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USE OF A TORSIONAL PENDULUM AS A HIGH-PRESSURE GAGE AND DETERMINATION OF VISCOSITY OF HELIUM GAS AT HIGH PRESSURES

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16. Abstract

Three torsional crystal parameters were examined for suitability in sensing pressure in gases up to 131×10^6 newtons per square meter (19 000 psi). The best parameters were found to be the change in crystal decrement at resonance and the change in crystal electrical resistance at resonance. The change in crystal resonant frequency did not appear to be a reliable pressure measuring parameter. Pure argon and pure helium gases were studied for use as working fluids. Helium functioned better over a wider pressure range. Calibration of the gage also provided a measure of the viscosity-density product of the gas as a function of pressure. These data, together with known extrapolated density data, permitted the determination of the viscosity of helium to 131×10^6 N/m^2 (19 000 psi).

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USE OF A TORSIONAL PENDULUM AS A HIGH-PRESSURE GAGE AND DETERMINATION OF VISCOSITY OF HELIUM GAS AT HIGH PRESSURES

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SUMMARY

Three torsional crystal parameters were examined to determine if an oscillating torsional crystal would be an effective gage sensor for the measurement of high fluid pressures: (1) change in crystal resonant frequency, (2) change in crystal resonant electrical resistance, and (3) change in the crystal decrement at resonance. In this high-pressure gage a piezoelectric, cylindrical, quartz crystal was driven in its fundamental torsional mode by the application of an alternating electric field. The gage can be designed so that the crystal is surrounded by a calibrated sample gas which can sense the pressure in an uncalibrated fluid through a differential pressure transmitter. Two pure gases, argon and helium, were studied for use as gage working fluids. The crystal resonant frequency was expected to decrease with increasing gas pressure. This was observed in argon gas, but the frequency increased in helium gas. For this reason it was concluded that measurement of either change in crystal resistance or crystal decrement is a more suitable parameter for a high-pressure torsional crystal gage. However, measurement of the crystal decrement directly should greatly simplify the instrumentation and measuring time of a torsional crystal pressure gage.

Calibration of the gage with helium also provided a measure of the viscosity-density product of this gas as a function of pressure. These $\eta\rho$ values for helium were in good quantitative agreement with other investigations up to their highest reported pressure of 17.2×10^6 newtons per square meter (2500 psi). Our helium data together with known extrapolated density data permitted the determination of the viscosity of helium to 131×10^6 newtons per square meter (19 000 psi). The data indicate a far less rapid increase with pressure than has been previously calculated.

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INTRODUCTION

Gages for the measurement of high fluid pressures ideally should be sensitive, accurate, reproducible, rapid, rugged, and, if possible, simple to operate. At pressures above 1000 atmospheres, bourdon tube gages suffer hysteresis effects and lose accuracy. The inherently slow pressure balance, or dead weight tester, requires many corrections and cannot be easily designed for pressures exceeding 3000 atmospheres. Resistance gages are useful at higher pressures but lose sensitivity and accuracy at lower pressures. The torsional crystal gage described in concept in this report offers the advantage of a wide dynamic range, negligible hysteresis, relatively short response time, continuous electrical readout, and, for certain applications, a pressure measurement independent of the gravitational field. It must, however, be calibrated for use with each gas, or, alternatively, appropriate interfacing means must be used to transmit the pressure of the fluid in question to the calibrated working fluid.

The working fluids studied in this work were high purity helium and argon. Based on our results, helium seems better for use in the torsional crystal gage because the viscosity and density of helium do not increase too rapidly with pressure, which simplifies the instrumentation required to measure the damping. Like the standard rotating cylinder viscosimeter, the torsional crystal system described here depends on the drag of a moving body in a viscous medium. The major difference is that the viscosimeter measures the drag by moving a body in one direction such as by rotation, and the torsional crystal measures the drag by having the body oscillate.

In principle there are three measurable quantities or parameters of an oscillating torsional crystal that can be measured to sense the gas pressure surrounding it: (1) Change in the crystal resonant frequency from its value in a vacuum to the measured value when surrounded by the gas at the pressure of interest, (2) change in the crystal's electrical resistance at resonance when immersed in the sample gas as compared with the corresponding electrical resistance in vacuum, and (3) change in the crystal decrement due to the surrounding gas from the corresponding crystal decrement in vacuum. More detailed information will be presented in the next section.

Because the gage measured the viscosity-density product of the working fluid, calibration data were obtained from which the viscosity against pressure for helium and argon could be obtained. For helium these represent an extension of known viscosity data to pressures of 1300 atmospheres. The data obtained can be used to check the validity of computer extrapolation of low-pressure thermodynamic and transport data to high pressures.

THEORY

The torsional pendulum used in this experiment consists of a single quartz crystal in the shape of a right circular cylinder. The cylinder is much longer than its diameter, and it twists such that each end rotates in opposite directions producing a region halfway between the two ends that does not move at all. This cylindrical alpha quartz crystal is piezoelectric and may be driven in this fundamental torsional mode of vibration by the proper application of an alternating electric field. The crystal's mechanical resonant frequency is given by

$$F_r \simeq \frac{1}{4L}\left(\frac{C_{66}}{\rho_Q}\right)^{1/2} \tag{1}$$

where 2L represents the total length of the cylinder, C_{66} is an elastic constant of quartz, which is approximately the rigidity modulus for the configuration, and ρ_Q is the density of the quartz crystal (ref. 1). Any piezoelectric crystal that is suspended at a velocity node can be represented by an equivalent electrical analog or electrical circuit, consisting of a resistance, an inductance, and capacitances. Equivalent electrical circuits for piezoelectric crystals are considered by Mason (ref. 1), but his discussion assumes that the crystal electrodes are coated directly on the surface of the piezoelectric crystal. In this investigation the torsional crystal electrodes are not in contact with the crystal surface but are capacitatively coupled to the crystal surface. The equivalent circuit for this torsional crystal used here is shown in figure 1 and has an additional capacitance C_g, which is not considered by Mason. The circuit consists of a series resonant branch, a shunt capacitance C_o, and a series capacitance C_g. At crystal resonance the electrical impedance of the series resonant branch depends on the viscosity η and the density ρ of the medium in which the crystal oscillates. The form of the dependence can be derived from consideration of the logarithmic decrement of a piezoelectric crystal damped in a laminar viscous fluid (ref. 2). This then leads to the expression

$$\eta\rho \simeq \frac{\left(R_x - R_{x,vac}\right)^2}{K_o^2 S^2 f_r \pi} \tag{2}$$

where R_x is the crystal resistance at resonance f_r, the subscript vac denotes a vacuum, K_o is the "crystal constant," S is the total surface area, and f_r is the electrically measured crystal resonant frequency, which would equal F_R if the crystal was in a vacuum with no electrode system. The term R_x measures the effect of the surrounding medium on the crystal plus the internal and suspension losses of the crystal. The resonant resistance of the crystal in vacuum $R_{x,vac}$ is due to internal friction and suspension losses. The crystal constant K_o is determined by measuring the band width and the resistance at series resonance. The crystal constant K_o and f_r of equation (2) are weak functions of pressure in contrast to $(R_x - R_{x,vac})$, which is a relatively strong function of pressure.

Displacement of the electrodes from the crystal surface results in a changed crystal system having a slightly different resonant frequency and perhaps a different resonant resistance than would be observed with the electrodes on the crystal surface.

Mason (ref. 3) has shown that the viscosity-density product can also be found from a measurement of the resonant frequency alone. If it is assumed that the reactive impedance loading due to end effects is smaller than the cylindrical surface impedance loading, then

$$\eta\rho \simeq \pi\rho_Q r^2 \frac{\left(f_r - f_{r,vac}\right)^2}{f_r} \tag{3}$$

where r is the radius of the cylindrical crystal and $f_{r,vac}$ is the series resonance frequency of the crystal in vacuum. It can be shown that the ratio of the surface impedance loading to the reactive impedance loading is in the same ratio as the length of the crystal to its radius, which is 68 to 1 in this experiment.

Equations (2) and (3) indicate two methods for measuring the viscosity-density product. Since the viscosity-density product is expected to increase with pressure as a well defined monotonically increasing function, measurement of the crystal parameters $f_r - f_{r,vac}$ and $R_x - R_{x,vac}$ should provide a sensitive measure of the pressure if the functional dependence is known or calibrated.

In this study, the explicit measurement of $\eta\rho$ provides the additional information about the variation of η with pressure, provided ρ against pressure is known. The ρ against pressure values are known or can be more reliably extrapolated for many gases up to very high pressures.

EXPERIMENTAL

The apparatus and procedures to be described here are those used to test the feasibility of measuring high pressures using the torsional crystal technique. The measurements also include obtaining explicit values for $\eta\rho$ from which viscosity against pressure information can be obtained. In an actual gage the instrumentation and procedures required would be greatly modified and simplified from those described here and an explicit determination of $\eta\rho$ would not be required for gage calibration. Some general discussion and recommendations in this regard are given in RESULTS AND CONCLUSIONS.

Apparatus

The cylindrical quartz crystal, 0.47 centimeter in diameter and 15.85 centimeters long, was suspended at its fundamental nodal point in a crystal holder by two nylon threads (see fig. 2). The holder of the crystal served as a support for four silver quadrants surrounding but not contacting the crystal. Polytetrofluoroethylene electrically insulates two of the silver quadrants from the holder. The space between the quadrants and holder surface (0.5 mm) is filled with the fluid of interest, in this case either helium or argon gas. Adjacent quadrants having opposite electrical polarity produce electrical field gradients in a region about the slots between adjacent quadrants. These gradients drive the crystal in a torsional mode. For more detail of the torsional crystal, see reference 2.

The alpha quartz may be driven in a relatively pure fundamental torsional mode by proper application of an alternating electric field. For this purpose one of the three electrical axes must be coincident with the geometric axis. This mode will be relatively pure if care is taken to aline the electric field with respect to the crystal's three geometric axes.

The torsional crystal and its holder, which was attached to the high pressure closure, was inserted into an OFHC-copper finned container. The crystal holder assembly was designed to minimize thermal gradients. The assembly was placed in the high-pressure vessel in a vertical position (see fig. 3). Electrical connections were made through leads located in the closure. The gas was pumped to pressure with intensifiers manufactured by the Harwood Engineering Co.

Figure 4 is a block diagram of the pressure and electrical system. Gas pressures were measured using a bourdon gage for the approximate pressure, and a dead weight gage with an oil interface tank for exact pressure. A rough pump was used to evacuate the system for vacuum reference measurements.

The crystal resistance was measured by capacitance coupling to the electrode quadrants, thereby eliminating the need for a mechanical contact. The electrode quadrants were connected to one arm of a modified Schering-capacitance bridge by a coaxial cable. The bridge used was a General Radio (type 716C) capacitance bridge. An attenuator sets the voltage level of the signal supplied to the bridge, and the band pass filter prevents any harmonics from reaching the bridge. A low noise preamplifier was used to increase the bridge sensitivity and together with a lock-in amplifier permitted detection of bridge voltages less than 1 microvolt. The bridge is excited either by a General Radio oscillator, which supplies a 10-kilohertz signal to the measuring system in order to obtain what will be called an *infinite balance measurement*, or by an ultrastable oscillator for the determination of R_x. For values of Q encountered in this experiment, the frequency must be ultrastable for at least a few seconds so that the bridge can be balanced to yield a determination of R_x of better than 1 percent precision. This precision was accomplished by starting with a frequency 1000 times higher than the resonant frequency of the crystal and dividing downward through a frequency divider. Using a high-frequency counter, this frequency could be read to one part in 10^8 hertz. A phase pattern on an oscilloscope was used to determine the bridge balance.

Gas temperature was measured using a high-pressure four-terminal platinum resistance thermometer guaranteed to 34.5×10^6 newtons per square meter (5000 psi). It was mounted in a small closure that was fixed to the copper chamber of the crystal assembly. The thermometer's resistance was determined by a potentiometer and a 100-microampere constant current source. Temperatures could be measured to a precision of less than $1/4^\circ$. As a cross-check, an external thermometer attached to the outside of the pressure vessel was used. The temperature differential between the two thermometers never exceeded 1.5° C. This temperature difference could be due to poor thermal contact or to error in the glass thermometer calibration.

Procedure

The bridge as shown in figure 5 is always used with impedance Z_a set equal to impedance Z_b. Hence, when a null signal is observed on the oscilloscope or on the lock-in amplifier, the bridge is balanced and $Z_u = Z_s$. An equivalent circuit for figure 1 is used in figure 5 to simplify analyses of the crystal system with impedance Z_u. The following procedure was used to establish the resonant frequency f_r and the crystal resistance at resonance: The bridge was first balanced at frequencies far from resonance where the crystal branch containing R_x', L_x, and C_x' essentially exhibits an infinite impedance. This was done by setting R_s equal to infinity and varying the resultant pure capacitance C_s in arm s. The capacitance C_s at which the bridge balances is then equal to the capacitance C'' of the crystal arm. With C_s set equal to C'' the bridge was then balanced at the resonant frequency such that $R_s = R_x$. In order to balance, both the frequency and the resistance R_s must be adjusted simultaneously until a unique balance is observed. Hence, such a balance yields both f_r and R_x, simultaneously. Since C'' contains C_g, it changes with pressure due to the change in dielectric constant of the sample gas with pressure. It is likely that $R_x' - R_{x,vac}'$ is slightly larger than the corresponding quantity in a crystal system with the electrodes plated on the crystal surface because of the dielectric constant change in C_g with pressure. However, the dielectric constant of helium gas changes by less than 3 percent over the entire pressure range in this experiment so the error in this quantity is expected to be small. This is verified by the fact that our experimental values for $\eta\rho$ in helium were in quantitative agreement with other investigators over the pressure range of their data.

The resonant frequency at bridge balance was obtained by viewing a counter and timer that has a maximum input frequency rate of 15 megahertz at a maximum gate time of 10 seconds. The crystal "constant" K_o was determined by measuring the logarithmic decrement Δ directly from the half width of the resonant peak. A plot of R_x divided by Z_x has a symmetric sharp peak at resonance. The half-power point of this peak occurs when the bridge resistance R_s equals $2R_x$. The Q of the crystal is defined as

$$Q = \frac{f_r}{\delta f_r} = \frac{\pi}{\Delta} \tag{4}$$

where δf_r is the width of the resonance curve at the half-power point. From the previous equation and from equation (A2) found in appendix A of reference 2, the following equation may be written:

$$K_o = \frac{R_x}{\pi M \delta f_r} \tag{5}$$

where M is the mass of the crystal. Equation (5) is the expression used in the determination of K_o for the particular temperature and pressure of interest. The determination of K_o requires the frequency to be measured with good precision.

For measurement of $f_{r,vac}$ and $R_{x,vac}$, the pressure vessel was evacuated over a period of not less than 12 hours using a rough pump connected to the dump valve of the pressure system. Vacuum pressure readings were taken at the dump valve since the vacuum gage could not be conveniently mounted at the pressure vessel. This scheme can cause a small error in the vacuum reading inside the vessel because of small gas leaks. These leaks were self-sealing when gas pressure was applied to the system. To determine the variation of $\eta\rho$ with temperature, an electrical heater was placed near the placed near the pressure vessel to change the pressure vessel's temperature. A 24-hour period was allowed to establish temperature equilibrium.

RESULTS AND DISCUSSION

This portion of the report will be divided into two parts. The first part considers the torsional pendulum as a pressure gage with emphasis on the change in the crystal's electrical resistance and the shift in the series resonant frequency as a function of pressure. Included in this portion of the report will be a discussion on improving the pressure gage readout system by periodically exciting the crystal and measuring its logarithmic decrement as a function of pressure. The second part deals with the determination of viscosity of helium and argon as a function of pressure.

Pressure Gage

The quartz torsional pendulum was investigated for its ability to measure high pressure. Three important properties of this gage are its decrement, electrical resistance, and series resonant frequency. These three parameters depend on the viscosity-density product of the gas in which the crystal is immersed.

Of the two gas properties, viscosity and density, the density is more sensitive to pressure changes. In fact, for an ideal gas, the density will be proportional to the pressure, while the viscosity will be independent of pressure.

In figure 6 the electrical resistance of the torsional pendulum is shown as a function of helium gas pressure. All the data have been corrected to 25° C. The curve indicates that at low pressure, the logarithm of resistance is proportional to the logarithm of pressure. At sufficiently high pressure, this does not hold true for a number of reasons. The bracketed numbers indicate the sequence of measurement. This sequence was used to determine if the gage would have any hysteresis. As can be seen, the degree of hysteresis. As can be seen, the degree of hysteresis is nil. Obviously, the resistance against pressure characteristic will be a function of the type of gas used. The larger the viscosity-density product, the higher the resistance.

The electrical resistance was also measured with argon in the pressure chamber. At pressures above 34.5×10^{6} newtons per square meter (5000 psi) the resistance became large and required a special bridge for reliable measurements. The bridge used here was limited to a few hundred thousand ohms for resistance measurements would be within the required accuracy. Argon was a suitable gas for the measurement of resonant frequency against pressure with this bridge and was used to test the suitability of resonant frequency as a gage parameter. Measurement of the shift in the series resonant frequency as a function of pressure offers the advantage of direct reading. However, even in argon, the shift in frequency is small, so that elaborate techniques are necessary in order to obtain the required precision. It is expected that the resonant frequency will decrease with increasing gas pressure (see fig. 7). The resonant frequency of argon decreased with increasing pressure, as expected. In figure 7 a comparison is made between the results from the present investigation and those of reference 4. The theoretical curve was adjusted so that the resonant frequency in vacuum coincided with the measured frequency at approximately 30 micrometers. The difference between the two argon curves may be due to extra reactive loading of the crystal. At high pressures the change in resonant frequency appears to be a less sensitive as a gage parameter.

When the vessel was pressurized with helium gas, the resonant frequency increased with increasing pressure (also shown in fig. 7). We believe that this anomalous behavior is due to the diffusion of helium into the surface region of the crystal. Since the highest stresses occur at the surface of the crystal, the modulus of elasticity could be affected by the helium atom occupying sites in the quartz. This effect also emphasizes the need to keep a crystal surface free of contamination.

As mentioned earlier, the torsional pressure gage has a relatively fast response that is limited only by the time required for the system to reach steady state. The bridge technique described in this experiment is probably not the best method to use in the actual gage. An automatic system could be designed to utilize the full potential of the torsional gage. Because the amplitude of a damped free oscillatory system decreases exponentially with time, a pressure gage can be constructed in which one measures the logarithmic decrement of such a system as a function of pressure. The decrement is given by the following expression:

$$\Delta = \frac{\ln\left(\frac{V_o}{V_t}\right)}{N} \tag{6}$$

where V_o is proportional to the amplitude of the induced voltage at the beginning of the cycle count, V_t is proportional to the induced voltage at the end of the count, and N is the number of cycles counted. Although the system is relatively simple, it should be pointed out that V_t, in practice, will be represented by $V_t \pm dV_t$ where dV_t is the error in V_t. For a given dV_t the choice of V_t will affect the value of the normalized error dN/N in the counting of N cycles. It can be shown that dN/N is minimum when the ratio V_o/V_t equals 2.72. The logarithmic decrement Δ becomes equal to 1/N under this condition. Figure 8 shows the relation between Δ and pressure when the gas surrounding the torsional pendulum is helium.

These experimental results and considerations indicate that the logarithmic decrement and the resonant resistance are the most suitable gage parameters and that resonant frequency is the least suitable parameter.

For versatility in the measurement of various uncalibrated or impure fluids, the gage can be designed to operate in a differential mode. The differential gage would consist of two chambers separated by a diaphragm. One side of the diaphragm would see the fluid whose pressure is to be determined, while the other side would be filled with a known gas such as pure helium and contain the quartz crystal. The diaphragm would incorporate a device to sense its deflection with respect to a reference and function as a null differential pressure indicator. The volume of the calibrated gas in the crystal chamber can be made very small, for example, a few cubic centimeters.

Viscosity

An oscillatory torsional crystal will propagate shear waves into the gas medium surrounding it. At high frequencies (e.g., 12 kHz) these waves will be damped out a short distance (μm) from the crystal surface. Fundamentally, the gas that surrounds the crystal affects the crystal characteristics in two ways. First, the gas absorbs the energy that is supplied by the crystal. This phenemenon is reflected as an increase in the crystal's resistance at its series resonant frequency. Second, the gas has a tendency to be dragged along as the crystal oscillates. This effectively increases the inertia of the crystal, causing the resonant frequency to be less than when the gas is not present. The effect of the gas on the crystal's electrical properties, called "crystal loading," is dependent on the viscosity-density product of the gas. This product can be determined by measuring the change in the crystal's resistance or by measuring the shift in the resonant frequency (eqs. (2) and (3)). Since the density of a gas is better known as a function of pressure either from experimental work or computer extrapolation, the viscosity can be determined from $\eta\rho$.

There are practical limitations to measuring both the crystal's resistance and the resonant frequency. Although the resistance is only several thousand ohms when the crystal is in a vacuum, its resistance increases very rapidly with pressure, and the measurement becomes less reliable at high pressures with the bridge used here. The change in frequency technique requires measurement of approximately 1 part in 10^6 to 10^8, depending on the gas pressure. In our opinion any unaccountable reactive loading could cause an appreciable frequency shift that would not reflect the true influence of pressure on the viscosity-density product. However, measurement by both techniques were attempted in this work.

Helium. - Because the density of helium is smaller than most other gases and because the frequency shift was not in the proper direction according to theory (see fig. 7), the resistance technique was used for determining the viscosity of helium as a function of pressure. The $\eta\rho$ product is related to the change in crystal resistance in the following manner:

$$\eta\rho \simeq \frac{\left(R_x - R_{x,vac}\right)^2}{K_o^2 S^2 f_r \pi}$$

as defined previously in equation (2).

From the results of this experiment the correction for K_o as a function of pressure is given by the following expression:

$$\left.\begin{aligned} K_0 &= 5.58\times10^3\left(\frac{P}{24.27\times10^6}\right)^{-0.0524} && \text{in SI units} \\ K_0 &= 5.58\times10^3\left(\frac{P}{3520}\right)^{-0.0524} && \text{in U.S. Customary units} \end{aligned}\right\} \tag{7}$$

where P is limited to a range between 24.3×10^6 to 135×10^6 newtons per square meter (3520 to 19 600 psi). Over this pressure range K_0 changes less than 9 percent.

The dependence of $\eta\rho$ for helium on pressure is shown in figure 9. Experimental data below 2500 psi as reported by Gracki et al. (ref. 5) are also shown in this figure. As can be seen, for pressures above 2500 psi, the data from the present investigation have a greater scatter, which in our opinion is due to band width measurements required to measure K_0. At the upper pressure region, the band widths were such that upper and lower half-power points did not fall in the same range of the ultrastable oscillator. Because of the partial breakdown of our frequency meter, dial reading of the ultrastable oscillator was used to measure frequency differences for band width measurements. The bracketed numbers represent the sequence in which the data were measured. There does not seem to be any inherent hysteresis in the torsional crystal system. Also, the gas temperature is indicated for each data point. The density against pressure as shown in the figure was determined using McCarty's computer program (ref. 6). Figure 10 shows a comparison between viscosity values η_{exp} determined from our measured $\eta\rho$ product against pressure and the viscosity data η_{th} generated from McCarty's program (ref. 6). The experimental viscosity values for helium gas were determined by dividing the measured product $\eta\rho$ from this investigation by density values obtained from McCarty's program. Since the calculated density of a gas can be assumed to be more accurate than the calculated viscosity from such a program, we conclude that the viscosity of helium at high pressures does not increase as rapidly with pressure as McCarty's program predicts.

Argon. - Because $\eta\rho$ of argon is about 11 times the $\eta\rho$ of helium, at room temperature and at the same pressure, the crystal loading will be approximately three or four times greater. From this investigation we found that for argon at 13.8×10^6 newtons per square meter (2000 psi) or higher our bridge was not very effective. On the other hand, argon should be very suitable for use in the frequency shift technique. This technique does not require that the absolute value of resonant resistance be known but only that the bridge is balanced at resonance.

The value of $\eta\rho$ as reported by Michels, Botzen, and Schuurman (ref. 4) and the results from this investigation are shown in figure 11 as a function of pressure. For ease of comparison our results were normalized to the data of reference 4 by adjusting our lowest data point to the data of reference 4. (In this investigation the results for helium gas were not normalized.) The density against pressure as shown in the figure was determined using the results from a NASA computer program called GASP (ref. 7). Assuming that the density of argon against pressure generated by GASP is correct, the corresponding measured products $\eta\rho$ from this investigation were divided by the GASP density values to obtain the experimental viscosity coefficient as a function of pressure. These values are shown in figure 12 along with results from other investigators (refs. 4, 5, and 7). The results from frequency shift measurements were not in good qualitative agreement with the published results of other investigators, so we conclude the resonant frequency shift is a poor method for measuring $\eta\rho$ and a poor pressure gage parameter. An unaccounted reactance term can produce a resonant frequency that is misleading. This is true even if the disturbing reactance term is small because the series resonant frequency, which is the root of the reactance equation, may be very sensitive to minor disturbances. In the case of the resistance technique, any small resistive disturbances will be comparatively less significant.

CONCLUSIONS

The torsional crystal was a suitable pressure sensor up to 131×10^6 N/m^2 (19 000 psi), and there is reason to believe that it could be used at considerably higher pressures. It exhibits no apparent hysteresis. The crystal parameters best suited for calibration as a function of pressure were the crystal decrement and the crystal resonant electrical resistance. Measurement of the crystal decrement directly should greatly simplify the instrumentation and measuring time required for pressure measurements. For pressure measurements above 7×10^7 newtons per square meter (10 000 psi) the torsional crystal gage should function best in a differential mode with pure helium gas surrounding the crystal at the pressure of interest, and this gas then coupled to the fluid pressure to be measured.

It we assume that McCarty's program can be used to estimate the density of helium gas above 7×10^7 newtons per square meter (10 000 psi) with better certainty than the viscosity coefficient, we conclude that McCarty's calculated values of η above this pressure are increasing far more rapidly with increasing pressure than the true viscosity values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 6, 1972,
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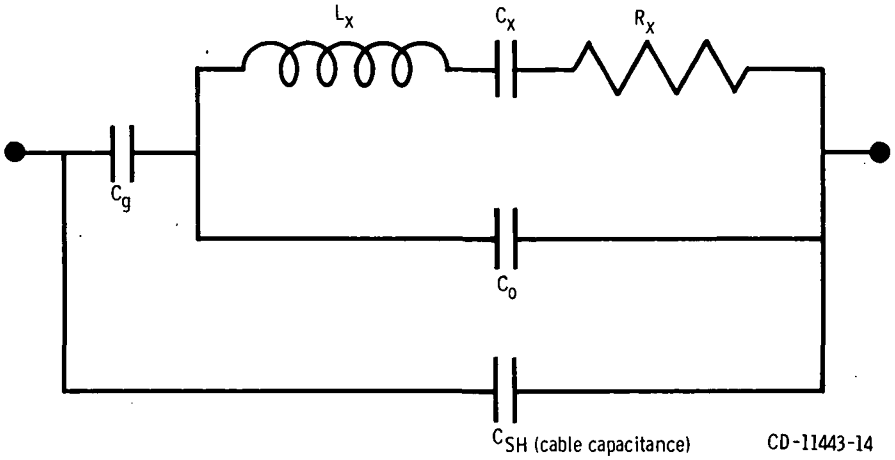

Figure 1. - Crystal equivalent circuit.

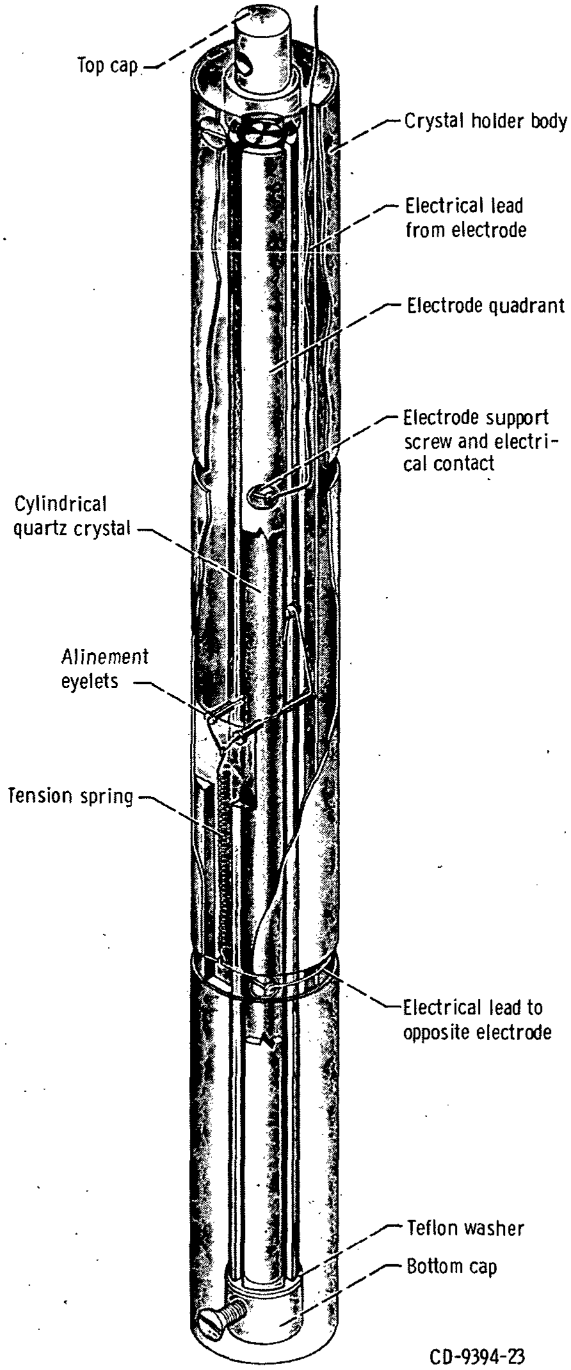

Figure 2. - Torsional crystal suspension system.

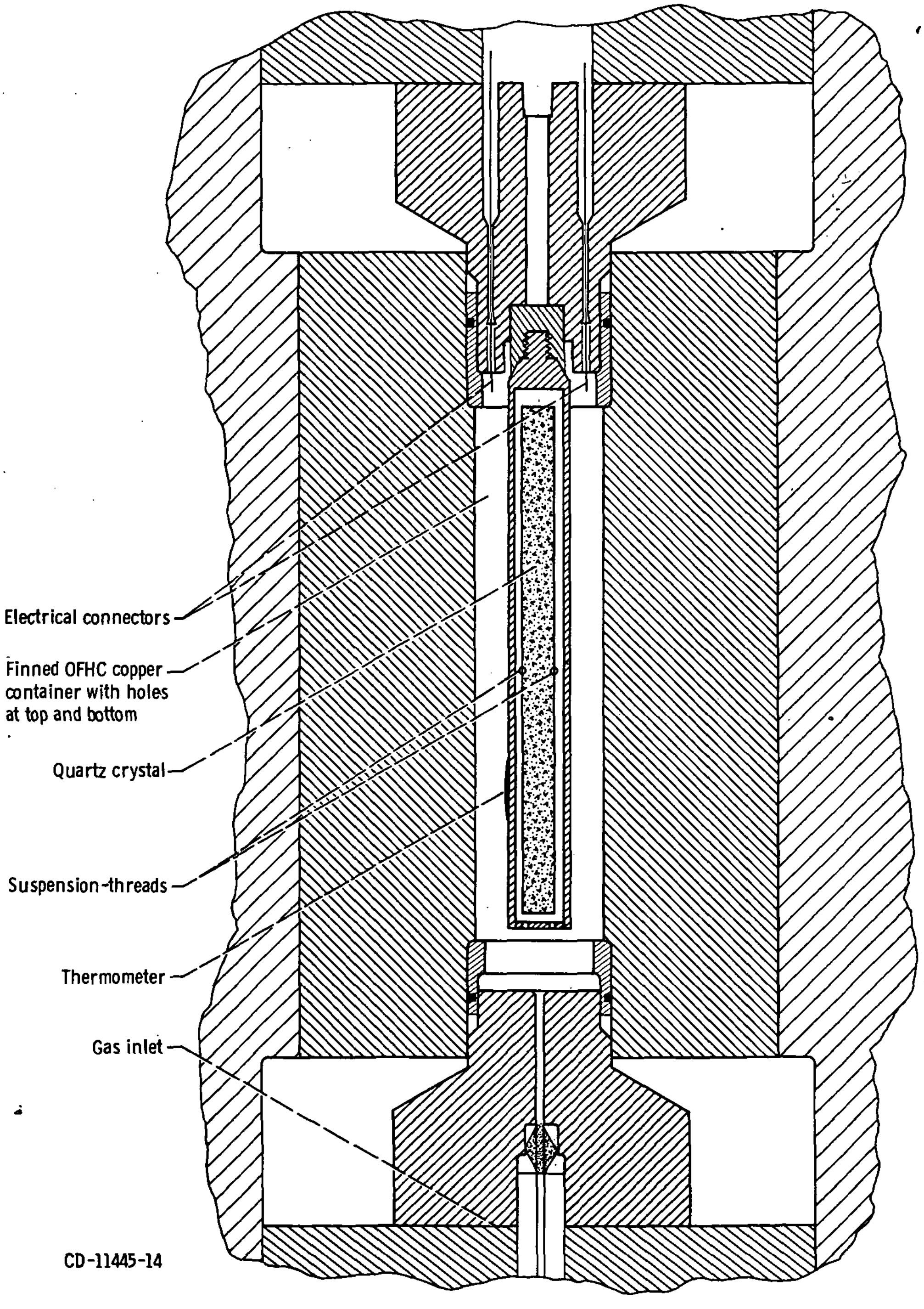

Figure 3. - Pressure vessel with torsional crystal holder.

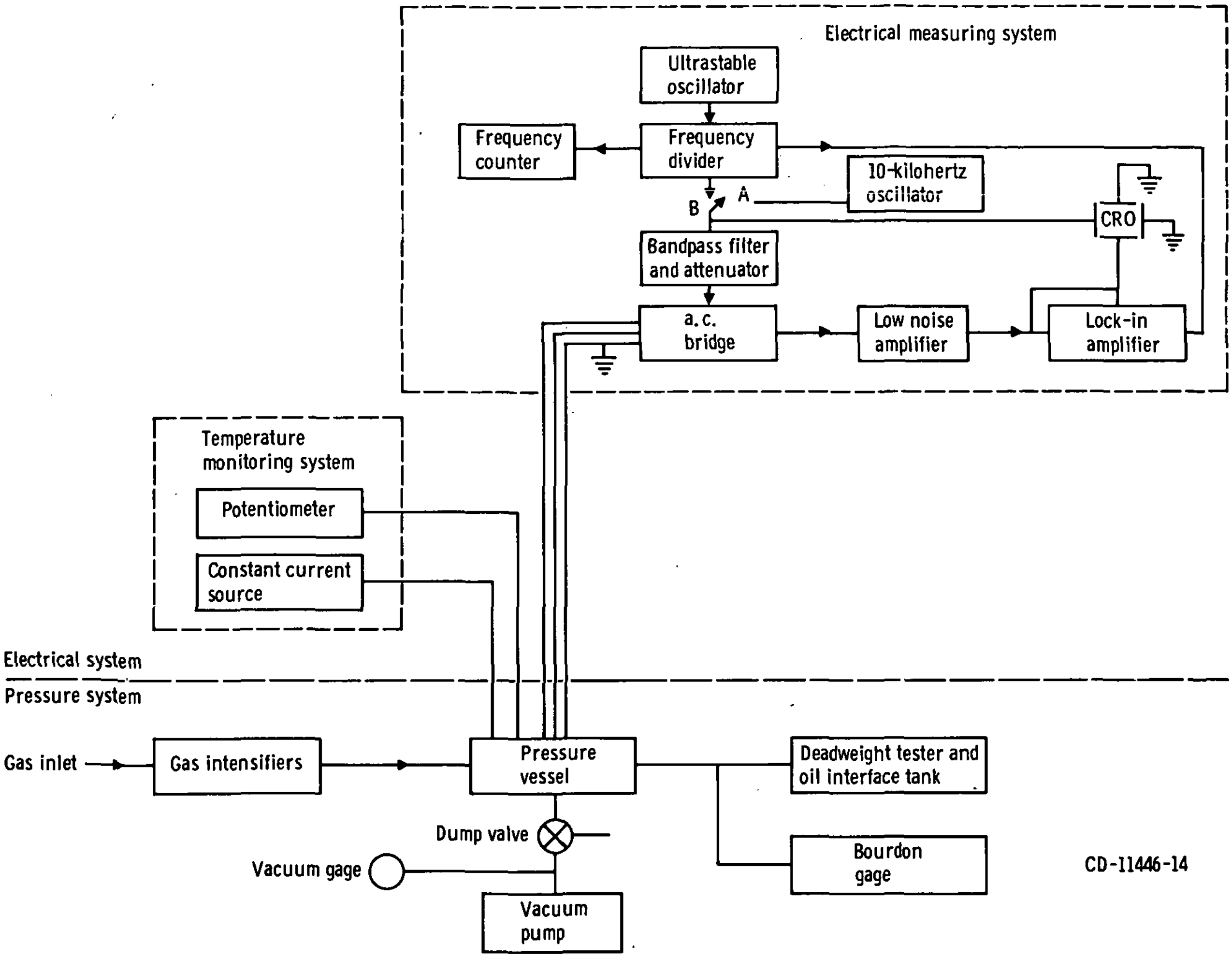

Figure 4. - Block diagram of experimental setup.

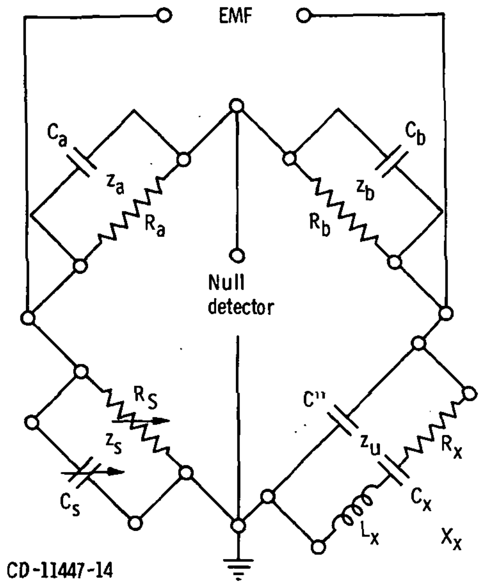

Figure 5. - Circuit of ac capacitance bridge for viscosity times density measurements. Crystal reactance (0 at resonance), and $z_a = z_b$, z_s, z_u are arm impedances.

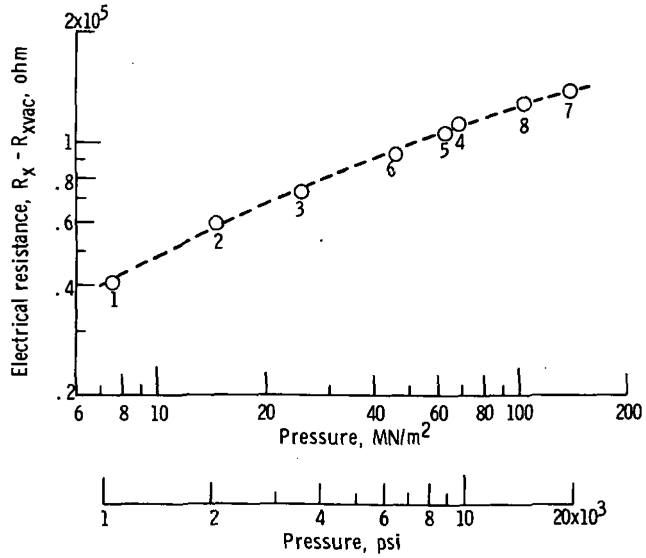

Figure 6. - Crystal series resonant resistance as function of pressure in helium gas. Crystal resonant resistance in vacuum, 1840 ohms. Numbers by data points show chronological order of data.

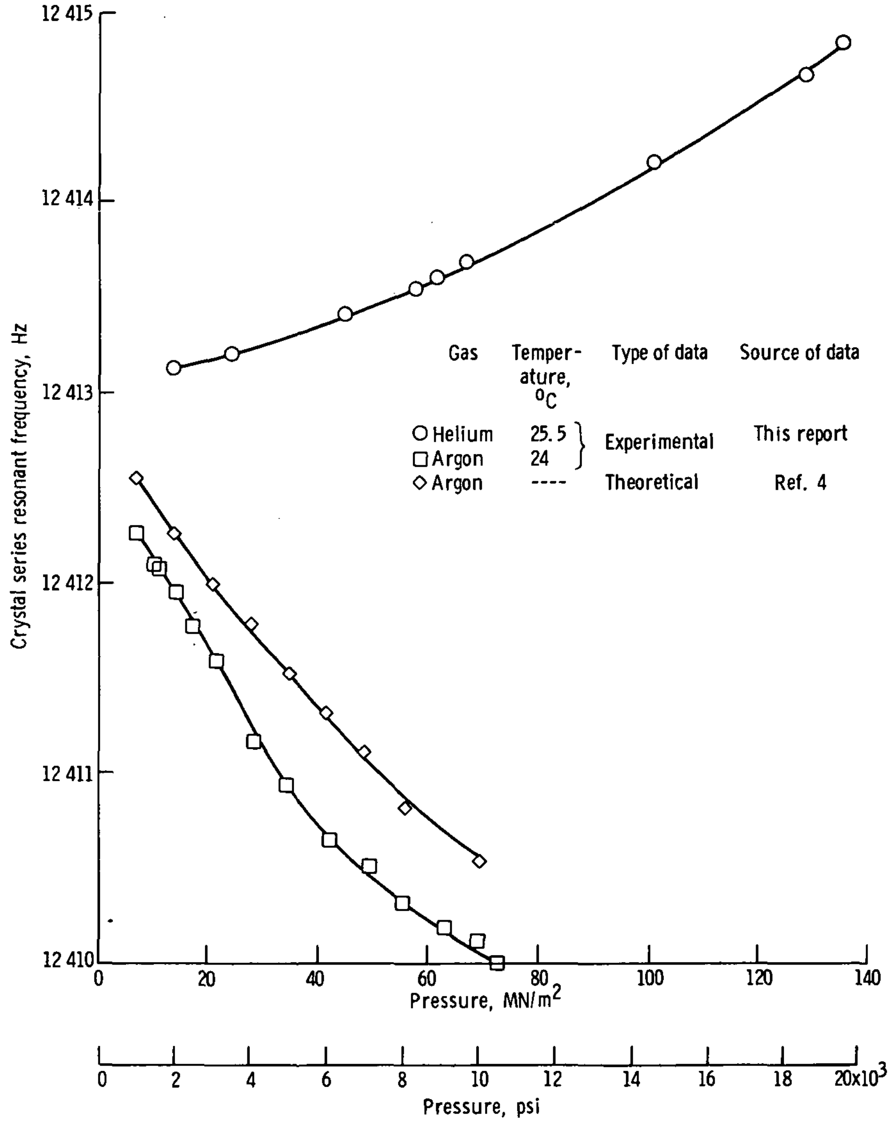

Figure 7. - Crystal resonant frequency as function of pressure (helium and argon gases).

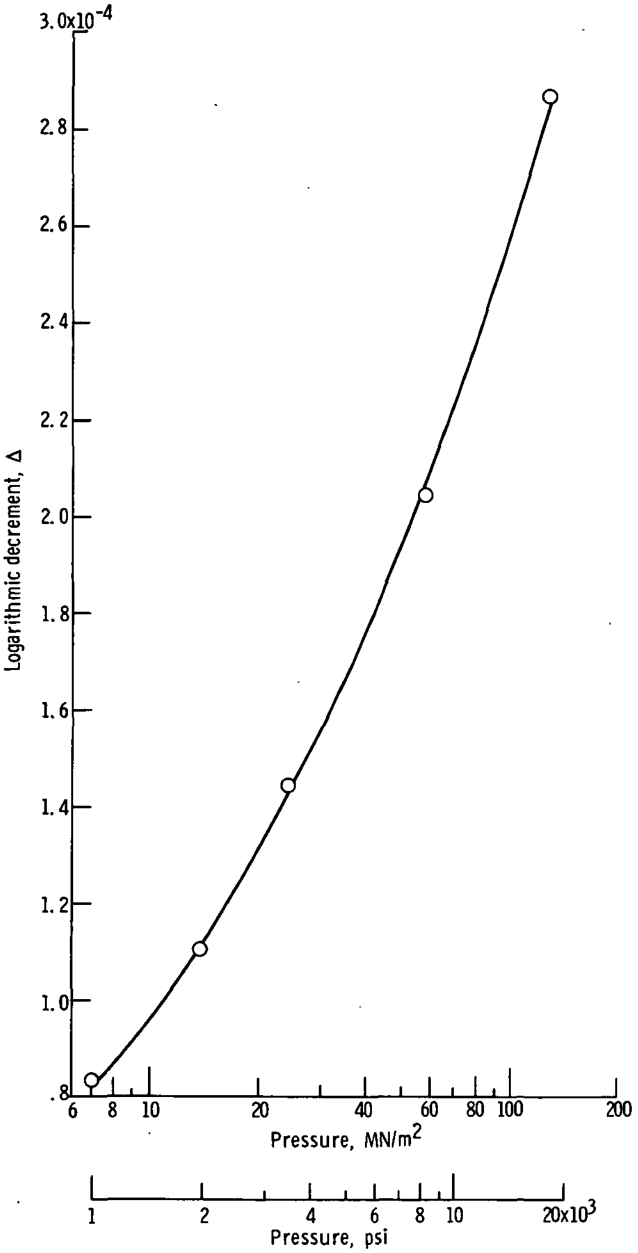

Figure 8. - Logarithmic decrement as function of pressure; gas, helium.

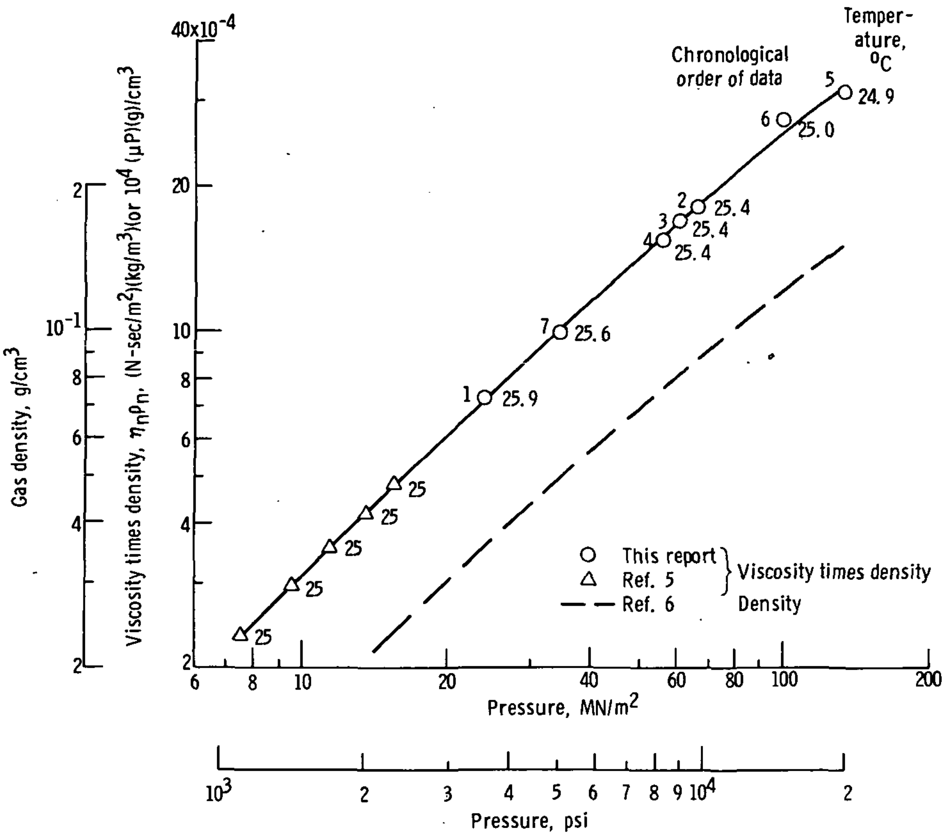

Figure 9. - Viscosity times density and density of helium as function of pressure.

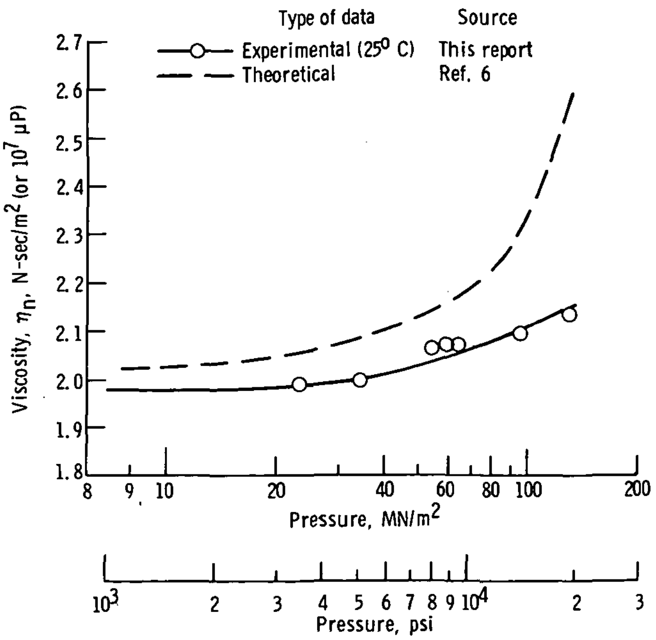

Figure 10. - Viscosity of helium as function of pressure.

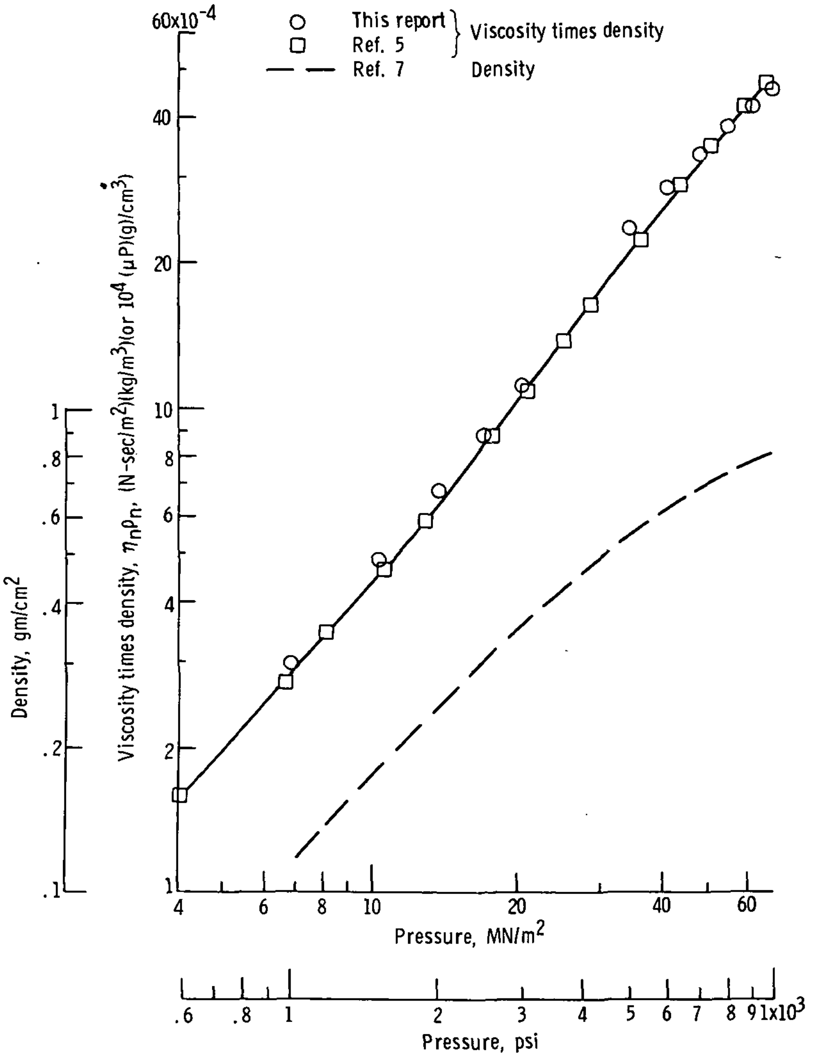

Figure 11. - Viscosity times density and density of argon as function of pressure.

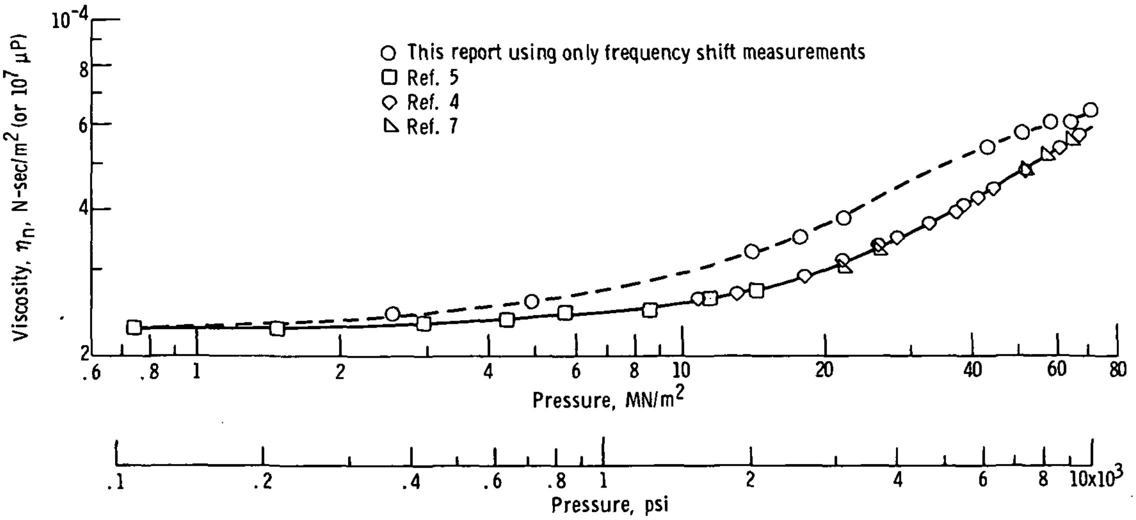

Figure 12. - Viscosity of argon as function of pressure.

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