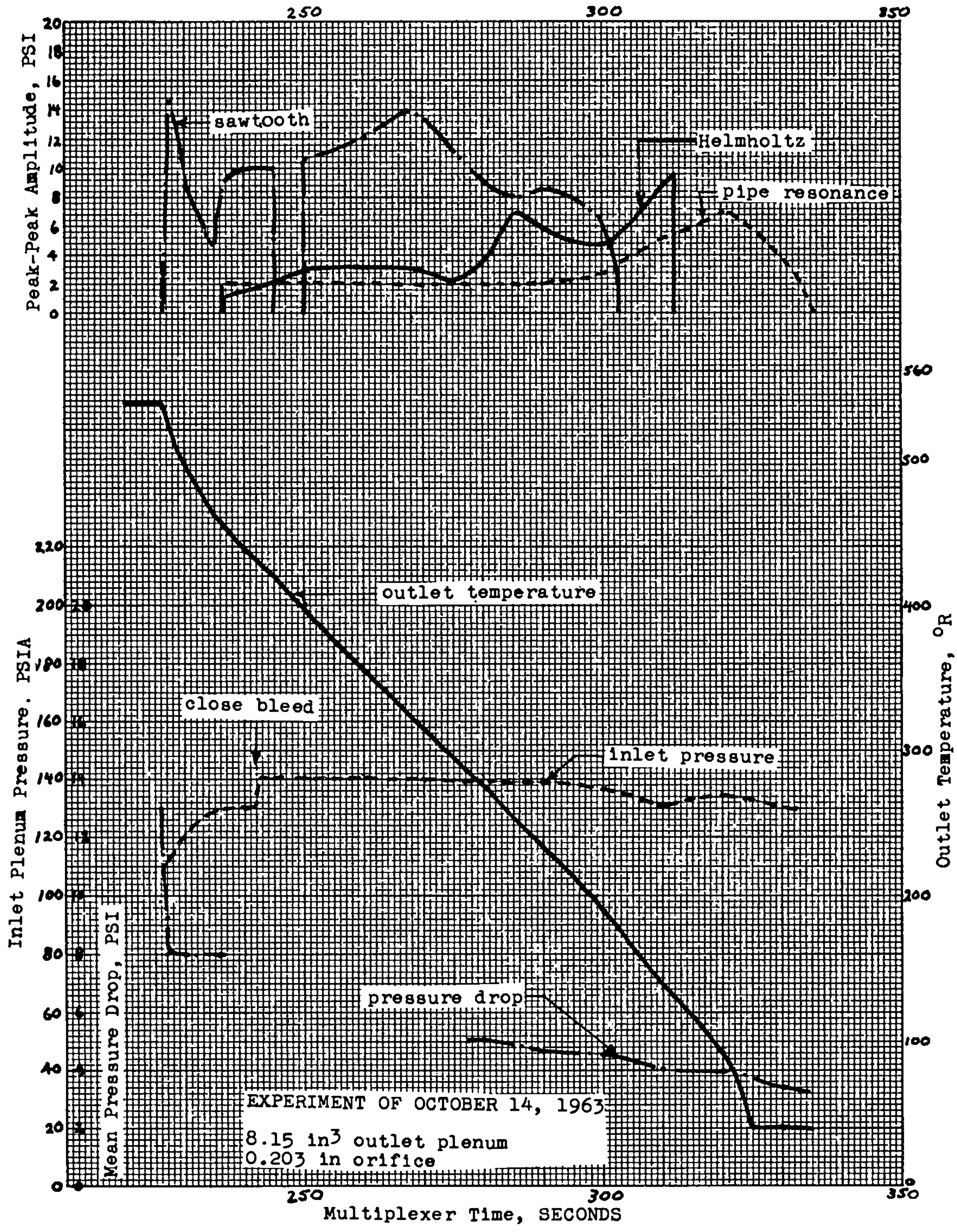


Figure 14. Pressures, Temperatures, Amplitudes - October 14, 1963

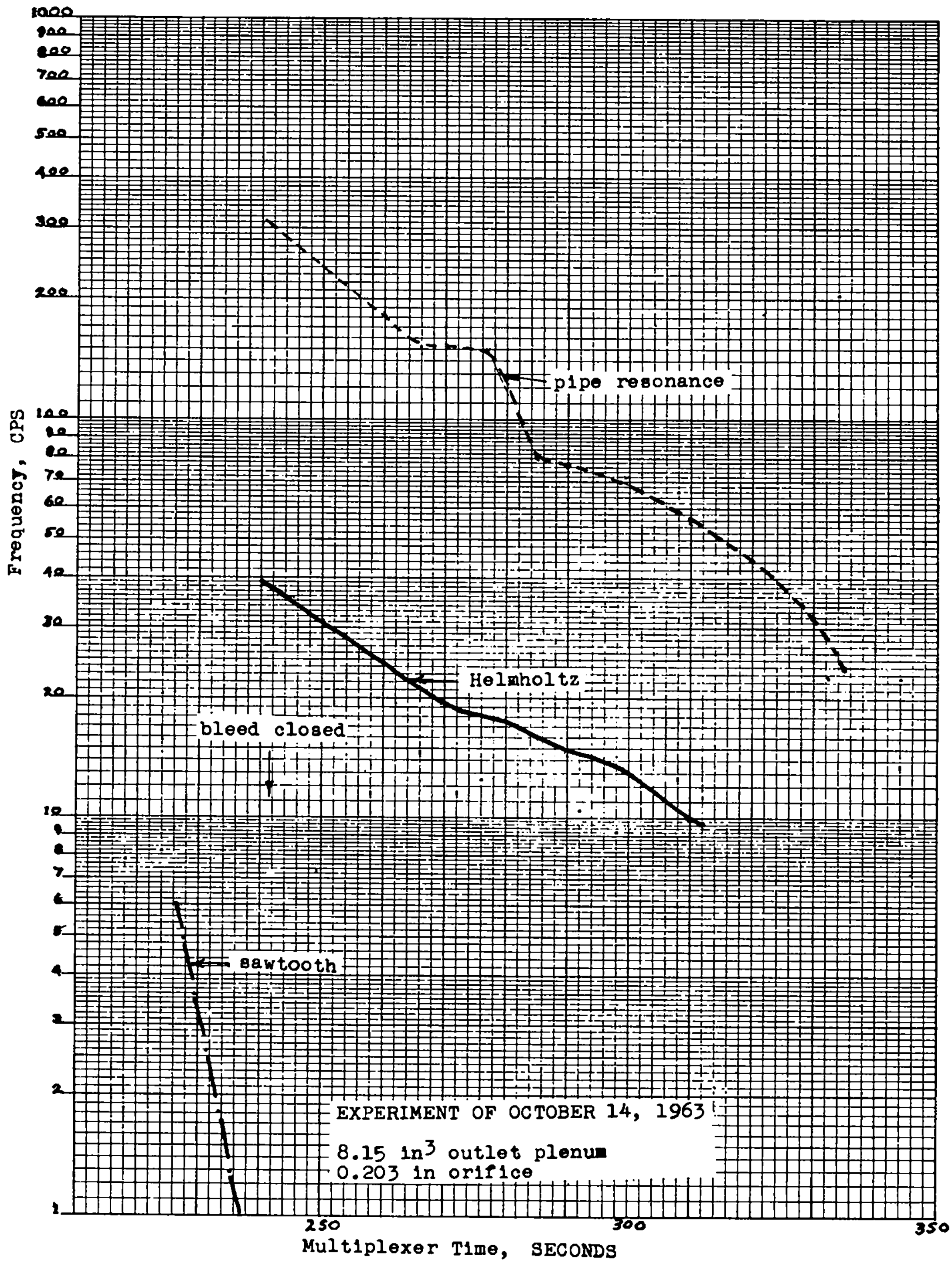


Figure 15. Frequencies - October 14, 1963

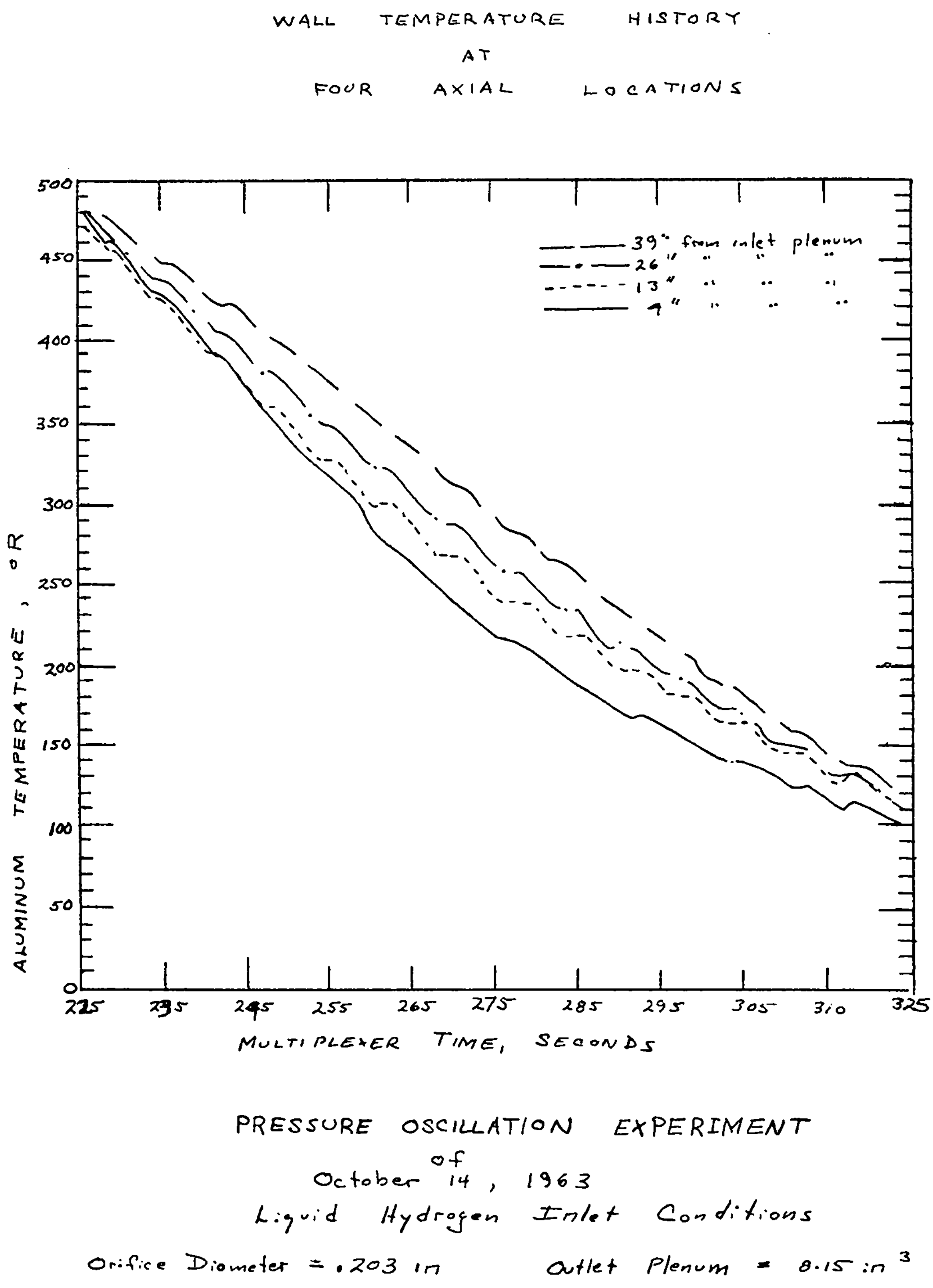


Figure 16. Axial Wall Temperatures - October 14, 1963

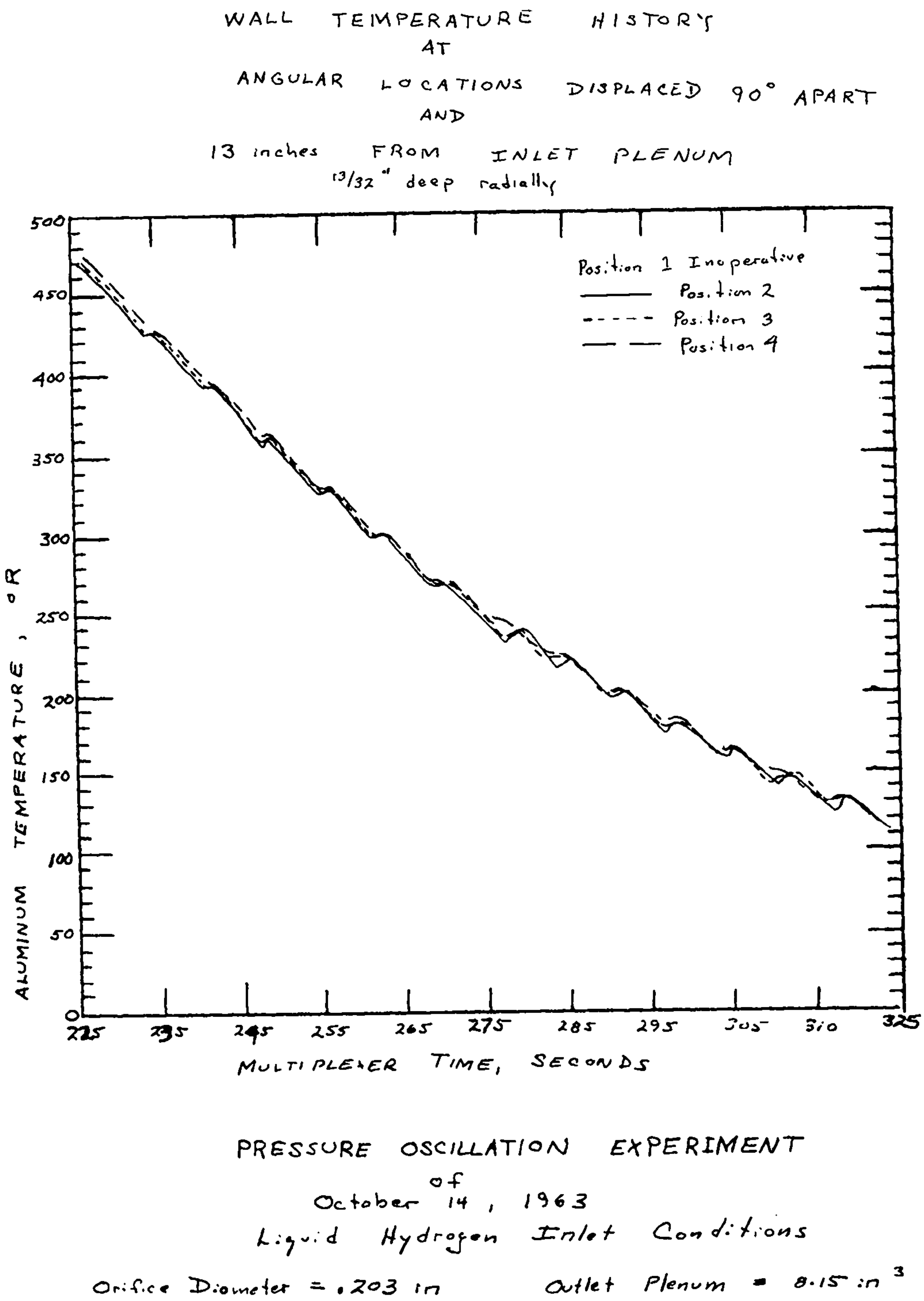


Figure 17. 13 inch Location Wall Temperatures - October 14, 1963

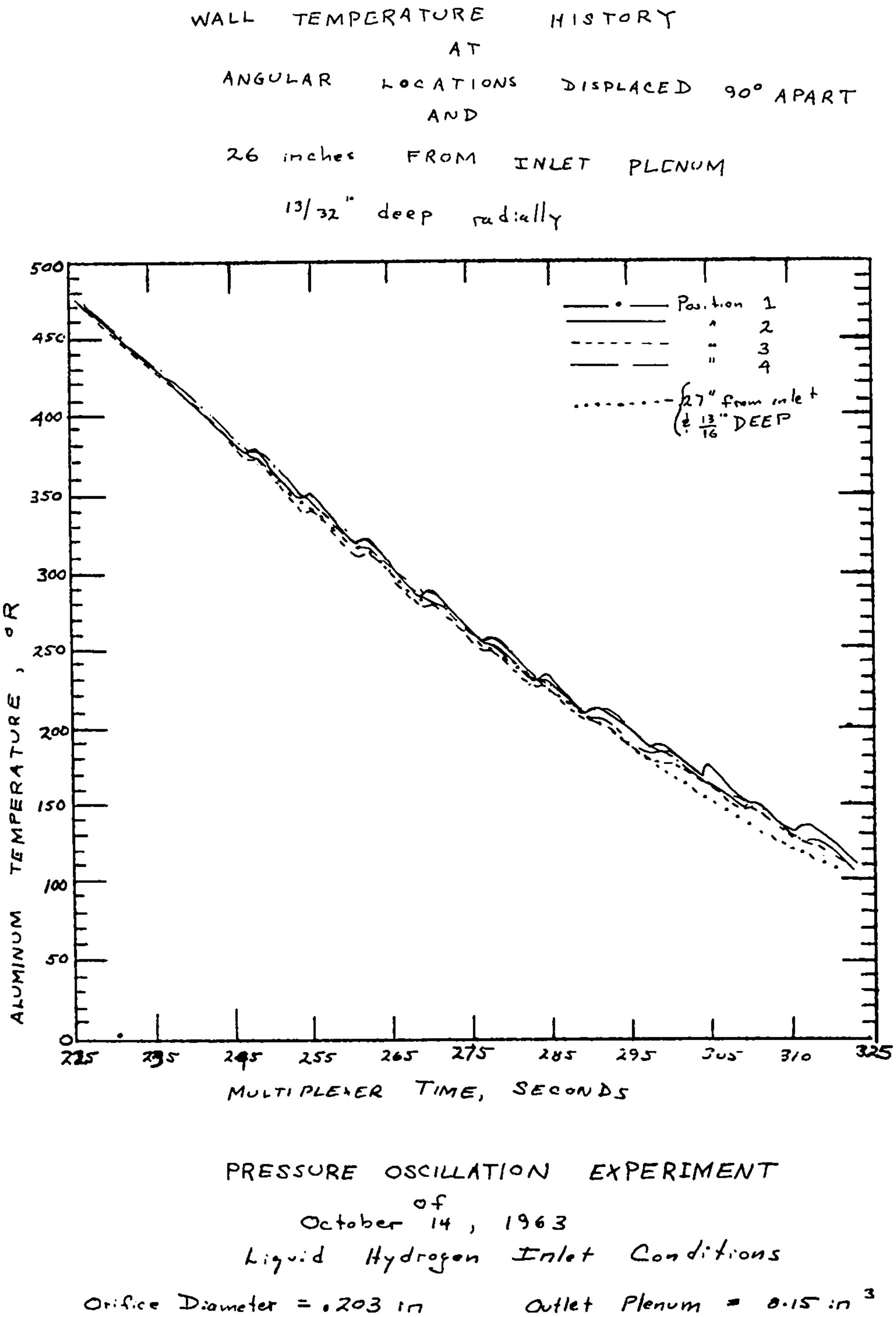


Figure 18. 26 inch Location Wall Temperatures - October 14, 1963

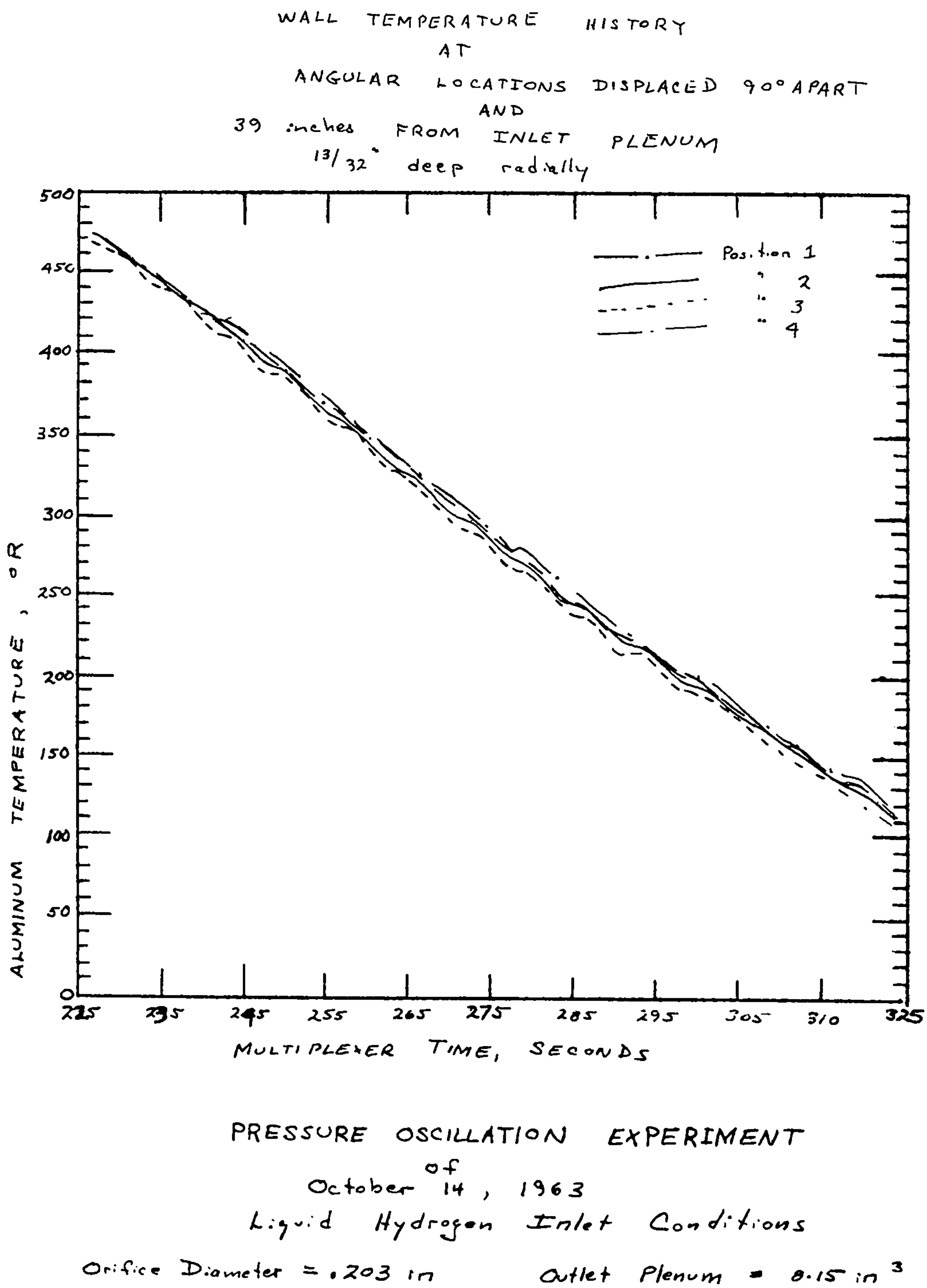


Figure 19. 39 inch Location Wall Temperatures - October 14, 1963

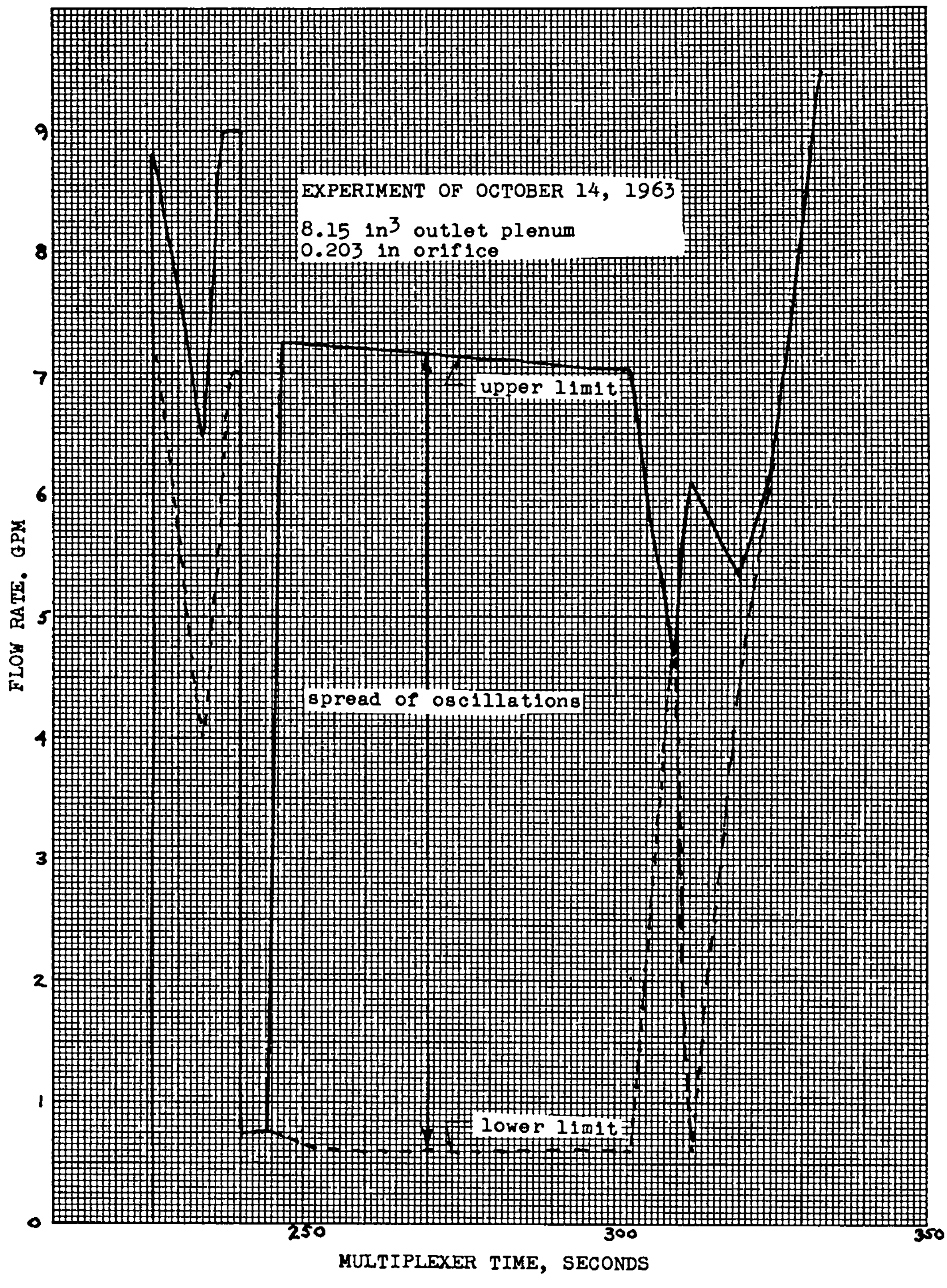


Figure 20. Flow Rate - October 14, 1963

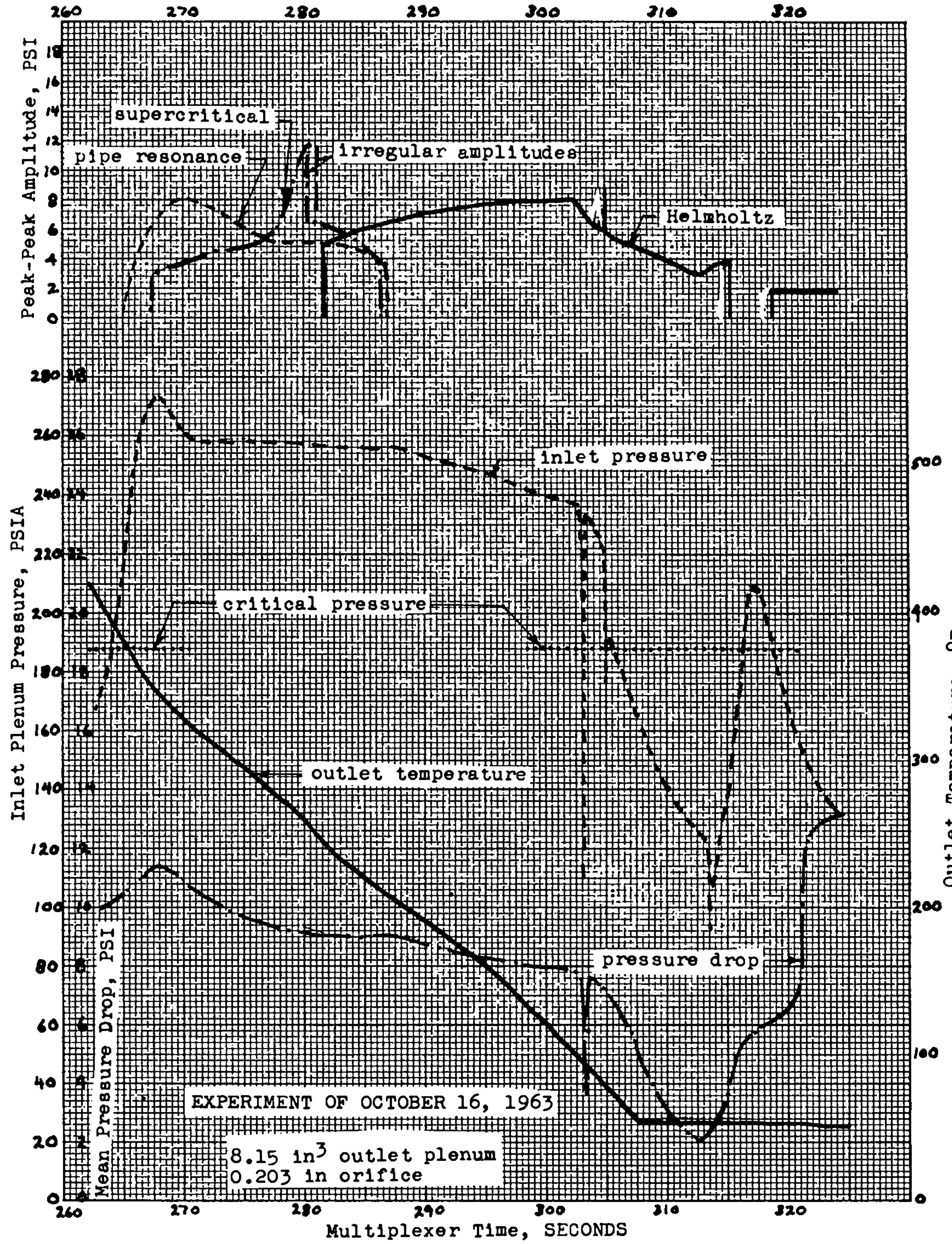


Figure 21. Pressures, Temperatures, Amplitudes - October 16, 1963

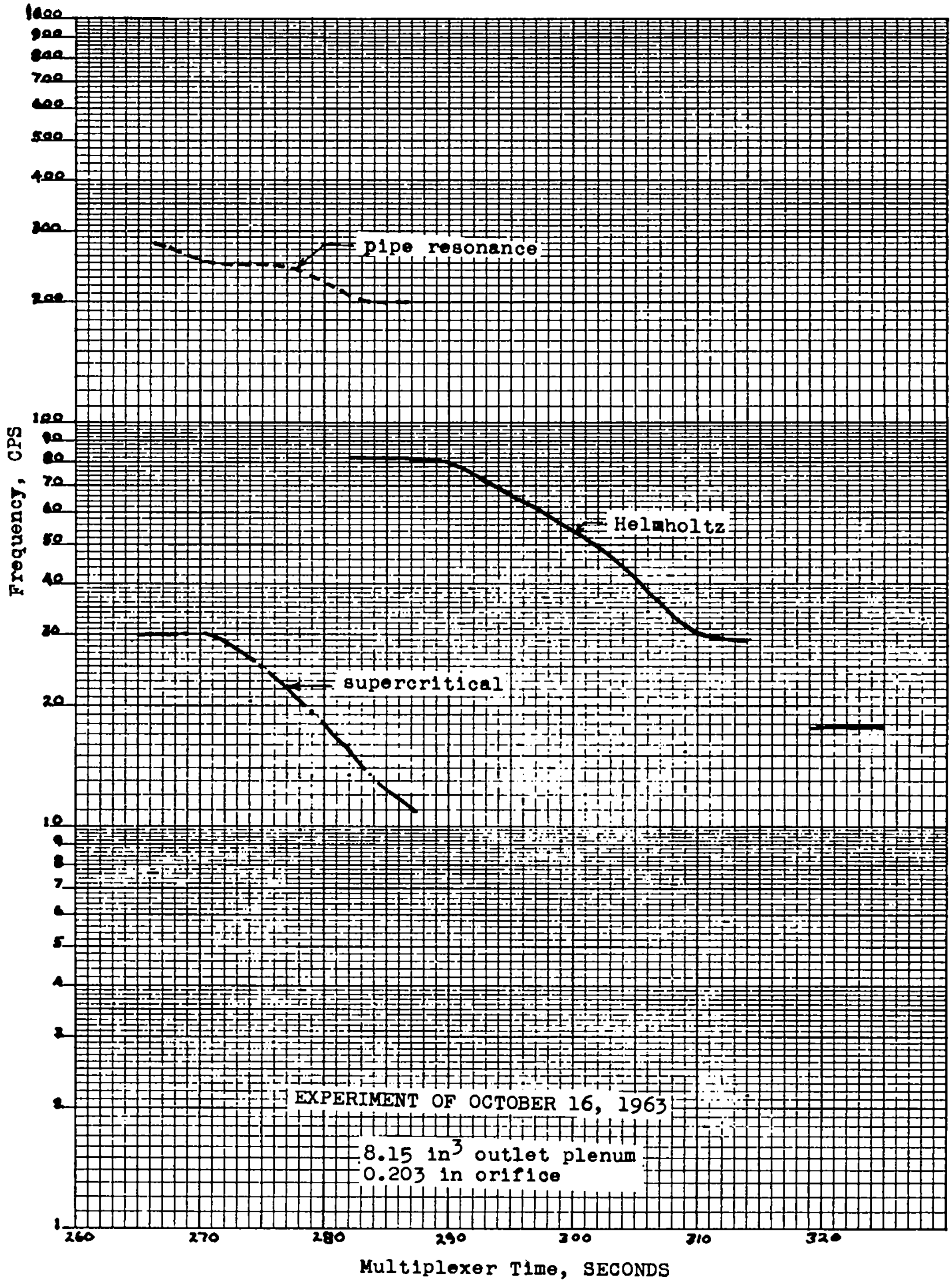


Figure 22. Frequencies - October 16, 1963

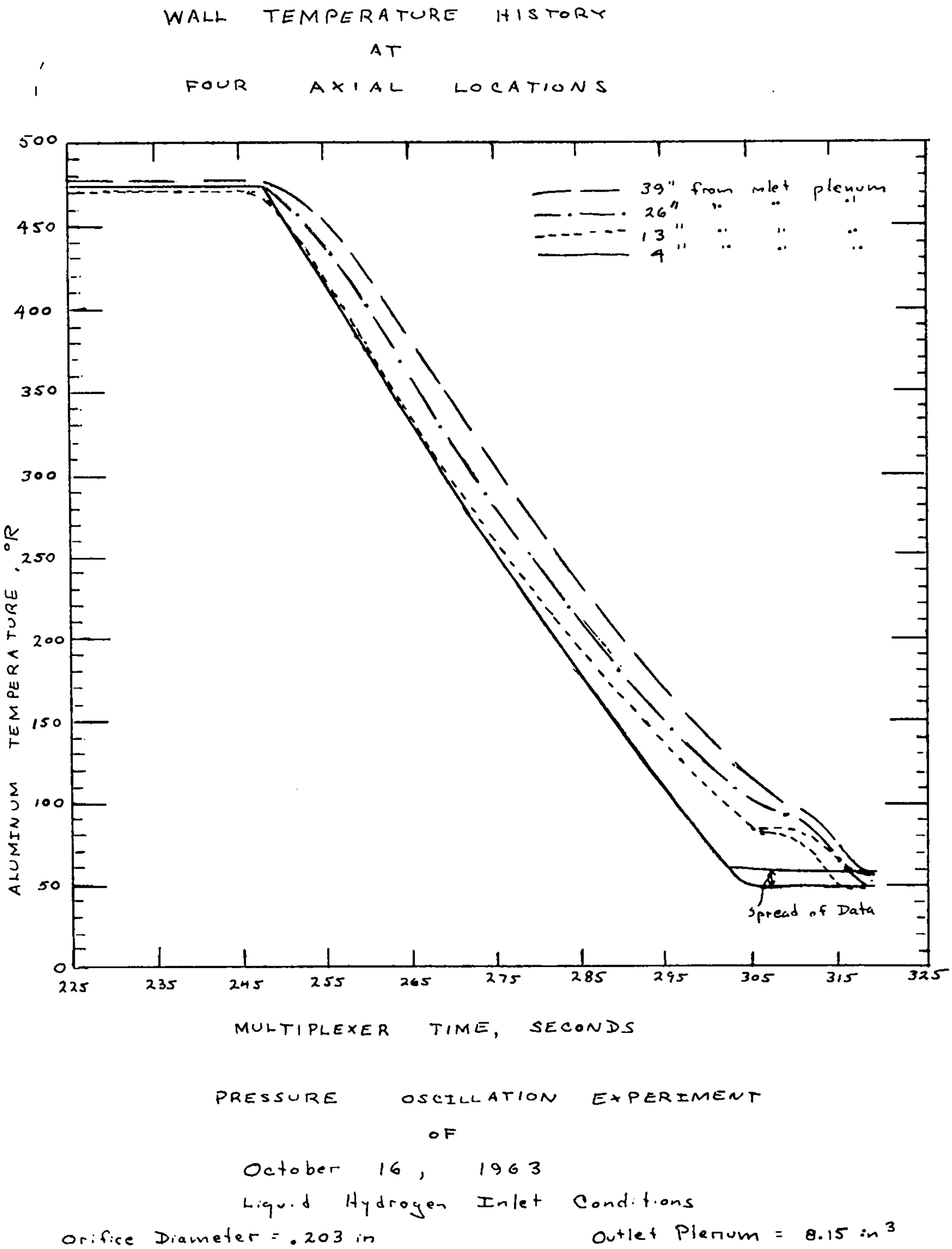


Figure 23. Axial Wall Temperatures - October 16, 1963

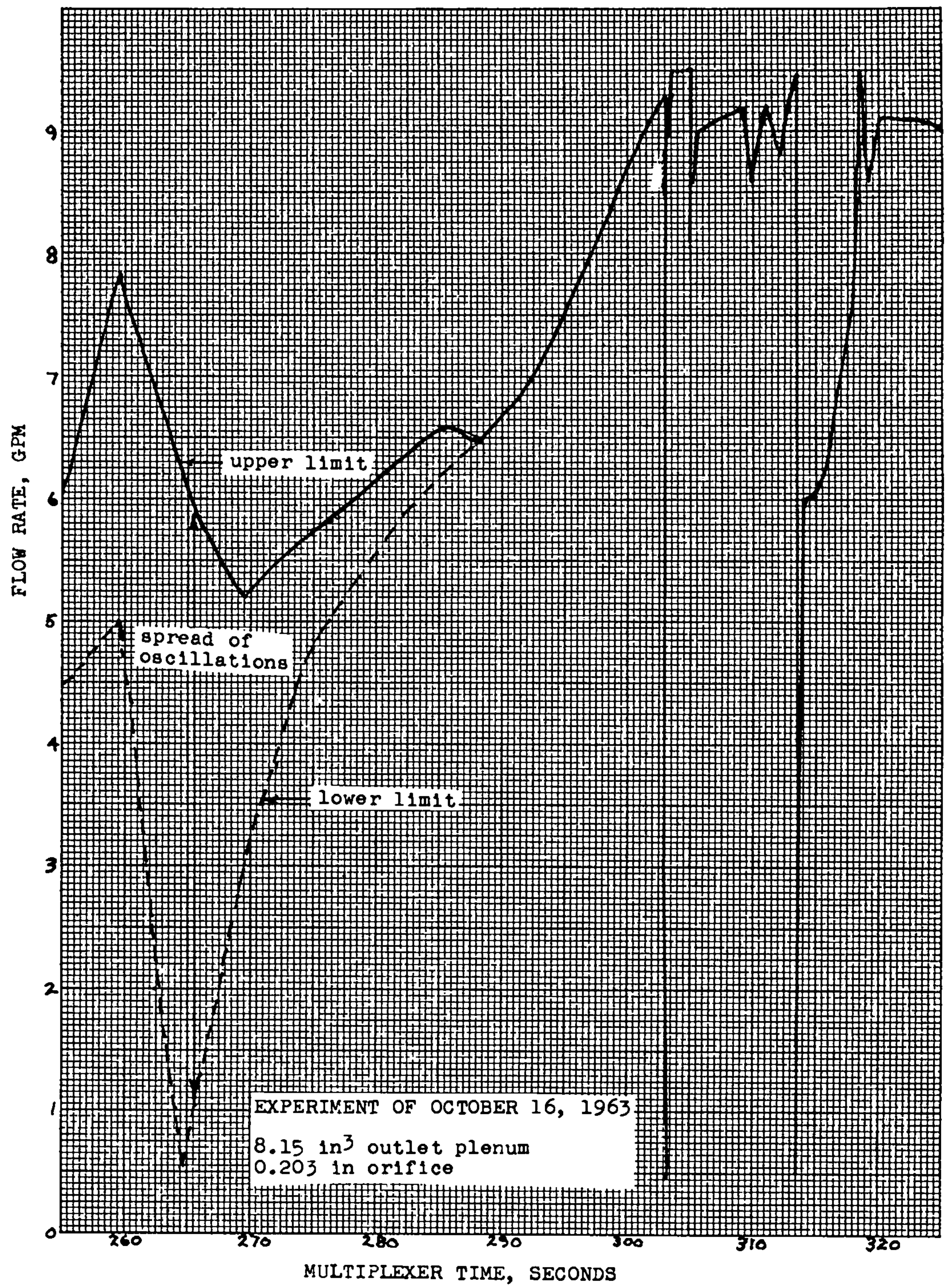


Figure 24. Flow Rate - October 16, 1963

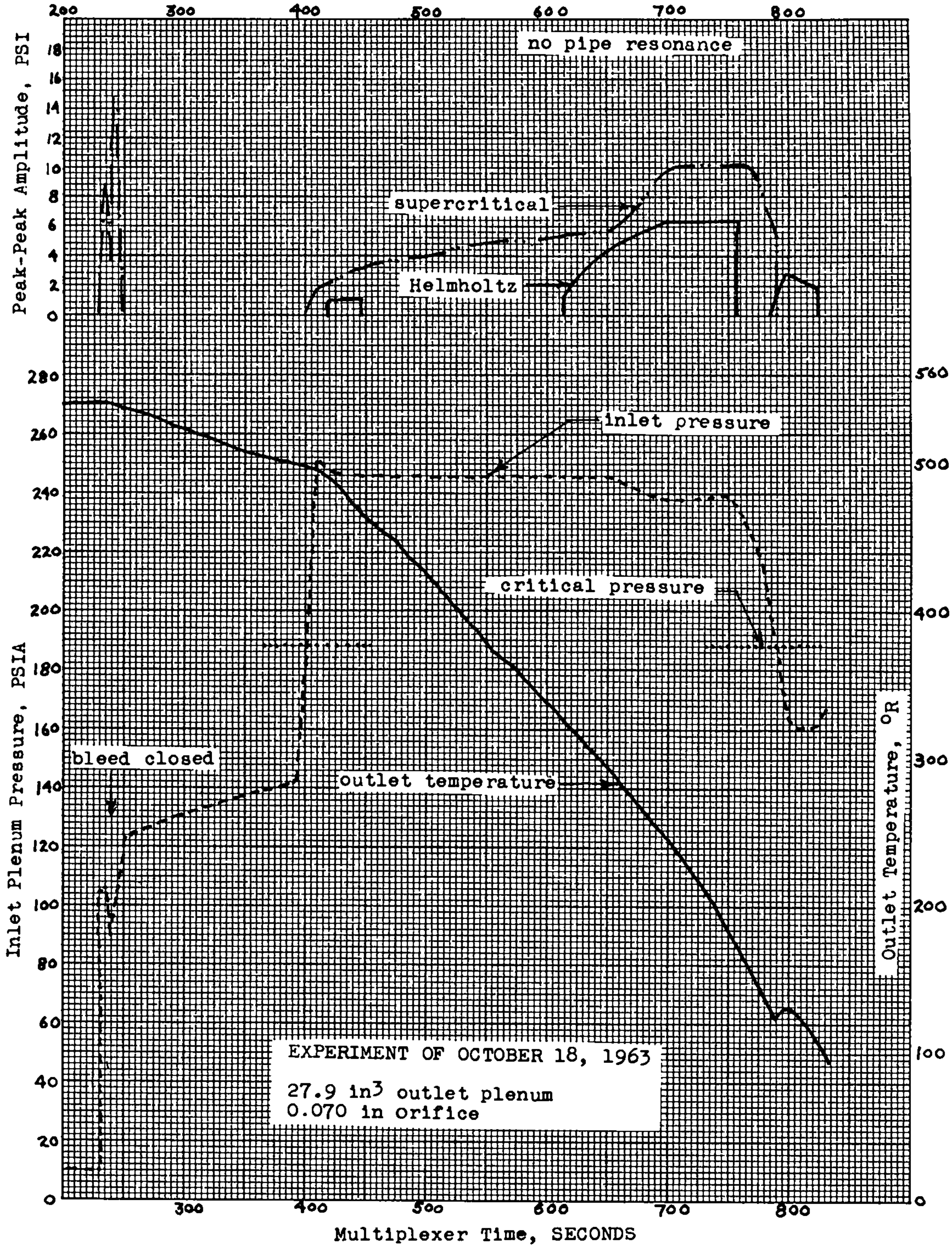


Figure 25. Pressures, Temperatures, Amplitudes - October 18, 1963

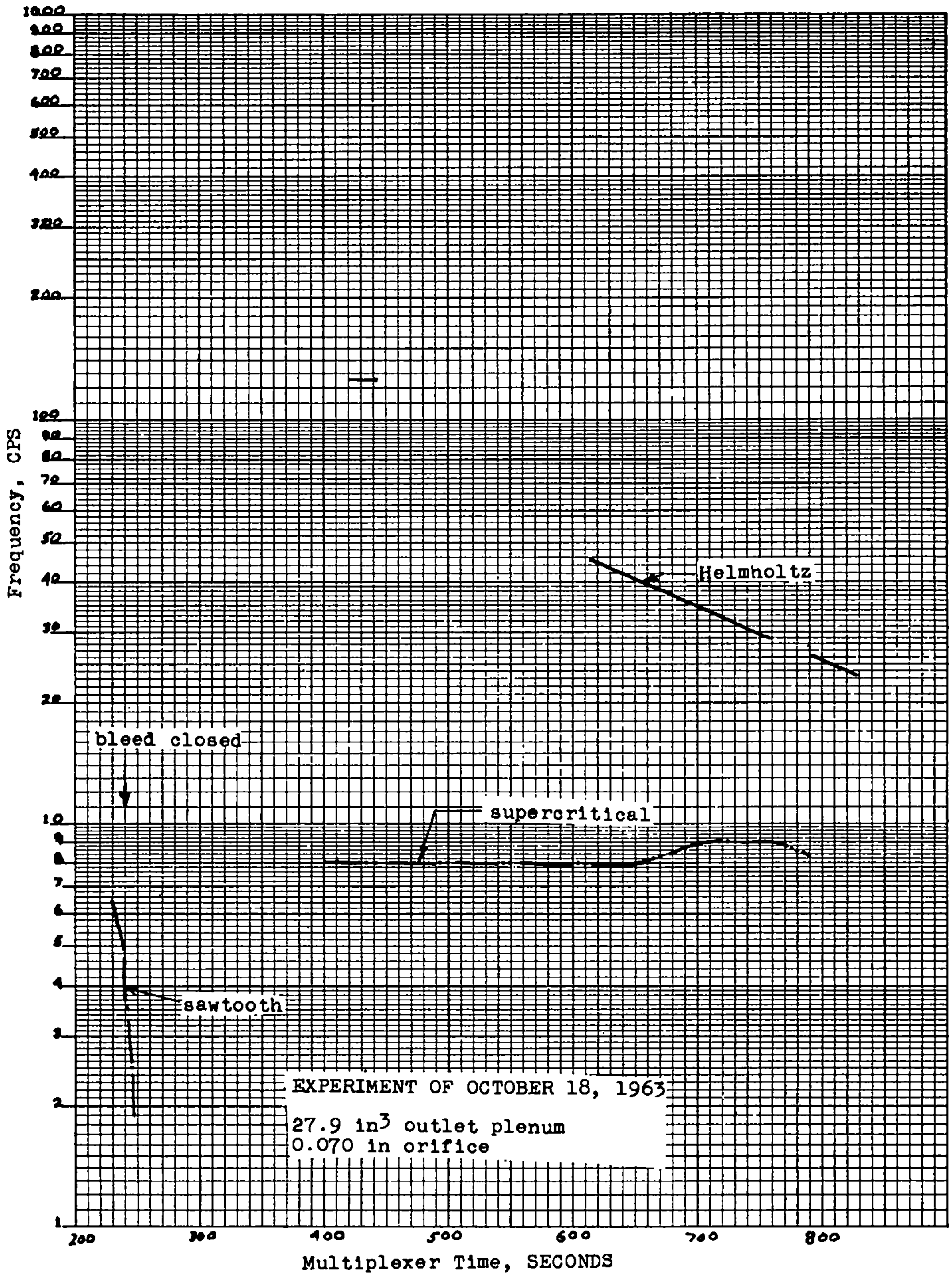


Figure 26. Frequencies - October 18, 1963

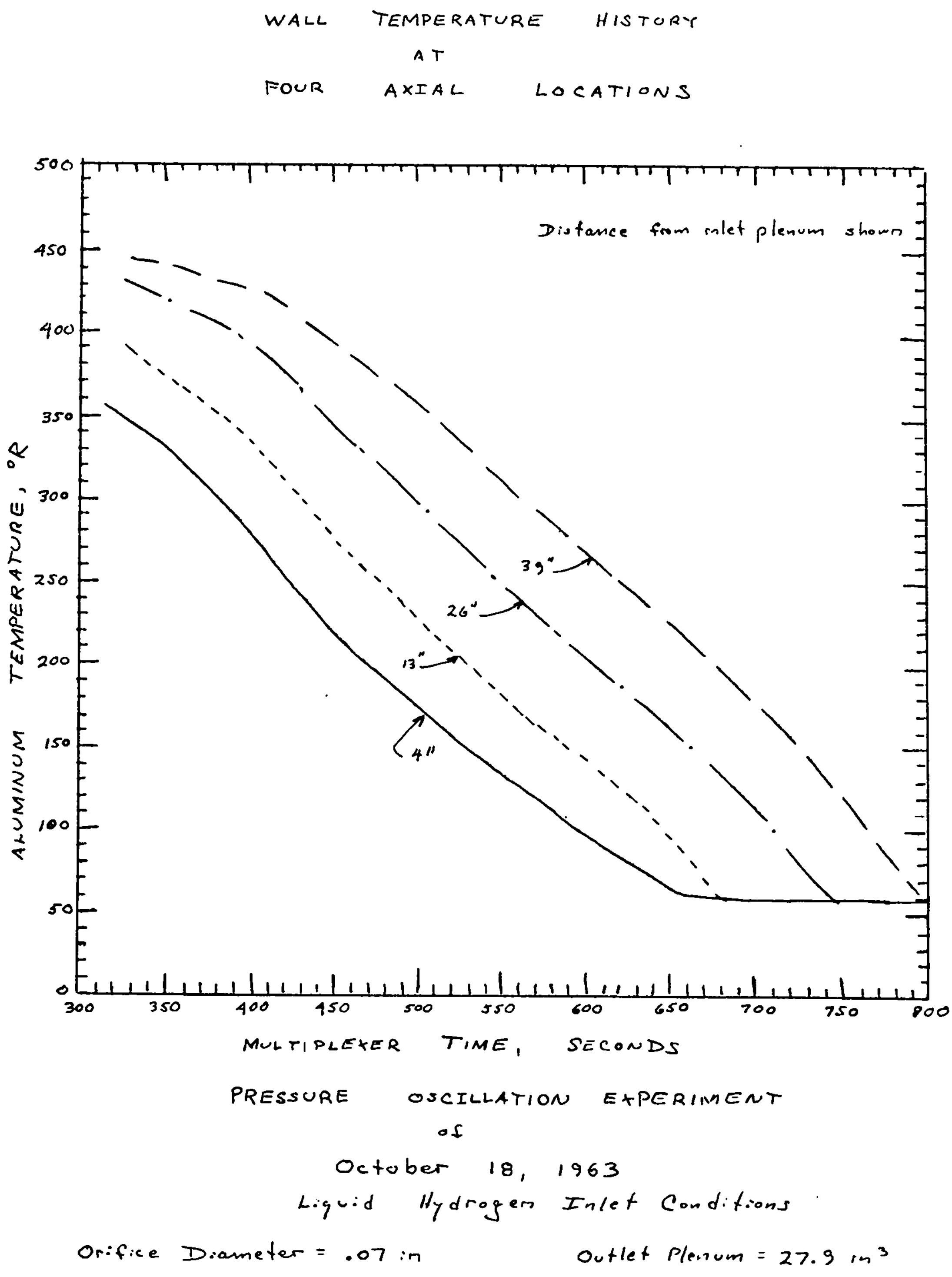


Figure 27. Axial Wall Temperatures - October 18, 1963

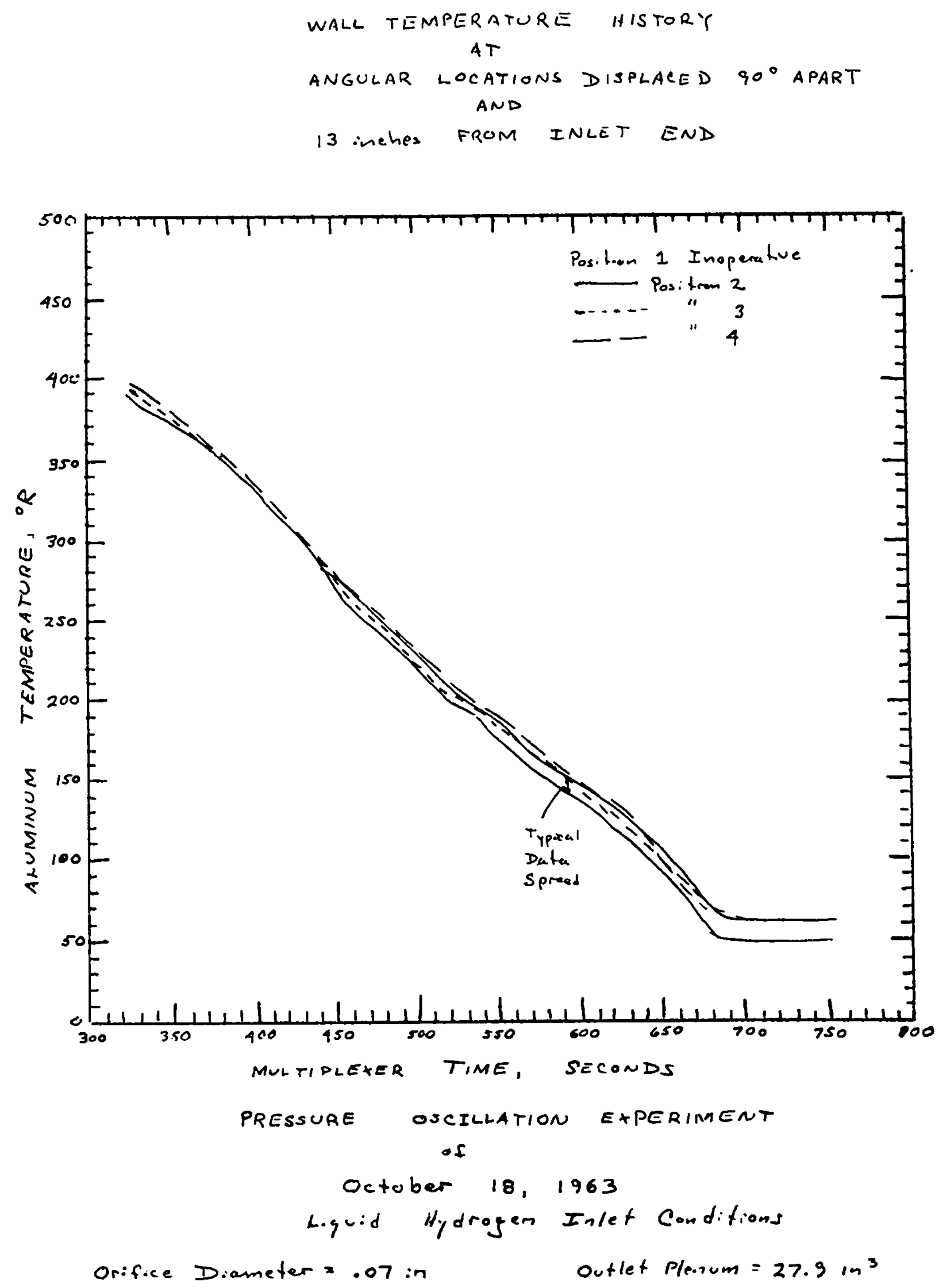


Figure 28. 13 inch Location Wall Temperatures - October 18, 1963

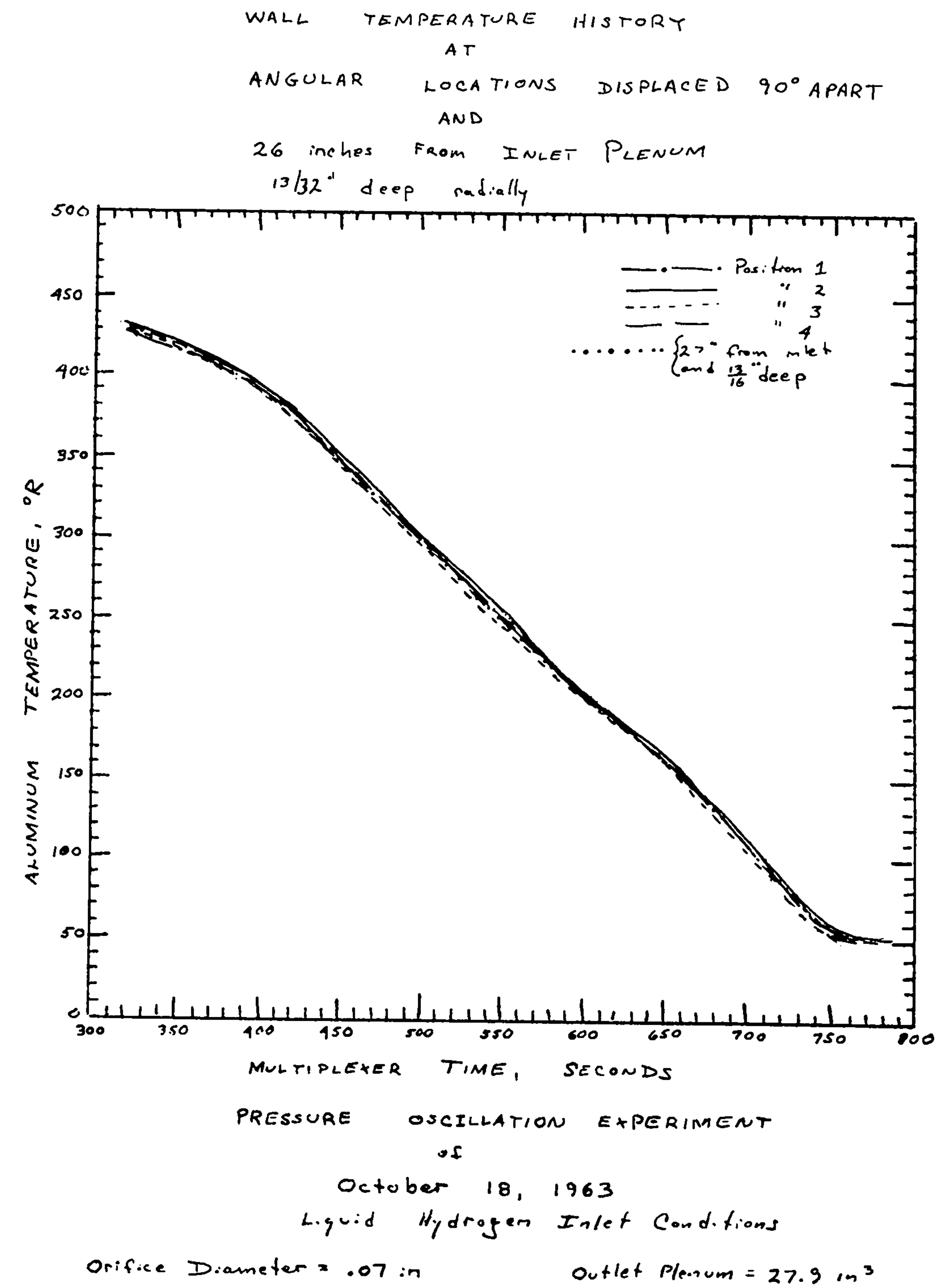


Figure 29. 26 inch Location Wall Temperatures - October 18, 1963

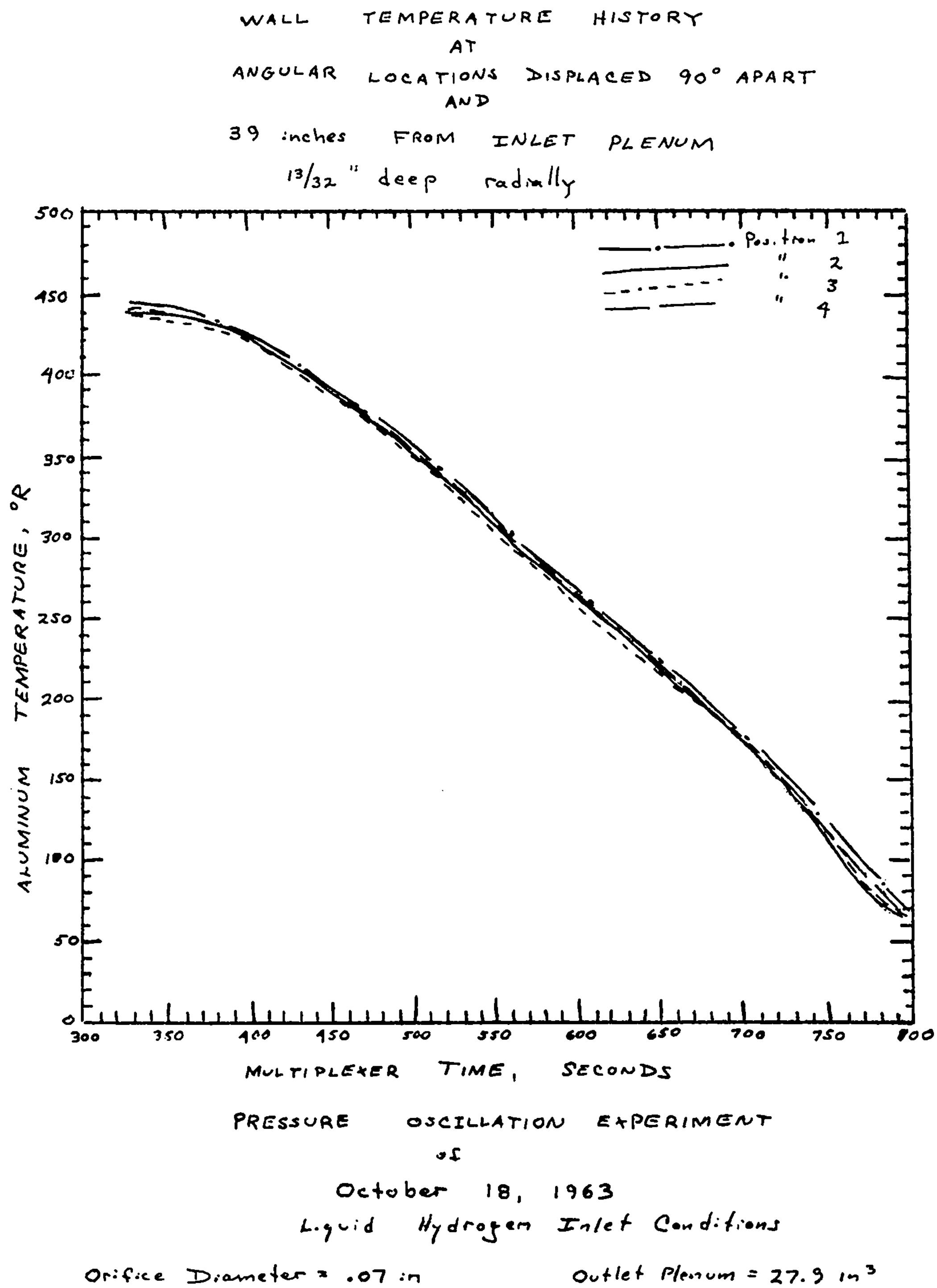


Figure 30. 39 inch Location Wall Temperatures - October 18, 1963

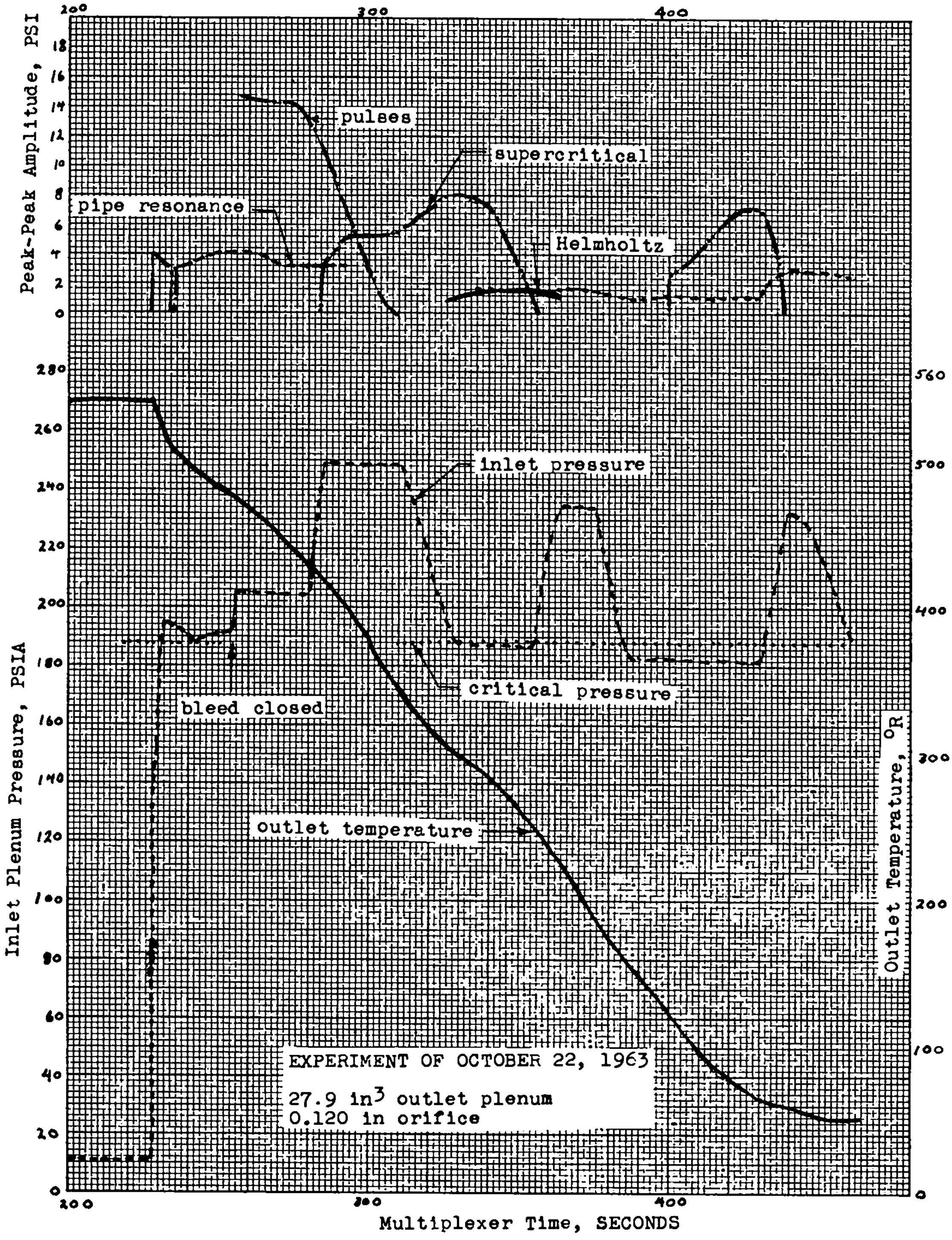


Figure 31. Pressures, Temperatures, Amplitudes - October 22, 1963

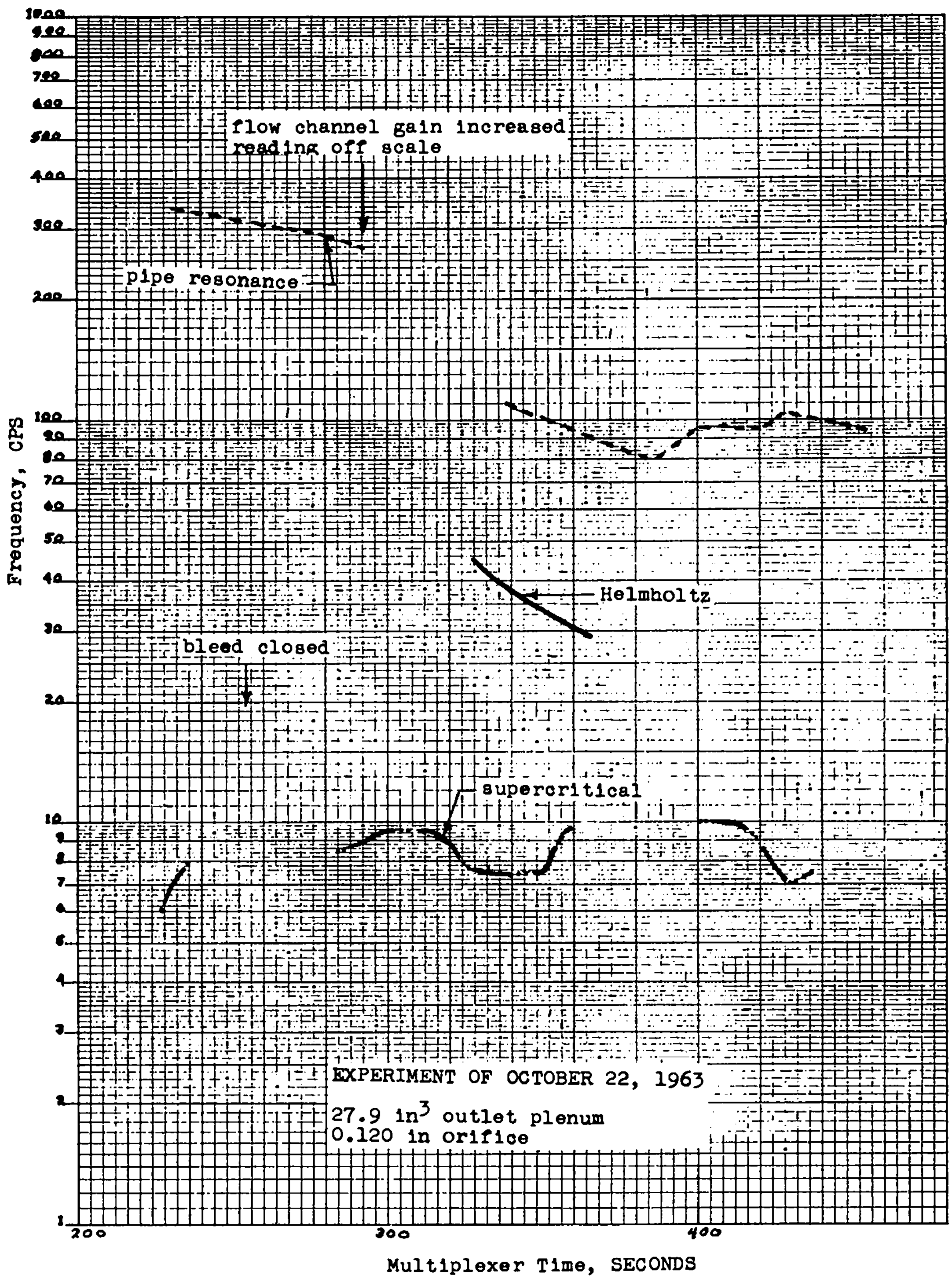


Figure 32. Frequencies - October 22, 1963

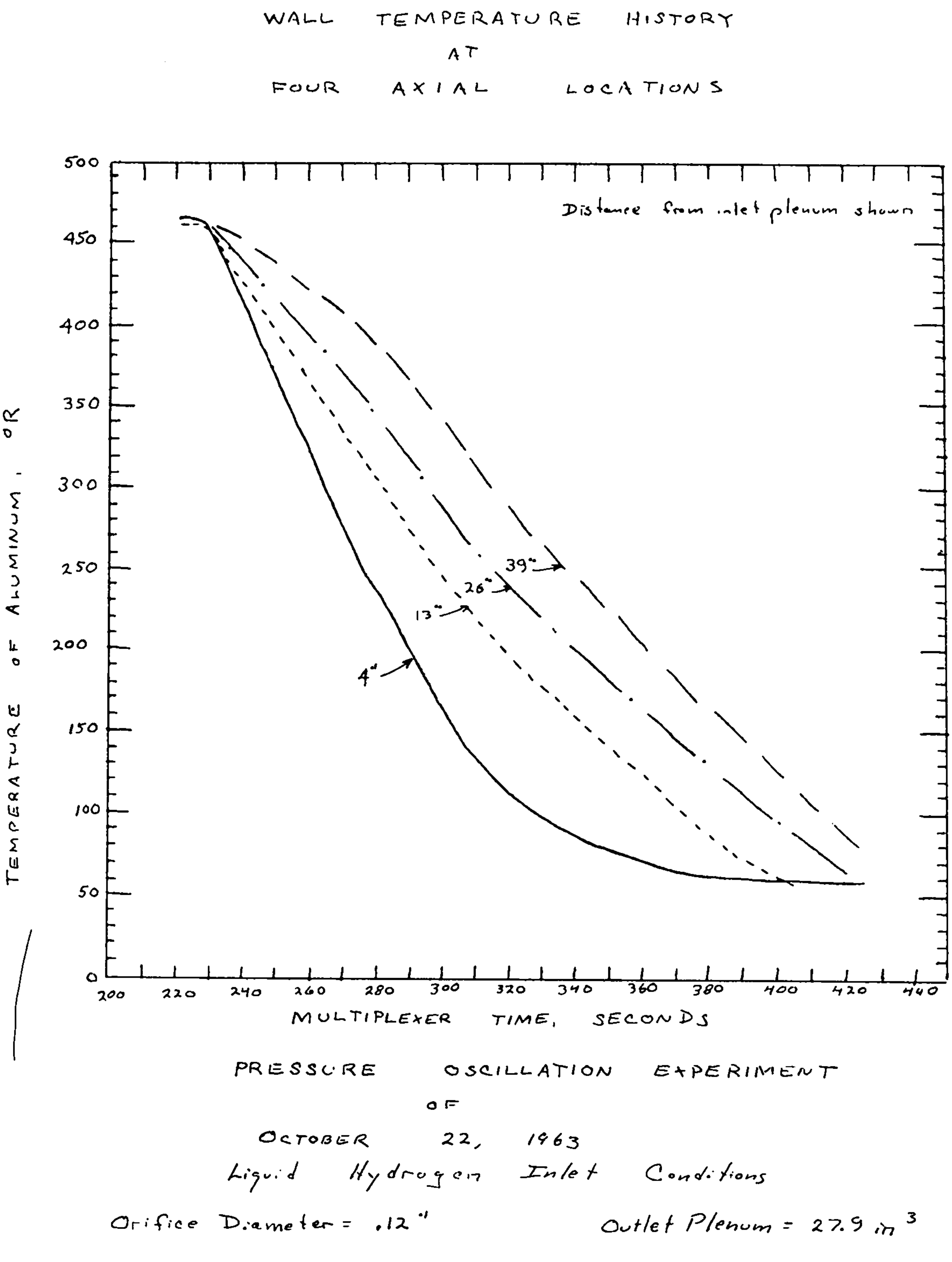


Figure 33. Axial Wall Temperatures - October 22, 1963

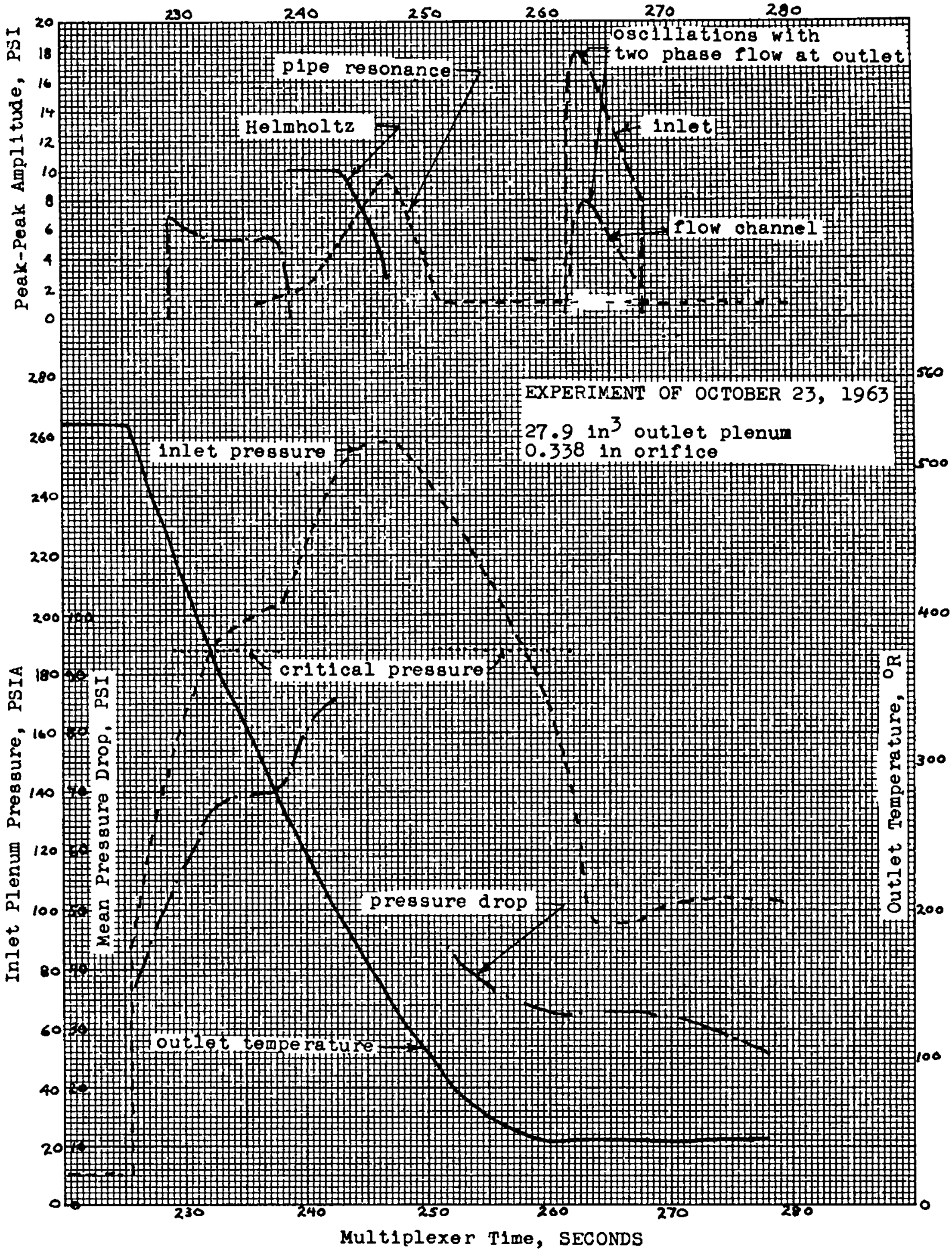


Figure 34. Pressures, Temperatures, Amplitudes - October 23, 1963

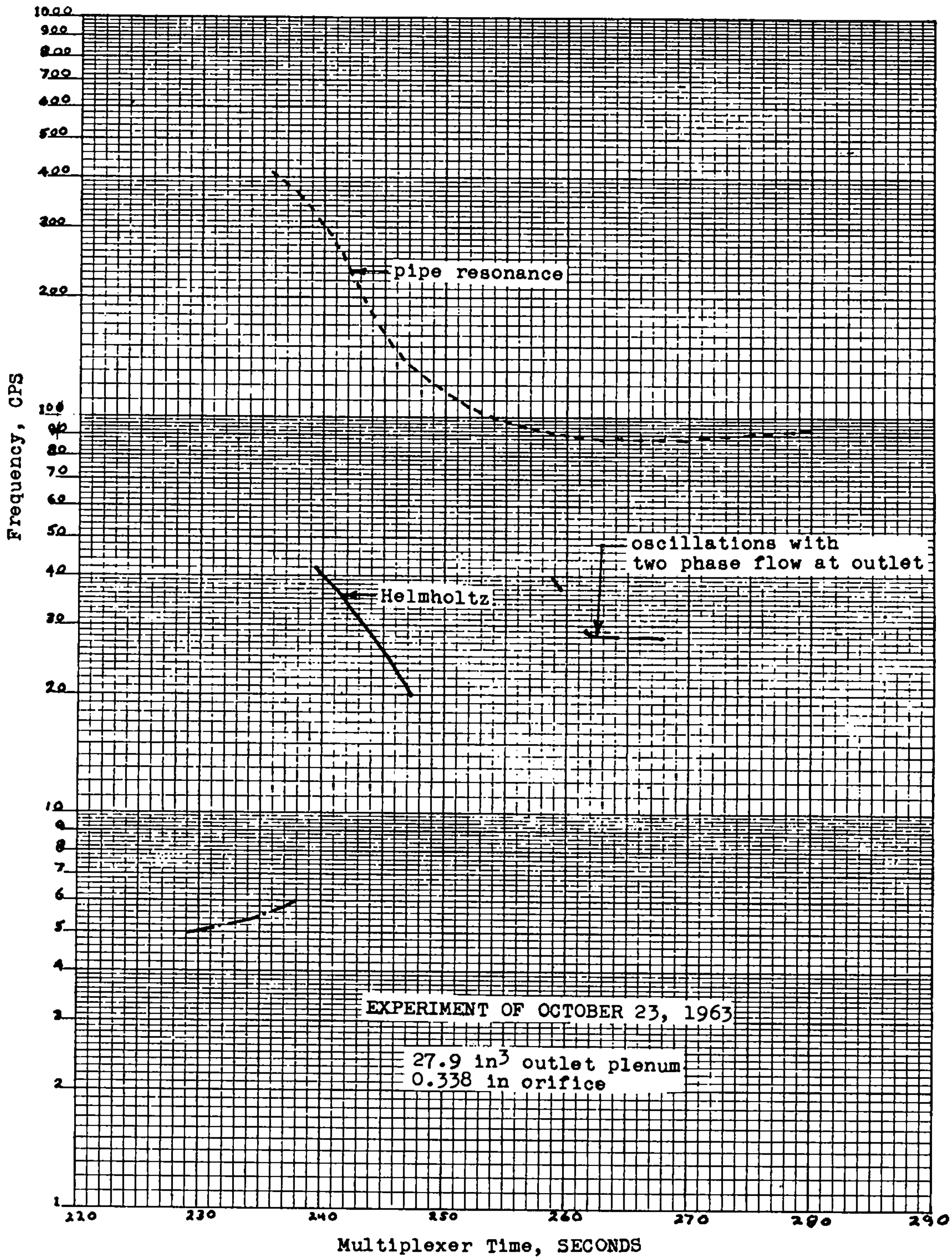


Figure 35. Frequencies - October 23, 1963

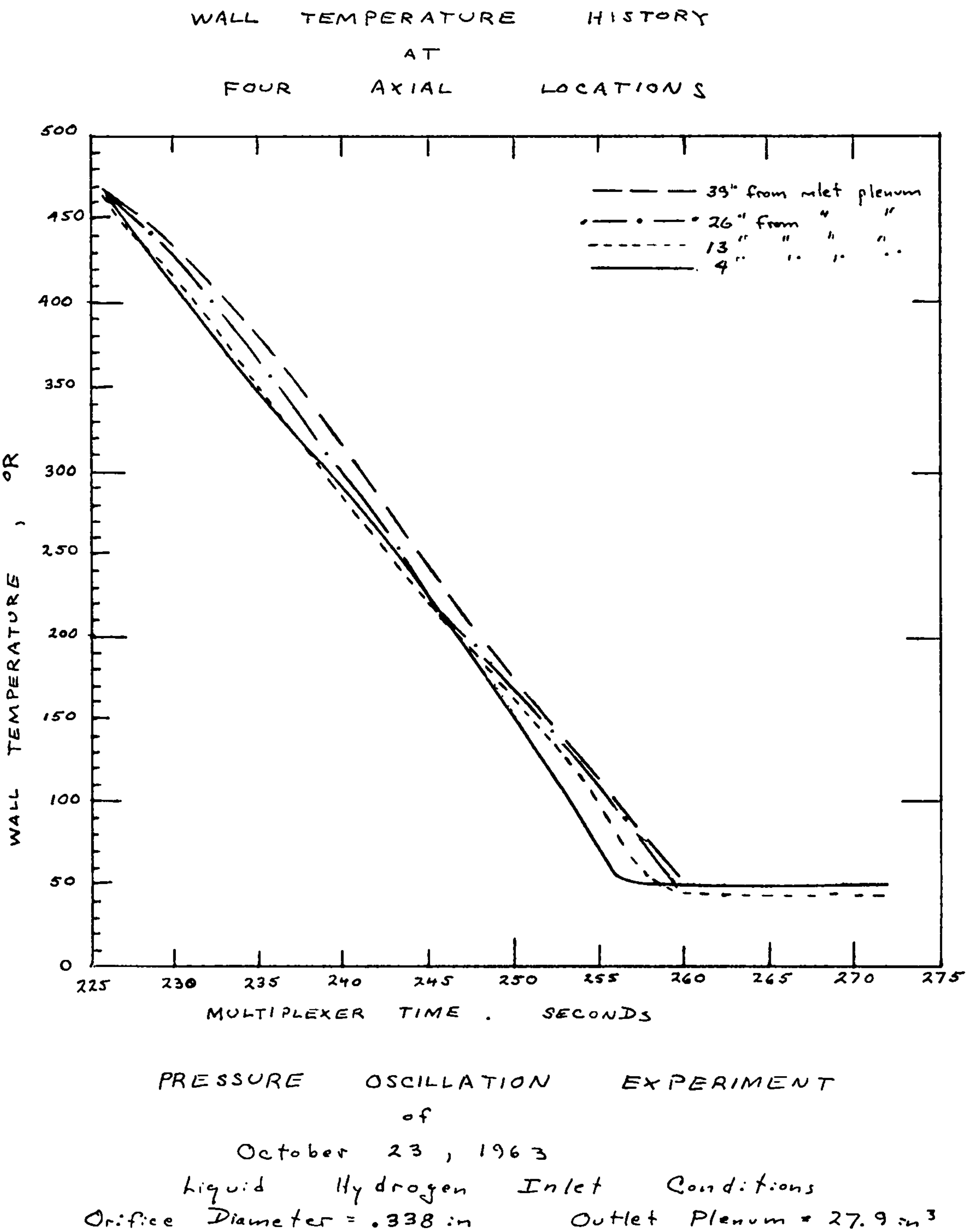


Figure 36. Axial Wall Temperatures - October 23, 1963

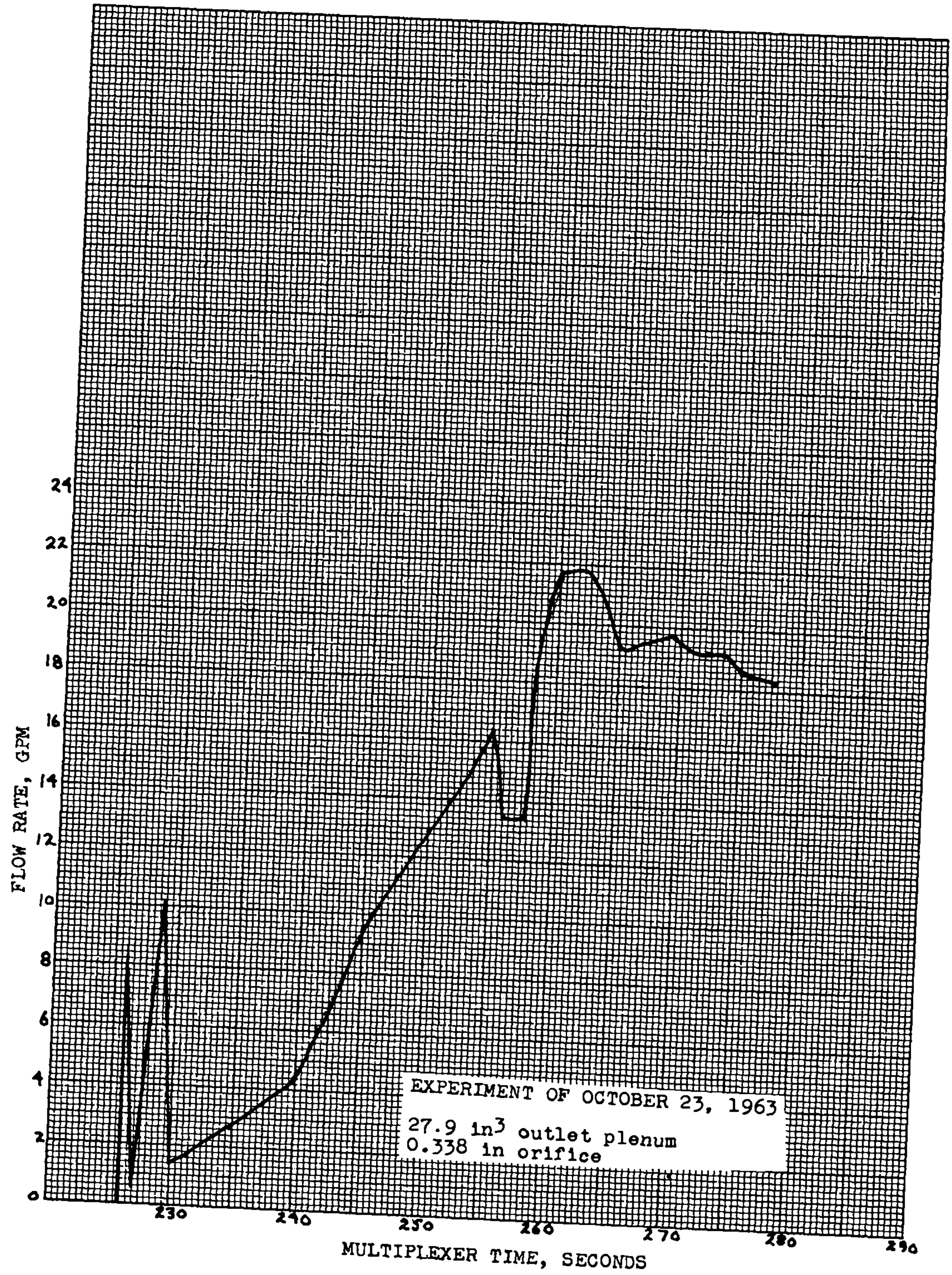
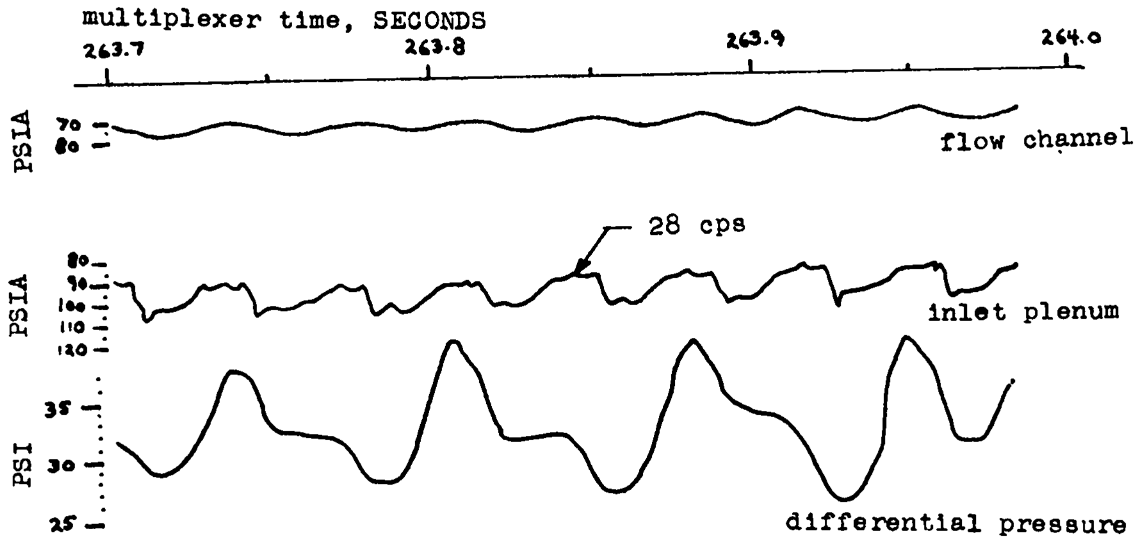


Figure 37. Flow Rate - October 23, 1963

HYDROGEN

EXPERIMENT OF OCTOBER 23, 1963

FOUR CHANNEL FLOW



EXPERIMENT OF NOVEMBER 6, 1963

SINGLE CHANNEL FLOW

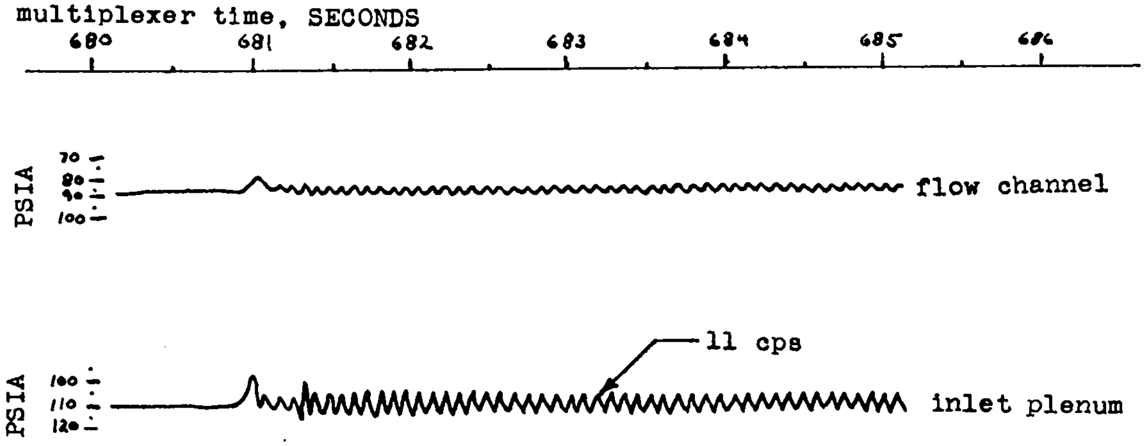


Figure 38. Pressure Trace of Oscillation Probably from Plug Flow

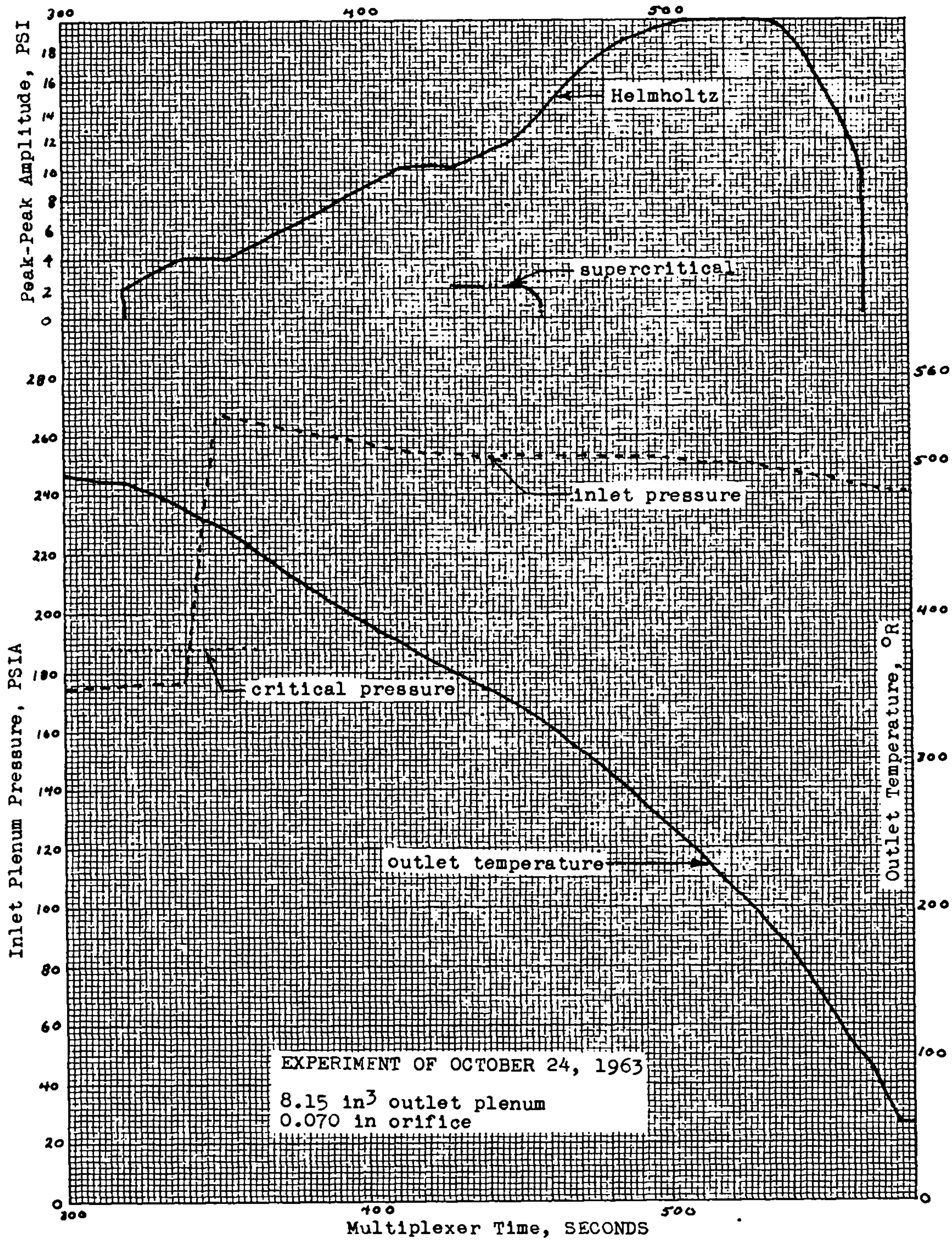


Figure 39. Pressures, Temperatures, Amplitudes - October 24, 1963

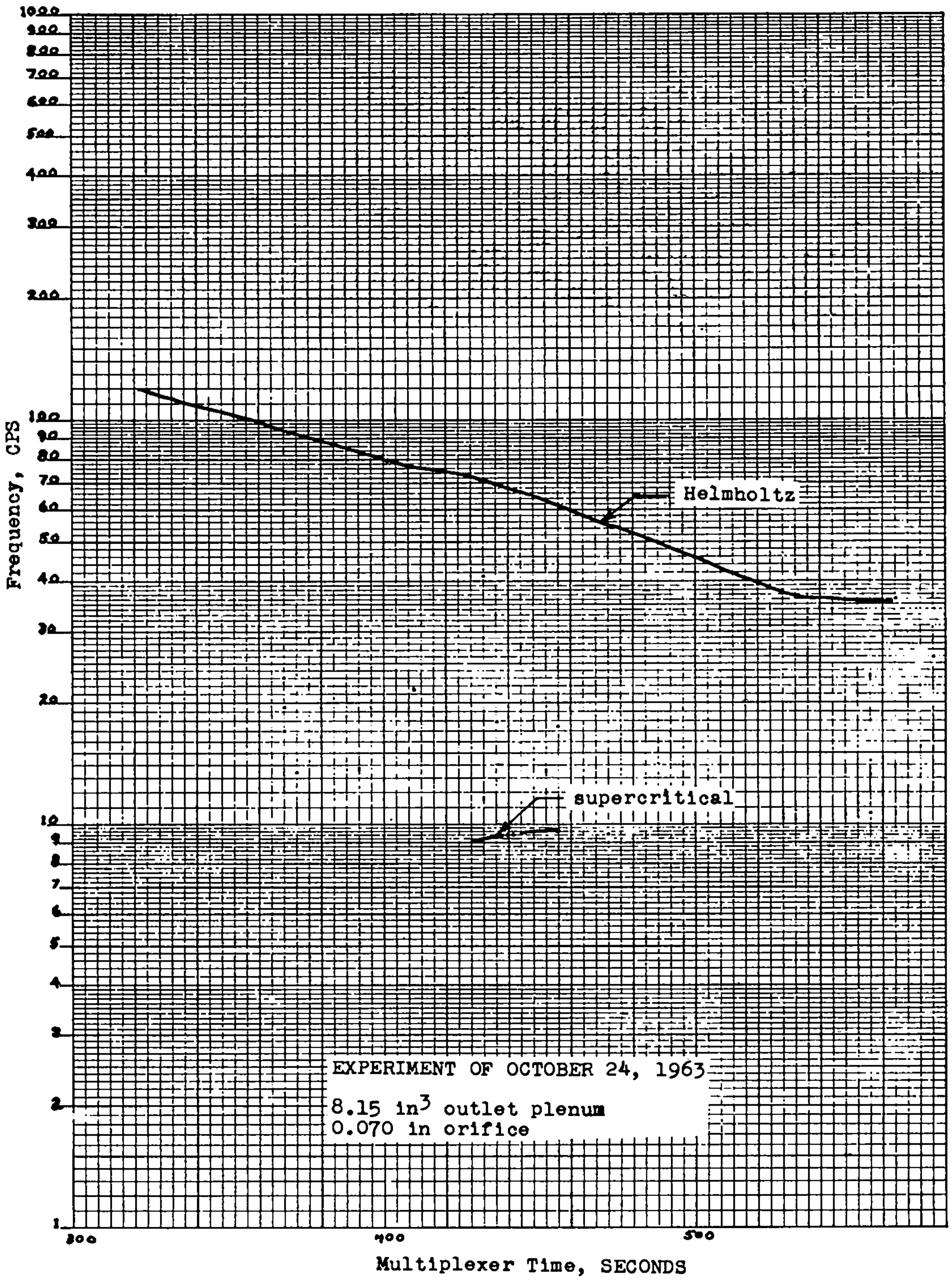


Figure 40. Frequencies - October 24, 1963

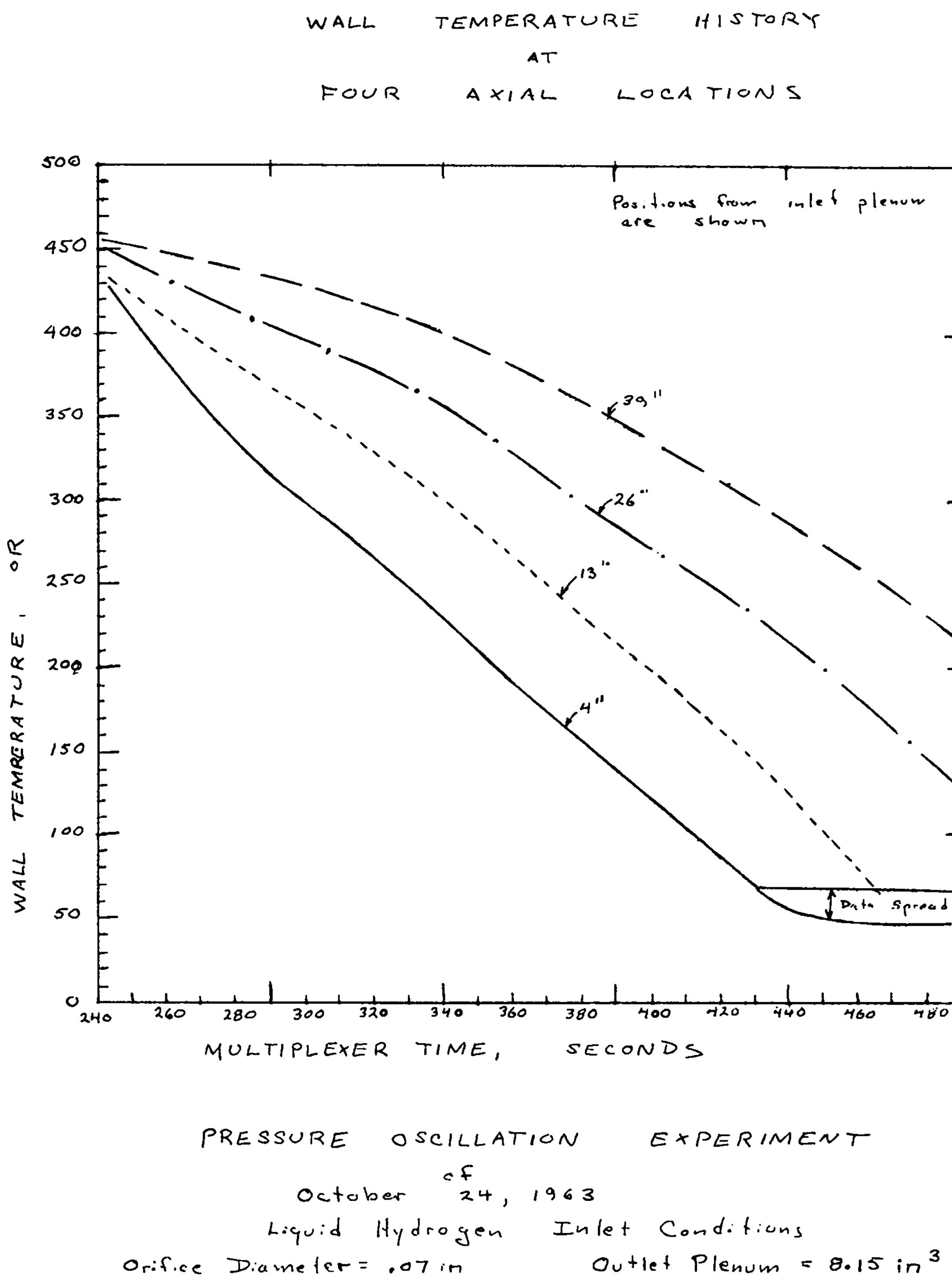


Figure 41. Axial Wall Temperatures - October 24, 1963

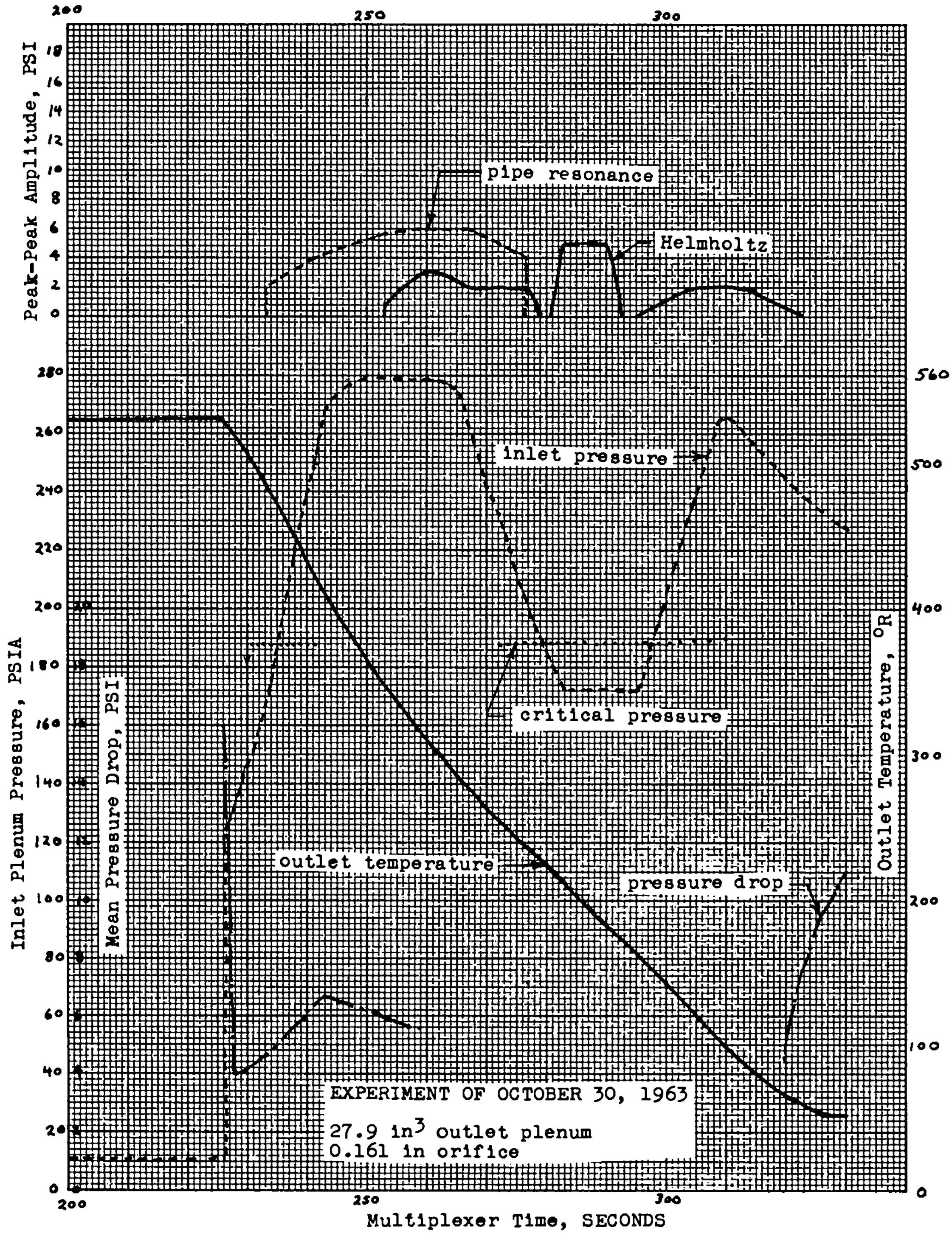


Figure 42. Pressures, Temperatures, Amplitudes - October 30, 1963

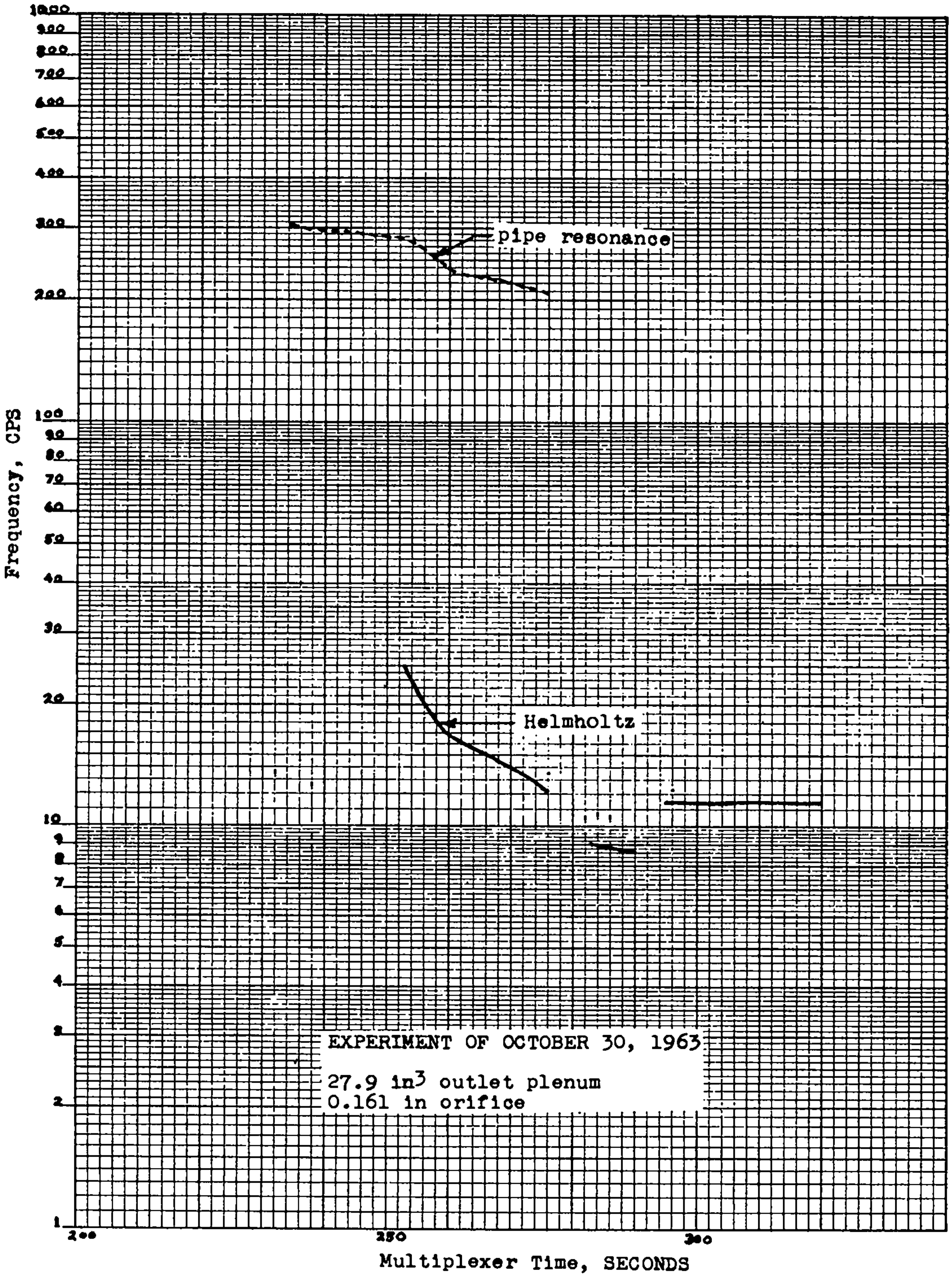


Figure 43. Frequencies - October 30, 1963

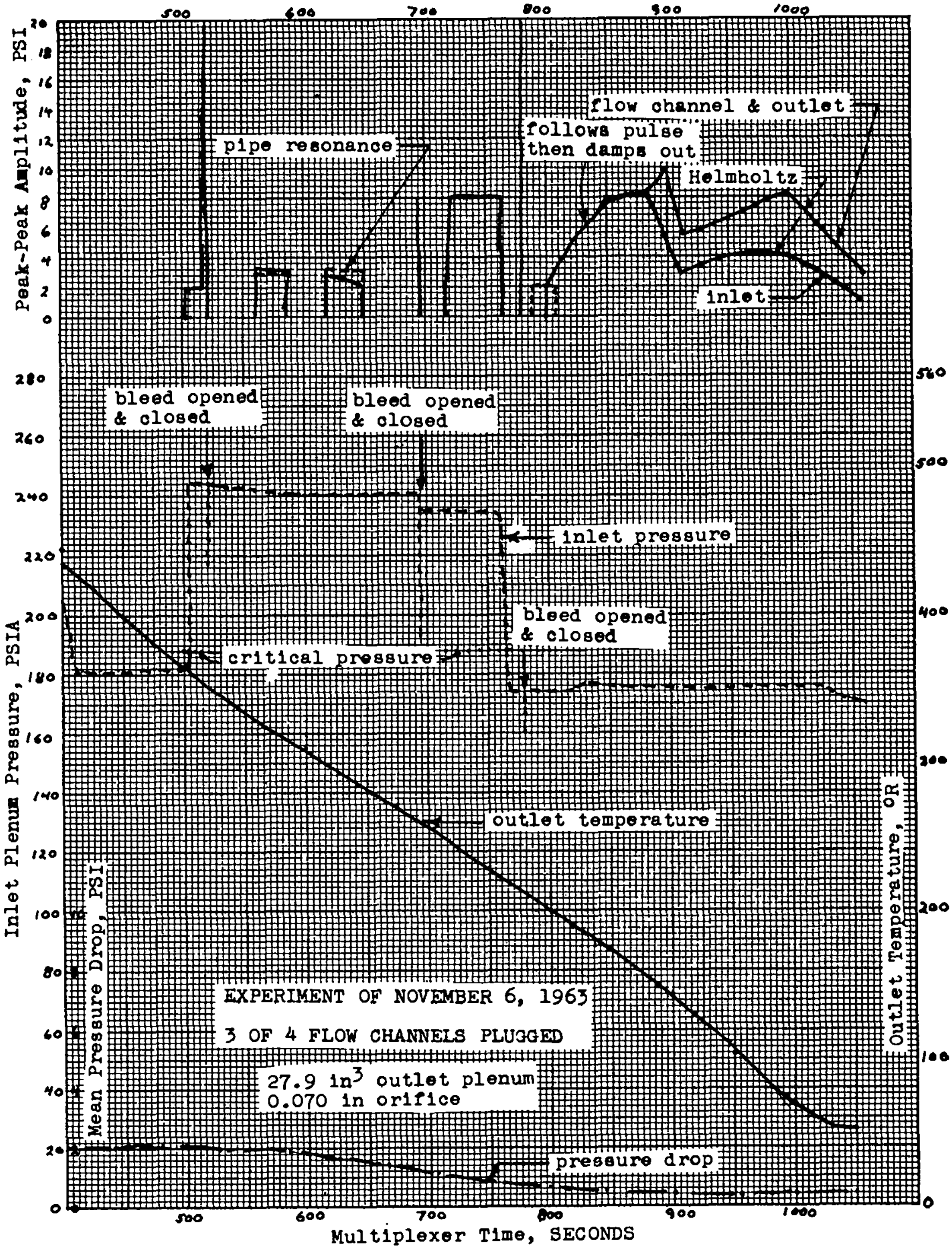


Figure 44. Pressures, Temperatures, Amplitudes - November 6, 1963

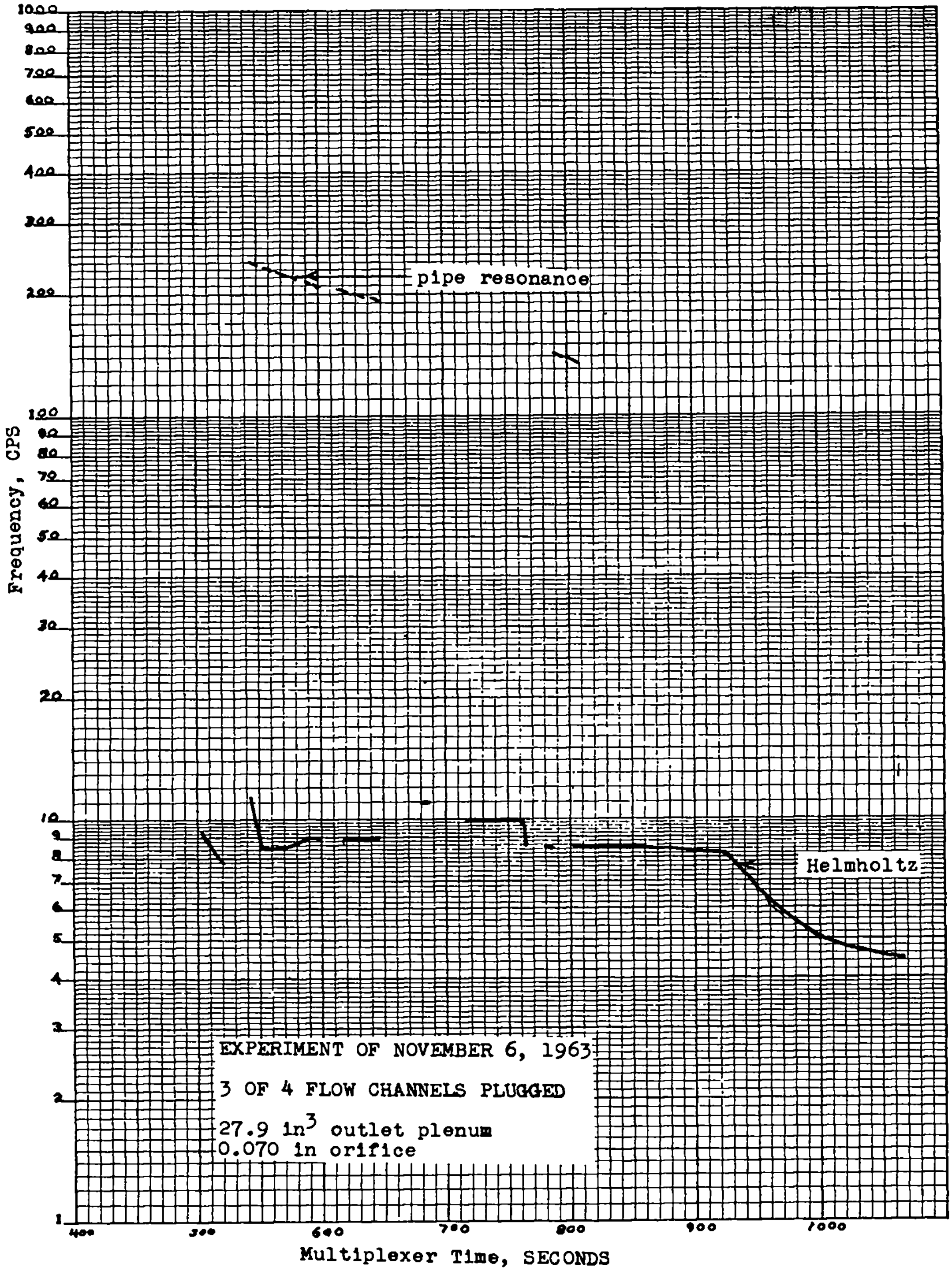


Figure 45. Frequencies - November 6, 1963

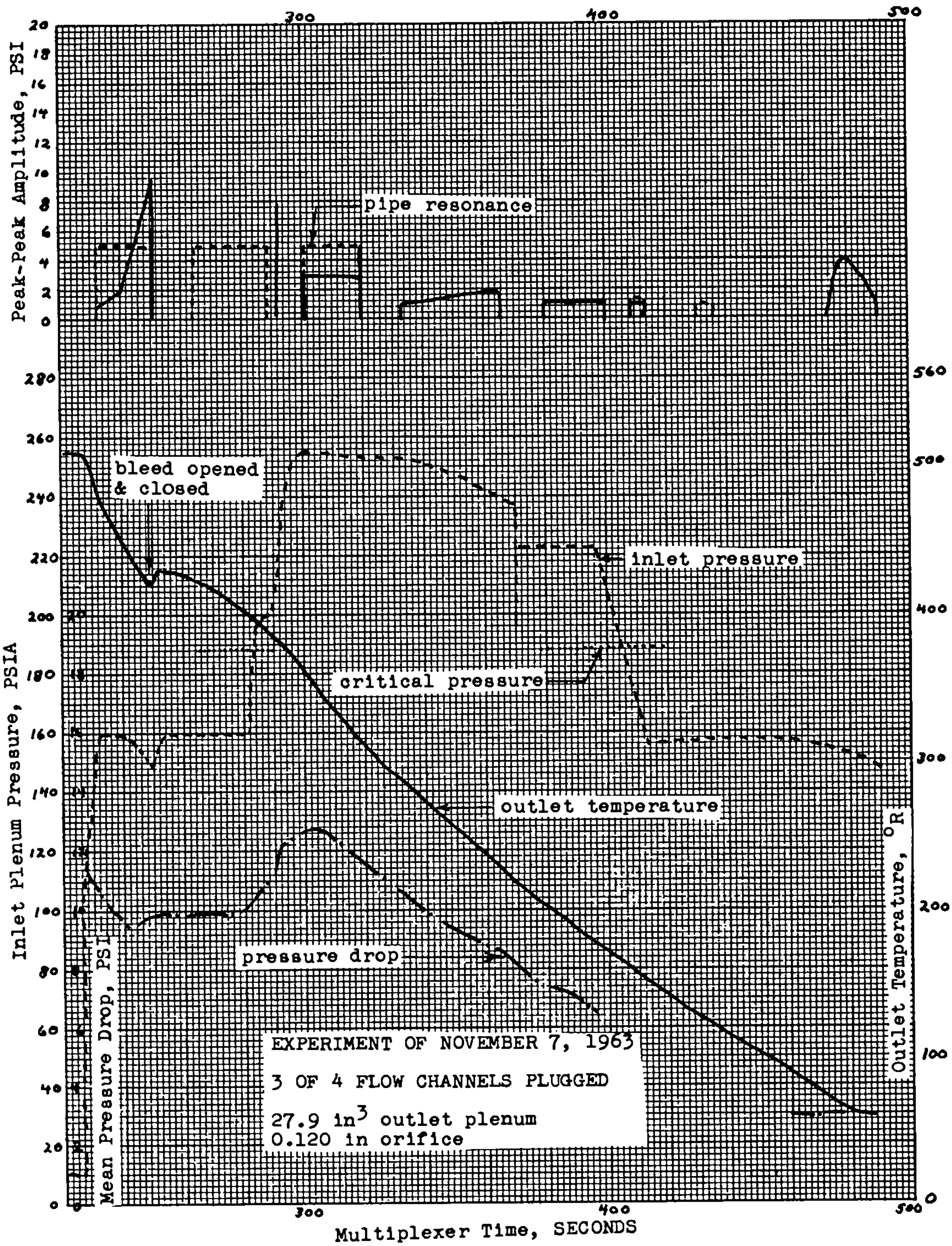


Figure 46. Pressures, Temperatures, Amplitudes - November 7, 1963

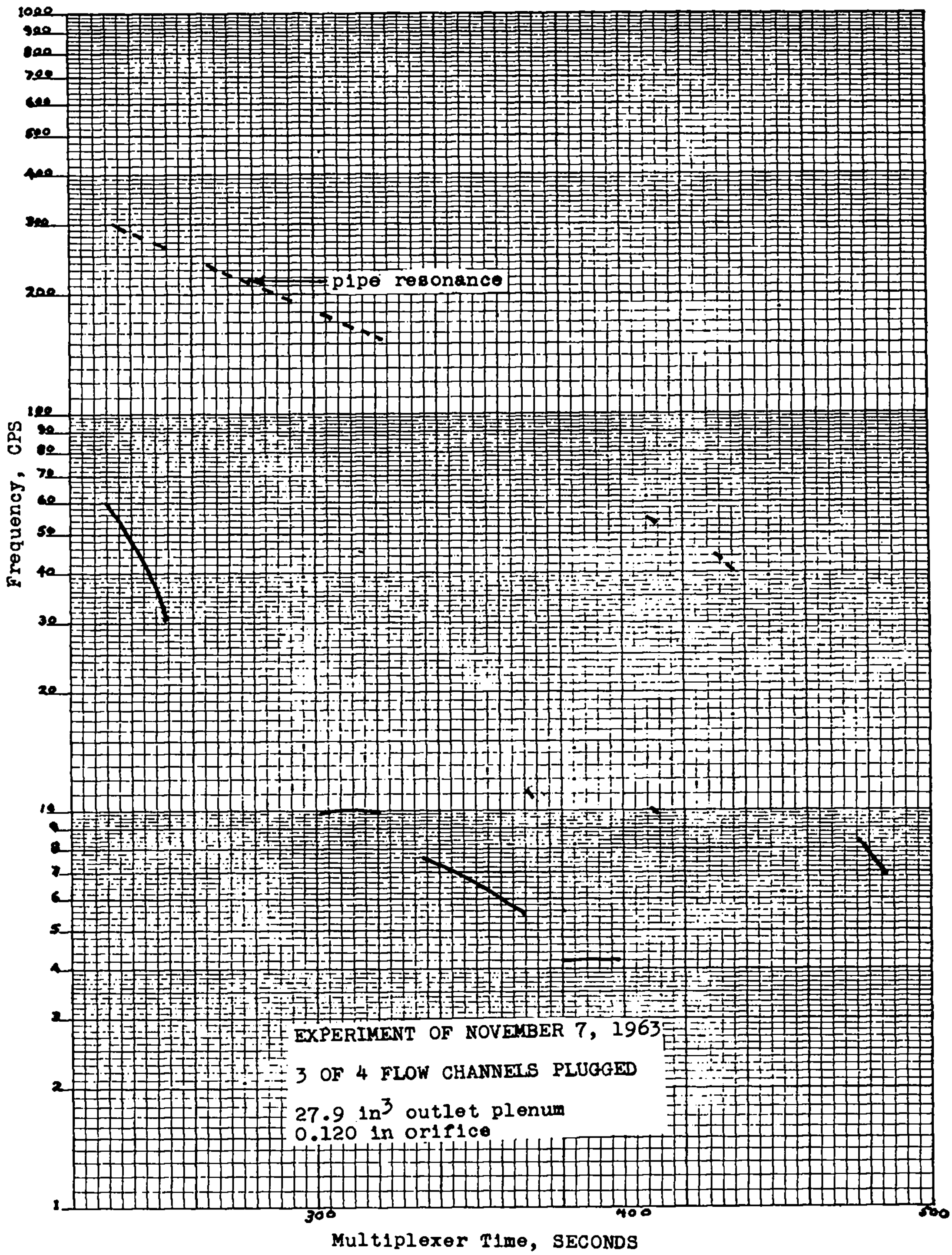


Figure 47. Frequencies - November 7, 1963

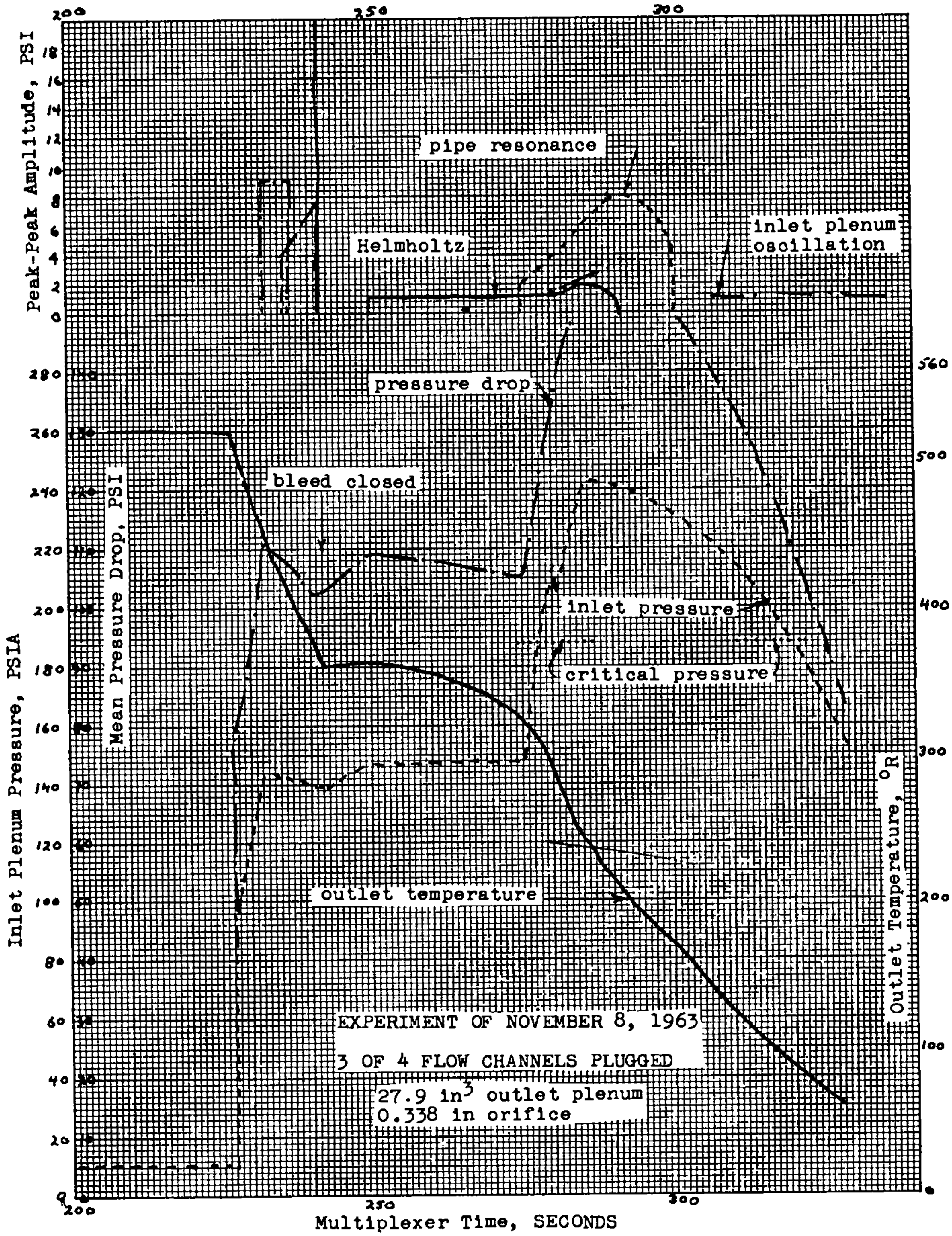


Figure 48. Pressures, Temperatures, Amplitudes - November 8, 1963

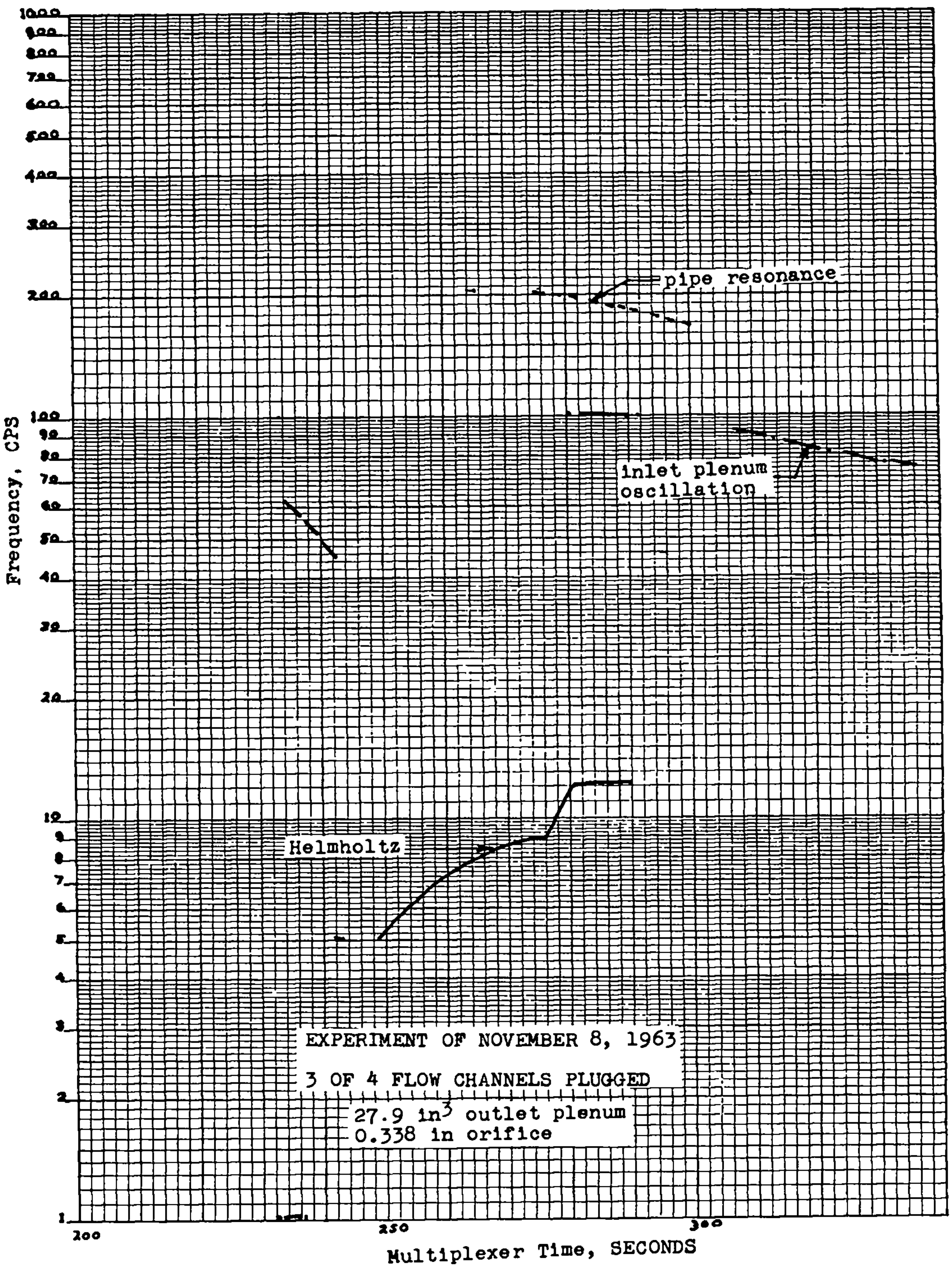


Figure 49. Frequencies - November 8, 1963

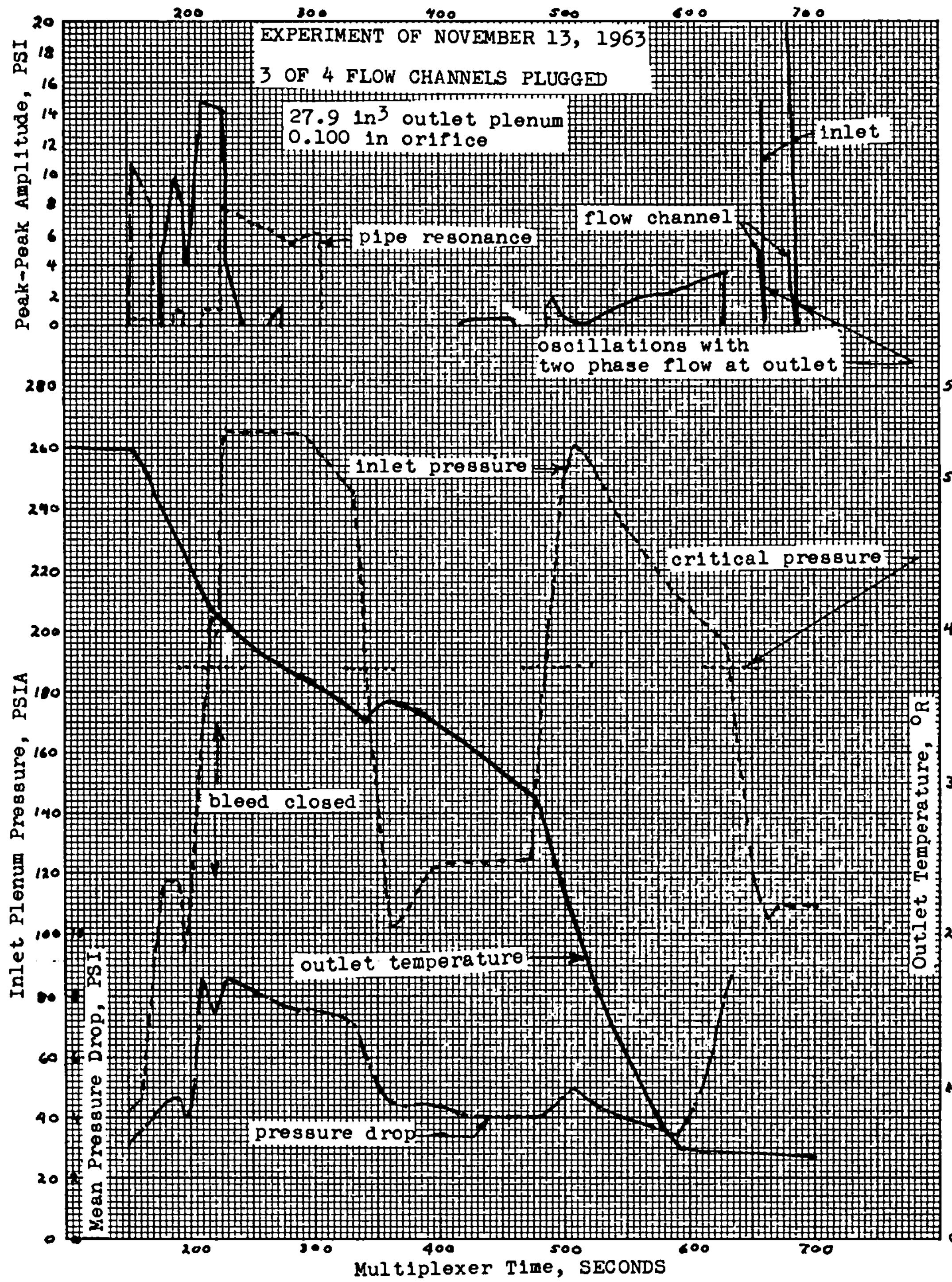


Figure 50. Pressures, Temperatures, Amplitudes - November 13, 1963

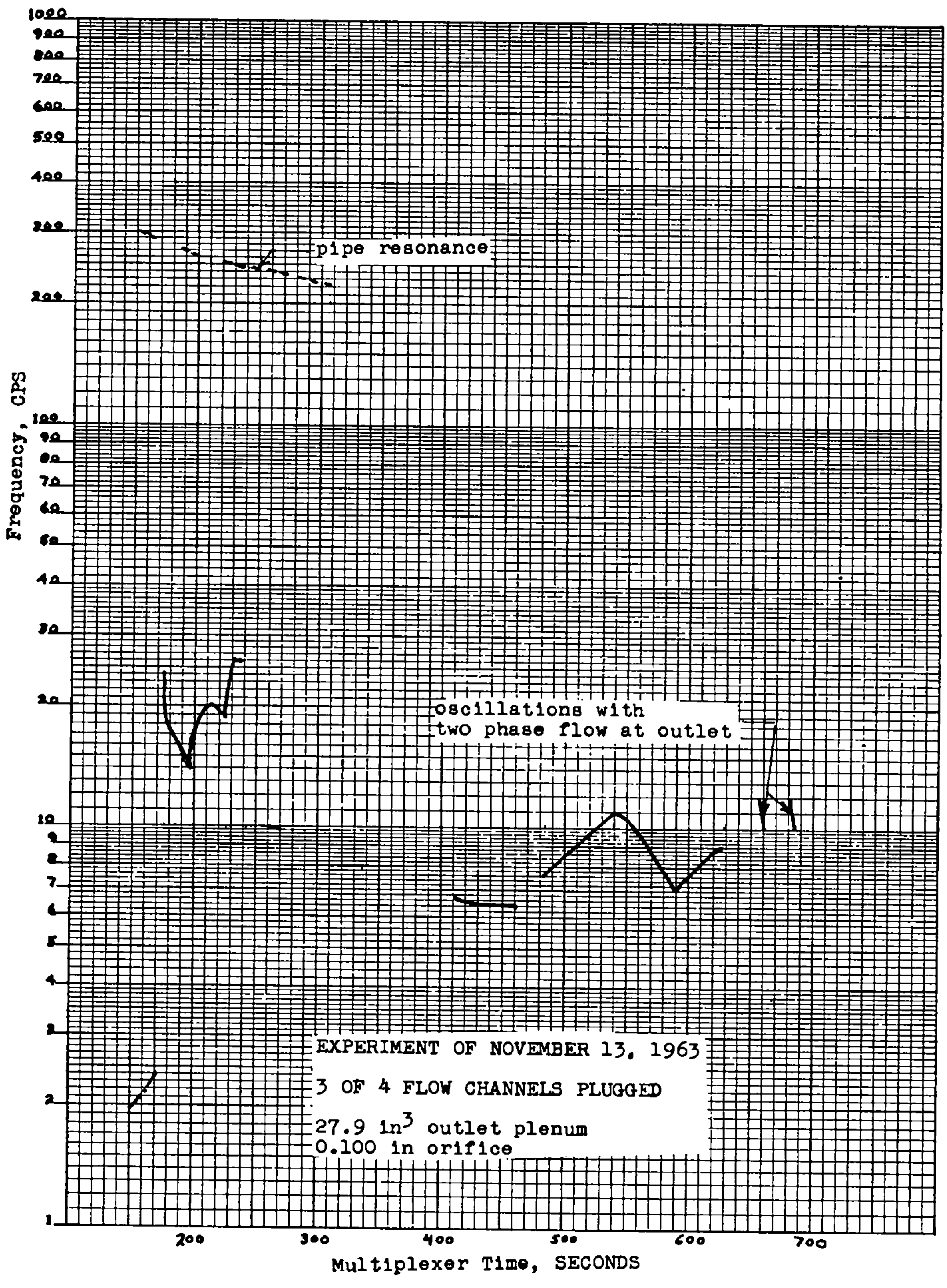


Figure 51. Frequencies - November 13, 1963