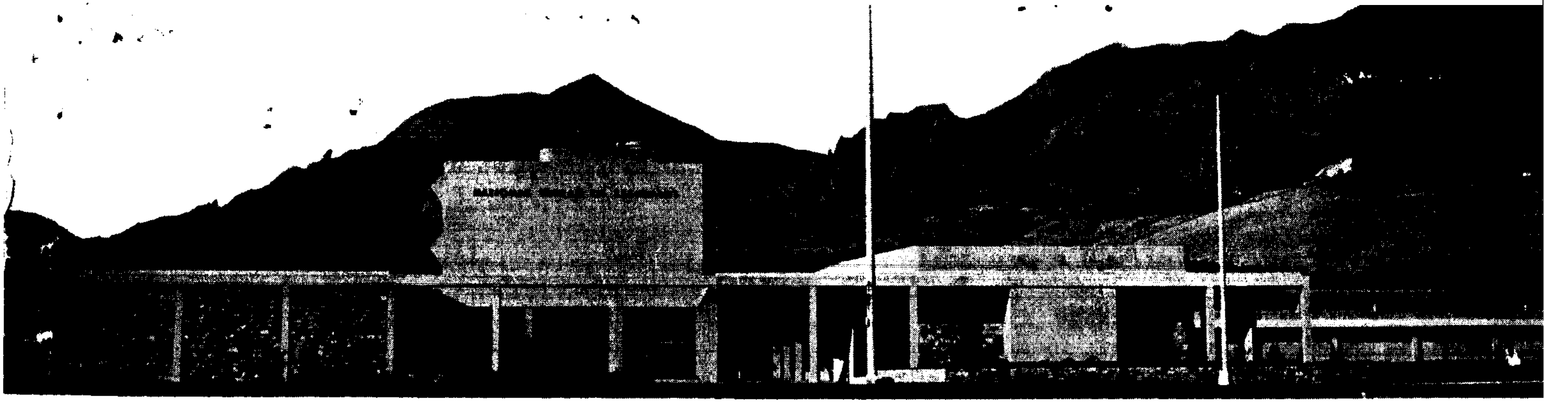


NBS REPORT
9264

An Experimental Report
on
COOLDOWN OF CRYOGENIC TRANSFER LINES
to
National Aeronautical and Space Administration
by
J. A. Brennan, E. G. Brentari, R. V. Smith, and W. G. Steward

GPO PRICE $
CFSTI PRICE(S) $

Hard copy (HC) 3.00
Microfiche (MF) 1.30

ff 653 July 65

FACILITY FORM 602

N67 16620
(ACCESSION NUMBER)

75
(PAGES)

CR-81338
(NASA CR OR TMX OR AD NUMBER)

(THRU)

1
(CODE)

23
(CATEGORY)

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
Boulder, Colorado

THE NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] provides measurement and technical information services essential to the efficiency and effectiveness of the work of the Nation's scientists and engineers. The Bureau serves also as a focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To accomplish this mission, the Bureau is organized into three institutes covering broad program areas of research and services:

THE INSTITUTE FOR BASIC STANDARDS . . . provides the central basis within the United States for a complete and consistent system of physical measurements, coordinates that system with the measurement systems of other nations, and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. This Institute comprises a series of divisions, each serving a classical subject matter area:

—Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic Physics—Physical Chemistry—Radiation Physics—Laboratory Astrophysics[2]—Radio Standards Laboratory,[2] which includes Radio Standards Physics and Radio Standards Engineering—Office of Standard Reference Data.

THE INSTITUTE FOR MATERIALS RESEARCH . . . conducts materials research and provides associated materials services including mainly reference materials and data on the properties of materials. Beyond its direct interest to the Nation's scientists and engineers, this Institute yields services which are essential to the advancement of technology in industry and commerce. This Institute is organized primarily by technical fields:

—Analytical Chemistry—Metallurgy—Reactor Radiations—Polymers—Inorganic Materials—Cryogenics[2]—Materials Evaluation Laboratory—Office of Standard Reference Materials.

THE INSTITUTE FOR APPLIED TECHNOLOGY . . . provides technical services to promote the use of available technology and to facilitate technological innovation in industry and government. The principal elements of this Institute are:

—Building Research—Electronic Instrumentation—Textile and Apparel Technology Center—Technical Analysis—Center for Computer Sciences and Technology—Office of Weights and Measures—Office of Engineering Standards Services—Office of Invention and Innovation—Clearinghouse for Federal Scientific and Technical Information.[3]

---

[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D. C., 20234.

[2] Located at Boulder, Colorado, 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia, 22151.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT		NBS REPORT
31507-12-3150470	November 7, 1966	9264

COOLDOWN OF CRYOGENIC TRANSFER LINES --AN EXPERIMENTAL REPORT

Prepared under Contract No. R-45

J. A. Brennan, E. G. Brentari, R. V. Smith, and W. G. Steward

Cryogenics Division
NBS Institute for Materials Research
Boulder, Colorado

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

TABLE OF CONTENTS

Cooldown of Cryogenic Transfer Lines--An Experimental Report

J. A. Brennan, E. G. Brentari, R. V. Smith, and W. G. Steward

Experimental data on pressure, temperature, and flow during cooldown of a transfer line are presented. Data using liquid hydrogen and liquid nitrogen are included in both subcooled and saturated liquid conditions. Calculated heat transfer coefficients are shown and compared to a steady state pool boiling correlation.

Key Words: Cooldown, heat transfer, hydrogen, liquid, nitrogen, transfer line.

1. Introduction

Proper design of cryogenic liquid transfer lines requires a knowledge of many quantities relating to the transients accompanying the initial inflow of the cryogen to a line at ambient temperature. Typical of these quantities are:

(1) The volume of liquid required, and

(2) The time required to effect cooldown.

(3) The line pressures to be expected.

(4) Flow rate variations during cooldown.

(5) Temperature history of the line.

Disastrous results could occur if these quantities are neglected from consideration. For example, line pressures that exceed the driving pressure cause reverse flows which might damage flowmeters, valves, etc., in addition to the problem resulting from the pressure itself.

Since general analytical predictions of transient flow characteristics during transfer line cooldown have not been too successful, an experimental program was started to study the phenomena, specifically, those parts which would cause serious operational problems. Experiments were designed to determine the significant variables and to show their effect so that they could be handled properly in a concurrent analytical program. This report contains some of the experimental information obtained. An attempt was made to present typical results where possible and comparisons where necessary. More information was collected than could be included in this report and this can be made available on request. Both liquid hydrogen and liquid nitrogen were included in this experimental program. The majority of the information was obtained with the liquid saturated at atmospheric pressure (approximately 620 mm Hg) although there were a few tests with liquid saturated at higher pressures.

A preliminary investigation, intended to compare experimental heat transfer coefficients during cooldown of the transfer line with correlations from the literature, is also included in this report. Experimental data are shown compared to nucleate and film pool boiling correlations. A more detailed, forced convection heat transfer analysis did not seem feasible at this time.

2. Experimental Equipment and Procedures

The experimental apparatus is shown schematically in figure 1 and was the same as reported by Steward [1]. All the tests included in this report were on a vacuum-insulated, copper transfer line 61.0 m (200 ft) long with an inner line 1.90 cm (3/4-in.) O.D. by 1.59 (5/8-in.) I.D. At four locations along the line, indicated by the numerals 1 through 4 in the figure, were located instrumentation stations where pressures and temperatures were measured. A typical station is shown encircled at the lower left in the figure. Pressures at stations 1 and 2 were measured on 0-35 atm pressure transducers; at station 3 and 4 on 0-21 atm and 0-7.5 atm pressure transducers, respectively. Temperatures were measured with copper vs. constantan thermocouples referenced to liquid nitrogen. Pressures at the pitot tubes and temperatures in the stream were only measured during a portion of the program and the results are not included in this report.

A turbine flowmeter and a vapor pressure thermometer were located inside the 300-liter supply dewar at the entrance to the transfer line. The flowmeter had been calibrated with liquid hydrogen, and this calibration was also used for liquid nitrogen. By using the hydrogen calibration for the nitrogen tests, advantage was taken of the known low temperature change in calibration which is not predictable from the warm calibration. There is only a small additional change in thermal expansion from nitrogen temperature to hydrogen temperature so a temperature correction did not seem required. This left only a small viscosity correction which was considered negligible. The temperature of the liquid in the supply dewar was only measured on runs in which the liquid was saturated at an elevated pressure. On all other runs the liquid temperature was assumed equal to the saturation temperature at atmospheric pressures.

The inlet valve was either a 1.90 cm (3/4-in.) port ball valve, a 2.54 cm (1-in.) port globe valve, or a 2.54 cm port gate valve. When the ball valve was used, it was located inside the dewar as shown encircled at the upper right in figure 1, but the globe and gate valve were located outside the dewar as indicated by the note and arrow in the figure.

To conduct a test, the supply dewar was filled, the liquid saturated at the selected level, and the recorder calibrated, the dewar was rapidly pressurized and the inlet valve actuated with a pre-set pneumatic pressure allowing variation of valve-opening for the tests. Liquid entered the transfer line, and the resulting pressures, temperatures, and flow were recorded continuously on a multi-channel oscillograph recorder. Only the pressure in the vapor pressure thermometer was read on a gage and written on the chart manually.

3. Results

The results shown in this paper are primarily data collected from a series of tests using both liquid nitrogen and liquid hydrogen. Most tests were run with liquid saturated at atmospheric pressure ($\approx$0.82 atm) and the liquid in those tests is referred to as subcooled liquid. A few tests were also run with liquid saturated at the selected driving pressure, and the liquid is referred to as saturated liquid. The temperature of the liquid when saturated at atmospheric pressure was approximately 19.5°K for hydrogen and 76°K for nitrogen; otherwise the temperature was the saturation temperature at the indicated driving pressure.

In addition to the obvious effect of changing cooldown time, the initial line temperature also affected the line pressures. The valve type and location in the system also had an apparent effect on line pressures but not on line temperature histories. Therefore, the results are divided into temperature histories irrespective of valve type and pressure data separated by valve type. Other conditions that affected pressures are shown for each valve type where necessary.

3.1 Temperature Histories

The question of cooldown time is usually an important one, but, unfortunately, this quantity is not uniquely defined. Several definitions have been used in the past with no specific one having a distinct advantage over others. For the purposes of this report, cooldown time was defined as the time associated with the low temperature knee in the temperature vs. time curve 60.4 m from the supply dewar. This definition of cooldown time is within a few seconds of the time taken to achieve steady flow and steady pressures, either of which could have been used as indicators. Since some of the steady flow rates on the low pressure nitrogen tests did not produce a suitable output for recording, this indicator was not available for all the runs. For consistency, then, the temperature indication was used instead of the flow and arbitrarily used instead of the pressures. No visual information on flow pattern at the transfer line discharge was available so this additional information could not be used in defining cooldown.

Temperature histories for liquid hydrogen runs are shown in figures 2 through 7 for several driving pressures and the two liquid conditions (saturated and subcooled). Cooldown time as a function of driving pressure is shown in figure 8. As will be seen later, a number of tests were run with the transfer line partially precooled at the inlet to observe the effect this had on pressure surges. None of those tests were used in determining cooldown time. One test was run, however, in which the initial line temperature distribution was such that the upstream portion of the line was warmer than the downstream portion. That test shows an interesting temperature history in that the heat from the upstream section of the line is transferred to the downstream section via the flowing stream and subsequently removed by the stream.

Figure 9 shows the results of that test, and the cooldown time is included in figure 8 where it fits the data from uniformly warm lines very well.

Temperature histories for liquid nitrogen runs are shown in figures 10 through 14 for the indicated driving pressures and liquid conditions. Figure 15 shows the cooldown time as a function of driving pressure where it can be seen that the temperature of the liquid in the supply dewar affected cooldown time for nitrogen as contrasted to hydrogen where no such an effect was observed.

The accuracy of the temperature data has been sacrificed in order to cover the entire range from ambient to liquid temperatures, but as indicators of the cooldown process and for computation of heat transfer rates the data are adequate. The crossing of temperature curves in the low temperature region in some tests is undoubtedly the result of inaccuracies in the measurement since this is where the largest errors would occur.

3.2 Pressure Histories

3.2.1 General

Line pressures were affected by a number of variables which were difficult to investigate independently by experiments alone. Some effort was made to at least indicate qualitative effects. Even though the line pressures were higher with nitrogen than with hydrogen, they were more easily altered by changing test conditions with liquid hydrogen. For this reason more tests were run with hydrogen.

In the course of a cooldown analysis in progress at this laboratory it has become apparent that some additional or more accurate test measurements would be desirable for the investigation of pressure surging. For example, an accurate measurement of the fluid temperature at the inlet valve and a more detailed measurement of the pipe temperatures near the inlet end are needed, since surging is very sensitive to these factors. For this reason future test sections will incorporate some of these changes.

3.2.2 Saturated Liquid

In tests where the liquid in the supply dewar was saturated at the driving pressure, line pressures exceeded the driving by very little. This was true for both hydrogen and nitrogen and appeared to be one of the best methods for controlling high pressures. Unfortunately this method of control is not always possible or even desirable. Other variables, such as valve type, had little effect on the magnitude of the pressure peaks in saturated liquid tests.

Figures 16 through 19 show results from two hydrogen tests where pressure maxima and minima were plotted and connected by straight lines. The first few seconds of each run are shown on an expanded time scale for ease in comparison with results from subcooled liquid tests where the first few seconds have some important pressure excursions.

3.2.3 Subcooled Liquid

Line pressures during the first few seconds of tests with subcooled liquid were generally much higher than pressures from tests with saturated liquid. Control of these high pressure peaks was sometimes difficult, especially in tests with nitrogen. One of the variables that had a rather consistent effect on the magnitude of the pressure peaks in the hydrogen tests was the type of valve used at the transfer line inlet. The globe valve tended to reduce the magnitude of the pressure surges quite noticeably. Figures 20 through 25 show results from three hydrogen tests where the ball valve was used, and figures 26 and 27 the results from a test using the globe valve. Figure 28 shows another comparison of results from tests using the two different valves. Figure 28 was prepared by tracing the results directly from the oscillograph record. To put the data in figure 28 into proper perspective it is necessary to remember that effects from other variables besides the valve type are superimposed on the results. Three other variables that could have had significant effects on the results shown in the figure are line temperature near the valve, valve opening time, and condition of the liquid just upstream of the valve. More will be said about these variables later.

Figures 29, 30, and 31 show the peak line pressures from all the hydrogen tests with the ball, globe, and gate valve, respectively. In general, the ball valve was more conducive to surging than the other valves and the globe valve was the least conducive. Although there were a number of tests with the globe valve that did surge, it was necessary to make a special effort to produce these results. For example, the line was partially precooled, a fast and smooth valve opening was effected, and liquid between the supply dewar and valve was drained off just before the valve was opened. All of these appeared to promote the possibility of surging. More will be said about these variables later.

Nitrogen was much harder to keep from surging than hydrogen. Figures 32 and 33 show results from two nitrogen tests at two driving pressures. One test was with the globe valve and one with the ball valve. Both resulted in significant surging. Figure 34 shows the peak line pressure as a function of driving pressure for all the tests with liquid nitrogen and includes results from all three valve types.

Figure 35 shows a trace of the pressure history during the first eight seconds of a nitrogen test which illustrates two important differences between nitrogen and hydrogen results. One difference is that the peak pressure was observed at station 2 on many nitrogen tests but never with hydrogen. This indicates that more of the transfer line experienced the high pressures during nitrogen tests than during hydrogen tests. Another important difference was the time between valve opening and peak pressure in the line. Typically, peak pressures occurred in hydrogen tests in about 0.2 seconds as shown in figure 35, while for nitrogen not until about 2 or 3 seconds after valve opening.

The magnitude of the pressure surges in all the tests showed a strong correlation with the first peak flow rate into the transfer line. Figures 36 and 37 show this correlation for the hydrogen tests and figure 38 for the nitrogen tests. Anything that tended to increase the amount of liquid that flowed into the line in the first inflow usually resulted in a higher surge pressure. For the globe valve, particularly, several methods of increasing the first inflow were tried and in general resulted in higher line pressures. The solid points in figure 37 denote runs in which the liquid between the supply dewar and the valve was drained off just prior to starting the test. This was done to see if liquid in that portion of the system was being warmed by heat leak and tending to saturate at higher pressures. Since the magnitude of the surges was dependent on the properties of the first liquid that entered the line, any tendency toward saturation next to the valve would reduce the possibility of high-surge pressures.

It should be understood that the peak flow rate plotted in figures 36 to 38 is simply the peak rate and not the actual amount of liquid that enters the line during the first inflow. Figure 39 shows a typical inlet flow from a hydrogen test that includes a flow reversal, and figure 40 shows the same information from a test with no pressure surge or flow reversal. These two figures are from the same tests as the pressure histories shown in figure 28. A typical inlet flow for nitrogen is shown in figure 41. The amount of liquid that entered the line is represented by the area under the flow trace on these three figures.

Valve opening time was another variable that had an effect on surging. Several methods were used in an effort to vary the opening time of the globe valve. These ranged from changing the actuation pressure on two different actuators to altering the valve plug tip. Even the method of operation of the valve actuator seemed to have an effect on the resulting pressures. If the opening action were fast and smooth, there was much more likelihood of a surge than if the motion were jerky or there were a hesitation in the opening.

Partially pre-cooling the upstream portion of the transfer line also tended to increase the possibility of surges provided the line was not pre-cooled too much. The overall effect of line temperature on surging may be to move the point of peak pressure in addition to making conditions more conducive to liquid inflow. This condition was noted when pressure was measured just downstream of the valve on a few hydrogen tests. With a warm line in these tests the peak pressure was observed at the valve, but with a partially pre-cooled line the peak pressure was usually observed at station 1.

Since maximum line pressures measured with liquid nitrogen were so high it was decided to try various methods of reducing them with devices placed in the flow stream in such a way as to change or somewhat control the flow pattern. Table 1 shows the results of those tests, along with one series with liquid hydrogen. All these tests were with subcooled liquid and the ball valve. The different inlet devices were located at the point where the globe valve was normally placed.

Table 1

Results with Inlet Flow Restrictions

Restriction	Fluid	Driving Pressure atm	Peak Line Pressure atm
Wire Crisscross	LN_2	2.52	6.81
		4.22	7.83 to > 24.6
Eight 90° elbows	LN_2	2.52	6.47
		4.22	9.18 - 13.5
		5.92	16.8
1.27 cm orifice	LN_2	2.52	6.81
		4.22	8.3
		5.92	9.32 to > 24.6
0.95 cm orifice	LN_2	2.52	5.38
		4.22	6.73
		5.92	8.51 - 9.67
		7.62	11.2
0.64 cm orifice	LN_2	2.52	3.54
		4.22	7.14 - 8.30
		5.92	10.1 - 10.6
		7.62	10.2 - 10.3
0.64 cm orifice	LH_2	2.52	2.99
		4.22	5.72
		7.62	7.62 - 8.43
		11.0	11.2 - 11.2

There was still some surging with all the devices tried and only the small orifices reduced the peak surge pressures to a tolerable level. In fact it was possible to test subcooled liquid nitrogen for the first time at a driving pressure of 7.6 atmospheres with both the 0.64 cm and 0.95 cm orifices without risking damage to the pressure transducers. One other device was tried which consisted of a brass tape one tube diameter wide, 20.3 cm long and 0.028 cm thick twisted approximately 180°. The ends of the tape were hard soldered to the inside of the tube. With liquid nitrogen at 5.9 atm the resulting line pressure with this device in place exceeded 24.6 atm from the supply dewar to some point beyond station 3, 43.0 m away. The tape tore away from around the solder joints on the upstream end and broke off a piece about 7.6 cm long which was blown back through the valve and flowmeter into the supply dewar. Figure 42 is a photograph of the resulting tape with the tube cut away along with the resulting debris recovered from the supply dewar.

Two other inlet devices are shown in figure 43. The wire crisscross section was used to determine if a liquid core were present that could be dispersed and possibly reduce the surges. The elbow section was used to see if localized, additional pressure drop near the inlet would change the surging. The three remaining devices were simple orifices 0.32 cm thick.

3.3 Heat Transfer Coefficient History

The purpose of this analysis was to provide order of magnitude comparisons between the nitrogen and hydrogen heat transfer coefficients as calculated from pool boiling correlations at one atmosphere, and the actual coefficients as measured from wall temperature data for the forced convection flow of the fluids. It was also hoped that these comparisons would provide some qualitative indication of the relative effect of forced convection during the cooldown of a cryogenic transfer line.

The upper portion of figure 44 indicates the location of the experimental stations (using the length scale at the bottom of the figure) and the type of model assumed for this analysis as the flow system might appear a few seconds after the test run had begun, when the liquid front had reached the indicated position. This part of the figure applies to both nitrogen and hydrogen. Two points should be emphasized. First, it was assumed that significant liquid splashing occurred in the portion shown as two-phase. This corresponds to the transition region usually shown between peak nucleate pool boiling and minimum film pool boiling, since a stable vapor film has not yet been found. Second, it was assumed that there was no penetration of the liquid from the core through the gas film region. This, of course, corresponds to the film pool boiling regime. Figure 44 also shows typical wall temperatures and pool boiling heat transfer coefficients, corresponding to the three boiling regimes for nitrogen, as functions of the transfer line length. (Note that figure 44 is a paradigm and does not present actual experimental data.)

In all experimental runs considered in this analysis, the inlet liquid was saturated at approximately 0.8 atm. The upper portions of figures 45 through 51 illustrate the wall temperature histories during nitrogen and hydrogen cooldown at the four locations shown in figure 44. One representative test run is shown for each driving pressure investigated.

It was assumed that the experimental heat flux into the flowing cryogens, $\left(\frac{q}{A}\right)_{Exp}$, was identical with the heat flux from the copper transfer line, as determined from the wall temperature histories. That is to say, thermal radiation from the vacuum jacket, heat conduction through the residual gas, temperature gradient across the transfer line wall, and axial heat conduction were considered to be negligible.

Then,

$$\left(\frac{q}{A}\right)_{Exp} \cong \left(\frac{D_o^2 - D_i^2}{4D_i}\right)\left(C_p \rho\right)_{Cu}\left(\frac{\Delta T}{\Delta t}\right) . \qquad (1)$$

The procedure for computer evaluation was to choose $\Delta t = 2$ seconds, which prescribed ΔT from the wall temperature histories at each consecutive two-second increment. Then, $\left(C_p\right)_{Cu}$ at the wall temperature was obtained from reference [2]. Finally, the experimental heat transfer coefficient was determined by dividing the experimental heat transfer flux by the temperature gradient between the wall and the saturated liquid; that is

$$h_{Exp} = \frac{\left(\frac{q}{A}\right)_{Exp}}{T_{wall} - T_{sat}} . \qquad (2)$$

These values for each representative nitrogen and hydrogen test run are shown in the lower portions of figures 45 through 51 as the solid lines, for each of the four experimental stations. The test run shown in figure 47 was also evaluated using $\Delta t = 0.5$ second. This produced small fluctuations in h_{Exp} around the values shown in figure 47, but there were no essential changes in magnitudes or trends.

For comparison, pool boiling heat transfer coefficients are shown in figures 45 through 51 as the dashed lines. These values for h_{Boil} were taken from the nucleate pool boiling correlation of Kutateladze, and the film pool boiling correlation of Breen and Westwater, as shown in figures 2.6 and 2.7 of reference [2], for nitrogen and hydrogen, respectively. Nucleate pool boiling values at one standard atmosphere, only, were used. For nitrogen, linear interpolation between the peak nucleate pool boiling flux and the minimum film pool boiling flux provided the h_{Boil} values in the transition region. For hydrogen, figures 47 through 51, the correlations do not rise to follow the experimental data as they do for the two nitrogen runs. This is because neither the correlations nor the data are reported for wall temperatures less than 70° K, due to suspected inadequacies in the data recording system at those lower temperatures. Since reference [2] shows the change from film pool boiling to transition pool boiling for hydrogen to occur at 40° K, figures 47 through 51 could not show the corresponding rise in the calculated coefficients that figures 45 and 46 show.

A predictive forced convection correlation using superposition was attempted. Reference [3], pages 35-39, recommended

$$h_{\text{Pred}} = h_{\text{Boil}} + h_{\text{F.C.}} \tag{3}$$

However, the experimental uncertainties in determining the mass flow rate made it almost impossible to evaluate $h_{\text{F.C.}}$ with any reasonable degree of accuracy.

Figures 45 through 51 indicate that using the steady state pool boiling approximation for transient forced convection boiling produces reasonable agreement with the nitrogen data but not with the hydrogen data for the heat transfer coefficients. This might be explained from the surface tension of hydrogen being only 1/4 that of nitrogen and the liquid phase to gas phase density ratio of hydrogen being only 1/3 that of the same ratio for nitrogen. Thus, forced convection could effect more mixing of the phases in hydrogen, break down the gas film boiling regime, and induce transition boiling at a wall temperature higher than that expected from pool boiling alone. However, experimental and data reduction uncertainties prevented a more quantitative analysis of the differences between boiling nitrogen and hydrogen.

Finally, figures 45 through 51 illustrate the effects on the heat transfer coefficients of increasing the driving pressure. This decreases the overall cooldown times, and increases the cooling rate and the deviations between h_{Exp} and h_{Boil}. These effects are to be expected, since the higher flow velocities resulting from the increased pressures would certainly increase the effect of $h_{F.C.}$ in equation (3). Thus, the qualitative effects of significance which these figures illustrate are the sharpness of the cold (liquid) front passing down the transfer line, as evidenced by the marked temperature drop and high heat transfer coefficients and the increased cooling effect of forced convection as the driving pressure increases.

4. Conclusion

With the test apparatus used in this program the single most successful method of controlling high pressure surges for both liquid hydrogen and liquid nitrogen was to run with saturated liquid in the supply dewar. Control of high pressure surges with subcooled liquid was possible if control of the amount of liquid entering the line the first time could be maintained. This control was easier with hydrogen where valve location, valve type, valve opening procedure, and line temperature seemed to affect final pressures. With nitrogen, however, only a throttled inlet gave any semblance of control.

Heat transfer coefficients during cooldown followed the general trend predicted for nitrogen by the steady state pool boiling approximations. The coefficients for hydrogen, however, did not follow the predictions.

5. Notation

C_p	specific heat capacity at constant pressure, $\frac{\text{J}}{\text{gm.}\,^\circ\text{K}}$.
D	diameter of transfer line, cm.
h	convective heat transfer coefficient, $\frac{\text{W}}{\text{cm.}^{2}\,^\circ\text{K}}$.
L	axial length variable along transfer line, cm.
(q/A)	heat transfer flux, $\frac{\text{W}}{\text{cm}^{2}}$.
T	temperature, °K.
t	time, sec.
ΔT	measured change in T_{wall} corresponding to the Δt, °K.
Δt	time increment over which ΔT was measured, sec.
ρ	density, $\frac{\text{gm}}{\text{cm}^{3}}$.

Subscripts

Boil	quantity evaluated for pool boiling only.
Cu	quantity evaluated for copper.
Exp	quantity evaluated from experimental data.
F.C.	quantity evaluated from forced convection considerations.
i	inner value.
o	outer value.
sat	quantity evaluated at saturation conditions.
wall	quantity evaluated at the transfer line wall.

6. References

1. Steward, W. G., Advances in Cryogenic Engineering, Vol. 10A, Plenum Press, N. Y. (1965), p. 313.

2. Johnson, V. J., (ed.) A Compendium of the Properties of Materials at Low Temperature, WADD Tech. Report 60-56, 1960.

3. Brentari, E. G., P. J. Giarratano, and R. V. Smith, Boiling Heat Transfer for Oxygen, Nitrogen, Hydrogen, and Helium, NBS Tech. Note No. 317, 1965.

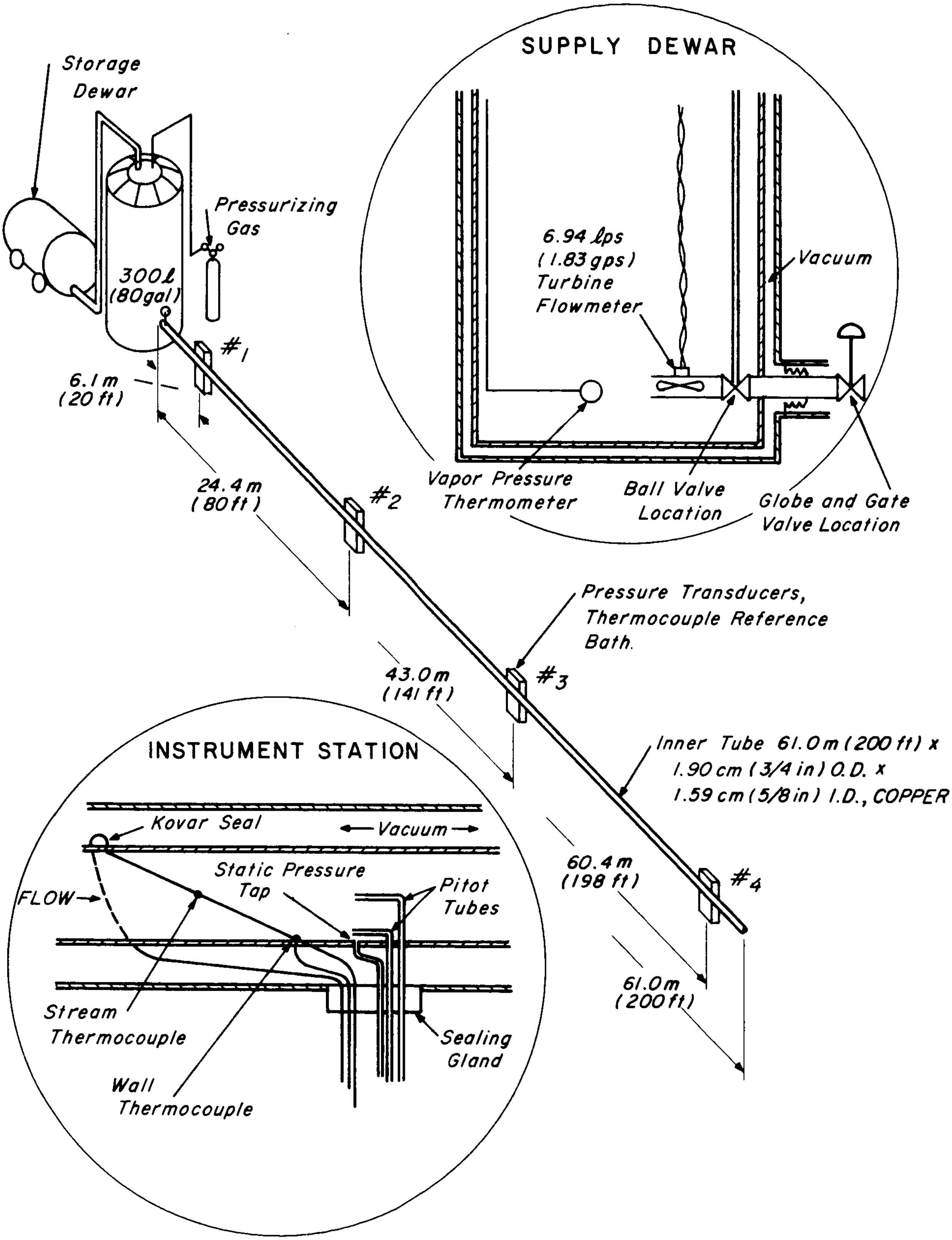


Fig. 1 Schematic of test apparatus.

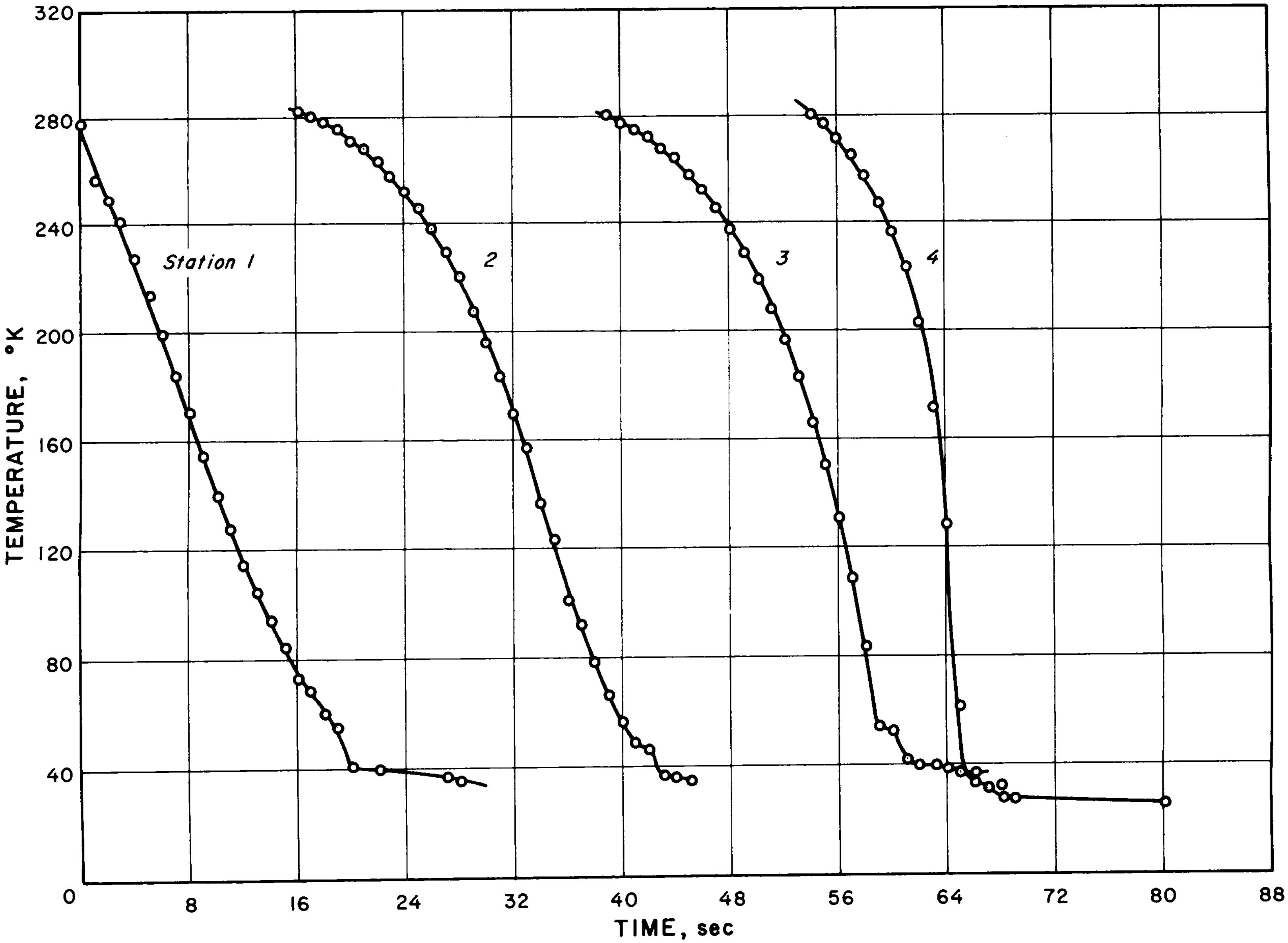


Fig. 2 Line temperature history with saturated liquid hydrogen at a driving pressure of 5.1 atm.

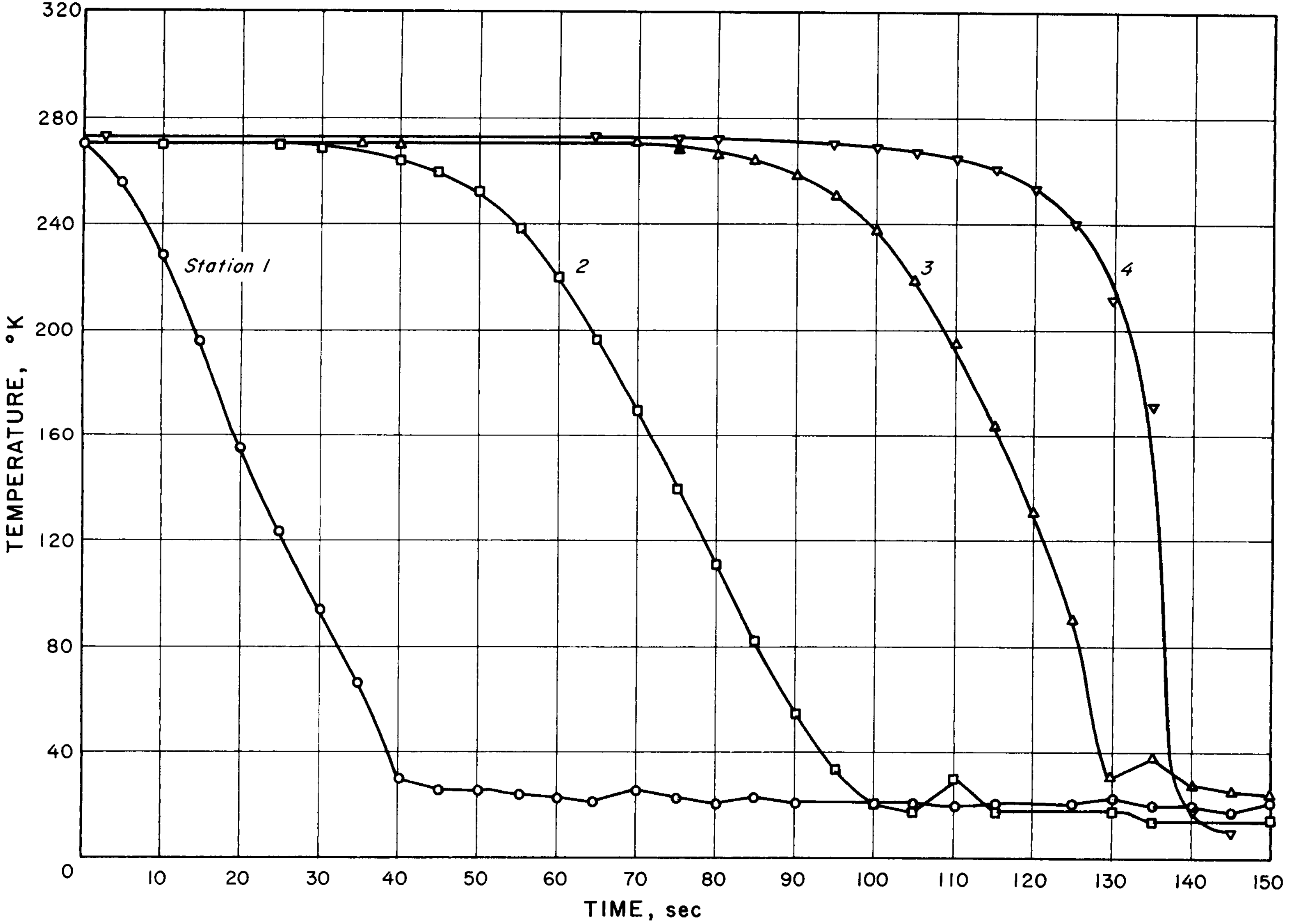


Fig. 3 Line temperature history with subcooled liquid hydrogen at a driving pressure of 2.5 atm.

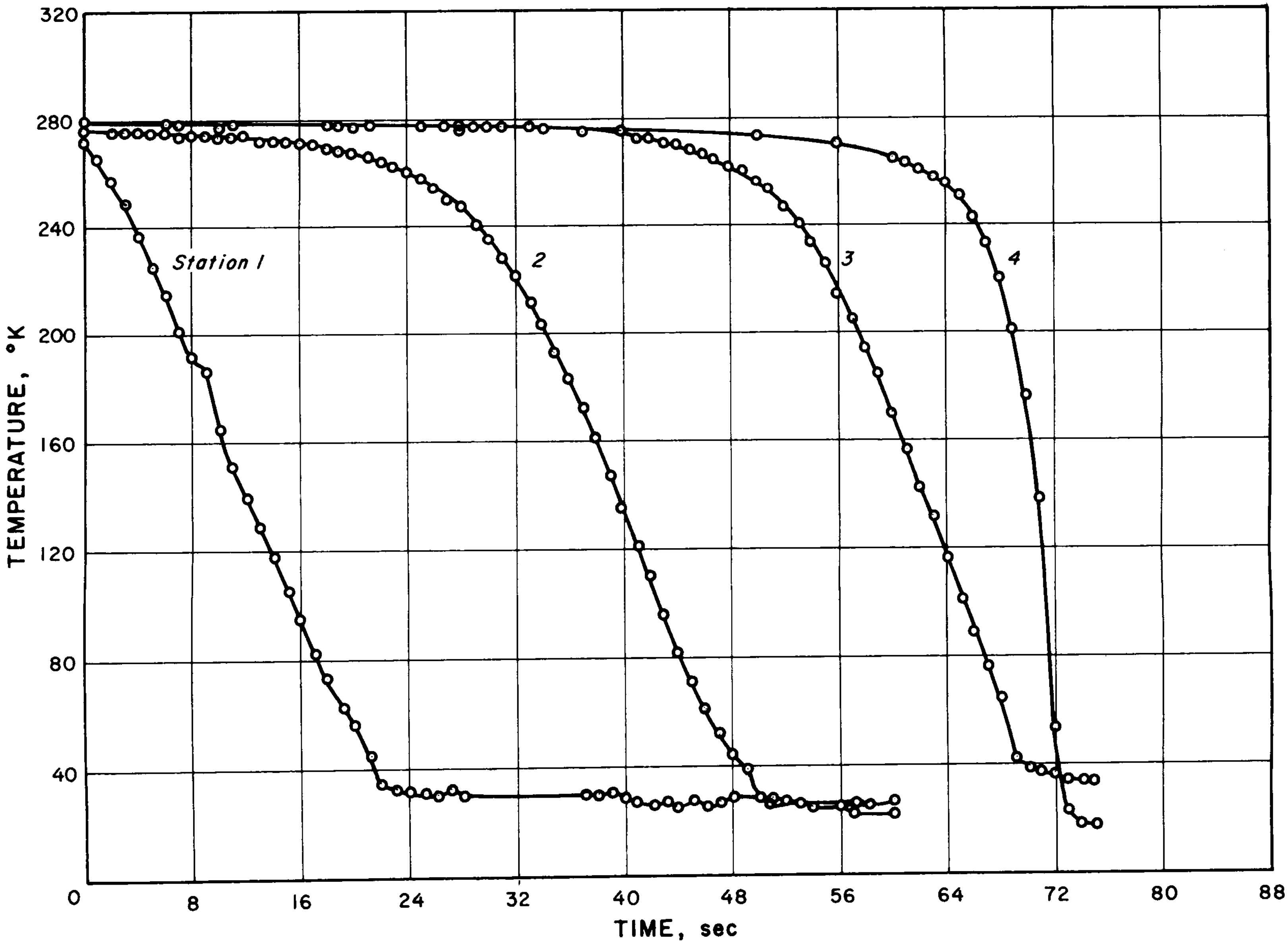


Fig. 4 Line temperature history with subcooled liquid hydrogen at a driving pressure of 4.2 atm.

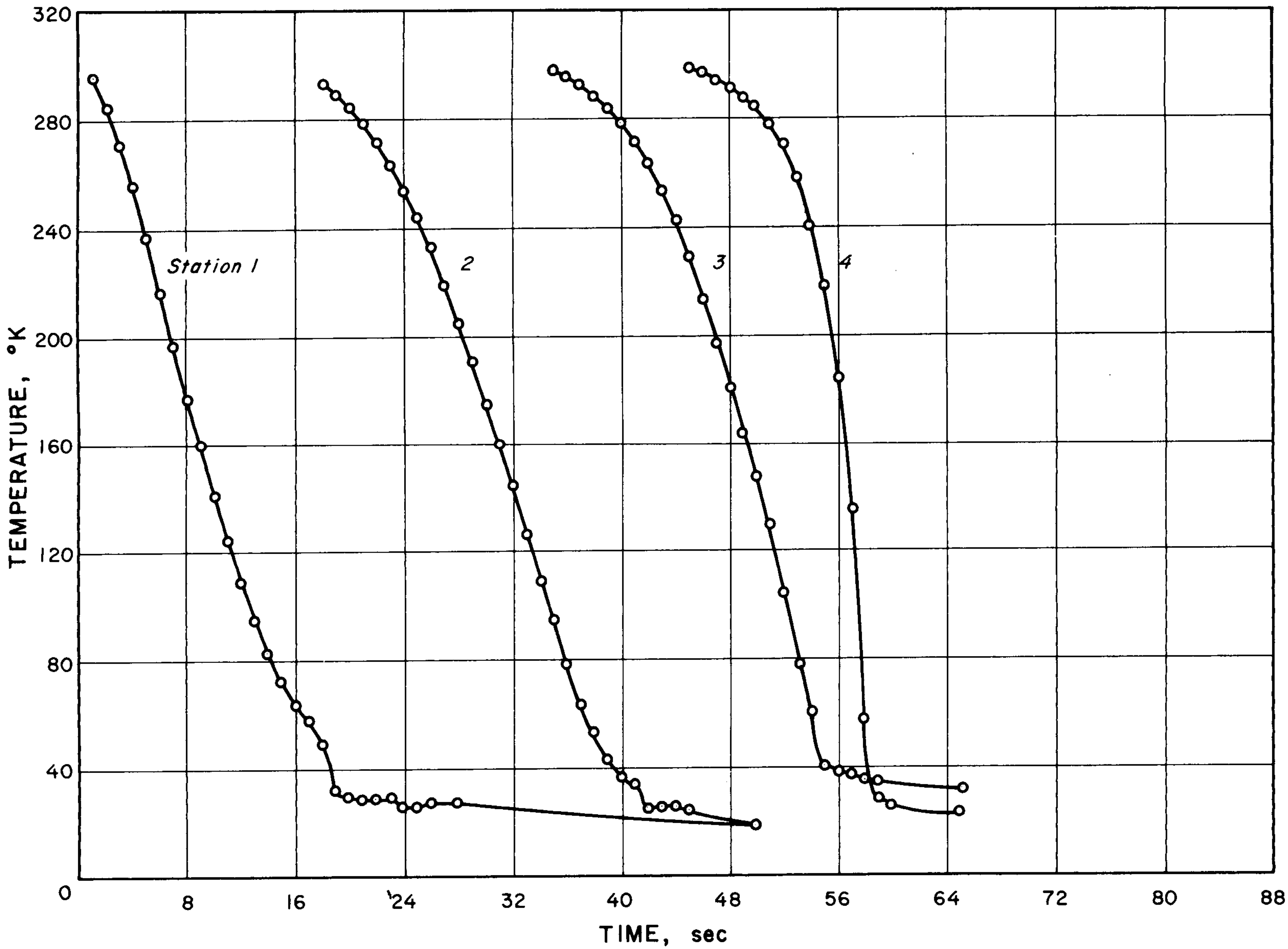


Fig. 5 Line temperature history with subcooled liquid hydrogen at a driving pressure of 5.9 atm.

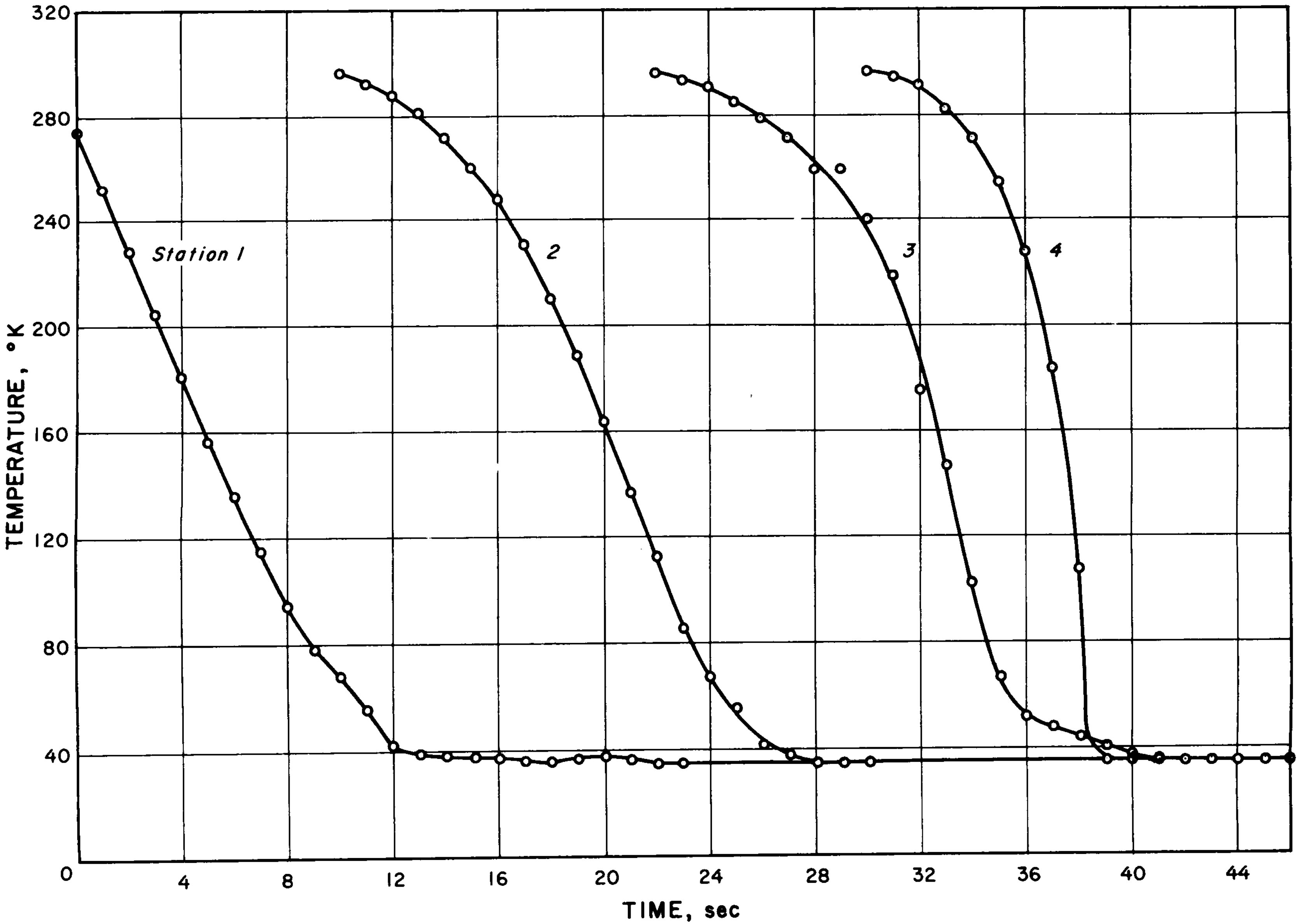


Fig. 6 Line temperature history with subcooled liquid hydrogen at a driving pressure of 7.6 atm.

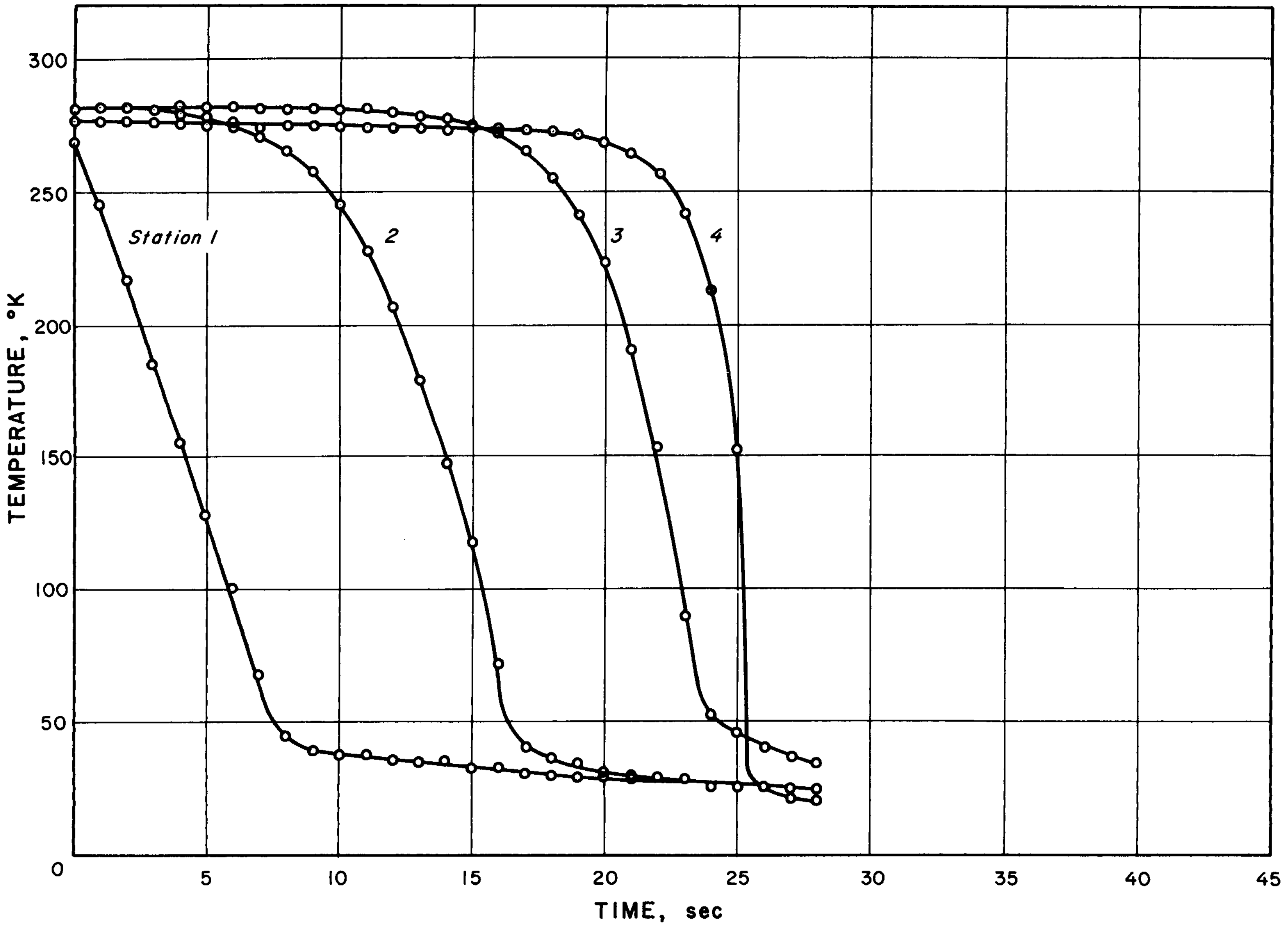


Fig. 7 Line temperature history with subcooled liquid hydrogen at a driving pressure of 11 atm.

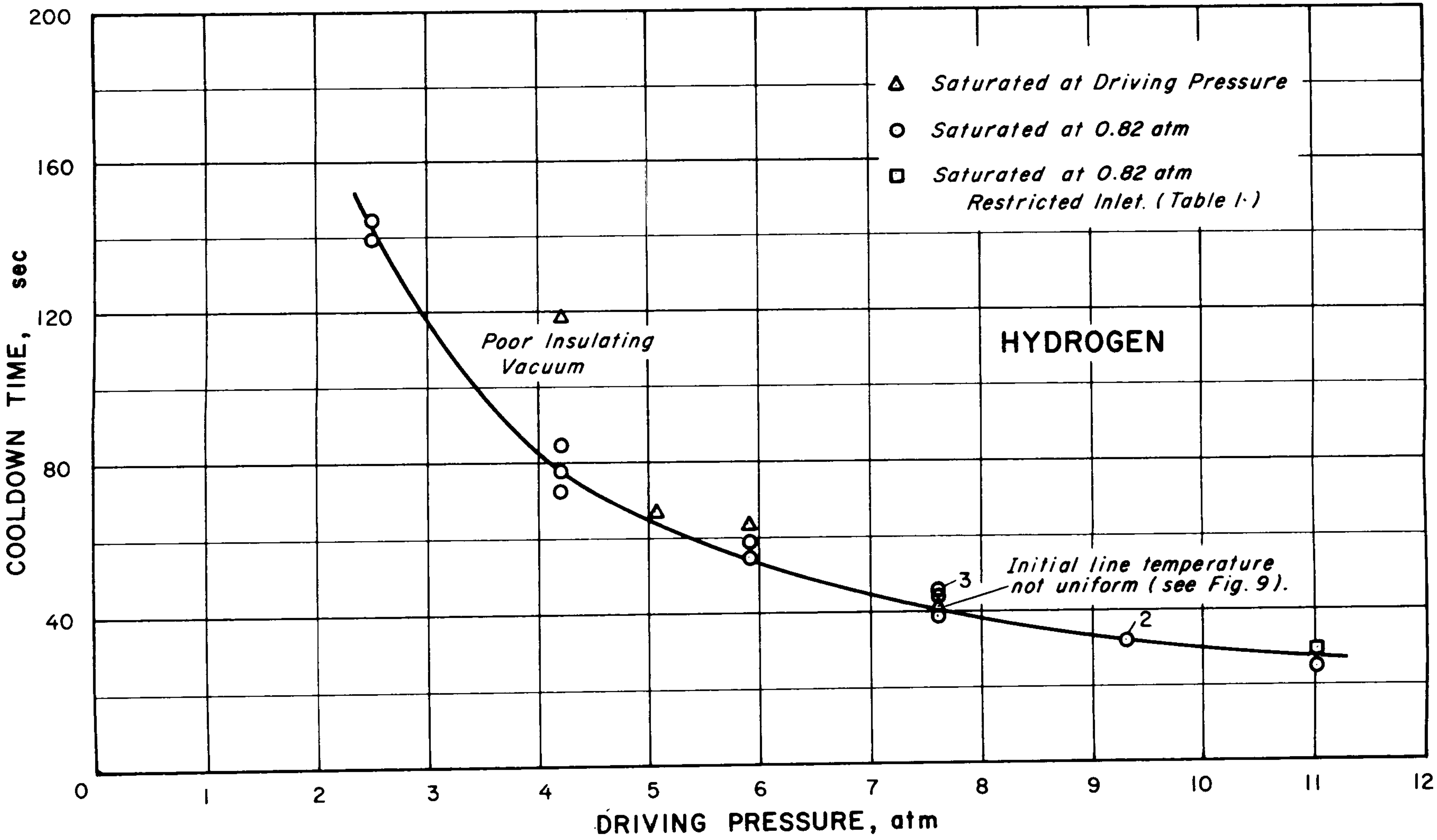


Fig. 8 The effect of driving pressure on line cooldown time with liquid hydrogen.

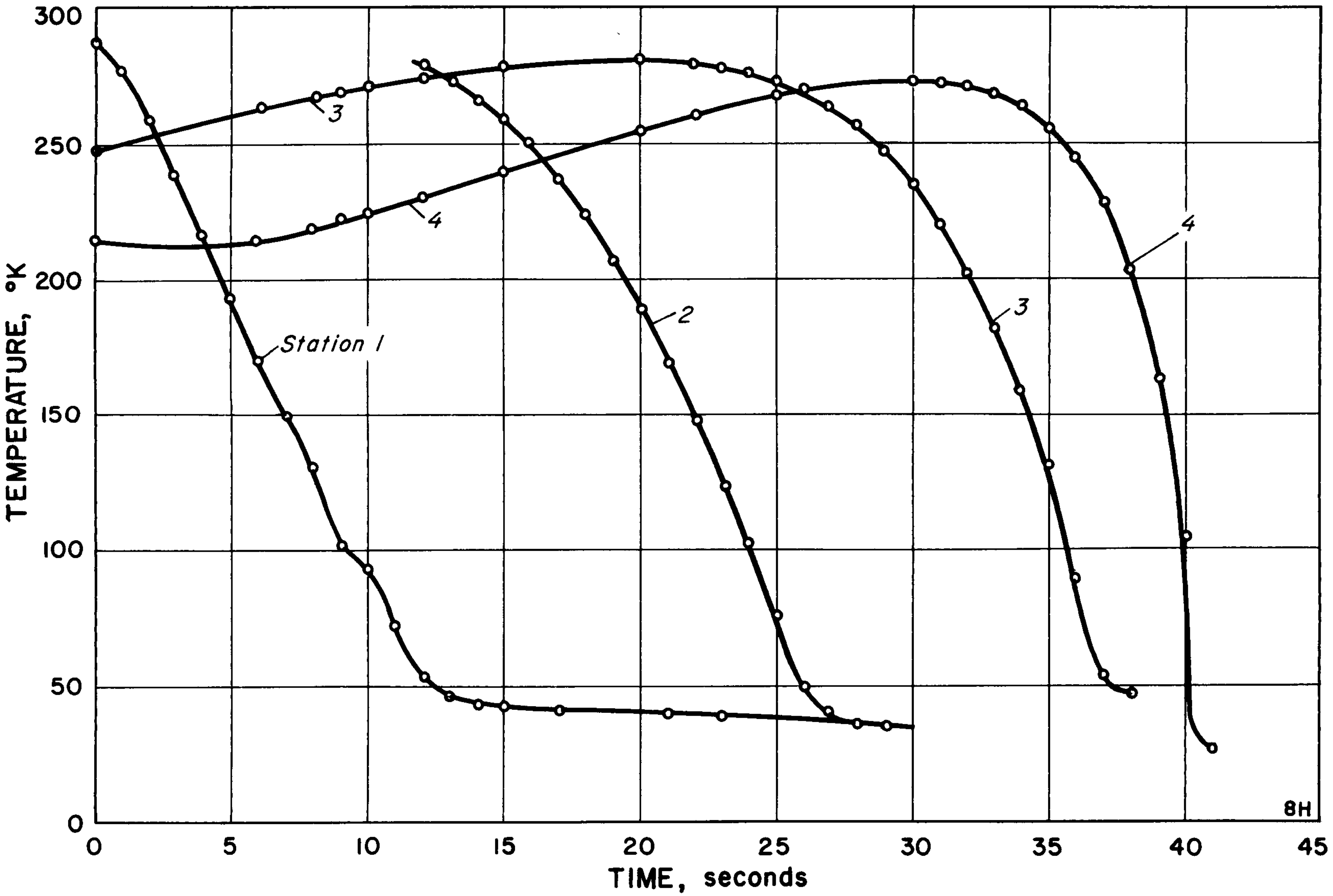


Fig. 9 Line temperature history with saturated liquid hydrogen at a driving pressure of 7.6 atm with the downstream portion of the line partially precooled.

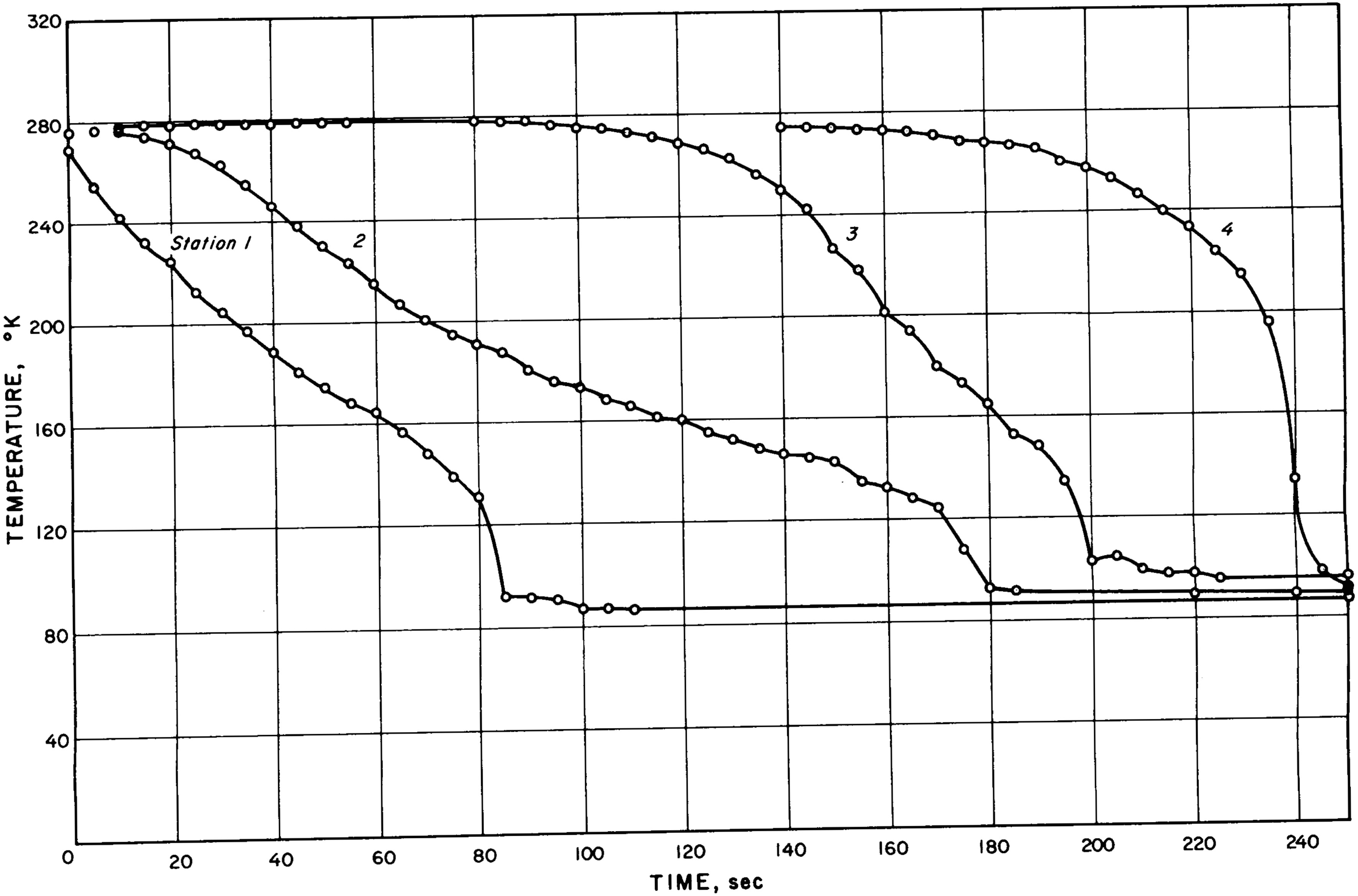


Fig. 10 Line temperature history with saturated liquid nitrogen at a driving pressure of 2.5 atm.

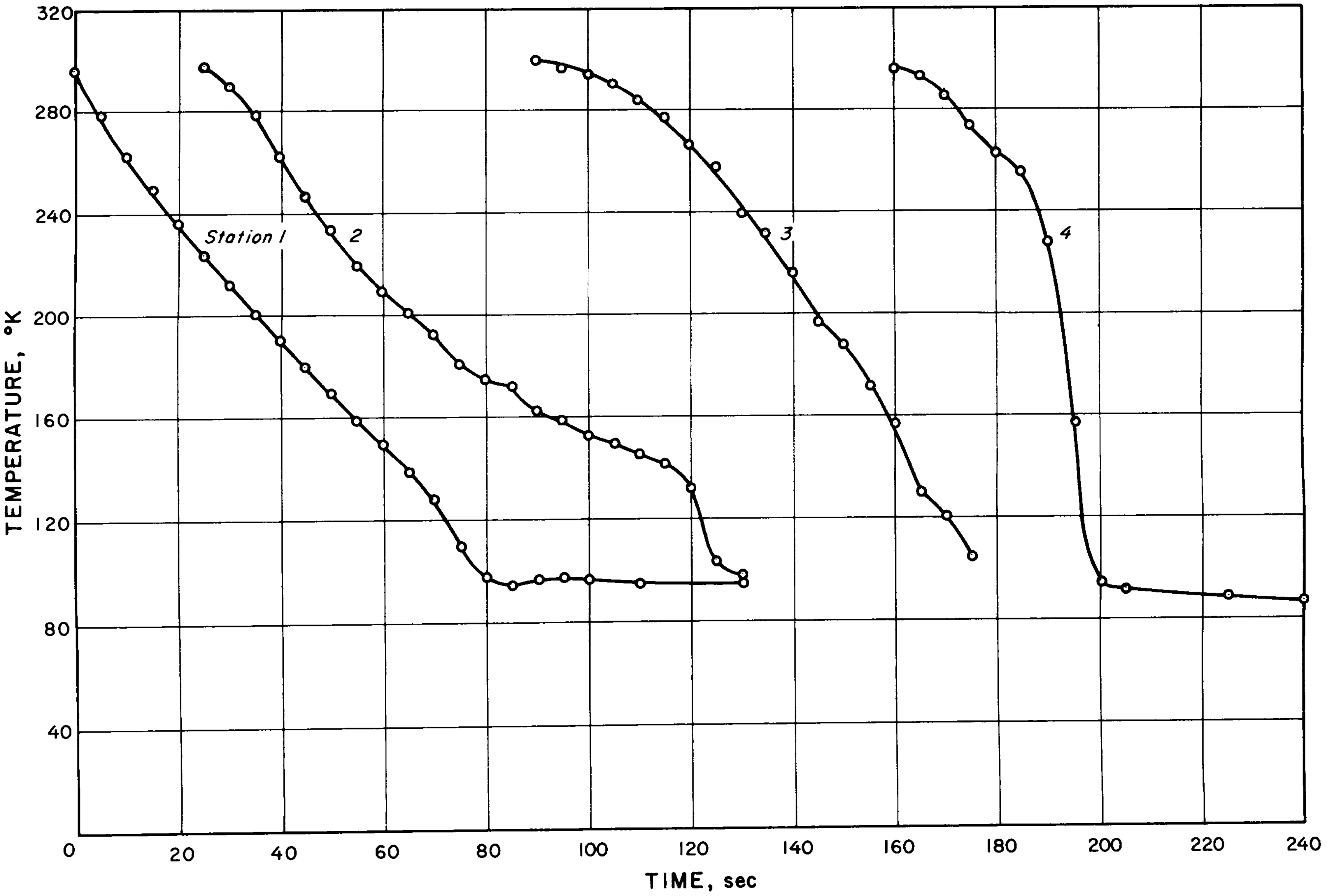


Fig. 11 Line temperature history with saturated liquid nitrogen at a driving pressure of 3.4 atm.

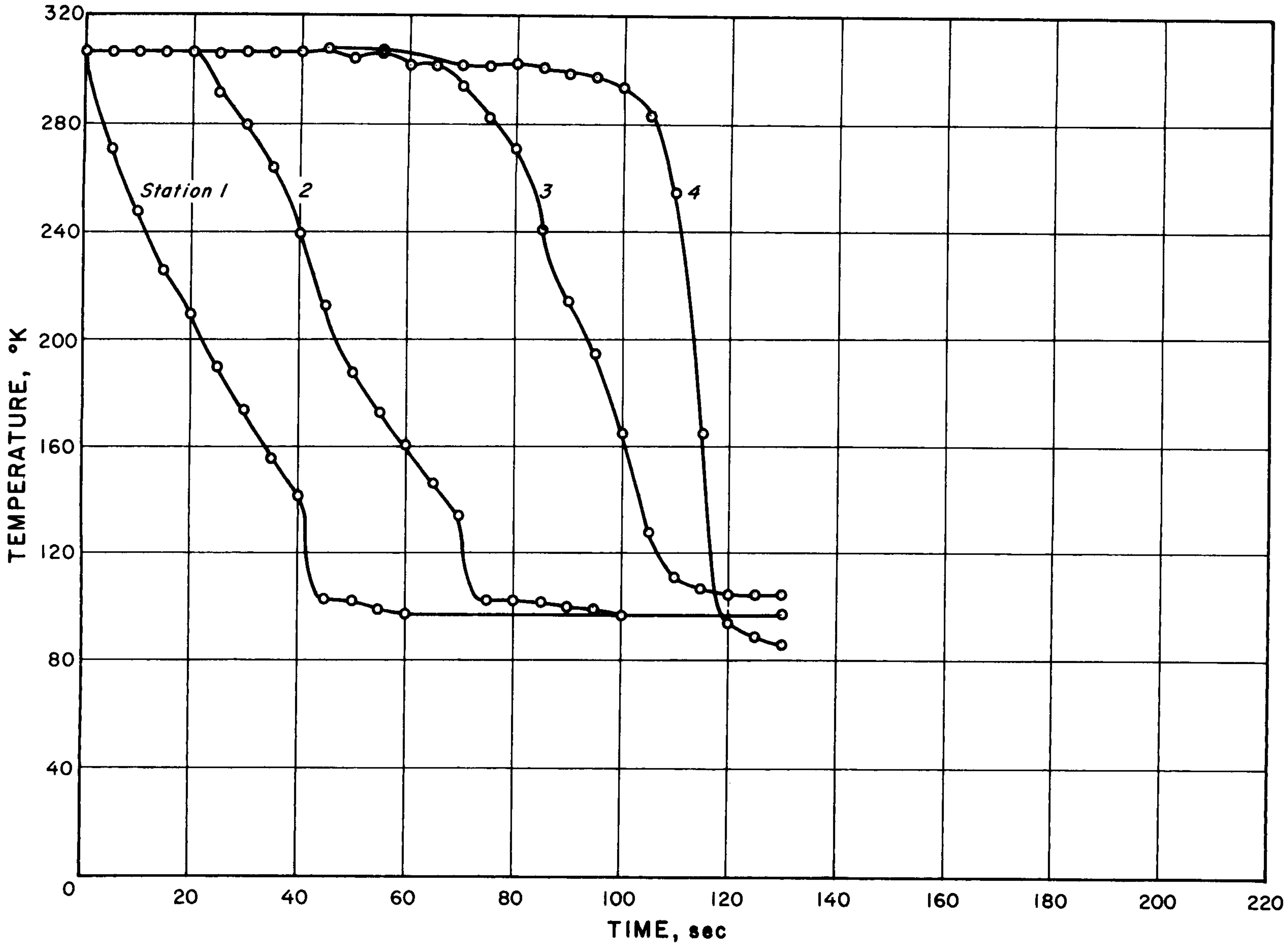


Fig. 12 Line temperature history with saturated liquid nitrogen at a driving pressure of 5.9 atm.

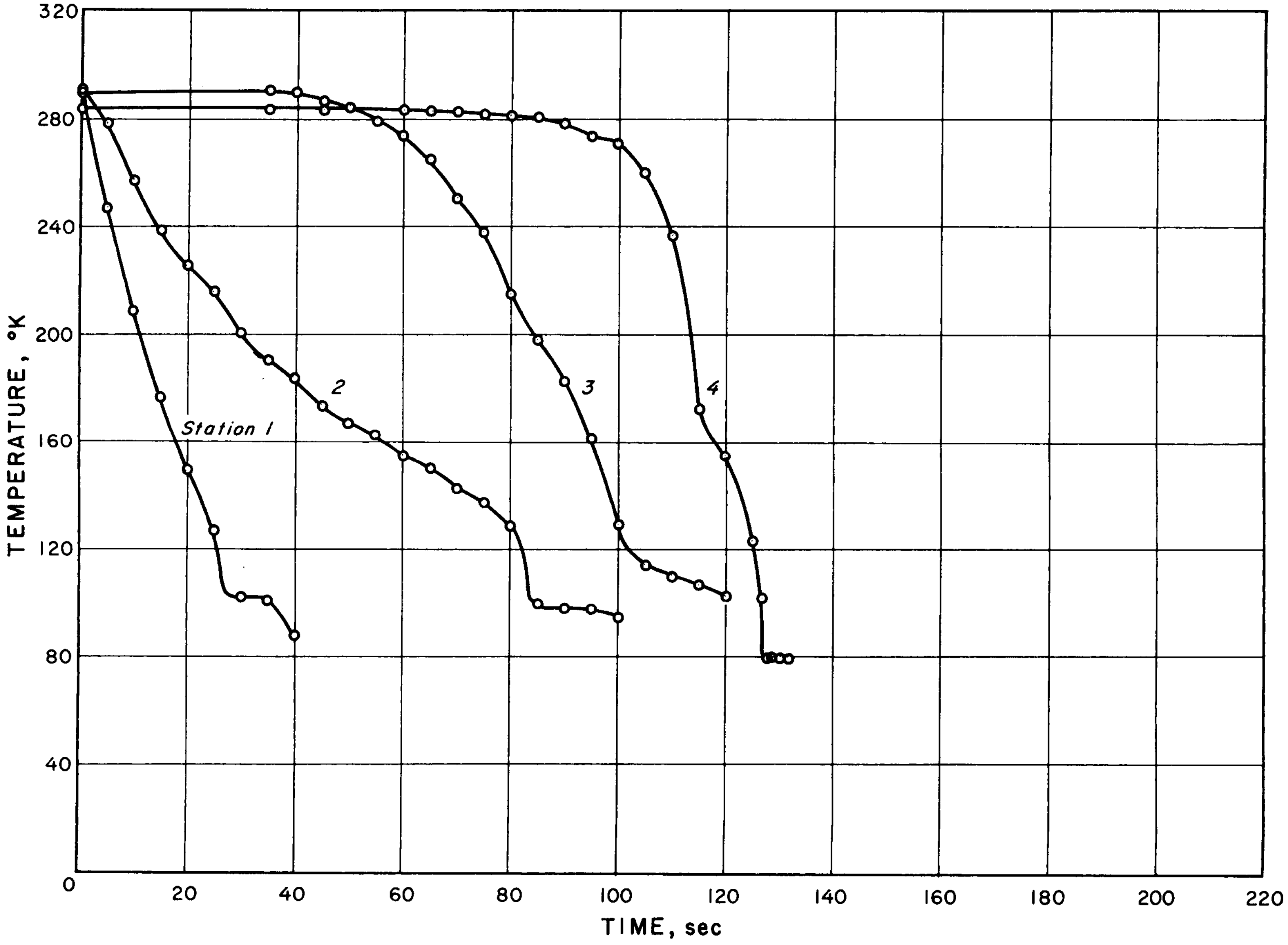


Fig. 13 Line temperature history with subcooled liquid nitrogen at a driving pressure of 4.2 atm.

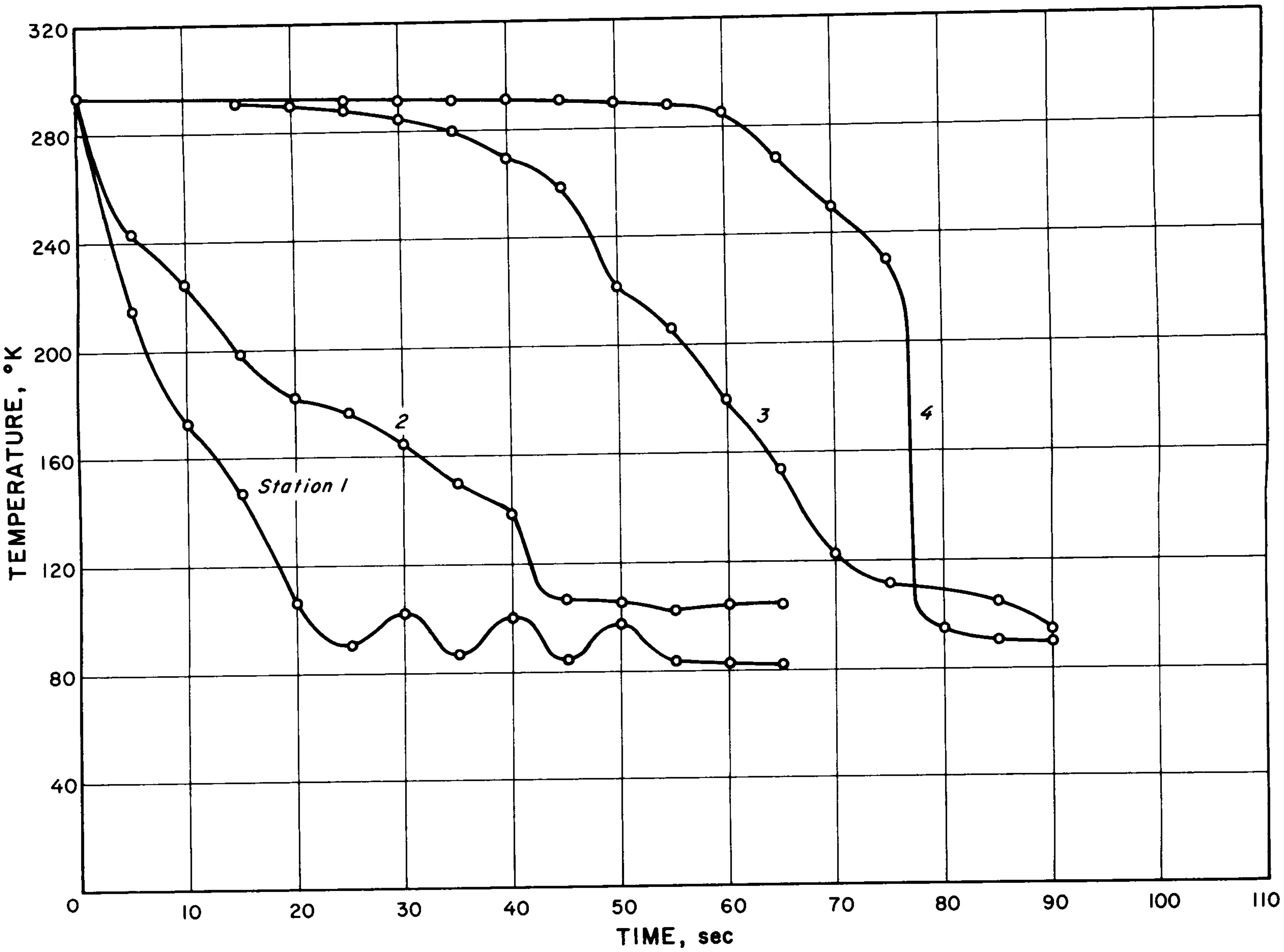


Fig. 14 Line temperature history with subcooled liquid nitrogen at a driving pressure of 5.9 atm.

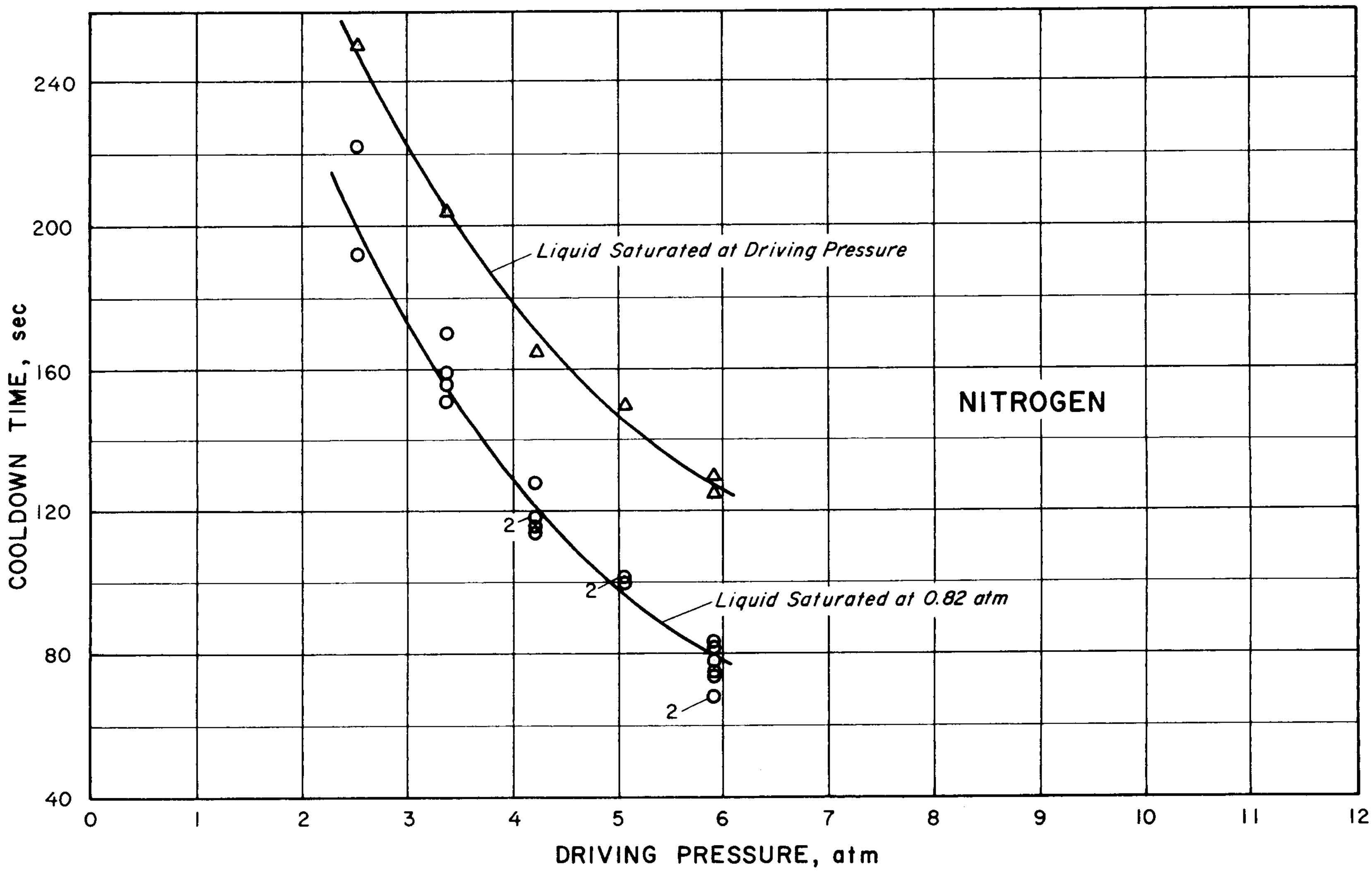


Fig. 15 The effect of driving pressure on line cooldown time with liquid nitrogen.

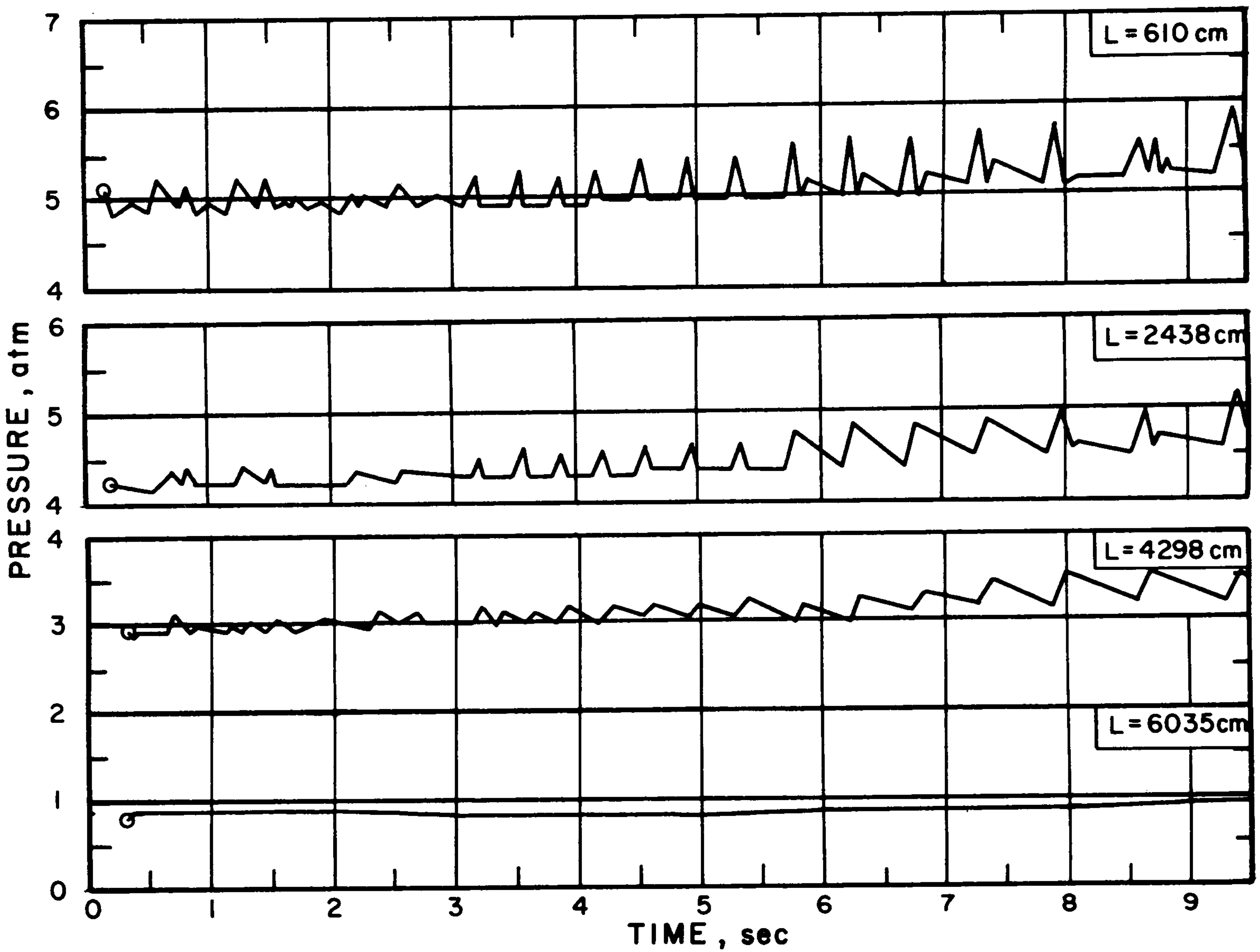


Fig. 16 Line pressure history with saturated liquid hydrogen at a driving pressure of 5. 1 atm using the ball valve.

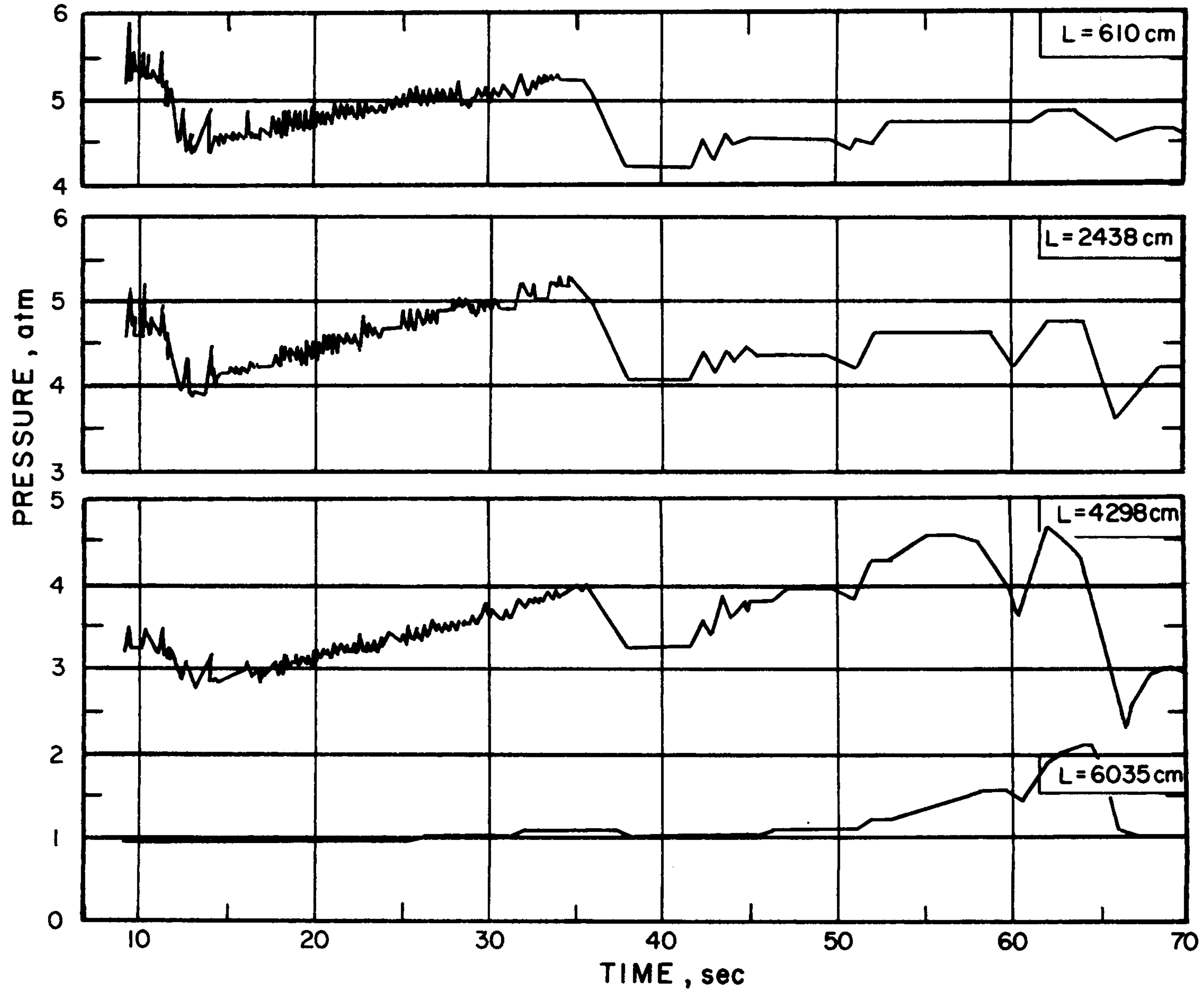


Fig. 17 Line pressure history with saturated liquid hydrogen at a driving pressure of 5. 1 atm using the ball valve.

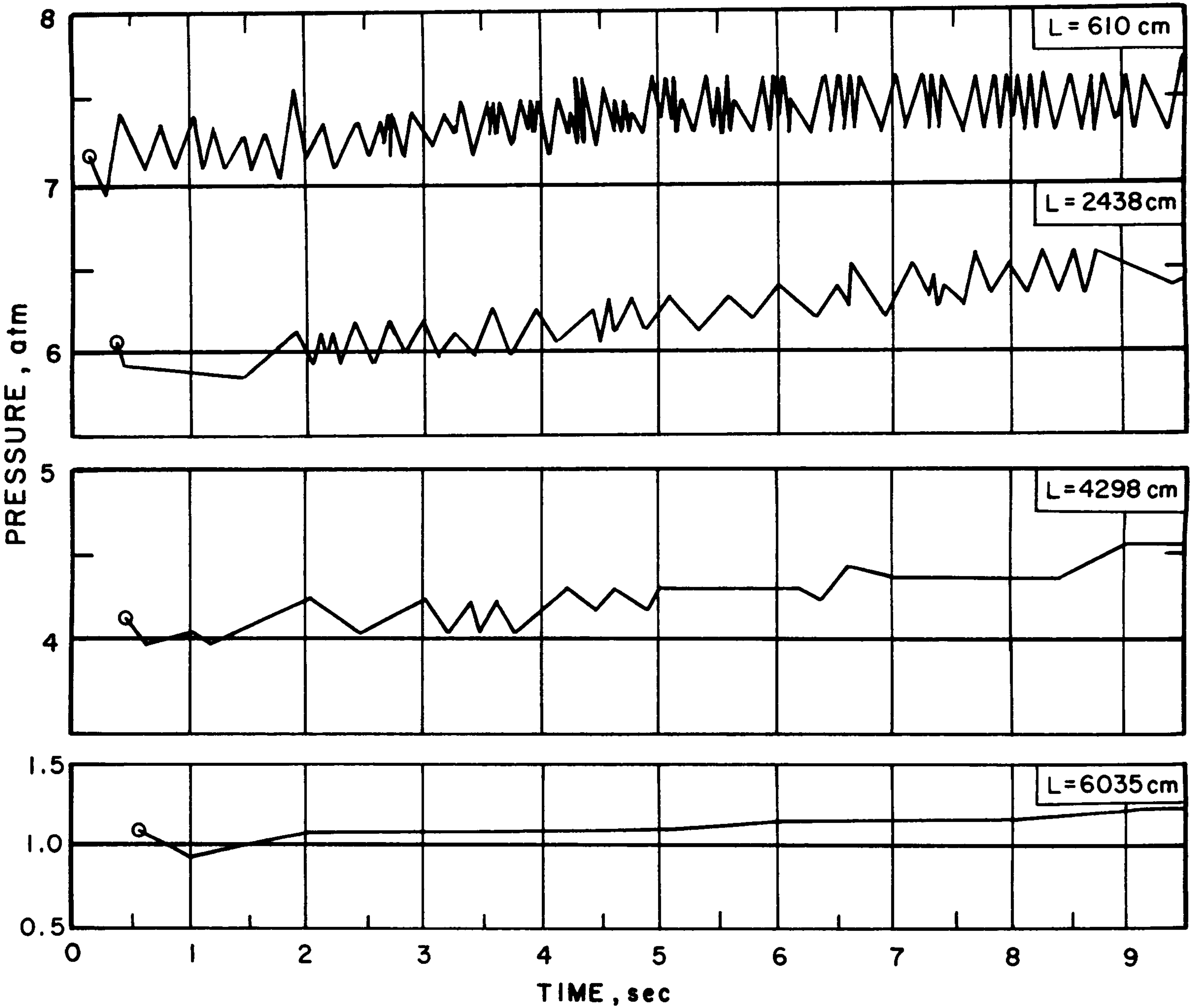


Fig. 18 Line pressure history with saturated liquid hydrogen at a driving pressure of 7.6 atm using the ball valve.

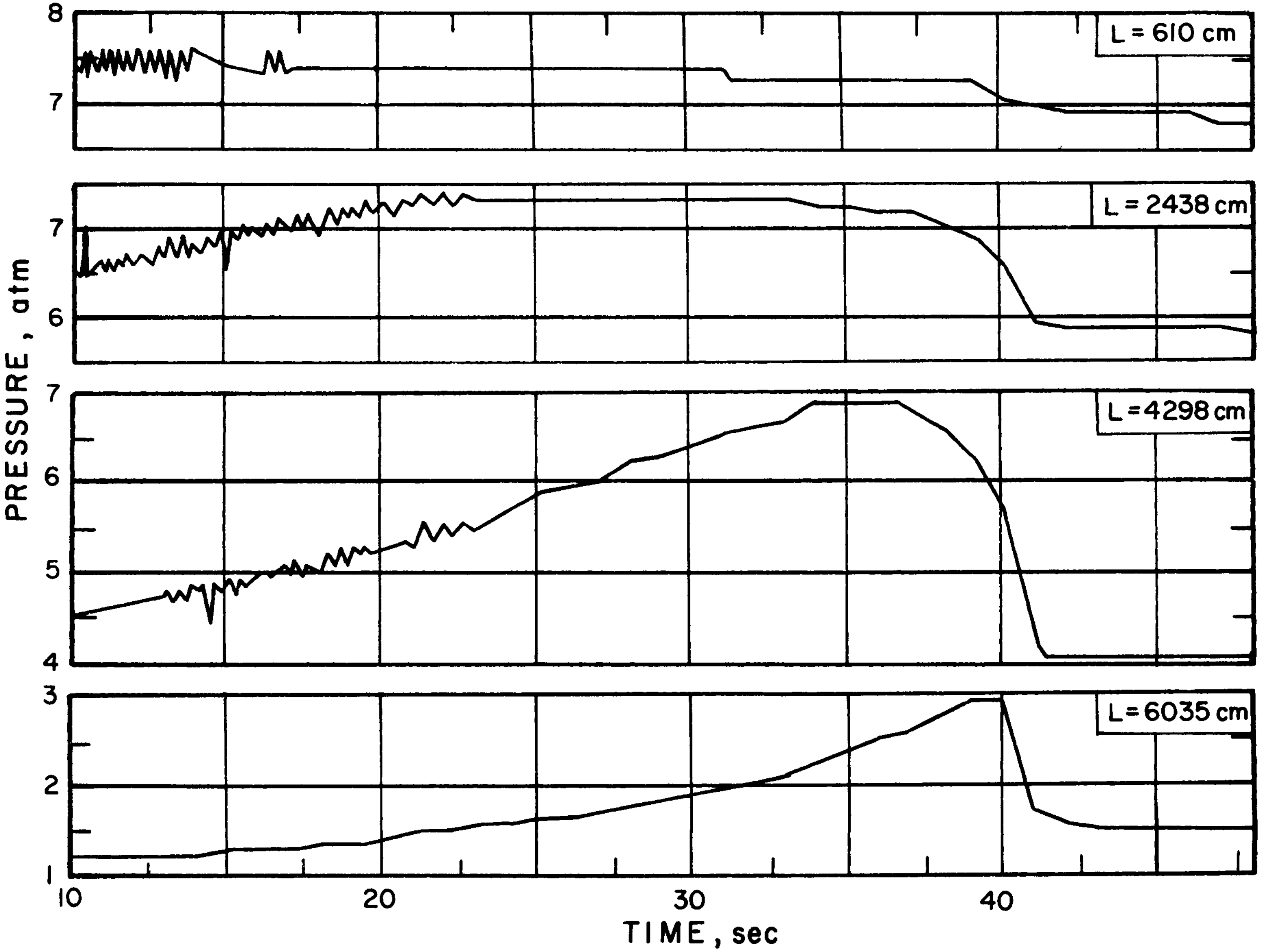


Fig. 19 Line pressure history with saturated liquid hydrogen at a driving pressure of 7. 6 atm using the ball valve.

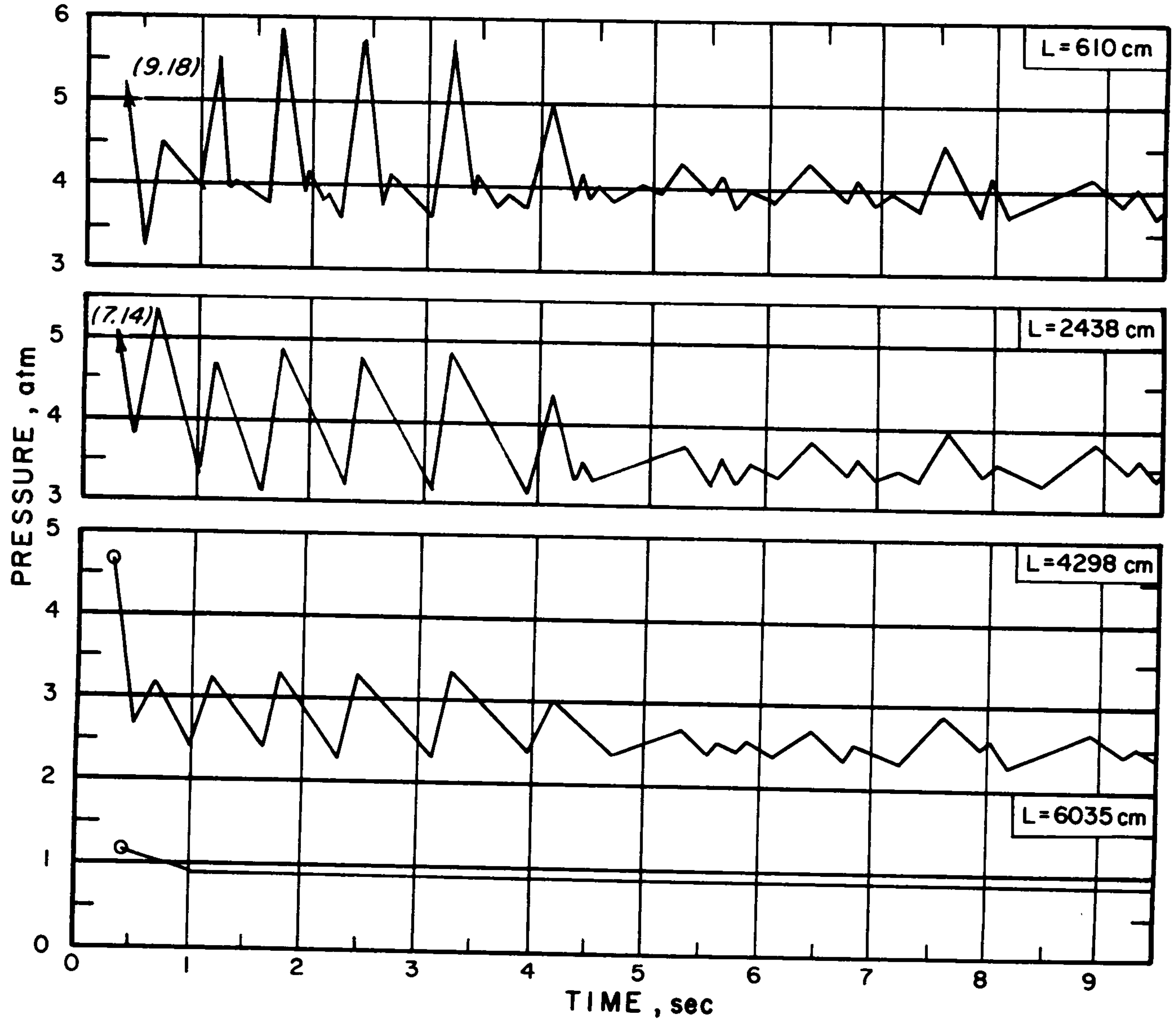


Fig. 20 Line pressure history with subcooled liquid hydrogen at a driving pressure of 4.2 atm using the ball valve.

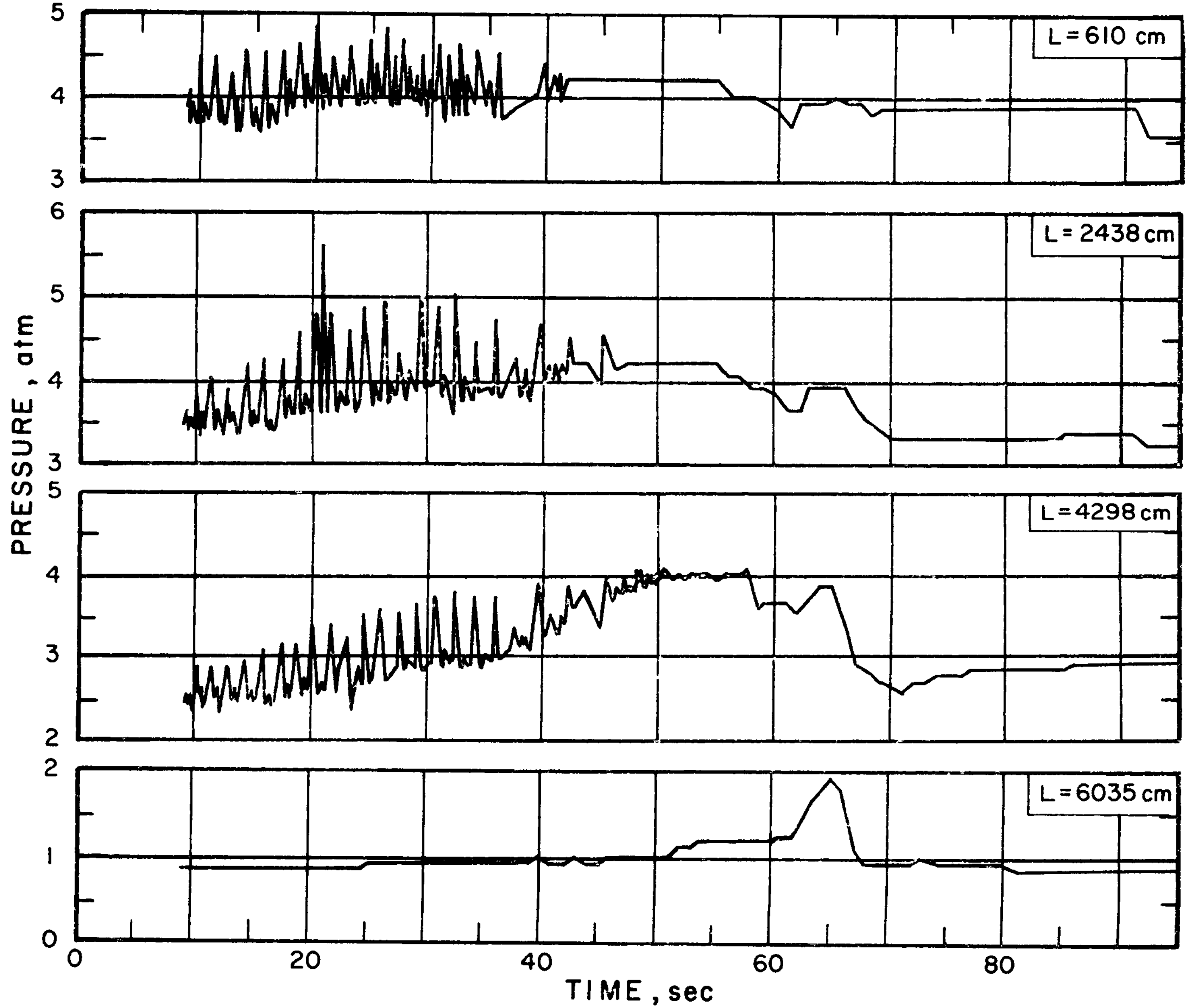


Fig. 21 Line pressure history with subcooled liquid hydrogen at a driving pressure of 4.2 atm using the ball valve.

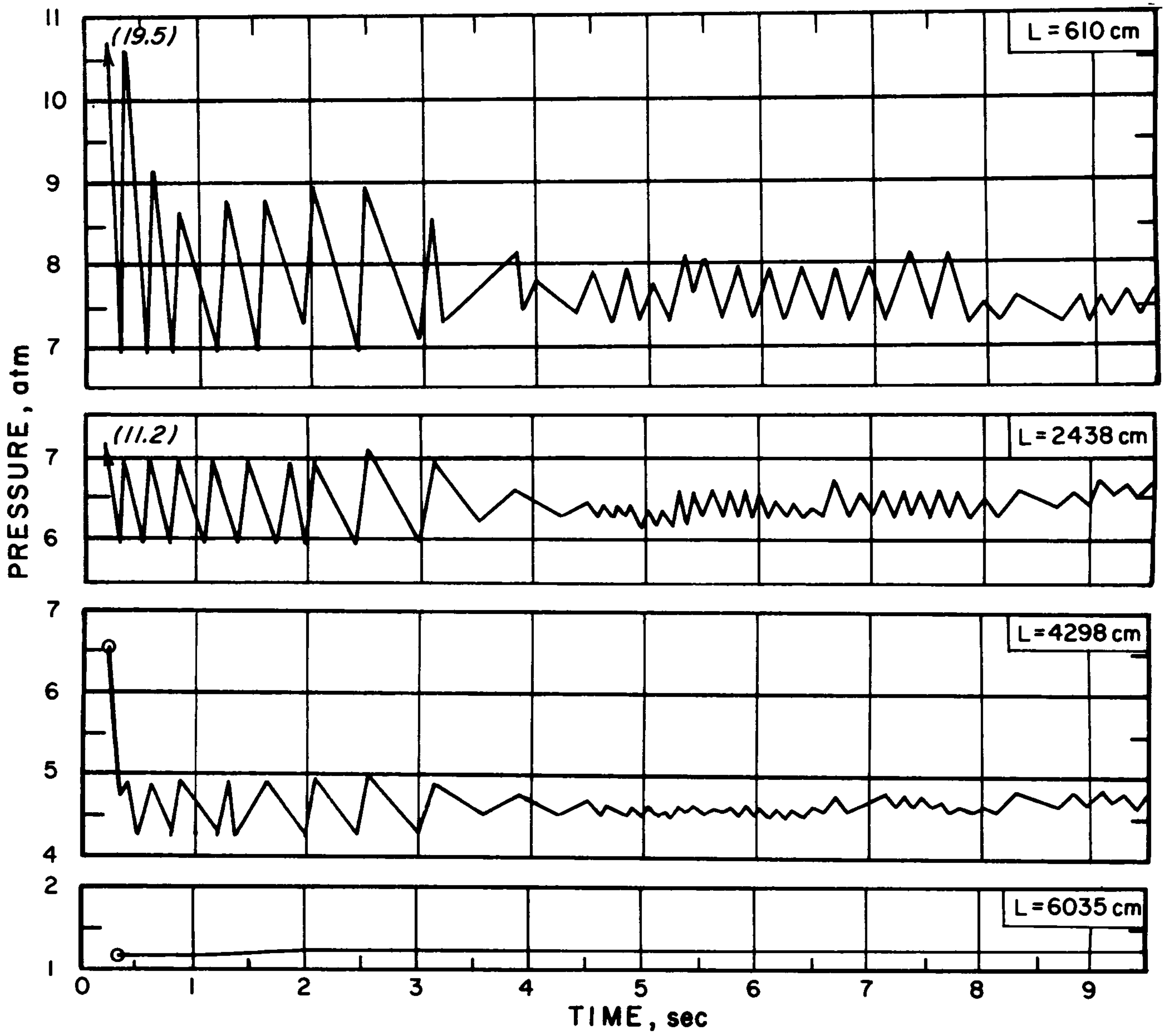


Fig. 22 Line pressure history with subcooled liquid hydrogen at a driving pressure of 7.6 atm using the ball valve.

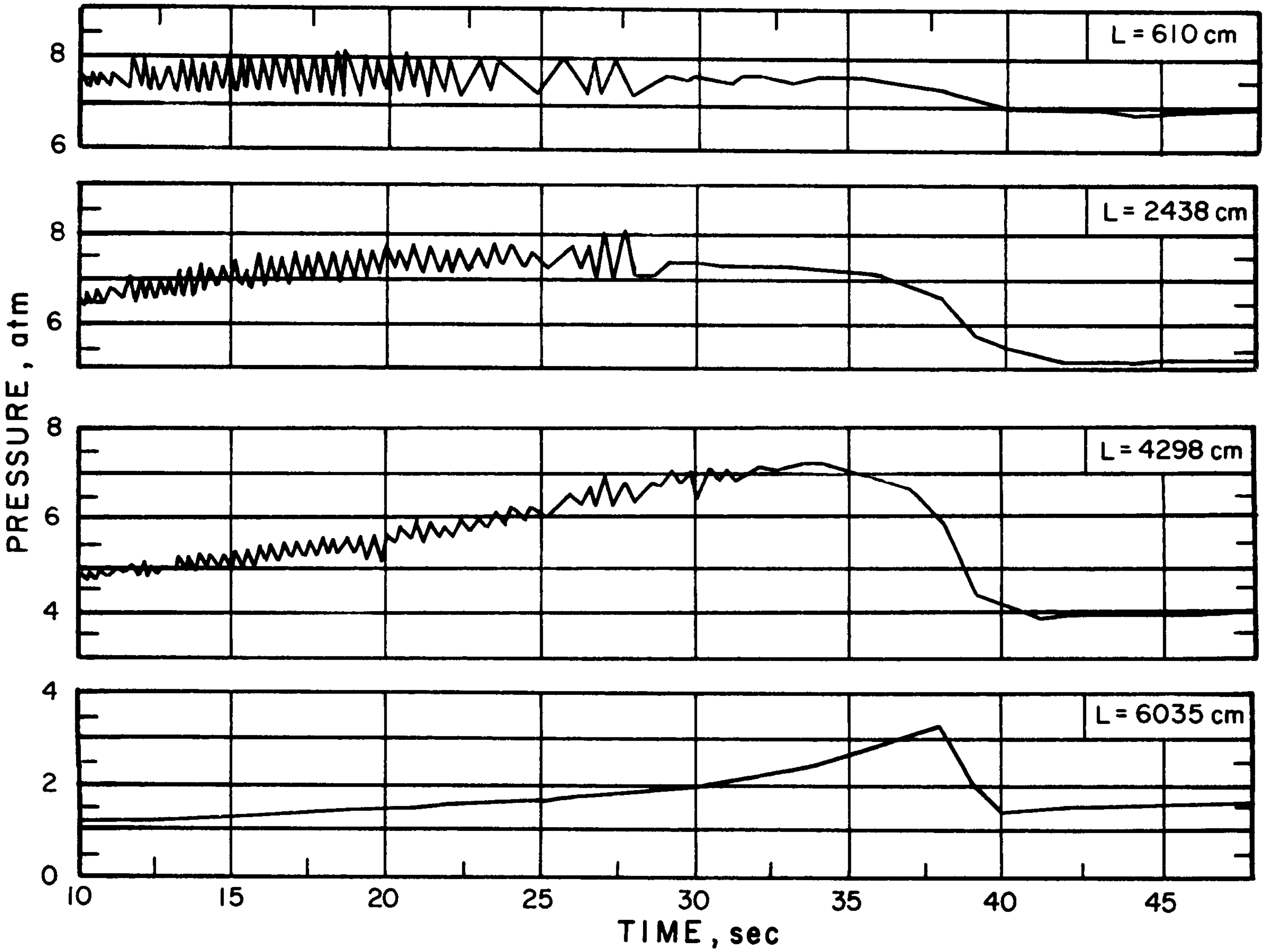


Fig. 23 Line pressure history with subcooled liquid hydrogen at a driving pressure of 7.6 atm using the ball valve.

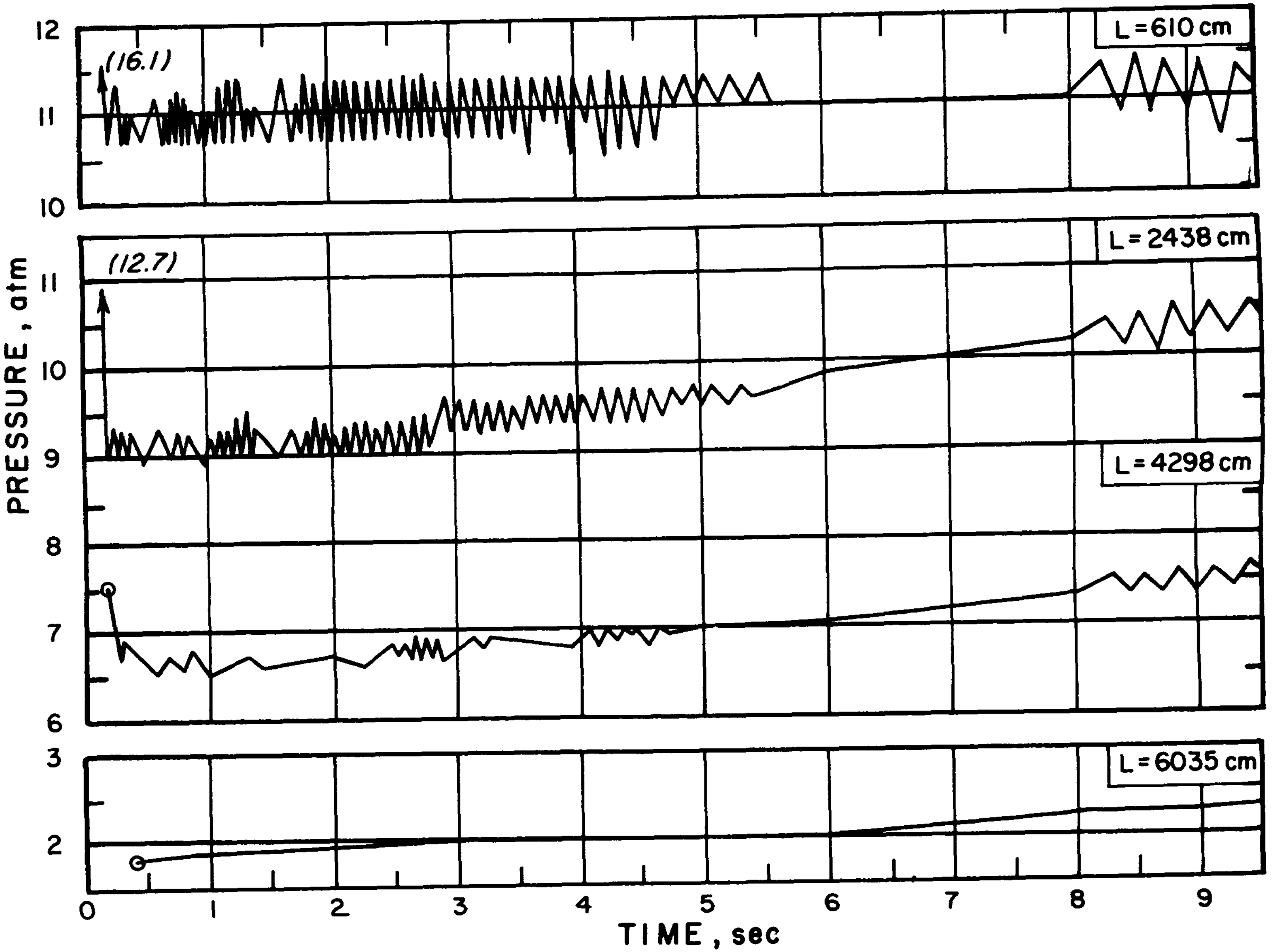


Fig. 24 Line pressure history with subcooled liquid hydrogen at a driving pressure of 11.2 atm using the ball valve.

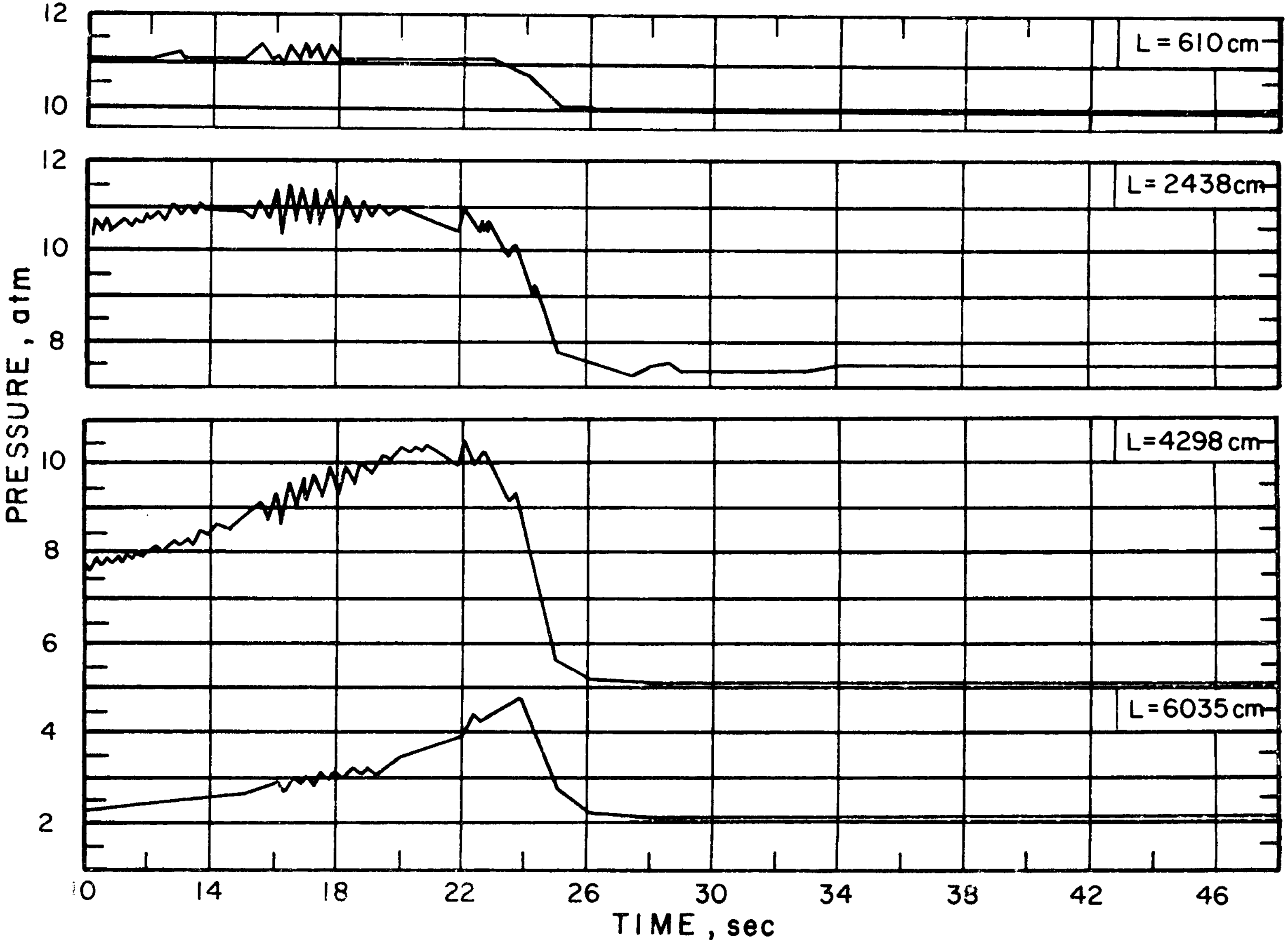


Fig. 25 Line pressure history with subcooled liquid hydrogen at a driving pressure of 11.2 atm using the ball valve.

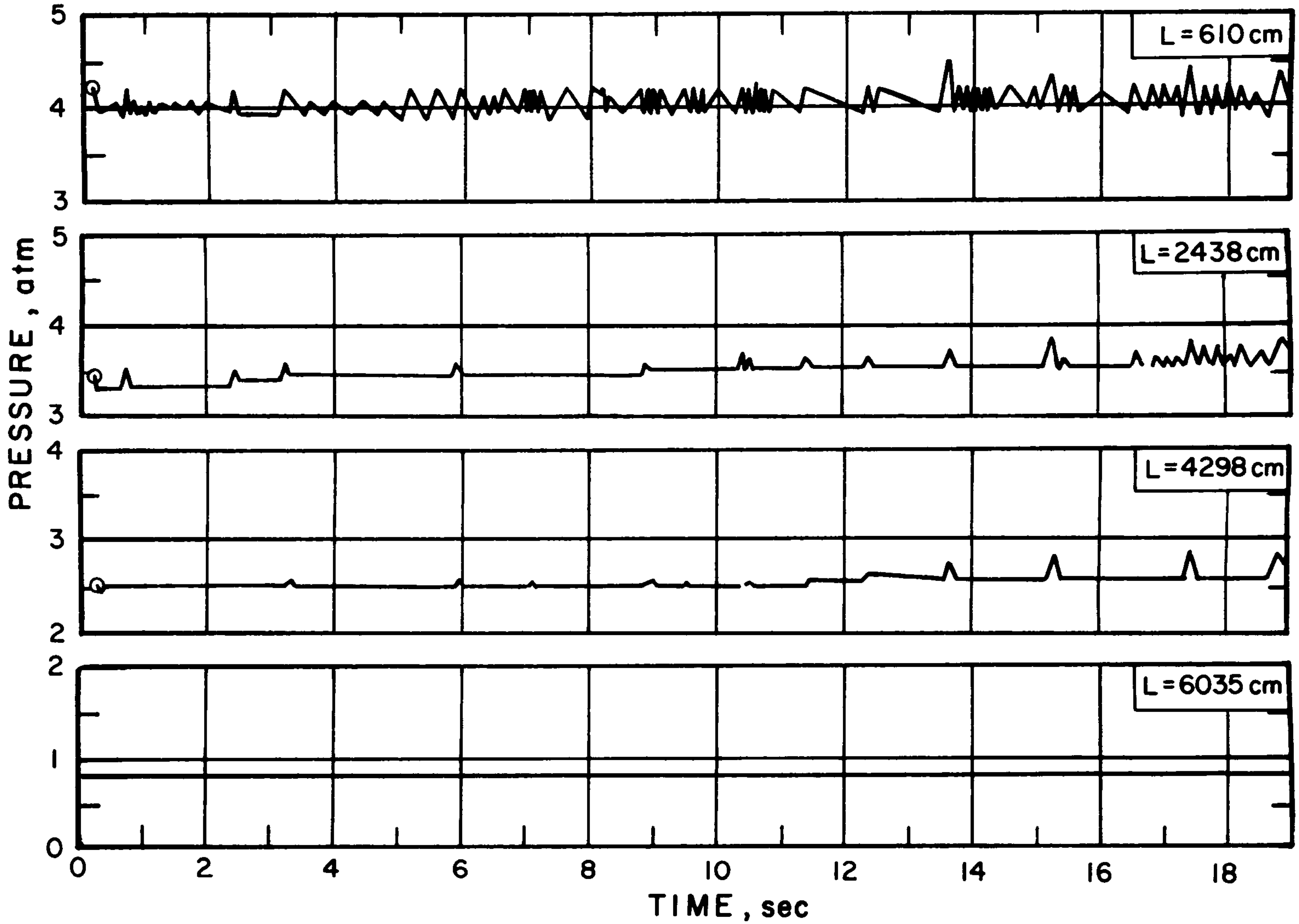


Fig. 26 Line pressure history with subcooled liquid hydrogen at a driving pressure of 4.2 atm using the globe valve.

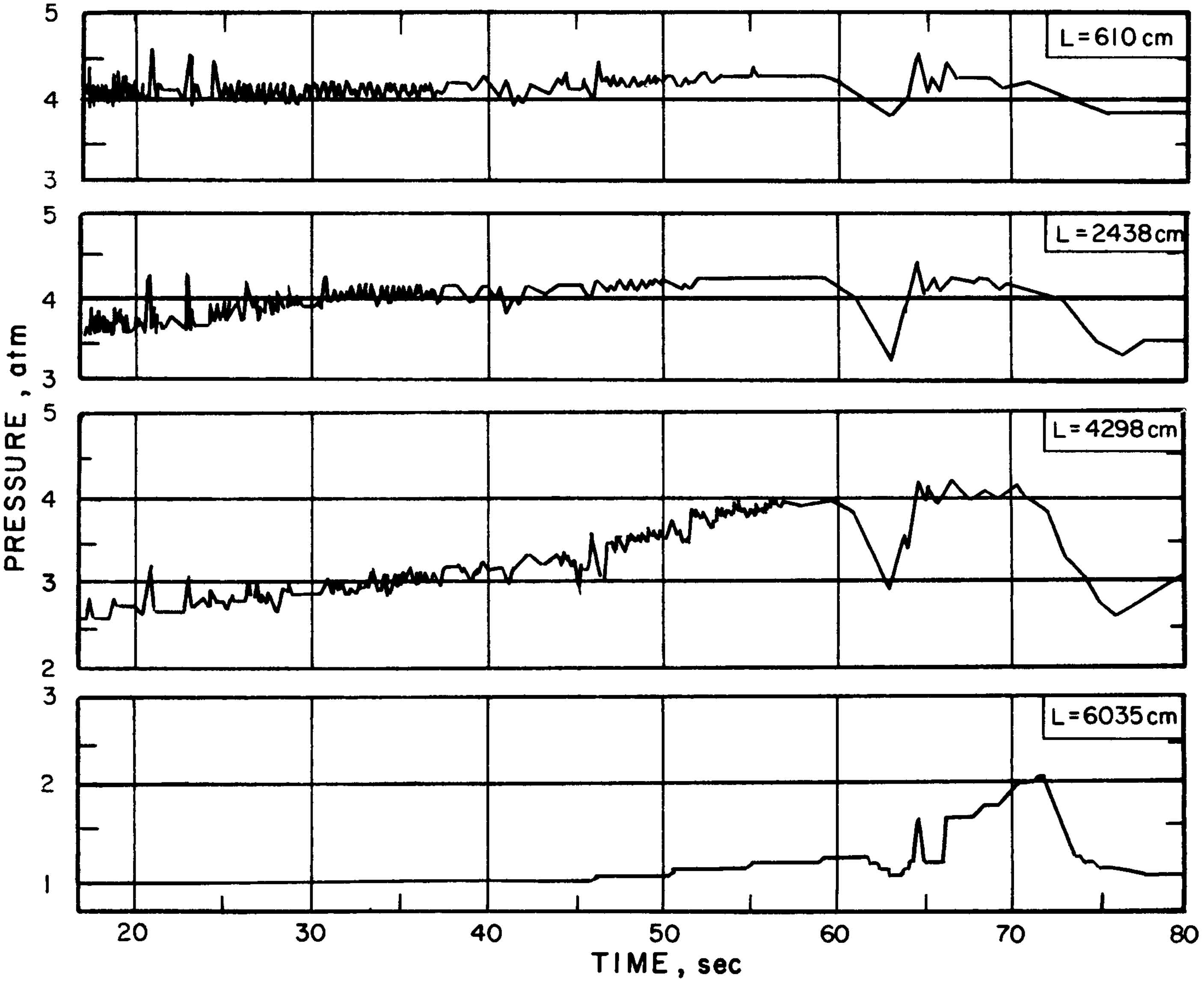


Fig. 27 Line pressure history with subcooled liquid hydrogen at a driving pressure of 4.2 atm using the globe valve.

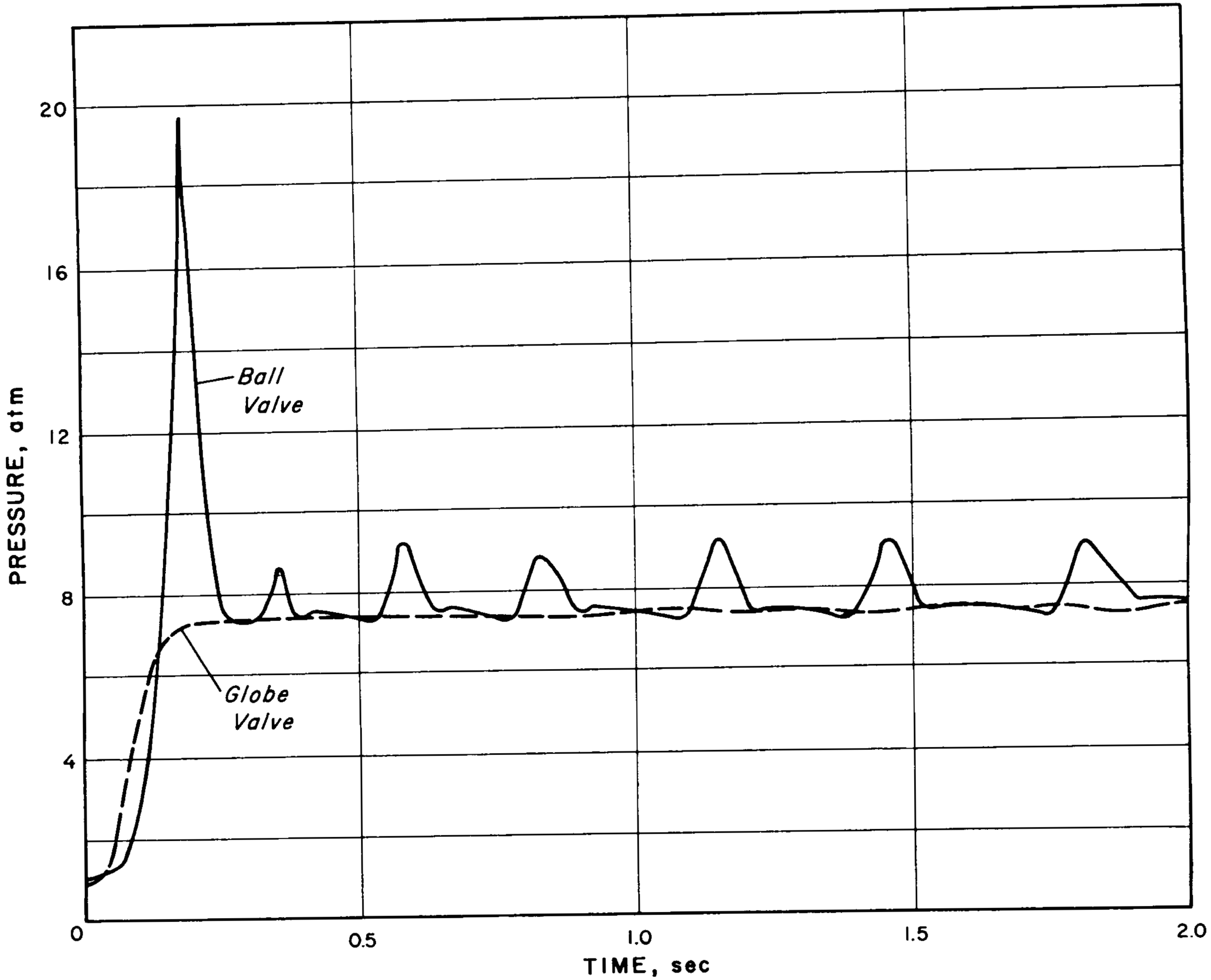


Fig. 28 Comparison of line pressure histories measured using the ball valve and the globe valve with subcooled liquid hydrogen at a driving pressure of 7.6 atm.

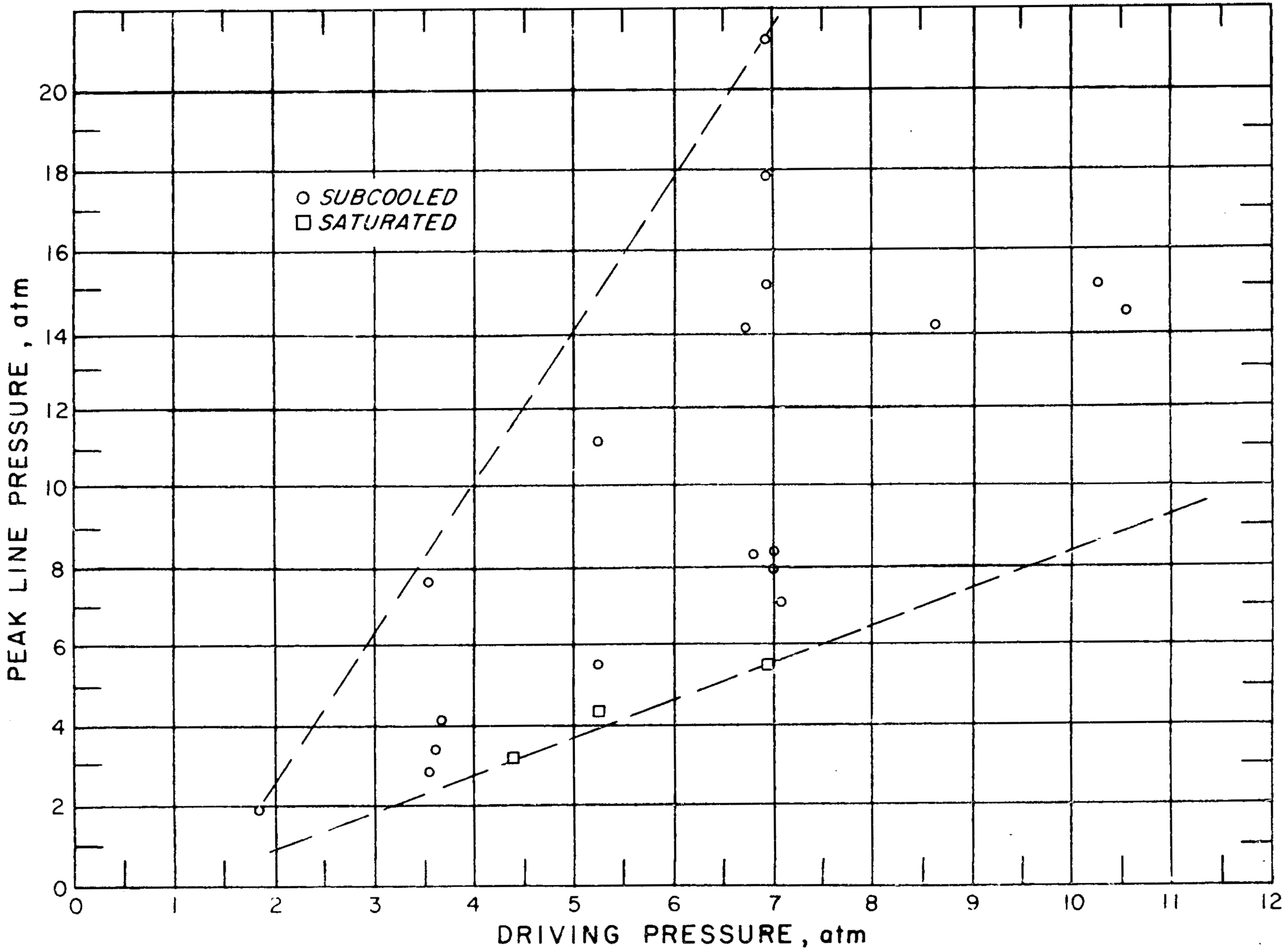


Fig. 29 The effect of driving pressure on peak line pressure with liquid hydrogen using the ball valve.

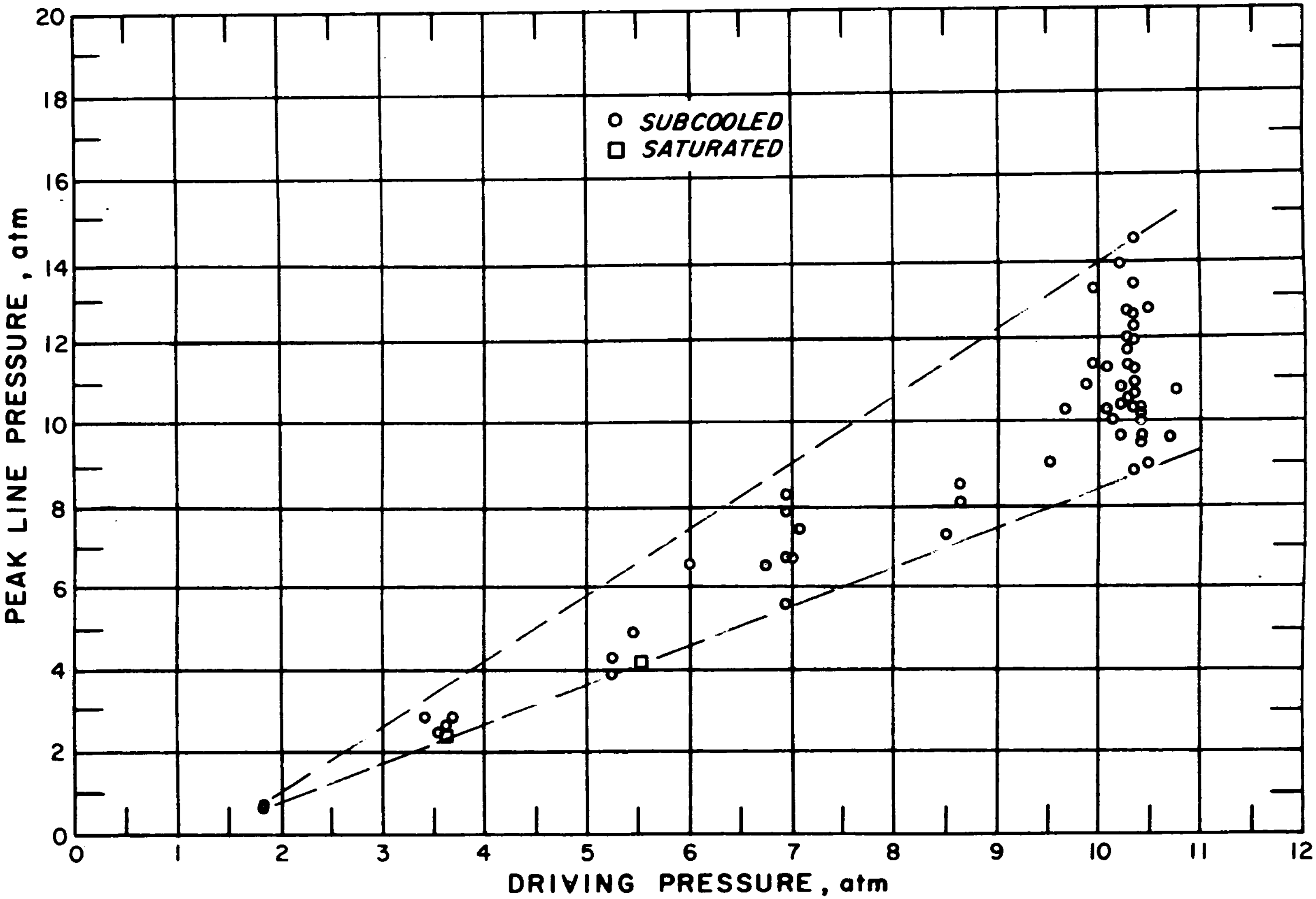


Fig. 30 The effect of driving pressure on peak line pressure with Liquid hydrogen using the globe valve.

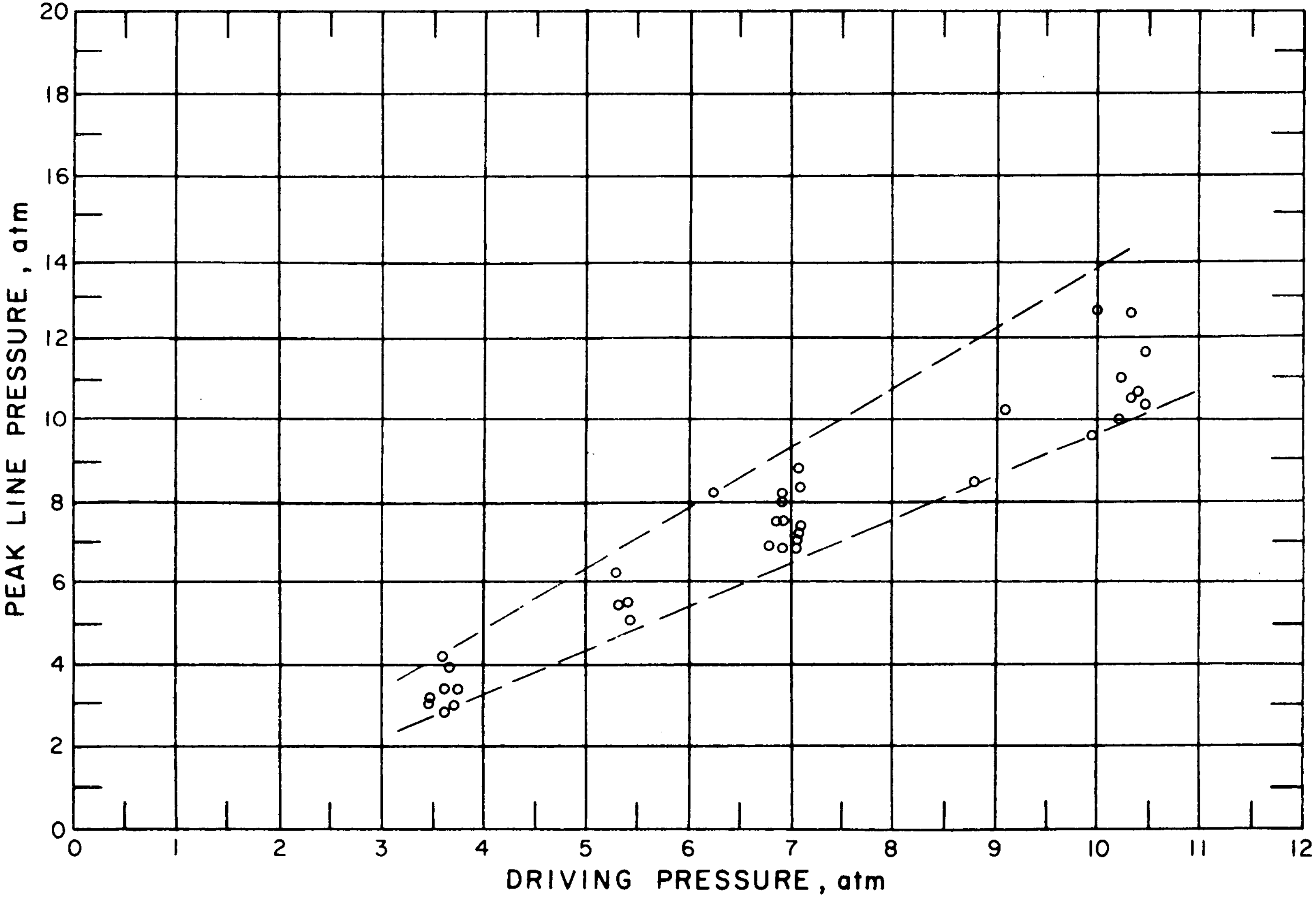


Fig. 31 The effect of driving pressure on peak line pressure with liquid hydrogen using the gate valve.

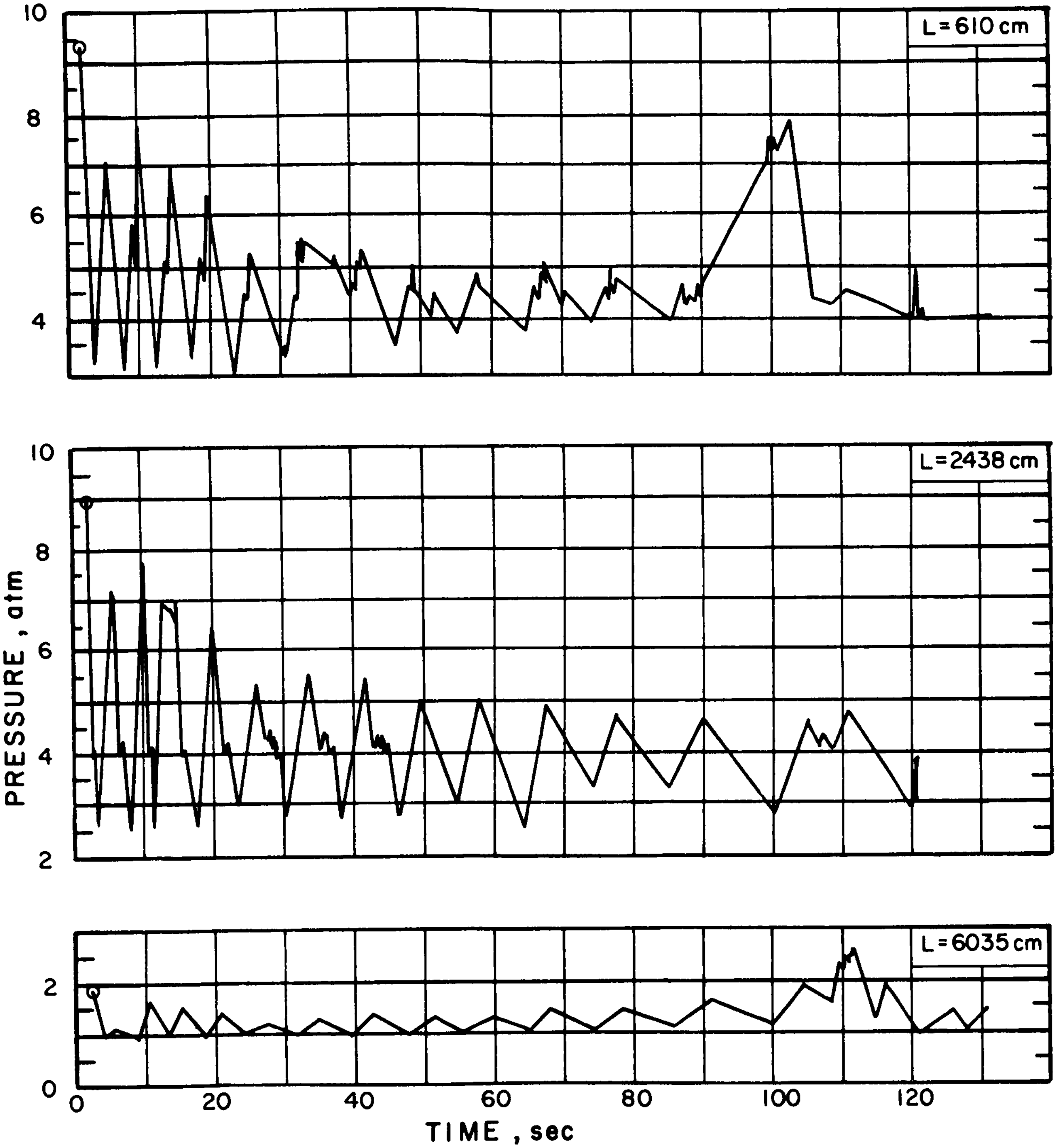


Fig. 32 Line pressure history with subcooled liquid nitrogen at a driving pressure of 4.2 atm using the globe valve.

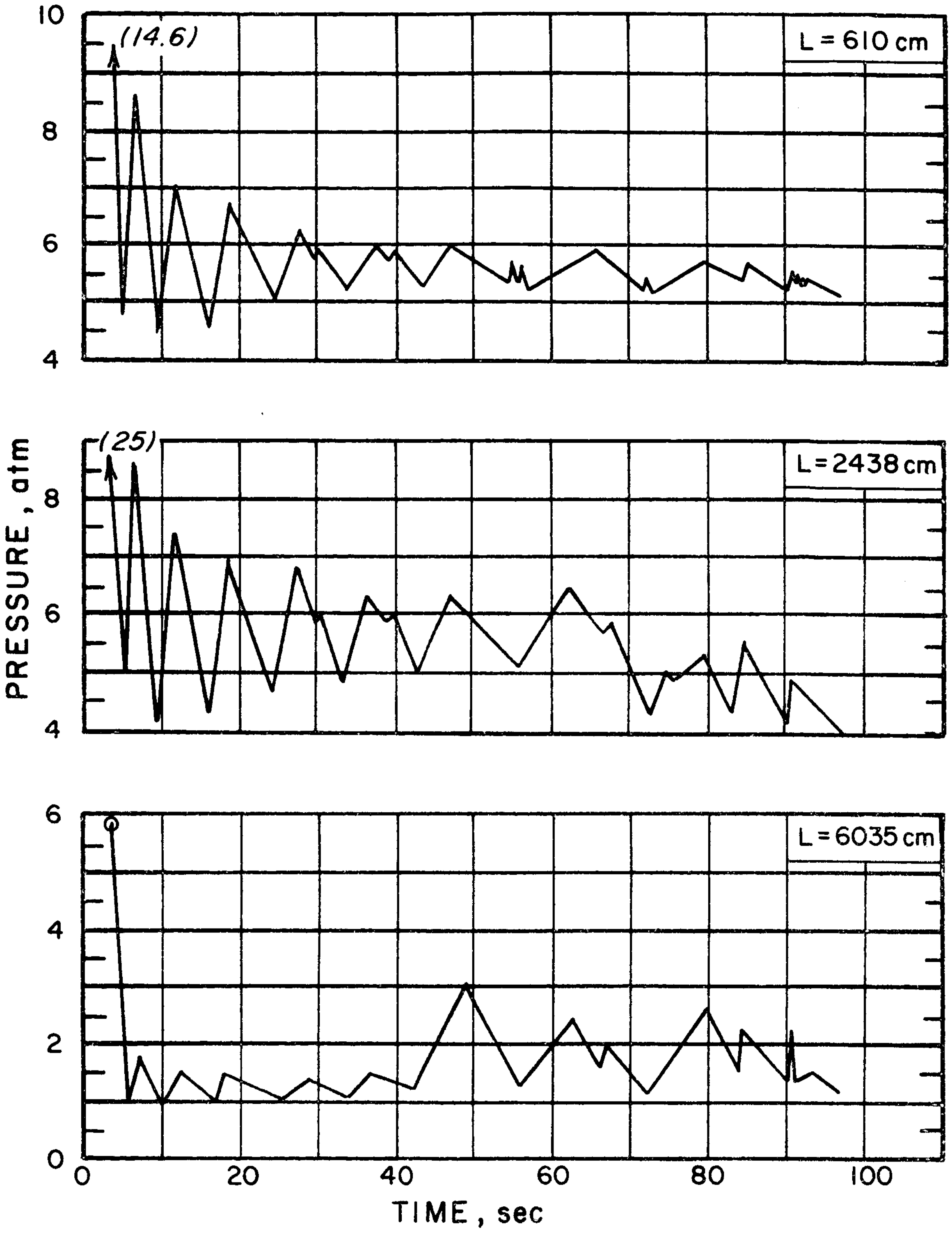


Fig. 33 Line pressure history with subcooled liquid lnitrogen at a driving pressure of 5.9 atm using the ball valve.

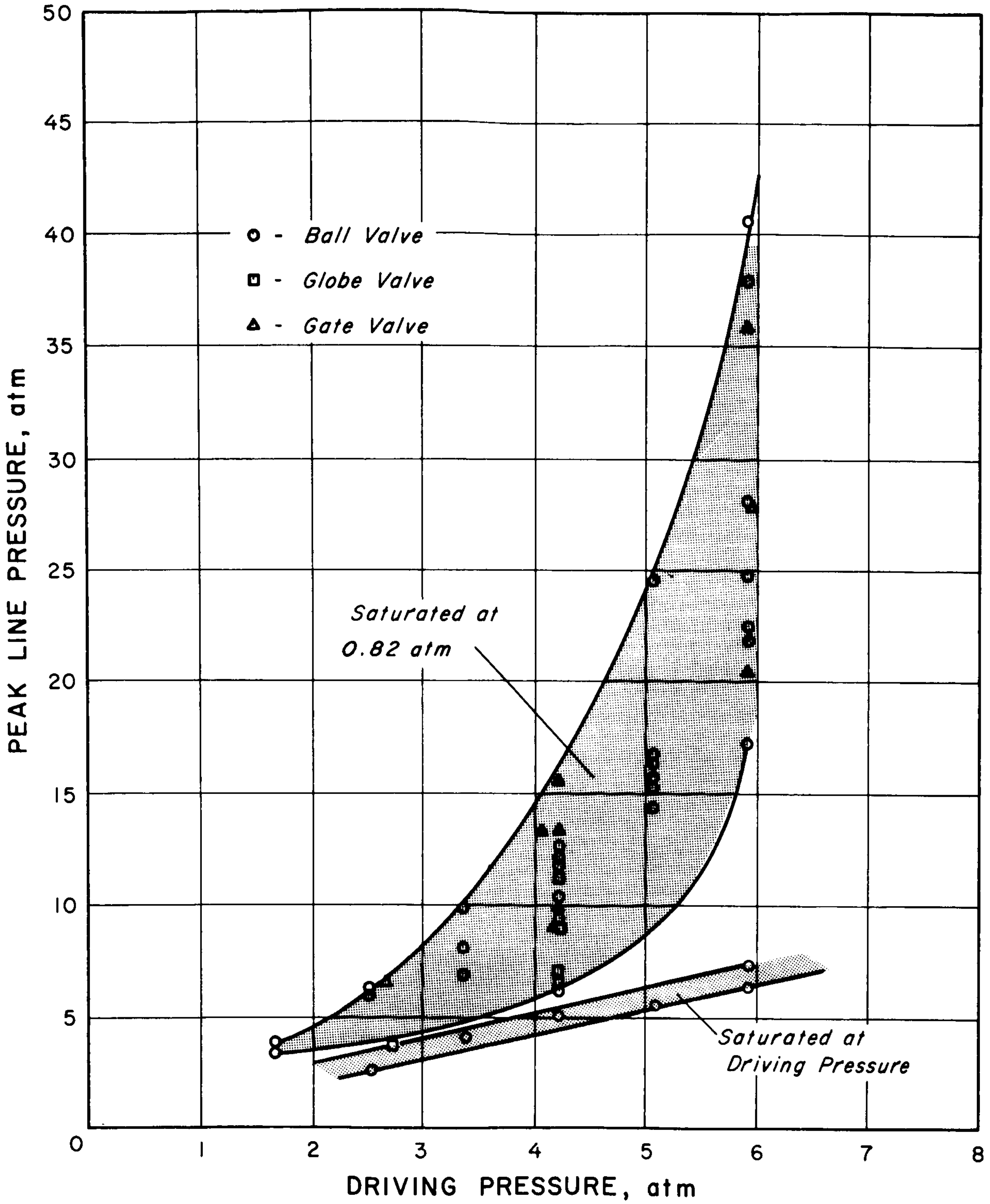


Fig. 34 The effect of driving pressure on peak line pressure with liquid nitrogen.

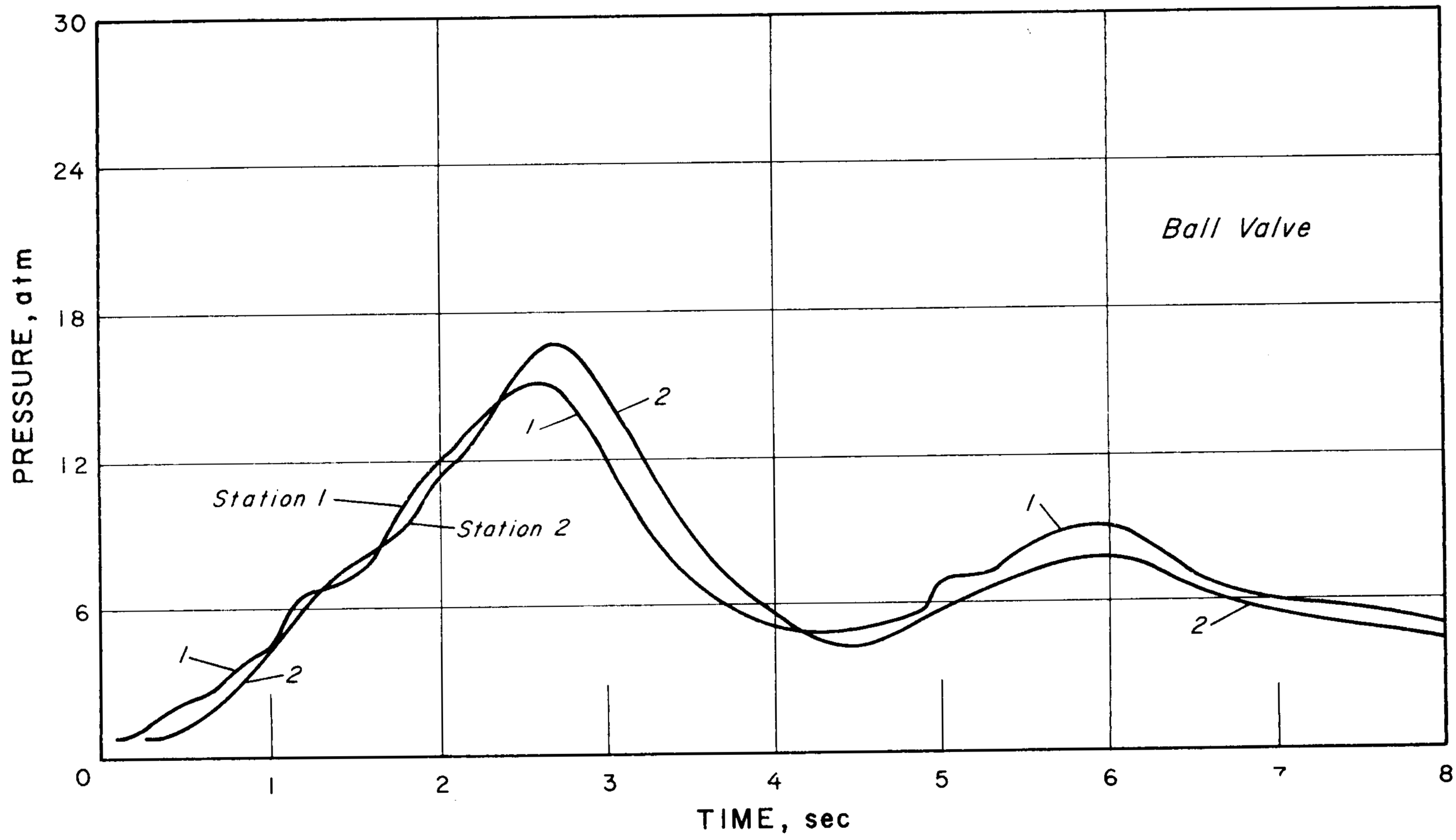


Fig. 35 Line pressure history with subcooled liquid nitrogen at a driving pressure of 5.1 atm using the ball valve.

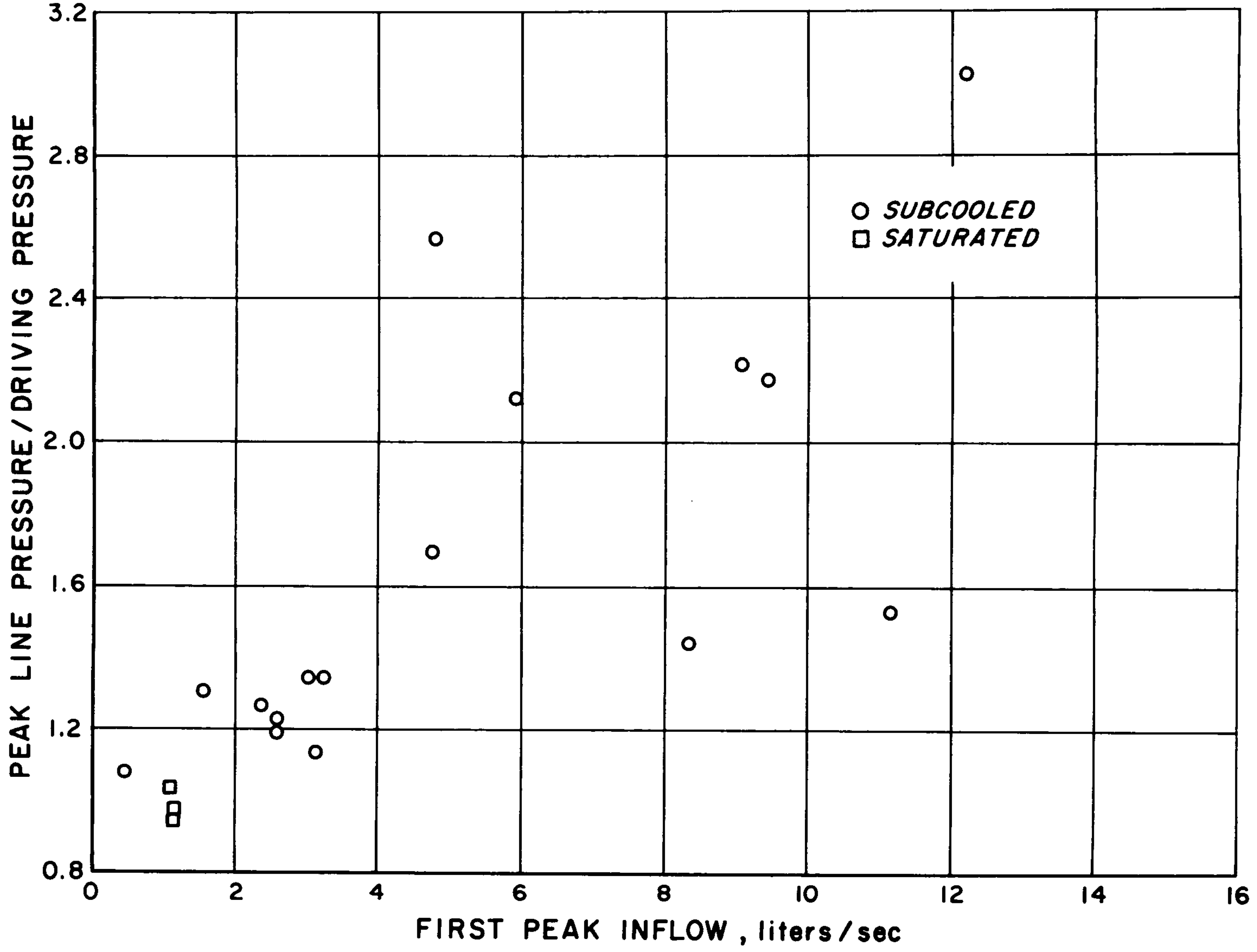
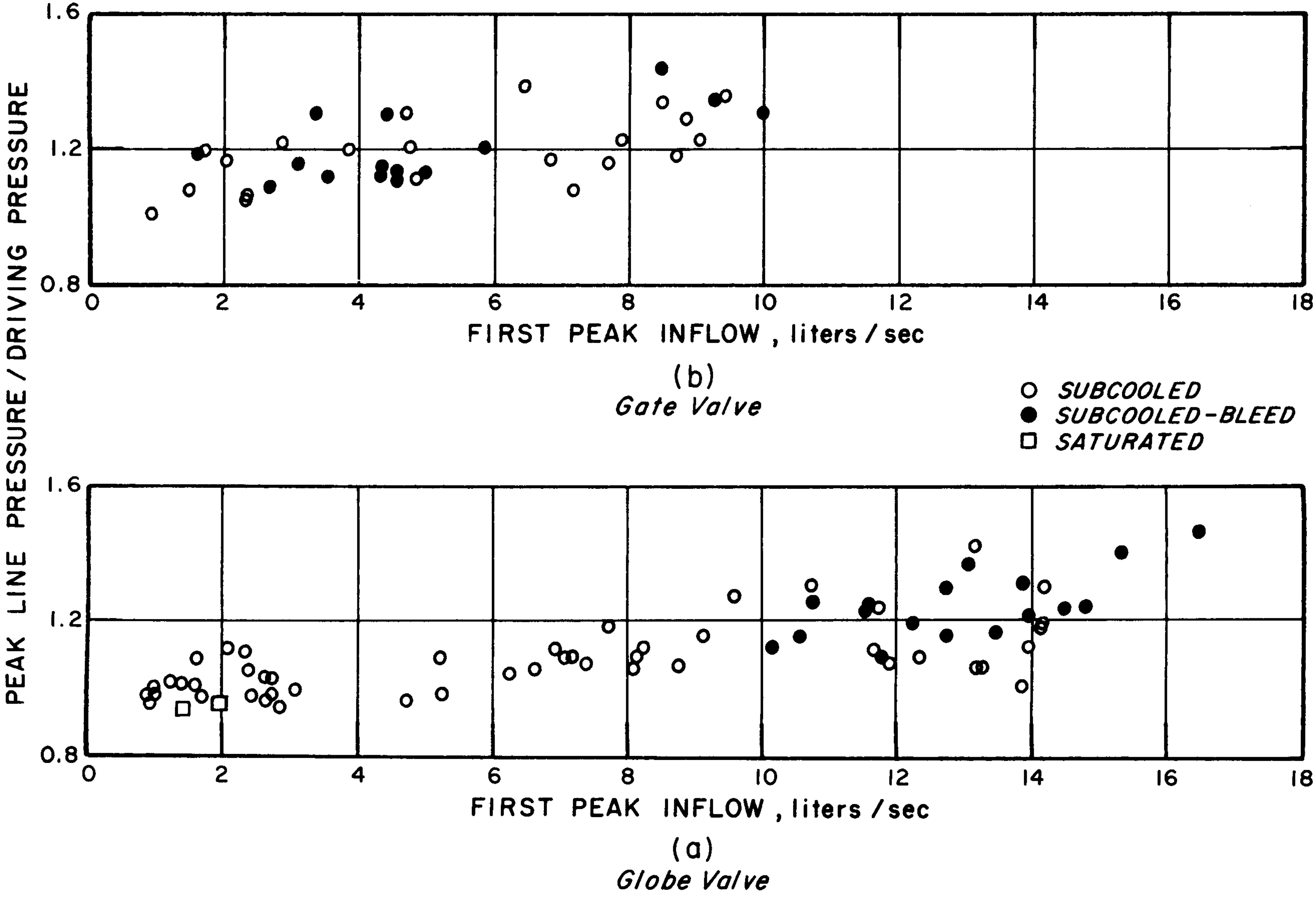


Fig. 36 The effect of peak inflow on peak line pressure with liquid hydrogen using the ball valve.



(b)
Gate Valve

(a)
Globe Valve

Fig. 37 The effect of peak inflow on peak line pressure with liquid hydrogen.

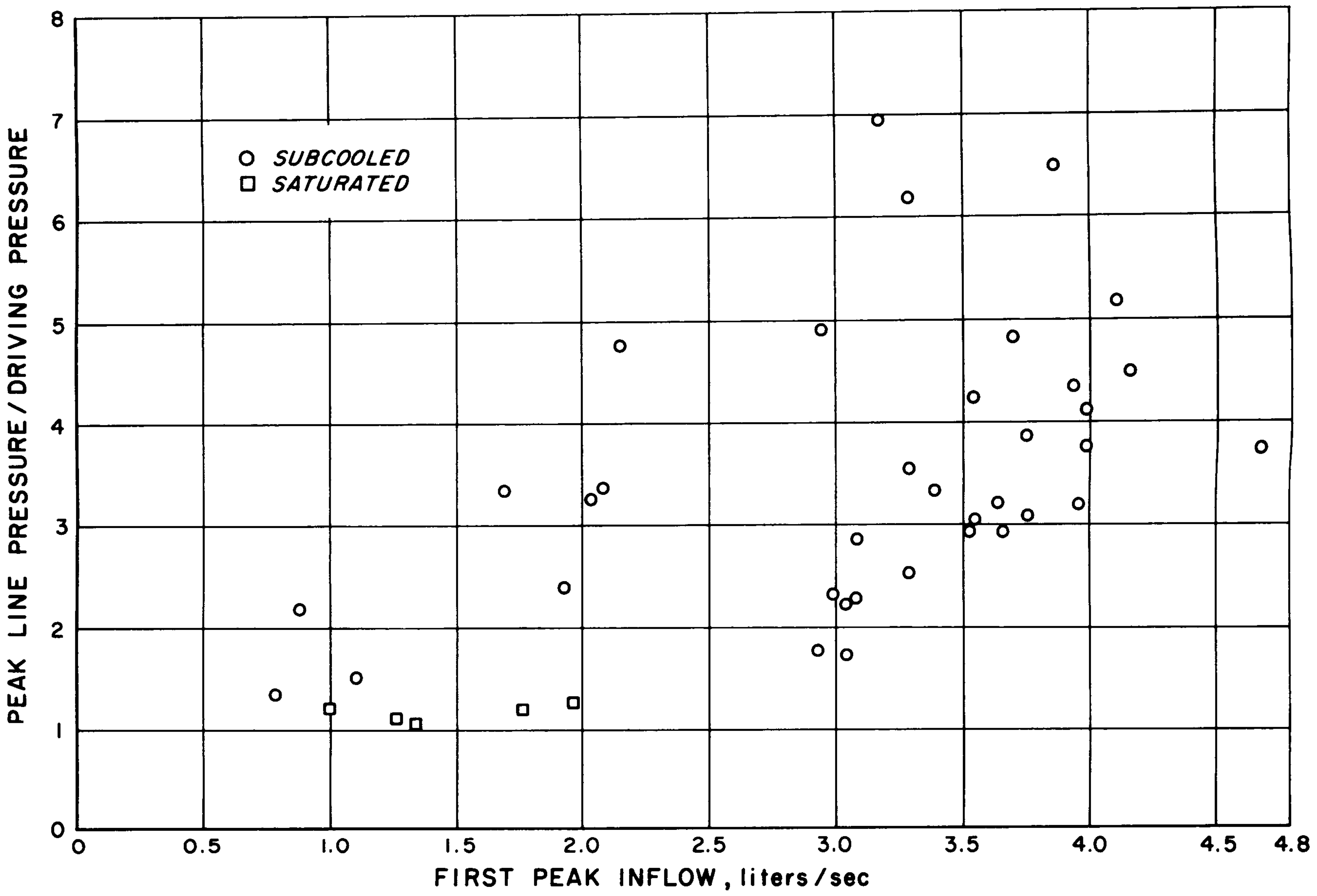


Fig. 38 The effect of peak inflow on peak line pressure with liquid nitrogen.

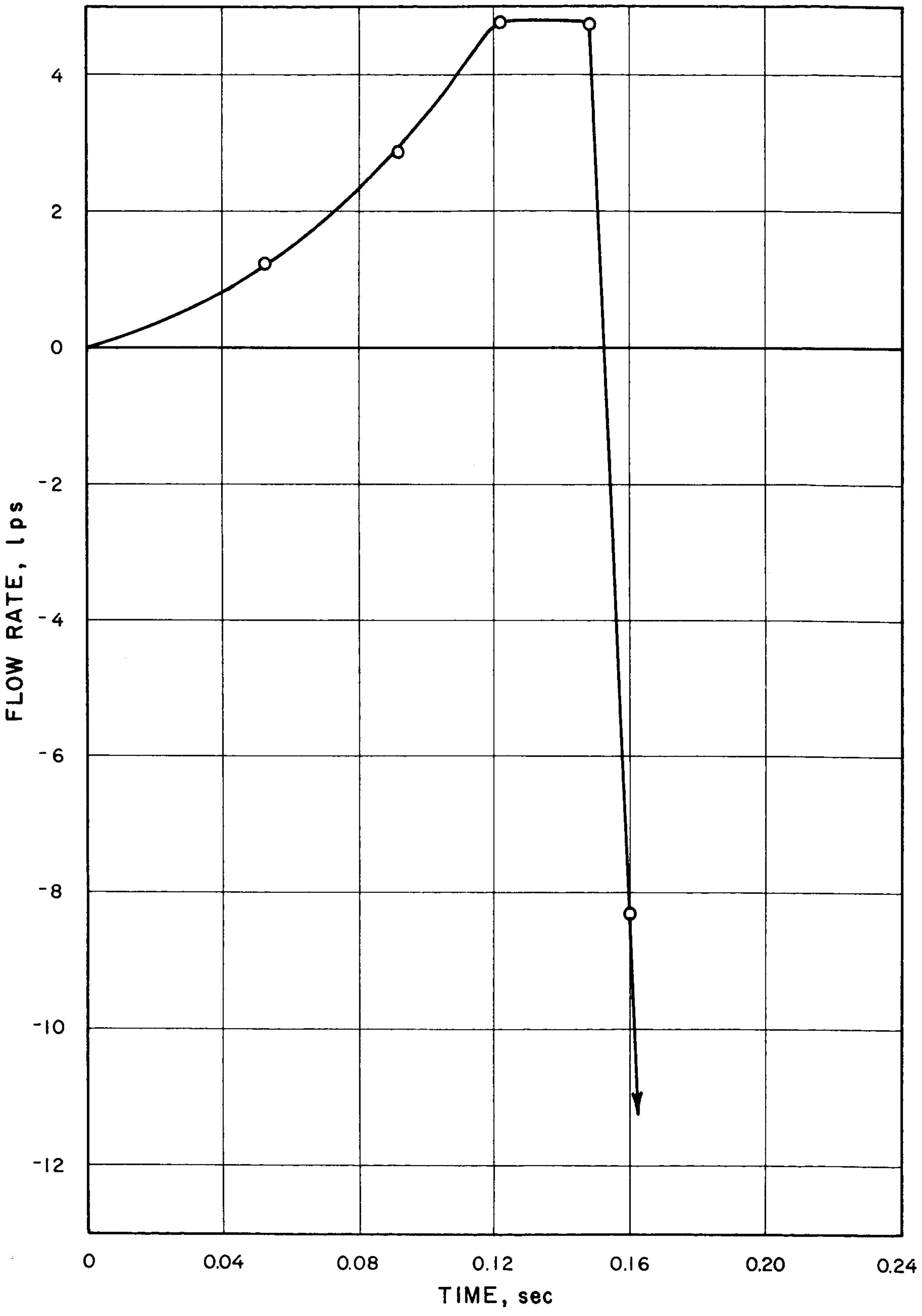


Fig. 39 Initial flow rate showing first reversal with subcooled liquid hydrogen at a driving pressure of 7.6 atm using the ball valve.

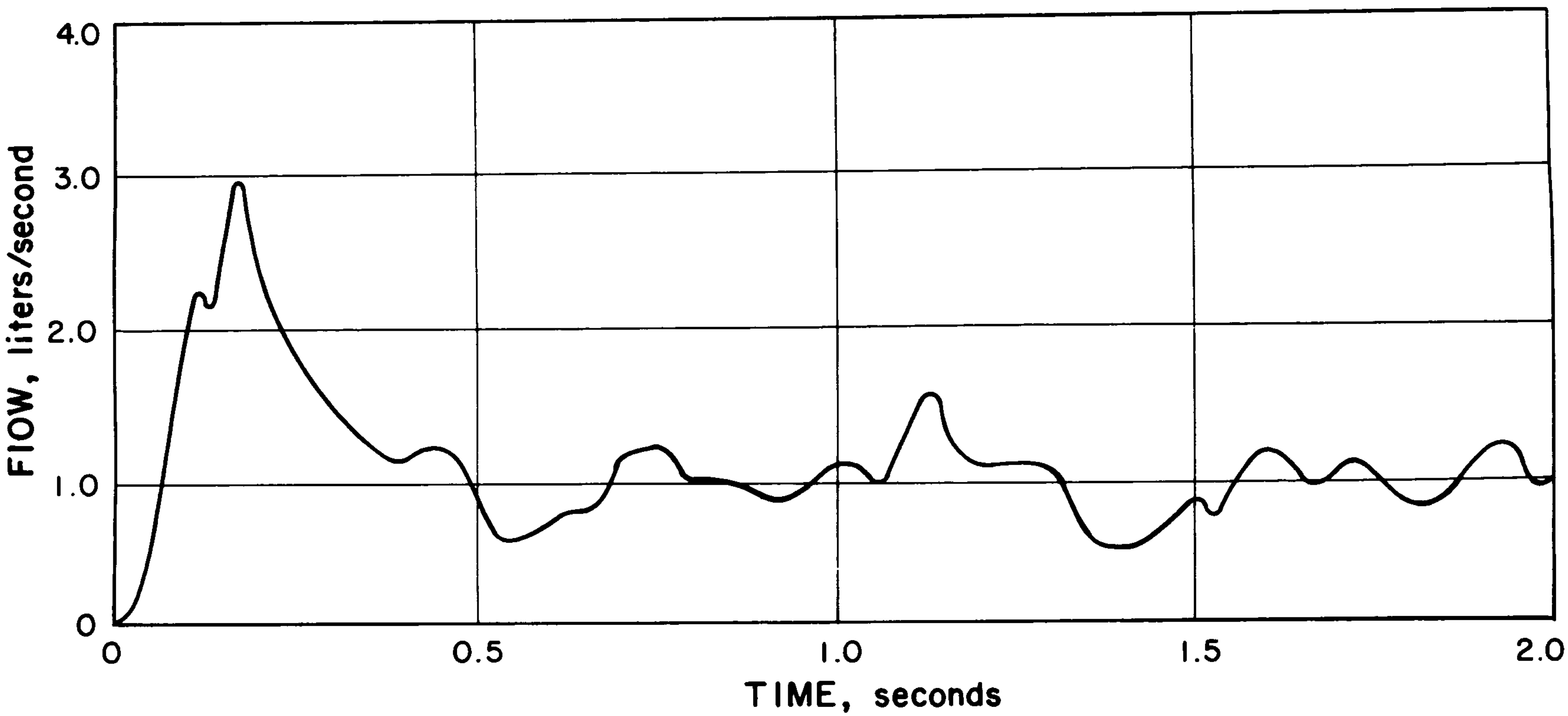


Fig. 40 Initial flow rate with no reversal with subcooled liquid hydrogen at a driving pressure of 7.6 atm using the globe valve.

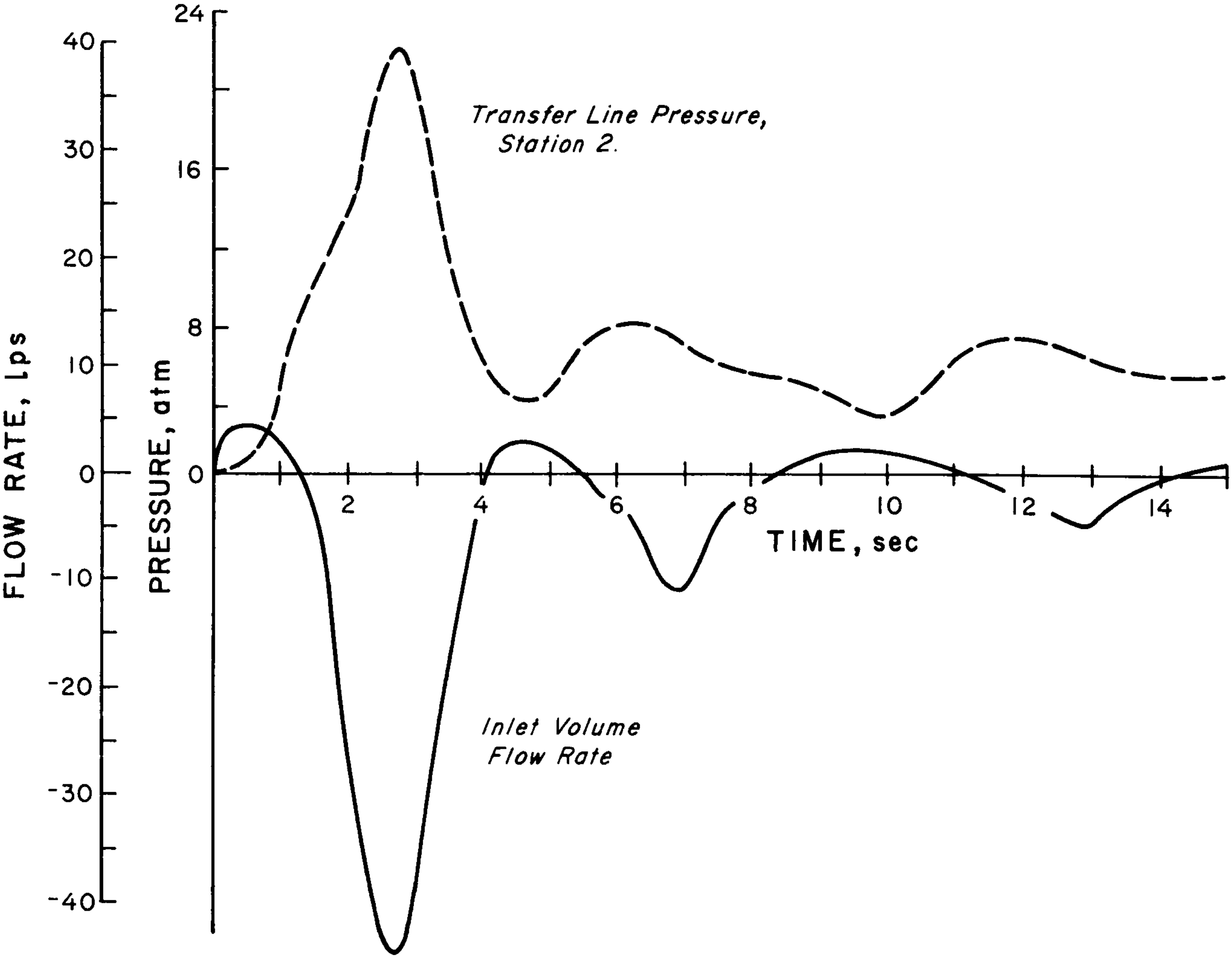


Fig. 41 Initial flow rate, showing three reversals, with subcooled liquid nitrogen at a driving pressure of 5.9 atm using the ball valve (From [1]).

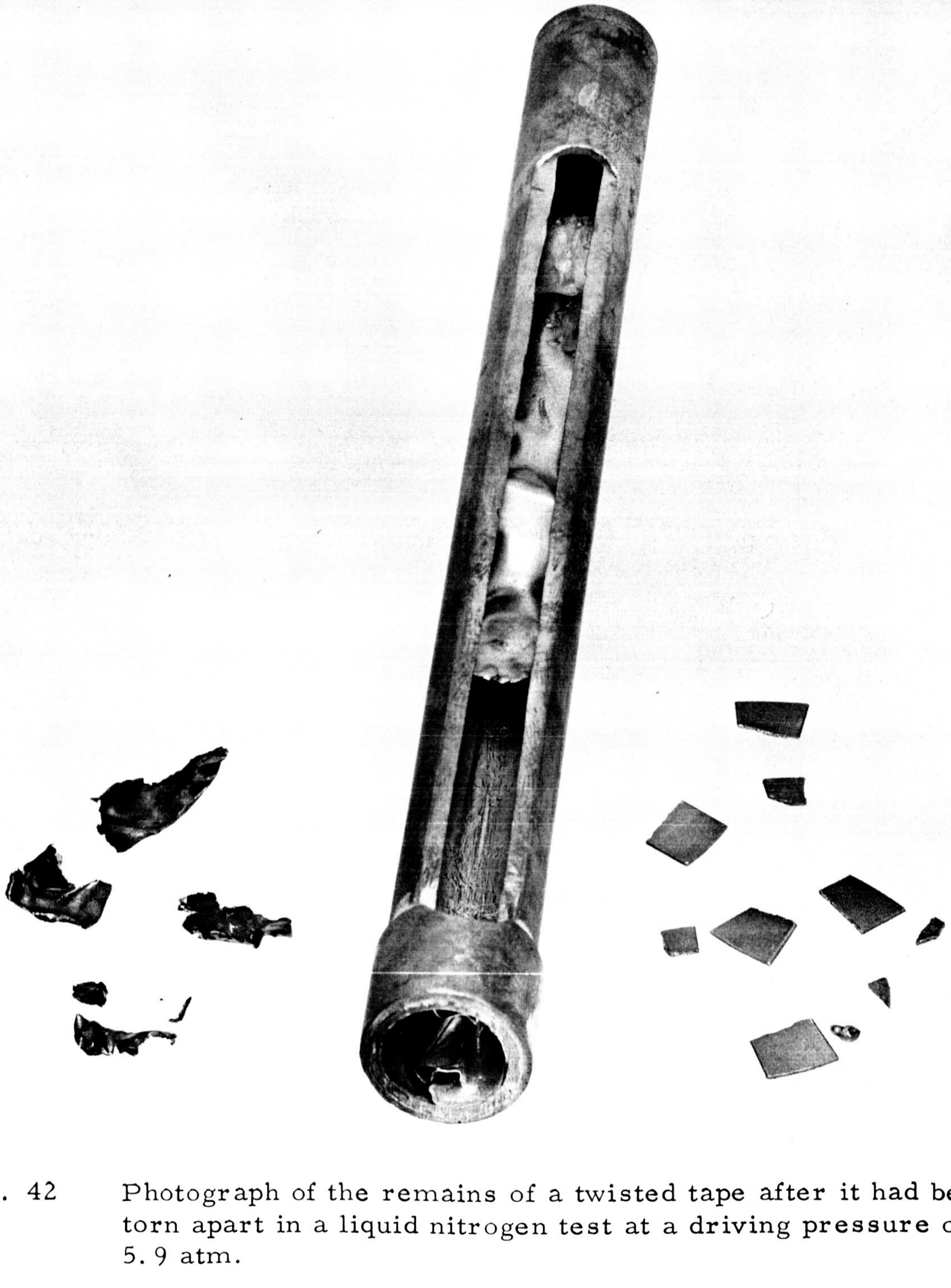
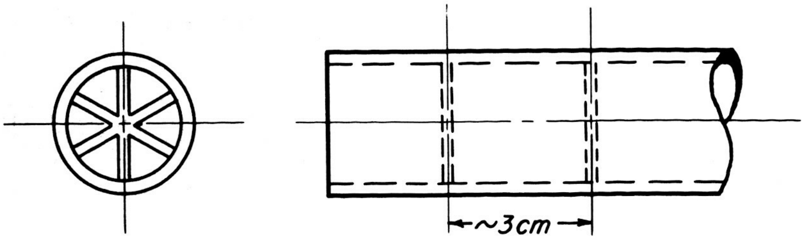
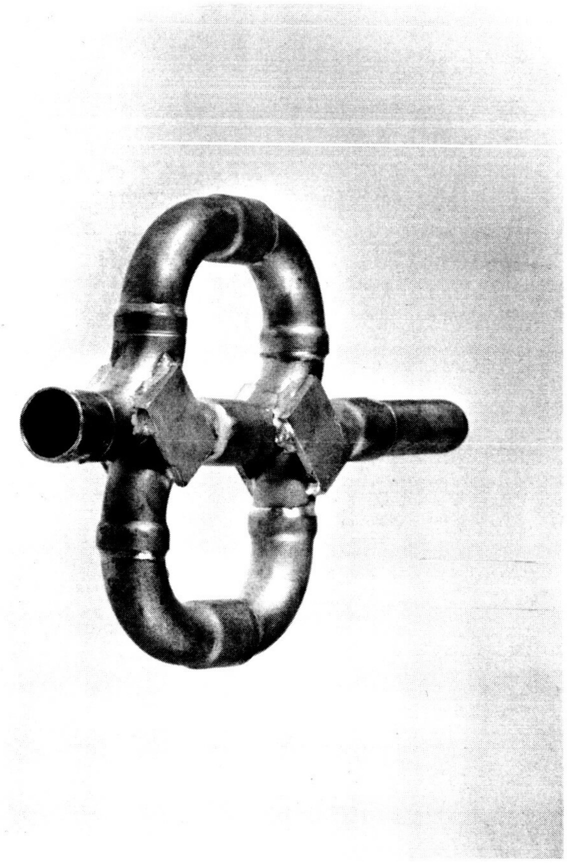


Fig. 42 Photograph of the remains of a twisted tape after it had been torn apart in a liquid nitrogen test at a driving pressure of 5.9 atm.



Wire Crisscross



Eight 90° Elbows

Fig. 43 Photograph and schematic of two flow restrictions.

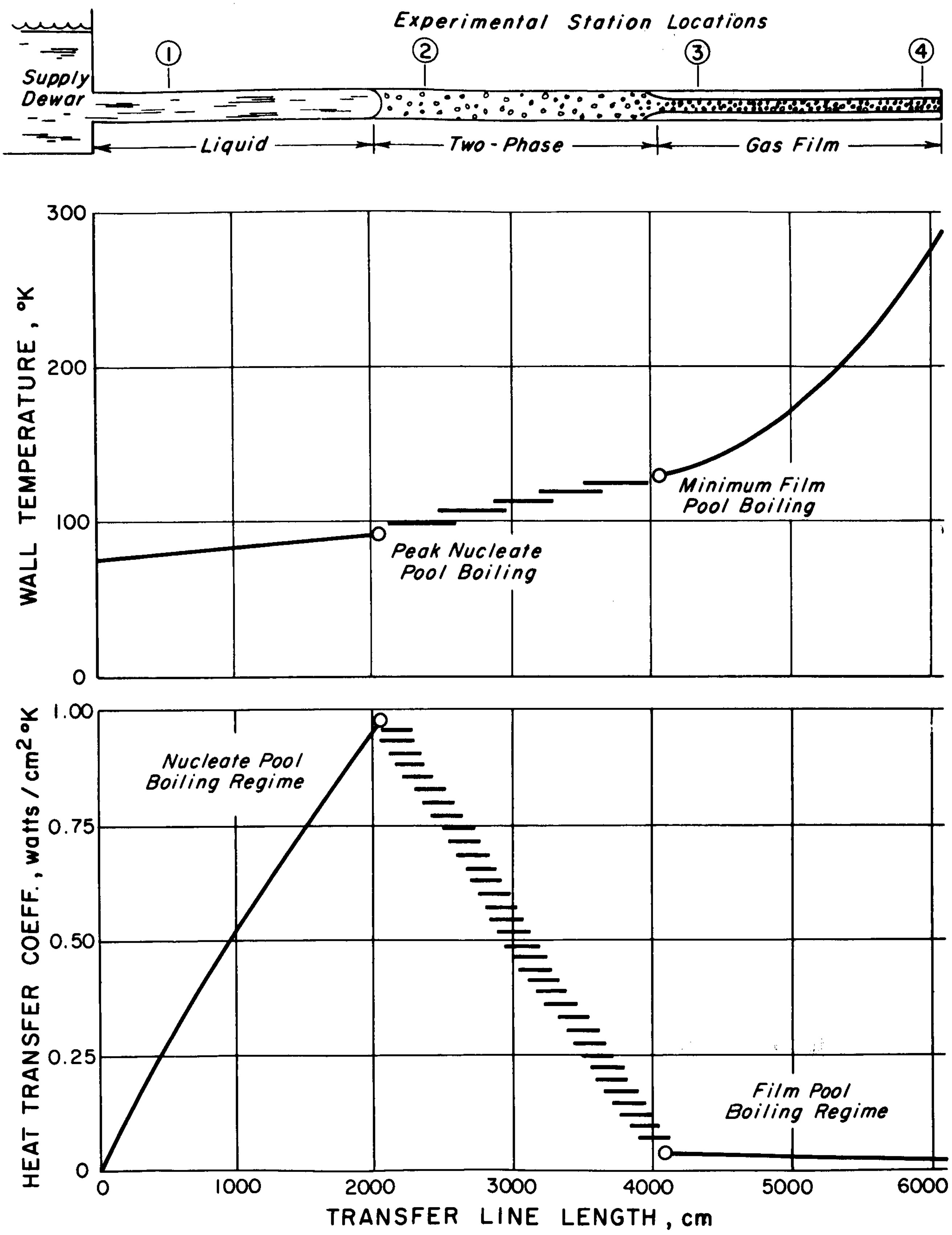


Fig. 44 Schematic of how heat transfer areas were defined.

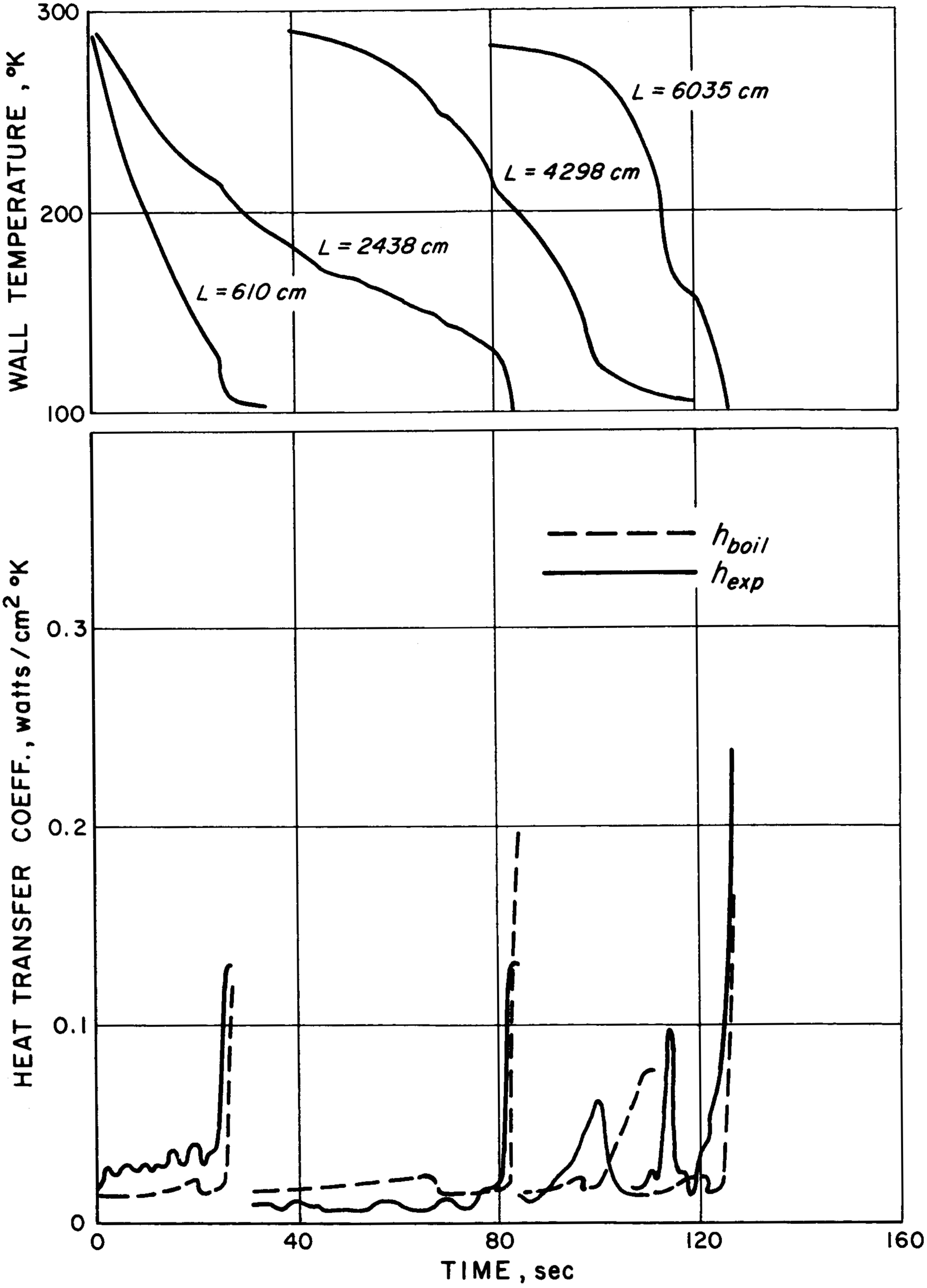


Fig. 45 Heat transfer coefficient as a function of time for subcooled liquid nitrogen at a driving pressure of 5.2 atm.

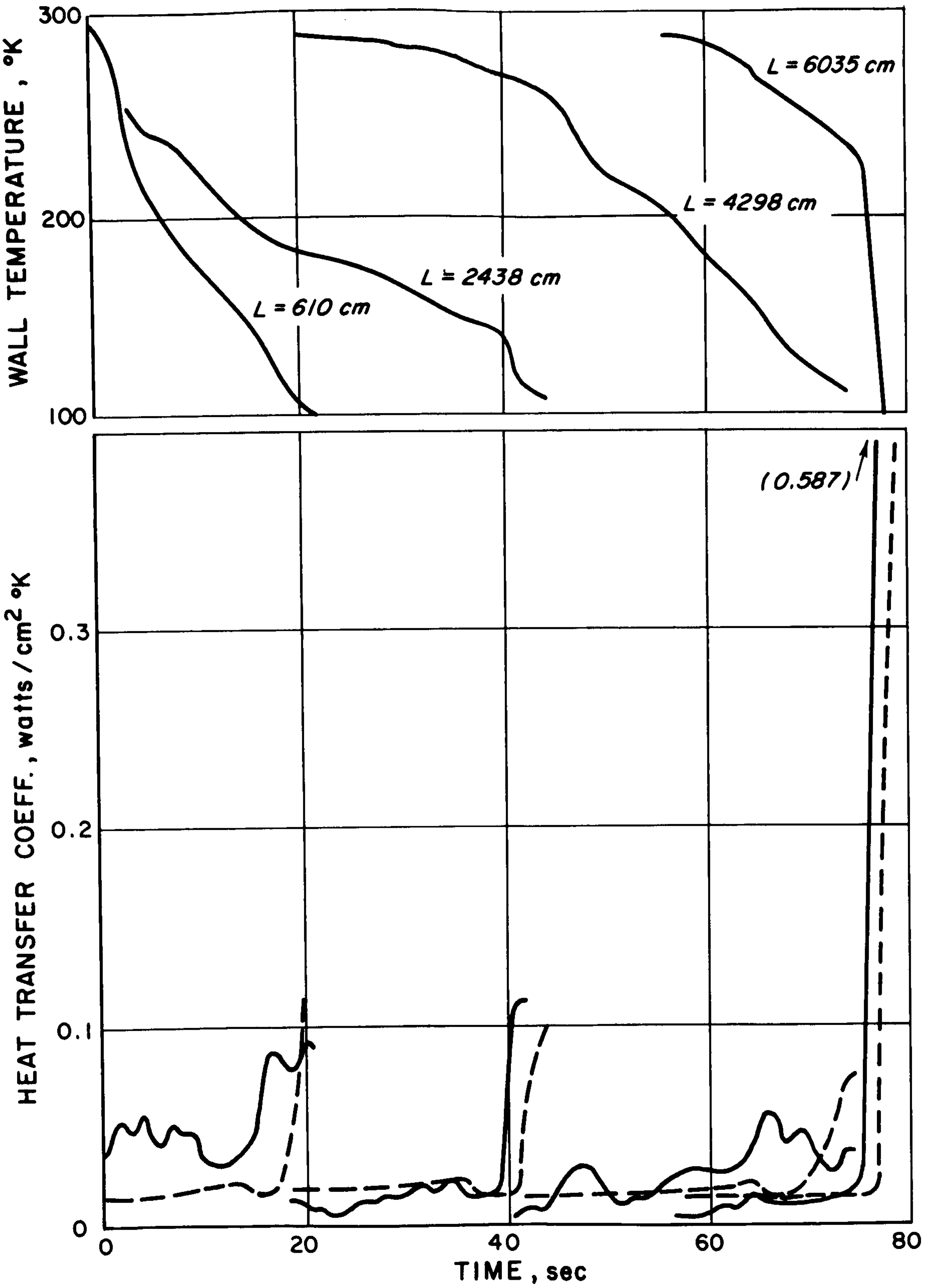


Fig. 46 Heat transfer coefficient as a function of time for subcooled liquid nitrogen at a driving pressure of 5.9 atm.

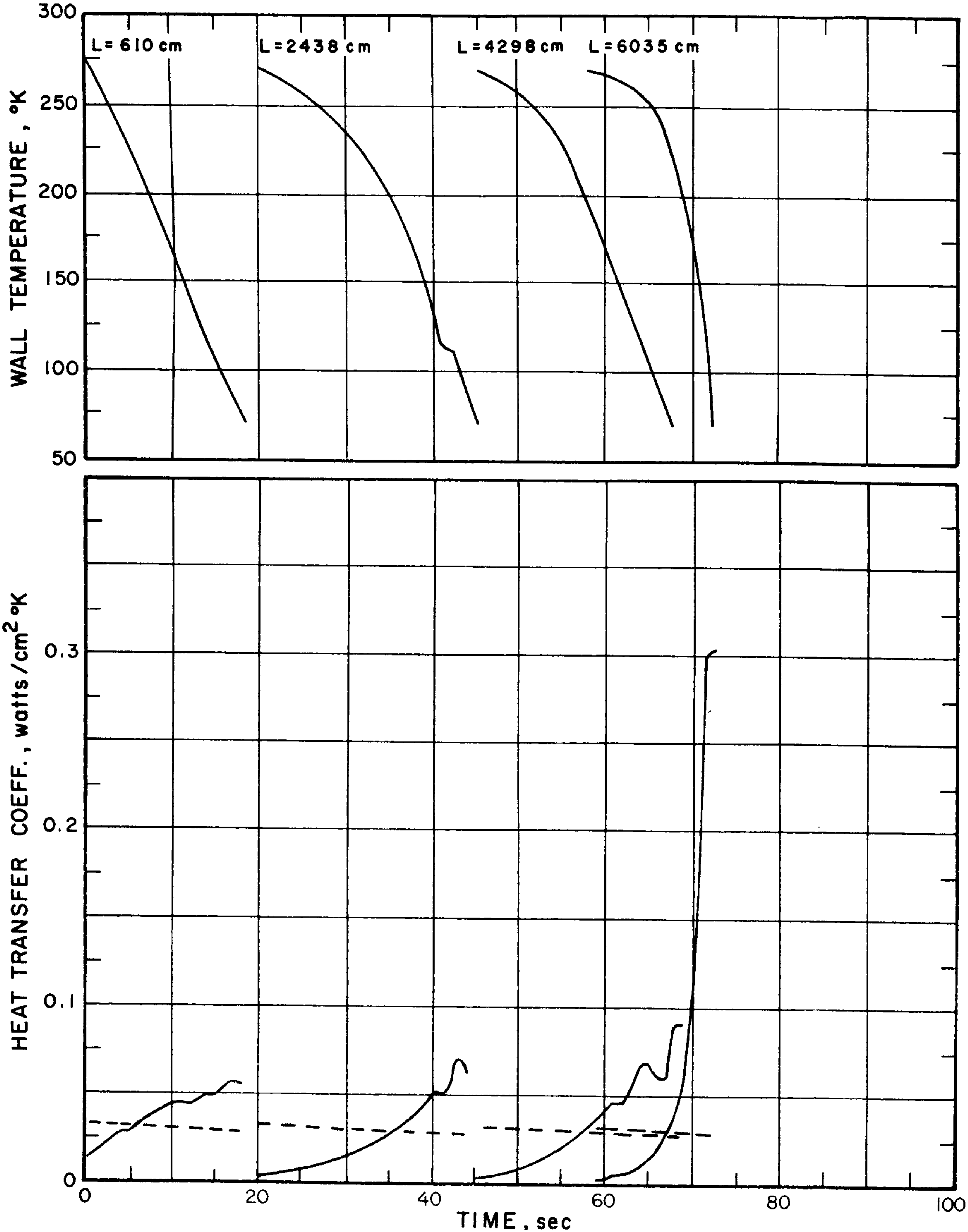


Fig. 47 Heat transfer coefficient as a function of time for subcooled liquid hydrogen at a driving pressure of 4.2 atm.

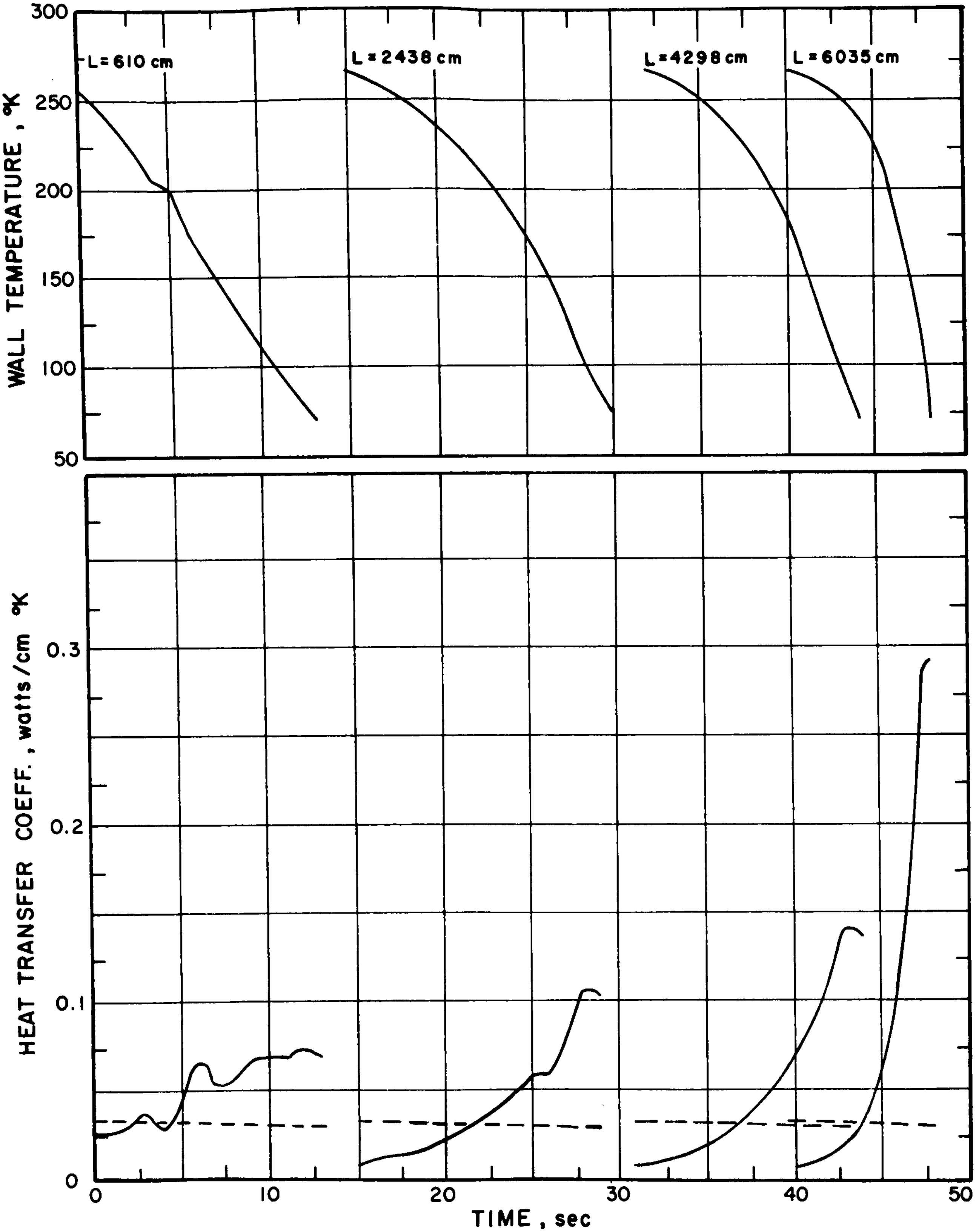


Fig. 48 Heat transfer coefficient as a function of time for subcooled liquid hydrogen at a driving pressure of 5.9 atm.

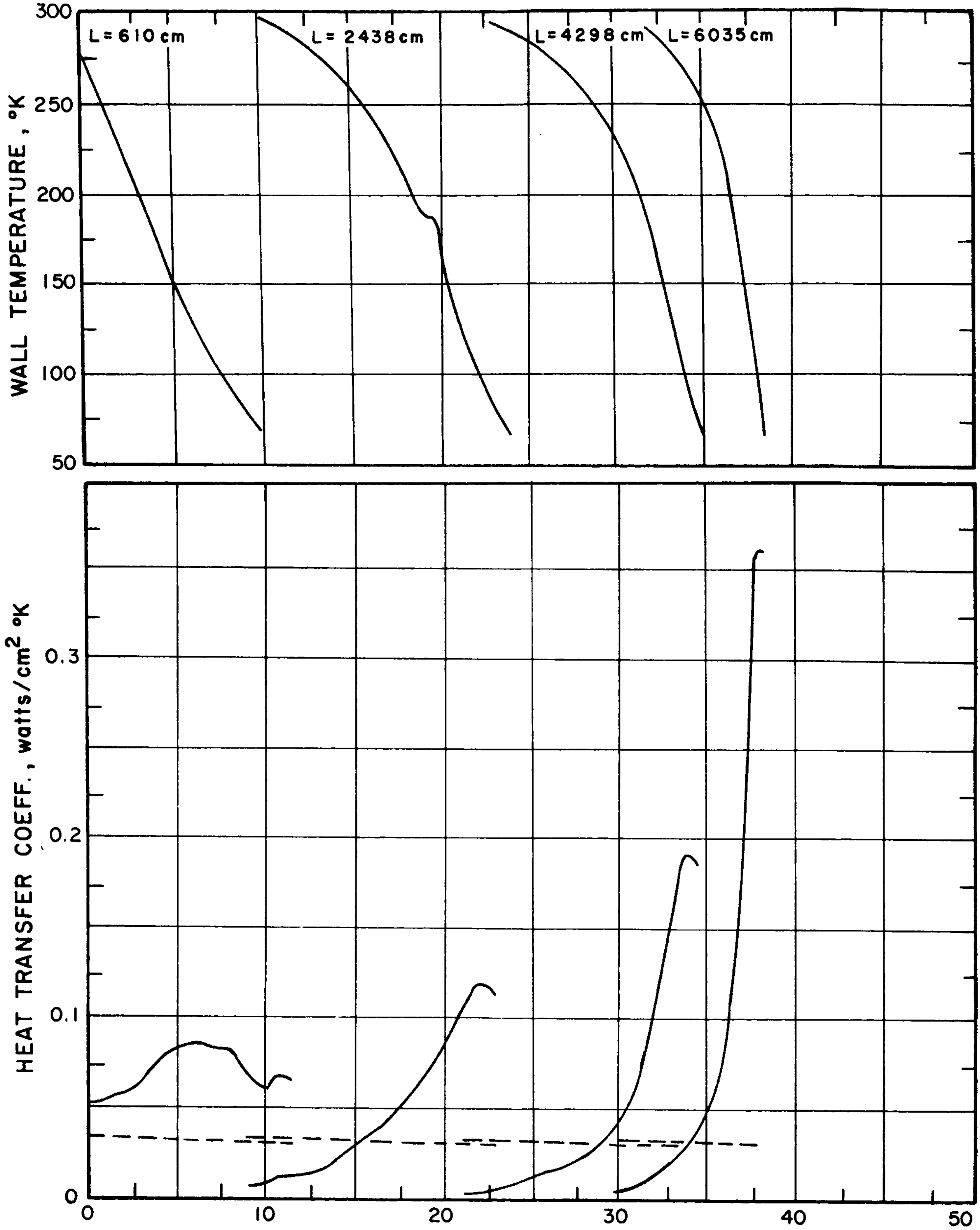


Fig. 49 Heat transfer coefficient as a function of time for subcooled liquid hydrogen at a driving pressure of 7.6 atm.

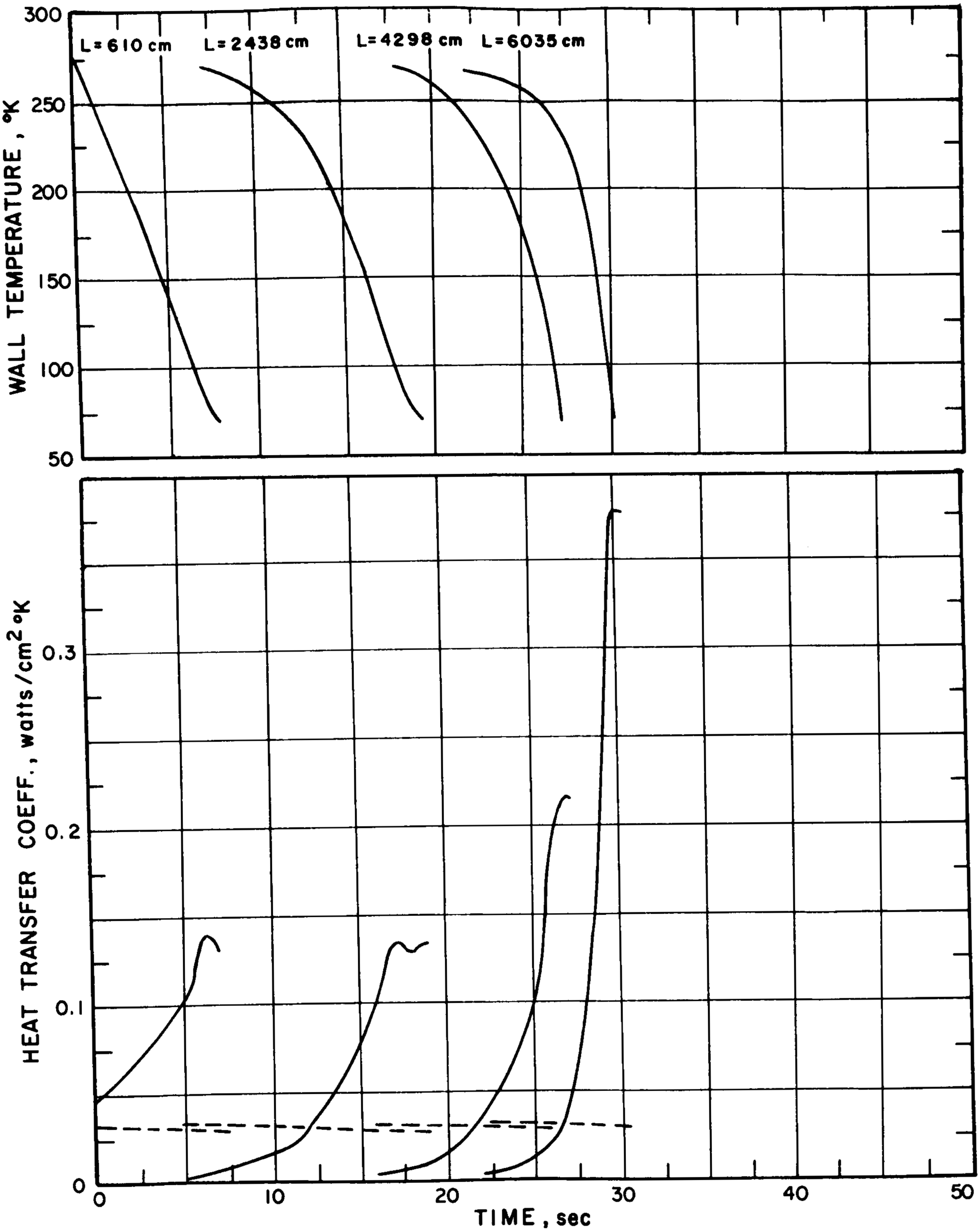


Fig. 50 Heat transfer coefficient as a function of time for subcooled liquid hydrogen at a driving pressure of 9.3 atm.

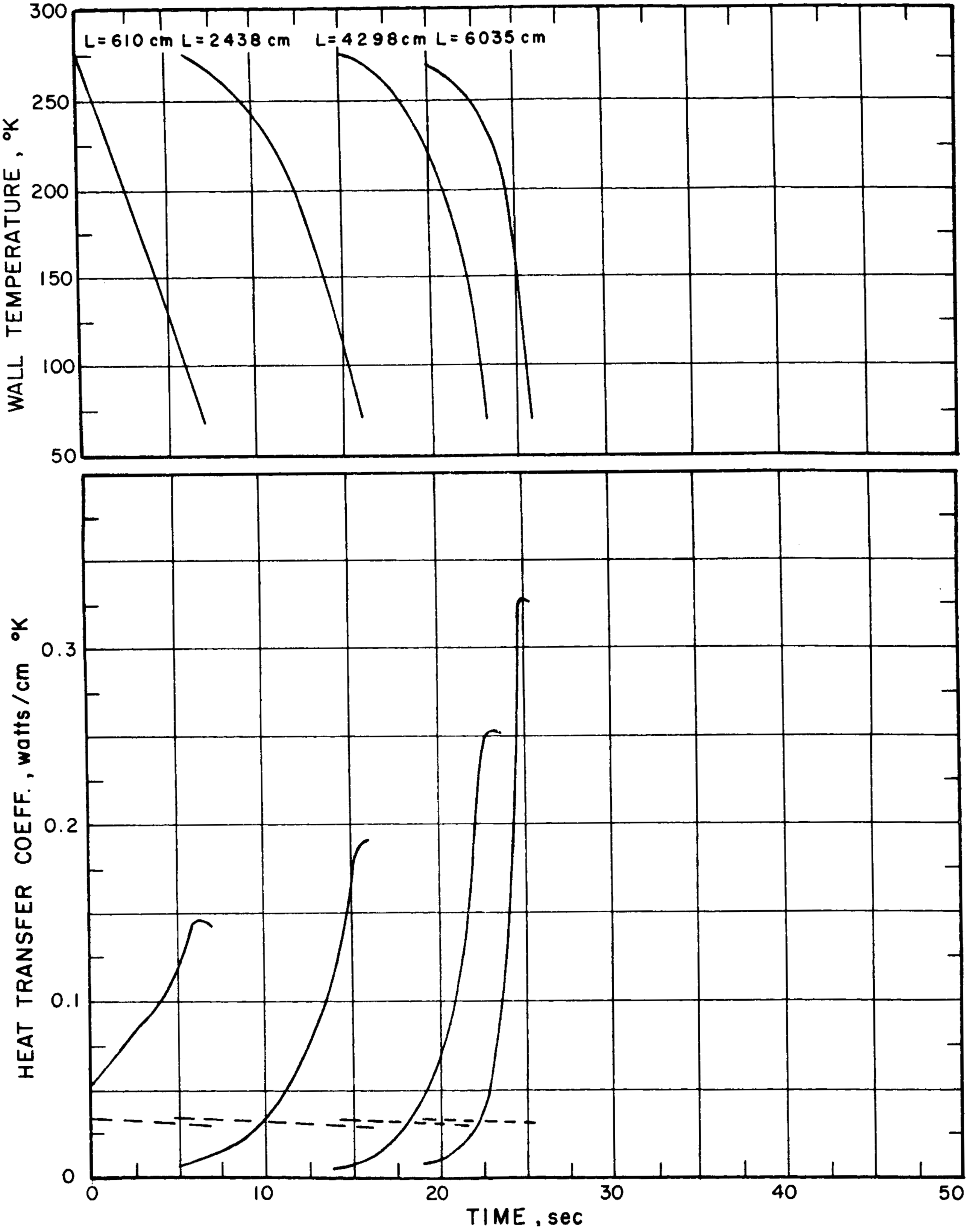


Fig. 51 Heat transfer coefficient as a function of time for subcooled liquid hydrogen at a driving pressure of 11.1 atm.