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PRESSURE LOCKING TEST RESULTS

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, is funding the Idaho National Engineering Laboratory (INEL) in performing research to provide technical input for their use in evaluating responses to Generic Letter 95-07, "Pressure Locking and Thermal Binding of Safety-Related Power-Operated Gate Valves." Pressure locking and thermal binding are phenomena that make a closed gate valve difficult to open. This paper discusses only the pressure locking phenomenon in a flexible-wedge gate valve; we will publish the results of our thermal binding research at a later date. Pressure locking can occur when operating sequences or temperature changes cause the pressure of the fluid in the bonnet (and, in most valves, between the discs) to be higher than the pressure on the upstream and downstream sides of the disc assembly. This high fluid pressure presses the discs against both seats, making the disc assembly harder to unseat than anticipated by the typical design calculations, which generally consider friction at only one of the two disc/seat interfaces. The high pressure of the bonnet fluid also changes the pressure distribution around the disc in a way that can further contribute to the unseating load. If the combined loads associated with pressure locking are very high, the actuator might not have the capacity to open the valve. The results of the NRC/INEL research discussed in this paper show that the relationship between bonnet pressure and pressure locking stem loads appears linear. The results also show that for this valve, seat leakage affects the bonnet pressurization rate when the valve is subjected to thermally induced pressure locking conditions.

INTRODUCTION

Background

When a wedge gate valve opens against an ordinary differential pressure load, the actuator must provide enough force to unwedge the disc from the seats and to overcome the resistance created by friction at the downstream disc/seat interface. (Other loads, such as the packing load, the stem rejection load, and the vertical pressure load on the disc also contribute to the total stem load by either assisting or resisting stem movement.) Under differential pressure conditions, the upstream

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pressure tends to decrease the disc load at the upstream disc/seat interface and increase the load at the downstream disc/seat interface. (This scenario can apply in varying degrees to wedging parallel and split wedge gate valves as well). Typical formulas for estimating valve operating requirements are based on differential pressure times disc area times friction at only one sealing surface.

Pressure locking occurs when the valve bonnet pressure is higher than both the upstream and downstream pressures. In most gate valves (including most flex-wedge gate valves, split wedge gate valves, parallel disc gate valves, and double disc gate valves), the bonnet cavity communicates with the area between the disc faces. The effect is that the pressure of the fluid between the discs presses both the upstream and downstream disc surfaces against the seats, introducing resistance to motion at both disc/seat interfaces rather than just one. As a result, the total force necessary to unwedge/unseat the valve disc can be higher than in the normal differential pressure situation. The various forces involved are indicated in Figure 1. At its worst, pressure locking can cause the valve to be locked in the closed position, such that the actuator is unable to open it.

Pressure locking loads are much more difficult to predict than the design basis differential pressure load described above, especially with flex wedge gate designs. (The flex-wedge design is the most widely used of all gate valve disc designs.) With parallel disc, double disc, and split wedge gate valves, both discs respond equally and independently to the pressure of the fluid between the discs. However, the disc assembly in a flex-wedge valve is made from a single piece of metal, with the upstream and downstream halves of the disc connected in the center by a hub. As with the parallel disc design, the two discs respond to the pressure of the fluid between them, but the area exposed to the pressure is less, because of presence of the hub.

With the flex-wedge design, not all of the disc area exposed to the bonnet pressure will result in additional force at the disc/seat interface. For this reason, we distinguish between the disc area exposed to the bonnet pressure, and the effective disc area responding to the bonnet pressure. When exposed to pressure locking loads, the disc assembly acts as a split load path component, with part of the pressure load deforming the disc and pressing it against the valve body seat, and part of the pressure load being reacted in the hub. The stiffer the disc, the more the pressure load is transferred to the hub. In simple terms, then, for each disc stiffness there is an effective area responding to the pressure load. Within a given pressure class of valve, the more flexible disc design will respond with a higher effective area.

One other feature of the flex-wedge gate design contributes to the effects of pressure locking. The angle of the disc, usually about 5 degrees from vertical in an upright valve, creates an effective area on the disc that is acted on by the bonnet pressure and the downstream pressure, and another acted on by the bonnet pressure and the upstream pressure. These areas are typically modeled as elliptical areas corresponding to the downstream and upstream orifices in the valve when viewed from above. The corresponding forces are indicated as F_{top} and F_{bottom} in Figure 1. In a six-inch valve opening against normal differential pressure (and assuming that the bonnet pressure is equal to the upstream pressure), there is no upstream vertical pressure load, and the downstream vertical pressure load (F_{top} - F_{bottom}), which resists opening, is offset by the stem rejection load ($F_{stem\ rej}$), which assists opening. However, in the pressure locked case, both the upstream and downstream vertical loads act to resist opening, resulting in yet another increase in the opening load, as compared to the normal differential pressure opening situation. The extent of the increase is dependent on the bonnet, upstream, and downstream pressures.

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Taken together, the load increases described in the preceding paragraphs can cause the thrust needed to open a pressure locked valve to be higher than the value typically calculated by industry formulas for the design basis differential pressure conditions. If the higher thrust demands exceed the capability of the actuator, the valve will fail to open.

The bonnet pressure that causes pressure locking can be either hydraulically or thermally induced. Hydraulically induced pressure locking can result from various operational sequences involving low-pressure system interface with high-pressure systems, or from system depressurization during an accident. For example, a valve closed at high pressure might experience pressure locking if an attempt is made to reopen the valve after both the upstream and downstream sides have been depressurized, and with the high pressure remaining in the bonnet. Such a scenario occurred, for example, in 1991 at the Fitzpatrick nuclear power plant. Thermally induced pressure locking can occur by thermal expansion of water trapped in the bonnet. For example, a valve closed under cold conditions might experience pressure locking if the valve were later heated by a slug of hot fluid coming into contact with the closed disc, or by a line break inside the containment.

The instance of pressure locking that occurred at the Fitzpatrick station was hydraulically induced (Information Notice 92-26). The utility hydro-tested the piping between the inboard and outboard low-pressure coolant injection (LPCI) valves. The inboard LPCI valve is a 24-in. flexible wedge motor-operated valve. After the hydro-test, the utility depressurized the piping between the valves and filled and vented the system to return it to service. About 10 hours later the utility commanded the inboard valve to open. The valve actuator was energized for about 30 seconds before the circuit breaker tripped. (The normal stroke time for this valve is 120 seconds.) The valve had failed to open. The root cause of the failure was pressure locking.

The magnitudes of possible loads due to pressure locking are specific to the valve design and to the plant system. The flexibility of the disc assembly is an important factor. Pressure locking can happen to valves that are required to be leak-tight in both directions, valves that have little or no leakage, or valves that have not been modified to prevent pressure locking. Typical modifications to gate valves to prevent pressure locking include venting the bonnet to the high-pressure side by drilling a hole through the disc, or by installing a vent line between the bonnet and the upstream side, with the line equipped with a check valve or a power-operated valve.

Purpose

The purpose of the INEL testing described in this paper is to provide technical information to the NRC in support of their effort to evaluate the pressure locking issue. (Thermal binding is being addressed separately.) The INEL effort consists of laboratory testing of two gate valves--a flex-wedge gate valve and a parallel disc gate valve. This paper describes the testing and results for the flex-wedge valve; results from testing of the parallel disc valve will be reported later, after testing and analysis are complete. The test program is designed to address the following questions:

1. Assuming low or zero pressure on the upstream and downstream sides of the disc, how much additional force is needed to open the valve as the bonnet pressure increases?

2. As the temperature of the fluid in the bonnet increases, how much does the bonnet pressure increase?

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3. How does the presence of air entrapped in the bonnet affect these pressure increases and the resulting thrust requirements? (Does the air bleed off? Does it dissolve in the coolant?)

4. How does valve leakage affect the bonnet pressure?

TEST SETUP

The flexible wedge valve tested in this project is a 6-inch, 600-lb-class Walworth valve. We believe that the more flexible the disc in a flex-wedge gate valve, the greater the response to the pressure locking load. ASME and other valve design codes provide stress rules that establish minimum disc thickness (stiffness) for the various pressure classes. Because the wedge in this particular design is relatively flexible for its pressure class, we assumed that it would respond with a relatively high effective pressure area. This valve had been used in previous testing. Before the pressure locking tests, the valve sealing surfaces were reconditioned, and leakage was well below accepted limits.

To preclude the possibility of stalling the motor, we equipped the valve with an SMB-0 actuator with a 25-ft-lb motor, which is about twice as powerful as would be used in a typical safety-related application for a valve this size in a commercial power plant. Figure 2 shows the test setup and instrumentation for the pressure locking tests.

Tests were conducted at various pressures and temperatures imposed on the upstream side, the bonnet, and the downstream side of the valve. Before any testing, the valve sealing surfaces were preconditioned to provide a reasonable disc friction factor. Preconditioning required more time than expected.

Stem force, stem torque, stem position, motor current and voltage, and other valve and actuator parameters were monitored at a frequency of 600 samples per second during valve operation. Upstream, downstream, and bonnet fluid temperatures and pressures were monitored at a frequency of one sample per second during heatup and pressurization.

The valve was subjected to two sets of tests: cold pressure locking tests, and thermally induced pressure locking tests. The cold pressure locking tests focused on the relationship between bonnet pressure and unwedging load. The hot pressure locking tests were intended to examine the relationship between bonnet temperature and bonnet pressure. The hot testing included tests to study the effects of valve leakage on the thrust requirement, as well as the effects of air entrapped in the bonnet. Cold tests were performed first. After the hot tests, another round of cold tests was conducted. The following discussion describes the tests and the results.

COLD PRESSURE LOCKING TESTS

The cold pressure locking tests were designed as a parametric study to evaluate the relationship between the opening thrust and the fluid pressures occurring at various locations in the valve.

Testing

The test matrix, shown in Table 1, consisted of various upstream, downstream, and bonnet pressures distributed across the full range of possible conditions. In addition to the tests shown in the table, we performed baseline valve strokes periodically throughout the testing; the baseline stokes allowed us to evaluate the wedging versus unwedging relationship, obtain upstream and downstream seat friction values, and determine the load due to packing friction. The baseline strokes included a no-pressure (static) valve closing and opening cycle and two differential pressure opening stokes, one with the downstream side and the bonnet pressurized, and one with the upstream side and the bonnet pressurized.

For the cold pressure locking tests, the valve was filled with deionized water under normal environmental conditions, and any trapped air pockets were eliminated. Each step began with the valve open and pressurized to 1200 psig. The valve was then closed and the pressures in the upstream leg, downstream leg, and bonnet were bled down to the test settings shown in Table 1. The valve was then opened and the stem force required to extract the valve disc was measured. A typical thrust trace from such an opening stroke is shown in Figure 3. As mentioned earlier, the valve did not leak significantly; pressure locking occurred easily.

An additional set of tests was conducted with the valve bonnet pressurized by another method. Instead of pressurizing the entire assembly and then closing the valve, we pressurized the bonnet with the valve already closed. The test parameters with the bonnet pressurized by this method are shown in Table 2.

Results

Figure 4 shows stem force traces for five tests where the bonnet was pressurized at 0, 300, 600, 900, and 1200 psig. The traces have been truncated to focus on the unwedging portion of the opening stroke. The plot shows a linear relationship between the bonnet pressure and the unwedging/unseating load.

THERMALLY INDUCED PRESSURE LOCKING TESTS

Tests similar to those described above were performed on the valve at elevated temperatures. The effort in these tests was to evaluate the impact of temperature changes on the rate of bonnet pressurization and on the associated thrust requirements to unseat the valve during opening. The effects of valve seat leakage on bonnet pressurization were also investigated, as were the effects of air entrapped in the bonnet.

We used two different methods to heat the water in the bonnet. One method was to heat the upstream fluid (by means of a coil installed in the upstream leg of the valve), such that the heat was conducted to the bonnet through the disc and the valve body. The other method was to heat the bonnet from the outside using heat tape wrapped around the valve body. These two heating methods were intended to simulate ways that a valve might be heated in a plant scenario, namely, a slug of hot fluid coming into contact with a cold valve, and a cold valve being heated from the outside during a loss-of-coolant accident. As in the cold pressure locking tests, baseline static strokes and differential

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pressure strokes were performed throughout the test series to determine wedging/unwedging loads, valve seat friction values, and the packing load.

Pressure, Temperature, and Stem Load

For the tests with internal heating of the upstream leg of the valve, the valve was filled with deionized water under normal environmental conditions, and any trapped air pockets were eliminated. The valve was closed and the upstream leg and bonnet were pressurized to 50 psig. The downstream leg was depressurized by opening the downstream high point vent line. The upstream side of the valve was heated at 80°F per hour to an upstream fluid temperature of 290°F while the upstream pressure was bled off to maintain the pressure at 50 psig during heatup. The discharge from the downstream high point vent line was measured as an indication of leakage from the bonnet to the downstream side. The pressures and temperatures were based on an accident scenario that resulted in a containment pressure of 50 psi with the fluid remaining subcooled.

The assumption that the bonnet leaked only to the downstream side was based on the results of earlier check-out tests, during which each chamber (bonnet, upstream side, downstream side) were pressurized. During these check-out tests, the bonnet leaked to the downstream side, but the upstream side maintained its pressure. Therefore the bleed-off to maintain 50 psig in the upstream leg during the heatup tests was due to the expansion of the upstream water only, and the discharge from the downstream side was mainly due to leakage from the bonnet.

The bonnet pressure was also monitored during heatup and compared to the measured leakage to establish the relationship between leakage and thermally induced bonnet pressurization. If and when the bonnet pressure reached 1200 psig, we opened the valve and measured the stem load.

The disc friction factors for both seats tended to be lower in the early tests than in the later tests. The friction factors stabilized during the hot tests and remained at the stable, high value during the subsequent round of cold tests. This is consistent with industry experience for elevated-temperature preconditioning. Because we regularly monitored the disc friction factor by conducting baseline tests, changes in the friction factor did not detract from the usefulness of the stem force measurements taken during the pressure locking tests.

Two of the heatup tests produced bonnet pressures capable of causing pressure locking loads. The results from opening strokes during those two tests showed that the required thrust is linear with pressure. The performance of the valve at elevated temperature, evaluated with consideration for the change in the disc friction factor, was consistent with the results from the earlier cold tests.

Effects of Valve Leakage

Leakage was monitored in tests with both internal and external heating. Table 3 presents leakage data from the various heatup tests. For this valve, it was necessary to pressurize the bonnet initially to establish a tight seal so that thermally induced pressure locking could occur. Table 4 shows the leakage rates for cold pressurization of the bonnet. All the measured leakage rates were very small, well within code requirements for this 6-in. Walworth valve.

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When we heated the unpressurized bonnet water, the leakage was sufficient to prevent pressurization as the fluid expanded. In contrast, when we began the heating test with the bonnet already pressurized to 700 psig, pressurization due to thermal expansion occurred. We assume that the initial pressure (before heating) caused the disc surfaces to seal to the seat surfaces more effectively than in the tests without initial pressure.

Note that evidence of valve leakage during a differential pressure test does not necessarily mean that leakage will prevent pressure locking. The disc elastic response during a pressure locked condition and its match-up to the seat is different in the pressure locking case, as compared to the differential pressure case. The effect of this difference was evident in the results we saw, where the leakage rates in the differential pressure tests showed no relationship to the leakage rates in the bonnet pressure tests. This demonstrates that the disc is matched up to the seat surface differently.

Effects of Entrapped Air

We performed other tests, with heat applied from the outside of the valve, to determine the effect of entrapped air on the bonnet pressure and on the associated opening stem load. We also investigated the extent to which the air will remain entrapped during operation, that is, whether the air pocket will remain intact, bleed off, or dissolve into the water.

Parametric tests were performed with air pockets representing 0.0, 0.5, 1.0, and 2.0 percent of the total valve volume. The valve was filled with deionized water, as in the previous tests, and air pockets were established by draining a known volume from the lower drain line while allowing air to enter through the high bonnet vent. Once the appropriate air volume was established, all external tubing was isolated and the valve was heated to 290°F using external heaters (heat tape). The pressure was monitored during the test and the valve was depressurized to 50 psig any time the pressure reached 1200 psi.

Figure 5 shows results from the heatup test with no entrapped air. The pressure increases rapidly after the bonnet pressure reaches 200 psig. Subsequent pressurization (following scheduled depressurizations) are very repeatable. Figures 6 through 8 show the same kind of data, but from tests with entrapped air volumes of 0.5, 1.0, and 2.0 percent air by volume. Here the behavior is similar, except that the initial pressurization begins at a higher temperature. As in the no-air test, subsequent repressurizations following depressurizations occur immediately. The fact that the presence of an air pocket delays the first pressurization but not the subsequent pressurization may indicate that the air pocket is either collapsed or forced into solution by the first pressurization cycle.

CONCLUSIONS

For this valve, the stem force required to overcome pressure locking loads appears linear with pressure. The flexibility of the disc determines the effective disc area responding to the bonnet pressure, which in turn affects the thrust needed to open the valve.

Small amounts of leakage can affect the pressurization rate in a thermally induced pressure locking scenario. Not enough data are available to quantify the leakage rate that would be necessary to prevent pressure locking from occurring. The leakage rates measured with a differential pressure across the valve were different from the leakage rates measured with only the bonnet pressurized.

We infer from this result that leakage in a differential pressure test is no guarantee that pressure locking will not occur.

In a thermally induced pressure locking situation, the presence of air trapped in the bonnet may delay the pressure buildup in the bonnet, but it will not prevent it.

To date we have completed testing of one valve. More data are needed to determine the extent to which these results apply to other gate valves.

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Table 1. Valve opening thrust versus valve pressure parametric tests.

Downstream pressure (psi)	Bonnet pressure (psi)	Upstream pressure (psi)
0	0	0
0	300	0
0	600	0
0	900	0
0	1200	0
300	1200	0
600	1200	0
900	1200	0
1200	1200	0
0	1200	300
0	1200	600
0	1200	900
0	1200	1200
300	1200	600
300	1200	300

Table 2. Direct bonnet pressurization tests.

Downstream pressure (psi)	Bonnet pressure (psi)	Upstream pressure (psi)
0	300	0
0	600	0
0	900	0
0	1200	0

Table 3. Leak rate data during heat-up tests.

Initial bonnet pressure (psig)	Average heat rate (°F/hr)	Average leak rate from bonnet to downstream (cm³/min)	Range of bonnet to downstream leak rates (cm³/min)	Average leak rate from upstream to maintain 50 psig (cm³/min)	Range of upstream leak rates to maintain 50 psig (cm³/min)
50	45	16.2	12.5 - 22.2		
600	NA	41.1	NA		
1200	NA	1.5	NA		
50	66.6	1.6	1.45 - 1.83		
50	54.1	1.2	0.91 - 3.12	2.33	1.38 - 3.12
50	85.2	24.2	4.97 - 130	2.15	1.82 - 2.49
700	13.8	2.3		9.7	

Table 4. Cold leak rate data.

Bonnet pressure range (psig)	Leak rate from bonnet to downstream (cm³/min)
1104 - 1326	0.216
504 - 640	1.233
1039 - 1294	0.114
572 - 670	0.078

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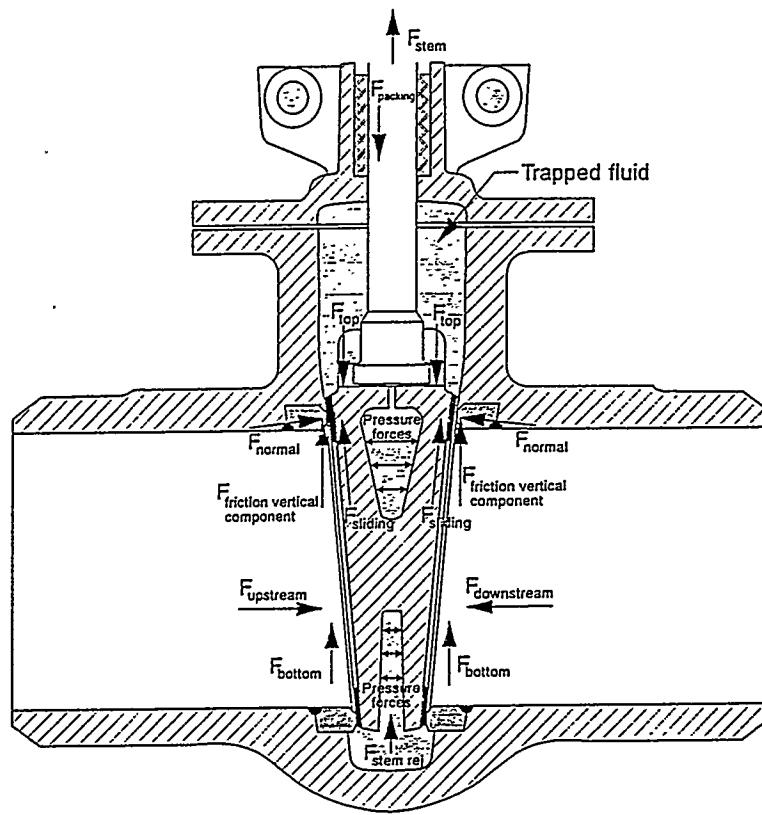
Figure 1. Diagram of a gate valve, showing the various forces involved when pressure locking occurs.

Legend

⊡	Low pressure pump
⊡	Pressure
⊞	High pressure pump
⊡	Temperature
⊡	Heater
⊡	Valve position
⊡	Valve current and power
⊡	Valve voltage
⊡	Torque spring deflection and force
⊡	Stem force and stem torque
⊡	Motor speed
⊡	Drain
⊡	Reservoir
⊡	D.I. water
⊡	Motor torque
⊡	Stem position
⊡	Air injection
⊡	High point vent
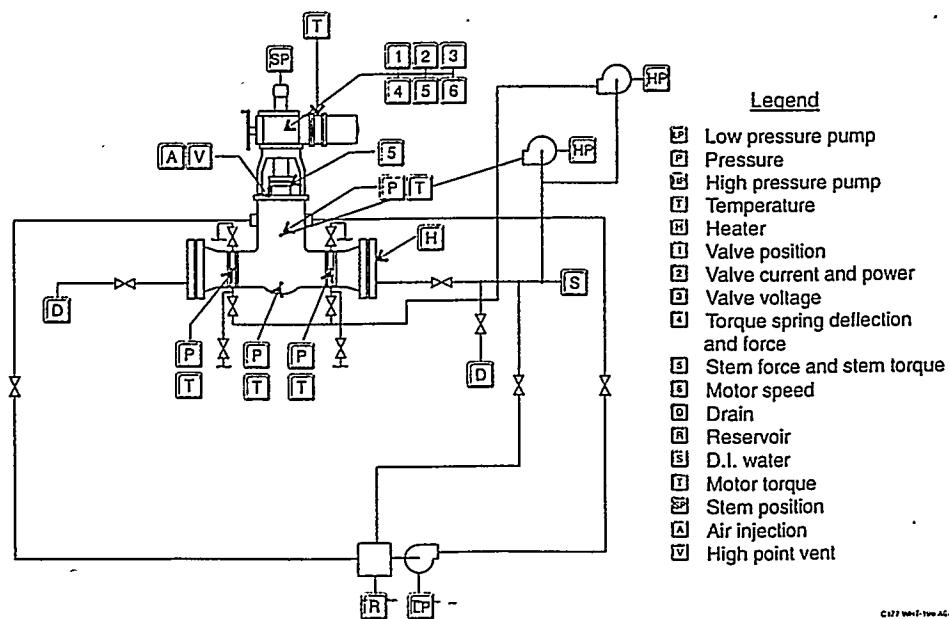
Figure 2. Test setup and instrumentation for the pressure locking tests.

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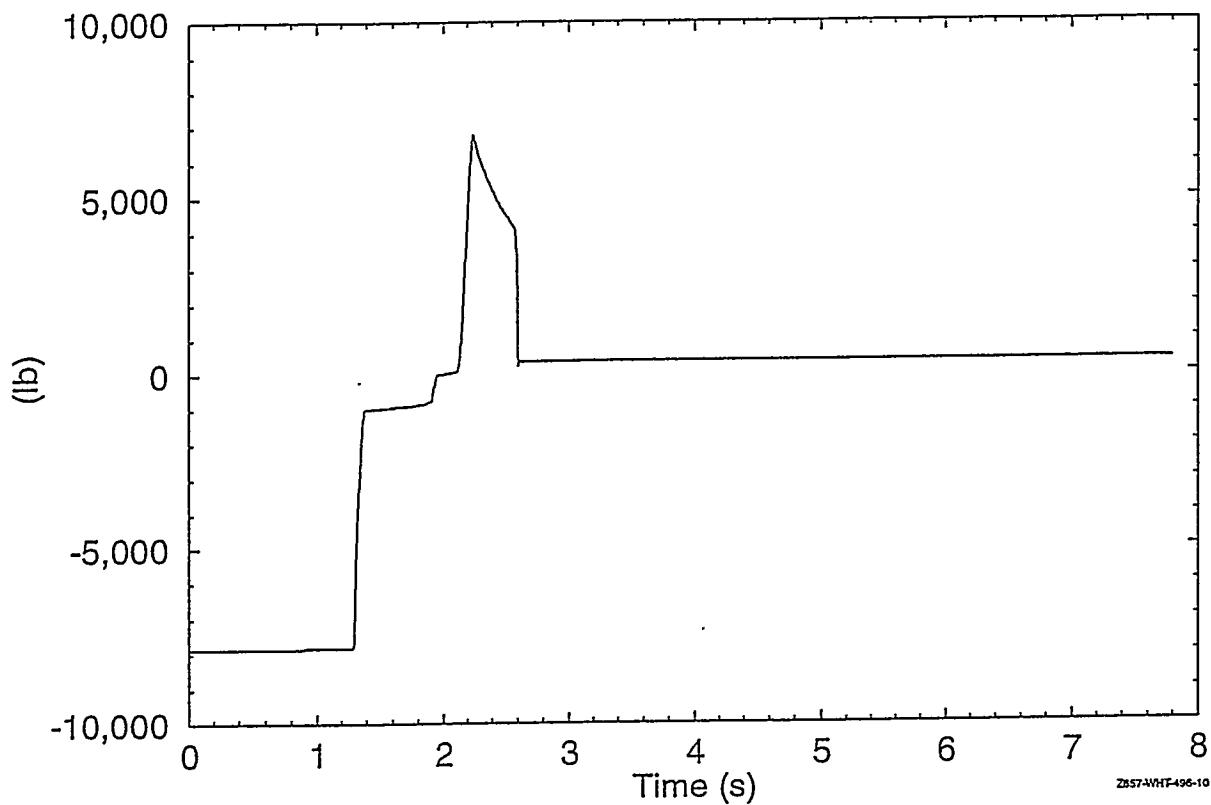
Figure 3. Thrust trace from a typical opening stroke in a pressure locking test.
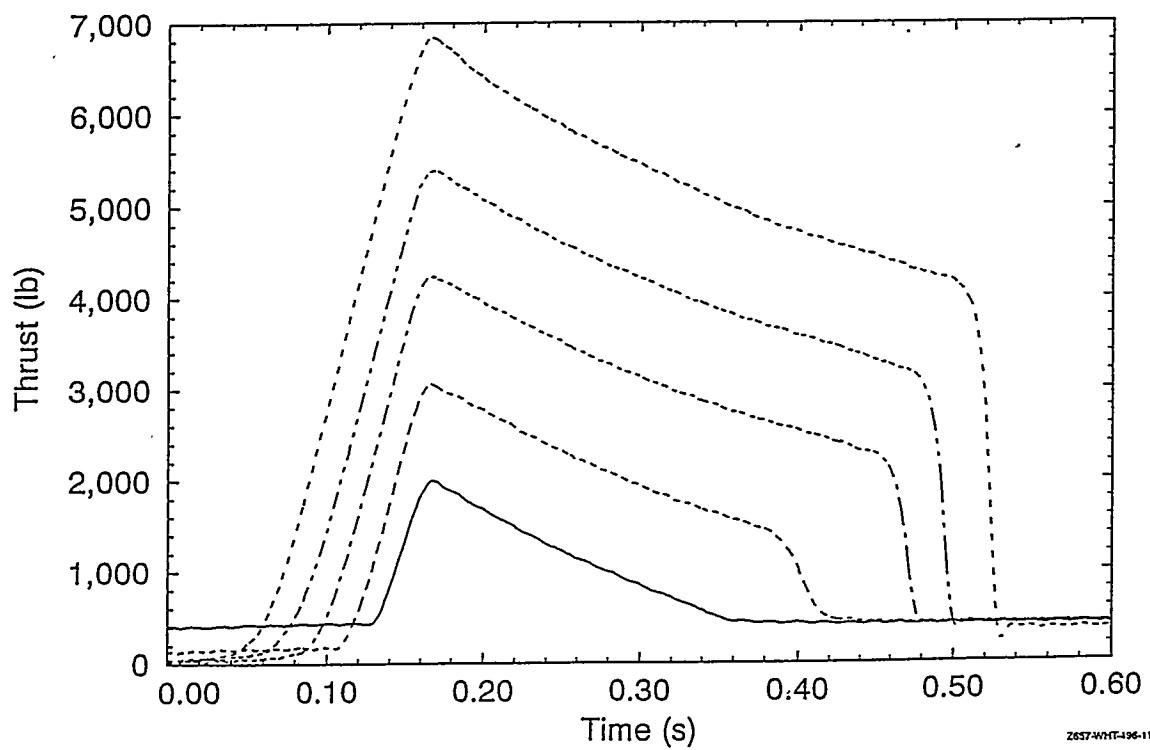

**Figure 4.** Opening thrust measurements from pressure locking tests at five different pressures.

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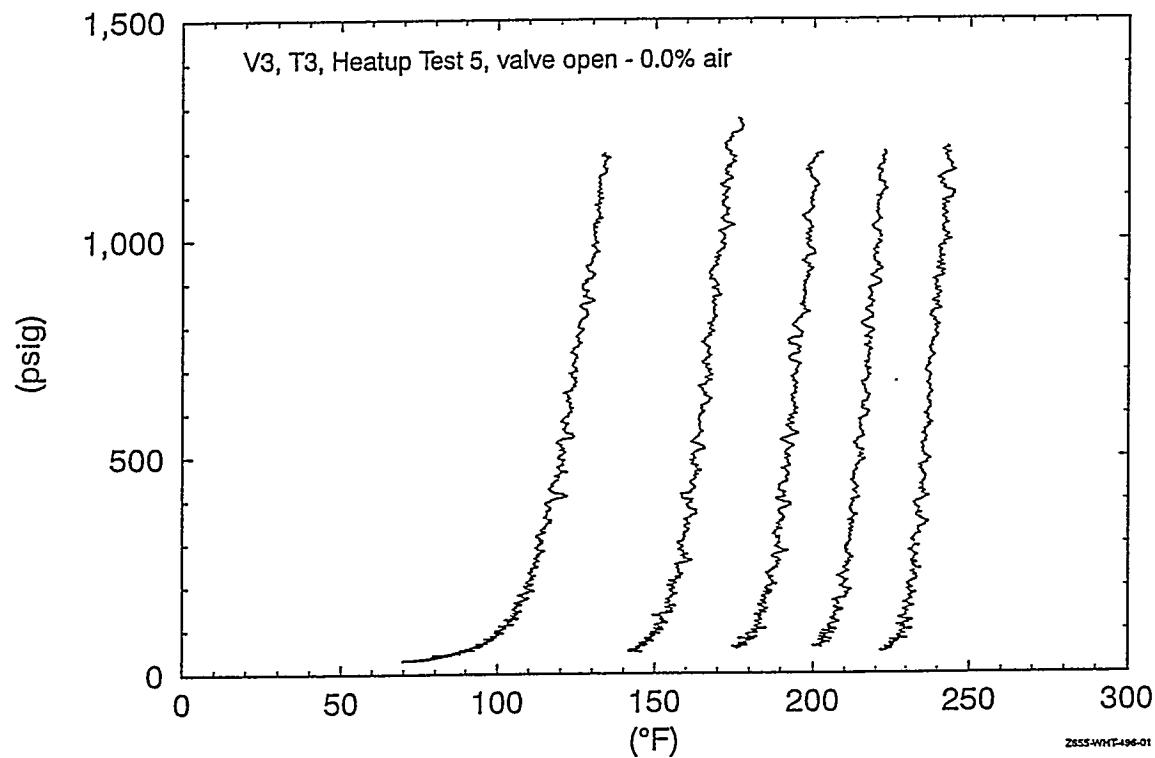
**Figure 5.** Pressure versus temperature with no entrapped air.
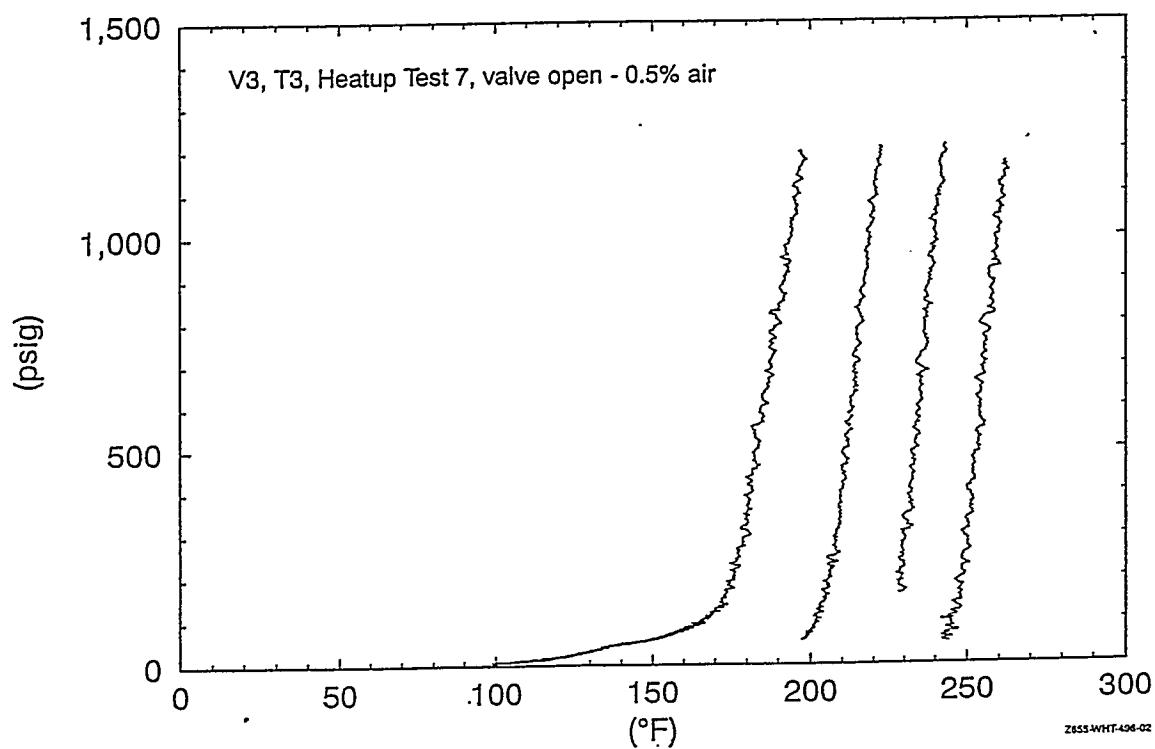
**Figure 6.** Pressure versus temperature with 0.5% entrapped air.

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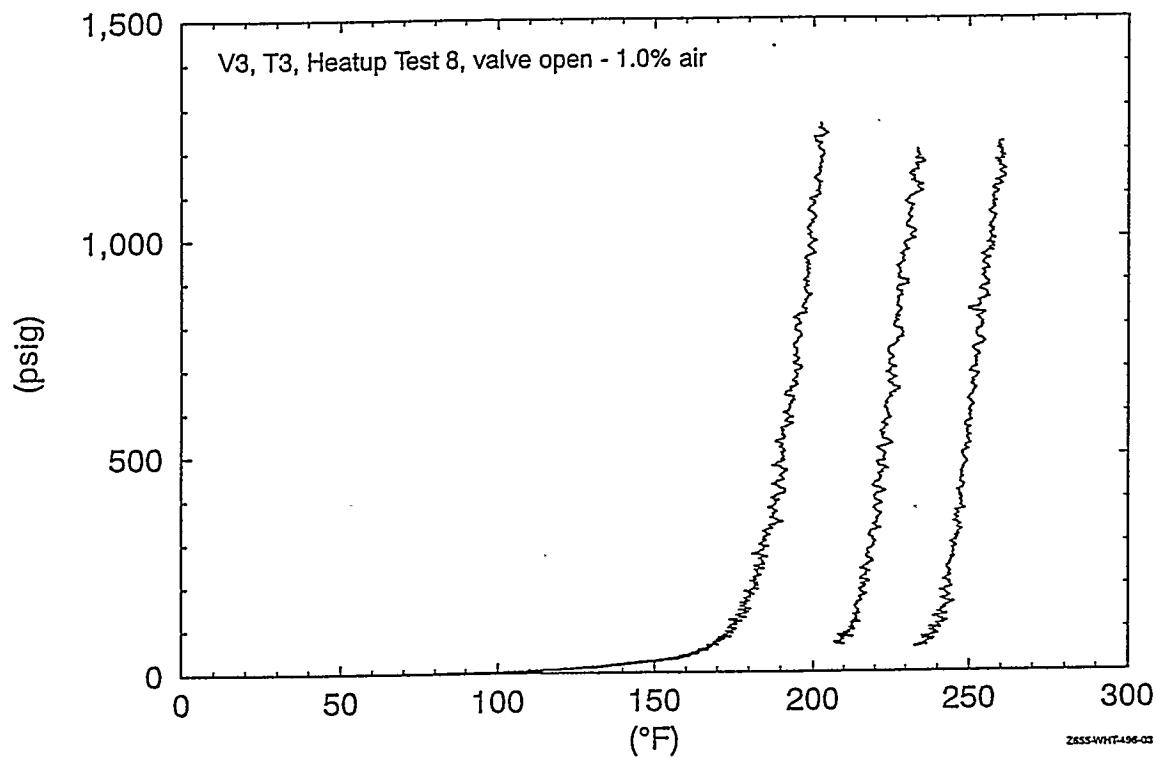
**Figure 7.** Pressure versus temperature with 1.0% entrapped air.
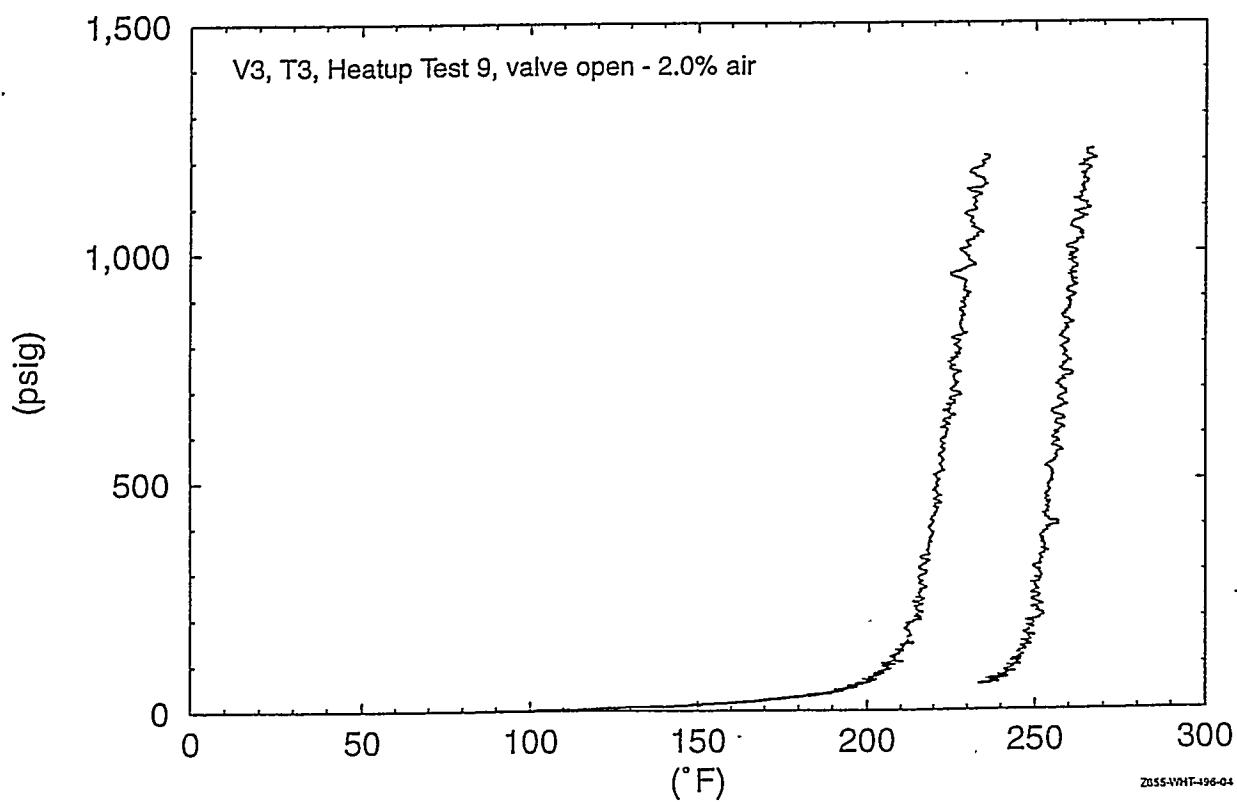
Figure 8. Pressure versus temperature with 2.0% entrapped air.

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