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REACTORS - GENERAL

THE USE OF A KNOCK-OFF TUBE AS A QUICK PRESSURE-RELEASE MECHANISM

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THE USE OF A KNOCK-OFF TUBE AS A QUICK PRESSURE-RELEASE MECHANISM

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ABSTRACT: The reactor-vessel containment work currently being conducted at the Naval Ordnance Laboratory is dependent largely upon ability to monitor the internal pressure-time histories of dynamically loaded model reactor vessels. These histories are determined through the use of tourmaline piezoelectric gages mounted on the internal walls of the vessel. The need for a calibration system that will accurately relate the output of the piezoelectric gages to known pressures is manifest. Inherent to a piezoelectric gage calibration system is a quick pressure-release mechanism that can release the pressure of a confined fluid very rapidly. The rapid release will produce transient loadings on the gages of the same order of magnitude as those obtained in the model reactor vessels.

This report presents an analysis of the use of a knock-off tube as a quick pressure-release mechanism. An equation relating the pressure-release time to the initial conditions of the calibration system has been derived and verified, within certain limitations, for select choices of the initial conditions that are compatible with requirements of the NOL Reactor-Vessel Containment Program (NOL-285).

A method for selecting a safe, workable knock-off tube that will give a required pressure-release time is presented, followed by a brief discussion of a universal knock-off tube for use in this Program.

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The work of this program was carried out under Task NOL-285, NOL Reactor-Vessel Containment Program, and completed in August 1963. An objective of the Task is to determine the elastic and plastic response of idealized model reactor vessels to internal simulated excursion loading as a function of vessel material, size, configuration, and constraint. The magnitude and time duration of the simulated excursion loading is monitored via tourmaline piezoelectric pressure gages. The report presents a study of the utility of a knock-off tube as a quick pressure-release mechanism for a hydraulic piezoelectric gage calibration system. This material was submitted in fulfillment of the thesis requirements for the M.S. degree in Mechanical Engineering at the University of Maryland.

The mention of names of proprietary products in this report constitutes neither an endorsement nor criticism of these products by the United States Government or by the Naval Ordnance Laboratory.

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Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

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NOMENCLATURE

A . . . . cross-sectional area of bore of knock-off tube, in^2

E_1 . . . fractional error of true pressure pulse on piezoelectric gage

$\bar{F}$ . . . . body forces per unit mass acting on fluid element, lb/slug

K_p . . . index of fluid compressibility, in^2/lb

L . . . . length of bore, in

m . . . . slope of viscosity-pressure curve, sec

P . . . . transient fluid pressure in compression chamber, psia

P_a . . . atmospheric pressure, psia

P_g . . . maximum hydrostatic pressure in pressure chamber prior to release, psig

Q . . . . volume rate of fluid flow through bore of pressure pot, in^3/sec

R_o . . . radius of bore, in

r, θ, z . radial, circumferential, and longitudinal coordinates, respectively, of cylindrical coordinate system in which longitudinal coordinate is directed along axis of bore through pressure pot, in, rad, in

t . . . . time, msec, sec

T_R . . . pressure-release time, msec, sec

u, v, w . radial, circumferential, and longitudinal velocities, respectively, of fluid within bore of pressure pot, in/sec

∇ . . . . operator del

V_o . . . volume of pressurized fluid that must escape compression chamber, via the bore, to reduce pressure in compression chamber from P_g to atmospheric, in^3

NOMENCLATURE (Continued)

V_1 . . . volume of compression chamber, in^3

V_2 . . . volume of fluid at atmospheric pressure that would create pressure P_g if compressed to volume V_1, in^3

$\overline{V}$ . . . . velocity vector representing velocity of fluid within bore of pressure pot, in/sec

F_1, F_2, F_3 radial, circumferential, and longitudinal body forces per unit mass, respectively, acting on fluid in bore of pressure pot, lb/slug

$\overline{\zeta}$ . . . . vorticity vector representing vorticity of fluid within bore of pressure pot, sec^{-1}

θ_1 . . . time constant of pressure-time history observed inside compression chamber, msec

θ_2 . . . time constant of voltage-time history observed at terminals of oscilloscope, msec

μ_o . . . coefficient of viscostiy of fluid under atmospheric pressure, $lb\text{-}sec/in^2$

μ . . . . coefficient of viscosity of fluid under pressure P, $lb\text{-}sec/in^2$

ν . . . . coefficient of kinematic viscosity of fluid, in^2/sec

INTRODUCTION

The Naval Ordnance Laboratory, by virtue of its experience and facilities in the fields of propellants and high explosives, is investigating the structural response of reactor vessels to accidental nuclear excursions. As the NOL effort is directed primarily to containing possible excursions within the reactor vessel proper, it has been appropriately titled the NOL Reactor-Vessel Containment Program. From an engineering point of view, the basic parameters of reactor-vessel containment design are material, configuration, constraint, and size. The purpose of the NOL program is to determine, through an investigation of these basic parameters, the optimum containment design of nuclear-reactor vessels for a large range of excursion-energy releases and fluxes.

Considerable experimentation is required to determine the significance of these parameters to the containment problem. One of the primary instrumentation problems in the program is to determine the internal pressure-time history of dynamically loaded model reactor vessels. This is accomplished, in part, through the use of tourmaline piezoelectric gages. Although much is known about these gages, their accuracy is limited by the accuracy of the system in which they are calibrated. This report presents a method of calibration wherein the gages are immersed in an oil-filled compression chamber and subjected to known pressures. Quick release of this pressure is accomplished by breaking a knock-off tube which in turn produces a pressure pulse of known magnitude and duration on the piezoelectric gages. Although this system uses a transient-pressure pulse, it is properly defined to be a static calibration in that there is negligible fluid flow around the gage. On the other hand, a dynamic calibration also uses a transient-pressure pulse, but the fluid flow may or may not be appreciable, depending upon the calibration medium, e.g., air or water shock tube calibration.

A method is presented by which a safe, workable knock-off tube can be selected that will give a prescribed pressure-release time, and hence, a prescribed static calibration pressure pulse. The method is verified, for the ranges of the test conditions investigated, by a series of 83 experimental tests.

PURPOSE AND OBJECTIVES

The broad purpose of this investigation was to provide design criteria for selecting the knock-off tube that corresponds to the desired pressure and pressure-release time correlative with the static calibration of piezoelectric gages.

The technical objectives were as follows:

1. To develop and design a pressure system capable of delivering and maintaining hydraulic pressures in the range of 0 - 50,000 psi within a thick-walled pressure pot.

2. To derive a relationship between the pressure-release time and the initial conditions of the calibration system such as, quantity, compressibility, and viscosity of the pressurized fluid and the length and inside diameter of the knock-off tube.

3. To develop relations required for the selection of a knock-off tube which, when acting in the capacity of a quick pressure-release mechanism, will give prescribed pressure-release times.

PRESSURE-RELEASE TIME

Accurate determination of the pressure-time curve from an explosion necessitates precise knowledge of the pressure sensitivity and time resolution of the blast-measuring instruments, namely here, tourmaline piezoelectric gages and associated recording instrumentation. The pressure sensitivity is usually evaluated in two parts: (1) piezoelectric gage sensitivity is determined in terms of the charge developed by the gage for a unit change in applied pressure and (2) charge sensitivity of the cables, high-impedance amplifiers, and so forth, is determined in terms of oscilloscope deflection per unit charge (recorded on film). The time resolution of the pressure-time curve on the film record is determined in terms of oscilloscope sweep rate.

The sensitivity of a piezoelectric gage is determined by measuring the charge developed by the gage when either a static or dynamic pressure pulse is applied to it. Again a static pressure pulse is defined to be a pulse for which negligible mass flow occurs around the gage, and a dynamic pressure pulse is defined to be one for which the flow of fluid around the gage may be appreciable. Since the piezoelectric gages used in this Program are mounted on the internal walls of the model reactor vessels, the mass flow of fluid about the gages is considered to be negligible. Thus a static calibration of the gage is sufficient.

Static calibration of a piezoelectric gage is ordinarily obtained by placing the gage in a compression chamber filled with oil that is subjected to a known pressure. When the pressure in the chamber is released, the charge developed by the gage is determined via electronic equipment as explained later in the paragraph Instrumentation. The existing pressure pot (compression chamber) used in the Program was designed for a knock-off tube as the quick pressure-release mechanism. This demanded a thorough investigation since the time duration of the static pressure pulse (pressure-release time) applied to the piezoelectric gage was varied through use of the knock-off mechanism.

Requirements. The model reactor vessels currently used in the Containment Program are hollow, right-circular cylinders closed with rigid, radial constraints at the ends. The closures are right discs fitted concentrically with the hollow cylinder. Dynamic loading of the vessels is achieved by initiating an explosive or propellant charge located at the centroid. A detailed description of the model vessels and the associated testing is presented in reference (a). The vessels are subjected to energy releases that generate maximum excursion pressures in the time range of 100 microseconds to 100 milliseconds. Thus the time range for which the piezoelectric gages must be calibrated is clearly defined. However, from an argument presented later in the paragraph Instrumentation, the accuracy of a gage calibration that is performed on Program instrumentation for a pressure-release time of less than 10 milliseconds, over the required pressure range, will be within 1 percent for response times in the subject time range. The range of excursion pressures encountered in the model reactor vessels is 0 - 50,000 psi. Thus the general requirements for calibration of the piezoelectric gages used in this Program are to subject the gages to static pressure pulses, ranging in magnitude from 0 to 50,000 psi, for a time duration of 10 milliseconds or less and to monitor the output in terms of standard pressures and times.

Instrumentation. The instrumentation currently employed for measuring the charge developed by the piezoelectric gage when subjected to a static pressure pulse consists of six major parts. A list of these parts along with a brief description of the function of each appears as follows: (1) standard capacitors for translating the piezoelectric gage output charge to a corresponding voltage signal, (2) a precision calibration-voltage supply and divider for accurately determining the voltage sensitivity of the signal-handling circuitry, (3) a vacuum-tube-fork frequency standard for generating a steady-state waveform of high amplitude and known frequency upon which all timing operations in the system are based, (4) high-impedance amplifiers (gain of 0.78) to provide the proper impedance match between the piezoelectric gages (150,000 megohms) and the recording oscilloscope (1 megohm), (5) a recording oscilloscope for displaying the voltage-time output of the gage, (6) a trigger mechanism for initiating a sweeptrace on the recording oscilloscope screen. Items (1) through (4) are housed in the pressure instrumentation console shown in Figure 1. A view of the Tektronix Oscilloscopes and Polaroid Land Cameras is shown in Figure 2. Each of the oscilloscopes is equipped with a type 53 C Dual-Trace Plug-in Preamplifier Unit. Figure 3 is a schematic diagram of the electronic circuitry. The trigger mechanism, specially designed for the subject investigation, was an adjustable lever device coupled to an electric contact switch which, upon opening, furnished a trigger pulse (40-45 volts) to the recording oscilloscope that initiated a sweep-trace. A descriptive view of the oscilloscope triggering mechanism is shown in Figure 4.

The static sensitivity of a tourmaline gage is directly proportional to the piezoelectric constant K of the tourmaline and to the total area of the electrodes A. It is common practice to denote the gage sensitivity by KA, expressed in the units of picocoulombs per psi (pq/psi). The magnitude of the voltage developed across a standard capacitor (including cable capacitance) corresponding to an applied pressure on the gages is obtained from the following relation

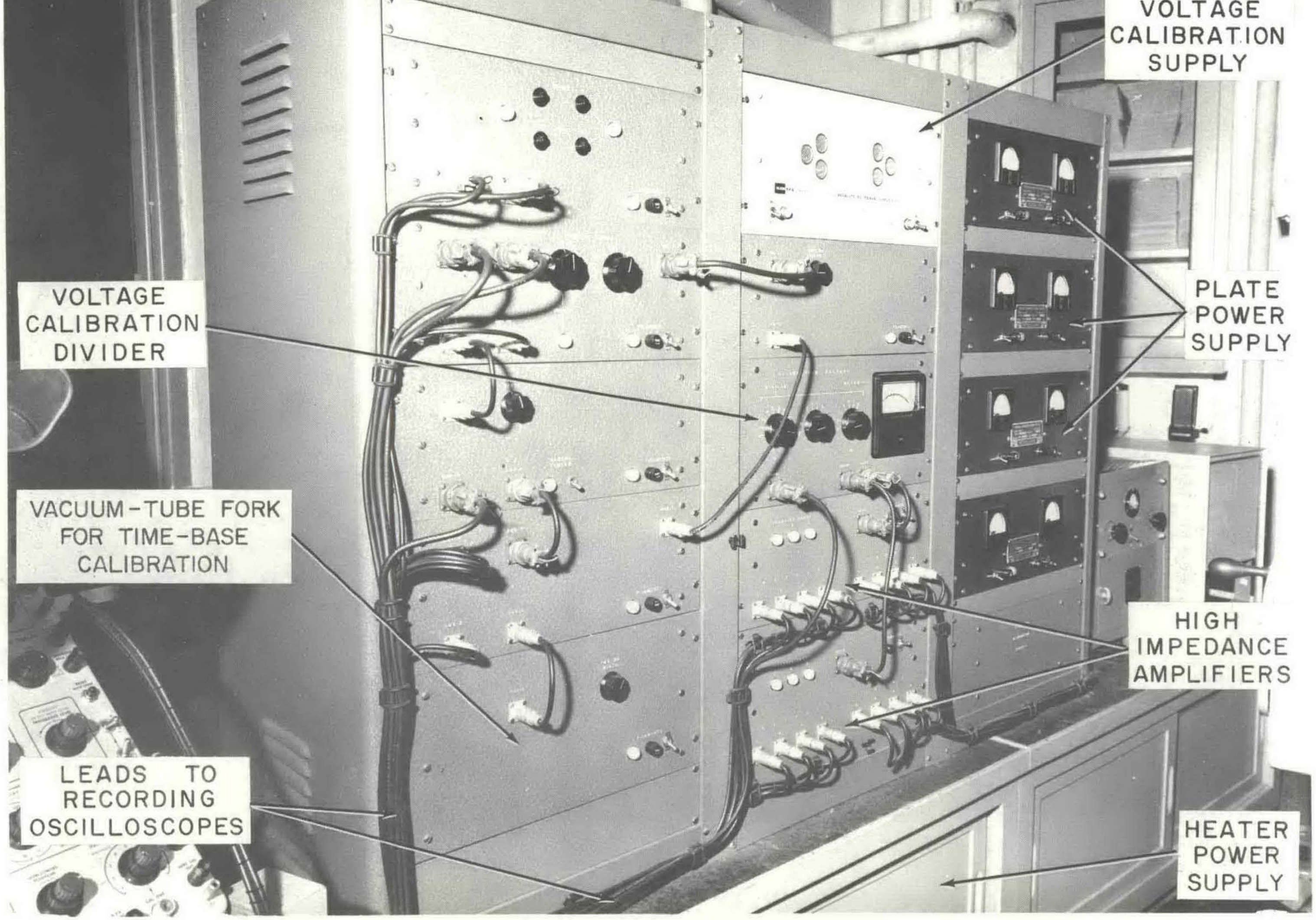
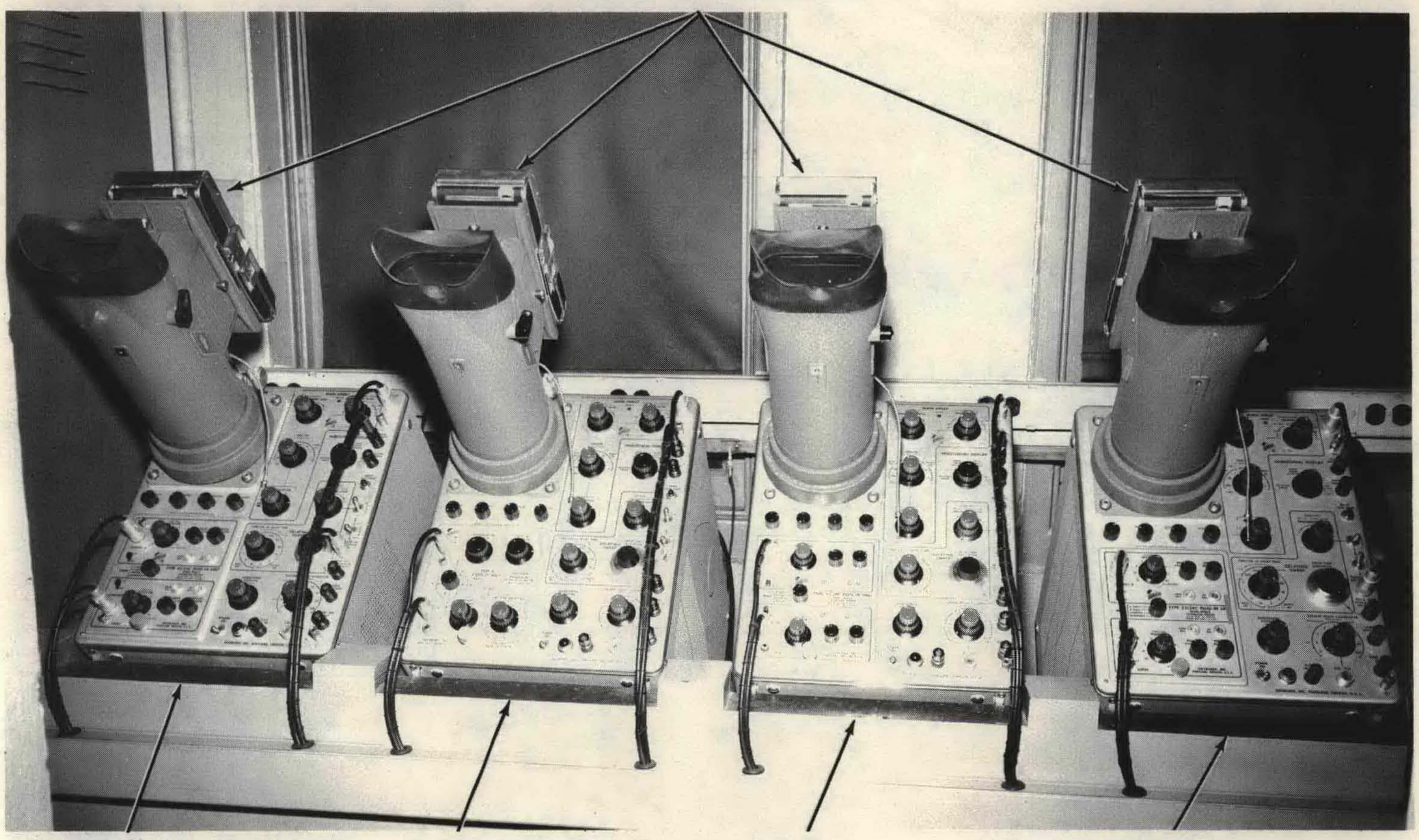


FIG. 1 PRESSURE INSTRUMENTATION CONSOLE

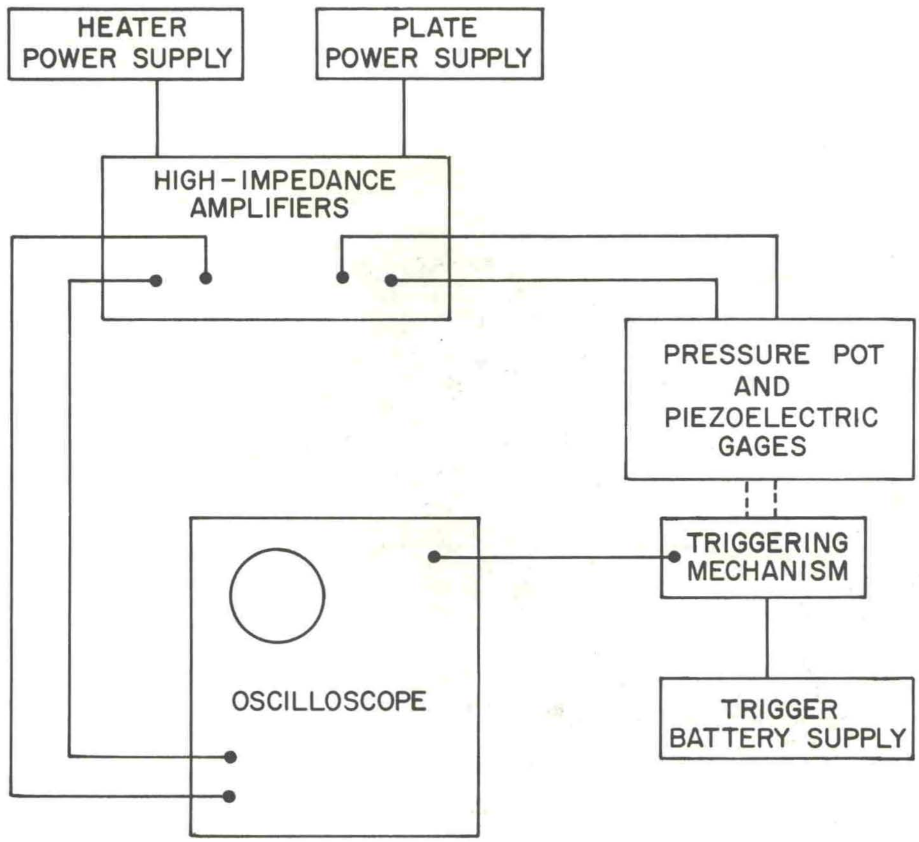
POLAROID CAMERAS



NO. 1 NO. 2 NO. 3 NO. 4

RECORDING OSCILLOSCOPE NO. 4 WAS USED EXCLUSIVELY FOR SUBJECT EXPERIMENTS

FIG. 2 RECORDING OSCILLOSCOPES



NOTE: ALL SIGNAL AND TRIGGER LEADS ARE COAXIAL CABLES

FIG. 3 SCHEMATIC DIAGRAM OF THE ELECTRONIC CIRCUITRY

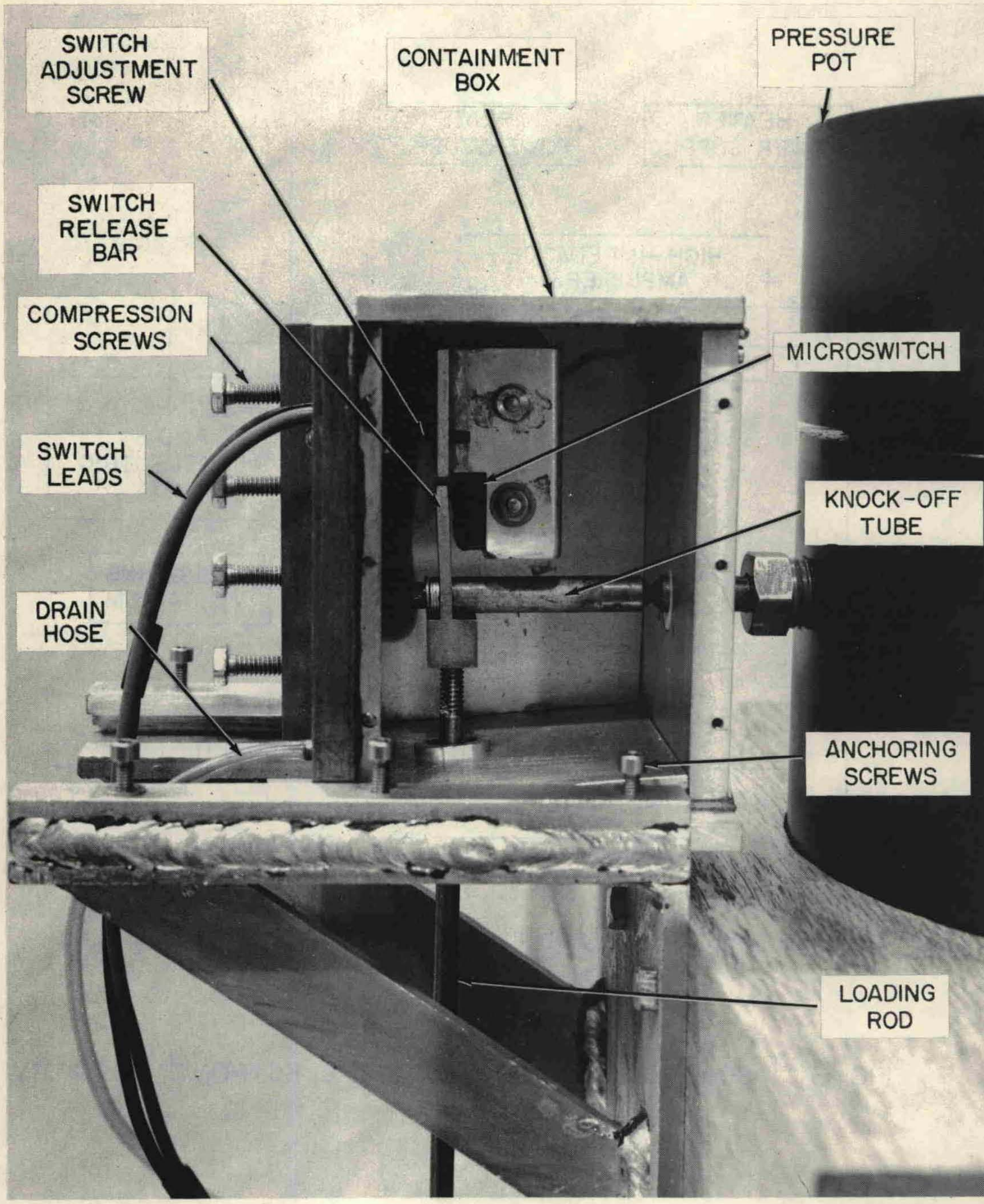


FIG. 4 OSCILLOSCOPE TRIGGERING MECHANISM

$$E = \frac{(KA)\ P}{(C_S + C_C)} \tag{1}$$

where the nomenclature is

E . . . signal voltage, volts

KA . . . gage sensitivity, picocoulombs/psi

C_S . . . standard capacitance, picofarads

C_C . . . cable capacitance, picofarads

P . . . pressure, psi

Equation (1) can be written as

$$KA = \frac{E(C_S + C_C)}{P} \tag{2}$$

The application of a known static pressure pulse on a piezoelectric gage creates a voltage across the standard capacitor, and by means of the electronic circuitry, this voltage is displayed on the oscilloscope screen. The image of the voltage-time curve is captured by a fixed-film camera, thus providing a permanent record that can be analyzed on a standard film reader. Once the signal voltage is determined for a given capacitance and pressure, the gage sensitivity is determined directly from equation (2).

The signal voltage determined in this manner is based on the assumption that all of the charge delivered by the piezoelectric gage is stored on the standard capacitor. This assumption is valid provided the time involved in establishing the signal (pressure-release time) is sufficiently short as to prevent leakage of a significant quantity of stored charge through the equivalent crystal circuit resistance. The decay of the signal voltage is exponential in character, its rate being determined by the product of the total capacitance and the leakage resistance (that is, the time constant of the gage circuit). In Appendix A it is shown that due to the time constant of the gage circuit, the measured positive pressure pulse is lower than the true value by a fractional error not in excess of

$$E_1 \leq \frac{T_R}{\Theta_2} \qquad (3)$$

where the nomenclature is

E_1 . . . fractional error of true pressure pulse

T_R . . . positive duration of pressure pulse (pressure-release time), msec

Θ_2 . . . time constant of gage circuit, msec

For an assumed piezoelectric gage sensitivity of 2 picocoulombs per psi (all of the gages used in this Program have sensitivities of this order) and a pressure range of 20,000 - 100,000 psi, a standard capacitor of 50,000 picofarads is employed. Under these conditions the leakage resistance of the circuit is approximately 200 megohms, and for a pressure-release time of 100 msec, it is seen from equation (3) that

$$E_1 \leq 0.01$$

A further study of this type indicates that a pressure-release time of 10 milliseconds or less is sufficient to ensure that the loss of the signal voltage is less than one percent for the time and pressure ranges required in this Program. Additional information concerning the method of operation of the instrumentation is presented more conveniently in the section Experimental Procedures and Results.

Time-Constant Equation. The experimental pressure-time traces shown in Figures 5, 6, and 7 indicate that in the pressure pot, the decay in pressure with respect to time can be represented by an exponential function. A look at the work done in the area of shock wave phenomena provides the motivation to try a simple exponential relation of the form

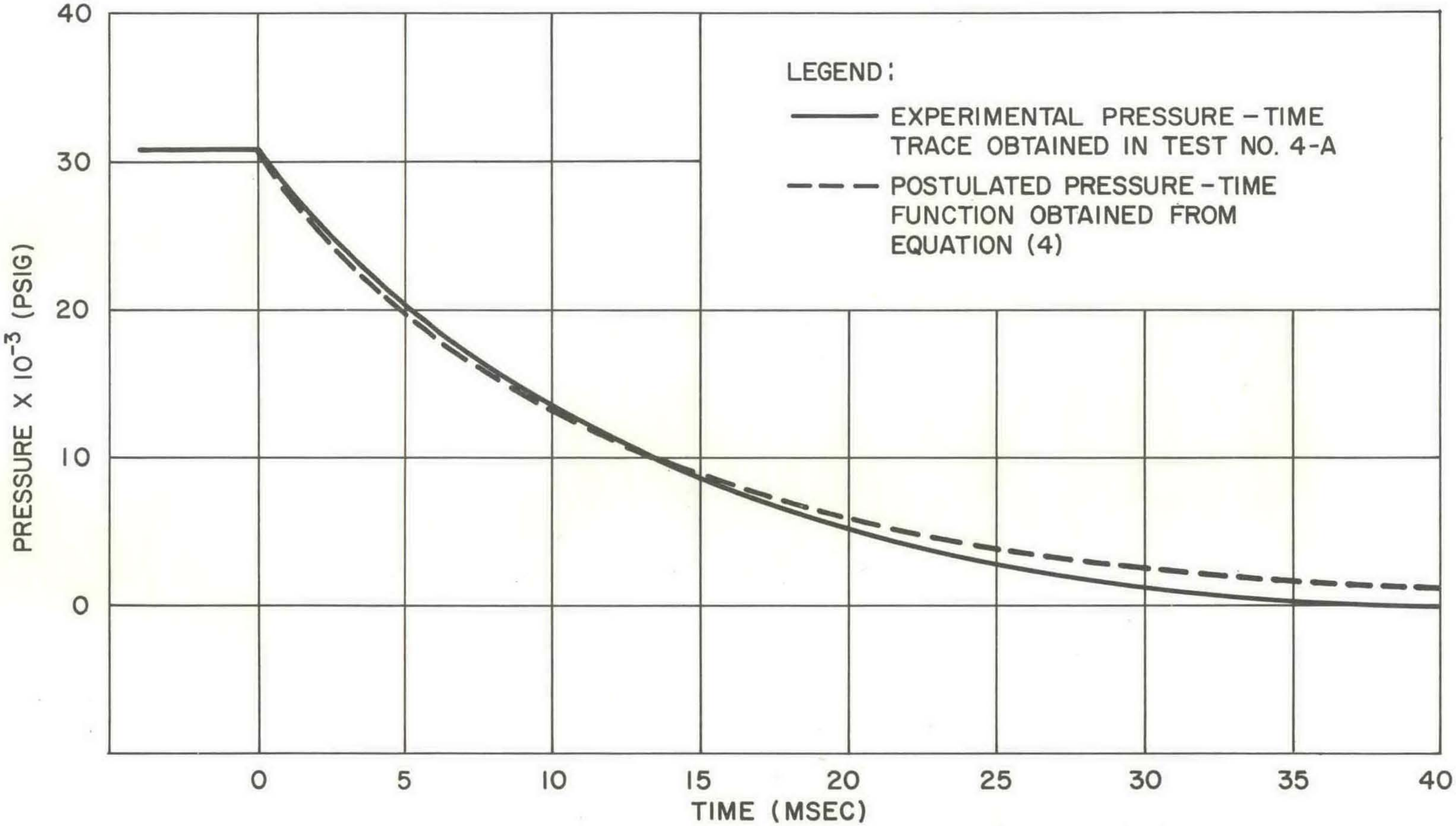


FIG. 5 CORRELATION BETWEEN POSTULATED AND EXPERIMENTIAL PRESSURE-TIME RELATIONS FOR 1/16" I.D. TUBE

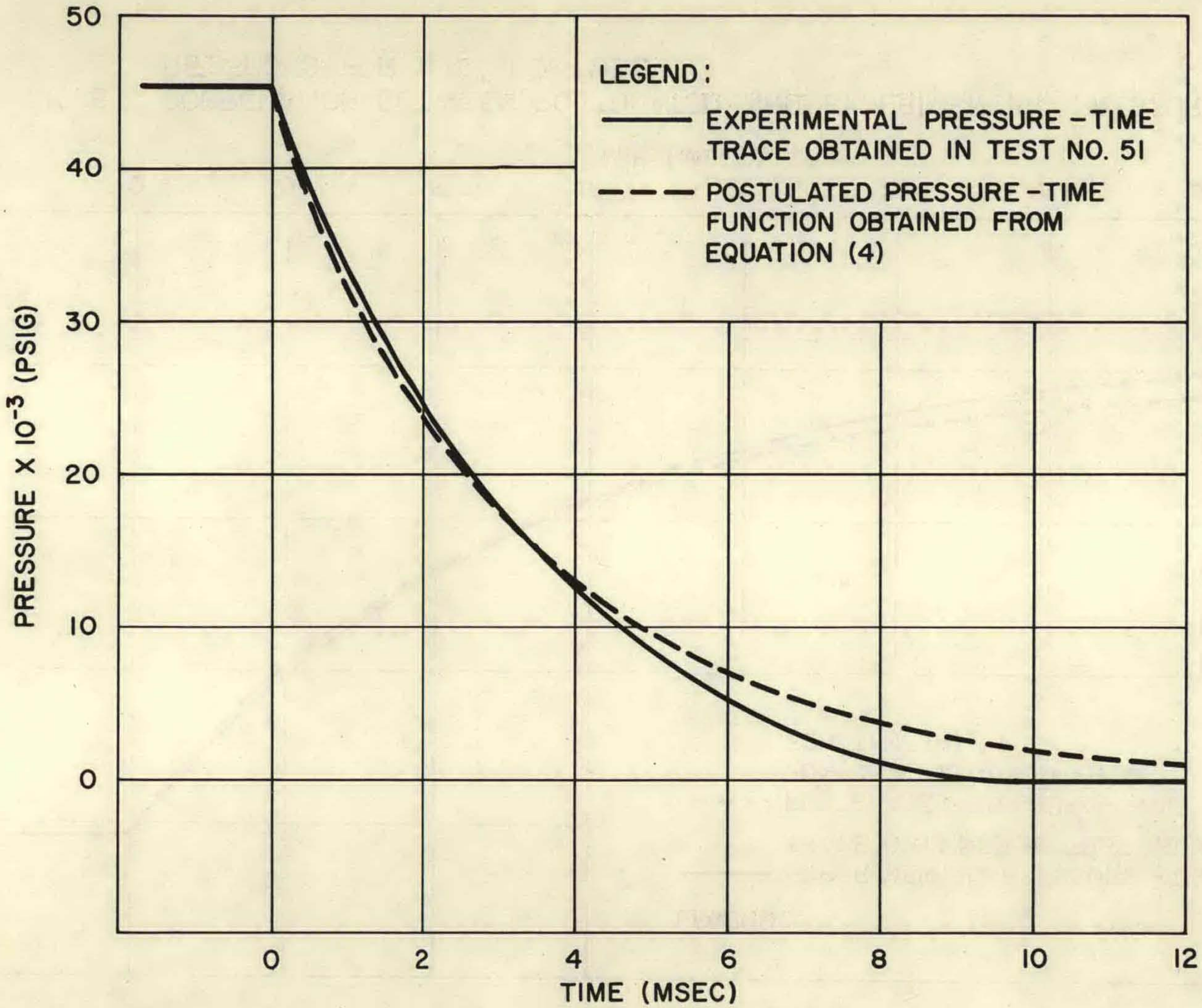


FIG. 6 CORRELATION BETWEEN POSTULATED AND EXPERIMENTIAL PRESSURE-TIME RELATIONS FOR 1/8" I. D. TUBE

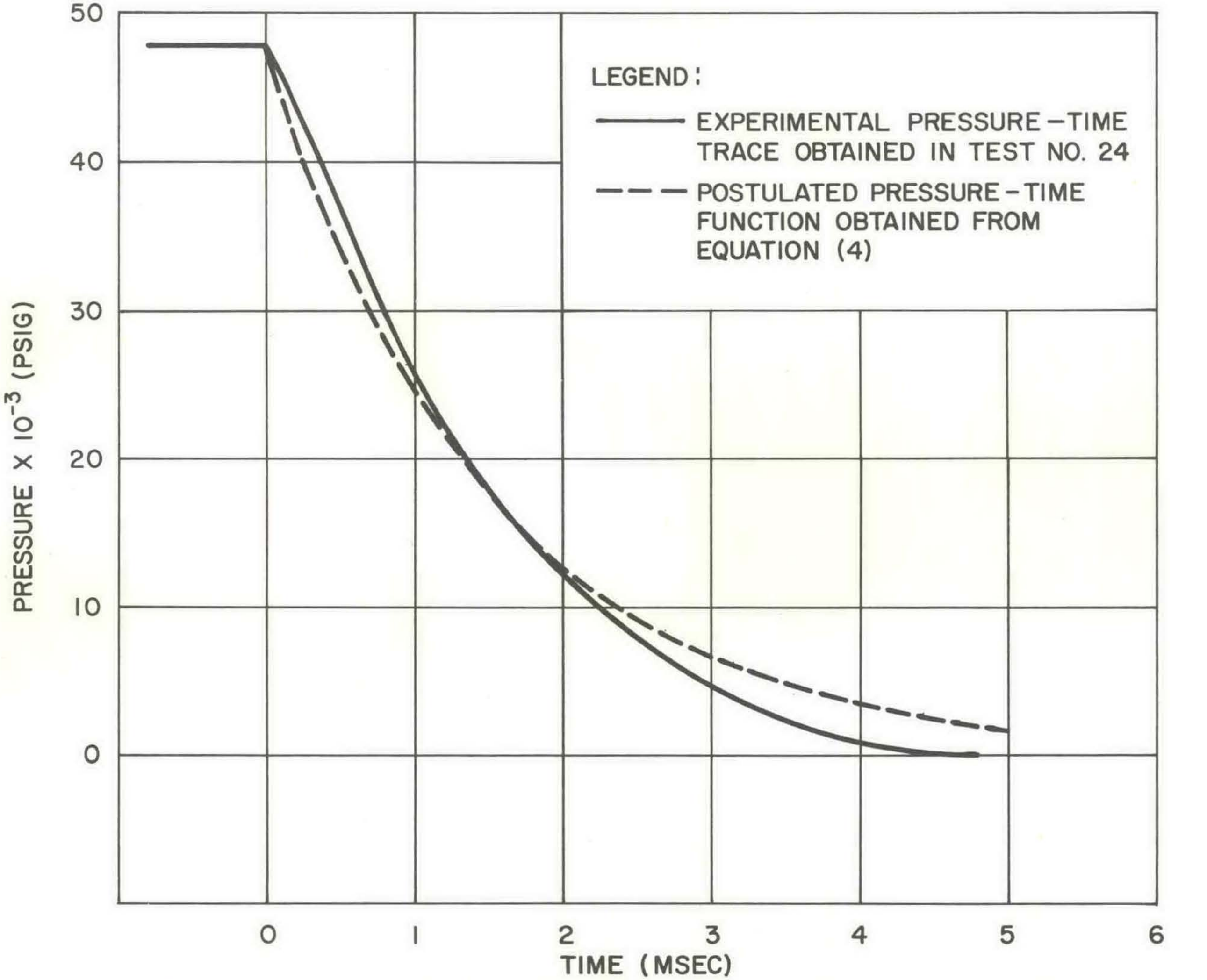


FIG. 7 CORRELATION BETWEEN POSTULATED AND EXPERIMENTIAL PRESSURE-TIME RELATIONS FOR 3/16" I.D. TUBE

$$P = P_g e^{-t/\Theta_1} \qquad (4)$$

where the nomenclature is

P_g . . . maximum hydrostatic pressure in compression chamber prior to release, psig

t . . . event time, msec

Θ_1 . . . time constant of pressure release, (i.e., time at which pressure becomes equal to P_g/e), msec

A correlation between the postulated pressure-time function as given in equation (4) and the experimental pressure-time traces obtained from tests numbers (4-A), (51), and (24), shown in the aforementioned figures, yields positive evidence as to the validity of the postulated pressure-time function. It is seen that maximum deviation occurs when $t = T_R$, where T_R is the pressure-release time or the time required for the pressure in the compression chamber to decay from P_g to ambient conditions. From these experimental curves, the pressure-release time can be expressed in terms of the postulated time constant Θ_1 as

$$T_R \approx 3\Theta_1 \qquad (5)$$

Then from equation (4), it is seen that postulated pressure at time T_R becomes

$$P = P_g e^{-\frac{3\theta_1}{\theta_1}} \approx 0.05\ P_g \qquad (6)$$

that is, after a time duration of magnitude $3\Theta_1$, the pressure in the compression chamber is less than 5 percent of its original value P_g.

From the above statements it appears that the postulated pressure-time function is a good one, and now it is necessary to determine only the time constant Θ_1, either analytically or experimentally, in order to completely describe the pressure-time history in the compression chamber, and hence, the pressure-release time T_R.

In an effort to express the time constant θ_1 analytically, the following analysis is made. A general expression for the equation of motion of a viscous, compressible fluid is derived in reference (c) and can be expressed in vector form as

$$\frac{\rho d\overline{v}}{dt} = \rho\overline{F} - \nabla P - \frac{2}{3}\nabla\left[\mu(\nabla\cdot\ \overline{v})\right] + \left[\nabla\cdot\ (2\mu\nabla)\ \right]\overline{v} + \nabla x(\mu\overline{\zeta}) \qquad (7)$$

where the nomenclature is

ρ . . . mass density of the fluid, slugs/in^3
$\overline{v}$ . . . velocity vector, in/sec
P . . . fluid pressure, psia
$\overline{F}$ . . . body forces per unit mass, lb/slug
μ . . . coefficient of viscosity of fluid, lb-sec/in^2
$\overline{\zeta}$ . . . vorticity vector, sec^{-1}
∇ . . . operator del

The vorticity vector $\overline{\zeta}$ is defined as the curl of the velocity vector

$$\overline{\zeta} = \nabla x\overline{v} \qquad (8)$$

Combining (8) with (7) and performing the operations indicated by the operator ∇, we have

$$\frac{\rho d\overline{v}}{dt} = \rho\overline{F} - \nabla P - \mu\nabla x\overline{\zeta} + \frac{4}{3}\mu\nabla(\nabla\cdot\ \overline{v})$$
$$+ 2(\nabla\cdot\nabla\mu)\ \overline{v} + \nabla\mu x\overline{\zeta} - \frac{2}{3}\ \mu(\nabla\cdot\ \overline{v}) \qquad (9)$$

If we invoke the condition of incompressibility

$$\nabla \cdot \overline{v} = 0 \tag{10}$$

and if we consider the coefficient of viscosity to be independent of the spatial coordinates

$$\nabla \mu = 0 \tag{11}$$

then equation (9) is simplified to the form

$$\frac{\rho d\overline{v}}{dt} = \rho\overline{F} - \nabla P - \mu \nabla x \overline{\zeta} \tag{12}$$

Combining this with equation (8), we have

$$\frac{d\overline{v}}{dt} = \overline{F} - \frac{1}{\rho}\nabla P + \nu \nabla^2 \overline{v} \tag{13}$$

where

ν . . . is kinematic viscosity of fluid = $\frac{\mu}{\rho}$, in^2/sec

Expanding equation (13) into its components in cylindrical coordinates, we obtain the familiar Navier-Stokes equations for a viscous, incompressible fluid

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{v}{r}\frac{\partial u}{\partial \theta} + w\frac{\partial u}{\partial z} - \frac{v^2}{r^2} = F_1 - \frac{1}{\rho}\frac{\partial P}{\partial r}$$

$$+ \nu\left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r^2}\frac{\partial^2 u}{\partial \theta^2} + \frac{\partial^2 u}{\partial z^2} - \frac{u}{r^2} - \frac{2}{r^2}\frac{\partial v}{\partial \theta}\right) \tag{14a}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + \frac{v}{r}\frac{\partial v}{\partial \theta} + w\frac{\partial v}{\partial z} + \frac{uv}{r} = F_2 - \frac{1}{\rho r}\frac{\partial P}{\partial \theta}$$

$$+ \nu\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} + \frac{1}{r^2}\frac{\partial^2 v}{\partial \Theta^2} + \frac{\partial^2 v}{\partial z^2} + \frac{2}{r^2}\frac{\partial u}{\partial \Theta} - \frac{v}{r^2}\right) \tag{14b}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + \frac{v}{r}\frac{\partial w}{\partial \Theta} + w\frac{\partial w}{\partial z} = F_3 - \frac{1}{\rho}\frac{\partial P}{\partial z}$$

$$+ \nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \Theta^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{14c}$$

where the nomenclature is

u,v,w . . . radial, circumferential, and longitudinal velocities, respectively, of fluid within bore of pressure pot, in/sec

F_1, F_2, F_3 . . . radial, circumferential, and longitudinal body forces per unit mass, respectively, acting on fluid in bore of pressure pot, lb/slug

If the condition of constant temperature is invoked, the coefficient of kinematic viscosity is a function of pressure only, that is

$$\nu = \nu(P) \tag{15}$$

From Figure 8, we see that the coordinate system is oriented such that there will be flow in the z-direction only, thus for axisymmetrical motion

$$u = v = \frac{\partial^2 w}{\partial \Theta^2} = 0 \tag{16}$$

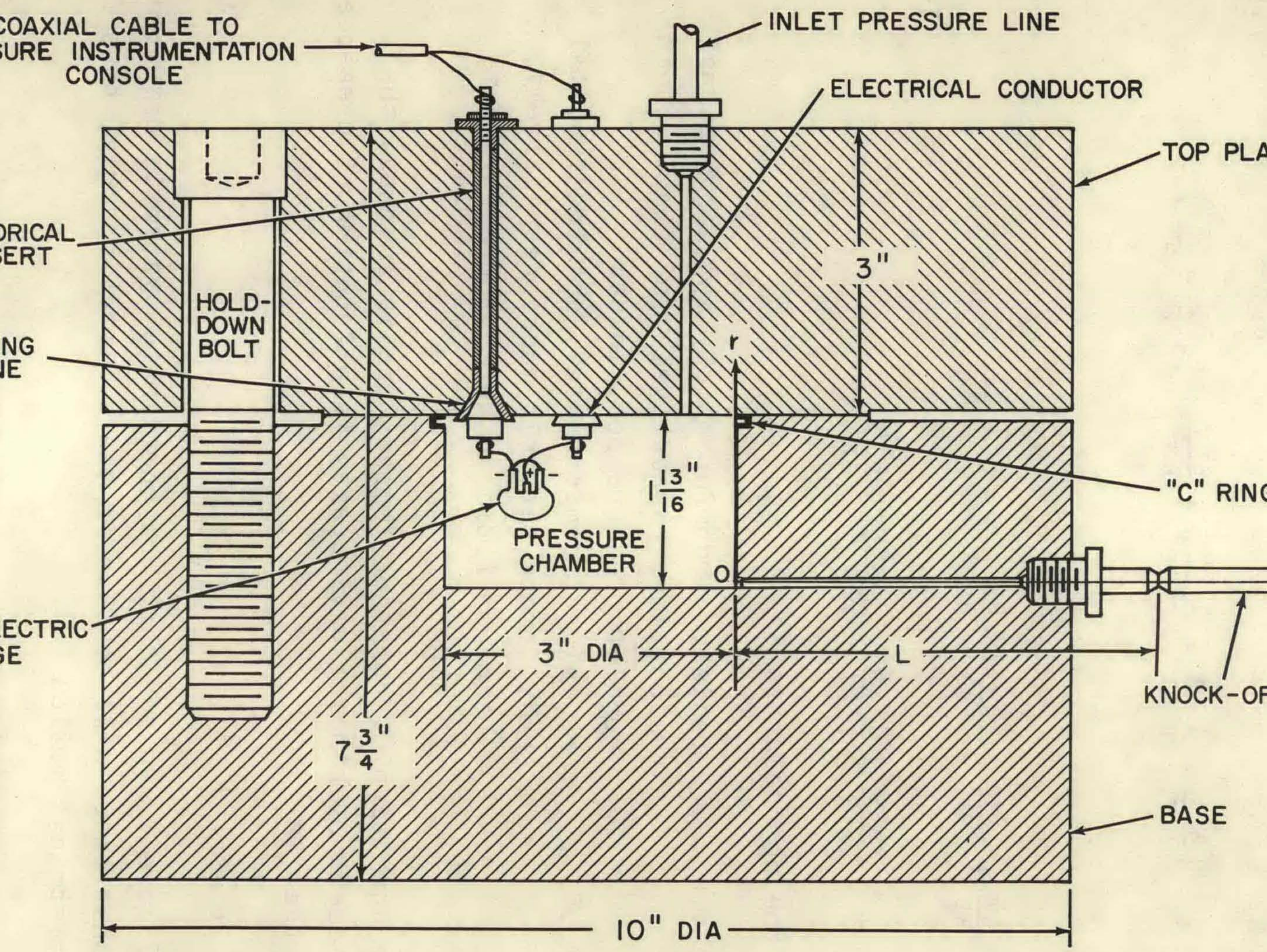


FIG. 8 CROSS-SECTIONAL VIEW OF PRESSURE POT

If we now consider the body forces per unit mass to be negligible, the Navier-Stokes equation (14) becomes

$$0 = \frac{\partial P}{\partial r} \tag{17a}$$

$$0 = \frac{\partial P}{\partial \Theta} \tag{17b}$$

$$\frac{\partial w}{\partial t} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) \tag{17c}$$

The first two of equations (17) yield

$$P = P\ (z,t) \tag{18}$$

that is, the pressure is, at most, a function of the z-coordinate and time.

The three-dimensional continuity equation in cylindrical coordinates can be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u r)}{r\partial r} + \frac{\partial(\rho v)}{r\partial \theta} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{19}$$

Combining the previous conditions of constant density and zero cross-flow with the continuity equation, we obtain

$$\frac{\partial w}{\partial z} = 0 \tag{20}$$

Thus the velocity w along the longitudinal axis of the tube is independent of the z-coordinate. Inserting this relation in equation (17c), we obtain

$$\frac{\partial w}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) \tag{21}$$

For the case of laminar flow we consider the pressure along the longitudinal axis of the tube to vary linearly from a maximum value in the compression chamber to atmospheric pressure at the terminal point of the tube. Therefore, if we neglect end effects the pressure within the tube can be expressed in terms of time and the coordinate z as

$$P = P_g e^{-t/\Theta_1}\left(1 - \frac{z}{L}\right) + P_a \tag{22}$$

where

L . . . is length of bore (see Fig. 8), in

Placing this expression for the pressure in equation (21), we have

$$\nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) - \frac{\partial w}{\partial t} = -\frac{P_g}{\rho L} e^{-t/\Theta_1} \tag{23}$$

The initial, final, and boundary conditions for the subject problem are

Initial condition: $w(r,0) = 0, \ 0 \le r \le R_o$ (24)

Final condition: $w(r,\infty) = 0, \ 0 \le r \le R_o$ (25)

Boundary condition: $w(R_o,t) = 0, \ t \ge 0$ (26)

Equation (23) and the above boundary conditions constitute the governing boundary value problem for determining the fluid velocity within the bore of the subject knock-off tube. We now proceed to determine a particular solution of equation (23).

The homogeneous part of (23) is written as

$$\nu\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r}\right) - \frac{\partial w}{\partial t} = 0 \tag{27}$$

The solution of equation (27) can be found by separation of variables. The function

$$w_h(r,t) = R(r)\ T(t) \tag{28}$$

is a solution, provided

$$\upsilon \left(R''T + \frac{1}{r}R'T\right) - RT' = 0 \tag{29}$$

or

$$\frac{T'}{\upsilon T} = \frac{1}{R}\left(R'' + \frac{1}{r}R'\right) \tag{30}$$

Since the member on the left is a function of time alone and that on the right is a function of the radius alone, they must be equal to a constant, say $-\lambda^2$; hence we have the equations

$$rR'' + R' + \lambda^2 rR = 0 \tag{31}$$

$$T' + \lambda^2 \upsilon T = 0 \tag{32}$$

Equation (31) is Bessel's equation, and its general solution is written as

$$R(r) = A\ J_0(\lambda r) + B\ Y_0(\lambda r) \tag{33}$$

where $J_0(\lambda r)$ and $Y_0(\lambda r)$ are Bessel functions of the first and second kind, respectively. G. N. Watson in reference (d) states that $Y_0(\lambda r)$ is infinite for interior problems, and consequently, $B = 0$. Thus the solution of equation (31) becomes

$$R(r) = A\ J_0(\lambda r) \tag{34}$$

The solution of equation (32), when ν is a constant, is

$$T(t) = De^{-\lambda^2 \nu t} \tag{35}$$

Then, upon substitution of (34) and (35) into (28), we immediately have

$$w_h(r,t) = C\, J_0(\lambda r)e^{-\lambda^2 \nu t} \tag{36}$$

A series of these solutions

$$w_h(r,t) = \sum_{j=1}^{\infty} C_j J_0(\lambda_j r)e^{-\lambda_j^2 \nu t} \tag{37}$$

represents a particular solution of the homogeneous equation (27).

A particular solution of equation (23) is

$$w_p(r,t) = -\frac{P_g \theta_1}{\rho L} e^{-t/\theta_1} \tag{38}$$

The sum of equations (37) and (38) represents the solution of the governing equation of the fluid velocity within the bore of the knock-off tube. Thus

$$w(r,t) = \sum_{j=1}^{\infty} C_j J_0(\lambda_j r)e^{-\lambda_j^2 \nu t} - \frac{P_g \theta_1}{\rho L} e^{-t/\theta_1} \tag{39}$$

In order to find the solution of equation (23) that satisfies the boundary conditions, we are motivated to reconstruct (39) in the form

$$w(r,t) = \sum_{j=1}^{\infty} \frac{C_j}{A_j} J_0(\lambda_j r) \left[e^{-\lambda_j^2 \nu t} - e^{-t/\theta_1} \right] \tag{40}$$

Upon substitution of (40) into the governing equation (23), we see that (23) will be satisfied identically provided

$$\sum_{j=1}^{\infty} \frac{C_j}{A_j} J_o(\lambda_j r) \left(\frac{1}{\theta_1} - \upsilon\lambda_j^2\right) = \frac{P_g}{\rho L} \tag{41}$$

If we prescribe that

$$A_j = \left(\frac{1}{\theta_1} - \upsilon\lambda_j^2\right) \tag{42}$$

then (41) becomes

$$\sum_{j=1}^{\infty} C_j J_o(\lambda_j r) = \frac{P_g}{\rho L} \tag{43}$$

According to the Fourier-Bessel expansion, the constants C_j are given as

$$C_j = \frac{\frac{P_g}{\rho L} \int_o^{R_o} r\, J_o(\lambda_j r)\, dr}{\frac{1}{2}R_o^2 \left[J_o^2(\lambda_j R_o) + J_1^2(\lambda_j R_o) \right]} \tag{44}$$

From equation (40) we see that the boundary condition (26) will be satisfied providing we define λ_j as the positive roots of the equation

$$J_o(\lambda_j R_o) = 0 \tag{45}$$

Combining equation (44) and (45), we have

$$C_j = \frac{2P_g}{\rho L R_o \lambda_j} \left[\frac{1}{J_1(\lambda_j R_o)}\right] \tag{46}$$

Inserting (42) and (46) into (40), we obtain

$$w(r,t) = \frac{2P_g}{\rho L R_o} \sum_{j=1}^{\infty} \frac{J_o(\lambda_j r)}{\lambda_j J_1(\lambda_j R_o)} \left[\frac{1}{\frac{1}{\theta_1} - \upsilon\lambda_j^2} \right] \cdot \left[e^{-\lambda_j^2 \upsilon t} - e^{-t/\theta_1} \right] \tag{47}$$

An inspection of equation (47) shows that conditions (24), (25), and (26) are satisfied. Thus equation (47) is the formal solution of the subject boundary value problem.

The volume rate of fluid Q passing through the tube in time t can be determined as follows:

$$Q = \int_o^A w(r,t)\, da \tag{48}$$

where A is the cross-sectional area of the bore of the knock-off tube. Substituting equation (47), we have

$$Q = \frac{4\pi P_g}{\rho L R_o} \sum_{j=1}^{\infty} \left[\frac{1}{\frac{1}{\theta_1} - \upsilon\lambda_j^2} \right] \left[e^{-\lambda_j^2 \upsilon t} - e^{-t/\theta_1} \right] \cdot \left[\frac{1}{\lambda_j J_1(\lambda_j R_o)} \right] \int_o^{R_o} r J_o(\lambda_j r)\, dr \tag{49}$$

from which

$$Q = \frac{4\pi P_g}{\rho L} \sum_{j=1}^{\infty} \left[\frac{1}{\frac{1}{\theta_1} - \upsilon\lambda_j^2} \right] \left[e^{-\lambda_j^2 \upsilon t} - e^{-t/\theta_1} \right] \left(\frac{1}{\lambda_j^2} \right) \tag{50}$$

We are now in a position to determine the volume of fluid V_o that must exit the compression chamber via the knock-off tube in order for the pressure within the compression chamber to decay to ambient conditions in accordance with the postulated pressure-time function given by (4). We write

$$V_o = \int_0^\infty Q \, dt \tag{51}$$

Since the volume rate of flow Q diminished in an exponential fashion, the limits of integration on the time t are zero and infinity.

From the combination of equations (50) and (51), we have

$$V_o = \frac{4\pi P_g}{\rho L} \sum_{j=1}^{\infty} \left[\frac{1}{\frac{1}{\Theta_1} - \nu\lambda_j^2} \right] \left(\frac{1}{\lambda_j^2} \right) \int_0^\infty \left[e^{-\lambda_j^2 \nu t} - e^{-t/\Theta_1} \right] dt \tag{52}$$

from which

$$V_o = \frac{4\pi P_g \Theta_1}{\mu L} \sum_{j=1}^{\infty} \frac{1}{\lambda_j^4} \tag{53}$$

Recalling that λ_j is defined by equation (45), we can obtain from reference (e)

$$\begin{aligned} \lambda_1 R_o &= 2.4048 \\ \lambda_2 R_o &= 5.5201 \\ \lambda_3 R_o &= 8.6537 \\ \lambda_4 R_o &= 11.7915 \end{aligned} \tag{54}$$

etc.

Thus equation (53) becomes

$$V_o \approx \frac{\pi \Theta_1 P_g R_o^4}{8\mu L} \qquad (55)$$

The time constant Θ_1 can be found from equation (55) providing V_o is known. It is understood that the pressure in the compression chamber is increased by forcing an additional quantity of fluid into the chamber. From reference (f) the compressibility of the subject fluids (SAE 10 and SAE 20 oil) can be closely approximated from the following equation

$$\frac{V_1}{V_2} = 1.00 - (4.31 \times 10^{-6})\, P_g + (6.51 \times 10^{-11})\, P_g^2 - (5.03 \times 10^{-16})\, P_g^3 \qquad (56)$$

where the nomenclature is

V_1 . . . volume of fluid under pressure P_g (volume of compression chamber), in^3

V_2 . . . volume of fluid under atmospheric pressure (volume that would create pressure P_g if compressed to volume V_1), in^3

Since $V_o = V_2 - V_1$, then

$$V_o = V_1 P_g \left[\frac{(4.31 \times 10^{-6}) - (6.51 \times 10^{-11}) P_g + (5.03 \times 10^{-16}) P_g^2}{1.00 - (4.31 \times 10^{-6}) P_g + (6.51 \times 10^{-11}) P_g^2 - (5.03 \times 10^{-16}) P_g^3}\right] \qquad (57)$$

To simplify the writing of (57), we introduce the term K_p, defined as follows for the subject fluids

$$K_p = \left[\frac{(4.31 \times 10^{-6}) - (6.51 \times 10^{-11}) P_g + (5.03 \times 10^{-16}) P_g^2}{1.00 - (4.31 \times 10^{-6}) P_g + (6.51 \times 10^{-11}) P_g^2 (5.03 \times 10^{-16}) P_g^3} \right] \tag{58}$$

Equation (57) becomes

$$V_o = V_1 P_g K_p \tag{59}$$

and combining equations (55) and (59), we have

$$\Theta_1 = \frac{8 \mu L V_1 K_p}{\pi R_o^4} \tag{60}$$

Equation (60) defines the time constant Θ_1 derived analytically for laminar flow of a pressurized fluid of constant viscosity through a tube of radius R_o and length L. Since the subject fluids do not possess the quality of constant viscosity throughout the required range of 0 to 50,000 psi, equation (60) will not yield the desired results in its present form. From reference (g) it is seen that the coefficient of viscosity μ for the subject fluids can be closely approximated in the pressure range 0 - 35,000 psi by the linear relation

$$\mu = m P_g + \mu_o \tag{61}$$

where the nomenclature is

μ_o . . . coefficient of viscosity under atmospheric pressure, $lb\text{-}sec/in^2$

m . . . slope of viscosity-pressure curve = 6.24×10^{-10} sec

The peak pressure P_g is used in equation (61), since, as explained in the section Calculated Results, the time constant Θ_1 is in general agreement with the experimental results for pressures up to 35,000 psi. For pressures that exceed 35,000 psi, a pressure equal to $\frac{3}{4}$ P_g in equation (61) yields a favorable comparison. Treating equation (61) as a correction factor in equation (60), we now have

$$\Theta_1 = \frac{8LV_1 K_p}{\pi R_o^4} \left[(6.24 \times 10^{-10})\ P_g + \mu_o \right] \tag{62}$$

While it is apparent that the density of the fluid undergoes a definite change for the pressures encountered in this investigation, a study of equations (56) and (57) indicates that this change is of the order of 10 to 15 percent. On the other hand, from reference (g) it is seen that the change in viscosity for these pressure changes is approximately 300 to 400 percent. Since the variable fluid viscosity has been accounted for, the relatively insensitive density variation can be considered negligible. Thus the assumption of constant density, i.e., incompressibility, equation (10), is justified.

A comparison of the results obtained from experiments described in the section Experimental Procedures and Results with the computed results from equation (62) is presented in the section Calculated Results.

EXPERIMENTAL FACILITIES

To complete a thorough investigation of the use of a knock-off tube as a quick pressure-release mechanism, it was necessary to conduct experiments. There were two major considerations: (1) sufficient experimental evidence must be found to assess the validity of the time-constant equation (62) and (2) experimental data establishing the utility of a knock-off tube as a quick pressure-release mechanism must be provided to aid the designer in selecting the optimum tube for a given set of conditions. By conditions is meant those specific values prescribed for the pressure-release time, chamber pressure, available load for breaking the knock-off tube, etc.

The experimental facilities employed in obtaining these data can be divided into six major parts: (1) composite pressure system, (2) pressure pot, (3) piezoelectric gages and conjoint instrumentation, (4) knock-off tubes, (5) loading mechanism, and (6) oscilloscope triggering mechanism. The instrumentation system and oscilloscope triggering mechanism have been previously described in the section pertaining to instrumentation.

The composite pressure system shown in Figure 9 consists of a hydraulic pressure generator and a high-pressure control system. The hydraulic pressure generator used in the program is an electrically driven, dual-action, variable stroke, hydraulic pressure pump. This pump is capable of delivering 5 gallons of fluid per hour at a pressure of 60,000 psi. However, the pumping rate was reduced considerably in all calibration tests to prevent undue pressure surges on the knock-off tube and the piezoelectric gages. A view of the hydraulic pressure pump appears in Figure 10. The high-pressure control system consists of a pressure intensifier

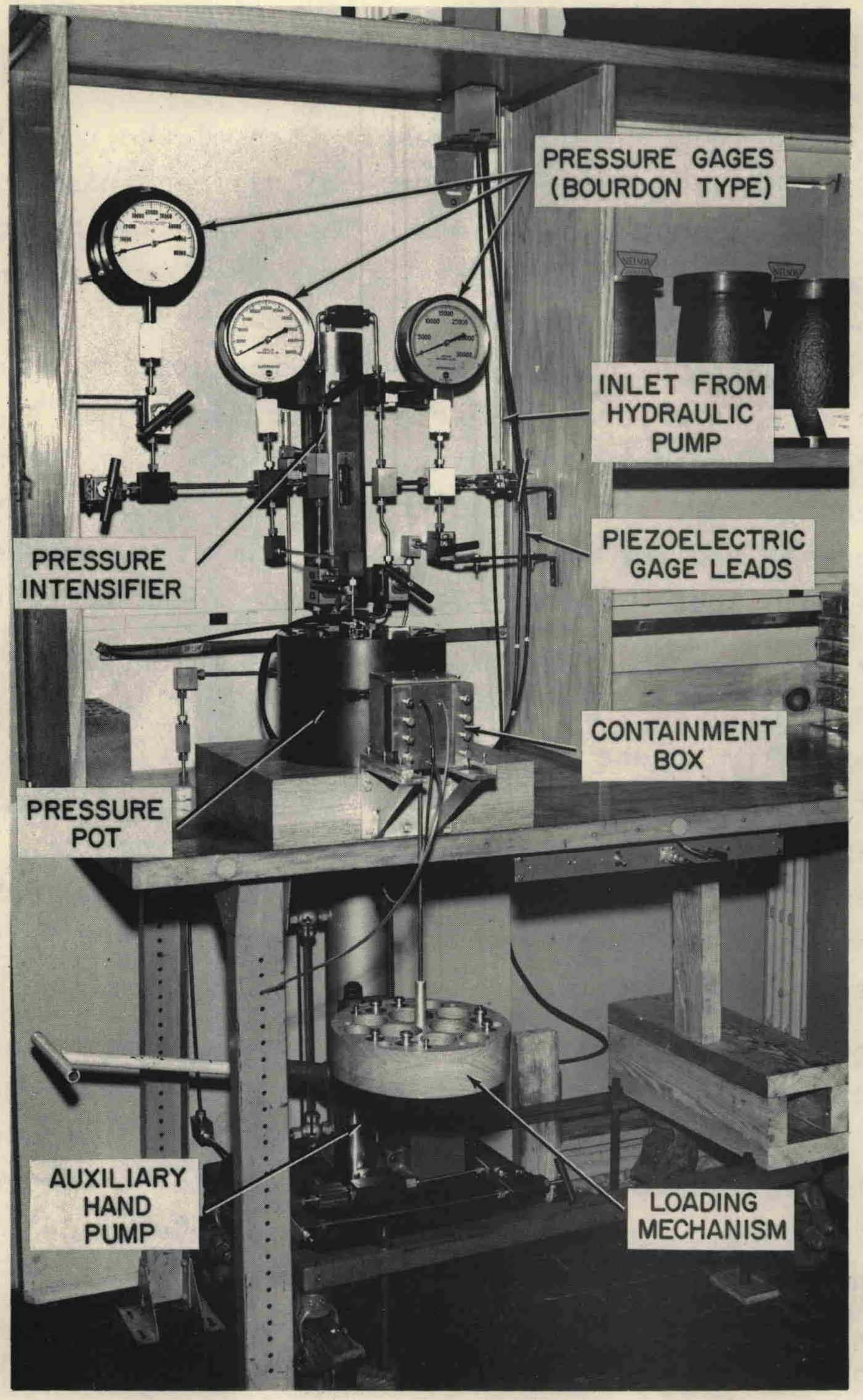


FIG. 9 COMPOSITE PRESSURE SYSTEM

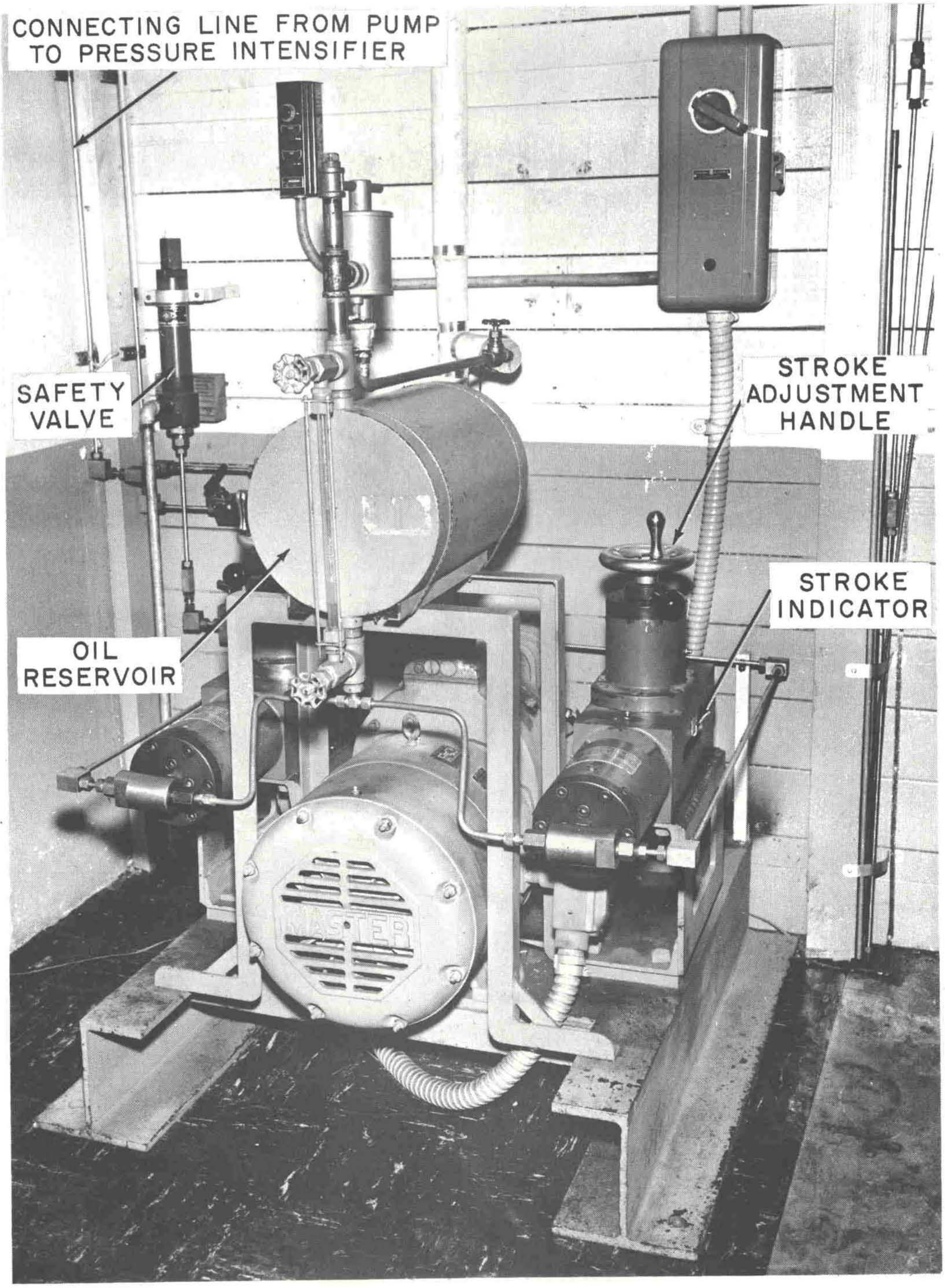


FIG. 10 DUAL-ACTION, VARIABLE-STROKE, HYDRAULIC-PRESSURE PUMP

and a suitable valve arrangement to permit delivery of pressures up to 100,000 psi to the pressure pot. A detailed description of the pressure intensifier and its mode of operation is presented in the section Experimental Procedures and Results. Figure 11 is a close-up view of the high-pressure control system.

A cross-sectional view of the pressure pot was shown previously in Figure 8. From this view it is seen that the pressure pot is essentially a two-pieced, thick-walled vessel that forms a 12.80 cubic-inch compression chamber. The top plate is secured to the base of the pressure pot with ten one-inch diameter, hardened, stainless-steel bolts. A standard, metal "C" ring provides a high-pressure seal between the top plate and the base of the pressure pot. The piezoelectric gages are suspended within the fluid-filled compression chamber, and electrical contact is made via specially designed, self-sealing electrical conductors. An important observation made during the testing program was that the electrical conductors would not function properly if the cylindrical insert was removed. This was a consequence of the sealing cone extruding from its intended position to the annular space between the stem of the conductor and the walls of the pressure pot left void by the removal of the insert. There are 12 electrical conductors in the pressure pot to provide for the simultaneous calibration of 6 piezoelectric gages.

A bore, corresponding to the bore of the knock-off tube, passes from the lower portion of the compression chamber through the wall of the pressure pot. The knock-off tube is secured to the pressure pot in a manner such that its longitudinal axis is colinear with the bore through the compression chamber. Once the knock-off tube has been severed, the high-pressure fluid within the compression chamber is free to exit through a constant diameter bore of length L.

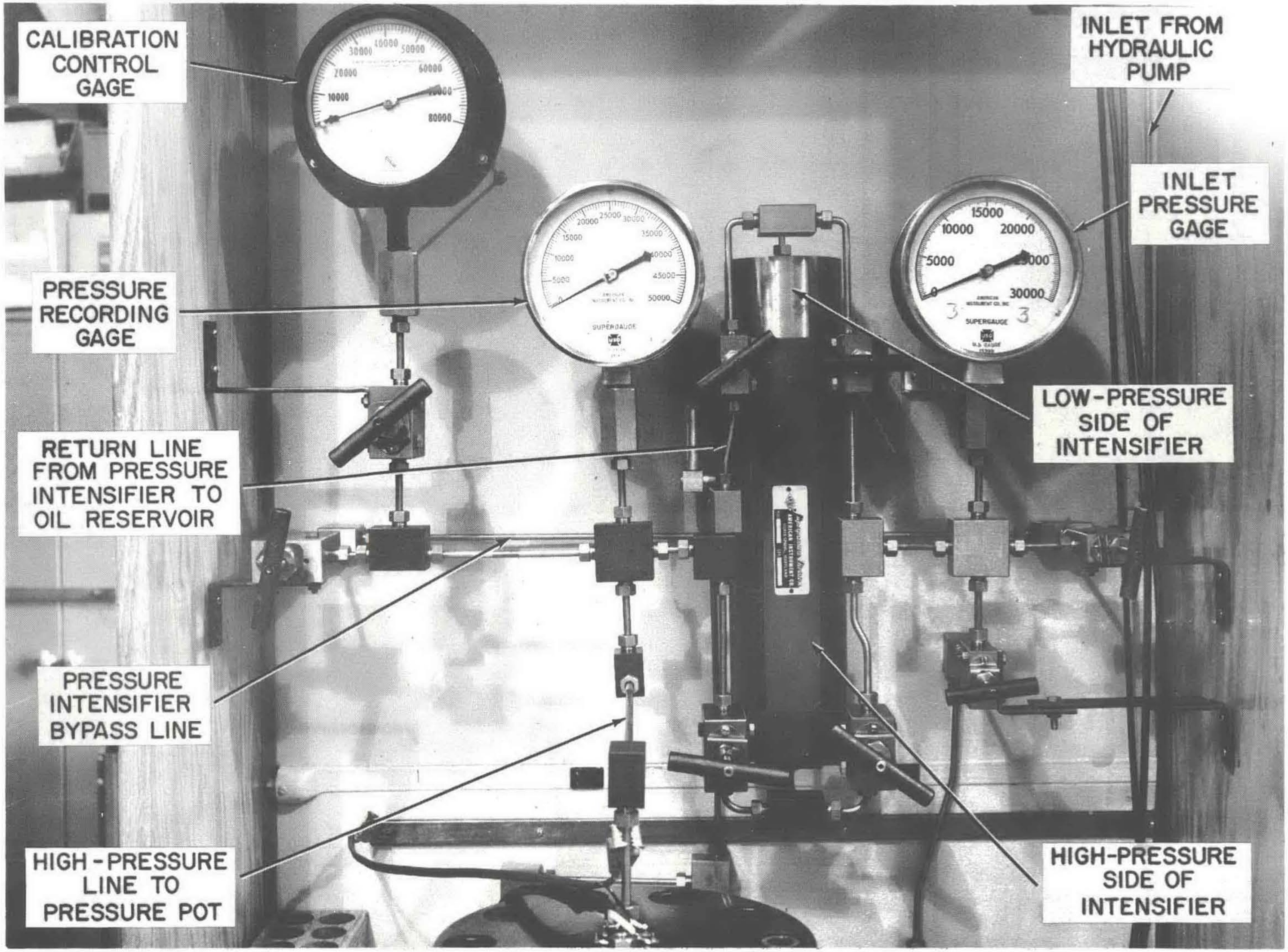
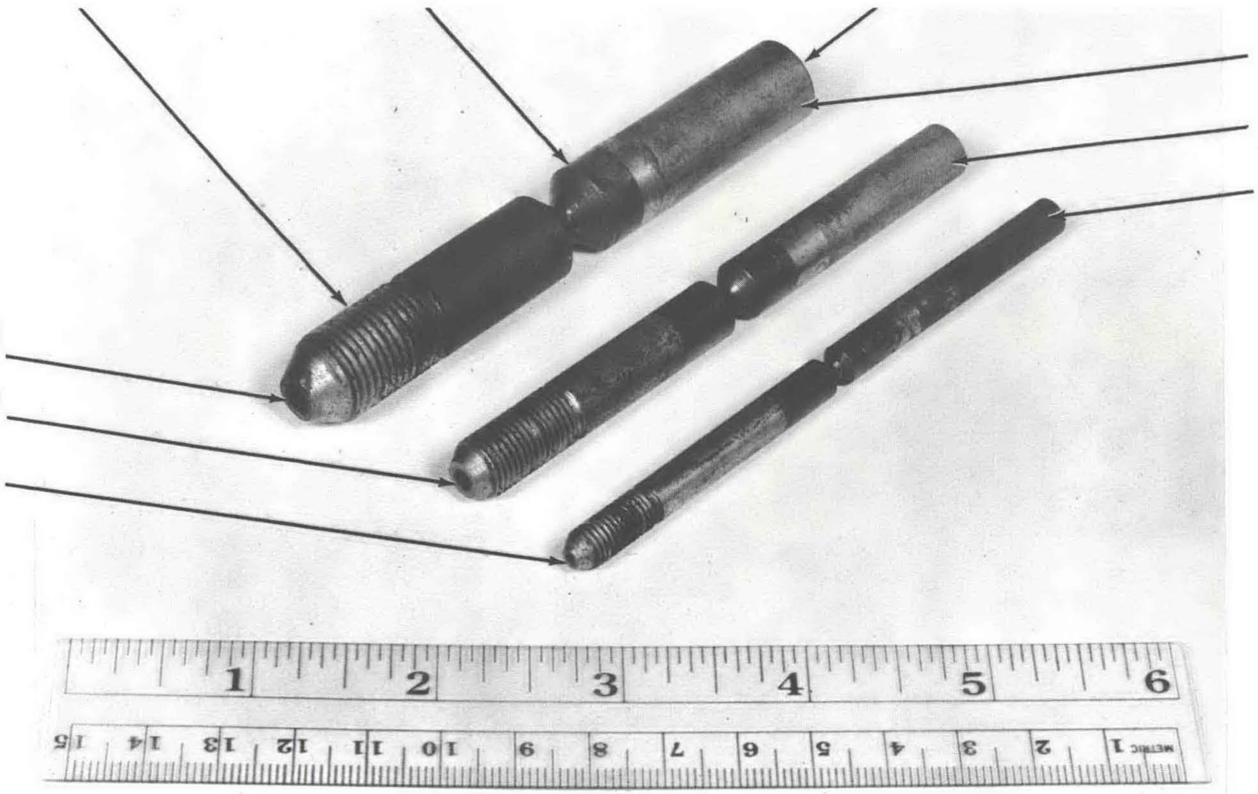


FIG. 11 HIGH-PRESSURE CONTROL SYSTEM

The two pressure pots used in this program were identical, except for the size of the bores from the compression chambers. Pressure Pot No. 1 had a 1/8-inch diameter bore (L = 5.00 inches) that was adapted to the 3/8-inch O.D. (1/8-inch I.D.) knock-off tube. Pressure Pot No. 2 had 1/16-inch and 3/16-inch diameter bores (L = 5.00 inches) that were adapted to the 1/4-inch O.D. (1/16-inch I.D.) and 9/16-inch O.D. (3/16-inch I.D.) knock-off tubes, respectively.

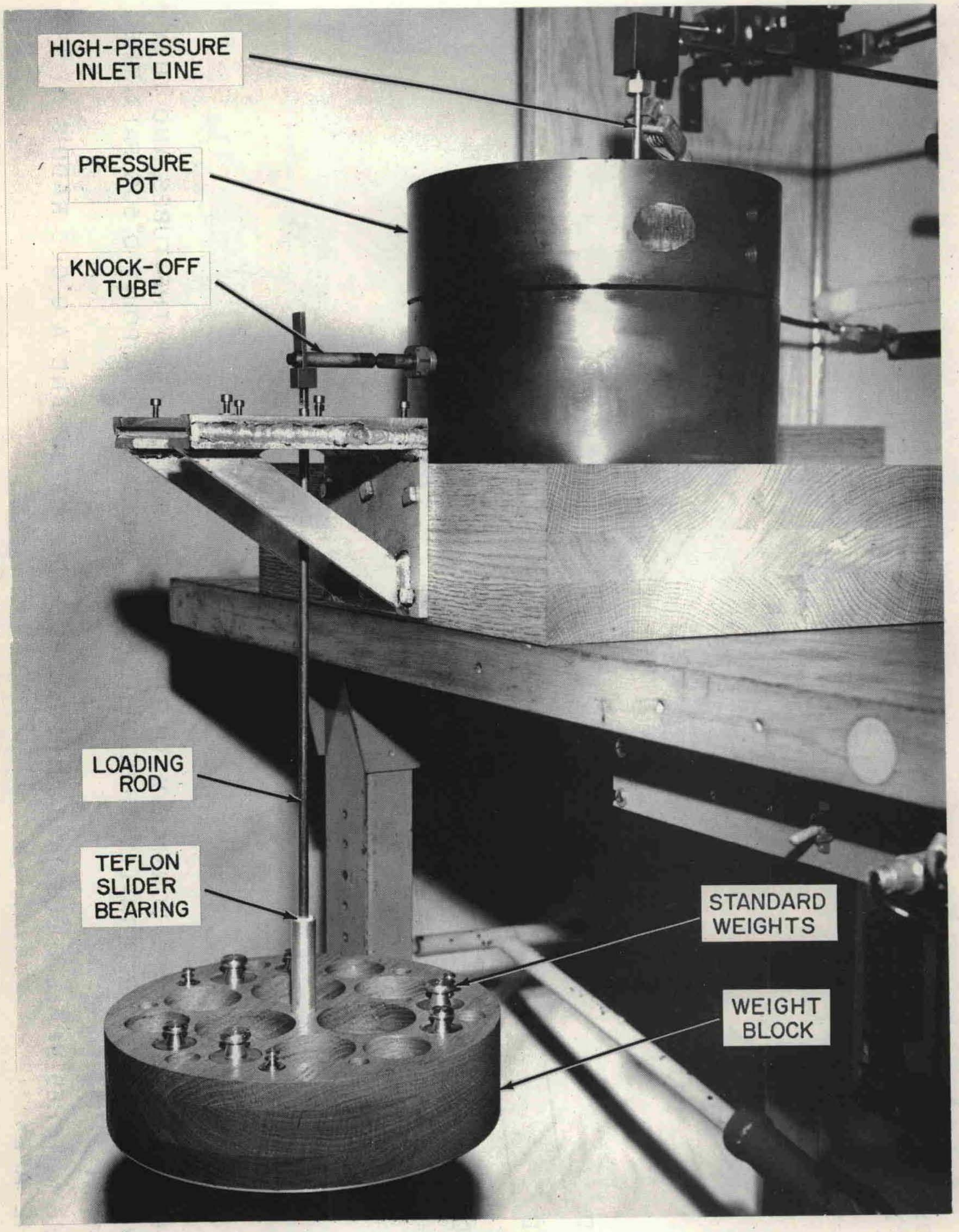
A view of the knock-off tubes appears in Figure 12. The dark area in the vicinity of the notch is the region that has been casehardened to a prescribed depth. The purpose of the casehardening was to provide insight as to its effect on the rupture strength of the knock-off tubes when subjected to static and dynamic loads. The casehardening process was carried out in an automatic Ipsen heat-treating unit. Further information on this process can be found in reference (h). The notch-wall thickness, defined as the wall thickness of the tube at the apex of the notch, was varied from a minimum of 0.005-inch to a maximum of 0.045-inch to evaluate its effect on the rupture-load characteristics. All of the knock-off tubes were made from AISI No. 4340 cold drawn, annealed, aircraft-quality, steel tubing having an approximate Brinell hardness number of 225.

The purpose of the loading mechanism, shown in Figure 13, was to provide means for applying static or dynamic loads to the end of the knock-off tubes. The loading mechanism consisted of the following parts: (1) a switch-release bar that permitted application of a vertical load to the end of the knock-off tube and that operated a micro-switch that initiated a trigger pulse to the recording oscilloscope, (2) a loading rod located in the vertical plane for transmitting loads from the source to the switch-release bar, and (3) a weight block that served as the



1. THE INSIDE BORES ARE COAXIAL WITH THE LONGITUDINAL AXIS OF THE TUBES, AND THEY EXTEND FROM THE EXTERNALLY THREADED END OF THE TUBE TO A POINT 0.500" PAST THE NOTCH.
2. THE NOTCHES IN ALL TUBES HAVE AN INCLUDED ANGLE OF 90° AND A 0.005" RADIUS AT THE APEX.

FIG. 12 KNOCK-OFF TUBES



WEIGHT BLOCK CAN BE HELD STATIONARY
OR BE ELEVATED 18 INCHES AND RELEASED

FIG. 13 LOADING MECHANISM

source of the loads applied to the knock-off tubes. The loading rod passed through the center-of-gravity of the loading block and was threaded into the switch-release bar. A special fastener was attached to the end of the loading rod and acted as a seat for the loading block. Standard weights were positioned on the loading block in a manner such that the loading rod always passed through its center-of-gravity. A teflon slider bearing was inserted between the loading rod and loading block to provide for frictionless, 1-dimensional motion of the loading block relative to the loading rod. The loading block with the standard weights could be elevated 18 inches or less, with respect to the fastener, and released. When the free-falling loading block made contact with the fastener, a dynamic load was transmitted through the loading rod directly to the end of the knock-off tube. Care was taken to ensure that the free-falling loading block made uniform contact with the fastener and that the contact surface of the fastener was in a plane normal to the axis of the loading rod.

EXPERIMENTAL PROCEDURES AND RESULTS

Eighty-three experiments were conducted in the piezoelectric gage calibration system to assess quantitatively the parameters that significantly affect the pressure-release time and the rupture-load characteristics of the knock-off tubes. The principal parameters examined in conjunction with the pressure-release time were the viscosity of the high-pressure fluid, the pressure within the compression chamber, and the exit-bore diameter (I.D. of the knock-off tube). The outside and inside diameters, notch-wall thickness, casehardened depth, internal pressure (equivalent to the pressure within the compression chamber), and the applied loads represented the chief parameters evaluated in relation to the rupture-load characteristics. Some of the experiments served in a dual capacity, i.e., data obtained from some of the experiments were pertinent to the pressure-release-time study as well as the study of the rupture-load characteristics of the knock-off tubes.

A chronological description of the procedure of a typical experiment is as follows. The piezoelectric gages to be calibrated, and subsequently used for monitoring the pressure-time history within the compression chamber, are secured to electrical connectors and then placed into the oil-filled compression chamber. A "C" ring is properly positioned, and the top plate is bolted to the base of the pressure pot. The knock-off tube is then mounted on the pressure pot. (It is understood that the pressure pot selected has a bore diameter corresponding to the inside diameter of the knock-off tube.) The container box is now positioned such that the end of the knock-off tube, including the notch, is completely enclosed. The switch-release bar is secured to the end of the knock-off tube, and the loading rod is in turn passed through a raised opening in the bottom of the container box and threaded into the switch-release bar.

The weight block (without the weights) is now slipped onto the loading rod and held in place by a fastener. The next step is to place the back panel of the container box in position and secure it with the compression screws. The micro-switch for initiating a sweeptrace on the oscilloscope is mounted on the back panel with two adjustment screws. By operating the adjustment screws, the micro-switch can be positioned such that a slight movement of the switch-release bar caused by motion of the knock-off tube will trip the micro-switch that will in turn send a trigger pulse to the recording oscilloscope. The hinged lid of the containment box is secured in place, and the entire containment box is anchored to the support bracket via the anchoring screws.

The pressure pot is now prepared for the build-up of pressure in the compression chamber. The manner in which high pressure is obtained in the pressure pot is best illustrated by referring to the schematic diagram of the pressure control system shown in Figure 14. The first stage of the pressure build-up is to pump fluid directly from the reservoir into the pressure pot until a pressure of 25,000 psi has been reached. This is accomplished by opening valve G and closing valves B and F. The pressure intensifier is now employed to increase the pressure in the compression chamber to the desired intensity. The pressure intensifier is operated in the following manner. With valves C, D, G, and E closed and valves A, B, and F open, oil is pumped from the reservoir through valve A into the low-pressure end of the intensifier. High-pressure oil from the high-pressure end of the intensifier passes out through valve B to the pressure pot. Pumping is continued until the intensifier piston reaches the bottom of its stroke as indicated by a rapid increase in pressure on the inlet pressure gage. The piston must then be returned to the top of its stroke. Valves A and B are first closed to retain high pressure in the compression

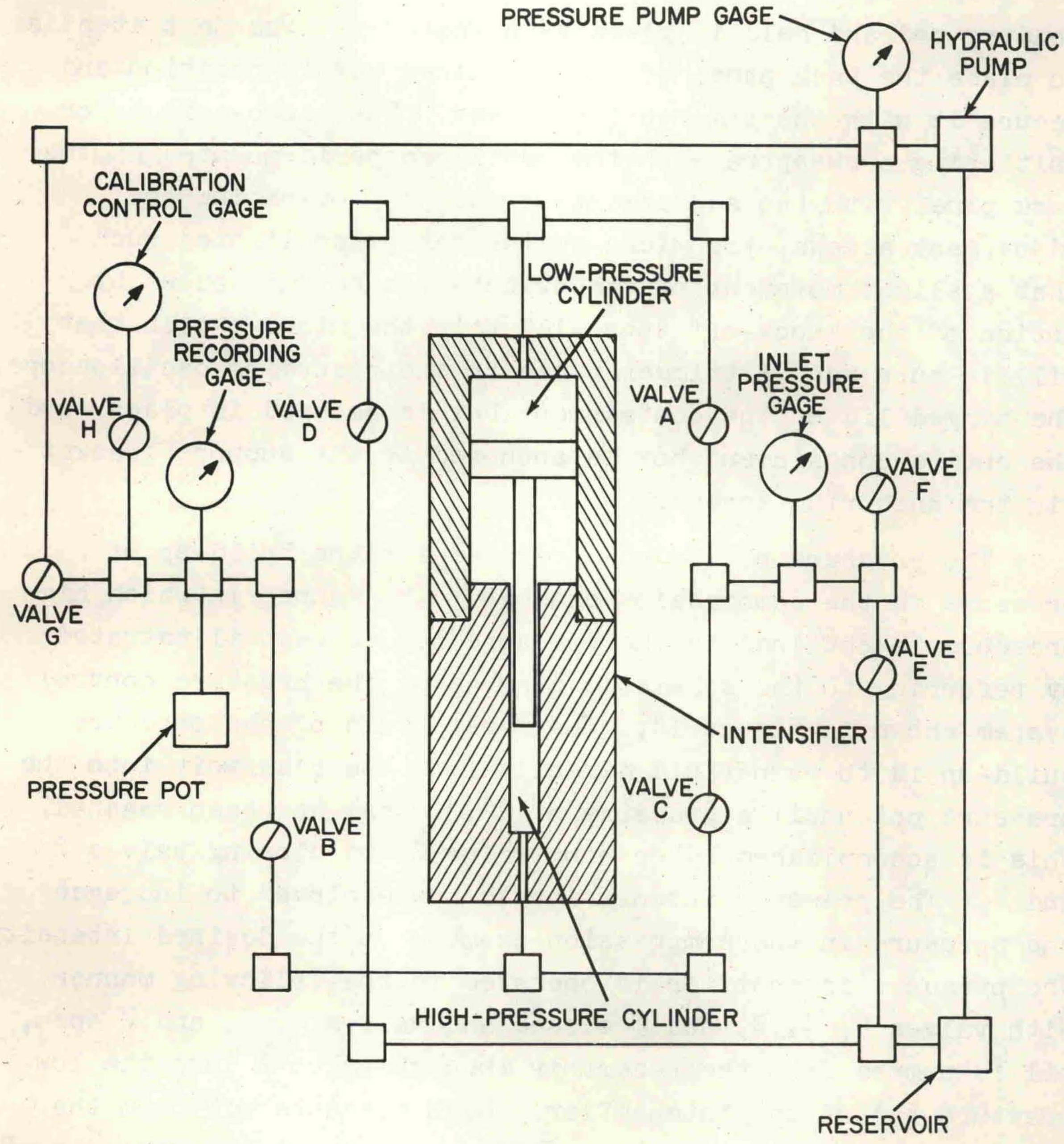


FIG. 14 SCHEMATIC OF PRESSURE CONTROL SYSTEM

chamber, and valves C and D are opened. Oil from the pump enters the high-pressure end of the intensifier through valve C to force the piston up and drive oil from the low pressure end of the intensifier through valve D back to the oil reservoir. The cycle is repeated as often as is necessary to build up the required pressure in the compression chamber. Since the pump is operating continuously, valves E and F are used to recycle the oil or to direct it to the point of use. The actual hydraulic pressure in the compression chamber is displayed continuously on the pressure recording gage. This gage is periodically checked against the calibration control gage to ensure its accuracy.

The next step is to prepare the instrumentation system for the ensuing test. This is accomplished primarily by turning on the heater and plate power supplies to the pressure instrumentation console; adjusting the beam intensity, gain, and sweeprate on the oscilloscope; and opening the camera shutter. The gain and sweeprate are adjusted in a manner such that the pressure-time curve will be displayed over a major portion of the oscilloscope screen. To gain reliability, two piezoelectric gages are used in each test. By using the chopper circuit of the plug-in preamplifier unit, pressure signals from both gages are displayed simultaneously on the oscilloscope screen.

The final step of the test is to apply either a static or a dynamic load to the knock-off tube via the loading mechanism that will cause the knock-off tube to fail at the notch and allow the pressurized fluid within the compression chamber to escape.

The pressure in the compression chamber at the time of rupture, the time constant of the pressure-time curve, and the magnitude of the static and dynamic loading weights are tabulated in Table 1. In those tests where the knock-off tubes were

TEST SPECIFICATIONS AND EXPERIMENTAL RESULTS

TEST SPECIFICATIONS							RESULTS			
TEST NO.	TUBE O.D. (IN.)	TUBE I.D. (IN.)	NOTCHWALL THICKNESS (IN.)	CASE-HARDENED DEPTH (IN.)	HIGH-PRESSURE FLUID	TEMP. (°F)	STATIC LOADING WEIGHT (LB.)	DYNAMIC LOADING WEIGHT (LB.)	TIME CONSTANT θ (MSEC)	RUPTURE PRESSURE (PSIG)
1-A	0.250	0.062	-	-	SAE 10	70	-	-	13.14	46,800
2-A	0.250	0.062	-	-	SAE 10	70	-	-	13.48	42,100
3-A	0.250	0.062	-	-	SAE 10	70	-	-	13.25	36,000
4-A	0.250	0.062	-	-	SAE 10	70	-	-	12.56	30,100
5-A	0.250	0.062	-	-	SAE 10	70	-	-	12.02	24,650
6-A	0.250	0.062	-	-	SAE 10	70	-	-	11.28	20,500
7-A	0.250	0.062	-	-	SAE 10	70	-	-	10.21	14,900
8-A	0.250	0.062	-	-	SAE 10	70	-	-	8.82	9,800
9-A	0.250	0.062	-	-	SAE 10	70	-	-	5.73	4,450
1-B	0.250	0.062	-	-	SAE 20	84	-	-	13.14	44,400
2-B	0.250	0.062	-	-	SAE 20	84	-	-	13.11	41,000
3-B	0.250	0.062	-	-	SAE 20	84	-	-	12.90	35,200
4-B	0.250	0.062	-	-	SAE 20	84	-	-	12.31	30,100
5-B	0.250	0.062	-	-	SAE 20	84	-	-	11.85	25,000
6-B	0.250	0.062	-	-	SAE 20	84	-	-	12.24	19,900
7-B	0.250	0.062	-	-	SAE 20	84	-	-	9.66	12,600
8-B	0.250	0.062	-	-	SAE 20	84	-	-	8.68	10,000
9-B	0.250	0.062	-	-	SAE 20	84	-	-	7.18	4,750
8	0.562	0.187	-	-	SAE 10	65	-	-	1.44	25,000
24	0.562	0.187	0.0217	0	SAE 10	65	-	1.0	1.53	48,000
25	0.562	0.187	0.0316	0	SAE 10	-	97.4	-	-	45,500
26	0.562	0.187	0.0368	0	SAE 10	65	-	4.1	1.49	46,000
31	0.375	0.125	0.0100	0	SAE 10	-	0	-	-	48,000
35	0.375	0.125	-	-	SAE 10	65	-	-	3.20	43,350
36	0.375	0.125	0.0407	0	SAE 10	-	88.5	-	-	46,000
46	0.375	0.125	0.0302	0	SAE 10	-	73.1	-	-	0
48	0.375	0.125	0.0302	0.005	SAE 10	-	53.0	-	-	0
49	0.375	0.125	0.0307	0.005	SAE 10	-	45.1	-	-	45,000
51	0.375	0.125	0.0295	0.010	SAE 10	65	28.0	-	3.25	45,500
53	0.375	0.125	0.0300	0.010	SAE 10	-	46.1	-	-	0
56	0.375	0.125	0.0300	0	SAE 10	-		3.5	-	0
57	0.375	0.125	0.0302	0.005	SAE 10	-	-	0.8	-	46,500
58	0.375	0.125	-	-	SAE 10	65	-	-	2.75	25,350
59	0.375	0.125	0.0317	0.005	SAE 10	-	-	2.0	-	0
60	0.375	0.125	0.0297	0.010	SAE 10	-	-	0.5	-	46,000
61	0.375	0.125	-	-	SAE 10	65	-	-	2.50	14,350
62	0.375	0.125	0.0285	0.010	SAE 10	-	-	1.3	-	0
63	0.375	0.125	0.0230	0	SAE 10	-	16.1	-	-	46,000
65	0.375	0.125	0.0212	0	SAE 10	-	-	1.3	-	0
66	0.375	0.125	0.0207	0.005	SAE 20	84	18.1	-	2.86	44,150
68	0.375	0.125	0.0205	0.005	SAE 20	-	28.1	-	-	0
69	0.375	0.125	0.0192	0.010	SAE 20	84	5.1	-	3.05	46,000
71	0.375	0.125	0.0197	0.010	SAE 20	-	21.0	-	-	0
72	0.375	0.125	0.0212	0	SAE 10	-		0.7	-	48,000
74	0.375	0.125	0.0207	0	SAE 10	-	41.1	-	-	0
75	0.375	0.125	0.0210	0.005	SAE 20	84	-	0.4	3.01	46,000
76	0.375	0.125	-	-	SAE 20	84	-	-	2.74	37,000
77	0.375	0.125	0.0212	0.005	SAE 20	-	-	1.3	-	0
78	0.375	0.125	0.0190	0.010	SAE 20	84	-	0.2	3.13	45,000
79	0.375	0.125	-	-	SAE 20	84	-	-	2.49	25,000
80	0.375	0.125	0.0212	0.010	SAE 20	-	-	0.5	-	0
92	0.562	0.187	0.0315	0.005	SAE 10	65	61.1	-	1.56	45,500
93	0.562	0.187	-	-	SAE 10	65	-	-	1.15	14,900
94	0.562	0.187	0.0297	0.005	SAE 10	-	98.1	-	-	0
98	0.562	0.187	0.0300	0.005	SAE 10	65	-	1.5	1.54	43,400
100	0.562	0.187	0.0302	0.005	SAE 10	-	-	4.1	-	0
109	0.562	0.187	0.0221	0	SAE 10	-	32.1	-	-	46,000
110	0.562	0.187	0.0211	0	SAE 10	-	75.1	-	-	0
111	0.562	0.187	0.0215	0	SAE 10	-	34.1	-	-	46,000
112	0.562	0.187	0.0200	0.005	SAE 10	-	10.1	-	-	47,000
113	0.562	0.187	0.0197	0.005	SAE 10	-	12.1	-	-	45,500
114	0.562	0.187	0.0210	0.005	SAE 10	-	55.1	-	-	0
115	0.562	0.187	0.0212	0	SAE 10	-	-	1.0	-	45,500
117	0.562	0.187	0.0235	0	SAE 10	-	-	3.0	-	0
118	0.562	0.187	0.0202	0.005	SAE 10	65	-	0.5	1.56	45,500
119	0.562	0.187	-	-	SAE 10	65	-	-	1.45	25,300
120	0.562	0.187	0.0207	0.005	SAE 10	-	-	2.0	-	0
123	0.375	0.125	0.0105	0	SAE 10	-	14.6	-	-	0
124	0.375	0.125	0.0120	0.005	SAE 20	-	-	0.8	-	45,000
125	0.375	0.125	-	-	SAE 20	84	-	-	2.12	12,300
126	0.375	0.125	0.0121	0.005	SAE 20	-	13.6	-	-	0
127	0.375	0.125	0.0095	0.010	SAE 20	-	0	-	-	33,000
128	0.375	0.125	-	-	SAE 20	84	-	-	1.58	4,300
129	0.375	0.125	0.0125	0.010	SAE 20	-	10.1	-	-	0
130	0.375	0.125	0.0110	0	SAE 10	-	-	0.5	-	0
133	0.375	0.125	0.0112	0.005	SAE 20	-	-	0	-	37,500
135	0.375	0.125	0.0100	0.005	SAE 20	-	-	0.3	-	0
136	0.375	0.125	0.0115	0.010	SAE 20	-	-	0	-	38,000
138	0.375	0.125	0.0115	0.010	SAE 20	-	-	0.2	-	0
139	0.375	0.125	0.0365	0	SAE 10	-	52.1	-	-	45,000
140	0.375	0.125	0.0377	0	SAE 10	-	-	4.1	-	45,500
141	0.562	0.187	0.0108	0	SAE 10	65	0	-	1.35	31,500
142	0.375	0.125	0.0345	0.005	SAE 10	-	53.1	-	-	45,500

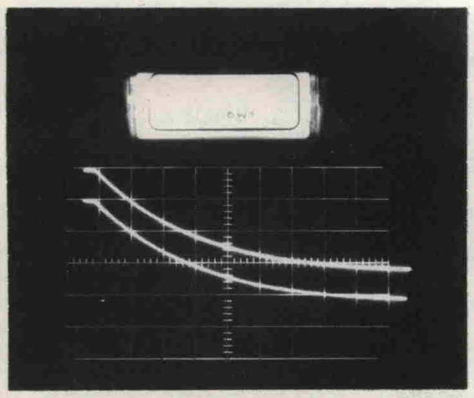
NOTES:

1. LOADING WEIGHTS WERE APPLIED TO KNOCK-OFF TUBES AT A POINT 2.00 INCHES FROM NOTCH.
2. DYNAMIC LOADING WEIGHT DROPPED FROM A HEIGHT OF 6 INCHES (IMPACT VELOCITY ≈ 68 IN/SEC).

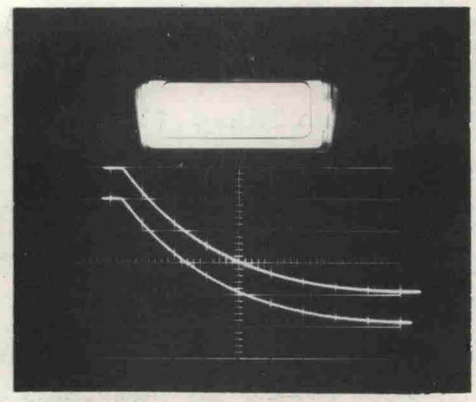
not casehardened, complete severage of the knock-off tube was not generally obtained. From these tests and, of course, the tests where pressure was not required, no data pertaining to the pressure-release time were acquired. In those tests where the test numbers are followed by the letters A or B, the sole objective was to determine the time constant. The test numbering system evolved from the manner in which the knock-off tubes were identified. Some of the numbered tubes were used in order to check instrumentation, experimental techniques and procedures, and replicability of the experimental results, while others were retained for future testing.

Typical pressure-time oscilloscope traces, obtained under various test conditions, for 0.062-inch, 0.125-inch, and 0.187-inch inside diameter knock-off tubes are shown in Figures 15, 16, and 17, respectively. Type 146-L Polaroid Land Film, used to record the voltage-time traces displayed on the oscilloscope, produced a positive transparency that was easily read and analyzed on a high-magnification Telereadex 29A film reader. The pressure-time traces were obtained by combining data from the voltage-time traces with the gain of the system and the pressure obtained from the pressure recording gage. That is, each voltage-time trace was converted directly to a pressure-time trace by multiplying the voltage by a constant factor.

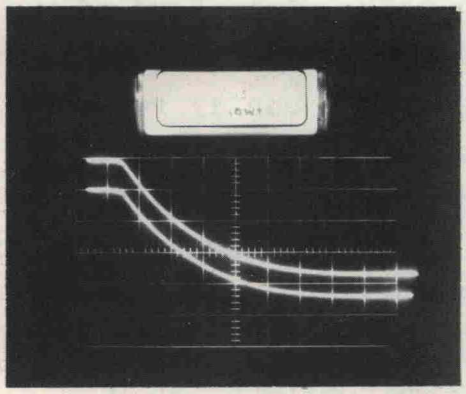
The effects of pressure and notch-wall thickness on the failure of 3/8-inch O.D. (1/8-inch I.D.) tubes, having zero, 0.005-inch, and 0.010-inch casehardened depths and subjected to static and dynamic loads, are illustrated in Figures 18, 19, and 20, respectively. As previously explained, the loads were applied to the end of the knock-off tubes. Since the notch was located 2 inches from the end of the tube, the effective moment arm between the notch and the line-of-action of the load was the same in all tests. The effects of pressure and



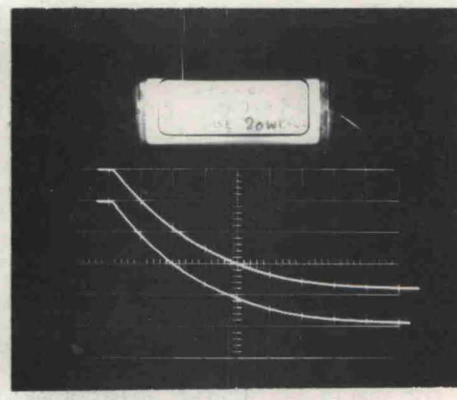
TEST NO. 1-A SAE 10 OIL
PEAK PRESSURE = 46,800 PSI
SWEEP RATE = 5 MSEC/CM



TEST NO. 4-A SAE 10 OIL
PEAK PRESSURE = 30,100 PSI
SWEEP RATE = 5 MSEC/CM



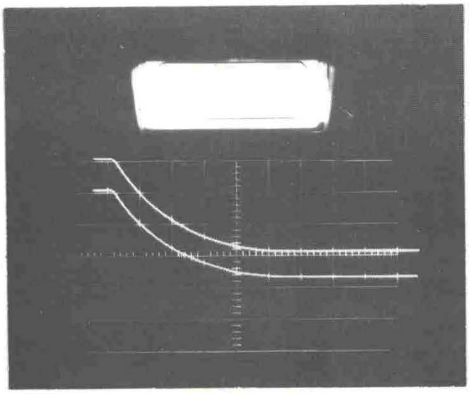
TEST NO. 7-A SAE 10 OIL
PEAK PRESSURE = 14,900 PSI
SWEEP RATE = 5 MSEC/CM



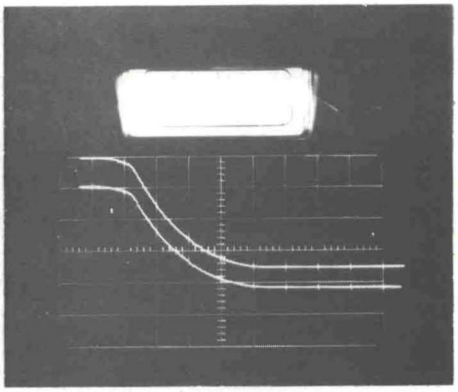
TEST NO. 4-B SAE 20 OIL
PEAK PRESSURE = 30,100 PSI
SWEEP RATE = 5 MSEC/CM

SPACING OF GRID-WORK ON OSCILLOSCOPE SCREEN IS 1 CM^2

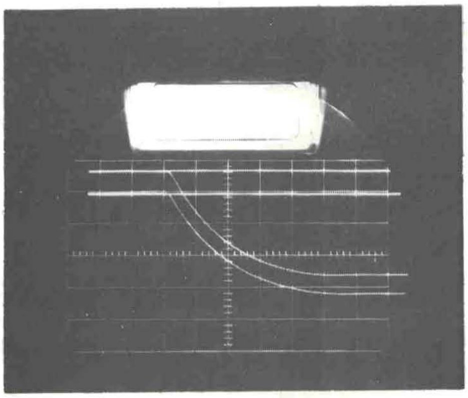
FIG. 15 PRESSURE-TIME OSCILLOSCOPE TRACES FOR 1/16" I.D. TUBES



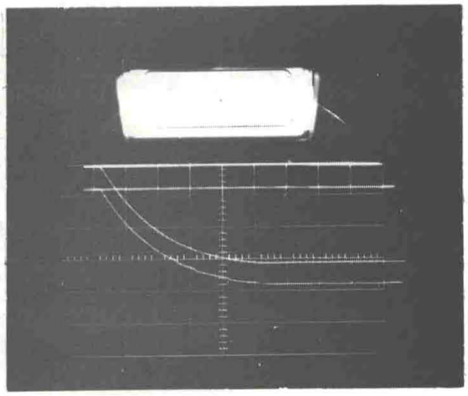
TEST NO. 51 SAE 10 OIL
PEAK PRESSURE = 45,500 PSI
SWEEP RATE = 2 MSEC/CM



TEST NO. 58 SAE 10 OIL
PEAK PRESSURE = 25,300 PSI
SWEEP RATE = 2 MSEC/CM



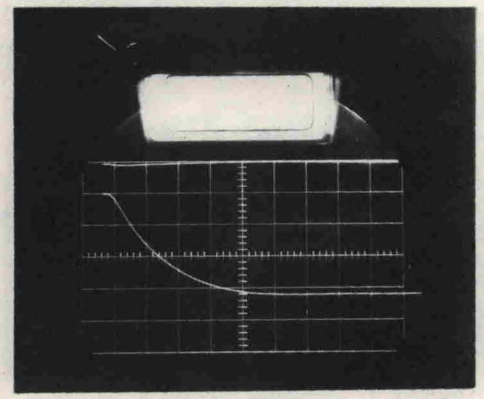
TEST NO. 75 SAE 20 OIL
PEAK PRESSURE = 46,000 PSI
SWEEP RATE = 2 MSEC/CM



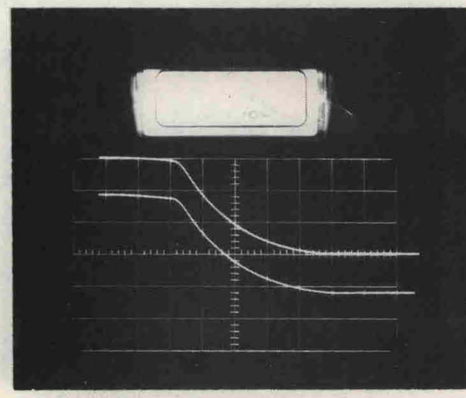
TEST NO. 78 SAE 20 OIL
PEAK PRESSURE = 45,000 PSI
SWEEP RATE = 2 MSEC/CM

SPACING OF GRID-WORK ON OSCILLOSCOPE SCREEN IS 1 CM^2

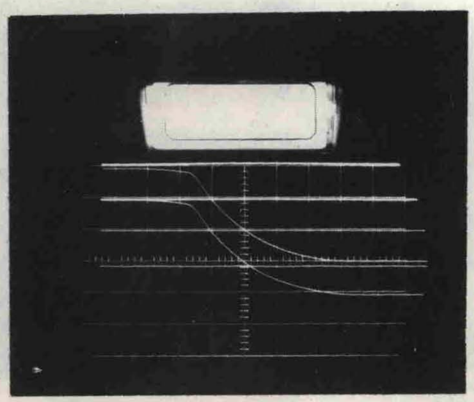
FIG. 16 PRESSURE-TIME OSCILLOSCOPE TRACES FOR 1/8" I.D. TUBES



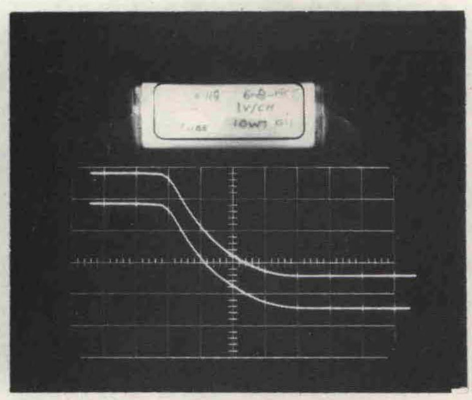
TEST NO.27 SAE 20 OIL
PEAK PRESSURE = 47,600 PSI
SWEEP RATE = 1 MSEC/CM



TEST NO.92 SAE 10 OIL
PEAK PRESSURE = 45,500 PSI
SWEEP RATE = 1 MSEC/CM



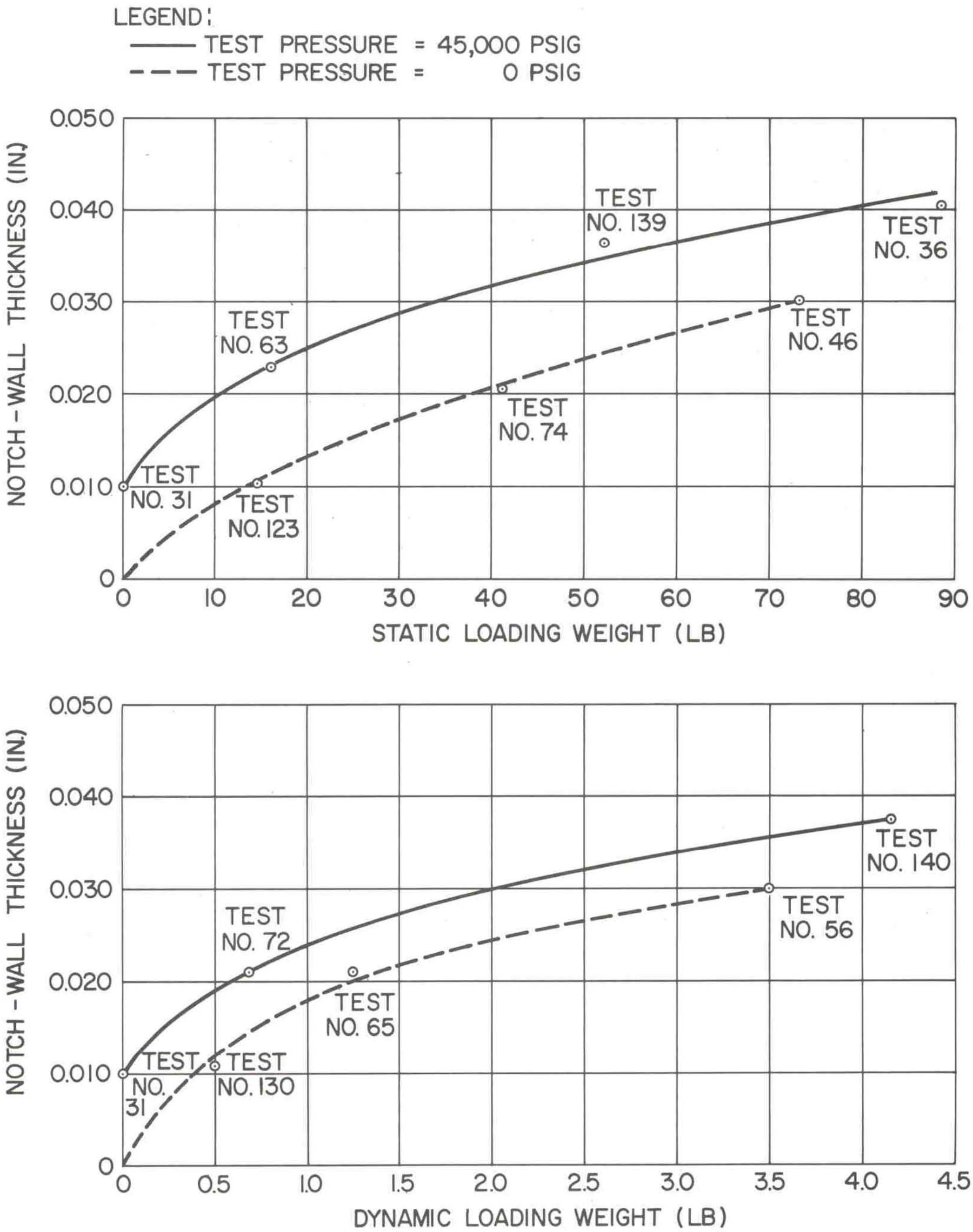
TEST NO.98 SAE 10 OIL
PEAK PRESSURE = 43,400 PSI
SWEEP RATE = 1 MSEC/CM



TEST NO.119 SAE 10 OIL
PEAK PRESSURE = 25,300 PSI
SWEEP RATE = 1 MSEC/CM

SPACING OF GRID-WORK ON OSCILLOSCOPE SCREEN IS 1 CM^2

FIG. 17 PRESSURE-TIME OSCILLOSCOPE TRACES FOR $3/16''$ I.D TUBES



NOTES:

1. LOADING WEIGHTS APPLIED TO KNOCK-OFF TUBES AT POINT 2.00 INCHES FROM NOTCH
2. DYNAMIC LOADING WEIGHTS DROPPED FROM HEIGHT OF 6 INCHES (IMPACT VELOCITY ≈ 68 IN./SEC)

FIG. 18 EFFECTS OF PRESSURE AND NOTCH-WALL THICKNESS ON FAILURE OF 3/8"O.D. (1/8"I.D.) TUBES, WITH NO CASEHARDENING, SUBJECTED TO STATIC AND DYNAMIC LOADS

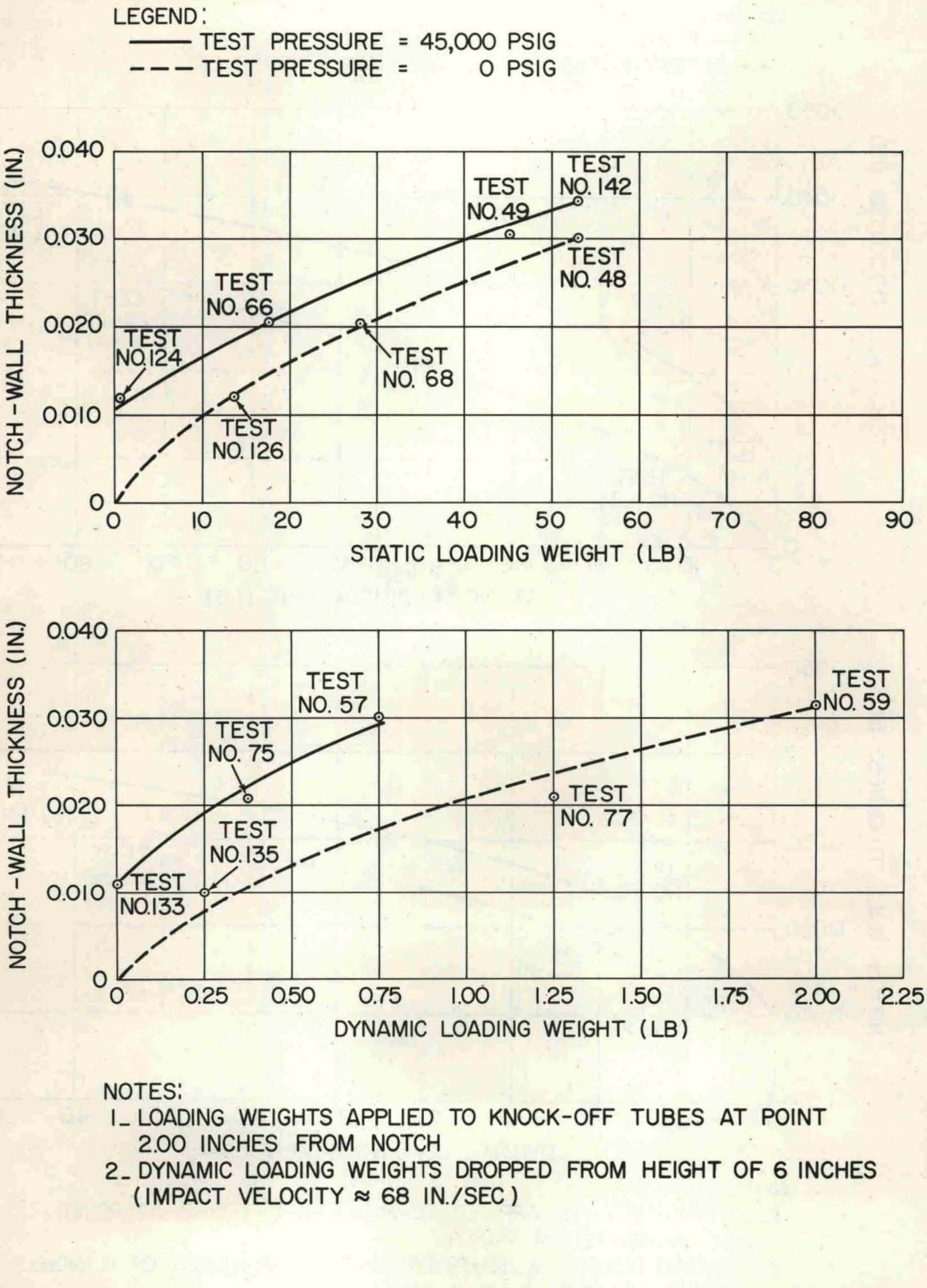
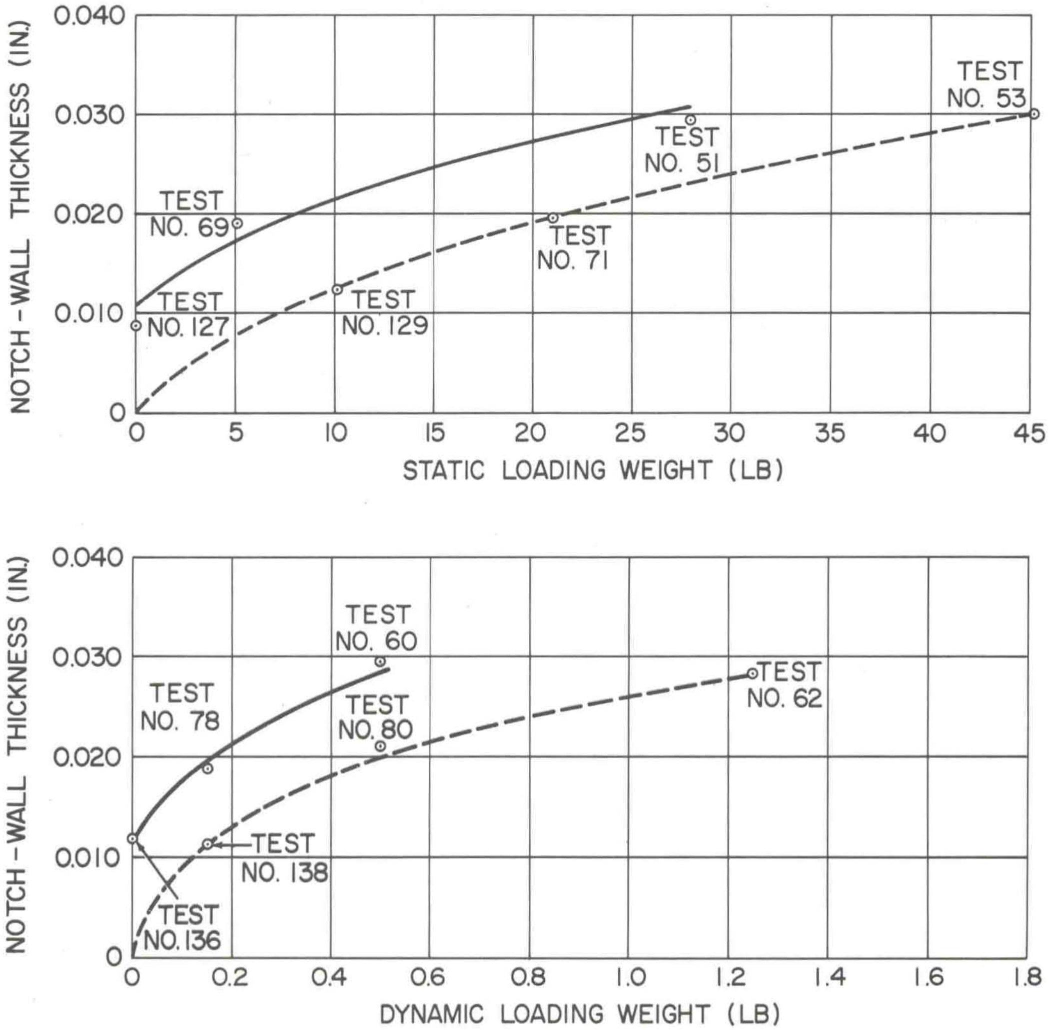


FIG. 19 EFFECTS OF PRESSURE AND NOTCH-WALL THICKNESS ON FAILURE OF 3/8"O.D. (1/8"I.D.) TUBES, WITH 0.005-INCH CASEHARDENED DEPTH, SUBJECTED TO STATIC AND DYNAMIC LOADS

LEGEND:
—— TEST PRESSURE = 45,000 PSIG
- - - TEST PRESSURE = 0 PSIG

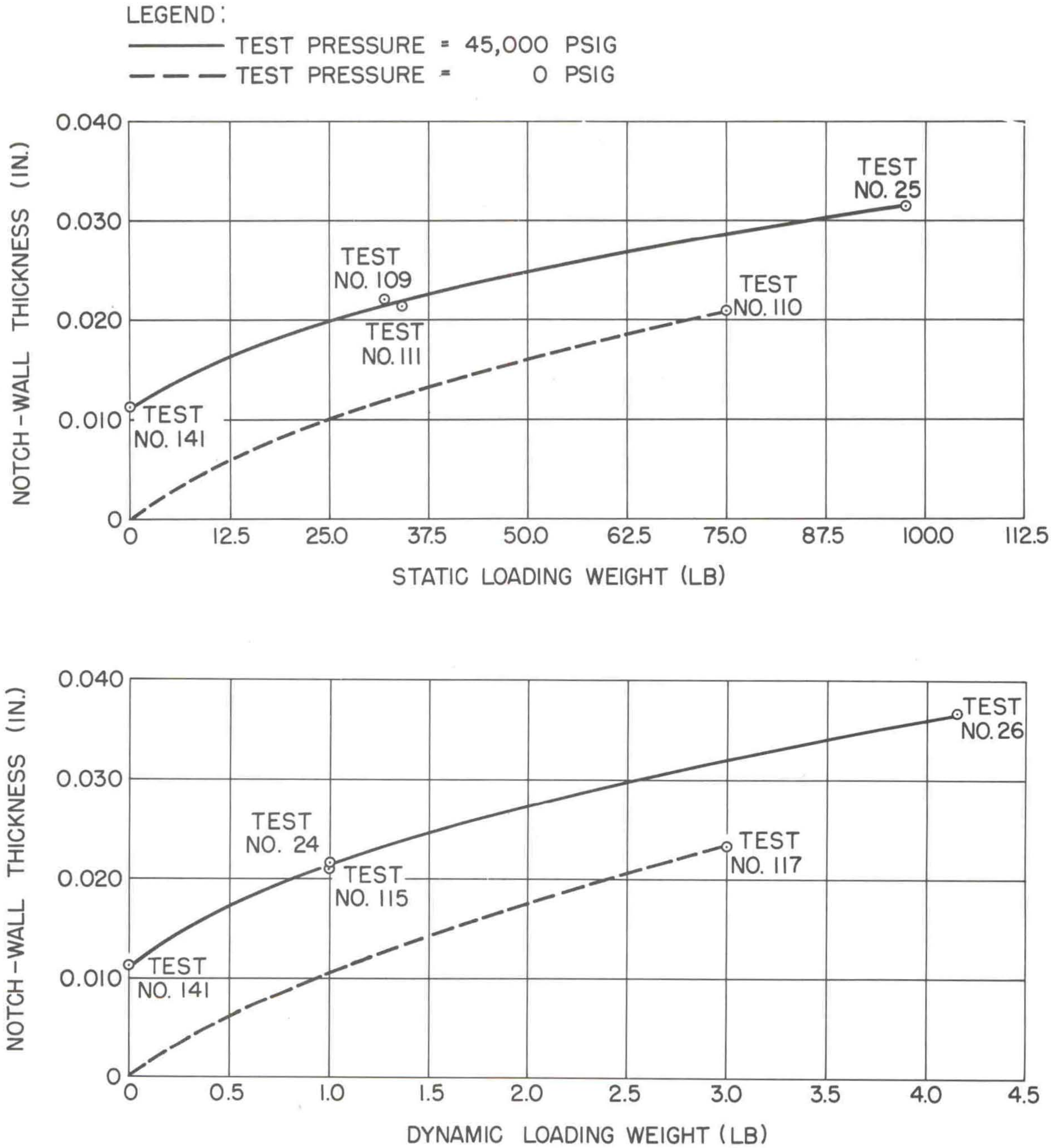


NOTES:
1. LOADING WEIGHTS APPLIED TO KNOCK-OFF TUBES AT POINT 2.00 INCHES FROM NOTCH
2. DYNAMIC LOADING WEIGHTS DROPPED FROM HEIGHT OF 6 INCHES (IMPACT VELOCITY ≈ 68 IN./SEC)

FIG. 20 EFFECTS OF PRESSURE AND NOTCH-WALL THICKNESS ON FAILURE OF 3/8" O.D. (1/8" I.D.) TUBES, WITH 0.010-INCH CASEHARDENED DEPTH, SUBJECTED TO STATIC AND DYNAMIC LOADS notch-wall thickness on the failure of 9/16-inch O.D. (3/16-inch I.D.) tubes, having zero and 0.005-inch casehardened depths and subjected to static and dynamic loads, are illustrated in Figures 21 and 22, respectively.

The last parameter to be evaluated in conjunction with the knock-off tube, rupture-load characteristics was the casehardened depth. The effects of casehardening and notch-wall thickness on the failure of 3/8-inch O.D. (1/8-inch I.D.) tubes subjected to static and dynamic loads are shown in Figures 23 and 24, respectively.

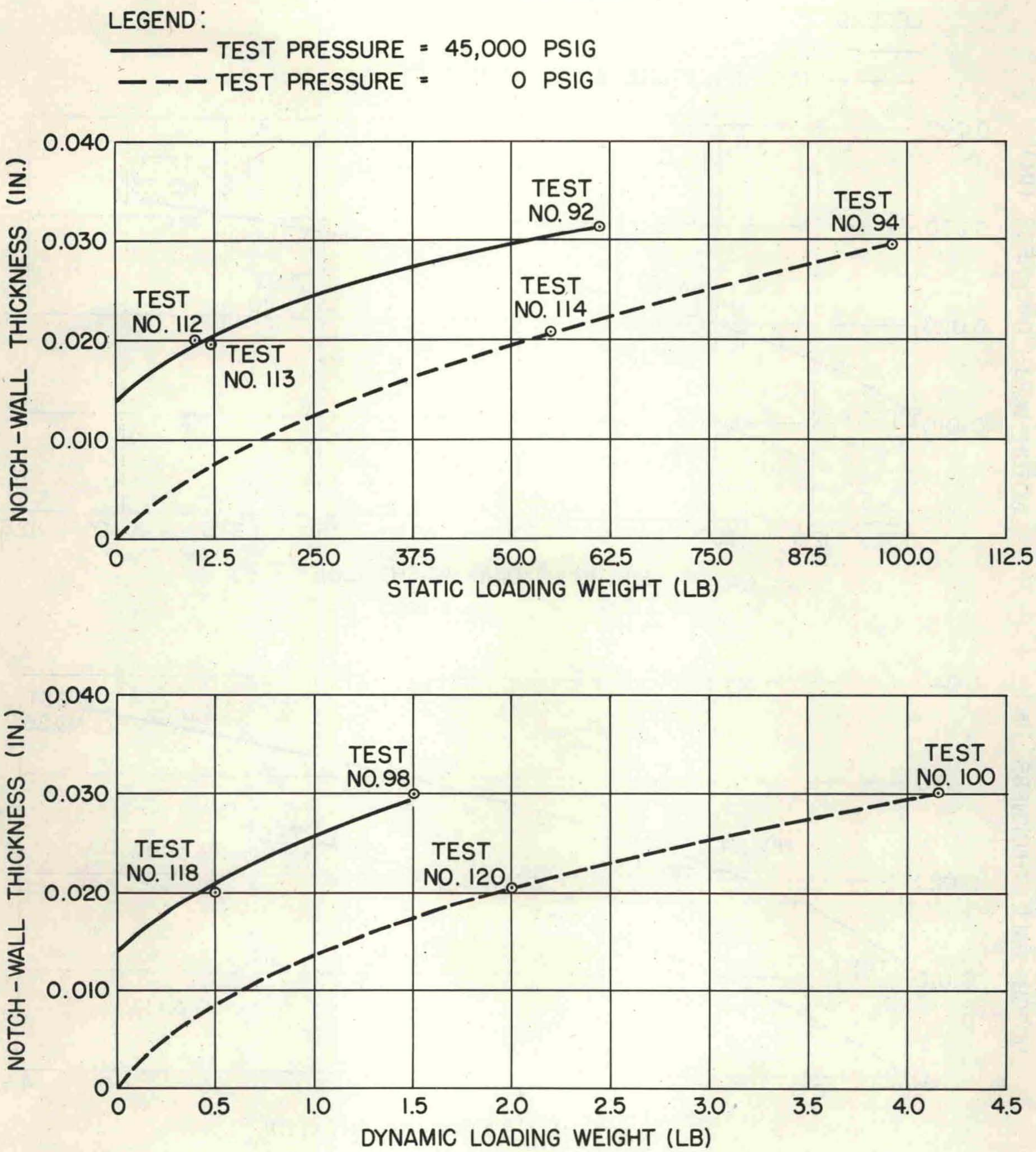
The curves shown in the aforementioned figures clearly indicate that there is a definite correlation between the various parameters that affect the knock-off tube, rupture-load characteristics. This correlation is further discussed in the section Selection of Knock-Off Tube.



NOTES:

1. LOADING WEIGHTS APPLIED TO KNOCK-OFF TUBES AT POINT 2.00 INCHES FROM NOTCH
2. DYNAMIC LOADING WEIGHT DROPPED FROM HEIGHT OF 6 INCHES (IMPACT VELOCITY ≈ 68 IN./SEC)

FIG. 21 EFFECTS OF PRESSURE AND NOTCH-WALL THICKNESS ON FAILURE OF 9/16" O.D. (3/16" I.D.) TUBES, WITH NO CASE-HARDENING, SUBJECTED TO STATIC AND DYNAMIC LOADS



NOTES:

1. LOADING WEIGHTS APPLIED TO KNOCK-OFF TUBES AT POINT 2.00 INCHES FROM NOTCH
2. DYNAMIC LOADING WEIGHT DROPPED FROM HEIGHT OF 6 INCHES (IMPACT VELOCITY ≈ 68 IN./SEC)

FIG. 22 EFFECTS OF PRESSURE AND NOTCH-WALL THICKNESS ON FAILURE OF 9/16" O.D. (3/16" I.D.) TUBES, WITH 0.005 INCH CASEHARDENED DEPTH, SUBJECTED TO STATIC AND DYNAMIC LOADS

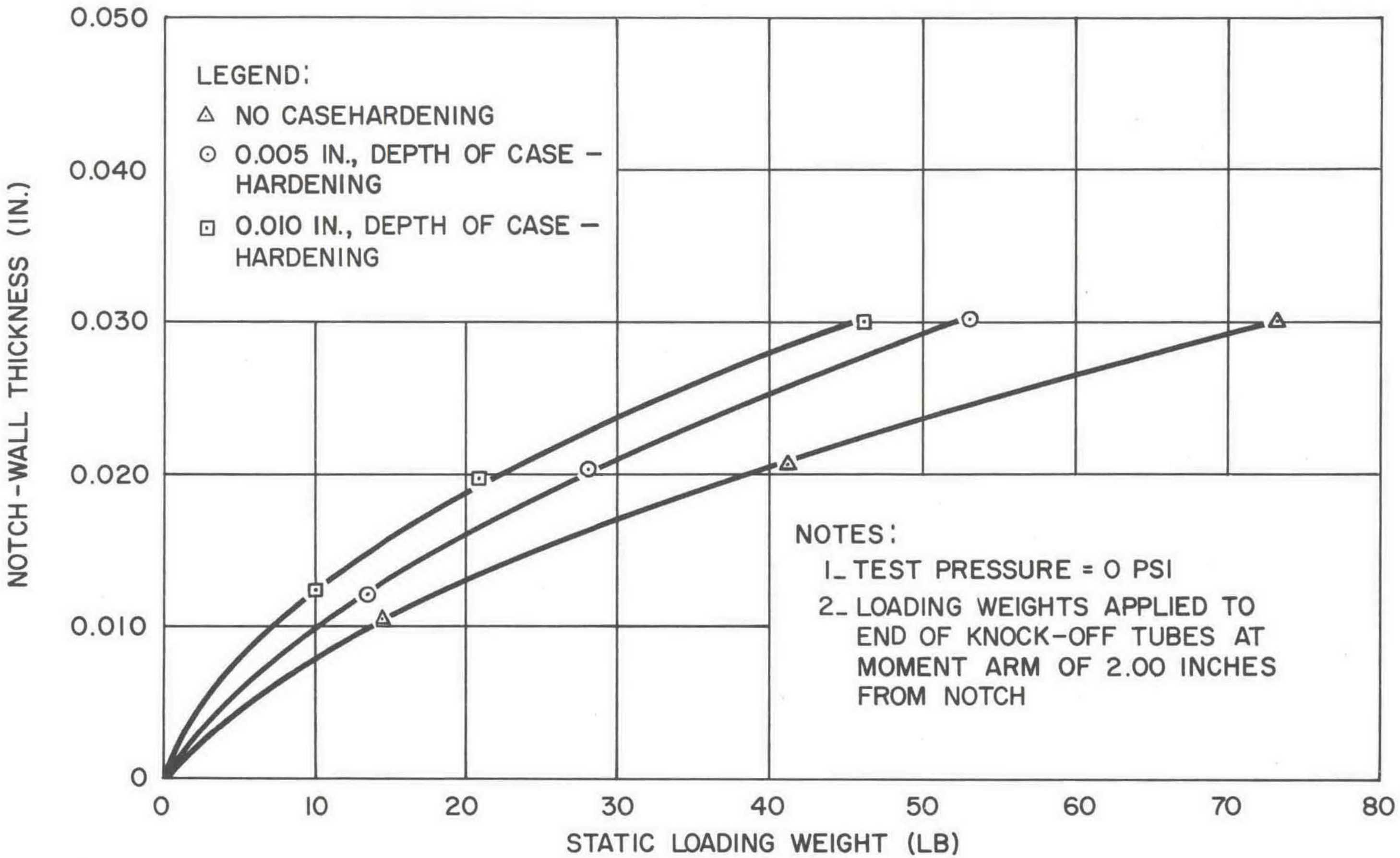


FIG. 23 EFFECTS OF CASEHARDENING AND NOTCH-WALL THICKNESS ON FAILURE OF 3/8" O.D. (1/8" I.D.) TUBES SUBJECTED TO STATIC LOADS

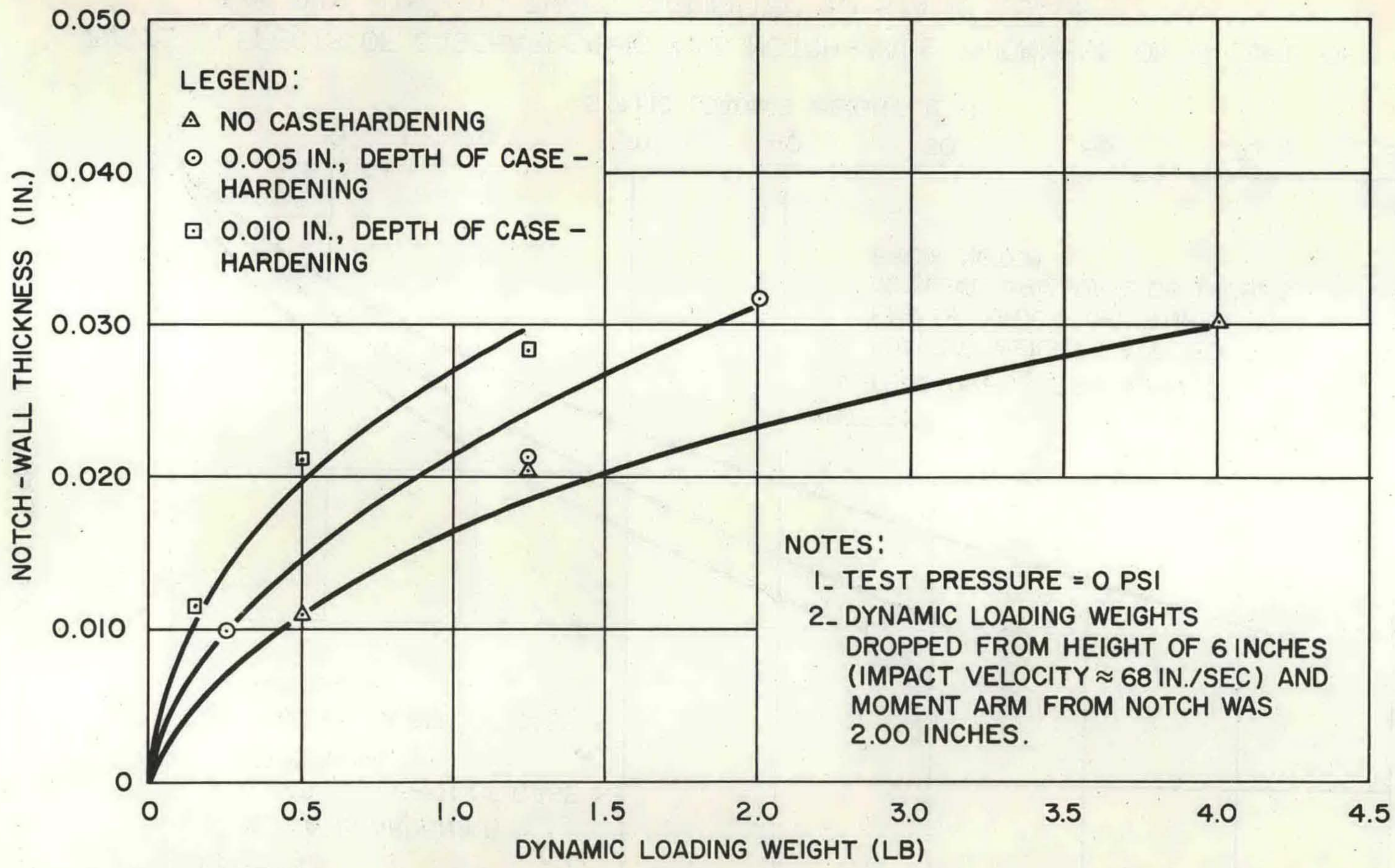


FIG. 24 EFFECTS OF CASEHARDENING AND NOTCH-WALL THICKNESS ON FAILURE OF 3/8" O.D. (1/8" I.D.) TUBES SUBJECTED TO DYNAMIC LOADS

CALCULATED RESULTS

As explained previously, the voltage-time trace depicted on the oscilloscope screen was readily converted to the corresponding pressure-time trace. The pressure-time traces were placed on the Telereadex film reader, and the time constants were obtained directly (time constant is the time corresponding to pressure P_g/e). The time constants determined in this manner are tabulated in Table I of the previous section.

Equation (62) was utilized to obtain time constant-pressure curves for fluids having various coefficients of viscosity. The effects of viscosity on the rate of release of pressurized fluid through 0.062-inch diameter orifices, as obtained from equation (62), are shown in Figure 25. Superposed on Figure 25 are the experimental data obtained under identical test conditions. The correlation between the analytical and experimental data is deemed good except at the extreme ends of the pressure scale. These discrepancies can be accounted for in the following manner. (1) The pressure recording gage and the calibration control gage are capable of measuring pressures in the range of 0 - 50,000 psi and 0 - 80,000 psi, respectively. However, a pressure gage does not respond accurately to pressures that occur at the extreme ends of its designed pressure range. (2) The viscosity-pressure relation defined in equation (61) for the subject fluids is valid only for pressures in the range of 0 - 35,000 psi.

In knock-off tubes where the bore diameter exceeds 0.062-inch, the flow of the pressurized fluid may cease to be laminar, i.e., the Reynolds number may be in excess of the critical value. Since the condition of laminar flow was invoked in the derivation of equation (62), it may not, in general, be valid for the larger diameter bores where the flow is transitional or turbulent. The pressure-release time data obtained for the

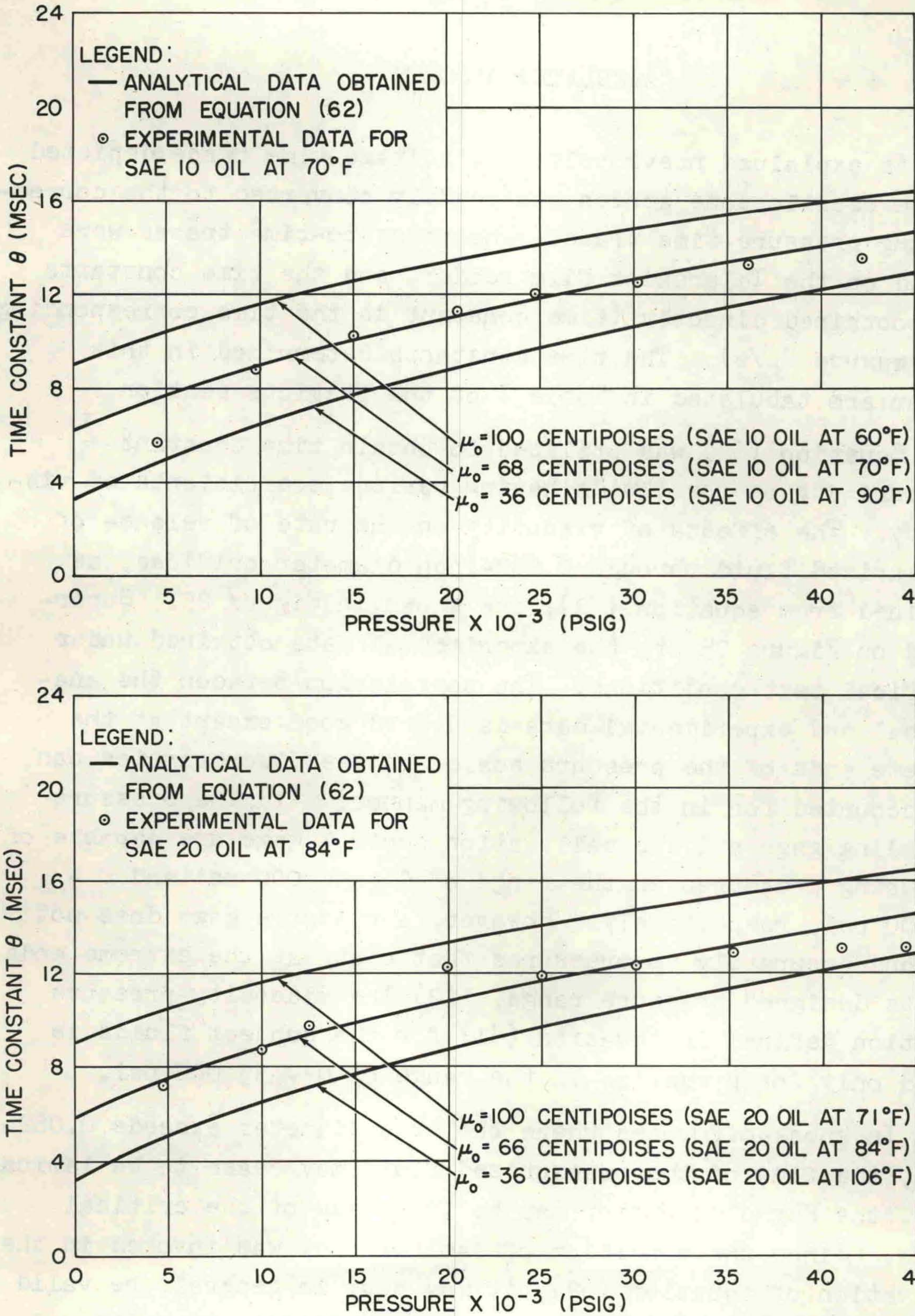
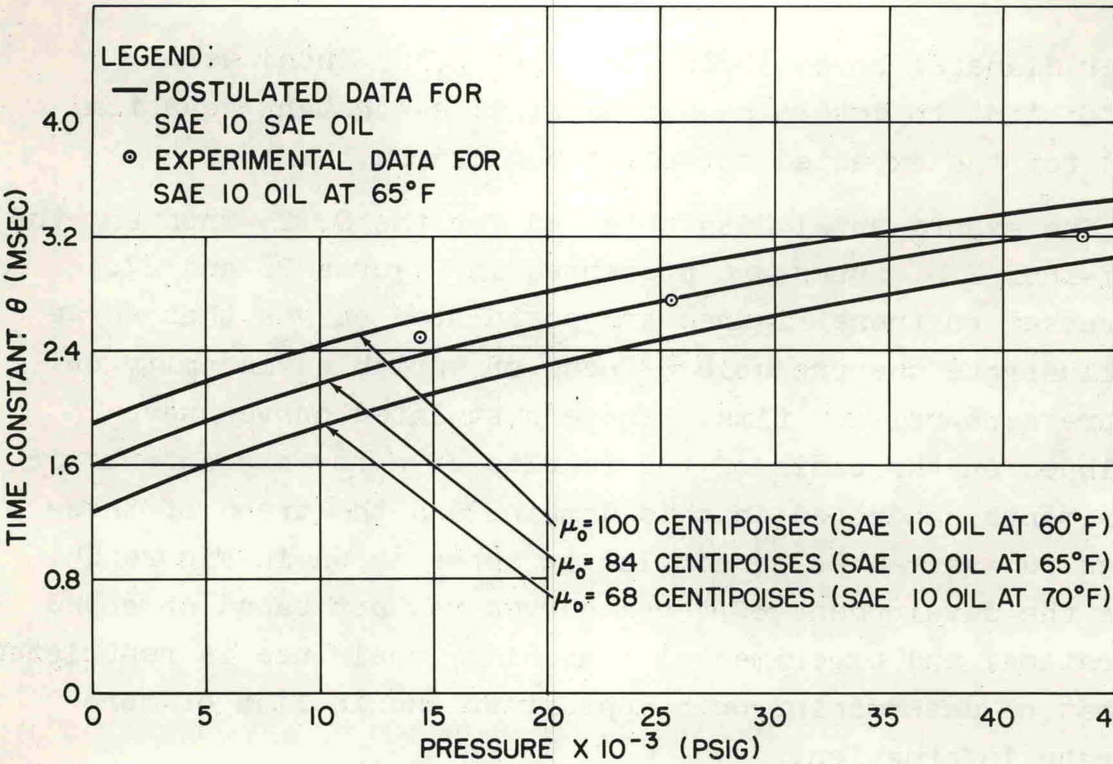


FIG. 25 EFFECTS OF VISCOSITY ON RATE OF RELEASE OF PRESSURIZED FLUID THROUGH 0.062-INCH DIAMETER ORIFICES

larger diameter bores (0.125-inch and 0.187-inch) were insufficient to determine a general time-constant equation valid for the expected turbulent conditions.

The experimental data obtained for the 0.125-inch and the 0.187-inch I.D. tubes are presented in Figures 26 and 27. Superposed on these Figures are postulated curves that serve to illustrate the probable effects of variable viscosity on the pressure-release time. These postulated curves were developed on the basis of the results of a few characteristic experiments conducted in this domain, and the trend of these curves is assumed to be similar to those shown in Figure 25. Since the development of these curves was not based on sound theoretical and experimental reasoning, their use is restricted to that of determining rough approximations in lieu of more accurate information.



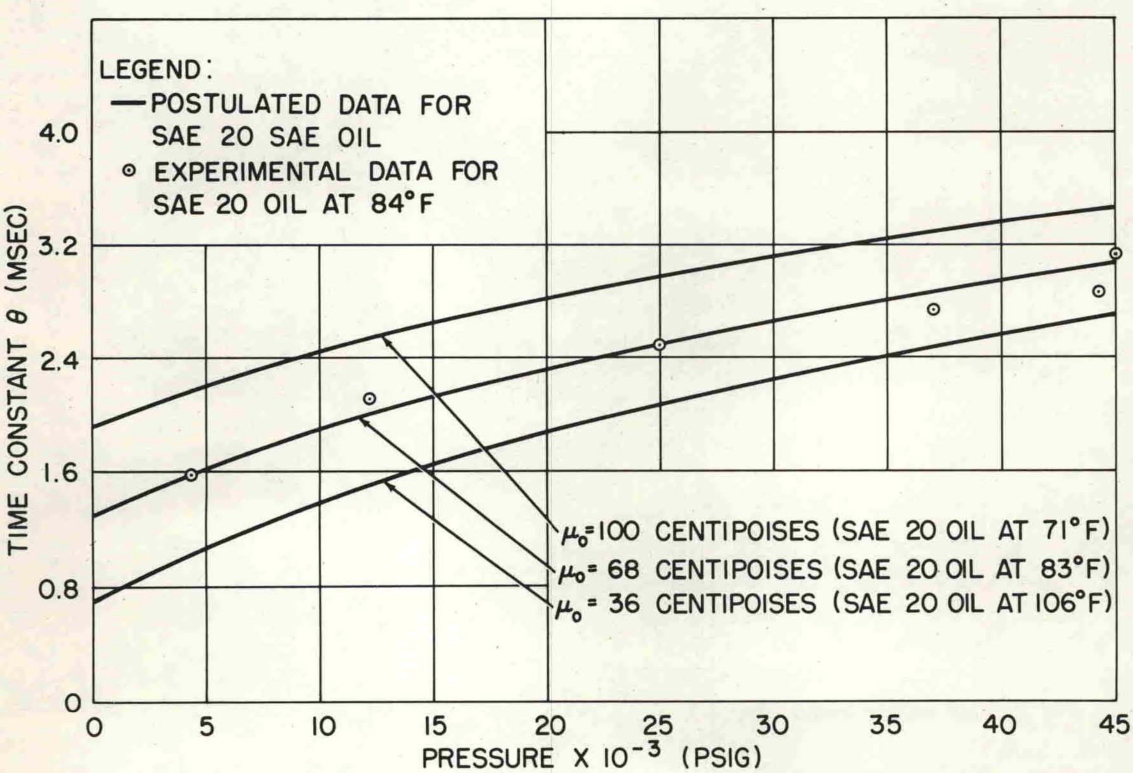


FIG. 26 EFFECTS OF VISCOSITY ON RATE OF RELEASE OF PRESSURIZED FLUID THROUGH 0.125-INCH DIAMETER ORIFICES

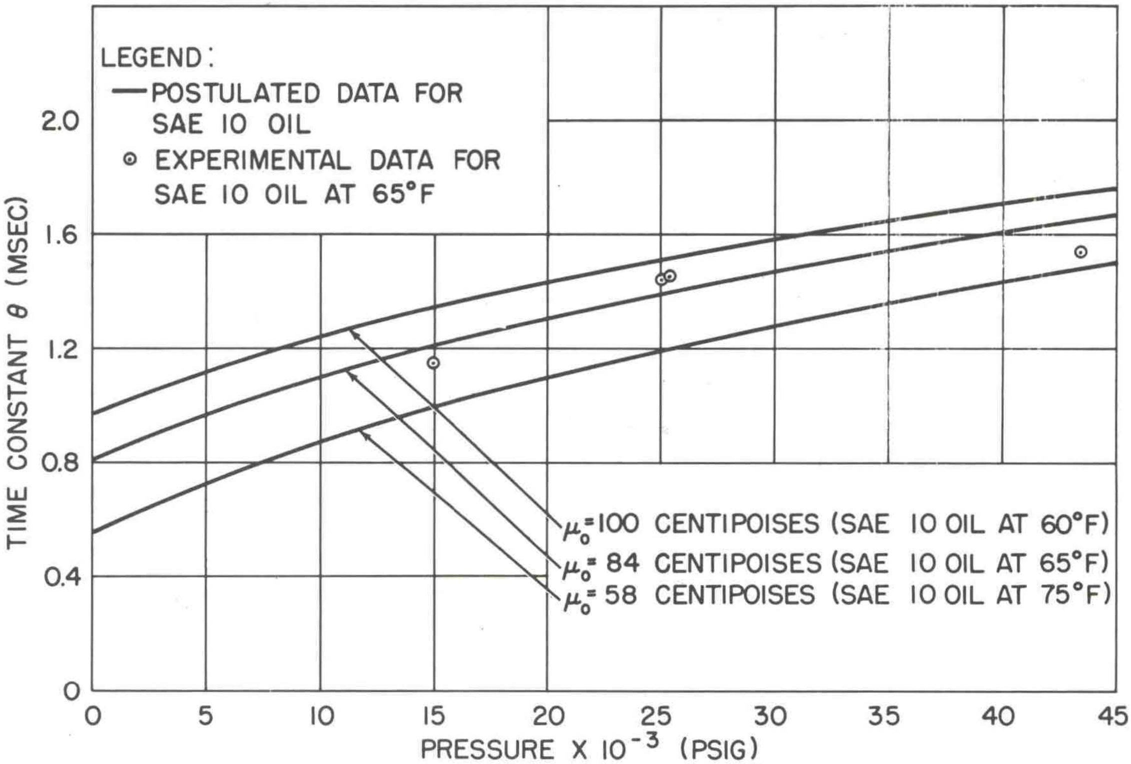


FIG. 27 EFFECTS OF VISCOSITY ON RATE OF RELEASE OF PRESSURIZED FLUID THROUGH 0.187-INCH DIAMETER ORIFICES

SELECTION OF KNOCK-OFF TUBE

The first step involved in the selection of a suitable knock-off tube is to determine the bore diameter corresponding to the required pressure-release time. If the pressure-release time is in the range 15-50 msec, the bore diameter is determined by combining equations (5) and (62) to obtain an equation relating the pressure-release time T_R and the bore radius R_o. For pressure-release times that are less than 15 msec, equation (5) must be used in conjuction with the postulated curves presented in Figures 26 and 27 to obtain an optimum bore diameter. For specific values of chamber volume, bore length, and the high-pressure fluid viscosity and compressibility data, the bore radius can be evaluated in terms of the pressure-release time. The outside diameter of the knock-off tube depends on the pressures to be encountered and the tube material. A numerical value of the O.D. can be found from the well-known Lame equations for thick-walled tubes.

Once the knock-off tube dimensions are known, the next step is to determine the notch size and configuration and the depth of casehardening. If the choice of the notch configuration and tube material coincides with that used in this program, then the curves appearing in Figures 18 through 24, shown previously, can be employed to determine the required notch-wall thickness and casehardened depth for a specific loading weight. The objective is to select the maximum notch-wall thickness (for safety reasons) that can be completely fractured with the available loading weight. The purpose of the casehardening is to enhance the prospect of obtaining complete instantaneous severage of the knock-off tube.

A sample calculation is presented next to illustrate the procedure for selecting a knock-off tube to serve as a quick pressure-release mechanism. To avoid duplication this sample calculation is based on the requirements of this Program, and the results represent the author's recommendations for a quick pressure-release mechanism to be used in conjunction with the piezoelectric gage calibration system employed in the NOL Reactor-Vessel Containment Program.

The system requirements and physical dimensions are as follows:

$T \le 10$ msec

$V = 12.80$ in^3

$L = 5.00$ in

$P \le 50{,}000$ psi

$\mu_o \approx 68$ centipoises $= 95.8 \times 10^{-7}$ lb-sec/in^2
(SAE 10 or SAE 20 oil)

From equation (5)

$$\Theta_1 = \frac{(10.0)}{3} = 3.33 \text{ msec}$$

Since the required pressure-release time is less than 15 msec, the prospect of using a 0.062-inch I.D. tube is eliminated. An examination of Figures 25 and 26 indicates that a 0.125-inch I.D. tube is the smallest tube that will satisfy all of the system requirements. Thus the bore diameter required in this Program is 0.125-inch.

Commercial, 3/8-inch O.D. (1/8-inch I.D.), annealed, AISI No. 4340 steel tubing is sufficient for pressures up to 60,000 psi, thus the knock-off tube dimensions are determined. For a casehardened depth of 0.010-inch and a 1-lb dynamically applied weight (impact velocity = 68 in/sec; moment arm from notch to point of application = 2 inches), the curve shown in Figure 20 indicates that a 0.030-inch notch-wall thickness is appropriate. As prescribed previously, the notch has an included angle of 90° and a 0.005-inch radius at the apex.

SUMMARY AND CONCLUSIONS

A pressure system capable of delivering pressures in the range of 0 - 100,000 psi has been developed, designed, fabricated, and employed for calibrating piezoelectric gages. This pressure system also has the desirable features of speed, simplicity, and high efficiency.

A theoretical equation relating the pressure-release time of the pressurized fluid with the system parameters has been derived, and with a plausible modification, it has been written in a form that is in excellent agreement with the experimental results.

The experimental results, in conjunction with the pressure-release time equation, have been utilized to obtain a procedure for selecting a knock-off tube that will give prescribed pressure-release times. The importance of knowing the pressure-release time is manifest once it is realized that the magnitude and the time duration of the static pressure pulse applied to the piezoelectric gage must be known before an accurate calibration can be made.

It is shown that if a 50,000-psi static pressure pulse, prevailing for 10 msec or less, is applied to the piezoelectric gages to be used in this Program, then their output, measured on the instrumentation system described herein, would be accurate to within 1 percent. A universal knock-off tube that would cause the required static pressure pulse to be applied to the gages has been determined from the procedure described above, and it will be used in future calibration work for this Program.

The general conclusion to be drawn from this work is that a knock-off tube is an excellent quick pressure-release mechanism for pressure-release times in the range of 5 - 100 msec.

The author acknowledges a special debt of gratitude to Dr. Walter R. Wise, Jr., Research Mechanical Engineer, for his advice and guidance in directing the subject Program. The author is grateful to Mr. James F. Proctor, Mechanical Engineer, for his encouragement, assistance, and careful technical review of the manuscript, and he is indebted to Mr. Walter R. Anderson, Electronic Technician, for his assistance in the operation of the instrumentation system used in obtaining the experimental results.

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APPENDIX A

PRESSURE PULSE ERROR

The charge developed by a piezoelectric gage is stored on a standard capacitor. Since the gage circuit has resistance, a certain portion of the charge will leak off. This discharge through essentially an RC circuit results in an exponential decay of the signal voltage, such as

$$E_R = E\, e^{-\frac{t}{\Theta_2}} \tag{A.1}$$

where the nomenclature is

E_R . . . . recorded voltage, volts
E . . . . true voltage (a function of time), volts
Θ_2 . . . . time constant of gage circuit, msec
t . . . . event time, msec

If the fractional error E_1 that occurs in recording the true voltage is defined as

$$E_1 = 1 - \frac{E_R}{E} \tag{A.2}$$

then from equation (A.1)

$$E_1 = 1 - e^{-\frac{t}{\Theta_2}} \tag{A.3}$$

If the exponential term is expanded into a series, the fractional error can be written

$$E_1 = \frac{t}{\Theta_2} - \frac{t^2}{2!\Theta_2{}^2} + \frac{t^3}{3!\Theta_2{}^3} - \frac{t^4}{4!\Theta_2{}^4} + \dots \qquad (A.4)$$

In general, instrumentation for piezoelectric gage recording is designed so that $\Theta_2 > t$, thus the bound of equation (A.4) becomes

$$E_1 \leq \frac{t}{\Theta_2} \qquad (A.5)$$

This equation is limited to the range

$$\frac{1}{4F} \leq t \leq \Theta_2 \qquad (A.6)$$

where F is the frequency response of the gage circuit. For the particular instrumentation used in this report, F exceeds 50,000 cycles/second. Thus equation (A.6) can be expressed

$$0.005 \leq t \leq \Theta_2 \text{ (msec)} \qquad (A.7)$$

The particular event time of prime importance here is the total time required to release the pressure in the compression chamber. If this total release time is denoted as T_R, then equation (A.5) becomes

$$E_1 \leq \frac{T_R}{\Theta_2} \qquad (A.8)$$

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Release	RELE	Conditions	CNDI		
Mechanism	MECH	Requirements	REQI		
Gage	GAGE	Instrumentation	INSM		
Piezoelectric	PIEZ	Test facilities	TESF		
Calibration	CALB	Test procedures	TESI		
System	SYST				
Equation	EQUA				
Reactors	REAC				
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