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RESPONSE OF A QUICK ACTING VALVE FOR UNDERGROUND
NUCLEAR BLAST CONTAINMENT

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ABSTRACT

The motion of a large, sliding piston impelled by the action of an inert gas at high pressure is modeled mathematically by assuming that the working fluid behaves as an ideal gas and that a steady flow process prevails. It is found from numerical solutions of the governing equations that as the aperture, which connects the gas reservoir and receiver, is enlarged, a critical size is reached, beyond which the valve response remains essentially independent of any further increases in the aperture dimension. With supercritical apertures and using, for example, 1.5 ft^3 of 15-kpsi nitrogen as the driver gas, the estimated time for a 2.6-ton piston to travel across a 6-ft wide tunnel is 31 milliseconds. Gases that have the largest number of molecular degrees of freedom theoretically impart the most motive power.

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Nomenclature

A	aperture flow area	(ft ²)
C	aperture flow discharge coefficient	
C ₁ C ₂ C ₃ ---	integration constants for velocity formula, Eq. (13)	(ft/sec) ²
D ₁ D ₂ D ₃ ---	integration constants for pressure formula, Eq. (15)	(lb/ft ²)
E ₁ E ₂ E ₃ ---	integration constants for temperature formula, Eq. (16)	(°R)
E	energy	(ft-lb)
c _p	gas specific heat at constant pressure	(ft-lb/slug°R)
c _v	gas specific heat at constant volume	(ft-lb/slug°R)
f	piston sliding-friction force	(lb)
g	gravitational constant	(ft/sec ²)
m	piston mass	(slug)
n	integer or molecular degrees of freedom	
P ₁	pressure in reservoir	(lb/ft ²)
P ₂	gas pressure in receiver	(lb/ft ²)
P ₀	gas initial pressure in reservoir	(lb/ft ²)
P _∞	ambient pressure	(lb/ft ²)
r	dimensionless exponent in Eq. (9)	
R	gas constant	(ft ² /sec ² °R)
Re _H	Reynold's number	
S	piston area	(ft ²)
t	elapsed time	(sec)
t̄	valve closure time	(sec)
T ₁	gas temperature in reservoir	(°R)
T ₂	gas temperature in receiver	(°R)
T ₀	gas initial temperature in reservoir	(°R)
T _∞	ambient temperature	(°R)
V	reservoir and receiver total volume	(ft ³)
V ₁	reservoir volume	(ft ³)
V ₂	receiver initial volume	(ft ³)

Nomenclature (cont'd)

w	gas weight	(lb)
W	work	(ft lb)
x	piston displacement	(ft)
$\bar{x}$	piston stroke	(ft)
Z	gas compressibility factor	
α	coefficient of radical in Eq. (8)	(ft/sec)
β	valve configuration parameter	(1/ft)
γ	gas ratio of specific heats	
γ_s	dimensionless isentropic exponent	
ζ	dimensionless transformation variable in Eq. (9)	
η	coefficient of velocity integral in Eq. (9)	(1/sec)
λ	isentropic flow factor	($\sqrt{R}$ /sec)
μ	gas coefficient of viscosity	(lb/ft sec)
ξ	dimensionless integral limit in Eq. (9)	

Subscripts

s	constant entropy
a	ambient

Note: A dot located above a symbol denotes a derivative with respect to time.

Summary

The translational motion of large, gas actuated valves used for the containment of debris produced by nuclear blasts in underground tunnels is modeled in an elementary manner by assuming that a quasisteady, one-dimensional flow process prevails and that the working fluid behaves as an ideal gas. It is found from numerical solution of the seven differential equations that there exists a critical size for the aperture, which joins the gas reservoir and receiver. In the subcritical region, the aperture constricts the gas transfer and consequently the valve closure time maintains an inverse proportionality relation with respect to the aperture area. With supercritical apertures, the piston inertia dominates to the extent that the response time becomes practically independent of the aperture dimension. The critical area ($A/S \approx 0.5$) depends neither upon the type of gas nor the reservoir initial conditions.

For systems utilizing supercritical apertures, the piston dynamical behavior may be approximated by assuming that the driver gas expands adiabatically. Although there are no known general solutions to the resulting first-order differential equation of motion, particular solutions exist for integer values of the function $f(n) = (n + 2)/2$, where n itself is any positive integer, some of which correspond identically to the molecular degrees of freedom of polyatomic gases. These closed-form solutions bracket the case of any monatomic or diatomic gas, and, in effect, determine the valve's functional dependence on the seven parameters that characterize the model: the reservoir volume, the piston area, mass and displacement, and the gas pressure, temperature and specific heats ratio. The predictions given by the idealized solutions underestimate the measurement of closure time obtained from functional tests. For example, with nitrogen at a supply pressure of 10 kpsi, the apparent time error amounts to 9%, and it increases to 26% at 15-kpsi pressure.

To improve the accuracy of the model at the higher operating pressures, a gas (nitrogen) in thermodynamic equilibrium was subsequently incorporated for the expansion process. Since the variability of specific heats usually cannot be taken into

account in a simple analytical form, resort was made to numerical techniques for solution. The resulting computer code limits the time errors to about ten percent for reservoir pressures ranging up to 15 kpsi.

It is shown that the category of gases having the largest number of molecular degrees of freedom impart the most motive power for a given initial pressure and temperature. The potential gain becomes significant, however, only if the related specific heats ratio approaches the extreme boundary of unity value.

RESPONSE OF A QUICK ACTING VALVE
FOR
UNDERGROUND NUCLEAR BLAST CONTAINMENT

Introduction

The valve mechanism consists of a chamber of rectangular cross-section which houses a reservoir of inert gas at high pressure, and a sliding gate or piston. To activate the system, a section of the wall of the reservoir is ruptured by means of an explosive shaped charge, which permits the gas to flow through the aperture formed by the explosion and on into the receiver. The pressure created inside the receiver acts directly on the exposed face of the piston, forcing motion.

A sketch of the apparatus is shown in Fig. 1. The left-hand side of the valve housing contains an identical gas reservoir and piston, which travels on a separate parallel track, so that there are, in effect, two complete systems. An important characteristic of this configuration is the time at which the pistons arrive at the half-stroke position, for they overlap and isolate the debris produced by the nuclear blast.

Previous designs allowed the reservoir rupture line to extend along a major meridian, which created an aperture of maximum possible size, thereby permitting the gas to flow from the receiver in an unimpeded manner. To facilitate an increase in reservoir volume and hence improve the valve response time, a modified design now is being considered. Because of spatial and structural limitations, the new design necessitates an aperture of reduced size. Consequently, an assessment of the effect of aperture area is required. This report addresses that concern and describes a computer code for evaluating the system's performance.

Piston Equation of Motion

The rapid transfer of gas from one chamber to another usually produces spatial nonuniformities in the fluid's state properties. The lack of uniformity is brought

about by the propagation of expansion and compression waves and their interactions with physical boundaries, particularly in relatively long containers, by jetting effects which arise from constrictions or changes in the flow geometry, by various modes of thermal mixing, and by the inherent dependence of the characteristics of the working fluid upon the thermodynamic properties. These kinds of effects often dominate the physical picture to the extent that information derived from the analysis of elementary models or models that rely on idealized conditions is not accurate.

In the present arrangement, however, the reservoir is, in effect, short, with a proportionally large aperture. When the piston has appreciable inertia, as in the current configurations, its velocity remains below the sound speed, and the gas transfer proceeds somewhat in the manner of an ordinary adiabatic expansion rather than by a strong flow process, with accompanying shocks and jets. Further, since the system is initially near room temperature, the gas thermodynamic constants tend to maintain an independent nature. Hence, a description that neglects the more complex gasdynamic phenomena is not inappropriate for engineering purposes.

In the following account of the gasdynamic aspects of the valve action, it is assumed that the flow consists of a sequence of steady states of an ideal gas. The fluid within the aperture is treated as a one-dimensional compressible flow in an equivalent nozzle of negligible length. Finally, by decree, no transfer of heat occurs between the working fluid and the containing walls. In that domain of validity, the relevant factors are the flow effects associated with area changes, the heat and mass transfer of the gas moving from the reservoir to the receiver, and mechanical friction.

The set of equations that depict the combined effects arising from quasisteady, quasi-one-dimensional flow and dynamical behavior of the thermally insulated mechanism take the form:

Equation of State (Chamber 1)

$$sp_1 V_1 = (\bar{w}_1 - \int \dot{w} dt) ZRT_1 \quad (1)$$

where

$$\bar{w}_1 = \frac{sp_0 V_1}{ZRT_0}$$

Equation of State (Chamber 2)

$$p_2(v_2 + s_2) = (\bar{w}_2 + \int \dot{w} dt) Z R T_2 \quad (2)$$

where

$$\bar{w}_2 = \frac{p_2 v_2}{Z R T_2}$$

Energy Equation

$$E - E_0 + \int \dot{w} dt = 0 \quad (3)$$

or

$$c_v(w_1 T_1 + w_2 T_2) - c_v(w_1 + w_2) T_0 + m \int \dot{x} \dot{x} dt = 0$$

where

$$w_1 = \bar{w}_1 - \int \dot{w} dt, \quad w_2 = \bar{w}_2 + \int \dot{w} dt \quad \text{and} \quad \int \dot{x} \dot{x} dt = (\dot{x})^2/2,$$

with

$$\dot{x}(0) = \dot{x}(0) = 0$$

Continuity Equation

$$w_1 + w_2 = \text{constant} = \bar{w}_1 + \bar{w}_2 \quad (4)$$

Gas Transfer Rate

$$\dot{w} = A C p_1 \lambda / \sqrt{\pi_1} \quad (5)$$

where

$$\lambda = B \sqrt{\left[\frac{2\gamma}{(\gamma-1)R} \right] \left[\left(\frac{2}{\lambda+1} \right)^{\frac{\gamma}{\gamma-1}} - \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]} \quad \text{if } p_2/p_1 \leq \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}}$$

and

$$\lambda = B \sqrt{\left[\frac{2\gamma}{(\gamma-1)R} \right] \left[\left(p_2/p_1 \right)^{2/\gamma} - \left(p_2/p_1 \right)^{\frac{\gamma+1}{\gamma}} \right]} \quad \text{if } p_2/p_1 > \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma}{\gamma-1}}$$

Equation of Motion

$$m\ddot{x} - (p_2 - p_{\infty})S + F = 0$$

where

$$x(0) = \dot{x}(0) = 0 \quad (6)$$

Thermodynamic Process (Chamber 1)

$$(p_1/p_0)^{\left(\frac{\gamma-1}{\gamma}\right)} = T_1/T_0 \quad , \quad (7)$$

where

$$T_0 = T_{\infty} \quad .$$

Equations (1) through (7) were solved with the aid of a hybrid (analog-digital) computer¹ to determine the valve response as a function of various fixed-sized apertures. The parameters c_v , f and ZR are taken to be known constants, as listed in Table I. The experimentally determined aperture flow discharge coefficient, $C = \dot{W}/\dot{W}_{\text{isentropic}}$, which varies as indicated in Fig. (2), is independent of Reynold's number ($Re > 10^7$) for the configurations of concern.²

Closed-Form Solution of Equation of Motion For Valve With Supercritical Aperture ($A/S = 1$)

In an idealized situation in which the piston is housed in a chamber having, in effect, no aperture between the gas reservoir and receiver, the motion may be approximately accounted for by assuming that the working fluid expands adiabatically, provided that the flow velocity remains small compared with the gas sound speed. This extreme arrangement of geometry furnishes a basis to audit the physics of the problem as dictated by the more complete description, Eqs. (1) through (7), which duly reduce to the equivalent of an adiabatic expansion system when the aperture exerts no restriction on the reservoir flow. For that purpose, the work done by the driver gas, $W = \int p dV$ where $pV^{\gamma} = c$, a known constant, is equated to the kinetic energy imparted to

the piston. When the specific-heats ratio is constant and friction negligible, the velocity history of the piston, written in terms of displacement, takes the form

$$\dot{x} = a \sqrt{1 - (1 + \beta x)^{1-\gamma}} \quad (8)$$

where

$$a^2 = 2p_0 V_1 / (\gamma m - m) \text{ and } \beta = S/V_1.$$

By changing variables in accordance with the dimensionless transform $\xi = (1 + \beta x)^{1-\gamma}$, Eq. (8) yields the following integral equation for the valve closure time, $\bar{t}$:

$$\bar{t} = \eta^{-1} \int_{\xi}^1 \frac{d\xi}{\xi^r \sqrt{1 - \xi}} \quad (9)$$

where

$$\eta = a\beta(\gamma - 1) \text{ and } r = \gamma/(\gamma - 1).$$

The integral's lower limit is $\xi = (1 + \beta x)^{1-\gamma}$, where $\bar{x}$ denotes the piston stroke.

It may be observed that the two parameters m , p_0 in the integral's coefficient η do not appear in the integrand. Therefore, for all γ 's, the theoretical closure time is directly proportional to the factor involving those parameters:

$$\bar{t} \sim \sqrt{m/p_0}, \quad (10)$$

where m represents the piston mass, and p_0 is the initial pressure in the reservoir.

Equation (10) provides a convenient means of scaling, in an approximate manner, various configurations of interest.

The integral formula, Eq. (9), has known solutions for positive integers of the exponent r . For example, with the initial conditions $x = \dot{x} = 0$ when $t = 0$, the particular solutions for the three cases corresponding to $r = 2, 3$ and 4 are, respectively,

$$\left. \begin{aligned} r\bar{t} &= (1/\xi)\sqrt{1 - \xi} + \ln \phi, & \text{where } \gamma &= 2 \\ r\bar{t} &= \left[(1/2)\xi^{-2} + (3/4)\xi^{-1} \right] \sqrt{1 - \xi} + (3/4)\ln \phi, & \text{where } \gamma &= 3/2 \end{aligned} \right\} \quad (11)$$

$$\text{and } \tau \bar{c} = \left[(1/3)\xi^{-3} + (5/12)\xi^{-2} + (5/8)\xi^{-1} \right] \sqrt{1 - \xi} + (5/8) \ln \xi, \text{ where } \gamma = 4/3, \quad (1)$$

with $\phi = \left(1 + \sqrt{1 - \xi} \right) / \xi^{1/2}$. These closed-form solutions for the valve closure time may be extended to include additional progressively smaller values of the specific-heats ratio ($\gamma = 5/4, 6/5, 7/6, \dots$), if required.

Since, according to an elementary molecular model for the kinetic theory of gases,³ the specific-heats ratio γ is related to the molecular degrees of freedom n by the formula $n = 2/(\gamma - 1)$, the higher order solutions are found to represent identically the case of certain non-rigid polyatomic gases—those having an even number of degrees of freedom, designated $n = 8, 10, 12$, etc.

The last two formulae in Eqs. (11) bracket the case of diatomic gases such as nitrogen ($\gamma = 7/5$). By evaluating and interpolating between solutions, the approximate sensitivity of the closure time to the various design parameters may be readily established. Table II summarizes the calculation results for a 6-foot valve used in the last nuclear diagnostic experiment - Diablo Hawk - at the Nevada Test Site in September, 1978. It may be seen that a one-percent change in, for example, piston mass, or reservoir initial pressure, alters the valve actuation time by about 0.501 percent. The physical characteristics of the configuration are listed in Table III.

Infinite Reservoir

With a gas reservoir of unlimited capacity, the pressure driving the piston remains constant, fixed at the maximum possible value throughout the period of operation. Consequently, a minimum closure time results. The formula describing this academic situation may be obtained directly by analytical integration of Eq. (6). When $A = S$, $p_2 = p_0$ and $f = 0$, the first and second integrals are, respectively, $\dot{x} = St(\Delta p)/m$ and $x = St^2(\Delta p)/(2m)$, where $\Delta p = p_0 - p_\infty$. Since the local ambient pressure during the test period is generally negligible ($p_\infty \approx 5 \times 10^{-3}$ mm Hg), the closure time is simply

$$\tau = \sqrt{2m\bar{x}/(Sp_0)} \quad (12)$$

Using the dimensions of the Diablo Hawk 6-foot valve (Table III), and with $p_0 = 14.9$ kpsi, Eq. (12) gives an actuation time of about 12 milliseconds, or 46% of the time theoretically required for the finite-reservoir design. This calculation serves to define the approximate limit for systems confined to inert propulsive fluids. Another source of energy would be needed to accrue any further improvements in the valve response.

Valve With Quasiequilibrium Gas

To improve the accuracy of the mathematical model at the valve's higher operating pressures, a fluid in thermodynamic equilibrium is now considered. For this purpose, use is made of the variable isentropic exponent $\gamma_s(p, T) \equiv \left[\partial \ln(p) / \partial \ln(p) \right]_s$ rather than the constant ratio of specific heats $\gamma = c_p / c_v$, as used in the ideal-gas relations of the previous sections. Applying Eq. (8) over a number n of segments of specified length, the total of which comprise the piston's stroke, the approximate velocities of the piston at the end of segments 1, 2 ... n are, respectively

$$\left. \begin{aligned} (\dot{x}_1)^2 &= c_1^2 \left[1 - (1 + \gamma_{s,1})^{1-\gamma_{s,1}} \right] + C_1 \\ (\dot{x}_2)^2 &= c_2^2 \left[1 - (1 + \gamma_{s,2})^{1-\gamma_{s,2}} \right] + C_2 \\ &\vdots \\ \text{and } (\dot{x}_n)^2 &= c_n^2 \left[1 - (1 + \gamma_{s,n})^{1-\gamma_{s,n}} \right] + C_n \end{aligned} \right\} \quad (13)$$

where $c_n^2 = 2p_{0,1} / (m \gamma_{s,n} - m)$ and $\gamma = S/V_1$.

The constants of integration $C_1 C_2 \dots C_n$ in Eq. (13) serve to maintain an energy balance, for these terms in effect, adjust the piston's kinetic energy at the beginning of each new segment to that attained at the termination of the previous segment. When the piston initial velocity is zero, the first constant C_1 reduces to zero. The remaining constants depend upon each previous constant of integration:

$$C_1 = 0$$

$$C_2 = \alpha_2^2 \left[1 - (1 + \beta x_1)^{1-\gamma_{s,1}} \right] - \alpha_2^2 \left[1 - (1 + \beta x_1)^{1-\gamma_{s,2}} \right] + C_1$$

⋮

$$\text{and } C_n = \alpha_n^2 \left[1 - (1 + \beta x_{n-1})^{1-\gamma_{s,n-1}} \right] - \alpha_n^2 \left[1 - (1 + \beta x_{n-1})^{1-\gamma_{s,n}} \right] + C_{n-1}$$

If every segment is made to be of the same length Δx , then $\bar{x} = n(\Delta x)$. In that situation, the time $\bar{t}$ required to move the piston through the distance $\bar{x}$, which is the sum of the incremental times required to traverse the individual segments, becomes

$$\bar{t} = 2(\Delta x) \sum_{j=1}^n 1/(\dot{x}_{j-1} + \dot{x}_j) \quad (14)$$

where $\dot{x}_0 = \dot{x}(0) = 0$.

To evaluate Eq. (14), the exponent γ_s must first be determined as a function of the reservoir pressure and temperature which can be written directly as functions of piston displacement. The pressures occurring at the end of segments 1, 2 ... n are, in accordance with the adiabatic expansion law, respectively,

$$\left. \begin{aligned} p_1 &= p_o / (1 + \beta x_1)^{\gamma_{s,1}} + D_1 \\ p_2 &= p_o / (1 + \beta x_2)^{\gamma_{s,2}} + D_2 \\ &\vdots \\ \text{and } p_n &= p_o / (1 + \beta x_n)^{\gamma_{s,n}} + D_n \end{aligned} \right\} \quad (15)$$

where the D_n constants are

$$D_1 = 0$$

$$D_2 = p_o \left[1 / (1 + \beta x_1)^{\gamma_{s,1}} - 1 / (1 + \beta x_1)^{\gamma_{s,2}} \right] + D_1$$

⋮

$$\text{and } D_n = P_0 \left[1 / (1 + \alpha_{n-1})^{v_{s,n-1}} - 1 / (1 + \alpha_{n-1})^{v_{s,n}} \right] \cdot D_{n-1} .$$

Similarly, the gas temperature is

$$\left. \begin{aligned} T_1 &= T_0 (p_1/p_0)^{(v_{s,1}-1)/v_{s,1}} + E_1 \\ T_2 &= T_0 (p_2/p_0)^{(v_{s,2}-1)/v_{s,2}} + E_2 \\ &\vdots \\ \text{and } T_n &= T_0 (p_n/p_0)^{(v_{s,n}-1)/v_{s,n}} + E_n \end{aligned} \right\} \quad (16)$$

where

$$\begin{aligned} E_1 &= C \\ E_2 &= T_0 \left[(p_1/p_0)^{(v_{s,1}-1)/v_{s,1}} - (p_1/p_0)^{(v_{s,2}-1)/v_{s,2}} \right] + E_1 \\ &\vdots \\ \text{and } E_n &= T_0 \left[(p_{n-1}/p_0)^{(v_{s,n-1}-1)/v_{s,n-1}} - (p_{n-1}/p_0)^{(v_{s,n}-1)/v_{s,n}} \right] + E_{n-1} . \end{aligned}$$

Defining an average pressure $\bar{p}_n = (p_{n-1} + p_n)/2$ and average temperature $\bar{T}_n = (T_{n-1} + T_n)/2$ over each segment, Eqs. (15) and (16) can be solved by iterative procedure using the tabular values of $v_{s,n} = v_{s,n}(\bar{p}_n, \bar{T}_n)$ from Ref. (5). Then, having established $v_{s,n}$ as a function of piston displacement, Eqs. (13) and (14) can be readily evaluated to determine the valve closure time.

The computer code that solves this quasiequilibrium gas dynamics problem is listed in Appendix A. Numerical experiments show that with $n = 10^4$, and with $v_{s,n}$ determined to five significant figures, the valve theoretical closure time converges to the known closed-form solution (Eq. 11), with an error less than 10^{-6} seconds. Appendix B displays typical output information derived from the code with the gas H_2 .

Results

To assess the effect of various fixed aperture sizes, the valve response, as gaged by Eqs. (1) through (7), was obtained for several types of working fluids, with various arrangements of piston geometry. Figure (3) shows the theoretical closure time as a function of the aperture area for nitrogen, with two levels of reservoir pressure, and for argon and helium. In all cases, it is found that if the aperture area A becomes less than approximately one half of the maximum possible area S , the closure time measurably increases, and the extent of the increase is inversely proportional to the aperture area; the constant of proportionality is such that the time penalty amounts to about one millisecond if A/S decreases to 0.2. Changes of 50% in the reservoir volume exhibit similar trends for the aperture critical size.

Figure (4) describes the response of the 6-ft diameter valve with arbitrary changes of 50% in the piston mass. As indicated in the previous graph, the closure time maintains an independent relation with respect to the aperture size if $A/S > 0.5$. From these observations it is concluded that, over the range of concern, the aperture critical area is essentially unaffected by both the reservoir initial conditions and the piston mass.

Figure (5) shows the broad variation in the pressure ratio that can act across the aperture as A/S is varied. The velocity-displacement history of the piston is described in Fig. (6). It may be observed that with supercritical apertures, i.e., with $A/S > 0.5$, and with negligible sliding friction f , which is the normal circumstance, the ideal gas flow expressions, Eqs. (1) through (7), duly reduce to the equivalent of an adiabatic expansion system, as represented by Eq. (8)—a conformity that serves to license the development of the quasiequilibrium gas expansion model, Eqs. (13) through (16).

Theoretical predictions resulting from the equilibrium gas model are compared with the time measurement obtained in the Diablo Hawk event in Fig. (7). At an initial pressure of 15 kpsi, the apparent error in the equilibrium gas model amounts to about one half that of the ideal gas model.

Table IV summarizes the time error associated with the two models, at two levels of pressure. The functional test involved a 5-ft diameter valve, with a piston weight of 4156 lbs, a reservoir volume of 1.31 ft^3 , and a piston area of 5.65 ft^2 . Based on that arrangement, the ideal gas model yields errors of less than ten percent at 10 kpsi pressure, but the apparent error at 15-kpsi pressure, which was obtained with a similar, slightly larger 6-ft diameter valve, increases by a factor of almost three. At pressures above 10 kpsi, the equilibrium gas model reflects a substantial improvement in accuracy.

It may be observed in Fig. (7) that working fluids in the polyatomic group dispense the most motive power, which results in the shortest closing time. The potential gain becomes significant, however, only with those here undefined gases that possess an unusually large number of molecular degrees of freedom, where the related specific heats ratio is very near one. At this extreme boundary, the validity of the elementary molecular model on which current predictions are based becomes subject to question. An experimental program is needed to properly evaluate candidate gases at the inordinate condition of $\gamma \approx 1$. The common gases shown in the polyatomic group in Fig. (7) theoretically yield small improvements of approximately ten percent. But these gases are either somewhat corrosive or explosive, or the thermodynamic properties are unsatisfactory or illdefined in the temperature range of interest. Carbon dioxide (CO_2) may possibly yield a small improvement in the valve closure time. The frozen family, with specific-heat ratios of approximately 1.1, have, unfortunately, very high boiling points compared with nitrogen. However, until evaluation tests are conducted, the diatomic gas nitrogen remains the preferred choice by default.

The reservoir pressure and the aperture Reynold's number — computed using Sutherland's viscosity formula⁶, which brings the effect of changes in the gas temperature into account — are shown as functions of elapsed time in Fig. (8). The reference dimension for the Reynold's number calculation was taken to be the diameter of an assumed circular aperture of equivalent area. In previous designs, the actual aperture was an elongated orifice with a height-width ratio of about nine, and was formed by fracturing the reservoir, which consisted of a cylindrical container with hemispherical

end caps, along a major meridian, in a plane normal to the direction of piston motion. Consequently, the aperture was the maximum possible size.

Conclusions

From a numerical analysis of a model based on ideal gas relations, it is found that the response characteristics of large valves with appreciable piston inertia are essentially independent of the size of the reservoir's aperture if the aperture area exceeds one half of the piston area. From theoretical considerations, the closure time for valves utilizing supercritical apertures and any ideal working fluid is shown to be directly proportional to the square root of the ratio of piston mass and reservoir initial pressure. The limiting case of a reservoir of infinite capacity reduces the response time by no more than a factor of approximately two for current designs with an inert gas.

The apparent error in the closure time given by the ideal gas model amounts to 9% with nitrogen at a reservoir pressure of 10 kpsi, and it increases to three times that value at 15-kpsi pressure. GATE, a digital computer code that incorporates a gas in thermodynamic equilibrium, confines the time errors to about ten percent throughout the operating range.

TABLE I

Gas Characteristics for Ideal Gas Model

Gas	γ	R/g (ft ² /°R)	c_v/Jg (BTU/lb°R)	$\mu_o \times 10^5$ (lb/ft sec)
N ₂	7/5	55.2	0.178	1.2
He	5/3	386.0	0.747	1.3
A	5/3	38.7	0.0746	1.5

TABLE II

Dimensionless Sensitivity Factors for Closure Time, $\bar{t}$
(6-ft Diablo Hawk Valve With N₂)

Reservoir Initial Pressure Effect,	$\frac{\Delta \bar{t}/\bar{t}}{\Delta P_o/P_o} = -0.501$
Reservoir Volume Effect,	$\frac{\Delta \bar{t}/\bar{t}}{\Delta V_1/V_1} = -0.348$
Piston Mass Effect,	$\frac{(\Delta \bar{t}/\bar{t})}{(\Delta m/m)} = 0.501$
Piston Area Effect,	$\frac{(\Delta \bar{t}/\bar{t})}{(\Delta S/S)} = -0.153$
Piston Displacement Effect,	$\frac{(\Delta \bar{t}/\bar{t})}{(\Delta \bar{x}/\bar{x})} = 0.846$
Gas Specific Heats Ratio Effect,	$\frac{(\Delta \bar{t}/\bar{t})}{(\Delta \gamma/\gamma)} = 0.694$

TABLE III

Physical Properties of 6-ft Valve Used in Diablo Hawk Event

Reservoir Initial Pressure	14,900 psi
Reservoir Volume	1.557 ft ³
Piston Weight	5200 lbs
Piston Area	6.481 ft ²
Piston Displacement	6.0208 ft
Working Fluid	N ₂

TABLE IV

Comparison of Valve Theories With Experiment ($A/S = 1$)

Test	Experiment		Theory	
	p_0 (kpsi)	$\bar{t}$ (sec)	$\bar{t}$, ideal gas (Error) (sec)	$\bar{t}$, equilibrium gas (Error) (sec)
Functional Test (5-ft Valve)	10.0	0.0295	0.02694 (9%)	0.03146 (7%)
Diablo Hawk (6-ft Valve)	14.9	0.0349	0.02591 (26%)	0.03090 (11%)

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Fig. 1 Sketch of Gas-Actuated Valve Showing Sliding Piston and Gas Reservoir

Fig. 2 Flow-Discharge Coefficient $C = \dot{m}/\dot{m}_{\text{isentropic}}$ as a Function of Size of Reservoir Aperture ($R_H > 10^6$)

Fig. 3 Valve Theoretical Closure Time Showing Region of Critical Aperture Size and Effect of Various Types of Gases

Fig. 4 Valve Theoretical Closure Time Showing Region of Critical Aperture Size and Effect of Piston Weight (Nitrogen Gas)

Fig. 5 Pressure Ratio Across Reservoir Aperture as a Function of Elapsed Time for Various Aperture Sizes (Nitrogen Gas)

Fig. 6 Piston Theoretical Velocity-Displacement History for Various Types of Gases and Various Reservoir Initial Pressures, With Supercritical Apertures ($A/S \approx 1$)

Fig. 7 Comparison of Ideal and Equilibrium Gas Models With Measurements From Diablo Hawk Event (6-ft valve, $p_o = 14.9$ kpsi, Nitrogen Gas)

Fig. 8 Reservoir Theoretical Pressure and Aperture Reynold's Number as a Function of Elapsed Time for 6-ft Valve (Diablo Hawk Event, $p_0 = 14.9$ kpsi, Nitrogen Gas)

APPENDIX A

GATE Digital Computer Program

LIST

C
C
C
C
C
C

EVALUATION OF GATE VELOCITY HISTORY VERSUS INCREMENTAL DISTANCE
TO DETERMINE CLOSURE TIME. FOR EQUILIBRIUM GAS, ETA IS FINITE;
FOR IDEAL GAS, ETA IS ZERO.

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PROGRAM NEGATE (INPUT, OUTPUT, TAPES=INPUT, TAPE6=OUTPUT)
REAL LPBR(12), LPNBAR, MASS
DIMENSION TEMP(7), DGAM(12,7), DGAMN(1,7), WK(33)
DIMENSION NPLAS(15), TPRT(15), XPRNT(15), XDPRNT(15), PPRNT(15),
1TEPRNT(15), GPRNT(15)
DATA LPBR/-1.1590,.0406,.4398,1.2389,1.4381,1.6372,1.8369,
12.0393,2.2507,2.4918,2.8211,3.3638/
DATA TEMP/0.,90.,180.,270.,360.,450.,540./
DATA DGAM/0.,.0005,.0034,.0243,.08,.61,1.25,2.75,4.25,6.05,
18.6,12.8,
20.,.0005,.0034,.0243,.07,.502,1.04,2.3,3.52,5.05,7.22,10.85,
30.,.0005,.0034,.0243,.062,.406,.82,1.84,2.83,4.07,5.92,8.92,
40.,.0005,.0034,.0243,.055,.315,.62,1.41,2.17,3.13,4.67,7.17,
50.,.0005,.0034,.0243,.049,.227,.44,1.01,1.52,2.25,3.47,5.6,
60.,.0005,.0034,.0243,.044,.143,.26,.6,91,1.43,2.39,4.27,
70.,.0005,.0034,.0243,.0406,.0664,.1167,.2049,.3720,.7151,
81.4831,3.2343/
DATA NPLAS/0,200,400,600,800,1000,2000,3000,4000,5000,6000,
17000,2000,3000,10000/

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C

```

NBAR=10000
POPSI=14900.
P0=POPSI*144.
PIPSI=14.696
PIHF=PIPSI*144.
TO=515.
WEIGHT=5200.
YBAR=1.557
ZBAR=.481
YBARF=.0206
IFD=12
NX=12
NY=7
NXL=1
NYL=1
IFLD=1
1 IEF=0
WRITE(6,1000)
READ(5,*)GAMMA0
IF(GAMMA0.EQ.0)GO TO 999
WRITE(6,1015)
READ(5,*)ETA
2 WRITE(6,1002)
READ(5,*)IREVIS
IF(IREVIS.EQ.0)GO TO 4
IF(IREVIS.EQ.1)GO TO 3
GO TO 2
3 CONTINUE
WRITE(6,1003)
READ(5,*)POPSI
P0=POPSI*144.
WRITE(6,1004)
READ(5,*)PIPSI
PIHF=PIPSI*144

```

```

WRITE(6,1005)
READ(5,*)T0
WRITE(6,1006)
READ(5,*)WEIGHT
WRITE(6,1007)
READ(5,*)YBAR
WRITE(6,1008)
READ(5,*)SEAR
WRITE(6,1009)
READ(5,*)XBAR
WRITE(6,1010)
4 READ(5,*)IREIN
IF(IREIN.EQ.0)GO TO 1
IF(IREIN.EQ.1)GO TO 5
GO TO 4
5 CONTINUE
MASS=WEIGHT/32.174
ALFA=2.*YBAR/MASS
BETA=SEAR/YBAR
DELX=YBAR/NBAR
TN=0.
PNBAR=P0./PINF
IF(PNBAR.LT.1.)PNBAR=1.
LPNBAR=ALOG10(PNBAR)
TEMP=T0
CALL IECIEU(DGAM,IFD,LPBAR,NX,TEMP,NY,LPNBAR,NXL,TEMP,NYL,
10DGAM,IFLD,MK,IER)
IF(IER.EQ.0)GO TO 7
WRITE(6,1035)IER
GO TO 1
7 GAMM=GAMMA0+DGAM*ETA
GAMNM=GAMM
GAMVNM=GAMMA0+DGAM*(ETA**2./GAMMA0)
GAMVNM=GAMVNM
GAMVRG=GAMMA0
BXN=1.
DNN=0.
PFNN=P0
EXGVNM=1.
CMM=0.
XDNN=0.
TPRNT(1)=0.
XPRNT(1)=0.
XDPRNT(1)=0.
PPRNT(1)=P0
TEPRNT(1)=T0
SPRNT(1)=GAMM
J=2
JCOUNT=NFLAG(J)
ICOUNT=1
DO 19 N=1,NBAR
PN=ALOG10(PN)
AN=PN*DELX
BXN=1./ (1.+BETA*AN)
EXG=BXN**GAMM
GAD=GAMM-1.
DN=P0-(P0-DNN)*(BXN** (GAMNM-GAMN))
PFN=(P0-DN)*EXG
PN=(PFNN+PFN)/2.
IF(PN.GT.0.)GO TO 12
WRITE(6,1020)PN
GO TO 1
12 PNBAR=PN./PINF
IF(PNBAR.LT.1.)PNBAR=1.

```



```

LPNBAR=ALOG10(PNBAR)
TEMN=T0*(PN/P0)**(GMD/GMND)
IF (TEMN.GT.0.) GO TO 13
WRITE(6,1021) TEMN
GO TO 1
13 IF (ETA.EQ.0.) GO TO 15
CALL IBCIEU(DGAM, IPD, LPBR, NX, TEMP, NY, LPNBAR, NYL, TEMN, NYL,
1DSAMN, IPFD, WK, IER)
IF (IER.EQ.0) GO TO 15
WRITE(6,1025) IER
GO TO 1
15 GAMN=GAMMA0+DSAMN*ETA
GAMVN=GAMMA0+DSAMN*(ETA**(2.*GAMMA0))
DELGAM=RES(GAMN-GCNVRG)
SCHVRG=GAMN
IF (DELGAM.GT.0.0001) GO TO 11
GVD=GAMVN-1.
BXGVD=EX**GVD
BXSGVD=BXN**GVD
CN=ALPHA*P0*(1./(GAMVN-1.))*(1.-BXGVD)-(1./(GAMVN-1.))
1*(1.-BXSGVD)+CNM
XDFN=SQRT((ALPHA*P0/GVD)*(1.-BXGVD)+CN)
XDN=XDFN*XDFN/2.
DELTH=DELN/XDN
TH=TH+DELTH
GAMMA=GAMN
GAMVN=GAMVN
BXN=EX
DN=DN
PFNN=PFN
BXGVN=BXGVD
CNM=CN
XDFN=XDFN
IF (ICOUNT.NE.JCOUNT) GO TO 18
TPRNT(J)=TH
XPRNT(J)=XN
XDPRNT(J)=XDN
PPRNT(J)=PFN
TEPRNT(J)=TEMN
SPRNT(J)=GAMN
J=J+1
JCOUNT=NFLAG(J)
ICOUNT=ICOUNT+1
18 CONTINUE
CALL DATE(DAY)
CALL TIME(TIM)
WRITE(6,1011) DAY, TIM
WRITE(6,1030) GAMMA0, P0PSI, P1PSI, T0, SEAR, XBAR, WEIGHT, VBAR
WRITE(6,1012)
DO 22 J=1,15
TBAR=TH
VMAX=XDFN
TPRNT(J)=TPRNT(J)/TBAR
XPRNT(J)=XPRNT(J)/XBAR
XDPRNT(J)=XDPRNT(J)/VMAX
PPRNT(J)=PPRNT(J)/P0
TEPRNT(J)=TEPRNT(J)/T0
SPRNT(J)=SPRNT(J)/GAMMA0
WRITE(6,1013) TPRNT(J), XPRNT(J), XDPRNT(J), PPRNT(J), TEPRNT(J),
15PRNT(J)
22 CONTINUE
WRITE(6,1021) TBAR, VMAX
GO TO 1
999 CONTINUE

```


APPENDIX B
GATE Computer Program Output

IDEAL GAS MODEL

GAMMA (GAMMA0) = 1.40000
RESERVOIR PRESSURE (P0PSI) = 14900.00000 PSI
AMBIENT PRESSURE (PIPSI) = 12.93060 PSI
TEMPERATURE (T0) = 515.00000 DEG.F
PISTON AREA (ABAR) = 6.48160 SQ.FT
PISTON DISPLACEMENT (XBARP) = 6.02080 FT
PISTON WEIGHT (WEIGHT) = 5200.00000 LBS
RESERVOIR VOLUME (VBARP) = 1.55700 CU.FT

T-TBAR	XBARP	V/VMAX	P/P0	T-T0	GAM-GAM0
0.000000	0.000000	0.000000	1.000000	1.000000	1.000000
.068106	.020000	.453726	.566868	.350288	1.000000
.190709	.040000	.576929	.378609	.757675	1.000000
.428251	.060000	.649396	.276880	.692875	1.000000
.153336	.080000	.699030	.214431	.644079	1.000000
.176925	.100000	.735890	.172764	.605522	1.000000
.233661	.200000	.936312	.081184	.488000	1.000000
.381511	.300000	.988760	.049841	.424503	1.000000
.475049	.400000	.920324	.034734	.382890	1.000000
.565931	.500000	.942516	.026074	.352766	1.000000
.654973	.600000	.953845	.020553	.329787	1.000000
.742644	.700000	.972458	.016772	.310985	1.000000
.829246	.800000	.983248	.014044	.295608	1.000000
.914982	.900000	.992284	.011998	.282601	1.000000
1.000000	1.000000	1.000000	.010414	.271399	1.000000

TBAR = .025905 SEC
VMAX = 274.410647 FPS

QUASIEQUILIBRIUM GAS MODEL

T-TBAR	XBARP	V/VMAX	P/P0	T-T0	GAM-GAM0
0.000000	0.000000	0.000000	1.000000	1.000000	2.637462
.064618	.020000	.382438	.142855	.226107	3.026998
.103082	.040000	.466550	.059447	.216181	1.561651
.135301	.060000	.540553	.028501	.243569	1.261143
.163726	.080000	.602318	.028671	.306211	1.072240
.189560	.100000	.654391	.023128	.329997	1.012216
.300790	.200000	.793392	.010119	.240462	1.039613
.398466	.300000	.856408	.006226	.211454	1.029087
.491064	.400000	.895979	.004458	.198973	1.017831
.580258	.500000	.924356	.003441	.190860	1.008863
.667081	.600000	.946149	.002770	.183686	1.002862
.752133	.700000	.963566	.002289	.176261	.999704
.835802	.800000	.977856	.001927	.168975	.998454
.918359	.900000	.989818	.001648	.161503	.998310
1.000000	1.000000	1.000000	.001428	.154720	.998762

TBAR = .030901 SEC
VMAX = 238.843949 FPS