DEVELOPMENT OF A VALIDATED PRESSURE LOCKING METHODOLOGY FOR GATE VALVES

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ABSTRACT

The capability of gate valves to open can be critical to the safe operation of a nuclear power plant. The unwedging thrust can increase and the capability of a wedge gate valve to open can be compromised when the valve is subjected to certain pressure and/or temperature changes between the time the valve is closed and is required to open. This paper presents a first principles model for predicting the increase in unwedging thrust resulting from changes in bonnet, upstream or downstream pressures that can cause pressure locking of a wedge gate valve. The methodology takes into account the flexibilities of the valve disc, body and topworks (stem/ yoke/operator) as well as the sequence of pressure changes after valve closure. All of these factors were found to be essential in accurately predicting the unwedging thrust under pressure locking conditions. Simplified equations/procedures for calculating the flexibilities of the valve disc, body and topworks have also been developed as a part of the methodology. The methodology has been validated and found to be in good agreement with the test data.

This paper described the details of the validated pressure locking methodology. A companion paper presents the development of a thermal binding methodology.

INTRODUCTION

U.S. Nuclear Regulatory Commission Generic Letters 89-10 (Supplement 6) and 95-07 recommend that all U.S. nuclear power plants identify and address the potential for pressure locking and thermal binding in gate valves in the safety-related systems. To resolve the pressure locking issue in most valves, simple physical modifications can be made and in many cases have been made (e.g., drilling a hole in upstream disc). However, the system requirements, operational constraints, or physical constraints do not permit such modifications in some applications. Furthermore, even if the bonnet pressure is equalized to the upstream pressure to eliminate the "traditional" pressure locking conditions, the unwedging thrust can still increase significantly in some valves after being subjected to pressure changes after closure [1,2]*. Therefore, there is a need for a methodology that can accurately predict the increase in unwedging thrust due to pressure changes.

Electric Power Research Institute (EPRI) performed a comprehensive Motor-Operated Valve (MOV) Performance Prediction Program [3] to address the major issues in Generic Letter 89-10; however, the gate valve methodology developed under this program is limited to

* Numbers in brackets denote references listed at the end of this paper.

valve applications which are not affected by pressure locking or thermal binding conditions. To analytically predict the unwedging thrust under pressure locking conditions, Entergy [4] and Commonwealth Edison (ComEd) [1] developed methodologies that have been widely used by U.S. nuclear power plants.

ComEd also performed pressure locking tests on three valves of different sizes and pressure ratings made by three different manufacturers to validate their methodology. These tests were performed under a quality assurance program that satisfies the 10CFR50 Appendix B requirements. The results showed that, even though the agreement between analytical predictions and test data was good for two of the three valves tested, the methodology was significantly unconservative for the third valve (Figure 1). A margin of over 40% was needed for ComEd predictions to bound the test data for this valve. The margin required for Entergy methodology was even higher. Another surprising result from the ComEd testing (that can be seen in this figure) was that *the unwedging thrust for this valve increased even when the "traditional" pressure locking condition was eliminated (i.e., the bonnet pressure was vented to the upstream side)!* Neither the Entergy, nor the ComEd methodologies could explain this increase.

To eliminate the limitations of the earlier methodologies, the authors of this paper undertook the development of a pressure locking methodology based upon a comprehensive, first principles approach that addresses all the key phenomena that can lead to pressure locking. The methodology takes into account the flexibilities of the disc, valve body and stem/topworks as well as the sequence of pressure changes between the time the valve is wedged closed and opened.

This paper describes the methodology, presents the results of validation against ComEd and NRC/INEEL test data, and provides a summary of conclusions. The methodology also includes simplified closed–form equations to calculate body stiffnesses required in the analysis. Details of the methodology, equations, validation results, and implementation are documented in Reference 12.

The generalized pressure locking methodology was found to be in good agreement with data for all of the test valves and can therefore be used as a reliable analytical approach to predict unwedging thrust.

MODEL DESCRIPTION

Development Background

Previous pressure locking methodologies only consider the disc to be flexible; the valve body and the valve topworks are implicitly assumed to be rigid. However, valve bodies have finite flexibility, and they respond elastically to changes in pressures, seat loads, or valve end loads. An increase in line pressure causes the seat faces to move apart and, conversely, a reduction in line pressure tends to move the seat faces closer together. If the disc is wedged between the seat faces, these movements cause an increase or decrease in the seat reaction forces. Furthermore, the valve stem/yoke assembly and the operator in a valve assembly also have finite flexibility, and are capable of storing elastic strain energy during the closure stroke that can drive the wedge further if the disc/seat friction can be overcome after being subjected to pressure changes.

For a wedge gate valve that is subjected to a certain sequence of pressure changes between the time the valve is closed and opened, the body flexibility and the release of stored strain energy in the valve topworks can cause "disc pinching" and an increase in the unwedging thrust. The increase in thrust due to this disc pinching phenomenon depends upon key valve dimensions and the magnitude of pressure changes. An increase in unwedging thrust due to the disc pinching phenomenon caused by previous changes can occur in flexible wedge gate valves (even the ones with a bonnet pressure-equalizing feature) as well as in solid wedge gate valves.

The disc pinching phenomenon resulting from the valve body and valve topworks flexibility and a sequence of pressure events has been confirmed by in-situ plant data [2, 11] and is described below (See Figure 2):

1. The valve is closed under a certain pressure. The closing thrust introduces compressive stress in the stem and tensile stress in the yoke. The self-locking stem/stem nut geometry stores this elastic strain energy in the stem and valve topworks during valve closure.

2. After closure, the pressure upstream of the valve increases during operation. This higher upstream pressure enters the bonnet because the upstream seat in solid wedge gates (as well as in typical flexible wedge gates) does not provide a leak tight seal. The higher upstream and bonnet pressures cause the body to elastically expand, thus moving the seats further apart. The stored strain energy (and the resultant stem force) from the stem and valve topworks pushes the disc further down between the seats, partially releasing the strain energy.

3. Under a subsequent decrease in upstream and bonnet pressure, the seats try to return to their original position; however, they are prevented from doing so by the disc, which has been wedged further. This causes disc pinching (i.e., an increase in the contact force between the seat and disc) and an increase in unwedging thrust.

"Generalized" Pressure Locking Phenomenon. The above case history as well as the ComEd test results (Figure 1) show that the increase in unwedging thrust after a gate valve is subjected to a sequence of pressure changes cannot be determined by considering only the "traditional" pressure locking scenario of a higher pressure being trapped in the bonnet. In fact, as discussed above, the final bonnet pressure does not have to be higher than the upstream pressure for the unwedging thrust to increase. Therefore, a more appropriate and "generalized" approach to addressing pressure locking phenomena must include changes in pressure conditions upstream, downstream, and in the bonnet of the valve that can potentially cause an increase in the unwedging thrust. The pressure locking methodology described in this paper takes into account the above generalized pressure locking phenomenon.

Description

The generalized pressure locking methodology is applicable to the following sequence of operation:

- The valve is closed with or without system pressure (static closure);
- The bonnet pressure is increased through upstream, downstream, or bonnet pressurization;
- Upstream, downstream, or bonnet pressure may change before unwedging.

The required unwedging thrust is the sum of force components: (1) unseating force to overcome the frictional resistance at both seat faces; (2) pressure load on projected areas of the wedge disc along the stem axis based on final upstream, downstream, and bonnet pressures; (3) stem piston effect force (assisting opening); (4) stem packing friction; (5) disc and stem assembly weight; and (6) torque reaction friction force, as given in the following equation:

$$F_o = \frac{F_{sr} - F_{relx} + F_{vert} + F_{pack} - F_p + F_w}{TRF}$$

where

F_o = Required unwedging force, lb

F_{sr} = Stem force to overcome the final seat reaction forces , R_1 and R_2, after the valve is subjected to the specified sequence of pressure changes, lb

= $(R_1 + R_2)(\mu \cos\theta - \sin\theta)$

F_{relx} = Opening force relaxation derived from actual static wedging/unwedging measurements, lb

F_{vert} = Reversed piston effect force, lb

F_{pack} = Stem packing friction force, lb

F_p = Stem rejection force, lb

F_w = Disc and stem assembly weight, lb

TRF = Torque reaction factor (dimensionless)

F_{relx} is calculated from the static wedging /unwedging thrusts. It represents the amount of actual unwedging force reduction from the theoretical prediction based on closing seat contact force, R_0. In the absence of static wedging/unwedging measurements, a 10 percent reduction in seat contact force, R_0, may be used in calculating F_{relx} based upon structural relaxation effects determined from a number of wedge gate valves tested under the EPRI MOV Performance Prediction Program [3].

The magnitudes of final seat reaction forces R_1 and R_2 are calculated starting from seat contact forces, R_0, under the initial static wedging, and are continuously updated throughout the sequence of pressure changes, as described below.

First, the seat reaction forces, seat-to-disc interference, and the strain energy stored in the valve topworks are calculated from the initial equilibrium conditions based on the wedging thrust. Next, the new disc equilibrium is established by considering free body equilibrium along the pipe axis as well as along the valve stem axis after the valve has been subjected to changes in pressures (either upstream, downstream, or in the bonnet). For equilibrium along the pipe axis, deflections of the disc and body seat faces due to the specified pressure changes are calculated to determine the new disc-to-seat interference and reactions at both seats. The disc equilibrium along the stem axis is evaluated next to determine if the disc will remain in position or will overcome the disc-to-seat friction and be wedged further. In some cases, changes in pressures can cause a loss of contact on one of the disc-to-seat faces. For such cases in which the status of the seat contact changes, the disc equilibrium is established and the new disc position is determined by a piecewise linear calculational approach for both the contacting and noncontacting portions of the disc movement.

Stem force on disc and seat reaction forces are updated for the new disc equilibrium position before applying the next pressure change. The general disc force equilibrium equations are used repeatedly throughout the sequence of pressure changes to obtain the final disc position and the final seat contact loads. Finally, the frictional forces at the seat under the final seat contact loads are combined with the other opening thrust components to calculate the total unwedging thrust. The detailed methodology equations are documented in Reference 12.

Disc, Body and Topworks Flexibilities

Disc, body and valve topworks flexibilities are required to perform the unwedging thrust calculations. The flexibilities of the disc and body for a specific valve can be determined from the closed-form equations given in the generalized methodology. The flexibility of the valve topworks can be calculated by using an equivalent stem length approach that utilizes the static thrust signature from the MOV closure. These flexibility calculational procedures developed under the methodology are described next.

Disc Flexibility. Disc flexibility for flexible wedge gate valves is calculated using closed-form, flat plate equations [7] in both the Entergy and ComEd methodologies [1, 4]. In order to evaluate the accuracy of these closed-form approaches, finite element analyses were performed on the discs representing the three valves that were tested by ComEd. Comparisons were performed for two different load cases: (1) uniform pressure load applied to the disc and (2) line load applied to the disc at the mean seat diameter location. From a comparison of the closed-form solutions and the FEA results (see Table 1), the following conclusions were drawn:

1. *FEA model with the same fixed edge at hub O.D. as in the closed-form model (Figure 3):* The results from both methods are within 5 percent. In this comparison, the flexibility of the hub, which is made of an elastic material (steel), is excluded from both methods.

2. *FEA model including hub flexibility (Figure 4):* The hub flexibility contribution is significant, as shown in the Table 1 comparison. In the closed-form solution in the ComEd methodology, the radial deflection (and the associated rotations) at the junction between the hub O.D. and the plate I.D. is assumed to be zero; i.e., the O.D. of the hub is assumed to be fixed (rigid) for the plate bending equations. In the ComEd methodology, the hub *axial* flexibility is included and combined with the plate bending flexibility to form the overall disc flexibility. In the FEA model, the effect of the hub being an elastic foundation (instead of being rigid) results in a rotation at the hub-to-plate junction, which in turn causes an additional deflection of the disc under bending. The overall result is that the disc is significantly more flexible under bending as compared to the ComEd closed-form model.

Although there is a large difference between the closed-form equations and the finite element results, sensitivity analysis calculations documented in Reference 12 show that the impact of disc flexibility (by itself) on unwedging thrust is relatively small using the ComEd methodology. This is due to the fact that even though the actual disc flexibility is higher because of hub elasticity, its magnitude is affected by roughly the same relative amount for both the pressure load case and the line load case.

To more accurately estimate disc flexibility, the ComEd closed form methodology was refined to include the contribution of hub elasticity to the disc flexibility under pressure and seat load. This was accomplished by including a portion of the hub radial length in the plate flexibility equation, as detailed in Reference 12. The results show that the refined closed-form equations can predict the disc flexibility, which closely matches the finite element results. The refined closed-form equations are used in the generalized pressure locking methodology.

Body Flexibility. Results of the finite element studies performed by the authors' analyses showed that the valve body flexibility can be significant and is often in the same order of magnitude as the disc flexibility. Pressure class, valve size, and specific geometry all contribute to the body flexibility of a specific valve design. The wedge gate valve body geometry is complex and no simple closed-form equations are available for calculating the valve body flexibility. Three types of body flexibilities are required to predict unwedging thrust: (1) K_{bp1}, body stiffness under bonnet pressure only, (2) K_{bp2}, body stiffness under bonnet pressure and seat load (or pipe end load), and (3) K_{bs}, body stiffness under seat load only.

A simplified closed-form approach was developed under the generalized pressure locking methodology to determine body flexibility for a given valve. A comprehensive matrix of three-dimensional finite element analyses was performed to develop closed-form equations for body stiffnesses using the geometry, boundary conditions, and key valve body dimensions shown in Figures 5(a), 5(b) and 5(c). The matrix of three-dimensional finite element analyses consisted of 19 different FEA models that covered variations in valve body shapes due to differences in manufacturers' designs, sizes, and pressure classes.

The following key dimensions are required to calculate the body stiffness:

D1 = Flow passage inside diameter, in

D2 = Body neck inside diameter, in

T1 = Flow passage pipe wall thickness, in

T2 = Body neck wall thickness, in

d1 = Distance from top of valve body to top of flow passage O.D., in

d2 = Distance from bottom of valve body to bottom of flow passage O.D., in

Evaluation of the FEA results showed that the first four key dimensions described above have the most significant influence whereas the last two have only a moderate influence on the body stiffnesses. These body dimensions can be readily obtained by field measurements (no disassembly required) or from the valve vendor. Valve thicknesses can be measured by ultrasonic testing.

To calculate body stiffnesses for a valve of specific size, its key dimensions are expressed in terms of dimensional ratios. Based on these dimensional ratios, the three body stiffnesses K_{bp1}, K_{bp2} and K_{bs}, can be calculated using five factors for each one of the three stiffnesses. The calculation procedure is relatively straightforward and is described in Reference 12.

Stem and Valve Topworks Flexibilities

Stem flexibility can be calculated directly from the stem dimensions. The valve topworks flexibility is more difficult to calculate due to its structural complexity. However, the topworks flexibility can be indirectly calculated using the information from the actual static closing thrust signature for the MOV. The rate of thrust increase (compression) at static wedging represents the combined effects of disc, body, stem, and topworks flexibilities. Therefore, with the known disc, body, and stem flexibilities (which can be calculated by using the equations described earlier), the flexibility of the topworks can be derived from the static signature. To simplify calculations, the flexibility of the stem and topworks can be combined and treated as one *equivalent stem flexibility*. The calculation procedure is documented in Reference12. It should be noted that the valve topworks flexibility includes the contribution from the actuator. Some gate valves are equipped with a spring loaded actuator (such as Limitorque SB actuators), which significantly increases the flexibility of the topworks, as in the case of the 4-inch Westinghouse valve used in the ComEd validation tests. The equivalent stem flexibility approach described above implicitly accounts for the contribution of the additional flexibility of the topworks due to the actuator spring.

METHODOLOGY VALIDATION

The generalized pressure locking methodology was validated by comparing model predictions for unwedging thrust against data obtained from ComEd and INEEL tests for four different valves. For the ComEd valves, validation was performed using body stiffnesses calculated in two different ways: (1) stiffnesses obtained from detailed 3-D finite element analyses and (2) stiffnesses obtained by using the simplified closed-form equations developed under the methodology. Actual valve dimensions for the three ComEd valves were provided by ComEd. For the INEEL valve, validation was performed using body stiffnesses calculated by using the simplified closed-form equations and key body dimensions that were taken from Reference 9. Thrust predictions were also performed using the ComEd pressure locking methodology for comparison. Validation results and the comparisons against the generalized methodology and ComEd methodology for the four valves are summarized below.

10-inch, 300-pound Borg-Warner Valve (tested by ComEd)

Figure 6 shows a comparison of the thrust predictions using ComEd and KEI generalized methodologies against pressure locking test results for the 10-inch, 300-pound Borg-Warner valve. It should be noted that this valve exhibited the largest disparities between the ComEd predictions and the actual test data, as discussed in the introduction. The valve was tested under two different torque switch settings [5]. The majority of tests were performed with the valve closed statically with no pressure in the valve body. The required bonnet pressure for the test conditions was achieved by pressurizing the upstream side of the valve. Exceptions to this procedure were in Tests 80, 81, 86, and 95. Tests 80 and 81 were performed with the entire valve pressurized before closing. Tests 86 and 95 were performed with upstream pressurization; however, the valve bonnet pressure was relieved prior to the opening stroke.

Key findings from this comparison are:

- A very good agreement was found between the KEI generalized methodology thrust predictions and actual test data.
- For tests 80 and 81, in which the valve was pressurized before closing, the generalized methodology took into account the exact sequence of pressure changes and showed a significant improvement in thrust prediction. It also confirmed that a valve body pressurized before closing causes the seat faces to move apart and the relief of upstream and downstream pressures creates disc pinching and higher unwedging thrust.
- Tests 86 and 95 were performed by pressurizing the upstream side of the valve disc and then relieving upstream and bonnet pressures. For this pressurization sequence, the KEI generalized methodology analysis showed that the disc moved downward during the upstream pressurization and resulted in a higher unwedging thrust that cannot be accounted for by traditional pressure locking calculations.
- Figure 6 comparison shows that, to bound the maximum error in predictions for this valve, a 12.1 percent margin needs to be applied to the KEI generalized methodology predictions as compared to a 39.1 percent margin to the ComEd methodology. The required margin for the KEI generalized methodology is reduced to 8.6 percent if the body stiffnesses are calculated using finite element method instead of using the closed-form equations for body flexibilities.

10-Inch, 900-Pound Crane Valve (tested by ComEd)

All tests were performed on this valve with the bonnet test pressure being achieved by pressuring through the upstream side of the valve; no variations in the pressurization sequence were introduced in these tests. Figure 7 shows the predicted thrusts versus test results using both the ComEd and KEI generalized methodologies. The predicted thrusts by both methodologies are in good agreement with test data for this valve.

4-Inch, 1500-Pound Westinghouse Valve (tested by ComEd)

All tests were performed with the valve pressurized before closing. The predicted stem thrusts are in excellent agreement with test data by both methodologies (Figure 8).

It should be noted that the measured seat friction coefficient for the valve is very low (0.13) as compared to typical values that may occur in actual service. This valve has a half-wedge angle of 7 degrees. For this geometry, a seat-to-disc friction coefficient of less than 0.123 (= tan 7°) corresponds to the nonlocking condition for the wedge. The actual friction coefficient is approximately in the same range. Under this nonlocking condition, an increase in seat contact load does not significantly impact the unwedging thrust.

6-Inch, 600-Pound Walworth Valve (tested by INEEL)

This valve was pressure-lock tested under ambient and high temperature conditions [8]. For the ambient temperature tests, the valve was closed with a pressure of 1200 psi. Then the upstream, downstream, and bonnet pressures were adjusted to the specified magnitudes corresponding to the desired test conditions. For the high temperature tests, the valve was closed statically, and the bonnet was pressurized directly to the desired magnitude.

Opening thrust predictions were performed using both ComEd and generalized methodologies (Figure 9). The results show that the generalized methodology provides slightly improved thrust predictions.

Table 2 summarizes the required margins for both KEI and ComEd methodologies to bound the test data. It shows that a maximum margin of 14.4 percent needs to be applied to KEI generalized methodology predictions as compared to a 39.1 percent margin to the ComEd methodology. As shown in the comparison, the required margin for the KEI generalized methodology is reduced to 8.6 when more accurate values of body stiffnesses determined by FEAs are used.

CONCLUSIONS

1. The generalized pressure locking methodology described in this paper overcomes the limitations of the earlier methodologies and provides good agreement with test data from all of the valves used in the validation. The maximum difference between the generalized methodology predictions and test results was found to be 8.6 percent if the body stiffnesses were calculated using the detailed finite element analysis for the specific valve, 14.4 percent when the closed-form equations for estimating the body stiffnesses were used.

2. The generalized pressure locking methodology is applicable to the following types of wedge gate valves and common operating sequences that can lead to pressure locking:
   - Flexible wedge gate valves with no bonnet pressure equalization feature
   - Flexible wedge gate valves with bonnet pressure equalization feature
   - The valve is closed with or without system pressure;
   - The bonnet pressure is increased through upstream, downstream, or bonnet pressurization;
   - Upstream, downstream, or bonnet pressure may change before the valve is unwedged.

3. The generalized methodology equations can also be used to predict the unwedging thrust increase due to pressure changes in solid wedge gate valves (as has been observed in some cases e.g., references 2, 12) by approximately extending the disc stiffness calculations for such valves.

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Disc Flexibility Comparison **Roark's Equations vs. FEA Results** *for Table 24, Case 1L [7]*				
Valve Identification	**Roark's Equations**	**FEA Results**	**Flexibility Ratio**	**Stiffness Ratio**
	Deflection in/(lb/in)	**Deflection in/(lb/in)**	**Roark/FEA**	**Roark/FEA**
10" x 900# Crane	9.05E-07	1.17E-06	77%	130%
4" x 1500# Westinghouse	2.98E-07	5.28E-07	56%	179%
10" x 300# Borg-Warner	5.69E-07	1.20E-06	47%	213%

Table 1. Disc Flexibility Comparison, Roark's Equations [7] vs. Finite Element Analysis Results for the Case In Wbich a Line Load Is Applied at the Seat Reaction Point

Valve I.D.	**Required Margin, %**		
	KEI1[1]	**KEI1[2]**	**ComEd**
10" x 300# Borg Warner	8.6	12.1	39.1[2]
10" x 900# Crane	2.5	0.8	1.9
4" x 1500# Westinghouse	6.4	6.2	0.6
6" x 600# Walworth	NA	14.4[2]	19.9

Notes:
1. KEI1 = Using FEA to calculate body stiffness.
   KEI2 = Using Closed-form equations to calculate body stiffness.
2. Maximum required margins.

Table 2
Maximum Required Margins to Bound Test Results for KEI and ComEd Pressure Locking Methodologies

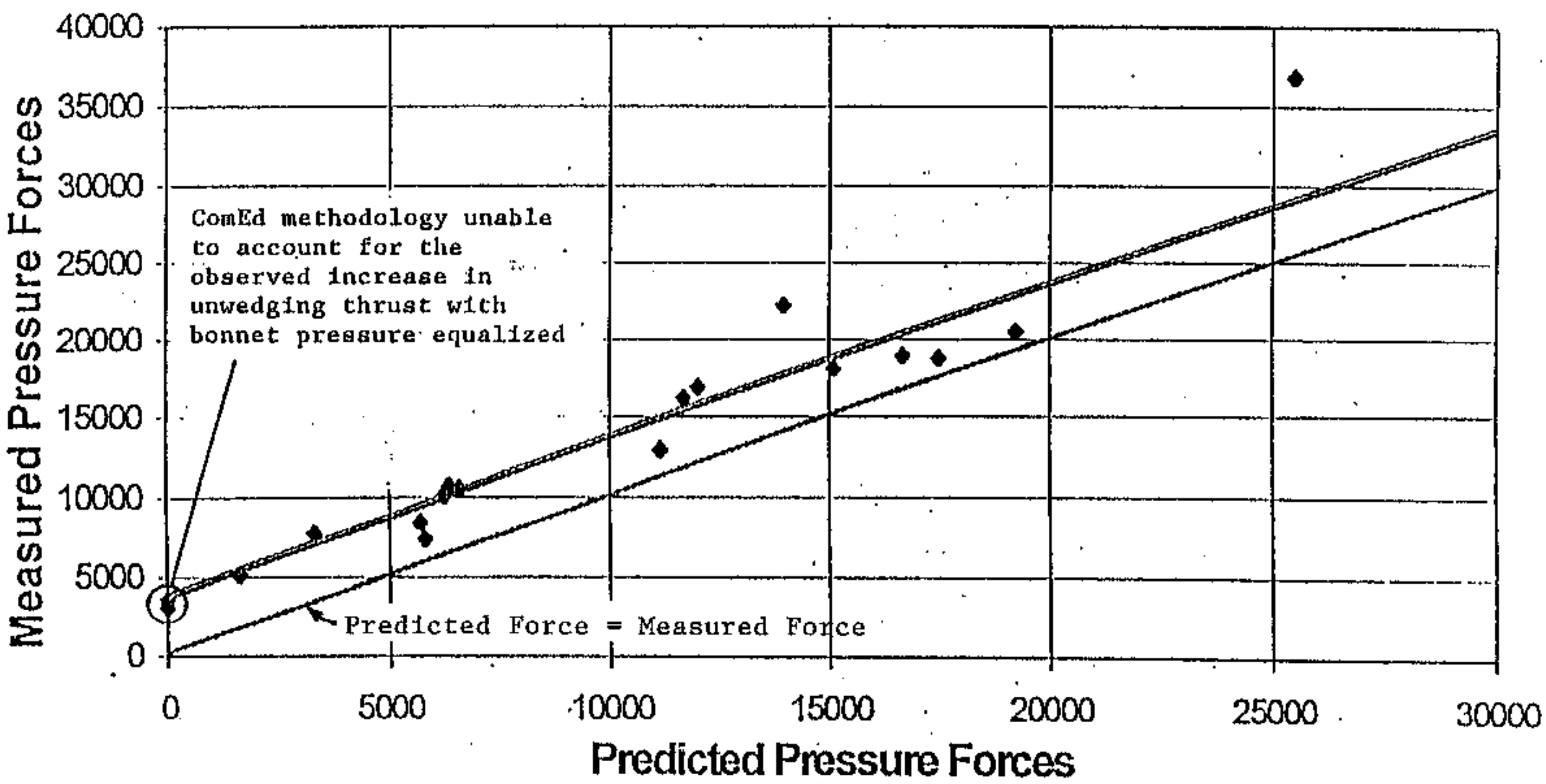


Figure 1. ComEd Methodology Prediction vs. Measured Portion of Unseating Thrust Due to Pressure Locking Forces for the Borg-Warner Valve Tested by ComEd [1]

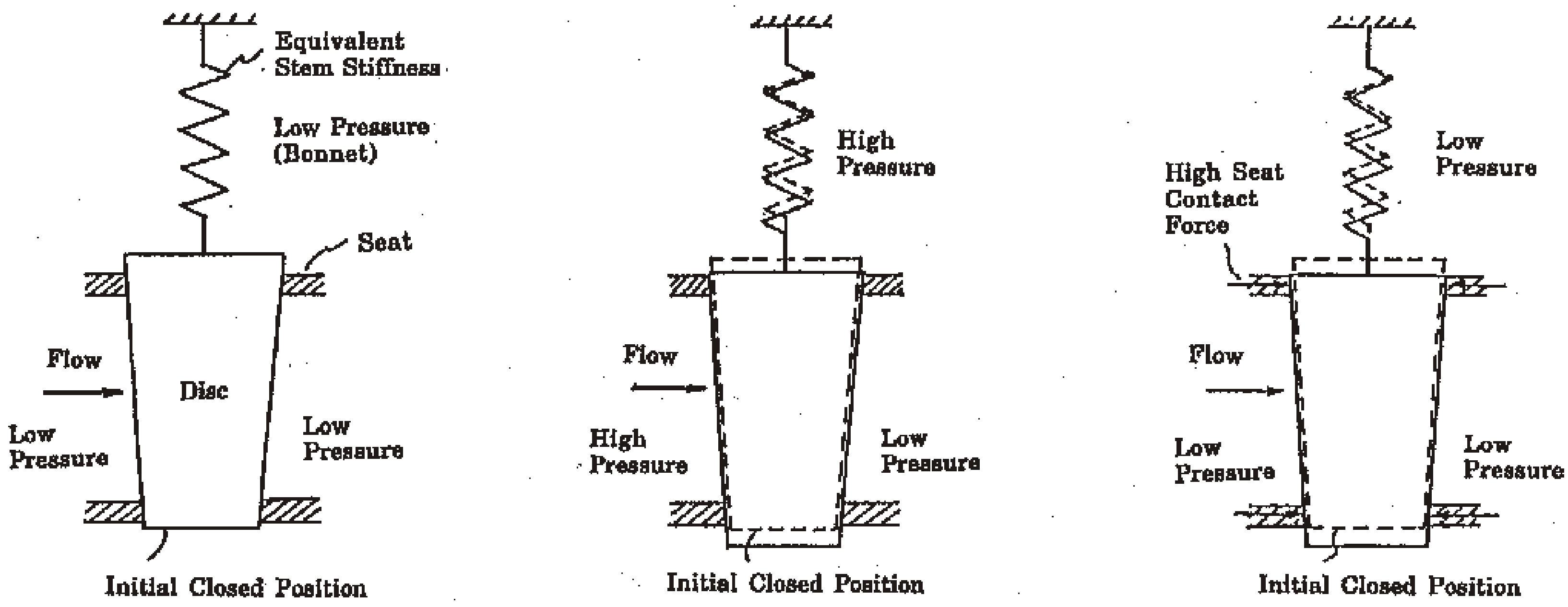


Figure 2. Disc Pinching Phenomenon Caused by the Combination of Body Flexibility and a Sequence of Upstream Pressure Changes between Valve Closing and Opening

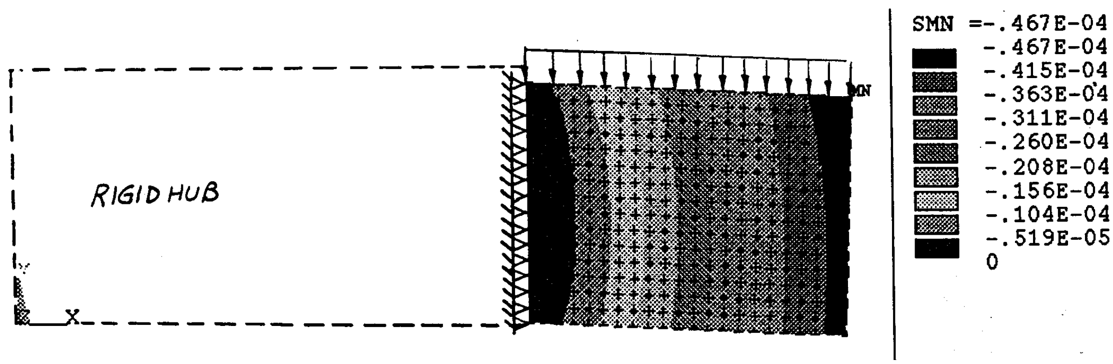


Figure 3. Finite Element Model for ComEd 10", Class 300 Borg-Warner Valve Disc with Fixed Edge at Hub O.D. for Disc Flexibility Analysis

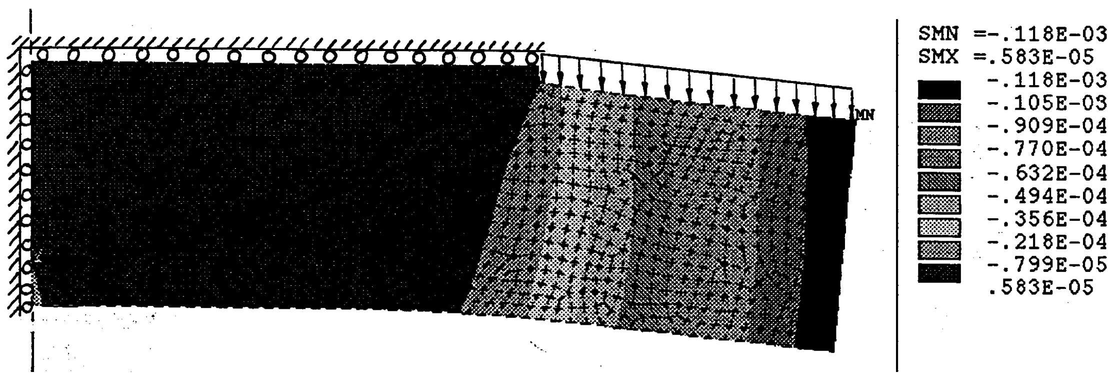


Figure 4. Finite Element Model for ComEd 10", Class 300 Borg-Warner Valve Disc

Including Hub Flexibility for Disc Flexibility Analysis

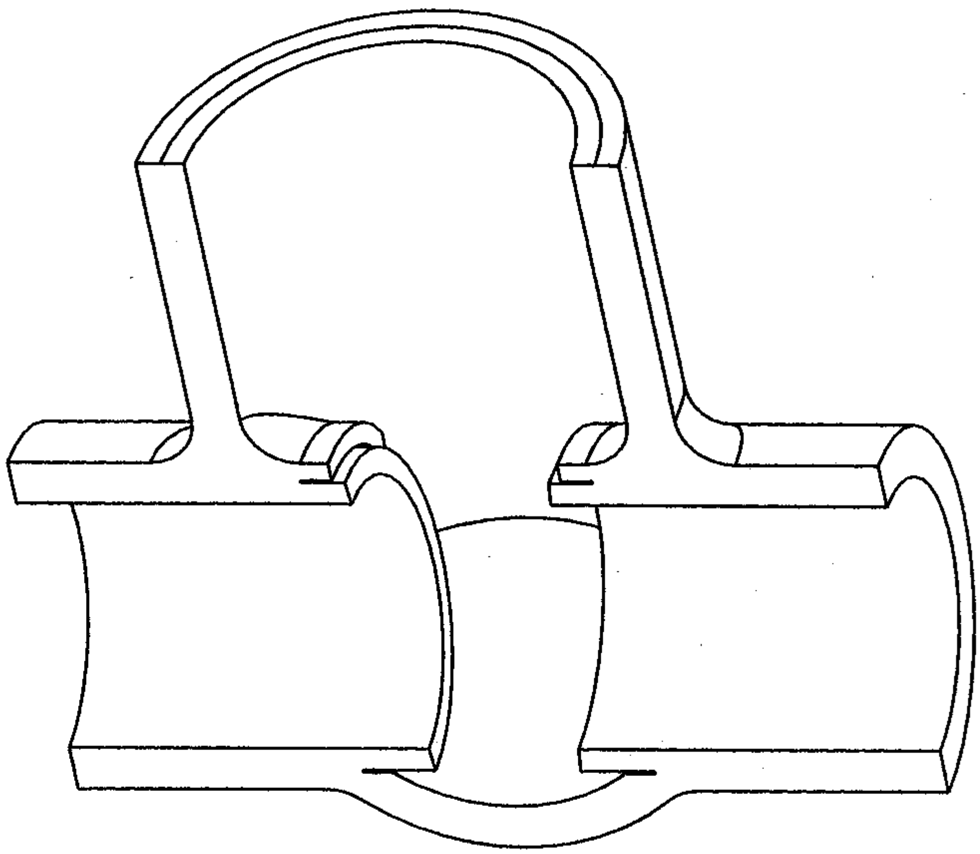


Figure 5(a). Generic Valve Body Geometry Used in the Three-Dimensional Finite Element Model for Valve Body Flexibility Analysis

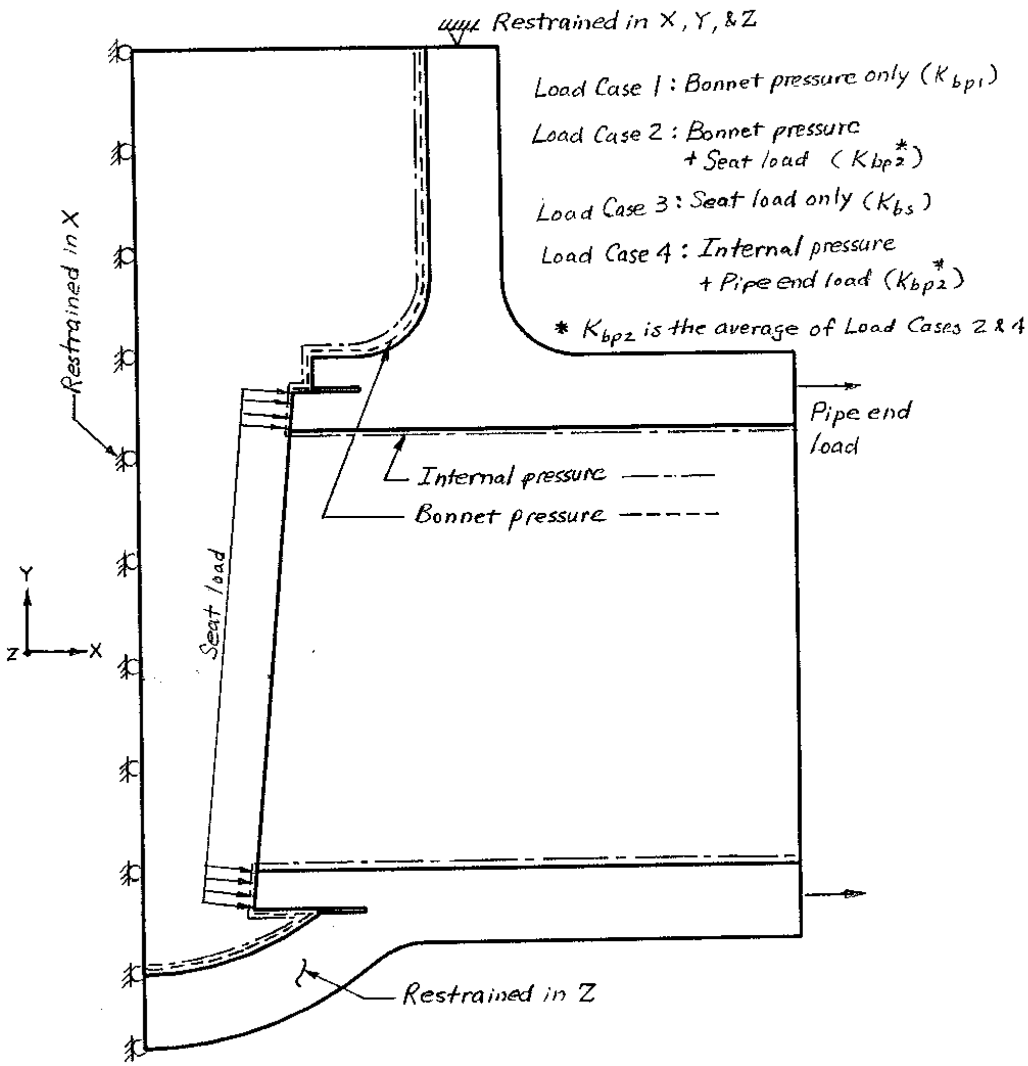


Figure 5(b). Load Cases and Boundary Conditions Used in the Three-Dimensional Finite Element Model for Valve Body Flexibility Analysis

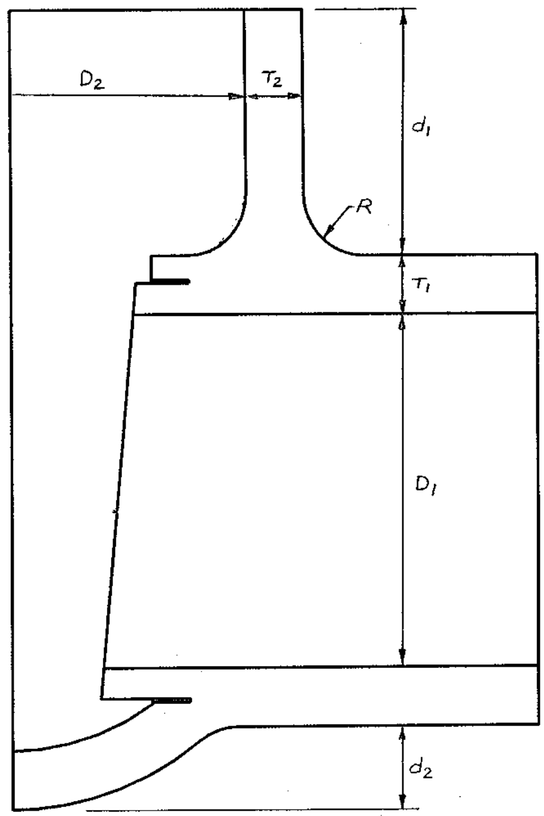


Figure 5(c). Key Body Dimensions Used in the Three-Dimensional Finite Element Model for Valve Body Flexibility Analysis

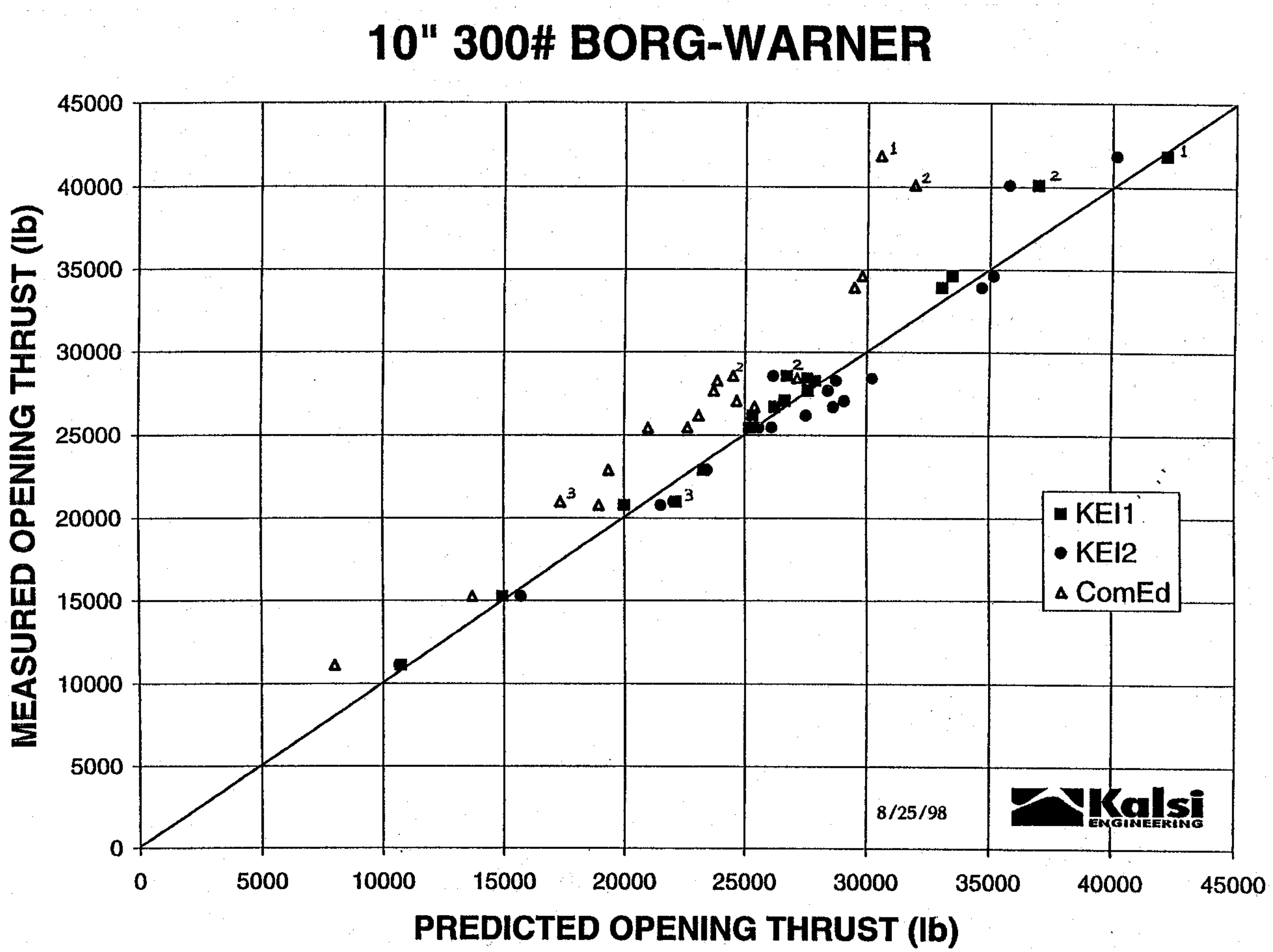
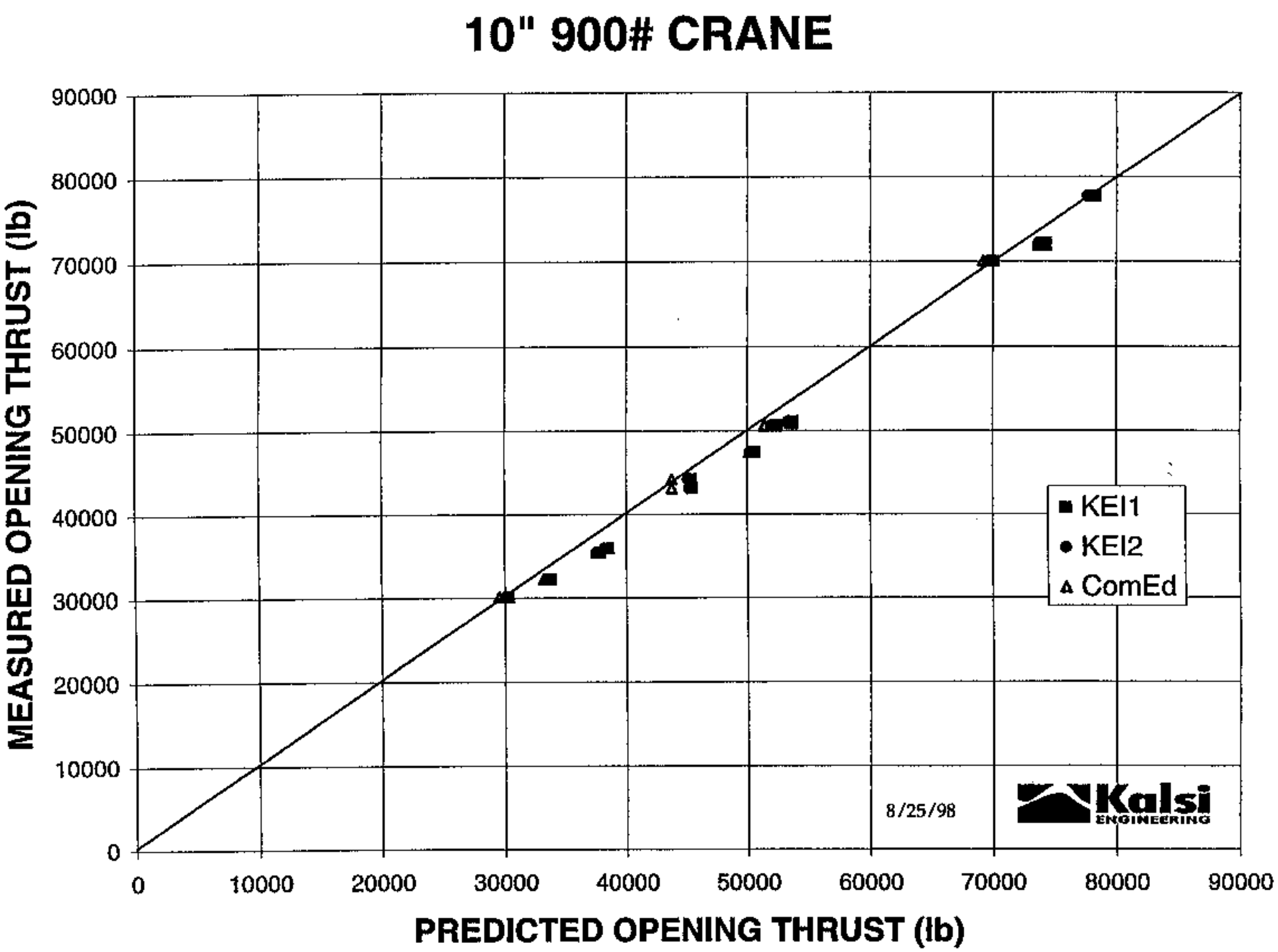
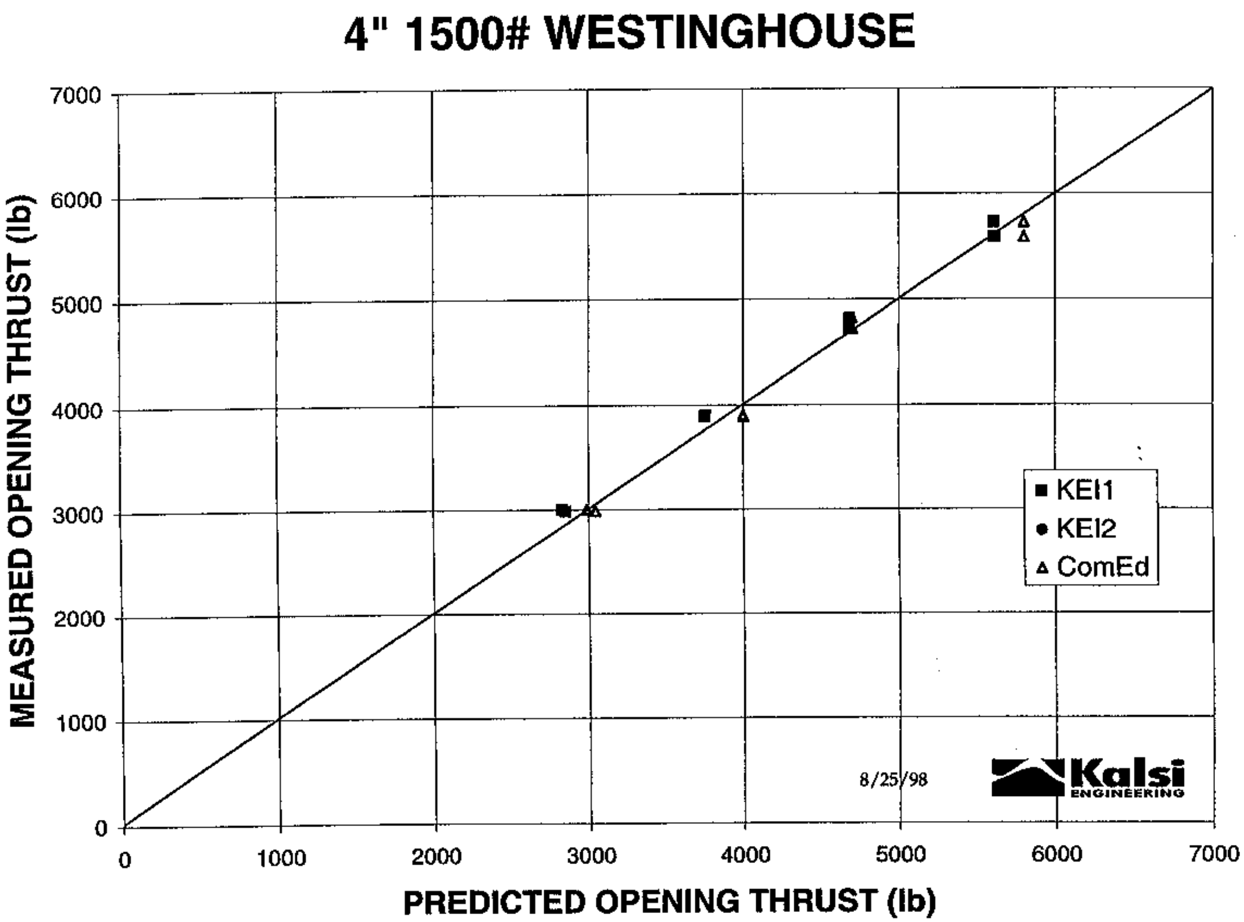


Figure 6. Comparison of KEI Generalized Methodology and ComEd Methodology Pressure Locking Predictions vs. Unwedging Thrust Test Results for the 10" Class 300 Borg-Warner Valve



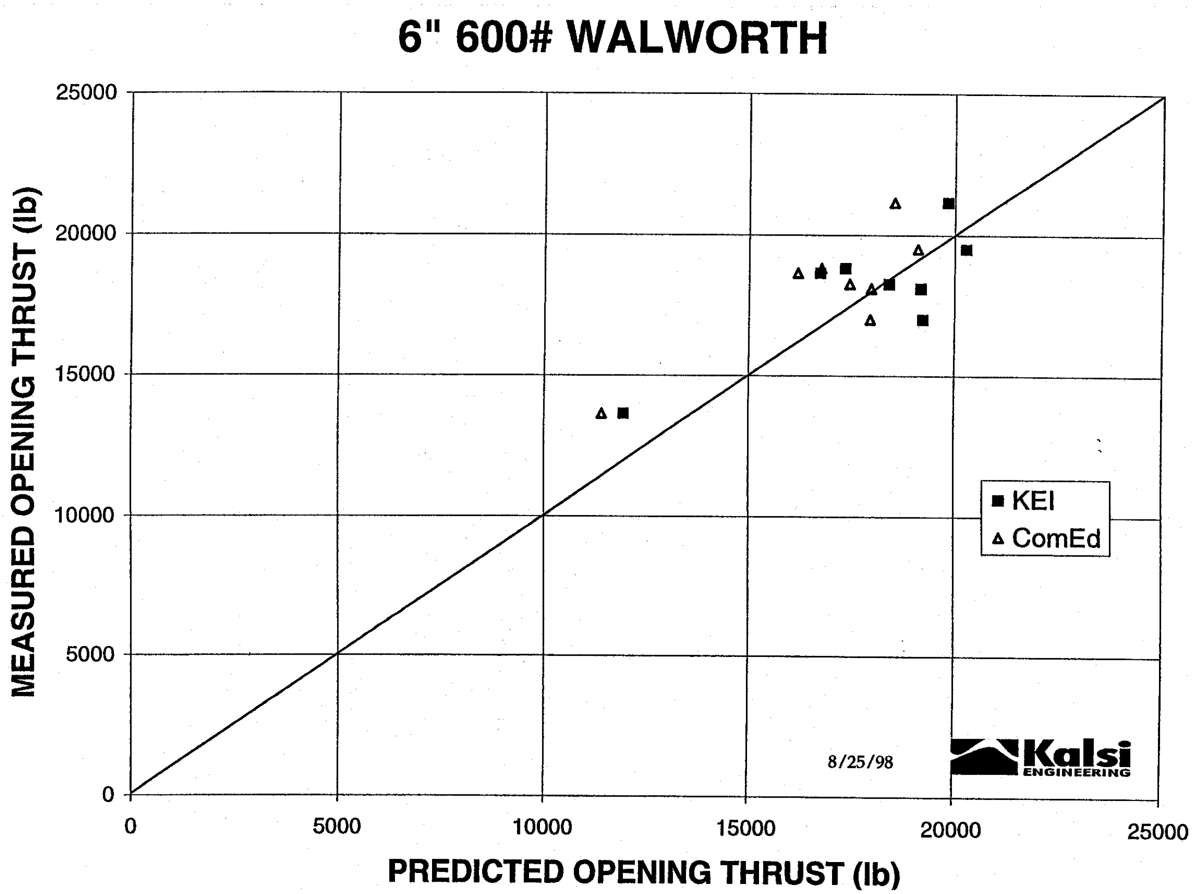
Note: For KEI1, valve stiffnesses obtained from FEA; for KEI2, valve stiffnesses obtained from closed-form equations.

Figure 7. Comparison of KEI Generalized Methodology and ComEd Methodology Pressure Locking Predictions vs. Unwedging Thrust Test Results for the 10" Class 900 Crane Valve



Note: For KEI1, valve stiffnesses obtained from FEA; for KEI2, valve stiffnesses obtained from closed-form equations.

Figure 8. Comparison of KEI Generalized Methodology and ComEd Methodology Pressure Locking Predictions vs. Unwedging Thrust Test Results for the 4" Class 1500 Westinghouse Valve



Note: Valve stiffnesses obtained from closed-form equations.

Figure 9. Comparison of KEI Generalized Methodology and ComEd Methodology Pressure Locking Predictions vs. Unwedging Thrust Test Results for the 6" Class 600 Walworth Valve