UNCLASSIFIED

AD NUMBER
AD808922
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited. Document partially illegible.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 1960. Other requests shall be referred to United States Naval Postgraduate School, Monterey, CA 93943.**
AUTHORITY
USNPS ltr, 21 Jun 1972

THIS PAGE IS UNCLASSIFIED

VELOCITY OF SOUND IN LIQUID AND SOLID HELIUM

ROBERT D. JORDAN

Cleared for Release by Thesis
Committee 2/15/67.

UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

VELOCITY OF SOUND IN
LIQUID AND SOLID HELIUM
by
Robert D. Jordan

VELOCITY OF SOUND IN
LIQUID AT [illegible] PRESSURE

* * * * *

Robert D. Jordan

VELOCITY OF SOUND IN
LIQUID AND SOLID HELIUM

by

Robert D. Jordan

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 6 0

VELOCITY OF SOUND IN
LIQUID AND SOLID HELIUM

by

Robert D. Jordan

This work is accepted as fulfilling
the thesis requirements for the degree of
MASTER OF SCIENCE
IN
PHYSICS
from the
United States Naval Postgraduate School

SUMMARY

The measurements of the velocity of sound in liquid and solid helium reported here were made as a part of a more comprehensive study to determine the elastic properties of substances at very low temperatures. The equipment described is capable of measuring velocities of sound as a function of temperature and pressure for temperatures between one and four degrees K and pressures between one and 80 atmospheres. The velocities in the liquid compare well with other published values. No previous measurements of velocity of sound in solid helium have been made. The three values for the velocity in solid helium obtained here are 404 meters per second at 1.54° K and 26.5 atm, 420 meters per second at 1.54° K and 28.6 atm, and 408 meters per second at 2.50° K and 62.2 atm.

The writer wishes to express his appreciation for the advice and assistance given him by Professors John [illegible] Neighbours and Daniel E. Wilson.

TABLE OF CONTENTS

Section [illegible]

LIST OF ILLUSTRATIONS

Figure Page

I INTRODUCTION

The measurements of the velocity of sound in liquid and solid helium reported here were made as a part of a more comprehensive study to determine the mechanical properties of substances at very low temperatures. The primary concern of this work is on the properties of solid helium since very little is known about them. Solid helium has many of the properties of common solids, but in most respects is quite different. The high zero point energy of solid helium is responsible for many of its peculiar characteristics. Because of the small interatomic forces and small atomic mass of helium atoms, the crystals of solid helium are unstable under their own vapor pressure. Under pressure greater than 25 atmospheres, the reduction in volume brings the atoms sufficiently close to allow their fields of force to interpenetrate and form a crystalline solid. This solid probably has a close packed hexagonal structure. The formation of the solid is a purely mechanical process at temperatures below one degree K, and is primarily mechanical below 1.7° K. The specific volume change in going from a liquid to a solid is practically zero, and the difference between the specific volumes is constant below 1.7° K. Since the latent heat of fusion decreases rapidly from approximately 2 cal/mole at the upper triple point to zero at one degree K, the internal energy of the solid is larger than that of the liquid at the same temperature. Thus, since little or no latent heat is involved, the melting and solidification is brought about by lowering or raising of pressure and is mechanical in nature.

The velocity of sound in liquid helium has been measured by a number of investigators.[1, 2] No previous measurements, however, have been made of the velocity of sound in solid helium. The velocity of sound as a function of temperature and pressure is required if the compressibility is to be calculated from thermodynamic data.

The need for specialized apparatus and instrumentation in these experiments was of primary importance since helium does not solidify at pressures below 25 atmospheres even at temperatures as low as one degree K as shown by its phase diagram.[3] The design and construction of experimental apparatus, together with the assembly of other commercially available items of equipment, represents the majority of effort in this study.

II. THE APPARATUS

The equipment is capable of measuring velocities of sound in liquid and solid helium as a function of temperature and pressure for temperatures between one and four degrees K and pressures between one and 80 atmospheres.

The various components of the apparatus can be placed in three convenient groups for purposes of description. They are the following: high pressure system, electromechanical system, and temperature-low pressure system.

<u>High Pressure System</u>

A number of methods for obtaining solid and liquid helium under high pressure and in an arrangement where velocities could be measured were considered. The most feasible method consisted of allowing gas to condense in a sample container that could be sealed at room temperature and then immersed in liquid helium. Preliminary experiments showed that the sound source and receiver must be in contact with the helium. The factor which makes external mounting of the transducers impossible is the extremely poor acoustic impedance match between liquid and solid helium and the metal sample holder. Acoustic impedances in units of gm cm^{-2} sec^{-1} are approximately 8 x 10^3 for solid helium and 4 x 10^6 for steel.

Because of the fragility of the quartz crystals used as transducers, it was deemed advisable to make them easily accessible for inspection and replacement between runs. Since these crystals must be inside the sample chamber, a

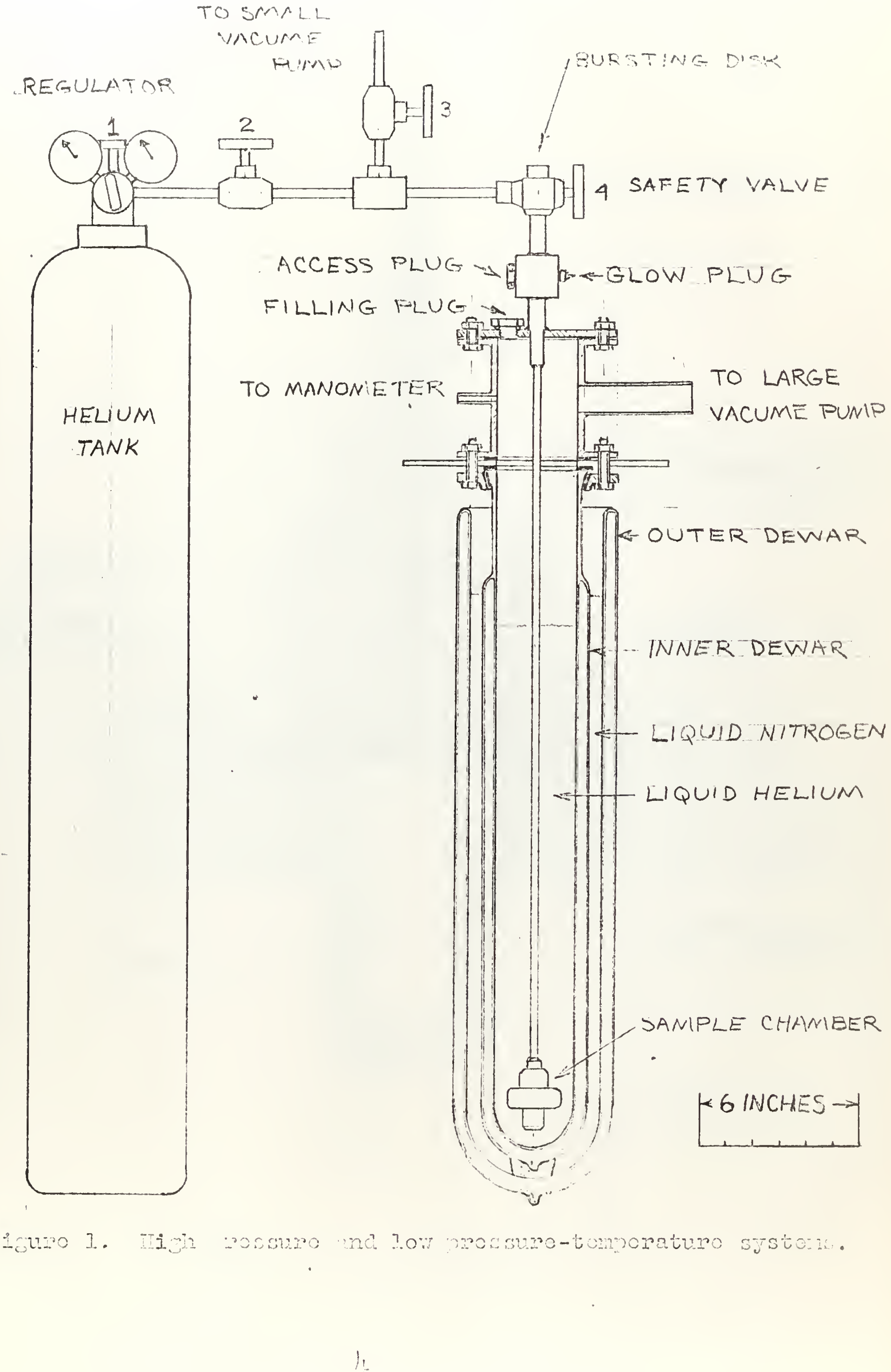


Figure 1. High pressure and low pressure-temperature systems.

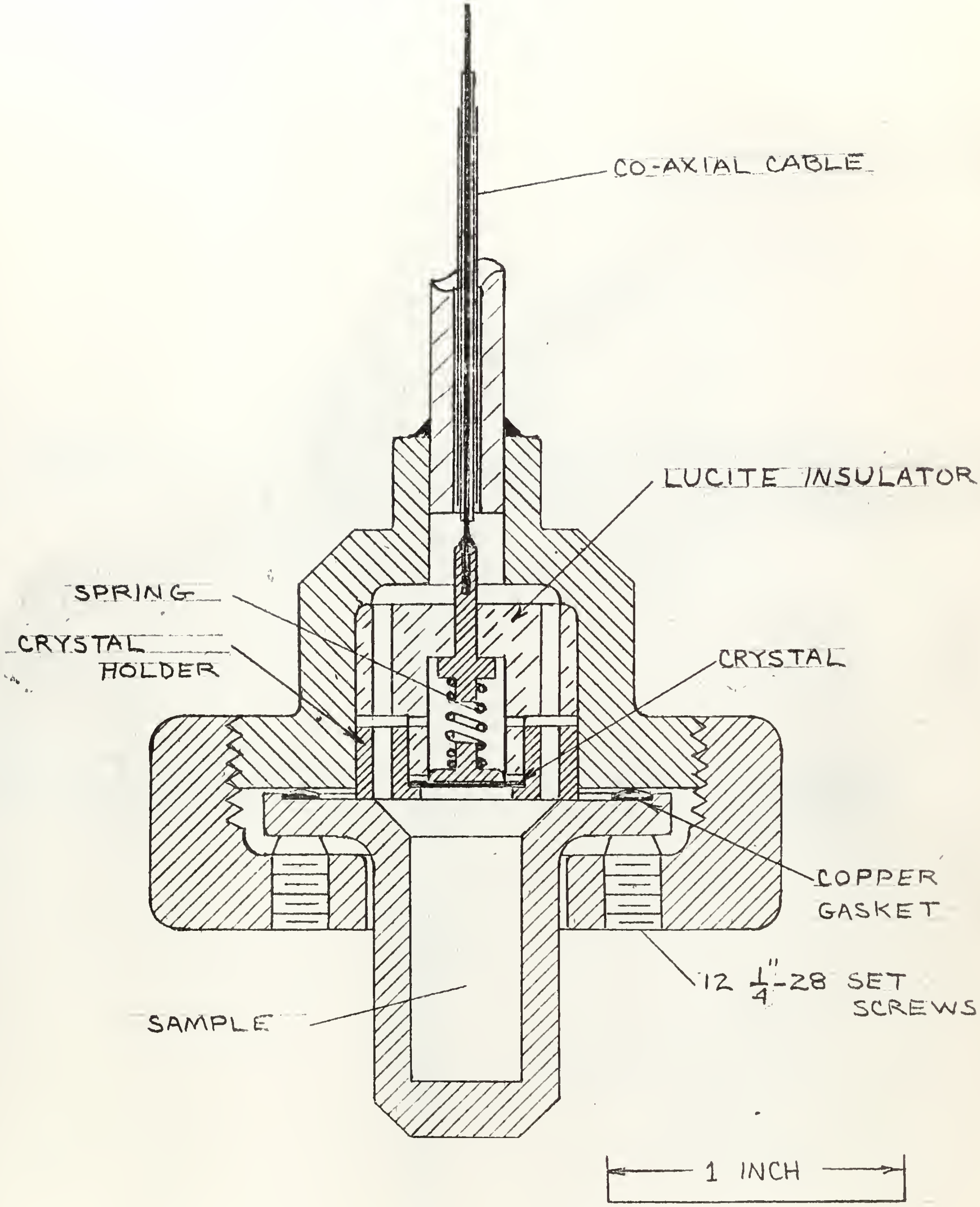


Figure 2. Sample Chamber

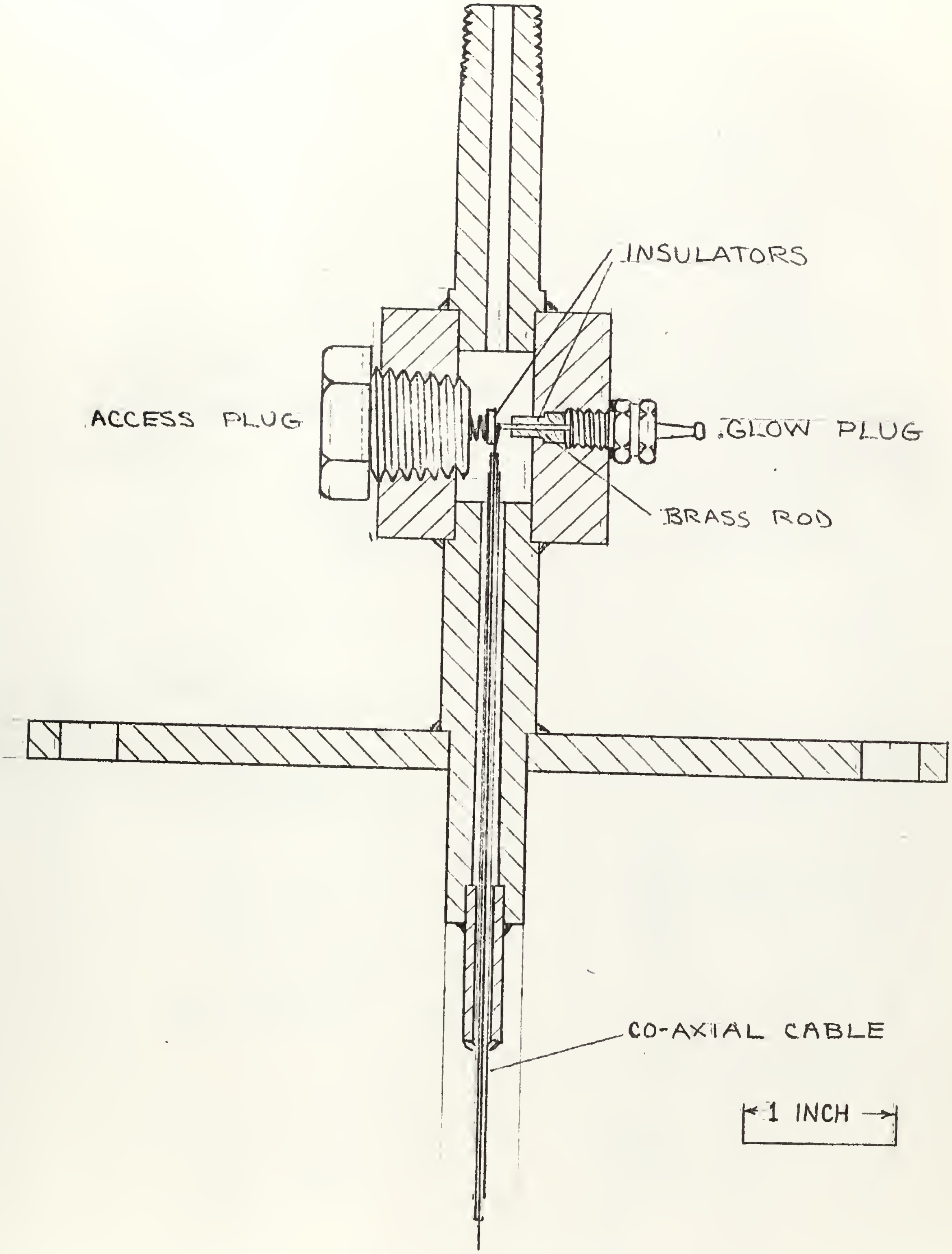


Figure 3. Conductor through wall of high pressure system.

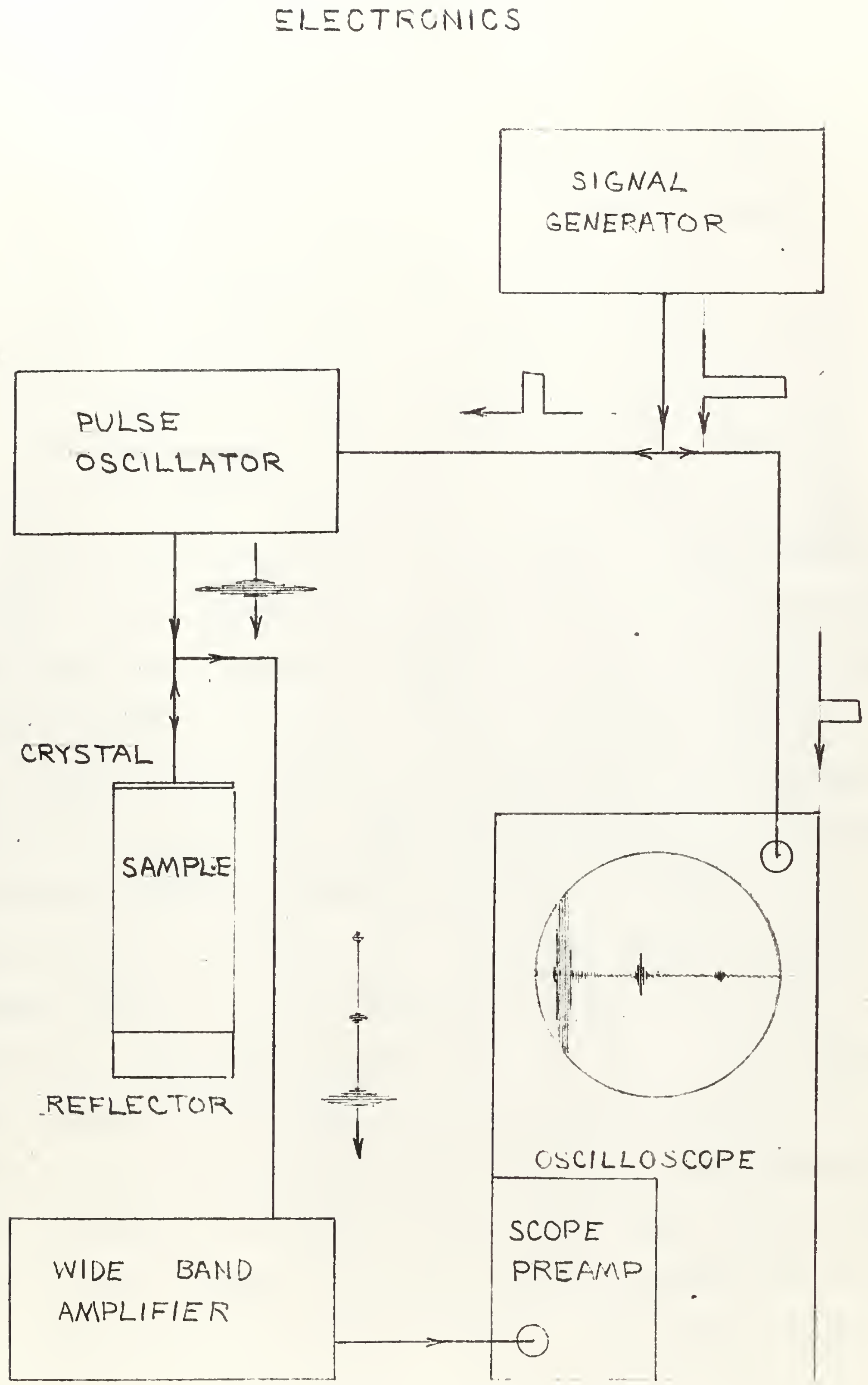


Figure 4. Block diagram of circuit.

Provision had to be made for carrying the necessary electrical signals in and out of the high pressure system. This insulated conductor through the wall was placed where it would be at room temperature to avoid the differential thermal expansion problems encountered at low temperatures. The apparatus is illustrated in Figs. 1, 2, 3, and 4.

Pressure on the system is applied by the same helium tank which furnishes the gas condensed in the sample chamber. The pressure is measured by a Hoke Model 511A Regulator. Since tank pressure is normally less than 3,000 psi, this was taken as the upper limit of operation. When possible, however, very liberal safety factors were applied to calculations involving strength of components. The fact that helium increases around 700 volumes when going from a liquid to a gas at room temperature was in a large degree responsible for much of the overdesign. All of the fittings and tubing from the helium tank to the safety valve shown in Fig. 1 are rated at 4,000 to 10,000 psi. The safety valve is of the bursting disc type and is designed to release at 2,600 to 3,000 psi. The valve and disc are in a direct line with the tube from the sample holder, and the disc is directed at the ceiling where it can produce little damage. With the possible exception of the model engine glow plug, shown in Figs. 1 and 3, used to carry electrical signals through the wall of the pressure system and the seal at the sample chamber, shown in Fig. 2, the remainder of the system is designed for 10,000 psi. Calculations indicate that the seal should not leak until the pressure exceeds 2,[illegible]0 psi. Bursting of the sample chamber would require a fast transient pressure rise of around 10,000 psi. The seal has been tested under a pressure of 1,200 psi at liquid nitrogen temperature without any sign of a leak. The pressure limit of the glow plug is unknown, but it has been subjected to 1,200 psi during test of the system and showed no sign of failure.

The most difficult feature encountered in the design of the high pressure system was that of the seal at the sample chamber. Its position and diameter are dictated by the required geometry of sample, crystal, and electrical lead to the crystal. Because of the low temperatures and high pressures which the seal must withstand, an annealed copper gasket is used. A section of the gasket is shown in Fig. 2. It is contained by the ridge shown, and compressed by 12 1/4-28 Allen set screws. The sharp edge on the upper surface of the gasket produces very high force concentrations and insures a good seal when the 12 screws are set up to 2 ft-lbs torque.

Electro-Mechanical System

The central element of this system is the 3/8 inch diameter, 15 megacycle, x-cut quartz crystal which acts both as the sound source and receiver. The electrical features of the system are shown schematically in Fig. 4, and the crystal and its accessories are illustrated in Fig. 2. The faces of the crystals have been coated with an evaporated layer of aluminum a few microns thick to carry the necessary electrical signals. One face is in direct contact with the helium sample over most of its area. It is supported by a brass holder which also acts as the electrical ground contact. Care was taken to keep the crystal as nearly parallel to the reflecting surface as possible since the sound pulses emitted by the crystal form a well defined beam. A spring loaded contact holds the crystal in place from above, and also carries the electrical signals. The distance from the crystal face to the reflecting surface is 2.490 cm at room temperature, and approximately 2.482 cm at liquid helium temperature. A 15 megacycle pulse from an Arenberg Model PG 650-C Pulse Oscillator is conveyed to the crystal by way of three feet of RG 57 co-axial cable, the glow plug, a short brass rod, 29 inches of 1/16" diameter co-axial cable, and the spring loaded contact. The reflected signal is returned to an Arenberg Wide Band Amplifier-WA-600. The amplified signal is fed to a Tektronix, Type L Plug-In Unit where it is amplified further before being presented on a Tektronix Type 545A Oscilloscope.

Temperature-Low Pressure System

The sample chamber is surrounded by a conventional double Dewar system.[4] The inner Dewar is sealed, and its interior pressure can be reduced by pumping with a model KD 30 Kinney Vacuum Pump. The pressure is controlled by a sensitive demand regulator valve,[5] and is measured with mercury and unity oil manometers.[4] The pressure is also used as a thermometer through the relationship between helium vapor pressure and temperature.

The outer Dewar when filled with liquid nitrogen serves as a heat shield for the helium containing inner Dewar.

III. EXPERIMENTAL PROCEDURE

The high pressure system is first cleared of air and water by applying a small vacuum pump to a stem on valve 3 (Fig. 1) with valves 2, 3, and 4 open and valve 1 closed. Valve 3 is closed and 1 opened and the pressure regulator adjusted to give a few psi helium pressure. The sample chamber and inner Dewar are then precooled with liquid nitrogen. The space between Dewars is also filled with liquid nitrogen at this time. The inner Dewar is then cleared of liquid nitrogen and filled with liquid helium. When the blow off reaches a reasonable level, the inner Dewar is then sealed and the pressure over the liquid reduced slightly by pumping. This causes liquid helium to condense slowly in the sample chamber. Slow condensation is necessary since any rapid changes in pressure or high flow rates of gas might break the quartz crystal.

After allowing sufficient time for the sample to form, the crystal is pulsed. If a reflected signal is received it indicates that the sample chamber is full of liquid. The pressure on the sample may then be adjusted to any desired value between one and 30 atmospheres using the tank pressure regulator. The temperature can be lowered by pumping on the vapor above the liquid helium.

The following measurements are made for each determination: the round trip time for the pulse as given by the oscilloscope; the pressure, read from the regulator gage; the temperature as a function of helium vapor pressure as indicated by the mercury or oil manometer. The time can be measured with a precision of ± .1 microseconds, but the accuracy as indicated by comparisons of readings is not nearly as good. The observed transit times are accurate to approximately ± 3 microseconds or two per cent. Since the mercury manometer can be read to ± .1 mm, the temperatures are accurate to ± .01° K. The pressure is estimated to be accurate to within ± 5 psi.

IV EXPERIMENTAL RESULTS

All of the measurements for which enough points were obtained with one variable held constant are presented graphically and are also listed in Table 1. The remaining values are listed in Table 2.

In Figs. 5 and 6, velocity is plotted as a function of pressure with temperature held constant. Both of these curves show the same general trend of increase in velocity with pressure. In Fig. 5, the transition from liquid to solid state near 26.4 atm and 1.4° K is apparent. The upper two points are those of the solid phase, the velocity immediately after the transition being 404 meter/sec and that at 28.6 atm 428 meters/sec.

Fig. 7 is a plot of velocity vs temperature for a pressure of 23.2 atm. The velocity is relatively insensitive to temperature above 2.5 K. but shows the expected cusp near the λ line.

Among the measurements which are not amenable to representation in graphical form, there is one velocity measurement which must be in the solid. It is a velocity of 488 meters per second at 2.50° and 62.2 atm.

TABLE I

Figure	Temperature °K	Pressure Atm	Velocity M/sec
5	1.54	1	266
5	1.54	3	274
5	1.54	7.3	297
5	1.54	14.6	319
5	1.54	18.0	332
5	1.54	21.4	346
5	1.54	23.45	352
5	1.54	25.5	358
5	1.54	26.1	360
5 (solid)	1.54	26.5	404
5 (solid)	1.54	28.6	428
6	3.00	14.6	313
6	3.00	21.4	349
6	3.00	24.8	364
6	3.00	28.2	381
6	3.00	31.6	386
6	3.00	35.0	393
6	3.00	38.4	409
6	3.00	41.8	423
7	1.63	28.2	349
7	1.95	28.2	364
7	2.01	28.2	366
7	2.10	28.2	359
7	3.00	28.2	381

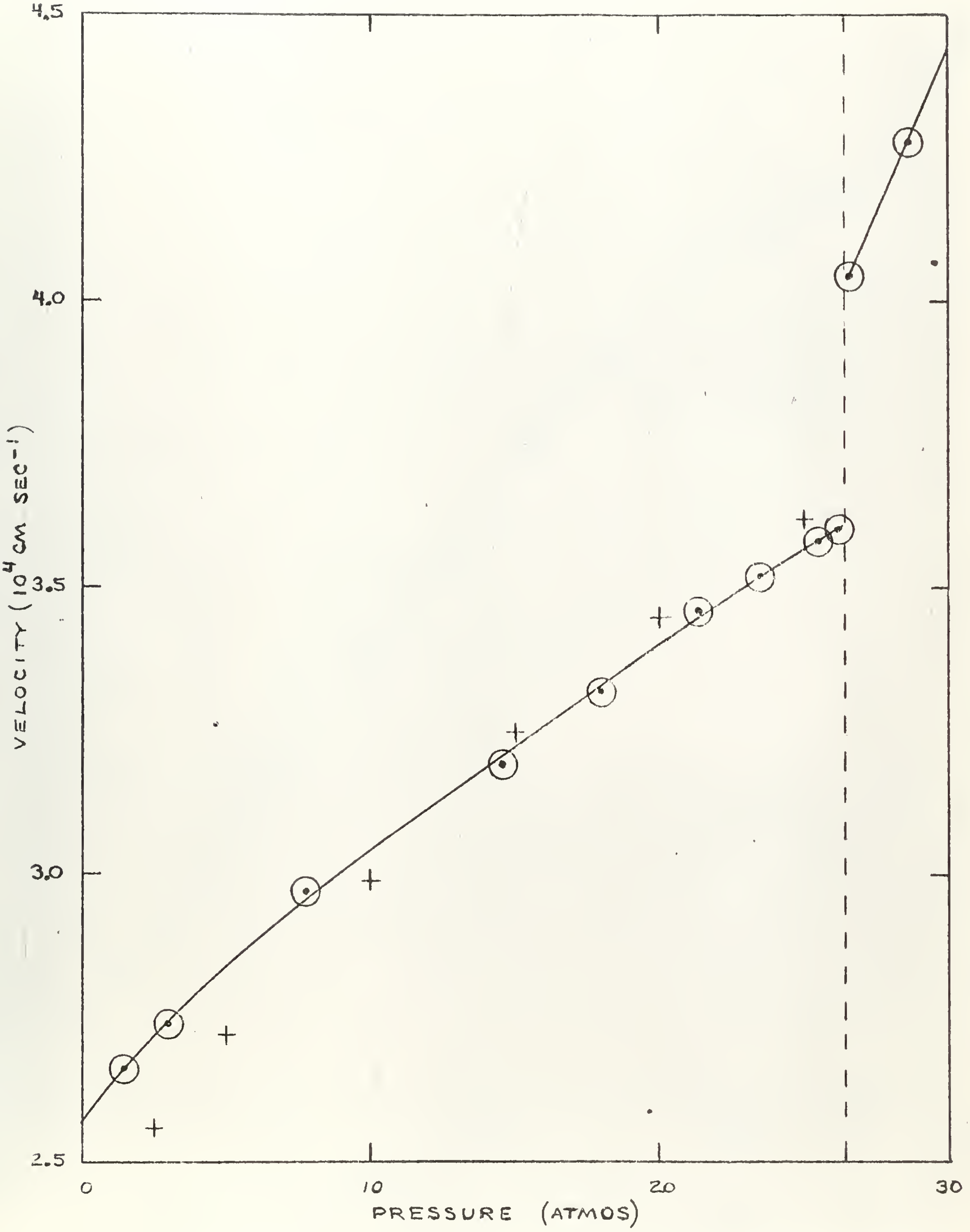
TABLE I (CONT'D)

Figure	Temperature °K	Pressure Atm	Velocity M/sec
7	3.72	28.2	373
7	4.10	28.2	373
7	4.216	28.2	374

TABLE II

Temperature °K	Pressure Atm	Velocity M/sec
1.43	21.25	335
1.43	23.45	348
1.52	23.45	350
1.57	18.0	329
1.57	21.25	337
1.62	18.0	326
1.65	23.45	336
1.65	28.6	352
1.74	18.0	326
1.75	23.45	341
1.79	28.6	363
1.[illegible]4	17.7	319
1.93	28.6	364
2.09	41.8	416
2.50	55.3	463
2.50	48.8	462
2.50 (solid)	62.2	488
3.08	41.8	421
3.51	41.8	415
3.72	41.8	421

Figure 5. Velocity as a function of pressure at 1.54° K. Crosses (+) are from Atkins (ref. 1) at 1.50° K. The dashed vertical line represents the liquid to solid transition pressure.



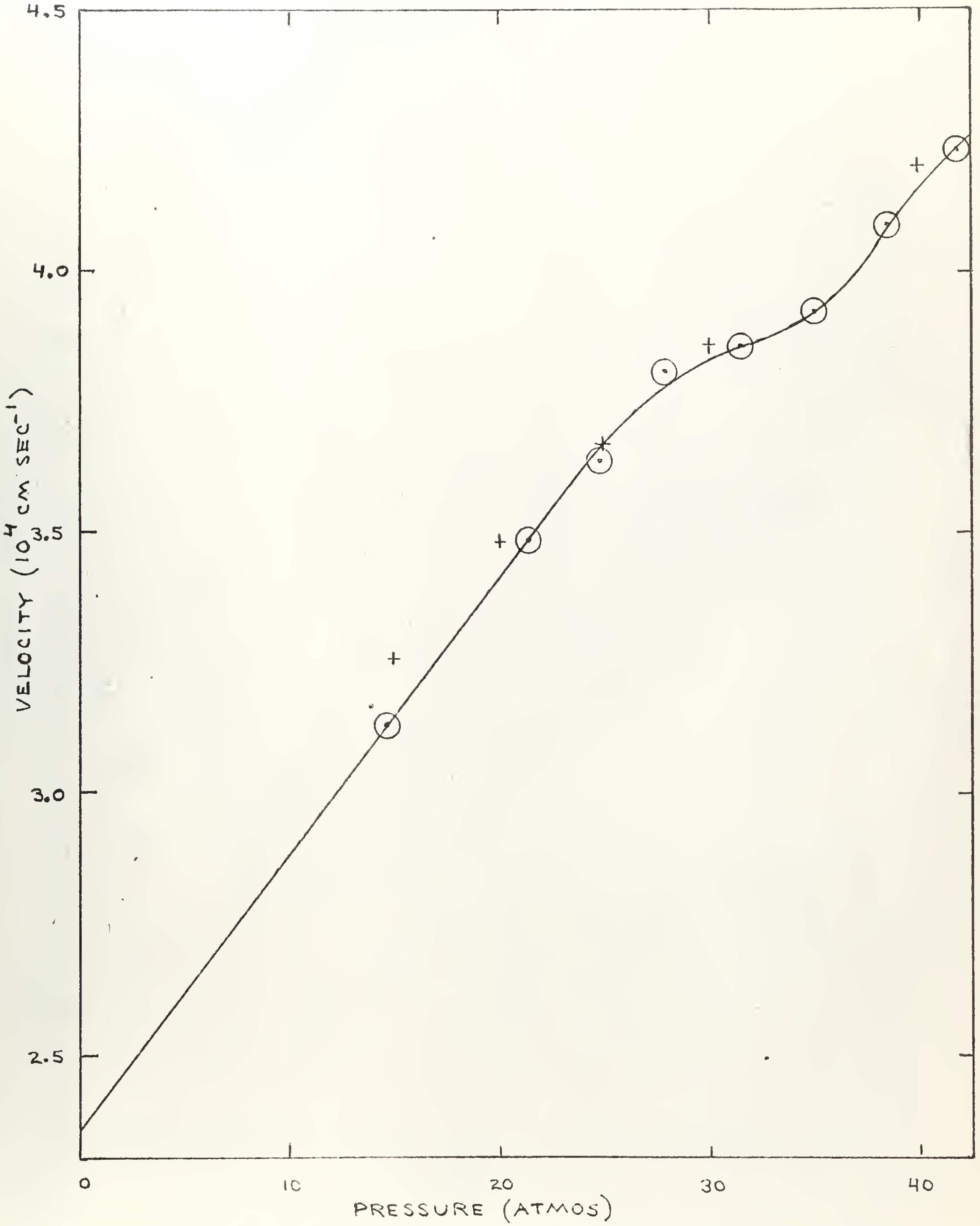


Figure 6. Velocity as a function of pressure at 3.00° K. Crosses at 3.00° K are from Atkins (ref. 1).

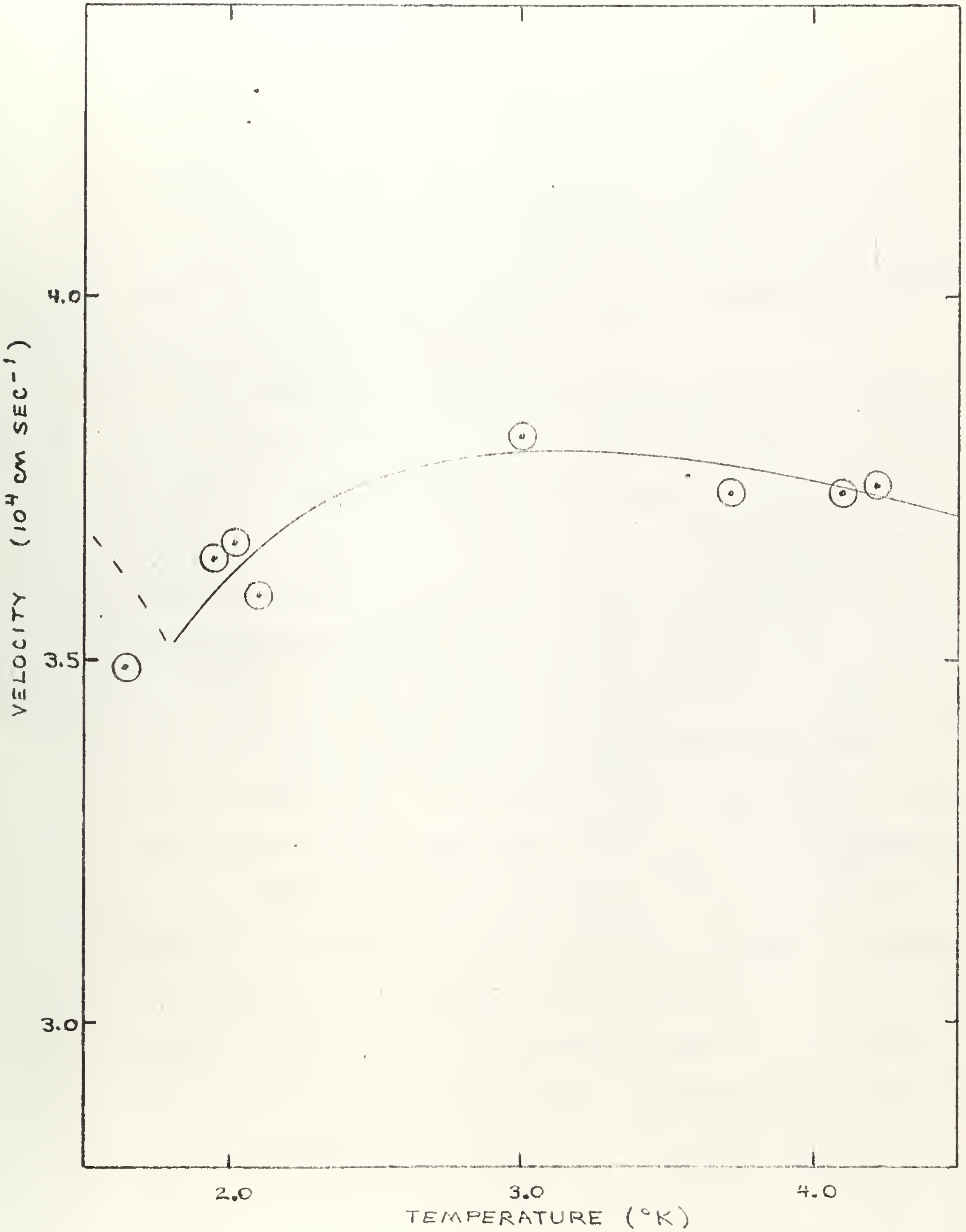


Figure 7. Velocity as a function
of temperature at 28.2 atmospheres.

V DISCUSSION

The results obtained for the velocity of sound compare very well with other published values.[1] They show a consistent rise in velocity with pressure and a relative insensitivity to change in temperature except near the λ line. At the λ line there is a rapid fall followed by a rise in velocity as the temperature is changed at a constant pressure. This fall in velocity corresponds to a maximum in density at the λ line.

No previous measurements of the velocity of sound in solid helium have been made. The reliability of the measurements obtained in this experiment must therefore be evaluated from considerations of the experimental conditions. The two values shown in Fig. 5 should be quite accurate. The temperature was held constant while all of these points were obtained. Several determinations were made at each point and the pressure was slowly changed and given time to stabilize at each point. The transition is clear and of sufficient magnitude to remove any doubts as to its occurrence.

The other velocity determination in the solid is not quite as reliable. It was also taken at constant temperature, but only three points were obtained, two of them in liquid. The velocity was measured twice in the solid at the same pressure, and there was a variation of about three per cent between the values. This was probably due to a slight change of temperature, since the first determination was made immediately following a decrease in temperature.

Since the velocity is much higher in the solid than in the liquid, even though the density rises from approximately .15 gm/cm^3 near zero atm to .18 gm/cm^3 at 35 atm, the adiabatic compressibility must be considerably greater in the solid. This is to be expected from considerations of the greater internal energy of the solid.

REFERENCES

1. K. R. Atkins, Liquid Helium, Cambridge University Press, London, 1959

2. C. F. Squire, Low Temperature Physics, McGraw-Hill Book Co., 1953

3. M. W. Zemansky, Heat and Thermodynamics, 4th Ed., McGraw-Hill Book Co., 1957

4. L. C. Jackson, Low Temperature Physics, Methuen and Co., London, 1955

5. Designed by Professor E. C. Crittenden of U. S. Naval Postgraduate School