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CC: E. B. Warming, L11W09
W. R. Stevens, III, 773-A
J. F. Ortaldo, 773-A
W. W. F. Yau, 709-G
M. D. Boersma
D. G. Kilpatrick
L. F. Landon
C. T. Randall
D. C. Iverson
T. L. Allen
SRL Records (4)

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TO: D. C. WITT

FROM: A. E. HAILEY aEH

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PERFORMANCE CHARACTERISTICS OF AN ISOTHERMAL FREEZE VALVE

INTRODUCTION

A freeze valve has been specified for draining the DWPF melter at the end of its lifetime. Two freeze valve designs have been evaluated on the Small Cylindrical Melter-2 (SCM-2). In order to size the DWPF freeze valve, the basic principles governing freeze valve behavior need to be identified and understood.

The operating principles of a freeze valve involve forming a glass plug to stop flow and melting the plug to initiate flow. The plug is formed and maintained by cooling a section of pipe which runs from the melter floor to the outside bottom of the melter shell. Heaters are used to melt the plug and initiate glass flow. For the glass formations and the melt pool depth planned for use in the DWPF a method is required for stopping the glass flow long enough to permit the cooled section of pipe to freeze the plug. A jet controlled valve that uses air pressure to stop the glass flow, has been successfully demonstrated on the Small Cylindrical Melter-2.

This paper discusses the performance characteristics of a freeze valve once glass flow is initiated. This is essentially an isothermal process. A theoretical model of the process is developed, verified, and then used on a DWPF-scale melter to evaluate the effect of glass properties and valve geometry on freeze valve performance. A major portion of the theory was developed by K. R. Routt.

SUMMARY

The flow behavior of an isothermal freeze value has been modeled. Glass flow through the valve is essentially a steady-state balance between the static head of the glass in the melter and the viscous forces generated along the walls of the valve. The model is limited to cases in which laminar flow is encountered. Calculations show that laminar flow occurs for all glasses with viscosities greater than 10 poise.

The model was verified by running freeze valve simulations, using silicone fluid in place of molten glass. Agreement between model predictions and experimental results was good.

The performance characteristics of a DWPF type freeze valve were also modeled, assuming a melt pool diameter of 6 feet, a glass depth of 2.8 feet and a glass viscosity of 60 poise. Drain rates were predicted (in pounds of glass per hour) for several valve sizes. A 1.0-inch-ID valve, 3 feet long would drain the melter at an average rate of 930 lb/hr (assuming glass melt rate viscosity of 80 poise). A valve this size could drain a completely full melter in about 15 hours (excluding time required for canister changes).

Theory

A typical freeze valve design is shown in Figure 1. Basically it consists of an inner pipe surrounded by an air cooled annulus and one of several types of heaters. During routine melter operation, the inner pipe is cooled by means of air flow in the surrounding annulus to some temperature below the softening point of the glass so that glass flow through the inner pipe does not occur. When it is desired to initiate glass flow, the air is turned off, and the glass in the inner pipe is heated by one of several techniques* until glass flow into the canister begins. When the canister is filled to the desired level, the glass flow must be stopped, and it is the technique for stopping the glass flow that is of primary interest in the discussion that follows.

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* See DPST-81—961 for a description of possible heating techniques.

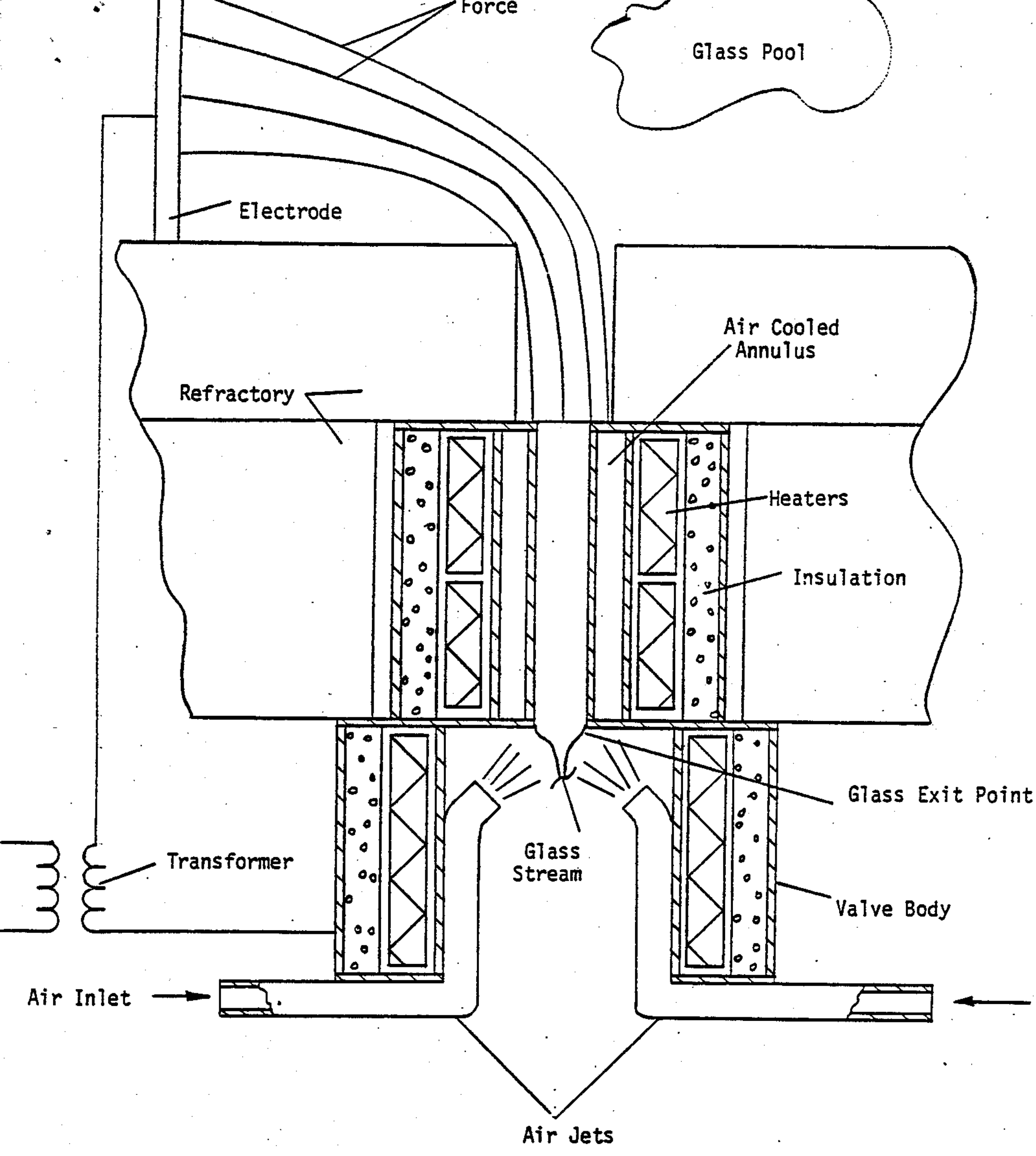


FIGURE 1 - JET CONTROLLED FREEZE VALVE

Conservation of mass in the melt pool above the freeze valve requires that

$$- \rho\pi R_{gp}^{2} \frac{d \left[z_{bgp} - z_{ms}(t)\right]}{dt} = \rho\pi R_{v}^{2} v(t) \qquad (1\text{-}1)$$

$$z_{ms} < z_{bgp}$$

where

ρ = density of the glass $[lb_m/ft^3]$,

R_{gp} = radius of the glass pool [ft],

z_{bgp} = distance from a reference elevation to the bottom of the glass pool [ft],

$z_{ms}(t)$ = distance from a reference elevation to the melt surface at time t [ft],

R_v = inside radius of the inner pipe of the freeze valve [ft],

$v(t)$ = glass velocity through the inner pipe of the freeze valve at time t [ft/sec],

t = time [sec].

Equation (1-1) simply relates the rate at which the melt surface falls to the rate at which glass flows from the melt pool into the top of the freeze valve.

Conservation of momentum in the melt pool above the freeze valve requires that

$$\rho\pi R_{gp}^{2} \frac{d}{dt} \left\{ \left[z_{bgp} - z_{ms}(t)\right] \frac{d z_{ms}(t)}{dt} \right\} = - \rho\pi R_{v}^{2} v(t)^{2}$$

$$+ 144_{go} P_{p} \pi R_{gp}^{2} - 144_{go} P_{1}(t)\pi \left(R_{gp}^{2} - R_{v}^{2}\right)$$

$$- 144_{go} P_{2}(t)\pi R_{v}^{2} + \rho\pi R_{gp}^{2} \left[z_{bgp} - z_{ms}(t)\right] g \qquad (1\text{-}2)$$

$$z_{ms} < z_{bgp}$$

where

P_p = absolute pressure in the plenum [psia],

g_o = standard gravitational constant [32.14 lb_m-ft/sec^2-lb_f],

P_1 = absolute pressure on the melter floor away from the freeze valve [psia],

P_2 = absolute pressure at the top of the freeze valve [psia],

g = local gravity [ft/sec^2].

The left hand side of (1-2) represents the net change in momentum of the glass pool. The first term on the right hand side is the momentum lost from the glass pool due to glass flowing through the valve. The second, third, and fourth terms are the sum of the pressure forces acting on the top and bottom surfaces of the glass pool. The fifth term is the gravitational force acting on the glass pool.

If one requires that the amount of glass in the freeze valve be constant so that there is no net mass constant so that there is no net mass increase or decrease in the valve with respect to time,* and further assumes that the glass is incompressible (i.e., constant density), then conservation of mass for the glass in the freeze valve requires that the glass velocity v be independent of position in the valve. In other words, the glass velocity at the top of the valve is the same as the velocity at the bottom of the valve.

Conservation of momentum for the glass in the freeze valve requires that

$$\rho \pi R_v^2 L_v \frac{dv(t)}{dt} = 144\ g_o\ P_2(t) \pi R_v^2 + \rho \pi R_v^2 L_v\ g - 8\pi\mu(\bar{T})\ L_v v(t) - 144\ g_o\ P_{bv}\ \pi R_v^2 \qquad (1\text{-}3)$$

* This is true as long as glass is flowing through the valve and the level z_{ms} does not drop below z_{bgp}. When $z_{ms} > z_{bgp}$ the melter is assumed to be virtually empty of glass.

where

L_v = length of inner pipe of freeze valve [ft],

g_o = standard gravitational constant [32.14 lb_m-ft/sec^2-lb_f],

$\mu(\bar{T})$ = glass viscosity at the average glass temperature $\bar{T}$ as it flows through the valve [lb_m/ft-sec],

P_{bv} = absolute pressure at bottom of the inner pipe of the freeze value [psia].

The left hand side of (1-3) represents the net change of momentum of the glass flowing through the valve as the velocity changes with respect to time, i.e., the effect of inertia. The terms on the right hand side respectively represent the downward force at the top of the valve, the gravitational force acting on the glass in the valve, the frictional force between the flowing glass and the inner pipe wall for laminar flow and the upward force due to the pressure at the bottom of the inner pipe.

Equations (1-1), (1-2), and (1-3) are coupled, nonlinear, differential equations in the unknowns $z_{ms}(t)$, $v(t)$, $P_1(t)$, and $P_2(t)$. The necessary fourth equation can be obtained by approximating

$$144_{go}\ P_1(t) \cong \left[144_{go}\ P_p + \rho g \quad z_{bgp} - z_{ms}(t)\right]. \qquad (1\text{-}4)$$

Dividing (1-2) through by πR_v^2 and using (1-4) and (1-3) to eliminate $P_1(t)$ and $P_2(t)$ gives

$$\frac{\rho\ R_{gp}^2}{R_v^2}\ \frac{d}{dt}\left\{\left[z_{bgp} - z_{ms}(t)\right]\frac{dz_{ms}(t)}{dt}\right\} = -\ \rho v(t)^2$$

$$+\ \rho g\left[z_{bgp} - z_{ms}(t)\right] + 144_{go}\left(P_p - P_{bv}\right)$$

$$-\ \rho\ L_v\frac{dv(t)}{dt} + \rho\ L_v g\ - \frac{8\ \mu(\bar{T})\ L_v\ v(t)}{R_v^{\ 2}} \qquad (1\text{-}5)$$

Now (1-1) can be integrated to give the depth of the glass pool $D_{gp}(t)$ as

$$D_{gp}(t) = z_{bgp} - z_{ms}(t) = z_{zbp} - z_{ms}(o) - \frac{R_v^{\ 2}}{R_{gp}^{\ 2}}\int_o^t v(t)dt \qquad (1\text{-}6)$$

Also (1-1) can be differentiated to give

$$\frac{d\ z_{ms}(t)}{dt} = \frac{R_v^2}{R_{gp}^2}\ v(t) \tag{1-7}$$

and

$$\frac{d^2 z_{ms}(t)}{dt^2} = \frac{R_v^2}{R_{gp}^2}\ \frac{dv(t)}{dt} \tag{1-8}$$

The derivative on the left hand side of (1-5) can be made a linear function in v(t) by using

$$\begin{aligned} \frac{d}{dt}\left\{\left[z_{bgp} - z_{ms}(t)\right]\frac{d\ z_{ms}(t)}{dt}\right\} &\cong \frac{d}{dt}\left\{\left[z_{bgp} - \bar{z}_{ms}\right]\frac{d\ z_{ms}(t)}{dt}\right\} \\ &\cong \left[z_{bgp} - \bar{z}_{ms}\right]\frac{d^2\ z_{ms}(t)}{dt^2} \\ &\cong \left[z_{bgp} - \bar{z}_{ms}\right]\frac{R_v^2}{R_{gp}^2}\frac{dv(t)}{d} \end{aligned} \tag{1-9}$$

where

$$\bar{z}_{ms} = \frac{\int_o^{t_d} z_{ms}(t)dt}{\int_o^{t_d} dt} \tag{1-10}$$

and t_d = time required to completely drain the glass pool [sec].

Using (1-7), the integral in (1-10) can be transformed into

$$z_{ms} = \frac{\int_{z_{ms}(o)}^{z_{ms}(t_d)} z_{ms}(t)\ d\ z_{ms}(t)}{\int_{z_{ms}(o)}^{z_{ms}(t_d)} d\ z_{ms}(t)}$$

$$= \frac{1}{2}\left[z_{ms}\ (t_d) - z_{ms}(o)\right]$$

$$= \frac{1}{2}\left[z_{bgp} - z_{ms}(o)\right] \tag{1-11}$$

The nonlinear term in $v(t)^2$ on the right hand side of (1-5) can be made a linear term in dv(t)/dt by expanding v(t) in a Taylor's series to obtain

$$v(t)^2 = \left[v(t-\Delta t) + \Delta t\,\frac{dv(t)}{dt} + \ldots\right]^2$$

$$\cong v(t-\Delta t)^2 + 2v(t-\Delta t)\ \Delta t\ \frac{dv(t)}{dt} \tag{1-12}$$

where

Δt = time step size [sec].

Using (1-6), (1-7), (1-10), (1-11), and (1-12), it is now possible to write (1-5) as a linear, integro-differential equation in v(t), i.e.,

$$- \frac{\rho R_v^2}{R_{gp}^2}\left[v(t-\Delta t)^2 + 2v(t-\Delta t)\ \Delta t\ \frac{dv(t)}{dt}\right]$$

$$+ \rho\left[z_{bgp} - z_{ms}(t-\Delta t) - \frac{\Delta t R_v^2}{R_{gp}^2}\ v(t-\Delta t)\right]\frac{dv(t)}{dt} =$$

$$- \rho v(t-\Delta t)^2 - 2\rho v(t-\Delta t)\ \Delta t\ \frac{dv(t)}{dt} + 144_{go}\left(P_p - P_{bv}\right)$$

$$- \rho L_v \frac{dv(t)}{dt}$$

$$\frac{-\ 8\ \mu(\bar{T})\ L_v\ v(t)}{R_v^2} + \rho g\left[z_{bgp} - z_{ms}(o) - \frac{R_v^2}{R_{gp}^2}\int_o^t v(t)dt\right] + \rho g L_v \tag{1-13}$$

Now define

$$\alpha_1 = \frac{-\,2\rho R_v^2\, v(t-\Delta t)\Delta t}{R_{gp}^2}$$

$$+\ \rho \left[z_{bgp} - z_{ms}(t-\Delta t) - \frac{\Delta t R_v^2}{R_{gp}^2}\, v(t-\Delta t) \right]$$

$$+\ 2\rho v(t-\Delta t)\,\Delta t + \rho L_v \qquad (1\text{-}14)$$

$$\alpha_2 = \frac{8\,\mu(\bar{T})L_v}{R_v^2} \qquad (1\text{-}15)$$

$$\alpha_3 = \frac{\rho g\, R_v^2}{R_{gp}^2} \qquad (1\text{-}16)$$

$$\alpha_4 = \rho v(t-\Delta t)^2 \left[\frac{R_v^2}{R_{gp}^2} - 1 \right] + \rho g \left[z_{bgp} - z_{ms}(o) \right] + \rho g L_v \qquad (1\text{-}17)$$

so that (1-13) can be written as

$$\alpha_1 \frac{dv(t)}{dt} + \alpha_2\, v(t) + \alpha_3 \int_o^t v(t)dt = \alpha_4 + 144_{go} \left(P_p - P_{bv}\right)$$

(1-18)

Equation (1-18) is the result of eliminating $P_1(t)$, $P_2(t)$, and $z_{ms}(t)$ in v(t) results. It will now be solved for v(t) using conventional techniques, after which v(t) will then be used to express $P_1(t)$, $P_2(t)$, and $D_{gp}(t)$.

Uninterrupted Isothermal Glass Flow

Assume that at time t=o, the freeze valve opens and glass flow begins. No attempt is made to interrupt the flow. Instead the glass is allowed to flow freely from the glass pool until the entire contents of the melter have been drained. The pressure in the plenum P_p and at the bottom of the valve P_{bv} are held constant as the glass is drained.

In (1-18), assume a homogeneous solution of the form

$$v_h(t) = e^{mt} \tag{2-1}$$

which then yields

$$\alpha_1 \; me^{mt} + \alpha_2 \; e^{mt} + \frac{\alpha_3}{m} \; e^{mt} = 0 \tag{2-2}$$

The characteristic equation of (2-2) is

$$\alpha_1 \; m^2 + \alpha_2 \; m + \alpha_3 = 0 \tag{2-3}$$

which has the roots

$$m_1 = \frac{-\alpha_2 + \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2\alpha_1} \tag{2-4}$$

$$m_2 = \frac{-\alpha_2 - \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2\alpha_1} \tag{2-5}$$

Thus the homogeneous solution of (1-18) is

$$v_h(t) = c_1 e^{m_1 t} + c_2 e^{m_2 t} \tag{2-6}$$

where c_1 and c_2 are constants to be determined.

For a particular solution v_p of (1-18) try

$$v_p = c_3 \tag{2-7}$$

which when substituted into (1-18) gives

$$\alpha_2 \; c_3 + \alpha_3 \; c_3 t = \alpha_4 + 144_{go} \left(P_p - P_{bv}\right) \tag{2-8}$$

Since (2-28) is valid for all values of t, it must also be valid at t=0, which gives

$$c_3 = \frac{\alpha_4 + 144_{go} \left(P_p - P_{bv}\right)}{\alpha_2} \tag{2-9}$$

The general solution to (1-18) is the sum of the homogeneous and particular solutions, i.e.,

$$v(t) = c_1 e^{m_1 t} + c_2 e^{m_2 t} + c_3 \tag{2-10}$$

$z_{ms} < 3_{bgp}$

To determine c_1 and c_2, two boundary conditions are needed. If at time t=0, one required that v(o) = 0, then (2-10) yields

$$0 = c_1 + c_2 + c_3 \tag{2-11}$$

For the second boundary condition (1-3) may be used to give

$$\frac{dv(o)}{dt} = \frac{144_{go}}{\rho L_v} \left[P_2(o) - P_{bv} \right] + g \tag{2-12}$$

where

$$P_2(o) \equiv P_p + \frac{\rho g}{144_{go}} \left[z_{bgp} - z_{ms}(t) \right] \tag{2-13}$$

Using (2-12) in (2-10) gives

$$\frac{144_{go}}{\rho L_v} \left[P_2(o) - P_{bv} \right] + g = c_1 m_1 + c_2 m_2 \tag{2-14}$$

Equations (2-11) and (2-14) can be solved to yield

$$c_1 = \frac{1}{m_1 - m_2} \left\{ \frac{144_{go}}{\rho L_v} \left[P_2(o) - P_{bv} \right] + g + c_3 m_2 \right\} \tag{2-15}$$

$$c_2 = -\left(c_1 + c_3 \right) \tag{2-16}$$

which completes the definition of the constants for v(t) in (2-10).

Using (2-10) in (1-6) gives the depth of the glass pool at any time t as

$$D_{gp}(t) = z_{bgp} - z_{ms}(o) \frac{-R_v^2}{R_{gp}^2} \left[\frac{c_1}{m_1} \left(e^{m_1 t} - 1 \right) + \frac{c_2}{m_2} \left(e^{m_2 t} - 1 \right) + c_3 t \right] \tag{2-17}$$

$z_{ms} < z_{bgp}$

The pressure at the bottom of the melt pool away from the freeze valve can be obtained from (1-4), (1-6), and (2-17), i.e.,

$$P_1(t) \cong \frac{\rho g}{144_{go}} D_{gp}(t) \tag{2-18}$$

$z_{ms} < z_{bgp}$

Flow Interruption by Pressure Drop Control

One method of interruption the glass flow through the valve is by control of the applied pressure drop across the valve. This can be accomplished by using air jets directed at the bottom of the valve to increase the valve bottom pressure P_{bv} or alternatively, by causing an appropriate drop in the plenum pressure P_p. In this section, the response of the glass flow through the valve to a step change in the applied pressure drop across the valve will be studied.

Assume that glass is flowing isothermally through the valve and at some time' there is a step change in the valve bottom pressure such that

$$P_{bv} = P_{bv},\ t < t'$$

$$= P_{bv}^*,\ t > t' \tag{3-1}$$

where

$$P_{bv}^* > P_{bv} \tag{3-2}$$

The solution to this problem is governed by the same equations that were derived and solved in sections 1 and 2 except that the boundary conditions are different. Equation (1-18) remains the same except that P_{bv} is replaced by P_{bv}^*. The characteristic Equation (2-2) and its roots (2-4) and (2-5) also remain the same. or a particular solution of the analog of (1-18), let

$$v_p = c_3^* \tag{3-3}$$

so that the analog of (2-9) becomes

$$c_3^* = \frac{\alpha_4 + 144_{go}\left(P_p - P_{bv}^*\right)}{\alpha_2} \tag{3-4}$$

let the analogous general solution (2-10) be

$$v^*(t) = c_1^* e^{m_1(t-t')} + c_2^* e^{m_2(t-t')} + c_3^* \tag{3-5}$$

$$t > t' \quad z_{ms} < z_{bgp}$$

To determine c_1^* and c_2^*, require that the velocity given by the two solutions be continuous at time t

$$v^* (t') = v(t') \tag{3-6}$$

where the right hand side of (3-6) is given by (2-10) evaluated at time t' using (3-6) in (3-5) gives

$$v(t') = c_1^* + c_2^* + c_3^* \tag{3-7}$$

For a second boundary condition, require that the slope of the velocity (i.e., the acceleration) given by the two solutions be continuous at time t'. Equating the derivatives of (2-10) and (3-5) at time t' gives

$$c_1 m_1 e^{m_1 t'} + c_2 m_2 e^{m_2 t'} = c_1^* m_1 + c_2^* m_2 \tag{3-8}$$

Equation (3-7) and (3-8) can be solved simultaneously for c_1^* to yield

$$c_1^* = \frac{c_1 m_1 e^{m_1 t'} + c_2 m_2 e^{m_2 t'} + m_2 \left[c_3^* - v(t')\right]}{m_1 - m_2} \tag{3-9}$$

$$c_2^* = v(t') - c_1^* - c_3^* \tag{3-10}$$

where c_1 and c_2 are defined by (2-15) and (2-16), and v(t') is the solution to (2-10) at time t'. Equations (2-4) and (2-5) define m_1 and m_2.

For any time t >t', the depth of the glass pool can be written from (1-6) as

$$D_{gp}^*(t) = z_{bgp} - z_{ms}(o) \frac{- R_v^2}{R_{gp}^2} \left[\int_o^{t'} v(t)dt + \int_{t'}^{t} v^*(t)dt \right] t > t' \tag{3-11}$$

However, by inspection of (1-6), (3-11) can be simplified to

$$D_{gp}^{*}(t) = D_{gp}(t') \frac{-R_v^2}{R_{gp}^2} \int_{t}^{t} v^{*}(t)dt \qquad (3\text{-}12)$$

$t > t'$

which, from (3-5) becomes

$$D_{gp}^{*}(t) = D_{gp}(t') - \frac{R_v^2}{R_{gp}^2}\left[\frac{C_1^*}{m_1}\left(e^{m_1(t-t')} -1\right) + \frac{c_2^*}{m_2}\left(e^{m_2(t-t')} -1\right) + c_3(t-t')\right] \qquad (3\text{-}13)$$

$t > t'$

which is the analog of (2-17).

The pressure at the bottom of the melt pool away from the freeze valve is the analog of (2-18)

$$P_1^{*}(t) \cong \frac{\rho g}{144 g_o} D_g^{*}(t) \qquad (3\text{-}14)$$

$z_{ms} < z_{bgp} \quad t > t'$

Computer Model

The theory explained in the previous section was encoded into a FORTRAN-IV program. This program uses data describing the physical properties of the fluid and the freeze valve dimensions as input and calculates instantaneous values of pool depth, fluid velocity through the valve, and mass flowrate through the valve. Appendix 1 contains a copy of the program and example of its output.

Verification of Theory

A small test station was built at the ETF to evaluate the validity of the isothermal freeze valve computer model. Silicone fluids were used instead of molten glass. Computer simulations of several tests were compared with data obtained during the experiments.

The test station consisted of an elevated holding tank 2-feet ID, 30-inches deep, with a flanged hole in the bottom (Figure 2). The flanged hole permitted the coupling of several different valve assemblies to the holding tank. A valve assembly consisted of a matching flange, a length of the appropriate diameter pipe, and a 1/4-turn ball valve. A catch tank was placed underneath the valve assembly to collect the draining fluids. Except for the PVC ball valves, all parts were constructed from 304L stainless steel.

Silicone fluid was chosen to simulate the molten glass. It is available in several viscosities at room temperature, including that of molten glass at 1150°C (10 to 150 poise). Silicone is also inert, noncorrosive, and nontoxic. Fluid with viscosities of 12 poise, 50 poise, and 75 poise were used during the experiment. Additional data on silicone fluids is provided in Appendix II.

The experimental procedure for each test consisted of three steps. First, a valve assembly was installed in the test station. The holding tank was then filled with silicone fluid. The fluid was allowed to sit for 30 minutes to allow air bubbles entrapped during tank filling to escape, and during this time period, the fluid temperature was measured (for determining the fluid density and viscosity). The ball valve was opened (to simulate the melting of the glass plug in an actual freeze valve). The time required to lower the fluid level in the holding tank one inch was recorded along with the tank depth. After the test was completed, a sample of the test fluid was analyzed by a HAAKE® viscometer to determine it's viscosity.

Table I lists the independent variables held constant during each test. Hereafter, these tests will be referred to by case letter.

Figures 2 through 4 compare the results of the silicone fluid experiment with predictions generated by the computer model. The fluid level in the holding tank is plotted as a function of time. The good agreement seen in these figures demonstrate the validity of the model.

The theoretical effect of valve bottom pressure, P_{bv}, on freeze valve performance has not been experimentally verified. However, tests conducted on the small cylindrical melter 3 (SCM-2) jet controlled freeze valve demonstrate that it is possible to interrupt glass flow by pressurizing the valve bottom. An experimental program for testing this technique is being developed.

DISCUSSION

Figures 6 through 9 show the predicted effects of varying valve dimensions and glass viscosity on isothermal freeze valve performance. The "holding tank" dimensions coincide with those of the DWPF melt chamber (6-foot diameter, 34 inches of fluid). In each prediction, it is assumed that the pressure difference between the melter plenum and the bottom of the freeze valve is negligible. A 60 poise glass with a density of 2.4 g/cm, an arbitrary valve radius of 1 inch, and valve length of 1.5 foot were chosen as references for comparison.

The effect of valve radius on freeze valve performance is shown in Figures 5 and 6. From Figure 6 it is seen that increasing the valve radius results in a significant decrease in drain time. Theoretically, the drain time is inversely proportional to the square of the freeze valve radius. Figure 7 represents the mass flowrate of glass exiting the freeze valve as a function of valve radius and glass pool depth. The mass flowrate through the valve is directly proportional to the radius of the valve raised to the fourth power.

The length of the freeze valve influences both the driving force and the resistance force governing valve performance. The static head motivating glass flow increases with increasing valve length. However, viscous resistance to flow is also directly related to freeze valve length. As Figure 8 shows, the increase in viscous effect completely overwhelms the static head effect generated by lengthening the valve. Increasing the valve length for a fixed diameter valve results in lower mass flow rates.

Figure 9 shows the theoretical effect of glass viscosity on freeze valve performance. This figure demonstrates the practical limitations of the isothermal freeze valve model. The theory used in the model assumes that flow through the valve is laminar and that contraction losses are minimal. However, for large diameter valves and low viscosity fluids this assumption is not valid. The theoretical flowrate through the valve approaches infinity as the fluid viscosity approaches zero. To determine if the model can be applied to a specific situation, the predicted Reynolds number can be used to determine if the assumption of laminar flow is valid.

Figures 6 through 9 can be used to determine a suitable freeze valve size for the DWPF melter. Extrapolation from Figures 7 and 9 indicate that a 1-inch-ID freeze valve, 1.5 feet long, would drain the melter at an average rate of 1125 lb/hr (assuming a molten glass viscosity similar to Frit 168 + simulation-2*). A valve this size could drain a full melter near the end of its lifetime in about 13 hours (plus time required for canister changes).

* 80 poise at 1100°C

CONCLUSION

Uninterrupted, isothermal flow of molten glass through a freeze valve has been modeled. The accuracy of this model is limited to cases in which laminar flow is encountered. Tests with silicone fluids have verified the sufficient information for sizing the diameter of the DWPF freeze valve is available.

QUALITY ASSURANCE

All data acquisitions were performed in accordance with the Defense Waste Processing Section Quality Assurance Plan and DPST-QA-83-2-2, "Quality Assurance Review for the Small Cylindrical Melter-2." All experimental data were recorded in registered laboratory notebook DPSTN-4071.

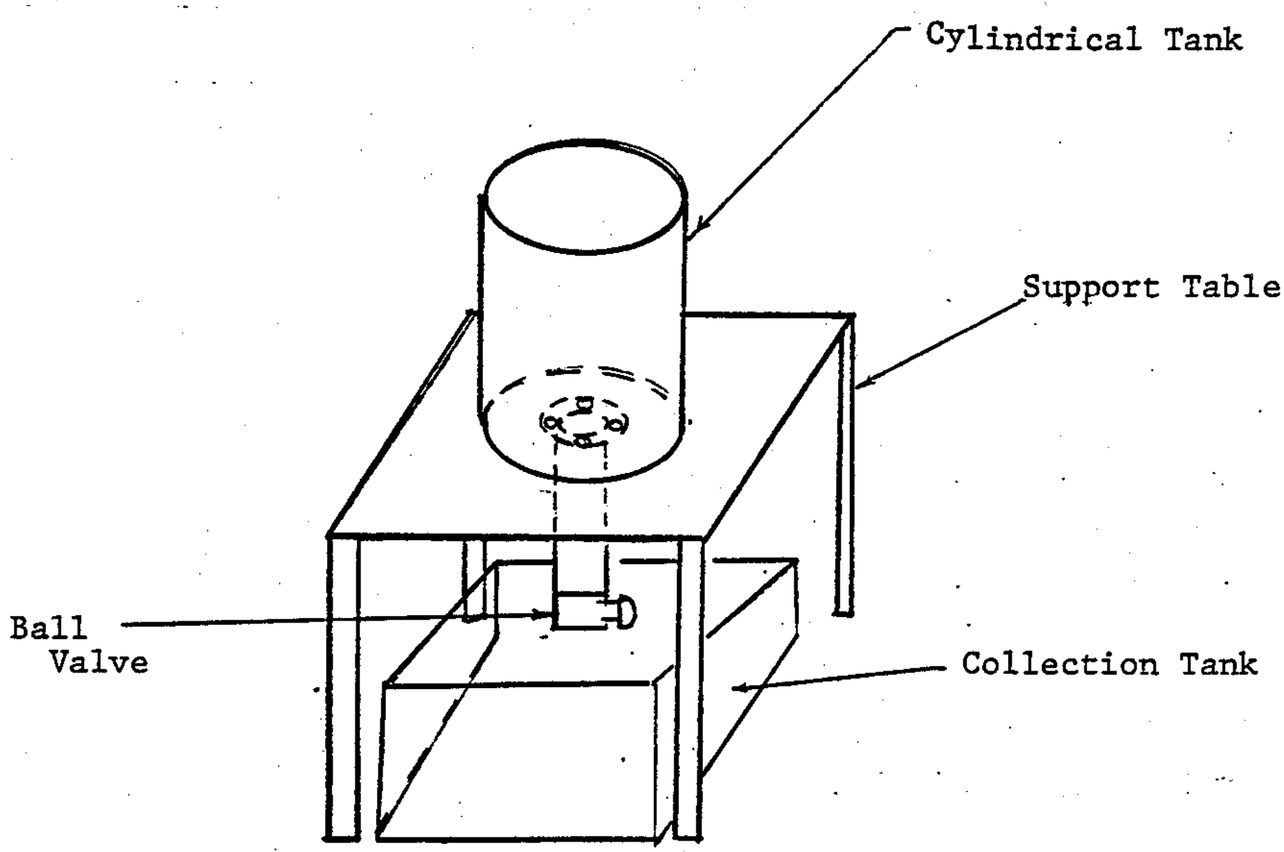


FIGURE 2

ISOTHERMAL FREEZE VALVE TEST STATION

TABLE 1

Dependent Variables for Experimental Tests

Case	Valve ID, Inches	Valve Length, Inches	Fluid Viscosity, Poise	Initial Tank Depth, Inches	Fluid Density, g/cc
A	0.639	24.5	48.4	11.25	0.994
B	1.113	22.5	47.8	11.75	0.994
C	2.125	24.5	51.4	10.875	0.906
D	0.639	24.5	12.66	9.0	1.102
E	1.113	22.5	12.66	8.75	1.102
F	2.125	24.5	12.66	9.0	0.967
G	1.113	22.5	76.74	10	0.969
H	2.125	24.5	76.74	11.25	76.74

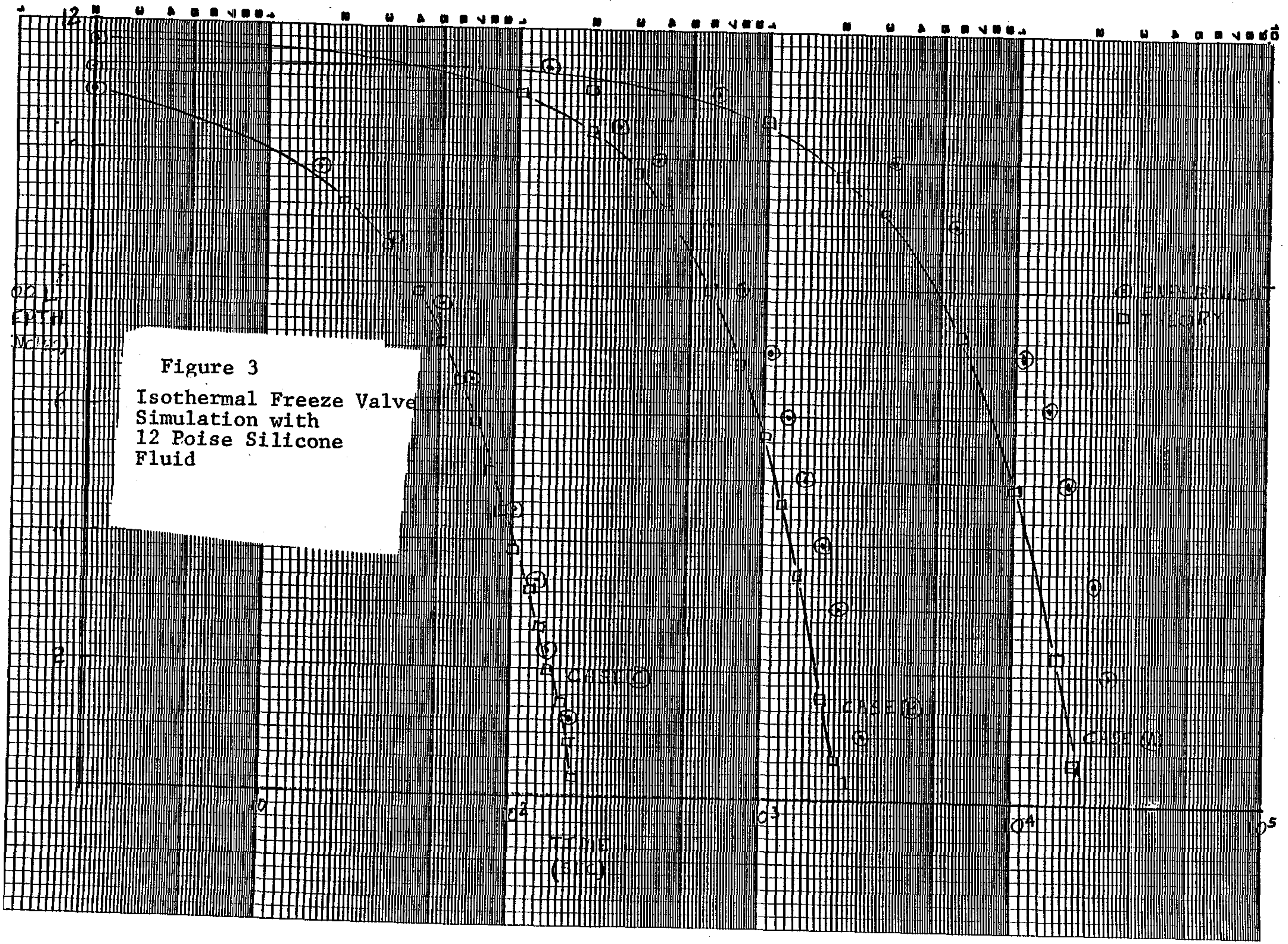


Figure 3

Isothermal Freeze Valve Simulation with 12 Poise Silicone Fluid

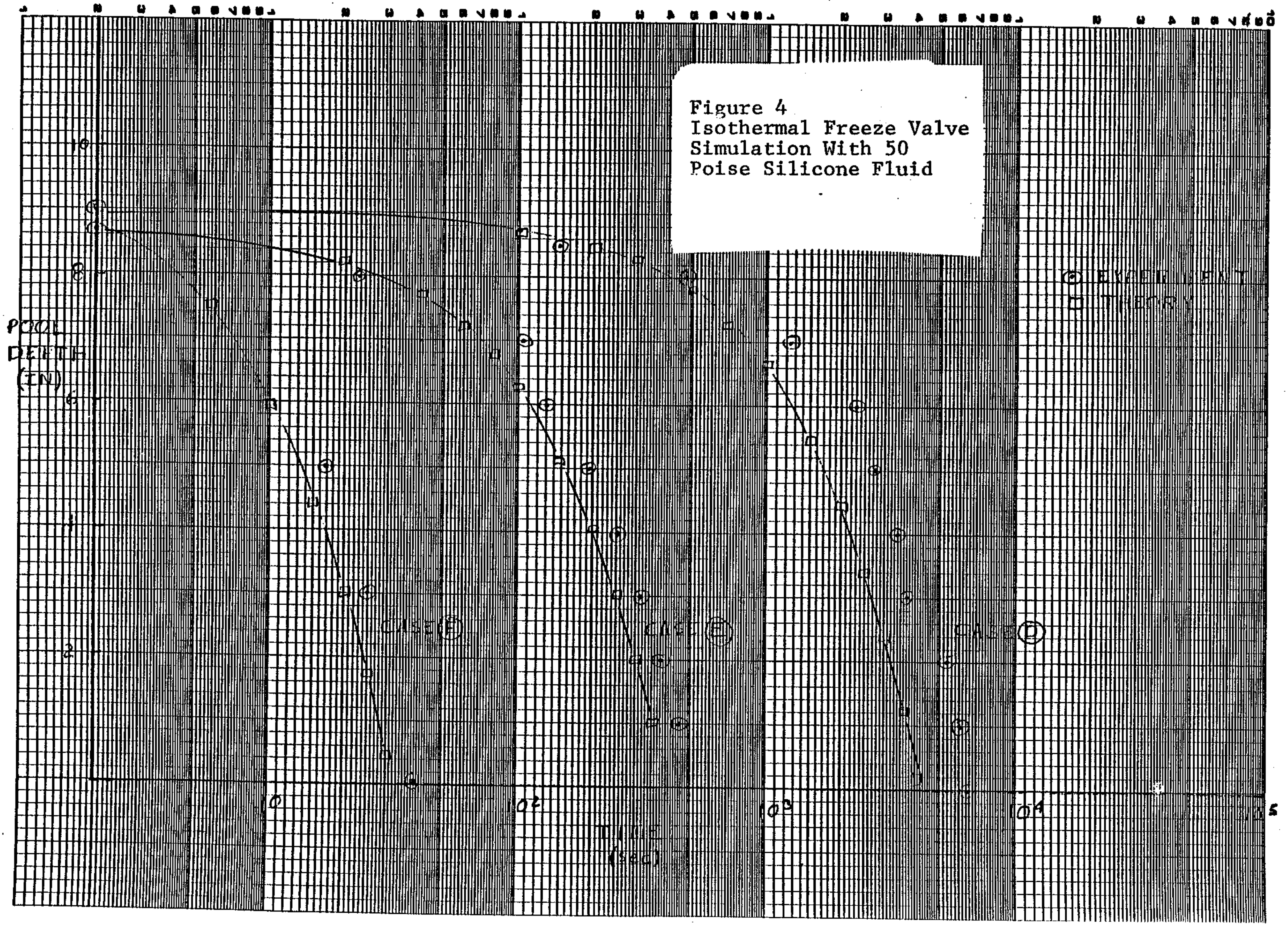


Figure 4
Isothermal Freeze Valve Simulation With 50 Poise Silicone Fluid

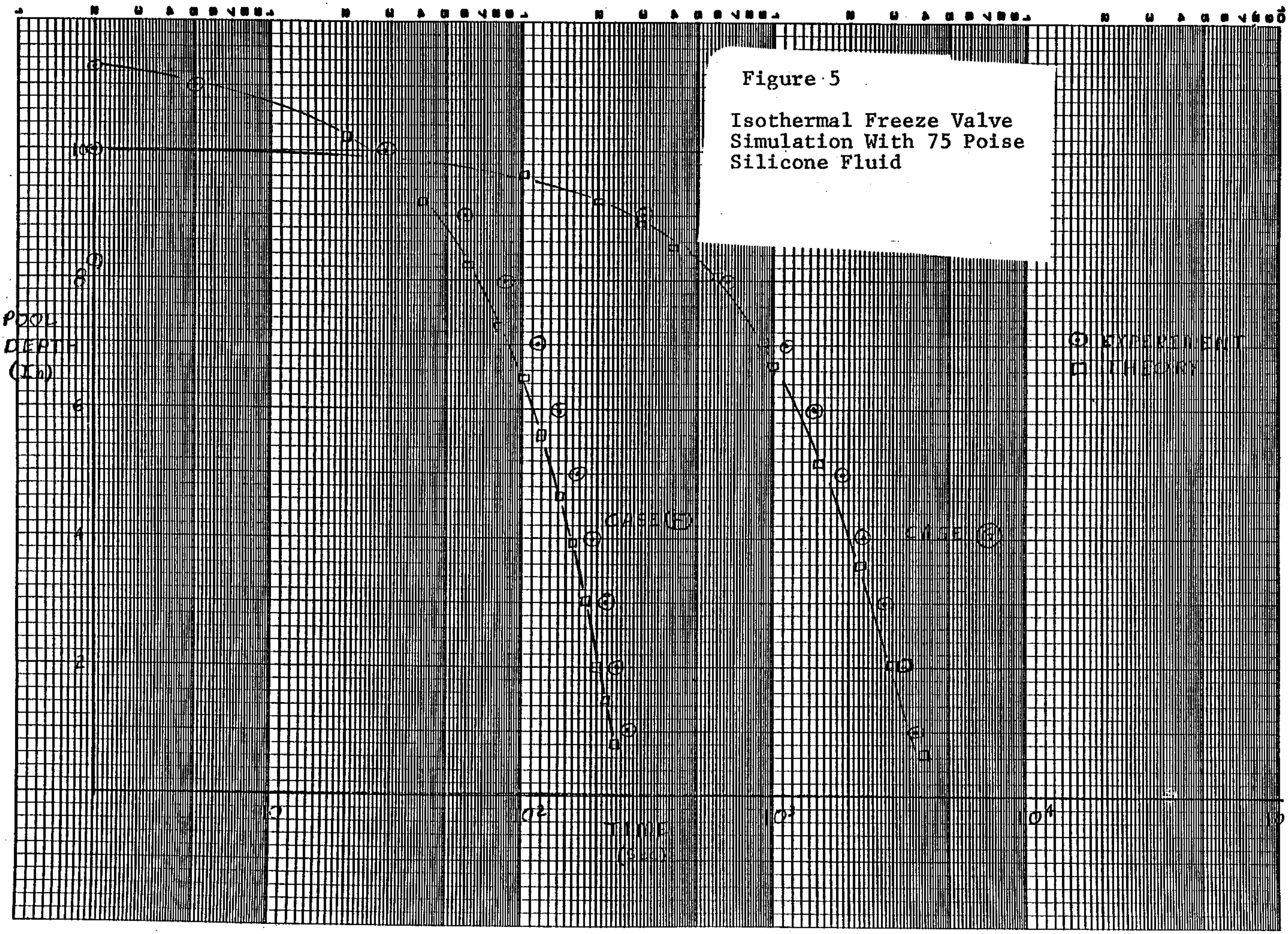
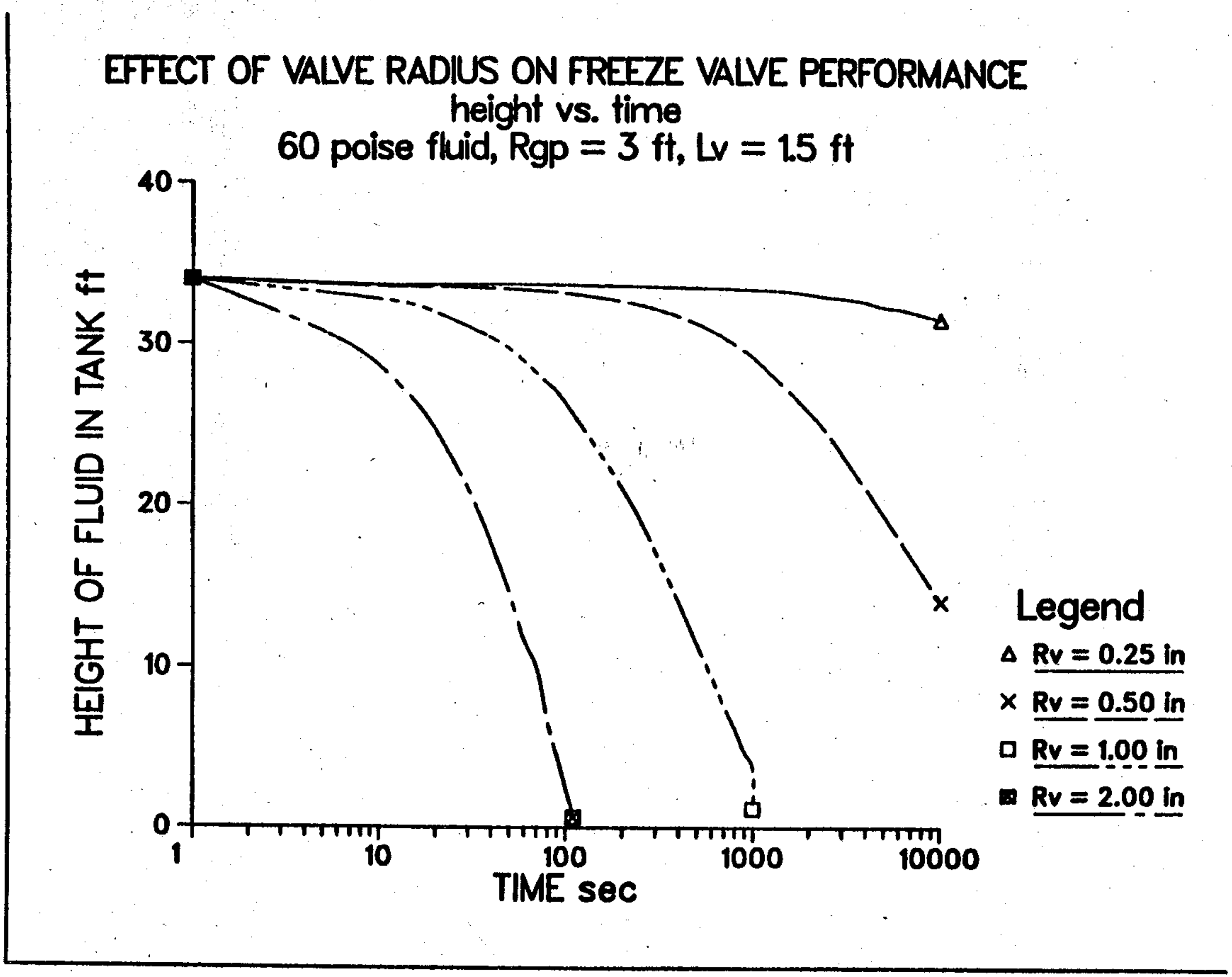


Figure 5

Isothermal Freeze Valve Simulation With 75 Poise Silicone Fluid

FIGURE 6



EFFECT OF VALVE RADIUS ON FREEZE VALVE PERFORMANCE
height vs. time
60 poise fluid, Rgp = 3 ft, Lv = 1.5 ft
HEIGHT OF FLUID IN TANK ft
0
10
20
30
40
1
10
100
1000
10000
TIME sec
Legend
Rv = 0.25 in
Rv = 0.50 in
Rv = 1.00 in
Rv = 2.00 in

FIGURE 7

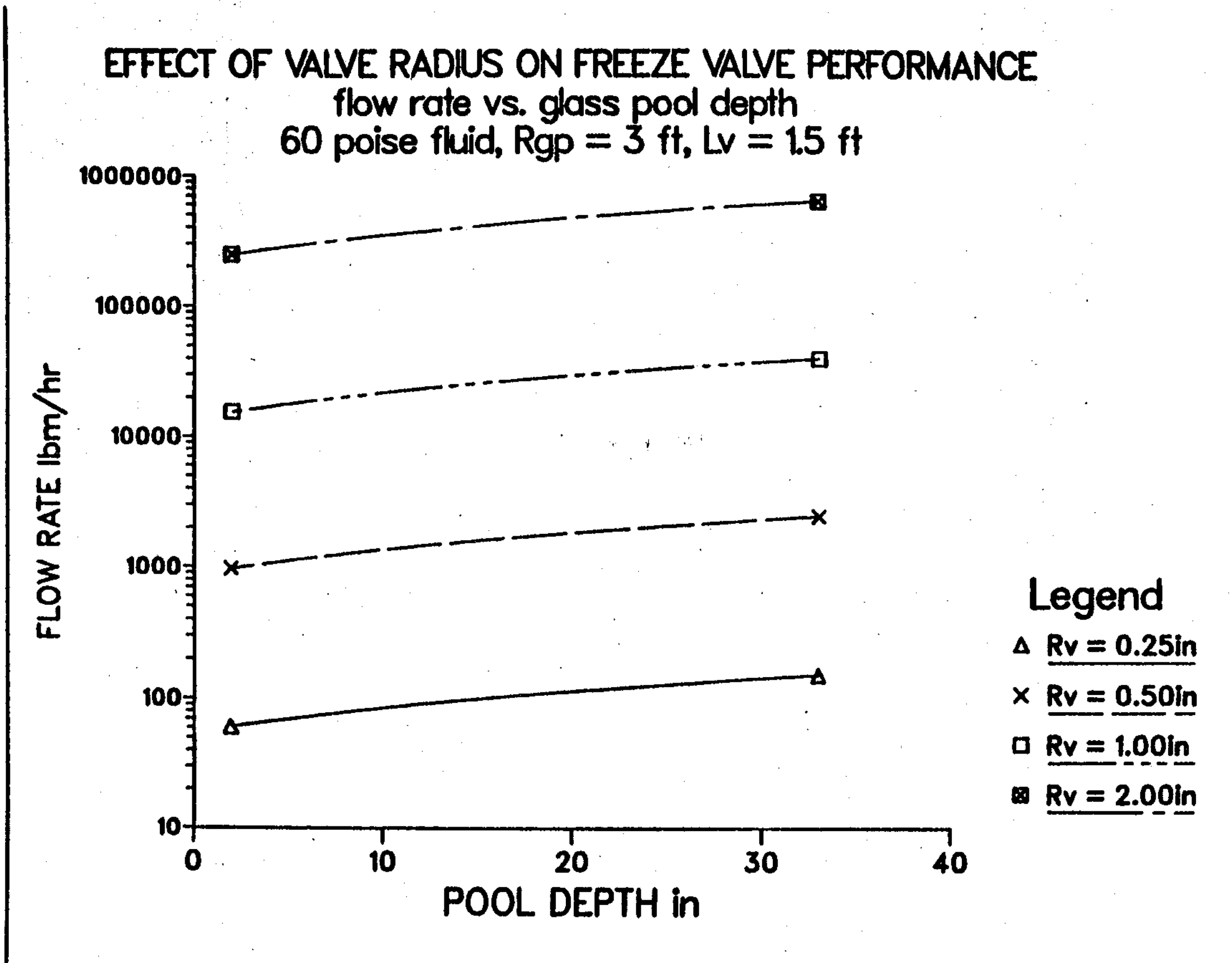
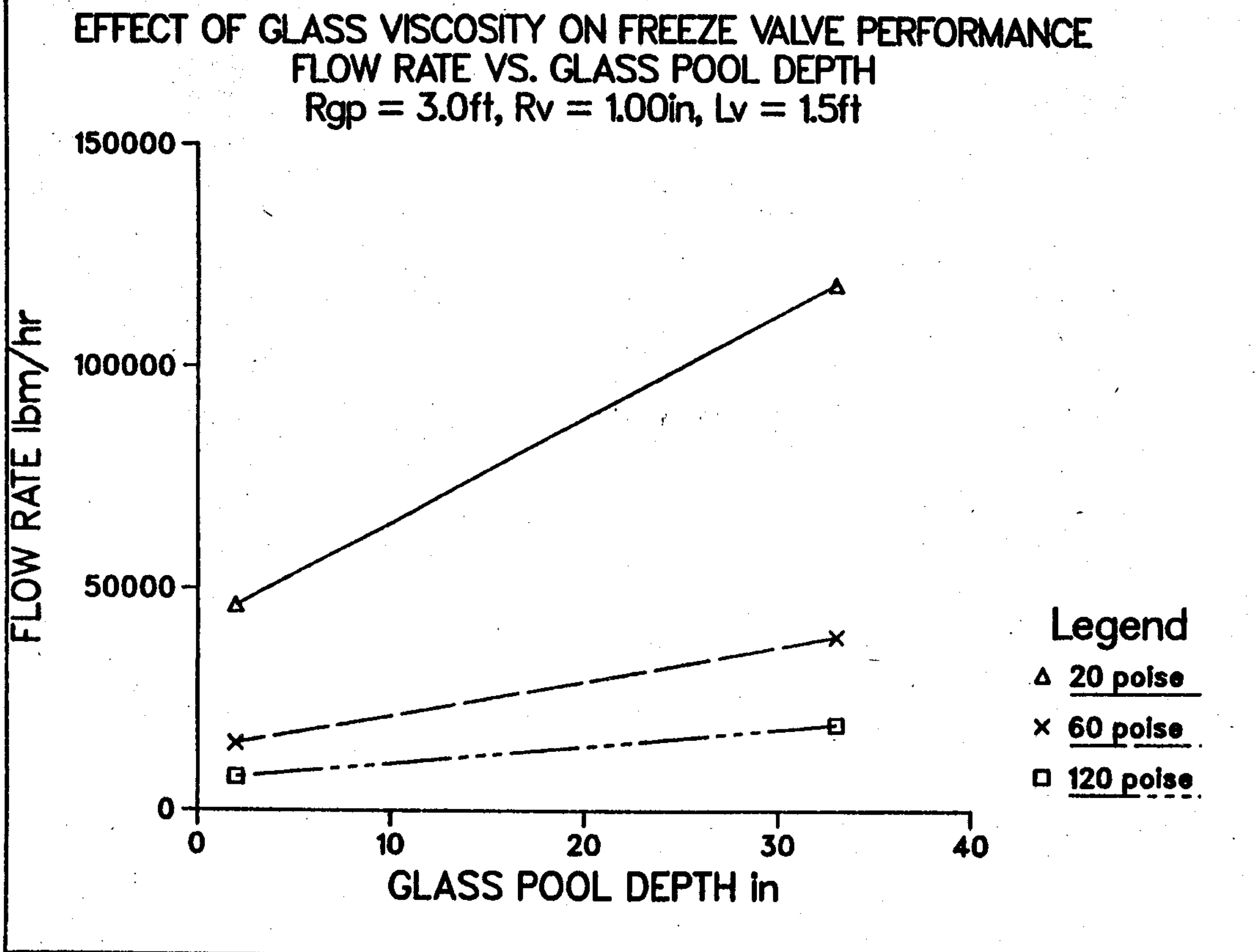
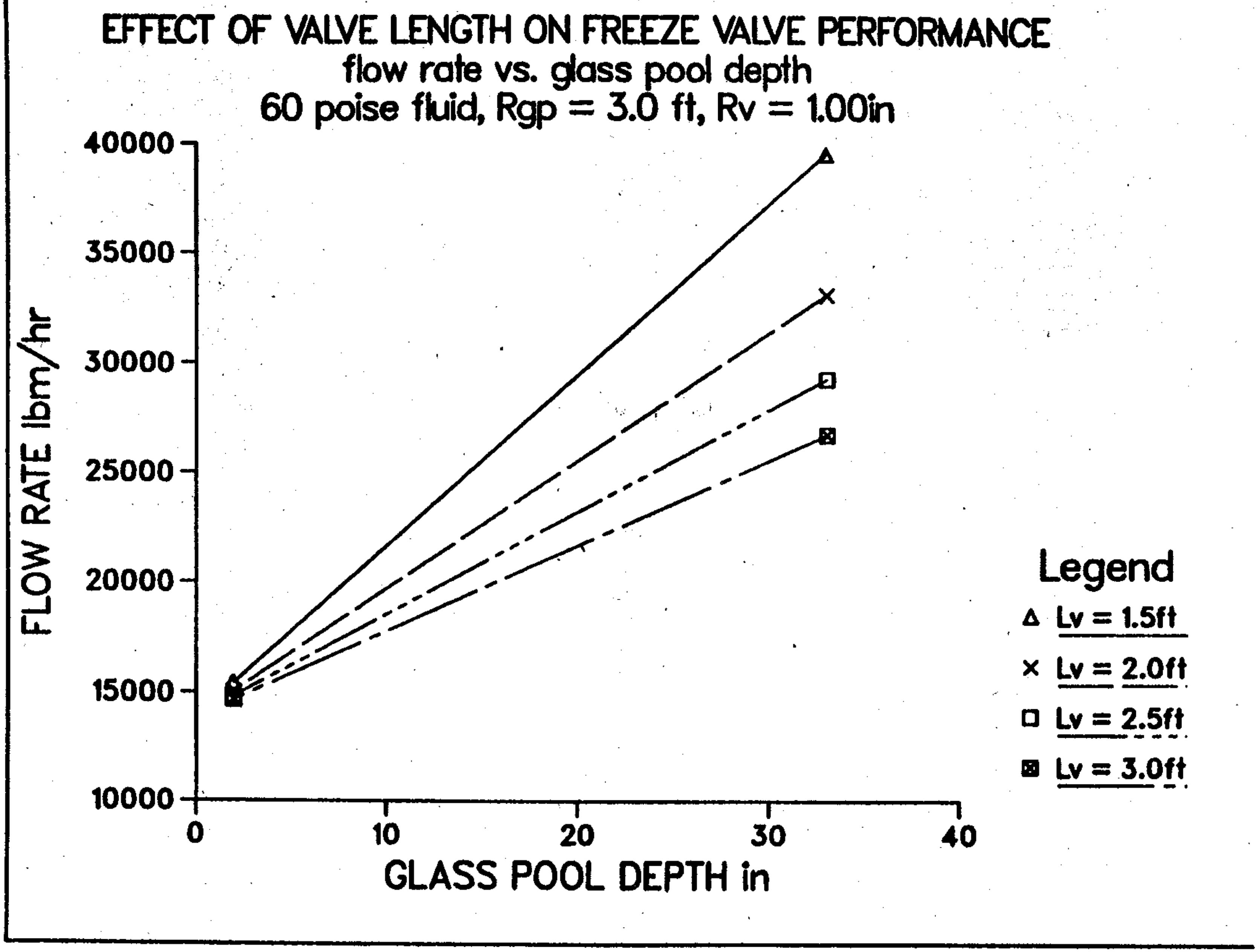

EFFECT OF VALVE RADIUS ON FREEZE VALVE PERFORMANCE
flow rate vs. glass pool depth
60 poise fluid, Rgp = 3 ft, Lv = 1.5 ft
FLOW RATE lbm/hr
1000000
100000
10000
1000
100
10
0
10
20
30
40
POOL DEPTH in
Legend
Rv = 0.25in
Rv = 0.50in
Rv = 1.00in
Rv = 2.00in

FIGURE 8



EFFECT OF GLASS VISCOSITY ON FREEZE VALVE PERFORMANCE
FLOW RATE VS. GLASS POOL DEPTH
Rgp = 3.0ft, Rv = 1.00in, Lv = 1.5ft
FLOW RATE lbm/hr
150000
100000
50000
0
0
10
20
30
40
GLASS POOL DEPTH in
Legend
20 poise
60 poise
120 poise

FIGURE 9


EFFECT OF VALVE LENGTH ON FREEZE VALVE PERFORMANCE
flow rate vs. glass pool depth
60 poise fluid, Rgp = 3.0 ft, Rv = 1.00in
FLOW RATE lbm/hr
40000
35000
30000
25000
20000
15000
10000
0
10
20
30
40
GLASS POOL DEPTH in
Legend
Lv = 1.5ft
Lv = 2.0ft
Lv = 2.5ft
Lv = 3.0ft

APPENDIX I

Fortran IV Computer Model of Isothermal Freeze Valve Theory

```
QUESTED OPTIONS: SOURCE,NOLIST,NOXREF,OPT(3),MAP,NOTERM
TIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(58) SIZE(MAX) AUTODBL(NONE)
                 SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF NOTERM IBM FLAG(I) XL

CT4158.EDIT.DATA(DVT)
C                    P R O G R A M   D V T '
C
C                    (DRAIN VALVE THEORY)
C
C
C          THIS PROGRAM PERFORMS THE STEPWISE CALCULATIONS FOR
C        A MATHEMATICAL MODEL DESCRIBING THE PATTERN OF FLOW
C        IN THE SCM-2 DURING A HYPOTHETICAL DRAIN VALVE EVACUATION.
C        THE THEORY WAS DEVELOPED BY K. R. ROUTT (DPST         ).
C        THE PROGRAM SHOULD BE OPERATED AND MAINTAINED IN THE FOLLOWING
C        MANNER:
C
C          ---INPUT PARAMETERS (LISTED BELOW) MUST BE ENTERED INTO
C             THE PROGRAM CODE. REMEMBER TO "SAVE" THE PROGRAM.
C
C          ---PROGRAM WILL GIVE ERROR SIGNAL FOR UNNACCEPTABLE INPUT.
C
C          ---PLEASE USE UNITS CONSISTENT WITH THOSE LISTED IN
C             VARIABLE LIST.
C
C
C
C                       I N P U T   V A R I A B L E S
C
C            DELTAT = TIME STEP SIZE (SEC.)
C
C            DPG(0) = DEPTH OF MELT POOL AT TIME T = 0 SEC (FT.)
C
C            LV     = LENGTH OF INNER PIPE OF FREEZE VALVE (FT.)
C
C            PBV    = ABSOLUTE PRESSURE AT THE BOTTOM OF THE INNER
C                     PIPE OF THE FREEZE VALVE (PSIA.)
C
C            PP     = ABSOLUTE PRESSURE IN THE PLENUM (PSIA.)
C
C            RGP    = RADIUS OF THE GLASS POOL (FT.)
C
C            RV     = INSIDE RADIUS OF THE INNER PIPE OF THE FREEZE
C                     VALVE (IN.)
C
C            RHO    = DENSITY OF THE GLASS (LBM/CU.FT.)
C
C            TMAX   = DEFAULT MAXIMUM TIME FOR PROGRAM EXECUTION (SEC.)
C
C            VISC   = GLASS VISCOSITY AT THE AVERAGE GLASS TEMPERATURE
C                     (LBM/FT.-SEC.)
C
C            ZMS(0) = DISTANCE FROM A REFERENCE ELEVATION TO MELT
C                     SURFACE AT TIME T = 0 SEC (FT.)
C
C
C
```

```
               C              P R I M A R Y   D E P E N D E N T   V A R I A B L E S
               C
               C          DPG     = DEPTH OF MELT POOL AT TIME T (FT.)
               C
               C          P1      = ABSOLUTE PRESSURE ON THE MELTER FLOOR AWAY
               C                    FROM THE FREEZE VALVE (PSIA.)
               C
               C          P2      = ABSOLUTE PRESSURE ON TOP OF THE FREEZE
               C                    VALVE (PSIA.)
               C
               C          TIME    = TIME ELASPED SINCE INITIATION OF TANK
               C                    DRAINING (SEC.)
               C
               C          VLCTY   = GLASS VELOCITY THROUGH THE INNER PIPE OF THE
               C                    FREEZE VALVE (FT./SEC.)
               C
               C             Q    = MASS FLOW RATE THROUGH VALVE (LBM./HR.)
               C
               C               ----
               C          ALPHA1 = T
               C                   I
               C          ALPHA2 = I
               C                   I       FUNCTIONS BASED ON GEOMETRY AND DIMENSIONS
               C          ALPHA3 = I       OF MELTER AND FREEZE VALVE
               C                   I
               C          ALPHA4 = T
               C               ----
               C
               C
               C                      C O N S T A N T S
               C
               C          G0      = STANDARD GRAVITATIONAL CONSTANT
               C                    (LBM.-FT./LBF-SQ.SEC.)
               C
               C          G       = LOCAL ACCELORATION OF GRAVITY (FT./SQ.SEC.)
               C
               C          C1
               C          C2      = PARTICULAR SOLUTION CONSTANTS
               C          C3
               C
               C          M1
               C          M2      = HOMOGENEOUS SOLUTION CONSTANTS
               C
               C          ZBGP    = DISTANCE FROM REFERENCE POSITION TO BOTTOM
               C                    OF GLASS MELT POOL
               C
               C          KICK    = VARIABLE USED TO PRINT RESULTS EVERY 10 SECONDS
               C
               C
               C                 D E C L A R E   V A R I A B L E S
               C
ISN 0002              REAL*8 STIME(3),SVLCTY(3),SDPG(3),SP2(3)
               C
ISN 0003              REAL*8 DPG, P2, TIME, VLCTY, DPG1, P21, TIME1, VLCTY1,APG
               C
               C
ISN 0004              REAL*8 TMAX,DELTAT,LV,PRV,PP,RGP,PV,RHO,VISC,G0,G,P1,ZMS,
```

```
                   *ALPHA1,ALPHA2,ALPHA3,ALPHA4, M1PAST, M2PAST, C1PAST, C2PAST         01181060
ISN 0005            REAL*8 C1,C2,C3,M1,M2,ZBGP,STP,NTIME,ANTIME,ZMS1,SM1, SM2,          01190083
                   *Q                                                                   01191083
              C                                                                         01200000
ISN 0006            INTEGER IFIN, START,KICK,J                                          01210000
              C                                                                         01220000
              C                                                                         01230000
              C                                                                         01240000
              C               L O A D   D A T A                                         01250000
              C                                                                         01260000
              C                                                                         01270000
ISN 0007            DATA DELTAT/0.02  /,DPG/0.0/,                                       01280052
                   *DPG1 /2.8    /,                                                     01290089
                   *LV/1.50 /,                                                          01300089
                   *PBV/14.7 /,                                                         01310000
                   *PP/14.70/,                                                          01320000
                   *RGP/3.00/,                                                          01340089
                   *RV/1.00 /,                                                          01341089
                   *RHO/152.0  /,                                                       01350089
                   *TMAX/35200.0/,                                                      01360069
                   *VISC/12.15 /,                                                       01370089
                   *ZMS/0.00/,ZMS1/0.0/,                                                01380000
                   *G0/32.2 /,                                                          01390000
                   *G/32.2 /,                                                           01400000
                   *ZBGP/2.8    /,                                                      01410089
                   *TIME1/0.00/,                                                        01420000
                   *VLCTY1/0.00/,                                                       01430000
                   *START/2/,C1PAST/0.0/,C2PAST/0.0/,M1PAST/0.0/,M2PAST/0.0/,           01431059
                   *STP/35200.0/,                                                       01432069
                   *NTIME/0.0  /,                                                       01433000
                   *TIME/0.0/,J/0/,K/0/                                                 01433104
              C                                                                         01433600
              C                                                                         01450000
              C            INITIALIZE ALL NECESSARY VARIABLES                           01460000
              C                                                                         01470000
ISN 0008            RV = (RV/12.0)                                                      01480000
ISN 0009            IFIN =(TMAX/DELTAT)                                                 01490000
ISN 0010            KICK = DINT(10.0/DELTAT)                                            01491089
              C                                                                         01510000
ISN 0011            P1 = PP + RHO*G*DPG1/(144.0*G0)                                     01520018
ISN 0012            P21 = P1                                                            01530000
              C                                                                         01540000
              C PRINT HEADINGS AND INPUT VARIABLES                                      01541000
              C                                                                         01542000
ISN 0013            WRITE (6,400) DELTAT,DPG1,LV,PBV,PP,RGP,RV,ZMS1,                    01543000
                   *TMAX,VISC,RHO                                                       01544000
              C                                                                         01545000
              C                                                                         01545164
ISN 0014                    ALPHA1= RHO*(ZBGP-ZMS) - (3.0*RHO*VLCTY*                    01545264
                   *DELTAT*((RV/RGP)**2))  + (2.0*RHO*VLCTY*DELTAT)                     01545366
                   * + RHO*LV                                                           01545482
              C                                                                         01545564
ISN 0015                    ALPHA2 = 8.0*VISC*LV/(RV**2)                                01545689
              C                                                                         01545764
ISN 0016                    ALPHA3 = RHO*G*((RV/RGP)**2)                                01545864
              C                                                                         01545964
ISN 0017                    ALPHA4 = RHO*(VLCTY**2)*(((RV/RGP)**2) -                    01546064
```

```
                *1.0) + RHO*G*(ZBGP-ZMS1 +LV)                                   01546182
          C                                                                      01546264
ISN 0018                TEST1 = (ALPHA2**2)-4.0*ALPHA1*ALPHA3                    01546364
ISN 0019                IF(TEST1.LT.0.0) GO TO  40                               01546464
          C                                                                      01546564
          C                                                                      01546664
          C               D E T E R M I N E   C O N S T A N T S                  01546764
          C                                                                      01546864
ISN 0021                M1 = ((-ALPHA2) + (TEST1**0.5))/(2.0*ALPHA1)             01546964
          C                                                                      01547064
ISN 0022                M2 = ((-ALPHA2) - (TEST1**0.5))/(2.0*ALPHA1)             01547164
          C                                                                      01547264
          C                                                                      01547364
ISN 0023                C3 =((PP-PBV)*144.0*G0 +ALPHA4)/ALPHA2                   01547464
          C                                                                      01547564
ISN 0024                C1 = (1.0/(M1-M2))*(144.0*G0*(P21-PBV)/(RHO*LV) +        01547664
                *G +(C3*M2))                                                     01547764
          C                                                                      01547864
ISN 0025                C2 = VLCTY1 -C1 -C3                                      01547964
ISN 0026         M1PAST = M1                                                     01548064
ISN 0027         M2PAST = M2                                                     01548164
ISN 0028         C1PAST = C1                                                     01548264
ISN 0029         C2PAST = C2                                                     01548364
          C                                                                      01548400
ISN 0030         WRITE (6,500)                                                   01549000
          C          S T A R T   M O D E L   C A L C U L A T I O N S             01550000
          C                                                                      01560000
ISN 0031         DO 1000 I = START,IFIN                                          01570000
          C                 COMPUTATION OF ALPHA VALUES                          01590000
          C                                                                      01600000
ISN 0032                TIME = TIME + DELTAT                                     01610000
ISN 0033                ANTIME = TIME - NTIME                                    01611000
          C                                                                      01620000
ISN 0034                ALPHA1= RHO*(ZBGP-ZMS) - (3.0*RHO*VLCTY*                 01630018
                *DELTAT*((RV/RGP)**2))  + (2.0*RHO*VLCTY*DELTAT)                 01640066
                * + RHO*LV                                                       01641082
          C                                                                      01650000
ISN 0035                ALPHA2 = 8.0*VISC*LV/(RV**2)                             01660089
          C                                                                      01670000
ISN 0036                ALPHA3 = RHO*G*((RV/RGP)**2)                             01680000
          C                                                                      01690000
ISN 0037                ALPHA4 = RHO*(VLCTY**2)*(((RV/RGP)**2) -                 01700000
                *1.0) + RHO*G*(ZBGP-ZMS + LV)                                    01710082
          C                                                                      01750000
ISN 0038                TEST1 = (ALPHA2**2)-4.0*ALPHA1*ALPHA3                    01760000
ISN 0039                IF(TEST1.LT.0.0) GO TO  40                               01780045
          C                                                                      01790000
          C                                                                      01800000
          C               D E T E R M I N E   C O N S T A N T S                  01810000
          C                                                                      01820000
ISN 0041                M1 = ((-ALPHA2) + (TEST1**0.5))/(2.0*ALPHA1)             01830000
          C                                                                      01840000
ISN 0042                M2 = ((-ALPHA2) - (TEST1**0.5))/(2.0*ALPHA1)             01850000
          C                                                                      01860000
          C                                                                      01970000
ISN 0043                C3 =((PP-PBV)*144.0*G0 +ALPHA4)/ALPHA2                   01980000
          C                                                                      01990000
```

```
ISN 0044           C1 = (1.0/(M1-M2))*(144.0*G0*(P21-PBV)/(RHO*LV) +          02000000
               *G +(C3*M2))                                                   02010000
            C                                                                 02020000
ISN 0045           C2 = VLCTY1 -C1 -C3                                        02030000
            C                                                                 02040000
            C                                                                 02050000
            C                                                                 02130000
            C                                                                 02140000
            C            D E T E R M I N E   V E L O C I T Y                  02150000
            C                                                                 02151000
            C                                                                 02152000
ISN 0046          SM1 = M1PAST * ANTIME                                       02153058
ISN 0047          SM2 = M2PAST * ANTIME                                       02154058
            C                                                                 02171000
ISN 0048          IF (SM1.LT.-75) SM1=-75                                     02171131
ISN 0050          IF (SM2.LT.-75) SM2=-75                                     02171231
            C                                                                 02172000
ISN 0052          VLCTY = C1PAST * (DEXP(SM1)) + C2PAST * DEXP(SM2)           02180075
                *+ C3                                                         02190000
            C                                                                 02200000
ISN 0053          Q = VLCTY * 3.1416 * (RV**2) * RHO * 3600.0                 02201083
            C                                                                 02202083
            C          D E T E R M I N E   M E L T   P O O L   D E P T H      02210000
            C                                                                 02220000
ISN 0054          DPG =ZBGP-ZMS1-((RV/RGP)**2)*(C1PAST/M1PAST*(DEXP(SM1)-1.0) 02230075
                *+C2PAST/M2PAST*(DEXP(SM2)-1.0)+C3*ANTIME)                    02240075
            C                                                                 02250000
ISN 0055          P1 = RHO*G*DPG/(144.0*G0) + PP                              02261003
            C                                                                 02270000
ISN 0056          P2 = P1                                                     02280058
            C                                                                 02310000
ISN 0057          M1PAST = M1                                                 02311058
ISN 0058          M2PAST = M2                                                 02312058
ISN 0059          C1PAST = C1                                                 02313058
ISN 0060          C2PAST = C2                                                 02314058
            C                                                                 02320000
ISN 0061      998 ZMS = ZBGP -DPG                                             02330045
            C                                                                 02340000
            C           STOP COMPUTATION IF MELT CHAMBER IS EMPTY             02350000
            C                                                                 02350100
ISN 0062          IF (DPG.LT.0.0) GO TO 35                                    02350200
ISN 0064          IF (VLCTY.LE.0.0) GO TO 35                                  02350339
            C                                                                 02350400
            C           CHECK FOR INPUT PRESSURIZATION                        02350500
            C                                                                 02350600
ISN 0066          IF(TIME.NE.STP) GO TO 999                                   02351004
            C                                                                 02352000
            C                                                                 02360000
            C                                                                 02370000
            C                      STEP INPUT BOUNDARY CONDITIONS             02371000
ISN 0068          VLCTY1 = VLCTY                                              02372000
ISN 0069          PBV = 54.7                                                  02373040
ISN 0070          PP = 14.7                                                   02374000
            C                                                                 02380000
ISN 0071          DPG1 = DPG                                                  02381000
ISN 0072          P21 = P2                                                    02383000
ISN 0073          NTIME = TIME                                                02384000
```

```
                 C                                                                            02385000
                 C PRINT RESULTS                                                              02386000
                 C                                                                            02387000
 ISN 0074          999 K = K + 1                                                              02387104
 ISN 0075              IF (K.NE.KICK) GO TO 1000                                              02387204
 ISN 0077               K = 0                                                                 02387307
 ISN 0078               APG = DPG * 12.0                                                      02387479
 ISN 0079              WRITE (6,600) TIME,VLCTY,APG,Q                                         02388083
                 C                                                                            02389400
                 C                                                                            02391000
 ISN 0080         1000 CONTINUE                                                               02411700
 ISN 0081           35 IFIN = I                                                               02412000
                 C                                                                            02420000
 ISN 0082           40 VLCTY = ALPHA4/ALPHA2                                                  02430045
 ISN 0083              Q = VLCTY * 3.1416 * (RV**2) * RHO * 3600.0                            02431083
 ISN 0084              DPG = ZBGP - ZMS1 - (VLCTY*DELTAT*((RV/RGP)**2))                       02440045
 ISN 0085              P1 = RHO * G* DPG/(144.0*GO)                                           02450045
 ISN 0086              P2 = P1                                                                02460045
 ISN 0087              GO TO 998                                                              02931290
                 C                                                                            02931300
 ISN 0088         4000 CONTINUE                                                               02932000
                 C                                                                            02940000
                 C                                                                            02950000
                 C                    F O R M A T   S T A T E M E N T S                       02960000
                 C                                                                            02970000
                 C                                                                            02980000
 ISN 0089          300 FORMAT('1',6X,'I N P U T   V A R I A B L E S',/,/,/)                   02990000
                 C                                                                            03000000
                 C                                                                            03010000
 ISN 0090          400 FORMAT (' ',4X,'DELTAT =',1PE10.3,3X,'SECONDS',/,/,                    03020000
                      *5X,'INITIAL DEPTH OF MELT POOL =',1PE10.3,3X,'FEET',/,/,               03030000
                      *5X,'VALVE LENGTH =',1PE10.3,3X,'FEET',/,/,                             03040000
                      *5X,'PRESSURE AT BOTTOM OF FREEZE VALVE =',1PE10.3,3X,'PSIA',/,/,       03050000
                      *5X,'ABSOLUTE PLENUM PRESSURE =',1PE10.3,3X,'PSIA',/,/,                 03060000
                      *5X,'RADIUS OF GLASS POOL =',1PE10.3,3X,'FEET',/,/,                     03070000
                      *5X,'RADIUS OF FREEZE VALVE INNER PIPE =',1PE10.3,3X,'FEET',/,/,        03080000
                      *5X,'REFERENCE DISTANCE TO MELT SURFACE =',1PE10.3,3X,'FEET',/,/,       03090000
                      *5X,'DEFAULT MAXIMUM EXECUTION TIME =',1PE10.3,3X,'SECONDS',/,/,        03100000
                      *5X,'GLASS VISCOSITY =',1PE10.3,3X,'LBM/FT-SEC',/,/,                    03110000
                      *5X,'GLASS DENSITY =',1PE10.3,3X,'LBM/CU.FT.',/,/)                      03120000
                 C                                                                            03130000
                 C                                                                            03140000
 ISN 0091          500 FORMAT ('1',5X,'P-R-I-M-A-R-Y  R-E-S-P-O-N-S-E  V-A-R-I-A-B-L-E-S'03150000
                      *,/,/,8X,'TIME',9X,'VLCTY',8X,'DPG',9X,'Q')                             03160083
                 C                                                                            03190000
                 C                                                                            03200000
 ISN 0092          600 FORMAT (3X,4(2X,1PE10.3))                                              03210083
 ISN 0093          601 FORMAT (3X,4(2X,I5))                                                   03220000
                 C                                                                            03230000
                 C                                                                            03340000
                 C                                                                            03360000
 ISN 0094          910 FORMAT(1X,3(1PE10.3,',',1PE10.3,1X))                                   03370012
                 C                                                                            03380000
                 C                                                                            03390000
 ISN 0095          950 FORMAT (' ','PROGRAM TERMINATED BECAUSE OF TEST1 FAILURE.              03400000
                      *  CHECK THE INPUT DATA',/,'FAILURE OCCURED AT  ',I5,'TH ITERATION 03410000
                      * AT TIME =  ',E10.4,3X,'SECONDS')                                      03420000
```

```
                  C                                                                                         03430000
                  C                                                                                         03440000
                  C                                                                                         03460000
                  C                                                                                         03470000
 ISN 0096                  STOP                                                                             03480000
                  C                                                                                         03490000
 ISN 0097                  END                                                                              03500000

                                                        /     MAIN /     SIZE OF PROGRAM 000C24 HEXADECIMAL BYTES

     NAME     TAG   TYPE  ADD.        NAME     TAG   TYPE  ADD.        NAME     TAG   TYPE  ADD.        NAME     TAG   TYPE  ADD.
        G  F        R*8   0004C8         I SF        I*4   0004A0         J           I*4    NR            K SF        I*4   0004A4
        Q SF        R*8   0004D0        CI SF        R*8   0004D8        C2 SF        R*8   0004E0        C3 SF        R*8   0004E8
       GO  F        R*4   0004A8        G0  F        R*8   0004F0        LV  F        R*8   0004F8        M1 SF        R*8   000500
       M2 SF        R*8   000508        PP SF        R*8   000510        PV           R*8    NR           P1 SF        R*8   000518
       P2 SF        R*8   000520        RV SF        R*4   0004AC       APG SF        R*8   000528       DPG SF        R*8   000530
      PBV SF        R*4   0004B0       PRV           R*8    NR          P21 SF        R*8   000538       RGP  F        R*8   000540
      RHO  F        R*8   000548       SM1 SFA       R*8   000550       SM2 SFA       R*8   000558       SP2           R*8    NR
      STP           R*8   000560       ZMS SF        R*8   000568      DEXP  F  XF    R*8   000000      DPG1 SF        R*8   000570
     IFIN SF        I*4   0004B4      KICK S         I*4   0004B8      SDPG           R*8    NR         TIME SF        R*8   000578
     TMAX  F        R*8   000580      VISC  F        R*8   000588      ZBGP  F        R*8   000590      ZMS1  F        R*8   000598
    NTIME SF        R*8   0005A0     START  F        I*4   0004BC     STIME           R*8    NR        TEST1 SF        R*4   0004C0
    TIME1           R*8    NR        VLCTY SF        R*8   0005A8    FRXPR#     XF    R*4   000000    ALPHA1 SF        R*8   0005B0
   ALPHA2 SF        R*8   0005B8    ALPHA3 SF        R*8   0005C0    ALPHA4 SF        R*8   0005C8    ANTIME SF        R*8   0005D0
   C1PAST SF        R*8   0005D8    C2PAST SF        R*8   0005E0    DELTAT  FA       R*8   0005E8    IBCOM#  F  XF    R*4   000000
   M1PAST SF        R*8   0005F0    M2PAST SF        R*8   0005F8    SVLCTY           R*8    NR       VLCTY1 SF        R*8   000600

SOURCE STATEMENT LABELS
  LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR
    998    61   000AFA              999    74   000B4E             1000    80   000B9C               35    81   000BA6
     40    82   000BA8             4000    88   000BF8 NR
COMPILER GENERATED LABELS
  LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR
 100000     1   0006A0           100001    21   00084A           100002    32   0008FC           100003    41   000982
 100004    49   000A28           100005    50   000A30           100006    51   000A3C           100007    52   000A44
 100008    64   000B10           100009    66   000B1A           100010    68   000B26           100011    77   000B58
FORMAT STATEMENT LABELS
  LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR              LABEL   ISN   ADDR
    300    89   000028 NR           400    90   000050              500    91   000245              600    92   00029E
    601    93   0002AC NR           910    94   0002B7 NR           950    95   0002CD NR

MBER    LEVEL                     FORTRAN H EXTENDED ERROR MESSAGES

E307I    4(W)      NAME      J      THE DATA STATEMENT CONTAINS A VARIABLE THAT IS NOT REFERENCED.
E307I    4(W)      NAME  TIME1      THE DATA STATEMENT CONTAINS A VARIABLE THAT IS NOT REFERENCED.
E610I    4(W)      LABEL  4000      THE STATEMENT NUMBER OR GENERATED LABEL IS UNREACHABLE.
PTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(58) SIZE(MAX) AUTODBL(NONE)
PTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT NOGOSTMT NOXREF NOALC NOANSF NOTERM IBM FLAG(I) XL
TATISTICS*      SOURCE STATEMENTS =        96, PROGRAM SIZE =       3108, SUBPROGRAM NAME =  MAIN
TATISTICS*    3 DIAGNOSTICS GENERATED, HIGHEST SEVERITY CODE IS  4

**** END OF COMPILATION ******                                    672K BYTES OF CORE NOT USED
```

```
DELTAT = 2.000D-02   SECONDS
INITIAL DEPTH OF MELT POOL = 2.800D+00   FEET
VALVE LENGTH = 1.500D+00   FEET
PRESSURE AT BOTTOM OF FREEZE VALVE = 1.470E+01   PSIA
ABSOLUTE PLENUM PRESSURE = 1.470D+01   PSIA
RADIUS OF GLASS POOL = 3.000D+00   FEET
RADIUS OF FREEZE VALVE INNER PIPE = 8.333E-02   FEET
REFERENCE DISTANCE TO MELT SURFACE = 0.0         FEET
DEFAULT MAXIMUM EXECUTION TIME = 3.520D+04   SECONDS
GLASS VISCOSITY = 1.215D+01   LBM/FT-SEC
GLASS DENSITY = 1.520D+02   LBM/CU.FT.
```

P-R-I-M-A-R-Y R-E-S-P-O-N-S-E V-A-R-I-A-B-L-E-S

TIME	VLCTY	DPG	Q
1.000D+01	2.932D+00	3.333D+01	3.500D+04
2.000D+01	2.912D+00	3.306D+01	3.476D+04
3.000D+01	2.891D+00	3.280D+01	3.452D+04
4.000D+01	2.871D+00	3.253D+01	3.428D+04
5.000D+01	2.852D+00	3.228D+01	3.404D+04
6.000D+01	2.832D+00	3.202D+01	3.381D+04
7.000D+01	2.813D+00	3.177D+01	3.358D+04
8.000D+01	2.793D+00	3.152D+01	3.335D+04
9.000D+01	2.774D+00	3.127D+01	3.312D+04
1.000D+02	2.755D+00	3.103D+01	3.289D+04
1.100D+02	2.737D+00	3.079D+01	3.267D+04
1.200D+02	2.718D+00	3.055D+01	3.245D+04
1.300D+02	2.700D+00	3.031D+01	3.223D+04
1.400D+02	2.682D+00	3.008D+01	3.202D+04
1.500D+02	2.664D+00	2.985D+01	3.180D+04
1.600D+02	2.646D+00	2.962D+01	3.159D+04
1.700D+02	2.628D+00	2.940D+01	3.138D+04
1.800D+02	2.611D+00	2.918D+01	3.117D+04
1.900D+02	2.594D+00	2.896D+01	3.096D+04
2.000D+02	2.576D+00	2.874D+01	3.076D+04
2.100D+02	2.559D+00	2.853D+01	3.055D+04
2.200D+02	2.543D+00	2.832D+01	3.035D+04
2.300D+02	2.526D+00	2.811D+01	3.015D+04
2.400D+02	2.509D+00	2.790D+01	2.996D+04
2.500D+02	2.493D+00	2.769D+01	2.976D+04
2.600D+02	2.477D+00	2.749D+01	2.957D+04
2.700D+02	2.461D+00	2.729D+01	2.938D+04
2.800D+02	2.445D+00	2.709D+01	2.919D+04
2.900D+02	2.429D+00	2.690D+01	2.900D+04
3.000D+02	2.413D+00	2.670D+01	2.881D+04
3.100D+02	2.398D+00	2.651D+01	2.863D+04
3.200D+02	2.382D+00	2.632D+01	2.844D+04
3.300D+02	2.367D+00	2.614D+01	2.826D+04
3.400D+02	2.352D+00	2.595D+01	2.808D+04
3.500D+02	2.337D+00	2.577D+01	2.790D+04
3.600D+02	2.322D+00	2.559D+01	2.772D+04
3.700D+02	2.308D+00	2.541D+01	2.755D+04
3.800D+02	2.293D+00	2.523D+01	2.737D+04
3.900D+02	2.279D+00	2.505D+01	2.720D+04
4.000D+02	2.264D+00	2.488D+01	2.703D+04
4.100D+02	2.250D+00	2.471D+01	2.686D+04
4.200D+02	2.236D+00	2.454D+01	2.669D+04
4.300D+02	2.222D+00	2.437D+01	2.653D+04
4.400D+02	2.208D+00	2.420D+01	2.636D+04
4.500D+02	2.195D+00	2.404D+01	2.620D+04
4.600D+02	2.181D+00	2.388D+01	2.604D+04
4.700D+02	2.167D+00	2.371D+01	2.588D+04
4.800D+02	2.154D+00	2.355D+01	2.572D+04
4.900D+02	2.141D+00	2.340D+01	2.556D+04
5.000D+02	2.128D+00	2.324D+01	2.540D+04
5.100D+02	2.115D+00	2.309D+01	2.525D+04
5.200D+02	2.102D+00	2.293D+01	2.509D+04
5.300D+02	2.089D+00	2.278D+01	2.494D+04
5.400D+02	2.076D+00	2.263D+01	2.479D+04
5.500D+02	2.064D+00	2.248D+01	2.464D+04
5.600D+02	2.051D+00	2.234D+01	2.449D+04
5.700D+02	2.145D+00	2.193D+01	2.560D+04

5.800D+02	2.134D+00	2.178D+01	2.547D+04
5.900D+02	2.123D+00	2.163D+01	2.534D+04
6.000D+02	2.112D+00	2.148D+01	2.521D+04
6.100D+02	2.101D+00	2.133D+01	2.508D+04
6.200D+02	2.091D+00	2.118D+01	2.496D+04
6.300D+02	2.080D+00	2.104D+01	2.483D+04
6.400D+02	2.070D+00	2.089D+01	2.471D+04
6.500D+02	2.059D+00	2.075D+01	2.458D+04
6.600D+02	2.049D+00	2.061D+01	2.446D+04
6.700D+02	2.039D+00	2.047D+01	2.434D+04
6.800D+02	2.028D+00	2.033D+01	2.422D+04
6.900D+02	2.018D+00	2.020D+01	2.409D+04
7.000D+02	2.008D+00	2.006D+01	2.398D+04
7.100D+02	1.998D+00	1.993D+01	2.386D+04
7.200D+02	1.989D+00	1.979D+01	2.374D+04
7.300D+02	1.979D+00	1.966D+01	2.362D+04
7.400D+02	1.969D+00	1.953D+01	2.351D+04
7.500D+02	1.959D+00	1.940D+01	2.339D+04
7.600D+02	1.950D+00	1.927D+01	2.328D+04
7.700D+02	1.940D+00	1.914D+01	2.316D+04
7.800D+02	1.931D+00	1.901D+01	2.305D+04
7.900D+02	1.922D+00	1.889D+01	2.294D+04
8.000D+02	1.912D+00	1.876D+01	2.283D+04
8.100D+02	1.903D+00	1.864D+01	2.272D+04
8.200D+02	1.894D+00	1.852D+01	2.261D+04
8.300D+02	1.885D+00	1.839D+01	2.250D+04
8.400D+02	1.876D+00	1.827D+01	2.239D+04
8.500D+02	1.867D+00	1.815D+01	2.229D+04
8.600D+02	1.858D+00	1.804D+01	2.218D+04
8.700D+02	1.849D+00	1.792D+01	2.207D+04
8.800D+02	1.840D+00	1.780D+01	2.197D+04
8.900D+02	1.832D+00	1.769D+01	2.186D+04
9.000D+02	1.823D+00	1.757D+01	2.176D+04
9.100D+02	1.814D+00	1.746D+01	2.166D+04
9.200D+02	1.806D+00	1.735D+01	2.156D+04
9.300D+02	1.797D+00	1.723D+01	2.146D+04
9.400D+02	1.789D+00	1.712D+01	2.136D+04
9.500D+02	1.780D+00	1.701D+01	2.126D+04
9.600D+02	1.772D+00	1.690D+01	2.116D+04
9.700D+02	1.764D+00	1.680D+01	2.106D+04
9.800D+02	1.756D+00	1.669D+01	2.096D+04
9.900D+02	1.748D+00	1.658D+01	2.086D+04
1.000D+03	1.740D+00	1.648D+01	2.077D+04
1.010D+03	1.732D+00	1.637D+01	2.067D+04
1.020D+03	1.724D+00	1.627D+01	2.058D+04
1.030D+03	1.716D+00	1.616D+01	2.048D+04
1.040D+03	1.708D+00	1.606D+01	2.039D+04
1.050D+03	1.700D+00	1.596D+01	2.030D+04
1.060D+03	1.692D+00	1.586D+01	2.020D+04
1.070D+03	1.685D+00	1.576D+01	2.011D+04
1.080D+03	1.677D+00	1.566D+01	2.002D+04
1.090D+03	1.669D+00	1.556D+01	1.993D+04
1.100D+03	1.662D+00	1.547D+01	1.984D+04
1.110D+03	1.654D+00	1.537D+01	1.975D+04
1.120D+03	1.647D+00	1.527D+01	1.966D+04
1.130D+03	1.640D+00	1.518D+01	1.957D+04
1.140D+03	1.632D+00	1.508D+01	1.948D+04
1.150D+03	1.625D+00	1.499D+01	1.940D+04
1.160D+03	1.618D+00	1.490D+01	1.931D+04
1.170D+03	1.610D+00	1.480D+01	1.923D+04

Appendix II

Information about Silicone Fluids

STEVE R. ROLKA
1-800-248-2345

DESCRIPTION

Dow Corning 200 fluid is a water-clear silicone fluid available in viscosities ranging from 0.65 centistokes to 100,000 centistokes. Important features of this fluid include:

- Little change in physical properties over a wide temperature span — a relatively flat viscosity-temperature slope, and serviceability from −40 to over 400 F (−40 to 204 C)
- Excellent water repellency
- Good dielectric properties over a wide range of temperatures and frequencies
- Low surface tension — readily wets clean surfaces to impart water repellency and release characteristics
- Low-toxicity — tests have established that Dow Corning 200 fluid is essentially non-toxic and non-irritating (although temporary discomfort may result if rubbed into the eye)

Dow Corning 200 fluid also exhibits heat stability, oxidation resistance, very low vapor pressures, and high flash points. It is insoluble in organic liquids other than active solvents, and is nongreasy, nonrancidifying, and virtually odorless.

DOW CORNING® 200 FLUID

(Approved for Federal Specification VV-D-1078A)

Type	Dimethyl siloxane polymer
Physical Form	Fluids with viscosities ranging from 0.65 to 100,000 centistokes
Special Properties	Thermal stability; water repellency; high dielectric strength; low surface tension; essentially nontoxic
Primary Uses	As a mechanical or electrical fluid, lubricant, antifoam, surfactant, chemical specialty additive

USES

Its unique combination of outstanding properties suit Dow Corning 200 fluid for a variety of application functions, as well as for a wide range of products and processes.

As a Release Material

Used along or as part of a compounded formula, Dow Corning 200 fluid provides an odorless, nontoxic, non-carbonizing mold release for rubber, plastics, and metal die castings.

As a Foam Preventive

Extremely small amounts of the fluid effectively control foam in many processing operations, especially in nonaqueous systems.

As a Mechanical Fluid

Excellent viscosity-temperature characteristics, thermal and chemical stability, shear-breakdown resistance, compressibility, and rubber compatibility make Dow Corning 200 fluid outstanding for mechanical/hydraulic uses. Typical uses include hydraulic stabilizers, damping mediums.

As a Surface-Active Material

Added to vinyl plastisols and liquid springs, Dow Corning 200 fluid improves the flow characteristics, de-aerates and lubricates the surface of the completed part.

As a Lubricant

The fluid provides excellent lubrication for plastic and elastomeric surfaces.

In Cosmetics and Skin Preparations

Dow Corning 200 fluid is an important ingredient in hand creams, skin protectants, suntan lotions, and hair grooming aids because it forms a non-greasy, protective film which resists water and waterborne irritants, yet allows the skin to breathe. Literature is available that details the use of the fluid in cosmetics.

In Polishes and Chemical Specialities

Dow Corning 200 fluid is used in most automobile and furniture polishes for its ease of application, high gloss with minimum rubbing, and a durable water-repellent film. It is also used in many other speciality formulations, including aerosol starches and fabric conditioners. Additional literature is available.

In Electrical/Electronic Equipment

With excellent dielectric properties, Dow Corning 200 fluid is widely used for both insulating and damping applications. Refer to specific literature on Dow Corning 200 fluid, electrical-grade and electronic-grade.

In Food Processing

Noncontaminating and nonadulterating, Dow Corning 200 fluid is suited to many food-processing applications. When considering the fluid for uses involving FDA regulations, refer to literature on Food-Grade Dow Corning 200 fluid.

SOLUBILITY

The solubility of Dow Corning 200 fluid varies somewhat according to the viscosity chosen. The low viscosity grades are more completely soluble in a given solvent than are the higher viscosity grades. Since solubility varies, testing is recommended before attempting volume operations. Solubility of the silicone fluid in a number of commonly-used solvents is indicated below. Flammability and toxicity should also be improtant considerations in the choice of a solvent.

Solvents

- Amyl acetate
- Benzene
- Carbon tetrachloride
- Chlorothene NU*
- Cyclohexane
- Diesel fuel
- Ethylene dichloride
- Ethyl ether
- 2-Ethyl hexanol
- Gasoline
- Hexyl ether
- Iso-octane
- JP-4 jet fuel
- Kerosene
- Methyl ethyl ketone
- Methylene chloride
- Methyl ether
- Mineral seal oil
- Naphtha VM&P
- Perchloroethylene
- Stoddard solvent
- Toluene
- Trichloroethylene
- Turpentine
- Xylene

Partial Solvents†

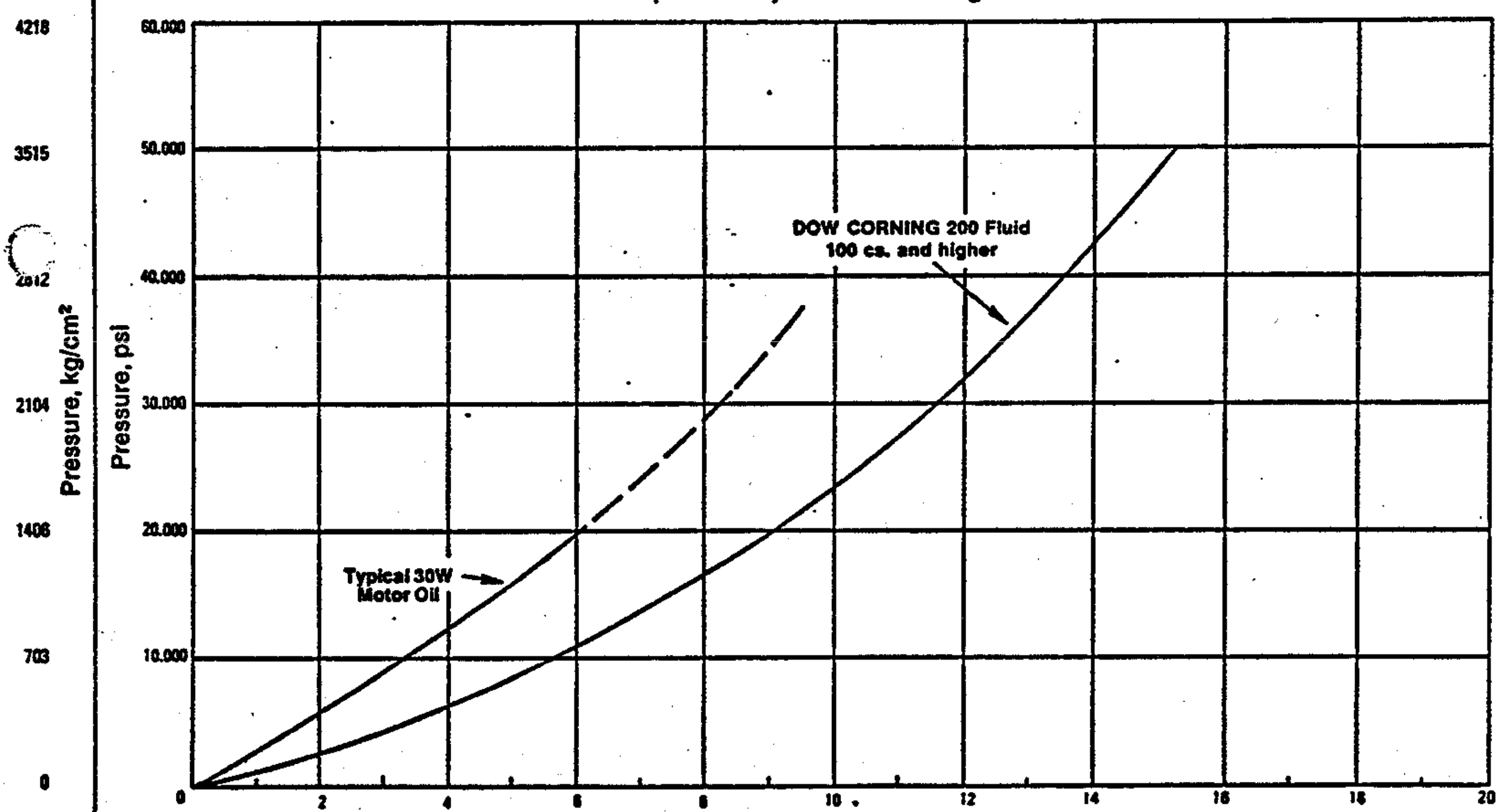
- Acetone
- Butanol
- Dioxane
- Ethanol
- Heptadecanol
- Isopropanol

Nonsolvents

- Cyclohexanol
- Dimethylphthalate
- Dodecanol
- Dowanol* DE
- Dowanol* EE
- Ethylene glycol
- Methanol
- Paraffin oil
- Propylene glycol
- Water

* The Dow Chemical Company
† Partial Solvents—for lower viscosity grades

Compressibility* of Dow Corning 200 Fluid



* Corporate test method CTM 0490.

TYPICAL PROPERTIES OF STANDARD VISCOSITY GRADES[1]

These values are not intended for use in preparing specifications.

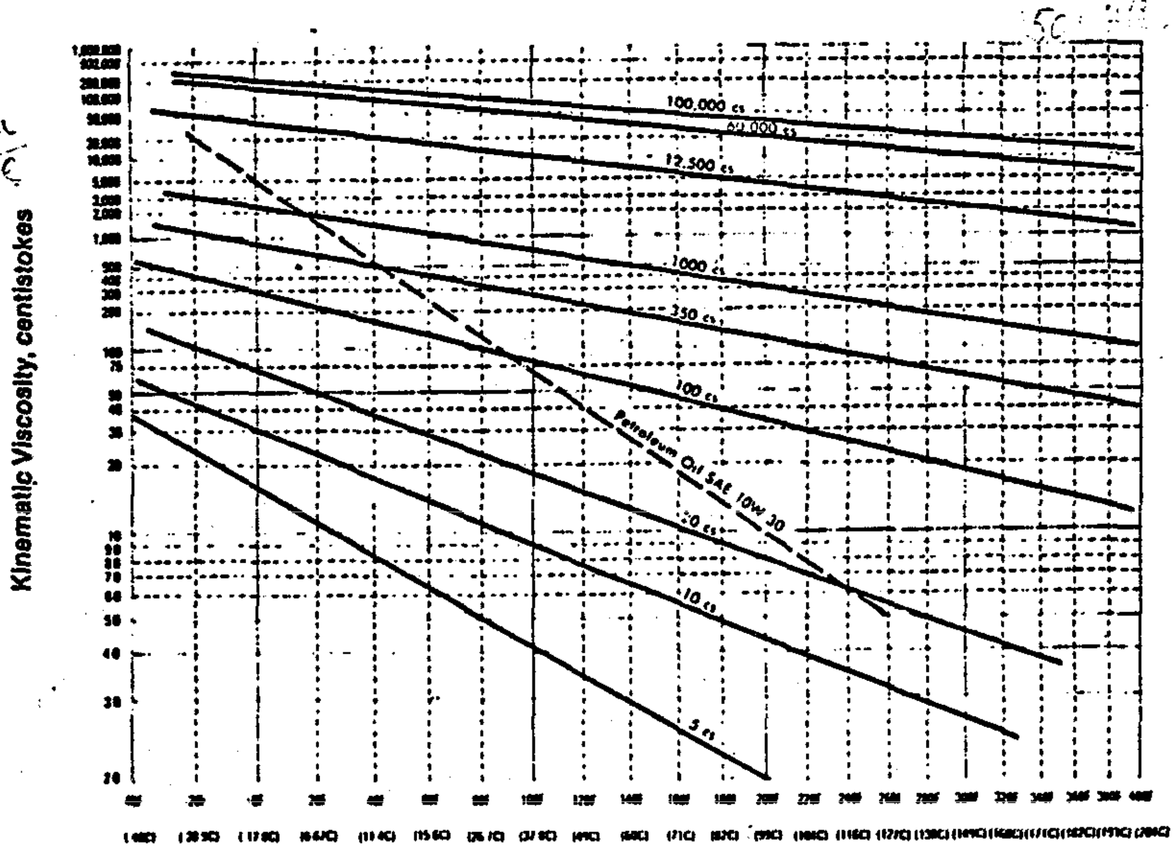
Viscosity[2] at 77 F (25 C), centistokes	Flash Point, closed cup[3]	Pour Point[5]	Specific Gravity[6] at 77 F (25 C), spindle reading	Viscosity Temperature Coefficient[7]	Coefficient of Expansion,[8] cc/cc/C	Refractiv Index[9] a 77 F (25
0.65	0 F (−18 C)	− 90 F (−68 C)	0.761	0.31	0.00134	1.375
1.0	92 F (33 C)	−148 F (−100 C)	0.818	0.41	0.00134	1.382
1.5	130 F (55 C)	−148 F (−100 C)	0.853	0.46	0.00134	1.388
2.0	189 F (87 C)	−148 F (−100 C)	0.873	0.48	0.00117	1.390
	open cup[4]					
5.0	275 F (135 C)	−148 F (−100 C)	0.920	0.55	0.00105	1.397
10	325 F (163 C)	−148 F (−100 C)	0.934	0.56	0.00108	1.399
20	450 F (232 C)	−121 F (−84 C)	0.949	0.59	0.00107	1.400
50	545 F (285 C)	−94 F (−70 C)	0.960	0.59	0.00104	1.401
100	600 F (315 C)	−85 F (−65 C)	0.960	0.60	0.00096	1.402
200	600 F (315 C)	−85 F (−65 C)	0.970	0.60	0.00096	1.403
350	600 F (315 C)	−85 F (−65 C)	0.970	0.60	0.00096	1.403
500	600 F (315 C)	−58 F (−50 C)	0.971	0.60	0.00096	1.403
1000	610 F (321 C)	−58 F (−50 C)	0.971	0.61	0.00096	1.403
12500	610 F (321 C)	−51 F (−46 C)	0.975	0.61	0.00096	1.403
30000	610 F (321 C)	−47 F (−43 C)	0.975	0.61	0.00096	1.403
60000	610 F (321 C)	−42 F (−41 C)	0.976	0.61	0.00096	1.403
100000	610 F (321 C)	−28 F (−33 C)	0.977	0.61	0.00096	1.403

1 Although only standard viscosity grades are listed, other viscosities may be made available on request.
2 CTM 0004
3 CTM 0021
4 CTM 0006
5 CTM 0133. Due to the effects of supercooling, this test method yields pour points lower than the temperatures at which these silicone fluids solidify when held at such temperature for a longer period.
6 CTM 001A

$\rho_w^{77°} = 62.244$ lb/ft³ $= 0.99559$ g/cc

Viscosity Temperature Chart * for Dow Corning 200 Fluid

$\nu = \mu/\rho$



...rface ...si... ...F ...C) ...ne/cm	Thermal Conductivity[11] at 122 F (50 C)	Boiling Point	Specific Heat, cal/gm/C 25 C	100 C	200 C
5.9	0.00024	211 F (100 C) at 760 mm	----	----	----
7.4	----	305 F (152 C) at 760 mm	----	----	----
8.0	----	377 F (192 C) at 760 mm	0.410	0.437	0.474
8.7	0.00026	158-212 F (70-100 C) at 0.5 mm	----	----	----
9.7	----	248-320 F (120-160 C) at 0.5 mm	----	----	----
		VOLATILITY[12] % max weight loss after 24 hrs at 302 F (150 C)			
0.1	0.00032	10	----	----	----
0.6	0.00034	10	----	----	----
0.8	----	2.0	----	----	----
0.9	0.00037	0.5	----	----	----
1.0	----	0.5	----	----	----
1.1	0.0038	0.5	0.379	0.405	0.440
1.1	----	0.5	----	----	----
1.2	0.00038	0.5	----	----	----
1.5	0.00037	2.0	----	----	----
1.5	----	2.0	----	----	----
1.5	----	2.0	----	----	----
		2.0	----	----	----

CTM 0747,1 — $\frac{\text{Viscosity at 210 F (99 C)}}{\text{Viscosity at 100 F (38 C)}}$

CTM 0420

CTM 0002

[illegible] 0461

CTM 0773. O.K. Bates, "Thermal Conductivity of Liquid Silicones", *Industrial and Engineering Chemistry*, Vol. 41, page 1966, September 1949, units are $\frac{\text{gm — cal}}{\text{(cm) (sec) (°C)}}$, multiply by 241.9 to convert to BTU/(hr) (ft) (°F)

12 CTM 208. Determined by heating a 2 gram sample in a 50 milliliter beaker for 24 hours at 302 F (150 C). The heating is carried out in an air-circulating oven.

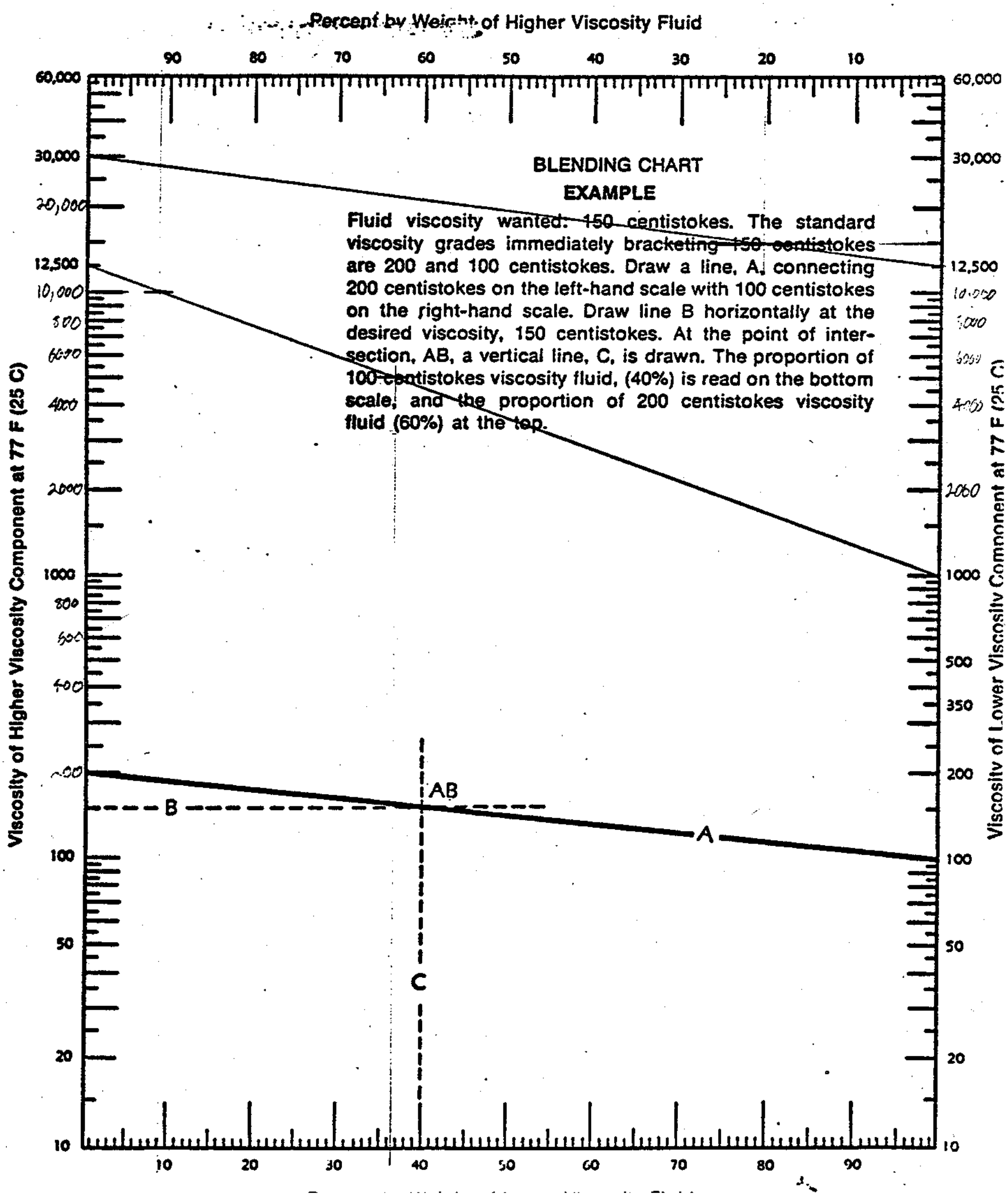
...pecification Writers: Please contact Dow Corning Corporation, Midland, Michigan, ...efore writing specifications on this product.

BLENDING

Blending of different viscosity grades of Dow Corning 200 fluid permits any desired viscosity. Although the fluid is available in a number of standard viscosity grades, occasionally an application will call for a fluid of a viscosity between the standard grades.

To use the blending chart: (1) Draw a line between two points—one on the lefthand scale representing the higher viscosity fluid available; and one on the right, the lower viscosity fluid. (2) Draw another line horizontally across the chart at the desired viscosity rating. (3) Draw a third line, vertically through the intersection of the first two lines. (4) Read off the top and bottom scales the proportions of the available fluids to blend to obtain the desir[ed] viscosity.

Accuracy will be increased by blending the two fluids which immediately bracket the desired viscosity. If a very accurate blend [is] required, it may be necessary to adjust the viscosity of the mixture [by] a second blending.



SHIPPING LIMITATIONS

None for high viscosity grades above 2 cs. DOT Classification: Flammable, for 0.65 and 1 cs. And effective January 1, 1975, 1.5 and 2.0 cs will have DOT classifications of Flammable.

STORAGE AND SHELF LIFE

Dow Corning 200 fluid has an unlimited useful life when stored at 77 F (25 C). Keep 2 cs & below viscosity grades away from heat and open flame.

PACKAGING

Standard viscosities of Dow Corning 200 fluid are supplied in 8-, 40-, and 440-pound containers. All weights, net.

W CORNING CORPORATION
)LAND, MICHIGAN 48640