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HIGH PRESSURE GAS METERING PROJECT

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SYMBOLS

A = Cross-sectional area of the capillary

a_0, a_1, a_2, a_3 = Coefficients that minimize the mean square error between the Z-values calculated by Eq. (5) and the actual Z-values over the range of pressure 0 to 185 MPa.

b_0, b_1, b_2, b_3 = Coefficients that minimize the mean square error between the speed of sound calculated by Eq. (10) and the actual speed of sound.

c = Speed of sound in the gas.

c(P) = Speed of sound approximated by Eq. (10).

k = Isentropic constant for the gas.

L = Length of the capillary.

M = Mach number of the flow.

$M[P_1(2), P_2(2)]$ = Mach number approximation used in Eq. (12) measured at time 2.

$\dot{m}$ = Mass flow rate.

$\dot{m}(1)$ = Mass flow rate at the starting time 1.

$\dot{m}(2)$ = Mass flow rate at some later time 2.

P_1 = Capillary entrance pressure.

P_2 = Capillary exit pressure.

$\dot{P}$ = Pressurization rate.

$\dot{P}(1)$ = Pressurization rate at the starting time 1.

$\dot{P}(2)$ = Pressurization rate at some later time 2.

$P_1(n)$ = Capillary entrance pressure at some time n.

R = Universal gas constant divided by the molecular weight.

T = Absolute temperature of the gas.

T_1 = Capillary entrance temperature.

T_2 = Capillary exit temperature.

T(1) = Temperature at the starting time 1.

T(2) = Temperature at some later time 2.

V_1 = Capillary entrance velocity.

V_2 = Capillary exit velocity.

v = Volume of the test vessel.

Z = Compressibility of the gas.

Z(P) = Compressibility approximated by Eq. (5).

$Z(P_2(2))$ = Compressibility approximated using the exit pressure measured at time 2.

$\dot{Z} = \frac{dZ}{dt}$.

ρ_1 = Capillary entrance density.

ρ_2 = Capillary exit density.

$\Delta\bar{\rho}$ = Average change in density in the capillary.

$\dot{\rho} = \frac{dZ}{dt}\rho$.

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ABSTRACT

This paper outlines the initial research and development of a system that uses high pressure helium gas to pressurize vessels over a wide range of pressurization rates, vessel volumes, and maximum test pressures. A method of controlling the mass flow rate in a test vessel has been developed by using the pressure difference across a capillary tube. The mass flow rate is related to the pressurization rate through a real gas equation of state. The resulting mass flow equation is then used in a control algorithm. Plots of two typical pressurization tests run on a manually operated system are included.

INTRODUCTION

Acoustic emission testing of pressure vessels has proven to be a valuable tool for nondestructive inspection. For accurate and interpretable results, this testing method requires that the test vessel pressure vs time profile be repeatable from test to test. In addition, it is desirable to be able to vary the pressure vs time profile, since acoustic emission from a test vessel is sensitive to the rate of pressurization.

Up until now, the only system available at Lawrence Livermore National Laboratory that could meet these two requirements, repeatability and variable pressure vs time profiles, is a liquid-filled system. For many tests it is desirable to use a gas-filled system, especially when the test vessel has been designed for such use. Unfortunately, a gas-filled system that meets the design requirements requires a much more sophisticated control scheme than that required for the liquid-filled system.

These design parameters for the gas-filled pressurization system are as follows:

- Test vessel volume: 5 to 1000 cm^3 (0.3 to 60.0 $in.^3$)
- Pressurization rate: 0 to 14.0 MPa/min (0 to 2000 psi/min)
- Test pressure: 0 to 185 MPa (0-27000 psi)

The worst case situation from a controller point of view is when the test vessel volume is near 5 cm^3, the pressurization rate is slow (350 kPa/min ≈ 50 psi/min), and the test pressure is near 185 MPa ≈ 27000 psi.

In this case, a conventional metering valve functions poorly because the flow is at the low end of its range and a small error in the positioning of the valve stem can drastically change the gas flow. An investigation of commercial, high pressure valves indicated that none were capable of the required positioning accuracy. In addition, the cross-seat leakage would become worse with use if the valve stem were repeatedly seated. The mass flow rate into the test vessel must be constantly varied to compensate for the compression of the gas, requiring continual valve stem positioning.

A fixed area restriction can provide the required small flow. The most direct way of varying the mass flow rate through a fixed area restriction is by controlling the pressure difference across it. This was successfully implemented in the experimental system.

The details of accurate mass flow control with a constant pressurization rate are covered in the next two sections.

ANALYSIS OF THE MASS FLOW RATE

The problem is illustrated in Fig. 1.

In Fig. 1 ρ_1 = entrance density,
T_1 = entrance temperature,
P_1 = entrance pressure,
ρ_2 = exit density,
T_2 = exit temperature,
P_2 = exit pressure,
$\dot{m}$ = mass flow rate into test vessel (mass/unit time).

The fixed area restriction shown in Fig. 1 is a capillary tube as used in the experimental system. The problem is to find $\dot{m}$, given some set of entrance and

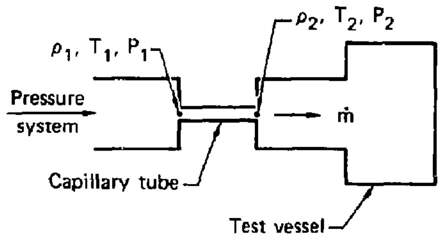

FIG. 1. Symbolic representation of gas flow analysis.

exit conditions; it can then be related to the pressurization rate of a known volume.

Since we are dealing with a closed system, the law of conservation of mass can be used. The law of conservation of mass[1] requires that

$$\rho_1 V_1 A = \rho_2 V_2 A + AL\, \Delta\, \bar{\rho} \quad \text{(see Fig. 2)}. \tag{1}$$

In Fig. 2 A = cross-sectional area of the capillary tube,

V_1 = entrance velocity,

V_2 = exit velocity,

L = length of capillary tube,

$\Delta\bar{\rho}$ = average change in density in the capillary tube $\cong \frac{\rho_2 - \rho_1}{2}$,

This relation is shown in Fig. 2. This means that the mass entering must equal the mass leaving plus the change in the mass of the gas in the tube. Because of the small size of the capillary tube, the last term in Eq. (1) can be ignored. This leaves us with

$$\rho_1 V_1 A = \rho_2 V_2 A \quad . \tag{2}$$

Since by definition $\dot{m} = \rho_1 V_1 A = \rho_2 V_2 A$, it seems at first glance that the problem of finding $\dot{m}$ is a trivial one; simply measure ρ_2, V_2, and A. Unfortunately, for the system we are dealing with, ρ_2 and V_2 are difficult to measure directly, so one must calculate them from pressure and temperature measurements using properties of real gases.

A thermally perfect gas is categorically defined by the perfect-gas equation of state:

$$P = \rho\ RT \quad , \tag{3}$$

where

P = absolute pressure of the gas

ρ = density of the gas

R = universal gas content divided by the molecular weight

T = absolute temperature of the gas.

The state of most all gases can be closely approximated using the perfect-gas equation of state when the gas is at high temperature and low

1. R. W. Fox and A. T. McDonald, Introduction to Fluid Mechanics (John Wiley and Sons, Inc., New York, N.Y., 1973).

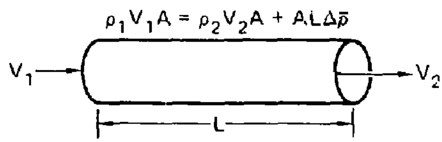

FIG. 2. Mass flow through capillary tube.

pressure. This is clearly not the condition in our system when the maximum test volume pressure is 185 MPa. One must therefore take into account two important properties of real gases: (1) compressibility and (2) the variability in the speed of sound with density as well as temperature.

The first property of real gases is accounted for by changing Eq. (3) to read

$$P = \rho ZRT \quad , \tag{4}$$

where

Z = compressibility of the gas.

Z is difficult to accurately calculate because it involves the thermodynamic and mechanical properties of the gas, which vary with pressure and temperature. Fortunately, Z values are tabulated for several common gases over a wide range of temperatures and pressures (see Appendix A[2]). Since the compressibility is a smooth function of pressure for a specific temperature, it can be approximately calculated by a third-order polynomial equation in pressure,

$$Z(P) = a_0 + a_1P + a_2P^2 + a_3P^3 \quad , \tag{5}$$

where a_0, a_1, a_2, a_3 = the coefficients that minimize the mean square error between the Z-values calculated by Eq. (5) and the actual Z-values over the range of pressure 0 to 185 MPa. Therefore, for a specific temperature the density of the gas exiting the capillary tube is a function of only the exit pressure that is easily measured. Rearranging Eq. (4) gives us

$$\rho = \frac{P}{Z(P)RT} \quad , \tag{6}$$

where Z(P) is approximated at temperature T.

The other variable from Eq. (2) that we need to calculate is the exit velocity, V_2. The exit velocity, V_2, can be determined from the pressures and temperatures of the system to obtain a very good estimate of the flow conditions in the capillary tube (see Recommendations for Further Work), but results in a complicated equation. By assuming a much simpler isentropic flow through the capillary, it is possible to get a fair estimate of the exit velocity from a single equation. (Isentropic flow is defined as a reversible

2. G. L. Clark, Real Gas Equation-of State Capability at Sandia Livermore, Sandia Laboratories, Livermore, CA, Rept. SAND 78-8200 (1978), p. 221.

adiabatic flow. The section just mentioned explains why this is a rather crude estimate of the flow.)

The ratio of the stagnation density to the static density of an ideal gas in isentropic flow is equal to a function of the Mach number of the flow.

$$\frac{\rho_0}{\rho} = \left[1 + \left(\frac{k-1}{2}\right) M^2\right]^{\frac{1}{k-1}} , \tag{7}$$

where

ρ_0 = stagnation density, e.g., the density that would be obtained at any point in the flow field if the fluid at that point were decelerated to zero velocity following an isentropic process.

ρ = static density, e.g., the density of the fluid at a point measured under local conditions of velocity.

k = isentropic constant for the gas.

M = local Mach number where the stagnation and static densities are measured.

An estimate of the exit Mach number can be obtained from Eq. (7) if we let $\rho_0 = \rho_1$, the entrance density, and $\rho = \rho_2$, the exit density. Since an isentropic flow was assumed, the entrance stagnation density equals the exit stagnation density. A further simplification equates the entrance stagnation density and the entrance density. This yields

$$\frac{\rho_1}{\rho_2} = \left[1 + \left(\frac{k-1}{2}\right) M^2\right]^{\frac{1}{k-1}} . \tag{8}$$

This means that the ratio of the entrance to exit densities which are related to pressure in Eq. (6), is equal to a function of the Mach number of the flow. The Mach number is defined by the equation

$$M = \frac{V}{c} , \tag{9}$$

where c = speed of sound in the gas where the velocity is measured.

So by knowing M and c one can find V. M is related to the pressures in the system through Eq. (7), therefore, an equation relating the speed of sound to pressure is also needed.

The equation for the speed of sound in a gas is the second property that distinguishes real gas properties from perfect gas properties. The equation for the speed of sound in a real gas is a complicated partial differential equation in Z, P, and T (see Appendix B[3]). From plotted values of c for real gases, one can see that it too is a smooth function of pressure for a specific temperature. Therefore, one can get a good estimate of c as a polynomial function of pressure just as we did with compressibility. So

$$c(p) = b_0 + b_1 P + b_2 \rho_2 + b_3 \rho^3 \quad , \tag{10}$$

where b_0, b_1, b_2, b_3 = the coefficients that minimize the mean square error between the speed of sound calculated by Eq. (10) and the actual speed of sound over the range of pressure 0 to 185 MPa.

Equation (8) is only valid when $\rho_1 \geq \rho_2$. By convention, V is always positive and c is the magnitude. Equation (9) restricts M to be a positive number. One can further restrict the values of M for our system to be between 0 and 1 by noting that the transition from subsonic to supersonic flow (i.e., $M > 1$) requires a converging-diverging nozzle which is absent in our system. Other factors related to the friction of the gas with the capillary tube wall further ensure that $0 \leq M \leq 1$ (see Recommendations for Further Work).

The condition $M = 1$ is called choked flow; it simply means that any increase in ρ_1/ρ_2 beyond some critical ratio will not increase M above one. The critical ratio is defined as

$$\frac{\rho_1}{\rho_2} = \left[1 + \left(\frac{k - 1}{2}\right)\right]^{\frac{1}{k-1}} \quad , \tag{11}$$

which is just Eq. (8) with $M = 1$.

It is possible now to use Eqs. (8), (9), and (10) to find the velocity V as a function of pressure.

$$V = cM \cong c(P)\ M\left[P_1, P_2\right] = c(P)\sqrt{\frac{2}{k-1}\left[\left(\frac{\rho_1}{\rho_2}\right)^{k-1} - 1\right]} \quad . \tag{12}$$

Equations (7) and (12) can be used to calculate $\dot{m}$ as a function of pressure.

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3. Compressed Gas Handbook, Revised, J. S. Kunkle, S. D. Wilson, and R. A. Cota, Eds., National Aeronautics and Space Administration, Washington, D.C., Rept. NASA SP-3045 (1969).

Now that one can calculate $\dot{m}$, one must relate $\dot{m}$ to the pressurization rate, $\dot{P}$, in the test vessel. By differentiating Eq. (4) with respect to time for a constant temperature one gets

$$\dot{P} = (\dot{\rho} Z + \dot{Z} \rho)\ RT \quad . \tag{13}$$

The $\dot{Z}\rho RT$ term only becomes a significant portion of $\dot{P}$ at pressures approaching 70 MPa (10 000 psi) and was ignored for simplicity in this study. This leaves us with the following equation for the pressurization rate:

$$\dot{P} = \dot{\rho} ZRT \ . \tag{14}$$

By noting that the density of the gas inside a fixed volume is equal to the mass of the gas divided by the volume of the vessel, one can write

$$\dot{P} = \frac{d}{dt} \left(\frac{m}{v} \right) ZRT \ , \tag{15}$$

where

v = volume of the test vessel.

Since the volume of the test vessel is a constant for this system, Eq. (15) can be rewritten as

$$\dot{P} = \dot{m} ZRT/v \ . \tag{16}$$

Now the pressurization rate of the test vessel is a function of the mass flow into the test vessel. A more accurate estimate of $\dot{P}$ for real gases can be derived by using Eq. (13) (see Recommendations for Further Work).

If the pressurization rate is to be a constant, then

$$\dot{P}(1) = \dot{P}(2) \ , \tag{17}$$

where

$\dot{P}(1)$ = pressurization rate at time 1.

$\dot{P}(2)$ = pressurization rate at some later time 2.

Substituting from Eq. (16) into Eq. (17) one gets

$$\dot{m}(1)\ \frac{1}{v}\ RT(1) Z(1) = \dot{m}(2)\ \frac{1}{v}\ RT(2) Z(2) \quad . \tag{18}$$

If one assumes the temperature of the gas is constant, then Eq. (18) can be reduced to

$$\dot{m}(1)Z(1) = \dot{m}(2)Z(2) \ . \qquad (19)$$

If we specify $\dot{m}$ and Z for any instant in time, then Eq. (19) can be used to calculate the correct $\dot{m}$ at a later instant in time that will give us a constant pressurization rate.

How one finds $\dot{m}$ and Z for that first instant in time, and how the equations of this section can be used to design a gas pressure ramping system will be presented next.

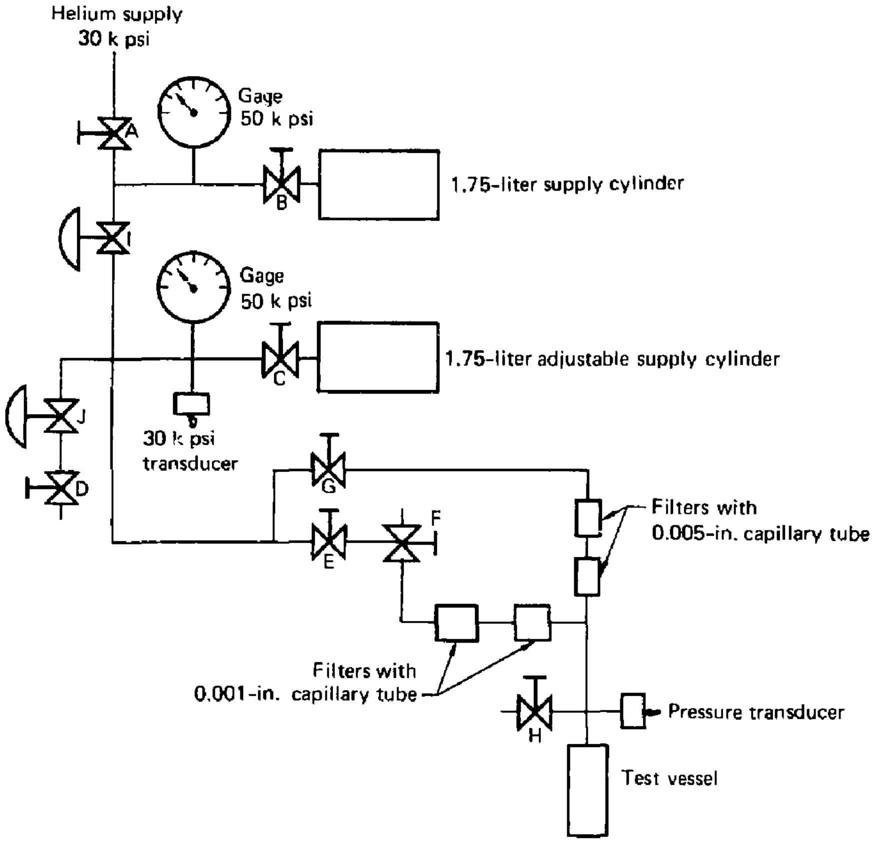
DESIGN OF THE EXPERIMENTAL SYSTEM

In previous sections, the cross-sectional area of the capillary tube, A, was assumed to be known. This assumption is not entirely correct.

A photomicrograph of the cross section of a sample of capillary tubes of the same nominal diameter reveals that the cross-sectional area varies significantly from tube to tube.

This variation along with other differences implies that the initial mass flow rate to be used in Eq. (19) must be found experimentally for each capillary tube to be used in the system. An experimental procedure will be presented later.

Figure 3 is a diagram of the experimental system used to control the pressurization rate of a vessel by adjusting the pressure drop across a capillary. In this system there are three different size restrictions between the adjustable supply cylinder and the test vessel. The restrictions are 0.001- and 0.005-in.-diam capillaries that can be individually selected by valves E and G or used together. Since the test vessel pressure is determined during the tests, one must adjust the entrance pressure of the restriction to achieve the correct flow by filling and venting the adjustable supply. Notice that the fill valve I is connected to a supply cylinder instead of directly to the house helium supply line. In the experimental system, pressure differences of more than 350 MPa across the slow acting fill valve would cause overfilling of the adjustable supply. The supply cylinder is the source of the lower pressure helium. Some possible methods of eliminating the supply cylinder are outlined in Recommendations for Further Work.



Valves

A. Supply inlet
B. Supply cylinder shutoff
C. Adjustable supply cylinder shutoff
D. Supply manual vent
E. Test/0.001-in. capillary
F. Vent 0.001-in. capillary
G. Test/0.005-in. capillary
H. Test vessel vent
I. Adjustable supply cylinder, air-operated
J. Adjustable supply vent, air-operated

FIG. 3. Diagram of the experimental system.

It was stated earlier that in order to use Eq. (19), both $\dot{m}(1)$ and $Z(1)$ need to be specified. $Z(1)$ can be approximated by 1.0 for pressures below 10.0 MPa.

From Eqs. (6) and (12)

$$\rho = \frac{P}{Z(P)RT} , \tag{6}$$

$$V = cM \cong c(P)\sqrt{\frac{2}{k-1}\left[\left(\frac{\rho_1}{\rho_2}\right)^{k-1} - 1\right]} , \tag{12}$$

where $\dot{m}(1) = \rho(1)AV(1)$ is a function of $P_1(1)$, $P_2(1)$, and A. Of the three variables, only $P_2(1)$, the initial test vessel pressure is known.

A test must be performed on the experimental system to determine $P_1(1)$ given that $P_2(2)$ equals one atmosphere and A is some unknown constant.

The adjustable supply cylinder is precharged to some $P_1(1)$ value and the initial pressurization rate of the test vessel is recorded. The supply pressure, $P_1(1)$, divided by the initial pressurization rate shows what supply pressure is needed for each MPa/min to determine the initial pressurization rate. This characterizes the capillary for the specific test vessel volume used in the experiment. Dividing this number by the volume of the test vessel makes the capillary characteristic independent of volume.

$$\text{Capillary characteristic} = \frac{\text{initial supply pressure}}{\text{test volume} \times \text{initial pressurization rate}} . \tag{20}$$

After the capillary characteristic is experimentally determined, then Eq. (20) can be rearranged to calculate the initial supply pressure for any arbitrary rate and volume.

At last we have all the pieces necessary to pressurize a test volume at some desired constant rate. The next section describes a computer algorithm that calculates the adjustable supply pressures needed for a given pressurization rate, test volume, and temperature.

A controlled depressurization of the test vessel has been achieved by controlling the restriction exit pressure. The details are very similar to the pressurization of the test vessel and therefore will not be discussed here.

CONTROL ALGORITHM

Before each test one must specify several parameters so the correct adjustable supply cylinder pressure will be calculated. These parameters are the test vessel volume, the pressurization rate, the maximum test pressure, the number of corrections to the adjustable supply cylinder pressure per minute, and the capillary characteristic of the capillary to be used. Choice of the last two parameters is not entirely free. The number of corrections per minute to the adjustable supply cylinder pressure is usually determined by the pressurization rate. Higher rates require more frequent corrections to the adjustable supply pressure. If the capillary is too small, then $P_1(1)$ will exceed the maximum available pressure. A capillary that is too large results in an uncontrollably small difference in pressure between the adjustable supply cylinder and the test vessel.

Using Eq. (19) we first specify $\dot{m}(1)$ and then calculate later adjustable supply pressures $P_1(2)$, so that $\dot{m}(2)$ and $Z(2)$ satisfies Eq. (19). Therefore, the output from the algorithm should be a tabulation of P_1, P_2, and the corresponding time. The FORTRAN programs, INTERACT and DOWNRAMP, for calculating this algorithm are listed as Appendixes C and D, respectively.

The first value of the adjustable supply pressure $P_1(1)$ is found expressionally as described in the previous section. All values of the test vessel pressure are determined by the equation

$$P_2(n) = (\text{pressurization rate}) \times (n) \times (\text{supply correction interval}), \quad (21)$$

where

n = integer time increments; 1, 2, 3...

Using $\dot{m} = \rho AV$ in the right hand side of Eq. (19) gives $m(1)Z(1) = \rho(2)V(2)AZ(2)$. Evaluating $\rho(2)$ and $V(2)$ at the entrance conditions using Eqs. (6) and (12), and $Z(2)$ at the exit condition yields

$$\dot{m}(1)Z(1) = \frac{P_1(2)}{Z(P_1(2))RT}\, C\left[P_1(2)\right]\, M\left[P_1(2),\ P_2(2)\right]\, AZ\left[P_2(2)\right] \quad . \qquad (22)$$

$P_1(2)$ is sufficiently embedded in Eq. (22) so as to make solving for it iteratively easier than solving for it explicitly. To do this one rewrites Eq. (22) as the error function

$$\text{error} = \frac{P_1(2)}{Z\left[P_1(2)\right]RT}\, C\left[P_1(2)\right]\, M\left[P_1(2),\ P_2(2)\right]\, AZ\left[P_2(2)\right] - \dot{m}(1)Z(1)\,. \qquad (23)$$

The error will be zero when $P_1(2)$ is exactly correct, positive when $P_1(2)$ is too large, and negative when $P_1(2)$ is too small. We can take advantage of this sign change when trying to find $P_1(2)$ by bracketing $P_1(2)$ into a smaller and smaller interval. Obviously one cannot hope to make the error exactly zero, so one sets a tolerance of $-\varepsilon \leq \text{error} \leq \varepsilon$ where ε is some small positive quantity.

An initial estimate is needed to start the iterative procedure for finding $P_1(2)$. A good selection for $P_1(2)$ is the previous value $P_1(1)$. Some multiple of the error is then subtracted from the initial guess to give us a better guess. Notice that as the magnitude of the error gets smaller so will the magnitude of the number subtracted. This will bracket each guess into a smaller interval until the error tolerance is satisfied. So, in general, $P_1(n)$ is found the same way using $P_1(n - 1)$ as the initial guess.

SAMPLE TESTS USING THE EXPERIMENTAL SYSTEM

Figures 4 and 5 are reproductions of two typical pressure histories for both the adjustable supply cylinder and the test vessel.

Figure 4 is the test of a 500 cm^3 test vessel at a pressurization rate of 250 psi/min to a maximum pressure of 7500 psi. Notice that the adjustable supply cylinder pressure goes down from its initial pressure and then goes up. This behavior is due to the compression of the gas in the test vessel. The rather jagged appearance of the adjustable supply cylinder pressure vs time curve is due to the opening and closing of the fill and vent valves, I and J in Fig. 3. This jagged pressure correction is all but completely isolated from the test vessel by the capillary. This capillary effect results in a smooth appearance of the pressure ramp.

Figure 5 is a test on a 100 cm^3 test vessel at a faster pressurization rate of 1000 psi/min, to a maximum pressure of 20,000 psi. The general shape of the adjustable supply cylinder pressure vs time curve is the same as the preceding test. Notice the more drastic changes in pressure of the adjustable supply clylinder. Figure 5 also illustrates that the difference between the adjustable supply pressure and the test vessel pressure goes smaller with

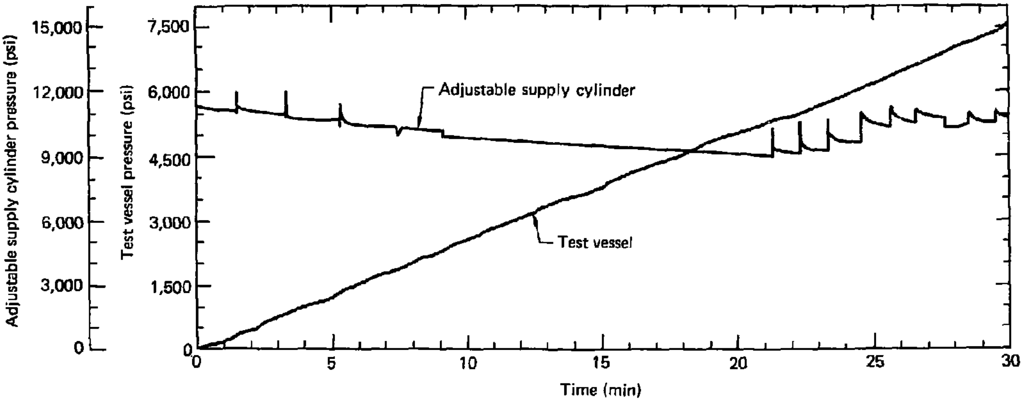


FIG. 4. Pressurization of a 500-cm^3 test vessel at 250 psi/min.

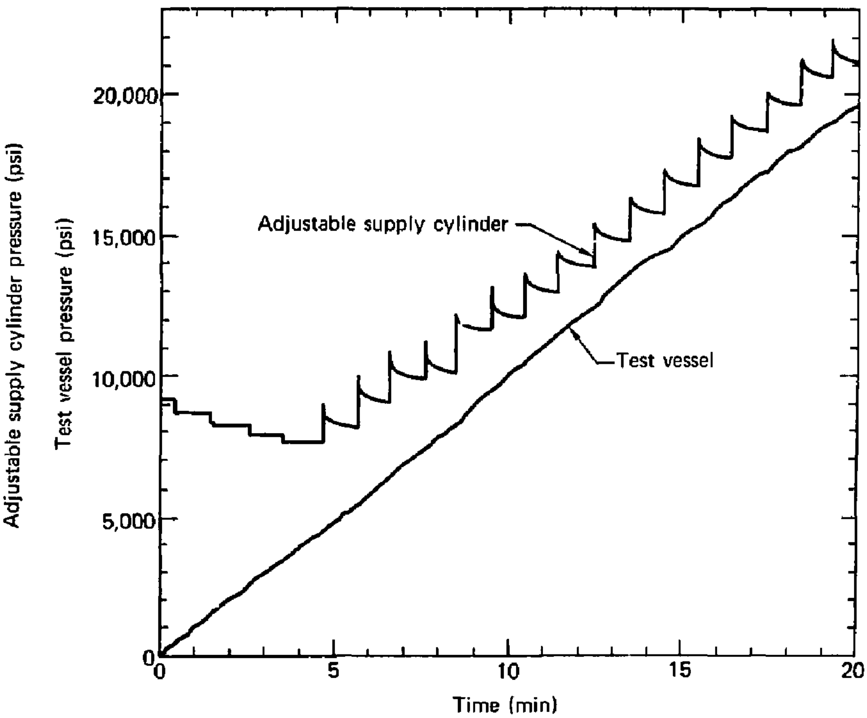


FIG. 5. Pressurization of a 100-cm^3 test vessel at 1000 psi/min.

higher pressures. This causes a problem in that small differences are hard to maintain and must be corrected more often.

Figure 6 is a plot by Clark Radewan; it generalizes the relationship between Q (the product of test vessel volume, pressurization rate, and the capillary coefficient), and the adjustable supply pressure. It shows that for values of Q below 5000, i.e., small volume and pressurization rate, the adjustable supply pressure will be very close to the test vessel pressure. This small difference is hard to maintain so an auxiliary volume, e.g. 250 cm^3, can be connected to the small volume test vessels. This combined larger volume is then pressurized. With this larger Q value the system pressures will be more easily controlled.

RECOMMENDATIONS FOR FURTHER WORK

A number of improvements can be made to the system to make it easier to operate and more accurate. In general these improvements come from a better description of the gas flow and from hardware improvements.

In the section, Analysis of the Mass Flow Rate, it was assumed that the flow through the capillary tube is isentropic, but in reality it is far from isentropic. A better flow assumption would be frictional adiabatic flow based on the following:

- The tubes are of small diameter (<0.1 in.) and the length-to-diameter ratio, L/D is high (>100); both of these combine to make the flow frictional.
- High gas velocity (near Mach 1) allows only an insignificant amount of heat to transfer to the tube wall per unit mass of gas. This makes the flow adiabatic.

Unlike isentropic flow, which has a simple equation for the critical pressure ratio (the pressure ratio which causes the exit velocity to equal Mach 1), the adiabatic frictional flow equation for the critical pressure ratio depends upon the frictional length-to-diameter ratio and the entering Mach number. This is due to the behavior of the gas properties and the Mach number along the Fanno line. The Fanno line tells us that no matter what the entering Mach number of the flow is (except for zero) there exists a frictional length-to-diameter ratio so that the exit Mach number is 1. This explains the dependence of the critical pressure ratio on the entering Mach number and frictional length. Obviously, this flow assumption will make calculating the mass flow rate more complicated and time-consuming. The

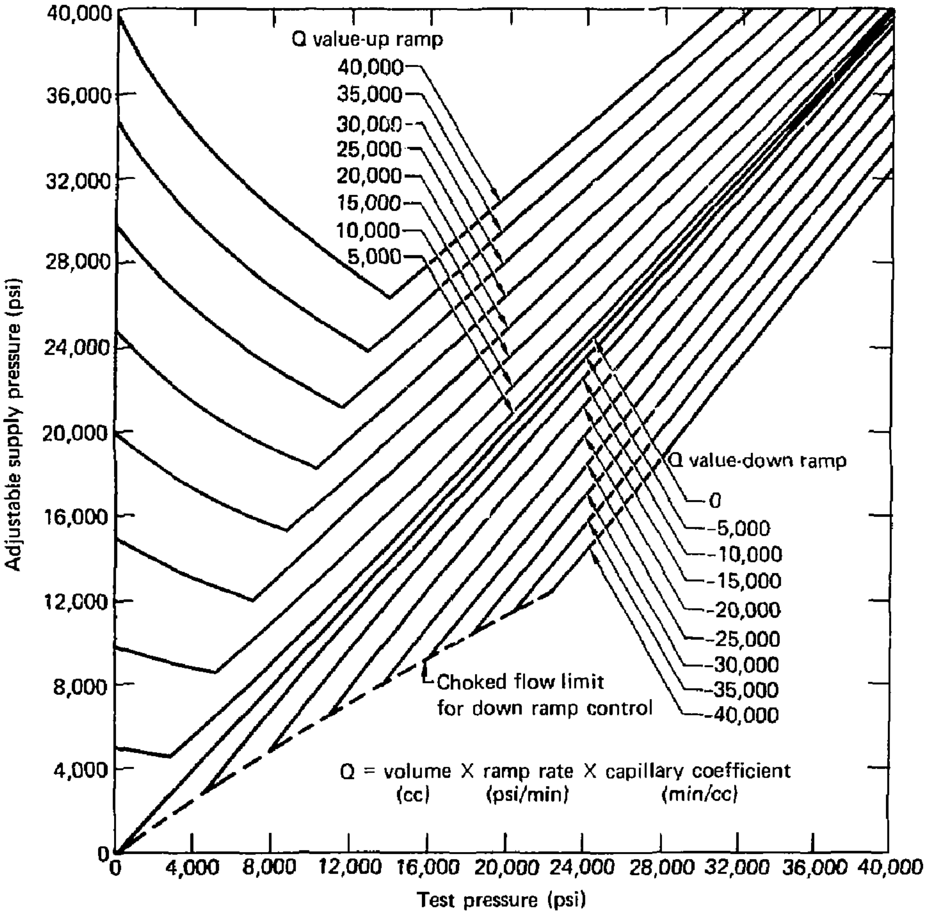


FIG. 6. Generalized supply cylinder pressure curves.

increased complexity may not be reflected in an overall system improvement because of the limited accuracy of the components and measurements.

One hardware improvement over the experimental system that would be desirable on later systems is to eliminate the need for a supply cylinder. Connecting the helium supply line to the adjustable supply cylinder requires a fast acting fill valve (valve I in Fig. 3). A fast acting valve will enable a small amount of gas to be transferred to the adjustable supply cylinder even with a large pressure difference between the two.

The next step past the manually operated valves of the experimental system is to have the valves operate automatically under the control of a minicomputer. This step is well under way under the guidance of Clark Radewan. It should enable an operator to type in certain requested information, such as the volume of the test vessel and the pressurization rate, and let the computer select the correct capillary and adjustable supply cylinder pressures. Such a system would also allow for feedback correction of errors caused by changes in the volume of the test vessel because of strain caused by pressurization. Figure 7 is a drawing of this proposed system.

CONCLUSION

A gas-filled system that can pressurize and depressurize a pressure vessel at a preselected rate is a much needed tool for acoustic emission testing. Such a system has been developed by controlling the mass flow through a capillary connected to the vessel. The mass flow for the selected rate is controlled by regulating the pressure difference across the capillary. Equations for calculating the correct pressure difference were derived, and a computer program was written to calculate the supply pressure. The technique was tested using a manually operated experimental system with very good results. An automatic system under minicomputer control can be realized using the same technique.

ACKNOWLEDGMENTS

I would like to thank Bill Billings for his technical support, without which the experimental system and verifying experiments would not have been completed.

Thanks are also due to Clark Radewan for his engineering ability and support.

I also thank Joe Cervelli for his dedication to the completion of this project and his guidance and support of my work.

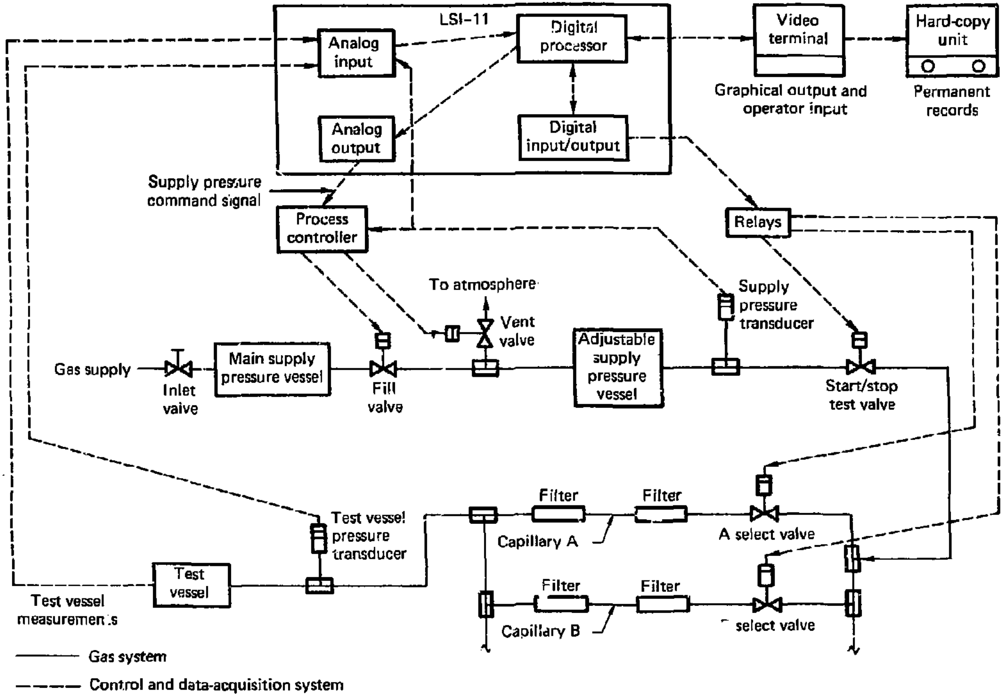


FIG. 7. Proposed high pressure gas metering system (LLNL High Pressure Facility).

APPENDIX A.

One table from Ref. 2 lists the compressibility of helium 4 for different pressures at a temperature of 295 K.

TEMPERATURE = 295.0 KELVIN HELIUM-4

PRESS ATM	DENS MOL/L	Z	PRESS ATM	DENS MOL/L	Z	PRESS ATM	DENS MOL/L	Z	PRESS ATM	DENS MOL/L	Z	PRESS ATM	DENS MOL/L	Z
10	.41	1.0049	510	17.03	1.2371	1010	28.79	1.4494	1510	37.88	1.6467	2010	45.32	1.8320
20	.82	1.0098	520	17.30	1.2415	1020	28.99	1.4535	1520	38.04	1.6505	2020	45.46	1.8356
30	1.22	1.0147	530	17.57	1.2459	1030	29.19	1.4576	1530	38.21	1.6543	2030	45.60	1.8392
40	1.62	1.0196	540	17.84	1.2503	1040	29.39	1.4617	1540	38.37	1.6581	2040	45.73	1.8428
50	2.02	1.0244	550	18.11	1.2547	1050	29.59	1.4657	1550	38.53	1.6619	2050	45.87	1.8464
60	2.41	1.0293	560	18.37	1.2591	1060	29.79	1.4698	1560	38.69	1.6657	2060	46.00	1.8500
70	2.80	1.0341	570	18.64	1.2635	1070	29.99	1.4738	1570	38.85	1.6695	2070	46.14	1.8536
80	3.18	1.0389	580	18.90	1.2679	1080	30.19	1.4779	1580	39.01	1.6733	2080	46.27	1.8571
90	3.56	1.0437	590	19.16	1.2723	1090	30.39	1.4819	1590	39.17	1.6771	2090	46.40	1.8607
100	3.94	1.0485	600	19.42	1.2766	1100	30.58	1.4860	1600	39.32	1.6809	2100	46.53	1.8643
110	4.31	1.0533	610	19.67	1.2810	1110	30.78	1.4900	1610	39.48	1.6847	2110	46.67	1.8678
120	4.69	1.0581	620	19.93	1.2853	1120	30.97	1.4940	1620	39.64	1.6884	2120	46.80	1.8714
130	5.05	1.0629	630	20.18	1.2896	1130	31.16	1.4980	1630	39.79	1.6922	2130	46.93	1.8750
140	5.42	1.0676	640	20.43	1.2940	1140	31.35	1.5020	1640	39.95	1.6959	2140	47.06	1.8785
150	5.78	1.0724	650	20.68	1.2983	1150	31.54	1.5061	1650	40.10	1.6997	2150	47.19	1.8821
160	6.14	1.0771	660	20.93	1.3026	1160	31.73	1.5101	1660	40.26	1.7034	2160	47.32	1.8856
170	6.49	1.0818	670	21.18	1.3069	1170	31.92	1.5140	1670	40.41	1.7072	2170	47.45	1.8892
180	6.84	1.0866	680	21.42	1.3112	1180	32.11	1.5180	1680	40.56	1.7109	2180	47.58	1.8927
190	7.19	1.0913	690	21.67	1.3155	1190	32.30	1.5220	1690	40.72	1.7147	2190	47.71	1.8962
200	7.54	1.0960	700	21.91	1.3198	1200	32.49	1.5260	1700	40.87	1.7184	2200	47.84	1.8998
210	7.88	1.1006	710	22.15	1.3241	1210	32.67	1.5300	1710	41.02	1.7221	2210	47.97	1.9033
220	8.22	1.1053	720	22.39	1.3284	1220	32.86	1.5339	1720	41.17	1.7259	2220	48.10	1.9068
230	8.56	1.1100	730	22.63	1.3326	1230	33.04	1.5379	1730	41.32	1.7296	2230	48.22	1.9103
240	8.89	1.1146	740	22.87	1.3369	1240	33.22	1.5419	1740	41.47	1.7333	2240	48.35	1.9139
250	9.23	1.1193	750	23.10	1.3412	1250	33.41	1.5458	1750	41.62	1.7370	2250	48.48	1.9174
260	9.56	1.1239	760	23.34	1.3454	1260	33.59	1.5498	1760	41.77	1.7407	2260	48.60	1.9209
270	9.88	1.1286	770	23.57	1.3496	1270	33.77	1.5537	1770	41.92	1.7444	2270	48.73	1.9244
280	10.21	1.1332	780	23.80	1.3539	1280	33.95	1.5576	1780	42.06	1.7481	2280	48.86	1.9279
290	10.53	1.1378	790	24.03	1.3581	1290	34.13	1.5616	1790	42.21	1.7518	2290	48.98	1.9314
300	10.85	1.1424	800	24.26	1.3623	1300	34.31	1.5655	1800	42.36	1.7555	2300	49.11	1.9349
310	11.17	1.1470	810	24.49	1.3665	1310	34.48	1.5694	1810	42.50	1.7592	2310	49.23	1.9384
320	11.48	1.1516	820	24.71	1.3707	1320	34.66	1.5733	1820	42.65	1.7628	2320	49.35	1.9419
330	11.79	1.1562	830	24.94	1.3749	1330	34.84	1.5772	1830	42.80	1.7665	2330	49.48	1.9454
340	12.10	1.1607	840	25.16	1.3791	1340	35.01	1.5811	1840	42.94	1.7702	2340	49.60	1.9489
350	12.41	1.1653	850	25.38	1.3833	1350	35.19	1.5850	1850	43.08	1.7739	2350	49.73	1.9523
360	12.71	1.1698	860	25.61	1.3875	1360	35.36	1.5889	1860	43.23	1.7775	2360	49.85	1.9558
370	13.02	1.1744	870	25.83	1.3917	1370	35.53	1.5928	1870	43.37	1.7812	2370	49.97	1.9593
380	13.32	1.1789	880	26.04	1.3958	1380	35.70	1.5967	1880	43.51	1.7848	2380	50.09	1.9628
390	13.61	1.1834	890	26.26	1.4000	1390	35.86	1.6006	1890	43.66	1.7885	2390	50.21	1.9662
400	13.91	1.1880	900	26.48	1.4042	1400	36.05	1.6044	1900	43.80	1.7921	2400	50.34	1.9697
410	14.20	1.1925	910	26.69	1.4083	1410	36.22	1.6083	1910	43.94	1.7958	2410	50.46	1.9732
420	14.50	1.1970	920	26.91	1.4124	1420	36.39	1.6122	1920	44.08	1.7994	2420	50.58	1.9766
430	14.79	1.2015	930	27.12	1.4166	1430	36.56	1.6160	1930	44.22	1.8031	2430	50.70	1.9801
440	15.07	1.2059	940	27.33	1.4207	1440	36.72	1.6199	1940	44.36	1.8067	2440	50.82	1.9835
450	15.36	1.2104	950	27.54	1.4248	1450	36.89	1.6237	1950	44.50	1.8103	2450	50.94	1.9870
460	15.64	1.2149	960	27.75	1.4290	1460	37.06	1.6276	1960	44.64	1.8139	2460	51.06	1.9904
470	15.92	1.2193	970	27.96	1.4331	1470	37.22	1.6314	1970	44.78	1.8176	2470	51.18	1.9938
480	16.20	1.2238	980	28.17	1.4372	1480	37.39	1.6352	1980	44.91	1.8212	2480	51.30	1.9973
490	16.48	1.2282	990	28.38	1.4413	1490	37.55	1.6391	1990	45.05	1.8248	2490	51.41	2.0007
500	16.76	1.2327	1000	28.58	1.4454	1500	37.72	1.6429	2000	45.19	1.8284	2500	51.53	2.0041

APPENDIX B.

A plot (from Ref. 3) of the speed of sound in helium for different temperatures and pressures.

COMPRESSED GAS HANDBOOK

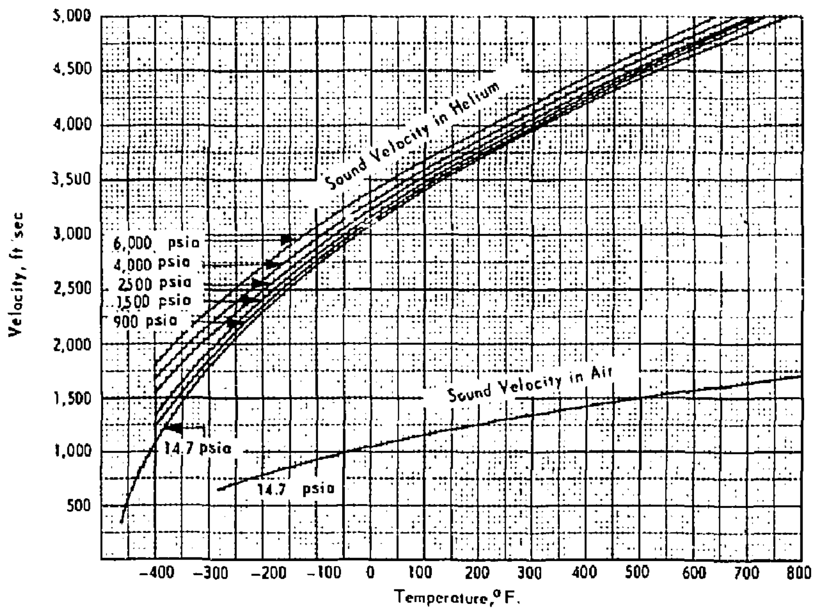


Figure D.9. Velocity of sound versus temperature. [*Courtesy of the Whittaker Corp.*]

APPENDIX C.

The FORTRAN program INTERACT calculates the adjustable supply cylinder pressure for pressurizing a test vessel.

```
      DIMENSION PTEST(81), PSUPPLY(81), FUNCT(81)
      REAL MACH, K, MAXTPRESS
      INTEGER DOLIMIT
      CHAR CAPILLARY
      DATA GASCONST/386.3/,TEMP/530.0/,K/1.66/,TIME/0.0/,
     1A0/1.00883/,A1/4.95038E-05/,A2/-1.27257E-09/,A3/2.33905E-14/
      ZFUNCT(PRESS)=A0+A1*PRESS+A2*PRESS**2+A3*PRESS**3
      WRITE(59,23)
   23 FORMAT(1X,'YOU MUST ANSWER THE FOLLOWING QUESTIONS BEFORE THE '//,
     2'IS STARTED.'//,'WHAT IS THE VOLUME OF THE TEST VESSEL IN'/,
     1'CUBIC CENTIMETERS?')
      READ(59,24) TVESSVOL
      WRITE(59,25)
   25 FORMAT(1X,'WHAT IS THE RAMP IN PSI/MIN?')
      READ(59,24) RAMP
      WRITE(59,26)
   26 FORMAT(1X,'WHAT IS MAXIMUM PRESSURE GOING TO BE IN THE TEST VESSEL?')
      READ(59,24) MAXTPRESS
      WRITE(59,27)
   27 FORMAT(1X,'HOW MANY PRESSURE STEPS PER MINUTE?')
      READ(59,24) STEPSPERMIN
      WRITE(59,28)
   28 FORMAT(1X,'WHAT SIZE CAPILLARY ARE YOU GOING TO USE (C OR D) ?')
      READ(59,29) CAPILLARY
      WRITE(59,30)
   30 FORMAT(1X,'CHOOSE A ERROR FUNCTION SLOPE (.001,.002,.005).')
      READ(59,24) DFUNCT
   29 FORMAT(A1)
   24 FORMAT(F15.2)
      CAPCHAR=0.0916
      IF(CAPILLARY.EQ.C) GOTO 31
      CAPCHAR=7.04E-03
   31 PRESSTEP=RAMP/STEPSPERMIN
      DESIREDRAMP=RAMP
      TIMESTEP=PRESSTEP/RAMP
      DOLIMIT=(MAXTPRESS/PRESSTEP)+1
      WRITE(59,14)
   14 FORMAT(1X,'ITER','         RAMP      ','     PSUPPLY      ',
     2'      PTEST      ','         MACH      ',' TIME ')
      DO 10 I=1,DOLIMIT
      WRITE(59,20) TIME
   20 FORMAT(1X,'WHAT IS THE TEST VESSEL PRESSURE AT',F6.2,'MINUTES?')
      READ(59,21) PTEST(I)
   21 FORMAT(F15.2)
      IF(ABS(PTEST(I)-DESIREDRAMP*TIME).LE.50.0) GOTO 22
      RAMP=RAMP+(DESIREDRAMP*TIME-PTEST(I))
   22 PSUPPLY(I)=RAMP*TVESSVOL*CAPCHAR
      V1=(PSUPPLY(I)+66000.0)/20.0
      RHO1=PSUPPLY(I)/(ZFUNCT(PSUPPLY(I))*GASCONST*TEMP*12.0)
      ZTEST=ZFUNCT(PTEST(I))
      RHOTEST=PTEST(I)/(ZTEST*GASCONST*TEMP*12.0)
        DO 8 J=1,20
      ZSUPPLY=ZFUNCT(PSUPPLY(I))
      RHOSUPPLY=PSUPPLY(I)/(ZSUPPLY*GASCONST*TEMP*12.0)
      MACH=((((RHOSUPPLY/RHOTEST)**(K-1.0))-1.0)*2.0/(K-1.0))**0.5
      IF(MACH.LE.1.0) GOTO 5
      MACH=1.0
    5 FUNCT(I)=MACH*((PSUPPLY(I)+66000.0)/20.0)*RHOSUPPLY-V1*RHO1/ZTEST
      IF(ABS(FUNCT(I)).LE.0.01) GOTO 9
    8 PSUPPLY(I)=PSUPPLY(I)-FUNCT(I)/DFUNCT
```

```
    9 CONTINUE
      PSUPPLY(I+1)=PSUPPLY(I)
      WRITE(59,15) J,RAMP,PSUPPLY(I),PTEST(I), MACH, TIME
   15 FORMAT(3X,I2,4E15.5,F6.2)
      RAMP=DESIREDRAMP
      TIME=TIME+TIMESTEP
      FMASS=RHOSUPPLY*MACH*((PSUPPLY(I)+66000.0)/20.0)
C  FMASS GIVES AN IDEA OF THE MASS FLOW RATE, BUT THE UNITS ARE
C  NOT CORRECT.  IT IS USEFUL FOR GETTING A RATIO OF MASS FLOW RATE.
   10 CONTINUE
      CALL EXIT
      END
```

APPENDIX D.

The FORTRAN program DOWNRAMP calculates the adjustable supply cylinder pressure for depressurizing a test vessel.

```
      DIMENSION PTEST(81), PSUPPLY(81), EFUNCT(81)
      REAL MACH, K
      INTEGER DOLIMIT
      DATA  PTEST(1)/35ØØ.Ø/, GASCONST/386.3/,CAPCHAR/7.Ø4E-Ø3/,TVESSVOL/74Ø.Ø/
     2,TEMP/53Ø.Ø/,AØ/1.ØØ883/, A1/4.95Ø38E-Ø5/,RAMP/5ØØ.Ø/,DOWNSTEP/25Ø.Ø/,
     3A2/-1.27257E-Ø9/,A3/2.339Ø5E-14/, K/1.66/,TIME/Ø.Ø/
      ZEFUNCT(PRESS)=AØ+A1*PRESS+A2*PRESS**2-A3*PRESS**3
      TIMESTEP=DOWNSTEP/RAMP
      PSUPPLY(1)=RAMP*TVESSVOL*CAPCHAR
      V1=(PSUPPLY(1)+66ØØØ.Ø)/2Ø.Ø
      RHO1=PSUPPLY(1)/(ZEFUNCT(PSUPPLY(1))*GASCONST*TEMP*12.Ø)
      DOLIMIT=PTEST(1)/DOWNSTEP
      WRITE(59,13) RAMP
   13 FORMAT(1X,'THESE VALUES ARE FOR A',F6.2,'PSI/MIN DOWN RAMP')
      WRITE(59,14)
   14 FORMAT(2X,'J','        FMASS      ','     PSUPPLY     ',
     2'     PTEST      ','       MACH       ',' TIME ')
      DO 1Ø I=1,DOLIMIT
      ZTEST=ZEFUNCT(PTEST(I))
      RHOTEST=PTEST(I)/(ZTEST*GASCONST*TEMP*12.Ø)
        DO 8 J=1,3Ø
      ZSUPPLY=ZEFUNCT(PSUPPLY(I))
      RHOSUPPLY=PSUPPLY(I)/(ZSUPPLY*GASCONST*TEMP*12.Ø)
      MACH=((((RHOTEST/RHOSUPPLY)**(K-1.Ø))-1.Ø)*2.Ø/(K-1.Ø))**Ø.5
      IF(MACH.GE.1.Ø) GOTO 16
    5 EFUNCT(I)=VI*RHOI/ZEFUNCT(PSUPPLY(I))-(MACH*((PTEST(I)+66ØØØ.Ø)/2Ø.Ø)
     1*RHOTEST/ZTEST)
      IF(EFUNCT(I).LE.Ø.Ø1.AND.-1.Ø*EFUNCT(I).LE.Ø.Ø1) GOTO 9
      DEFUNCT=.Ø1
    8 PSUPPLY(I)=PSUPPLY(I)-EFUNCT(I)/DEFUNCT
    9 CONTINUE
      PSUPPLY(I+1)=PSUPPLY(I)
      PTEST(I+1)=PTEST(I)-DOWNSTEP
      FMASS=RHOTEST*MACH*((PTEST(I)+66ØØØ.Ø)/2Ø.Ø)
C  FMASS GIVES AN IDEA OF THE MASS FLOW RATE, BUT THE UNITS ARE
C  NOT CORRECT.  IT IS USEFUL FOR GETTING A RATIO OF MASS FLOW RATE.
      WRITE(59,15) J,EFUNCT(I),PSUPPLY(I),PTEST(I),MACH,TIME
   15 FORMAT(1X,I2,4E15.5,F6.2)
      TIME=TIME+TIMESTEP
   1Ø CONTINUE
   16 WRITE(59,17)
   17 FORMAT(1X,'TEST PRESSURE TOO LOW TO MAINTAIN LINEAR DECILNE.'/1H ,
     1'VENT TEST VESSEL TO ATMOSPHERE THROUGH DISCHARGE CAPILLARY.')
      CALL EXIT
      END
```

RD/kt