Plant Experience Based Upon Application of New Validated Models for Air-Operated Valves

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INTRODUCTION

To meet an important industry need for evaluating capability of safety-related Air-Operated Valves (AOVs) to operate under design basis conditions, Kalsi Engineering, Inc. initiated a comprehensive program to develop validated models for quarter-turn valves. The program included development of first principle models, extensive computational fluid dynamics (CFD) analyses, and flow loop tests (incompressible and compressible flow) on all common types of AOV quarter-turn valves. The test program included systematic evaluation of elbow orientations and proximities to quantify elbow effects on required torque. The program was conducted under a quality assurance program that meets 10CFR50 Appendix B requirements. Earlier papers [1,2][*] describe Phases I and II of the program. The products of this program are validated models and software (KVAP™) for AOV design basis calculations [11].

The new models and KVAP software have significantly advanced the state-of-the-art in accurately predicting torque requirements for AOV's in nuclear power plant applications. This paper provides an overview of the previous industry developments relevant to this program and summarizes plant experience and the benefits obtained by the utilities from application of these new models at 30 nuclear power plants.

OVERVIEW OF PREVIOUS INDUSTRY DEVELOPMENTS AND CURRENT STATUS

Fundamental Difference Between MOV and AOV Margin Evaluation

There is a fundamental difference between outputs from typical MOV actuators and AOV actuators that directly affects the evaluation of minimum margin between the actuator output torque capability and the valve torque requirements (Figure 1). Since the output capability from a typical AC powered MOV actuator is constant throughout the stroke, only the peak required torque magnitude, regardless of the stroke position where it occurs, is required to determine the minimum margin throughout the stroke. The prediction models for MOVs therefore do not have to have position-dependent accuracy as long as the model provides bounding predictions for the peak torque. However, the output of a typical quarter-turn AOV actuator (e.g., Scotch Yoke) as well as the margin varies with disc position. Therefore, the Required Torque prediction models

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[*] Numerals in brackets denote references listed at the end of this paper.

for the valve need to have *position-dependent accuracy* to correctly determine the minimum AOV margin throughout the stroke.

An overview of the manufacturers' techniques, industry programs, and models for predicting valve torque requirements for MOVs and AOVs is provided below.

1. Limitations of Manufacturers' Data for Torque Predictions

A survey was conducted by Kalsi Engineering, Inc. to determine which types of quarter-turn valves are commonly used in AOV applications. The survey included data from 20 plants that had categorized their valves for Category 1 and 2 applications based on the AOV Joint Owners Group recommendations. Eight types of quarter-turn valves were found to cover the AOV population in U.S. plants:

- Symmetric Disc Butterfly
- Single-Offset Disc Butterfly
- Double-Offset Disc Butterfly
- Triple-Offset Disc Butterfly
- Spherical Ball
- Segmented (V-Notch) Ball
- Eccentric Plug (Camflex)
- Cylindrical/Tapered Plug

The triple offset butterfly valve design has a relatively small population in the U.S. plants. Earlier surveys by NRC/INEL [5] and EPRI/NMAC [6,7] showed that manufacturers do not have validated models or methodologies for reliable torque predictions of quarter-turn valves that appropriately take into account the variations in disc geometry as a function of valve size, pressure class, model; fluid media (compressible or incompressible); and pressure drop ratios for compressible flow (from fully choked, unchoked, low ΔP, and vacuum applications). Many manufacturers have performed tests on a limited number of valve sizes (usually 8" or smaller) and developed sizing predictions for their entire product line without considering the geometric deviations with valve size/pressure class and validating the predictions against large valve tests. The effect on torque requirements of various elbow configurations and their proximity upstream of the valve has also not been evaluated by most manufacturers. Compressible flow tests have typically been performed with low flow/low ΔP unchoked conditions across the valve; choked flow conditions and the effects of pressure drop ratios have not been evaluated.

In fact, NRC/INEL testing [4,5] showed that the single offset disc butterfly valves (shaft downstream) that the *manufacturers* had *predicted to be self-closing* (based upon the manufacturers' in-house tests) *were found to be self-opening* throughout the stroke under the choked flow conditions typically encountered in containment purge and vent valves. Therefore, the NRC recommended ΔP testing or the use of *validated* models for the design basis evaluation of containment purge valves, and later for other MOVs under NRC Generic Letter 89-10. For the same reasons, ΔP testing or the use of validated models is recommended for the design basis evaluation of safety-related and high risk significant AOVs under NRC Regulatory Issue Summary 2000-03 [3].

2. EPRI MOV Performance Prediction Methodology Scope & Limitations

EPRI MOV PPM program was very comprehensive. One of the program objectives was to develop validated models of symmetric and single-off disc butterfly valves [6,7,8]. Even though the analytical model development included both incompressible and compressible flow, EPRI testing for butterfly valves was limited to incompressible flow. The objective of the EPRI MOV PPM was to develop a methodology to provide *bounding* torque requirements for these types of butterfly valves used in *MOV* applications. For MOV evaluations, only a *single value* for the *peak required torque* is needed, regardless of where the peak occurs. Therefore, the analytical model development of EPRI MOV PPM did not require a position-dependent accuracy in torque predictions as long as the maximum required torque prediction bounded the maximum measured torque. The analytical models that form the basis of EPRI MOV PPM symmetric and single offset butterfly valve methodology were based on simplified 2D streamline analysis approximations for thin discs. Adjustments for disc aspect ratio were based upon simplified hydraulic resistance calculations. Sufficiently large margins were included in the models to cover uncertainties in predictions based upon evaluation of available industry data from various sources and engineering judgment [6,7].

Important Difference Between REQUIRED TORQUE *and* TORQUE SIGNATURE *Predictions from EPRI MOV PPM*

EPRI MOV Performance Prediction Methodology Report provides two results: *Required Torque* prediction and *Torque Signature* prediction. The Required Torque prediction is used for evaluating the capability of the MOVs to work under design basis conditions. As stated in the EPRI MOV PPM model report, Torque Signature is provided for *reference only* to be used for interpreting in-situ test results, etc. [6,7,10]. The Torque Signature was neither developed nor validated for providing bounding predictions at all disc positions, e.g., in AOVs.

Validation of the EPRI MOV PPM models against flow loop and in-situ test data showed that the *Required Torque* predictions were bounding in all cases [7,8]. However, the PPM *Torque Signature* predictions were in some cases overly conservative, and in other cases significantly nonconservative over large portions of the stroke, as shown in Figures 2, 3, and 4, which include both compressible and incompressible flow. The validation results showed that the degree of conservatism or nonconservatism in the Torque Signature varied significantly for different valve designs and applications based upon disc shape (symmetric or single offset), disc aspect ratio, fluid media (compressible or incompressible), and pressure drop/flow conditions. For example, Figures 3 and 4 show that Torque Signature prediction for one of the test valves had a very large positive margin over actual test data (~300% at 65º) whereas for another test valve there was *significant negative margin* over a large portion of the stroke (from ~40º towards full open). It should be noted however that, in each case, the Required Torque prediction, which is the only value used for design evaluation of MOVs, is bounding.

From the above discussion, one can see that EPRI MOV PPM Required Torque provides bounding predictions for MOV evaluations. However, EPRI MOV PPM Torque Signature predictions or predictions based on utilizing EPRI MOV PPM torque/flow coefficients in other software (e.g., ACE, AirBase, Excel spreadsheets) to perform AOV evaluations can be overly conservative or nonconservative.

3. NRC/INEL Containment Purge and Vent Valve Test Program Scope and Limitations

Under the NRC/INEL program, three butterfly valves were tested with gaseous nitrogen under blowdown conditions [4,5]. This testing was limited to single offset disc design, because the NRC survey results showed that this design had the dominant population in the U.S. nuclear power plants. Symmetric disc, double- and triple-offset disc designs were not included in this test program. Furthermore, the NRC/INEL program did not include testing of two valves in series. NRC testing focused on the ability of the valve to close under high ΔP, fully choked containment purge and vent pressure conditions. Tests under low ΔP, unchoked flow conditions were not included. The NRC/INEL upstream elbow tests were limited to elbows at 0 pipe diameters from valve inlet. NRC/INEL provided recommendations for further testing to overcome these limitations. However, since the conclusion of the NRC/INEL program in 1985, no additional compressible flow tests have been performed by the industry to overcome these limitations. Recently, Kalsi Engineering conducted a comprehensive validated model development program, including compressible flow testing, to overcome these limitations [1,2].

4. Kalsi Engineering, Inc.'s Advanced Model Development Program for AOVs/MOVs

To develop validated models with position-dependent accuracy for all common types of quarter-turn valves in nuclear power plants, Kalsi Engineering conducted a comprehensive development program that included advanced analytical modeling, compressible and incompressible flow testing, to overcome the limitations of the EPRI MOV PPM, NRC/INEL Containment Purge and Vent Test Program, and manufacturers' data as discussed above. The program spanned three years and was conducted in two phases: Phase I focused on the analytical model development, flow loop testing, and validation for incompressible flow applications. Under Phase II, advanced models were developed based upon Computational Fluid Dynamics (CFD) analysis and compressible flow testing covering a wide range of pressure drop ratios from highly choked to unchoked conditions (Figure 5). CFD analyses and subsequent testing also showed that the presence of a downstream valve in series can significantly affect the upstream valve torque requirements (Figure 6). The details of this program have been covered in earlier papers [1,2]; only the overall scope and highlights are summarized below.

The test matrix included all common AOV quarter-turn valve designs with different aspect ratios (15 designs for Phase I and 9 designs for Phase II). Tests were performed with baseline configuration (no upstream elbows within 20 pipe diameters) and with three elbow configurations and three elbow proximities (from 0 to 8D) as shown in Figure 7. The test sequence for each valve installation configuration consisted of 17 static/dynamic strokes for incompressible flow testing (Table 1), and up to 24 strokes for compressible flow testing (Table 2). This resulted in a total matrix of 1,272 tests for incompressible flow (Figure 8) and 1,116 tests for compressible flow (Figure 9). The flow loop testing provided a massive database of nondimensional hydrodynamic torque/flow coefficients (for incompressible flow) and aerodynamic torque coefficients (for compressible flow) for various valve geometries over a wide range of flow conditions. Figures 10 and 11 show that the torque coefficients for incompressible flow do not depend upon ΔP, whereas there is a strong dependence of aerodynamic torque coefficients on $\Delta P/P_{up}$ ratio for compressible flow.

Table 3 shows the scope of advanced validated models that were developed under this two-phase program and their comparisons against the previously available methodologies and other industry softwares.

The KVAP software. The new validated models that have position-dependent accuracy as well as the massive database of coefficients were incorporated in a software, KVAP (Kalsi Valve and Actuator Program), to efficiently perform interpolations for appropriate torque/flow coefficients to be used for design basis calculations based upon valve geometry parameters (disc shape, aspect ratio,) installation parameters (disc orientation, elbow configuration and proximity), and operating parameters (fluid media, pressure, flow rate). The software was developed with emphasis on making it very intuitive and user friendly. In addition to incorporating the new validated models for quarter-turn valves, KVAP software includes all other types of linear valves (gate, globe, diaphragm) as well as all commonly used quarter-turn and linear actuators for performing complete design basis evaluations of the entire AOV population at nuclear plants.

Example KVAP evaluation for an actual plant installation. Figures 12 and 13 show a typical input screen and a margin plot from KVAP analysis of an AOV from an actual plant evaluation of a symmetric disc butterfly valve with a Scotch Yoke actuator used in the service water system. It is interesting to note that for this evaluation, even though the unseating torque is significantly higher than the total dynamic torque at all stroke positions, the minimum AOV margin is at around the 25-degree location (Figure 13). This example shows the importance of position-dependent accuracy in predicting valve torque requirements.

Quality assurance. All testing, model development, and KVAP software development activities were conducted in accordance with our quality assurance program, which satisfies 10CFR50 Appendix B requirements.

PLANT EXPERIENCE AND BENEFITS

Since the release of the KVAP program in November of 2000, the software has been used for AOV evaluations at more than 30 nuclear plants. In a significant number of these plants, substantial cost savings (often in excess of $500,000 at each plant) have been realized by the utilities by avoiding unnecessary modifications due to "apparent" negative margins that had been identified by other methodologies/software.

Figures 14 and 15 show typical improvement in margins based upon the use of the more accurate models in KVAP for incompressible and compressible flow applications. In many instances, modifications of AOV groups containing multiple valves (up to eight in several cases) were successfully avoided.

Another significant cost benefit provided by the validated models incorporated in KVAP is that they provide an alternative to dynamic ΔP testing to evaluate the capability of the AOV to operate under design basis conditions.

CONCLUSION

The advanced, validated models and KVAP software successfully fills the industry need for reliable position-dependent torque predictions for AOVs. Validated models provide an alternative to DP testing. Plant experience has shown significant cost savings by avoiding equipment modifications in many applications. The benefits in margin improvement from KVAP are also applicable to MOV applications. KVAP software is an efficient, intuitive, and user friendly software developed under our 10CFR50 Appendix B QA program to provide reliable predictions for safety-related applications.

ACKNOWLEDGEMENTS

Kalsi Engineering and the authors acknowledge contributions made by the valve manufacturers, NRC/INEL, EPRI/NMAC, and the utility engineers who have helped us over the years by giving us the opportunity to solve challenging valve and actuator problems.

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STROKE	TEST TYPE	DIRECTION	FLOW %	PRESS %	DP %
PRE-TEST PACKING FRICTION					
1	STATIC	O to C	0	0	0
2	STATIC	C to O	0	0	0
3	STATIC	O to C	0	100	0
4	STATIC	C to O	0	100	0
BEARING TESTS					
5	STATIC	C to10° O	Any	100	100
6	STATIC	10° O toC	Any	100	100
FLOW AND ∆P PARAMETRIC TESTS					
7	DYNAMIC	O to C	100	100	100
8	DYNAMIC	C to O	100	100	100
9	DYNAMIC	O to C	100	67	67
10	DYNAMIC	C to O	100	67	67
11	DYNAMIC	O to C	100	33	33
12	DYNAMIC	C to O	100	33	33
13	DYNAMIC	O to C	200	100	100
14	DYNAMIC	C to O	200	100	100
POST-TEST PACKING FRICTION					
15	STATIC	O to C	0	0	0
16	STATIC	C to O	0	0	0
17	STATIC	O to C	0	100	0
18	STATIC	C to O	0	100	0

Table 1
Test Sequence for Each Test Configuration for Incompressible Flow

Stroke No.	***Stroke Description***	***Downstream Throttle Valve Angle***	**Target Upstream**	***Stroke Direction***
1	Static Stroke	O	O	O → C → O
2	Static Stroke	O	Max Pressure	O→ C → O
3	Partial Stroke (10º)	Preset Angle	75	C → O → C
4	Dynamic Stroke	Preset Angle	75	O → C
5	Dynamic Stroke	Preset Angle	75	C → O
6	Partial Stroke (10º)	Preset Angle	60	C → O → C
7	Dynamic Stroke	Preset Angle	60	O → C
8	Dynamic Stroke	Preset Angle	60	C → O
9	Partial Stroke (10º)	Preset Angle	45	C → O → C
10	Dynamic Stroke	Preset Angle	45	O → C
11	Dynamic Stroke	Preset Angle	45	C → O
12	Partial Stroke (10º)	Preset Angle	30	C → O → C
13	Dynamic Stroke	Preset Angle	30	O → C
14	Dynamic Stroke	Preset Angle	30	C → O
15	Partial Stroke (10º)	Preset Angle	15	C → O → C
16	Dynamic Stroke	Preset Angle	15	O → C
17	Dynamic Stroke	Preset Angle	15	C → O
18	Partial Stroke (10º)	Preset Angle	10	C → O → C
19	Dynamic Stroke	Preset Angle	10	O → C
20	Dynamic Stroke	Preset Angle	10	C → O
21	Partial Stroke (10º)	Preset Angle	5	C → O → C
22	Dynamic Stroke	Preset Angle	5	O → C
23	Dynamic Stroke	Preset Angle	5	C → O
24	Static Stroke	O	O	O → C→ O

Table 2

Standard test sequence for compressible flow. The complete sequence of tests is repeated with different preset angles to simulate different downstream resistances.

	Valve Types Prevalent in AOV Population	NRC/INEL Cont. Purge	EPRI MOV PPM (Note 1)	Ace, AirBase, Others (Note 2)	KVAP Software
1	Symmetric Butterfly	**None**	√	**None**	√
2	Single-Offset Butterfly	√	√	**None**	√
3	Double-Offset Butterfly	**None**	**None**	**None**	√
4	Segmented V-Ball	**None**	**None**	**None**	√
5	Spherical Ball	**None**	**None**	**None**	√
6	Eccentric Plug	**None**	**None**	**None**	√
7	Tapered/Cylinder Plug	**None**	**None**	**None**	√

Note 1: EPRI MOV PPM models provide bounding predictions for MOVs. EPRI Torque Signature predictions can be nonconservative over portions of the stroke.

Note 2: ACE, AirBase, and other software, e.g., Excel spreadsheet, do not have built-in validated torque/ flow coefficients. Predictions based on the use of EPRI MOV PPM coefficients in these softwares can be nonconservative over portions of the stroke.

Table 3

Comparison of Validated Models Available in KVAP Against Other Methodologies/Software

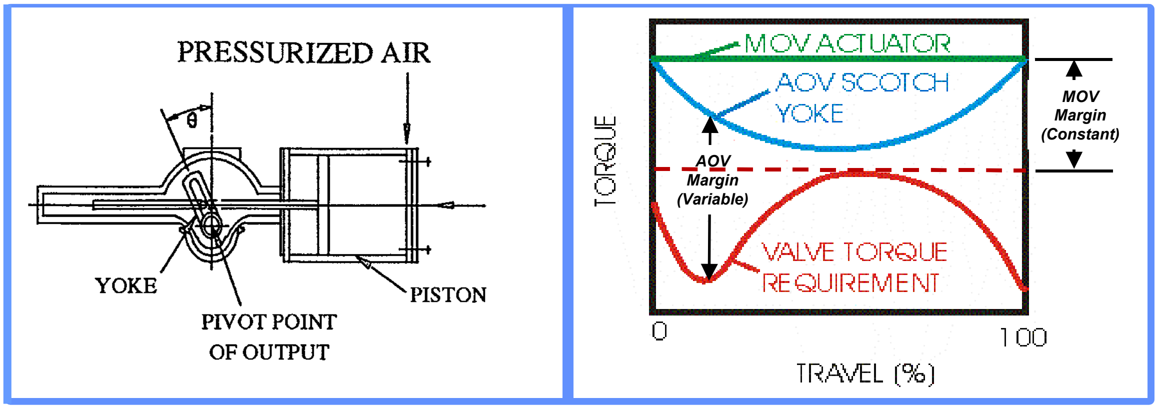


Figure 1: Required Torque Prediction Models for AOVs must be accurate at all positions throughout the stroke for reliable evaluation of AOV margin.

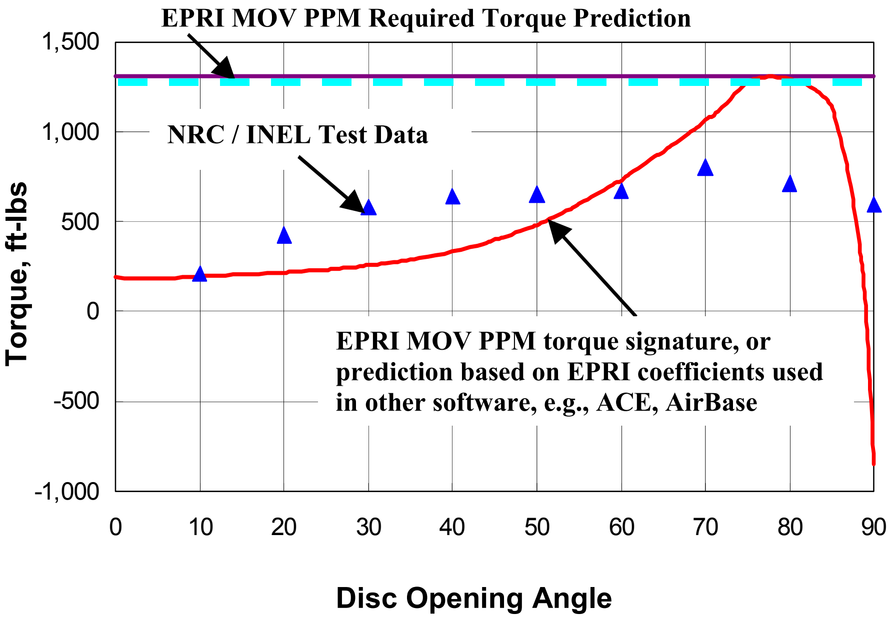
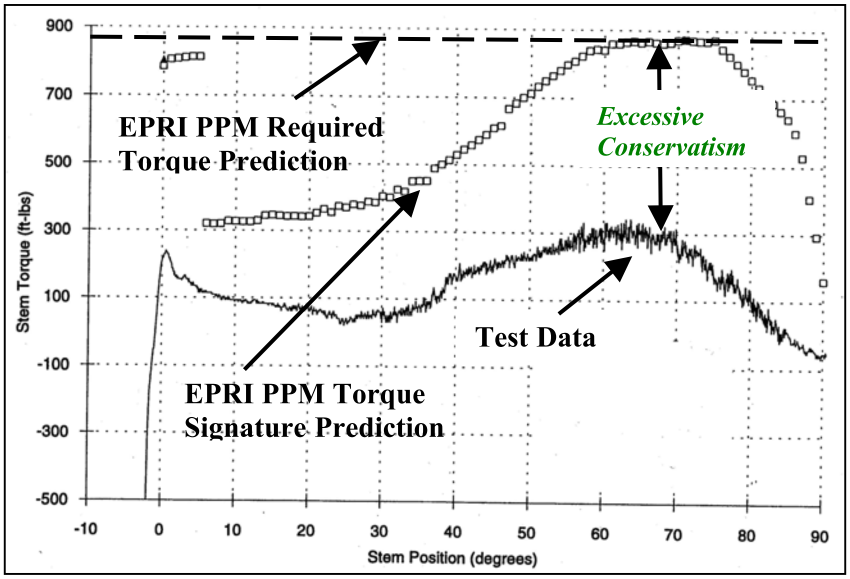
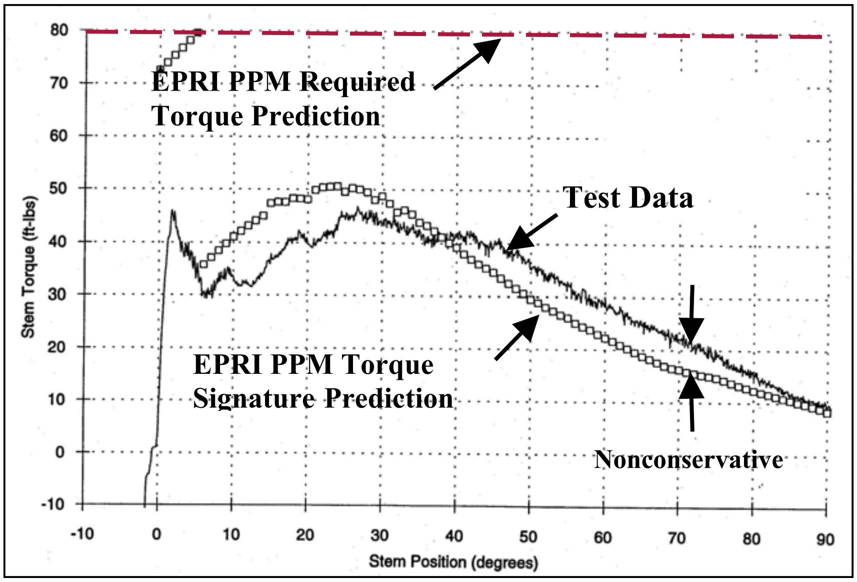


Figure 2: EPRI MOV PPM Required Torque bounds test data, but Torque Signature predictions are nonconservative over a large portion of the stroke for this valve (compressible flow example).



EPRI Valve Test No. F-55

Figure 3: Both the Required Torque and Torque Signature predictions from EPRI MOV PPM have large conservatism for this valve (incompressible flow example).



EPRI Valve Test No. I-27

Figure 4: The Required Torque prediction from EPRI MOV PPM is bounding, but the Torque Signature prediction is nonconservative over a large portion of the stroke for this valve (incompressible flow example).

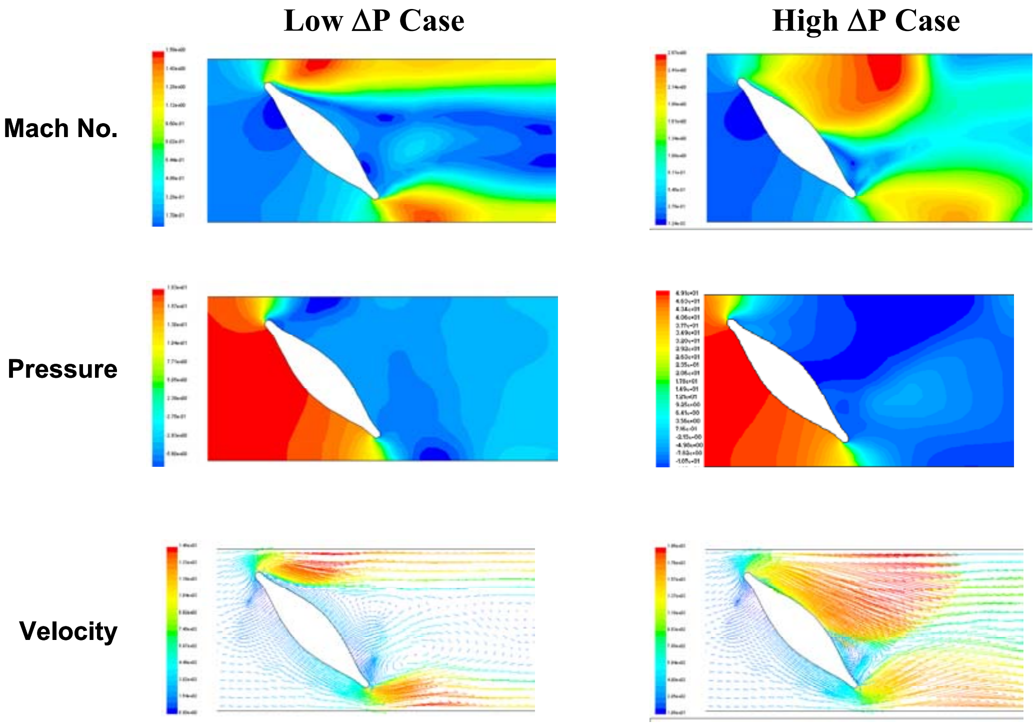


Figure 5: Compressible flow CFD analyses under low ΔP and high ΔP conditions show how the pressure drop distribution changes significantly over the downstream disc face, thus affecting the aerodynamic torque requirements.

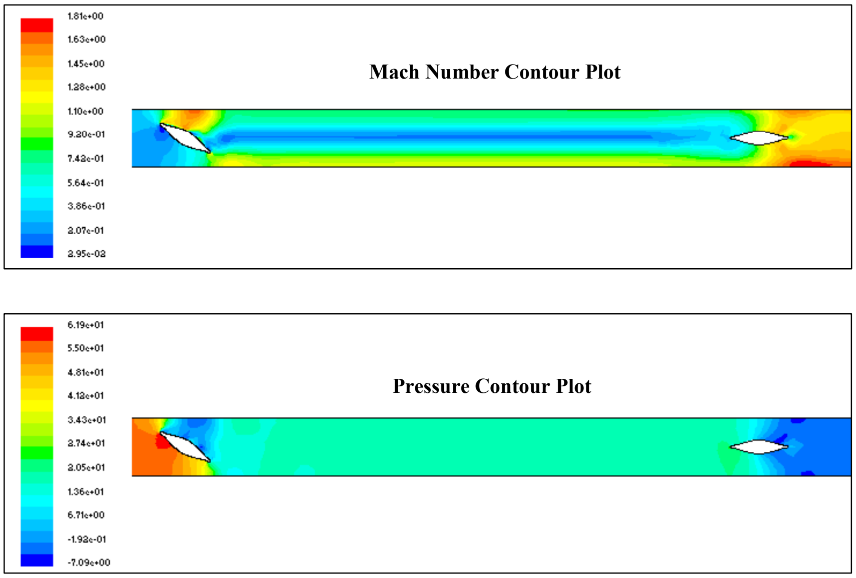


Figure 6: Choked Flow at the Downstream Valve Significantly Alters Aerodynamic Torque Requirements of Upstream Valve

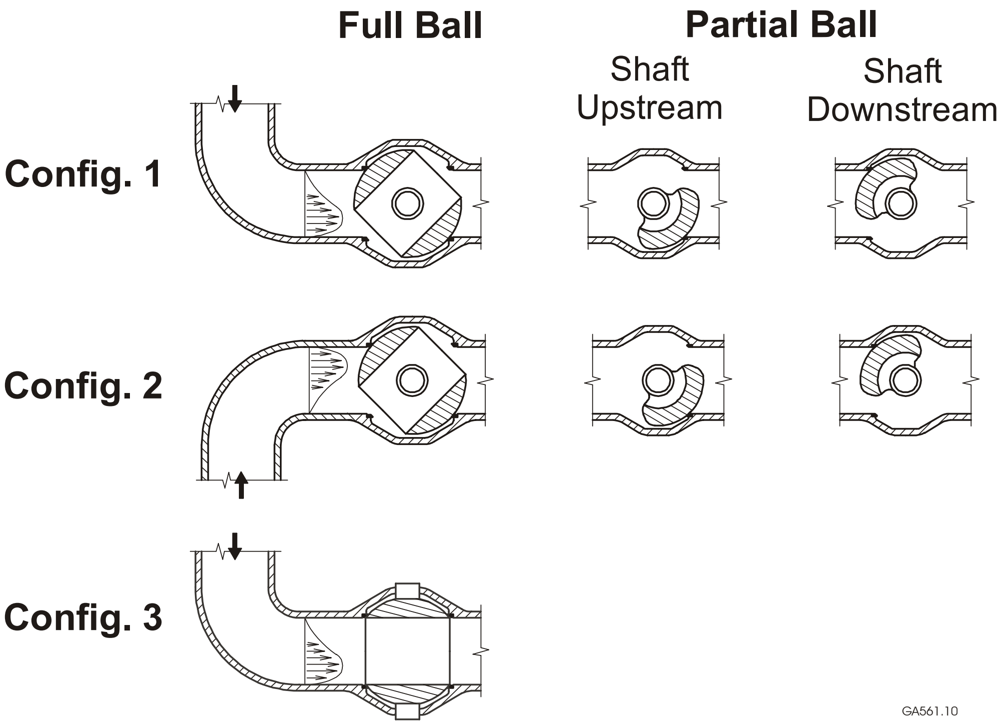


Figure 7: Test configurations included baseline (no elbows) and 3 elbow configurations at 4 proximities.

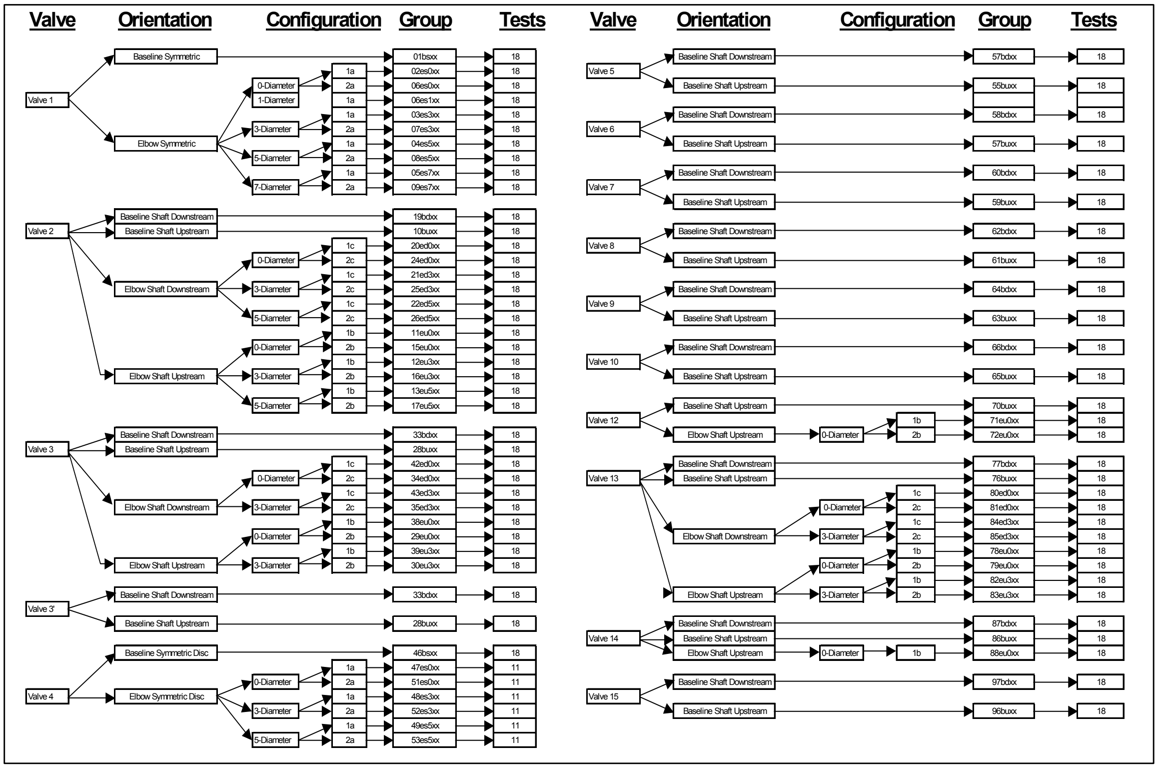


Figure 8: Incompressible flow matrix included 15 valve designs, 71 configurations, 1,272 tests.

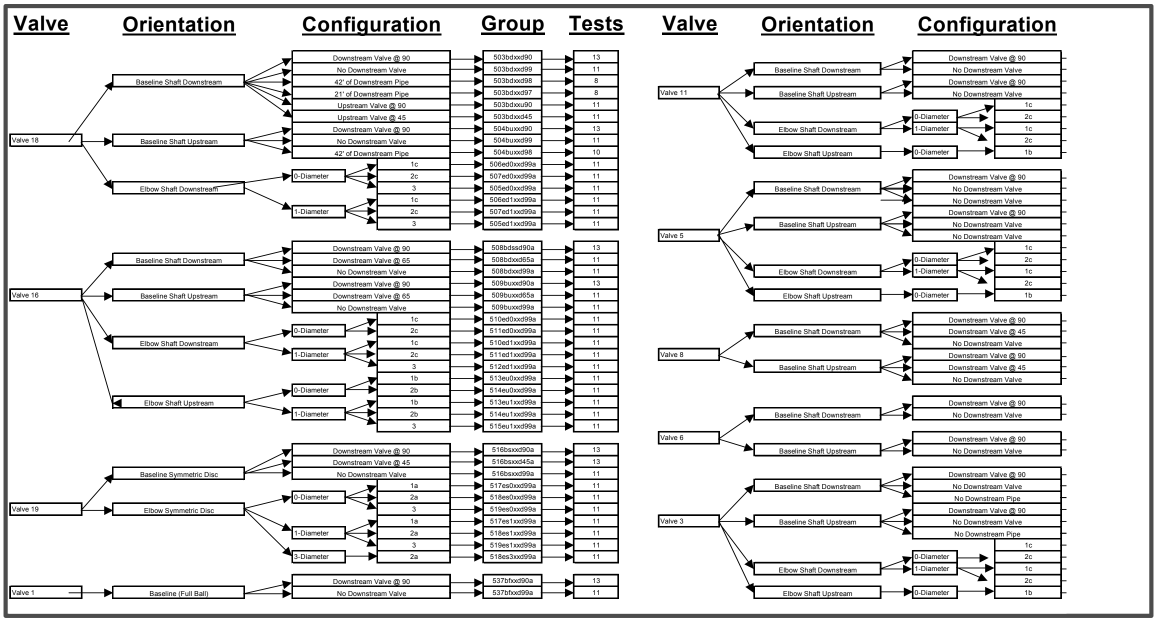


Figure 9: Compressible flow matrix included 9 valve designs, 84 configurations, 1,116 tests.

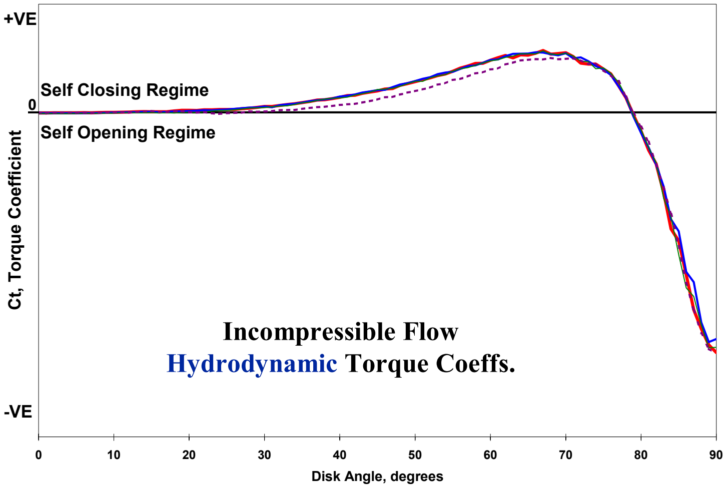


Figure 10: For incompressible flow, torque coefficients are independent of pressure drop.

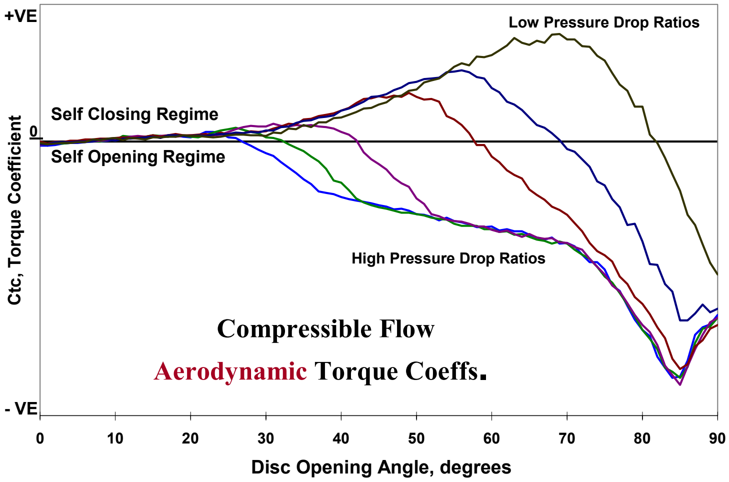
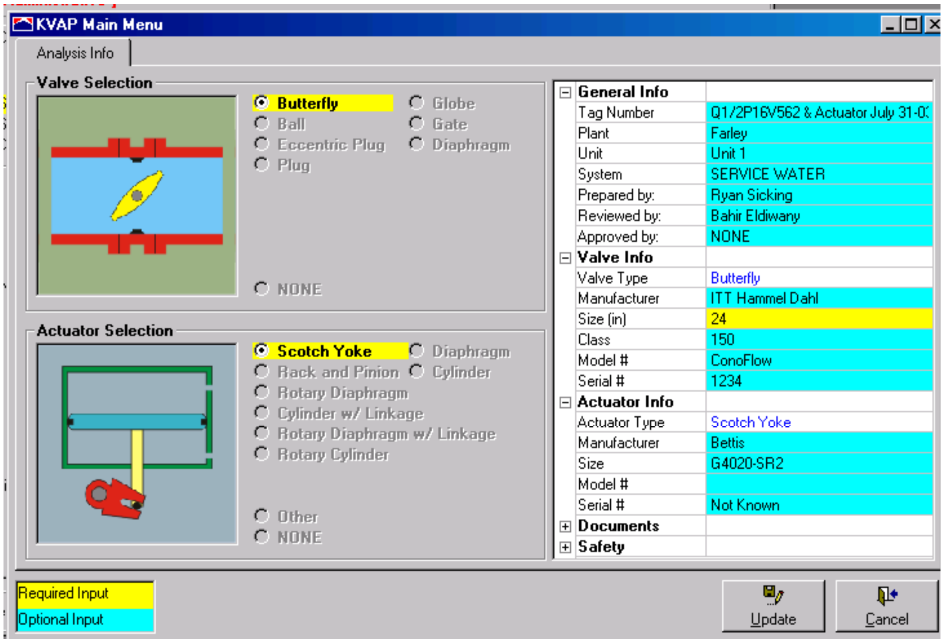


Figure 11: For compressible flow, torque coefficients are strongly dependent on the ratio of ΔP/upstream pressure; and can change valve torque requirements from self-closing to self-opening.



Valve Selection

● **Butterfly**
○ Ball
○ Eccentric Plug
○ Plug
○ Globe
○ Gate
○ Diaphragm
○ NONE

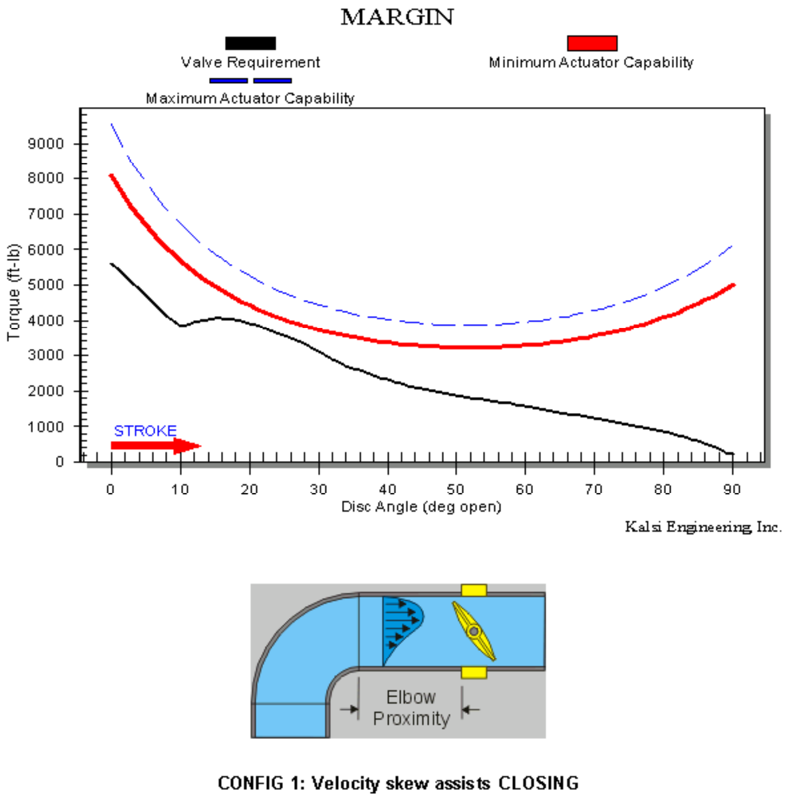
Actuator Selection

● **Scotch Yoke**
○ Rack and Pinion
○ Rotary Diaphragm
○ Cylinder w/ Linkage
○ Rotary Diaphragm w/ Linkage
○ Rotary Cylinder
○ Diaphragm
○ Cylinder
○ Other
○ NONE

General Info	
Tag Number	Q1/2P16V562 & Actuator July 31-0
Plant	Farley
Unit	Unit 1
System	SERVICE WATER
Prepared by:	Ryan Sicking
Reviewed by:	Bahir Eldiwany
Approved by:	NONE
Valve Info	
Valve Type	Butterfly
Manufacturer	ITT Hammel Dahl
Size (in)	24
Class	150
Model #	ConoFlow
Serial #	1234
Actuator Info	
Actuator Type	Scotch Yoke
Manufacturer	Bettis
Size	G4020-SR2
Model #	
Serial #	Not Known
Documents	
Safety	

🟨 Required Input
🟦 Optional Input

Figure 12: Typical KVAP Input Screen



CONFIG 1: Velocity skew assists CLOSING

Figure 13: Margin Plot from KVAP Analysis of a Butterfly AOV

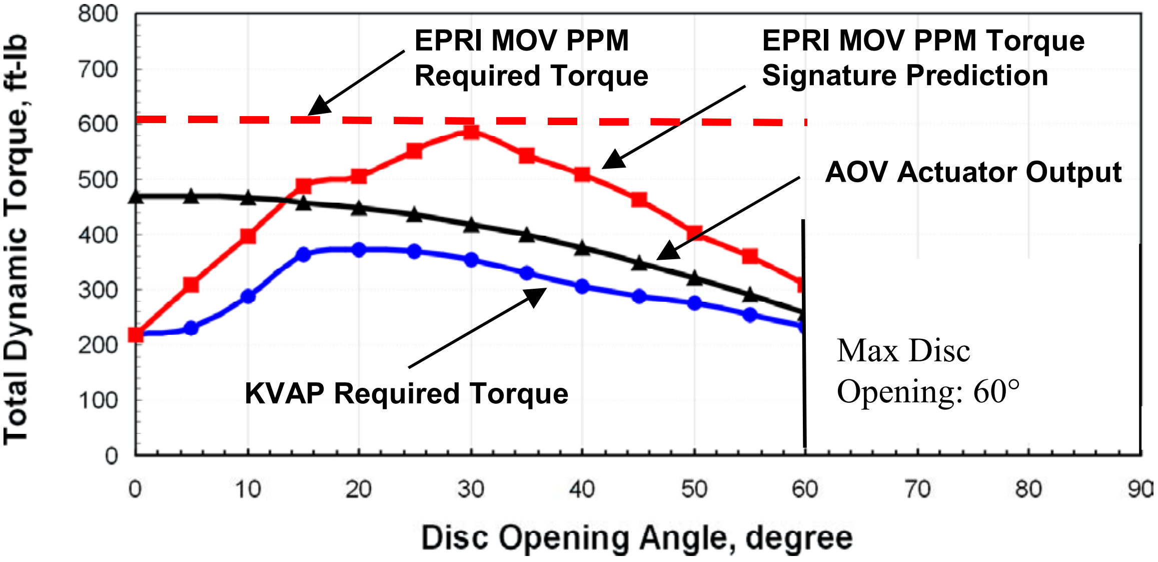


Figure 14: Margin improvement achieved by use of KVAP models in an incompressible flow (service water) application at a plant.

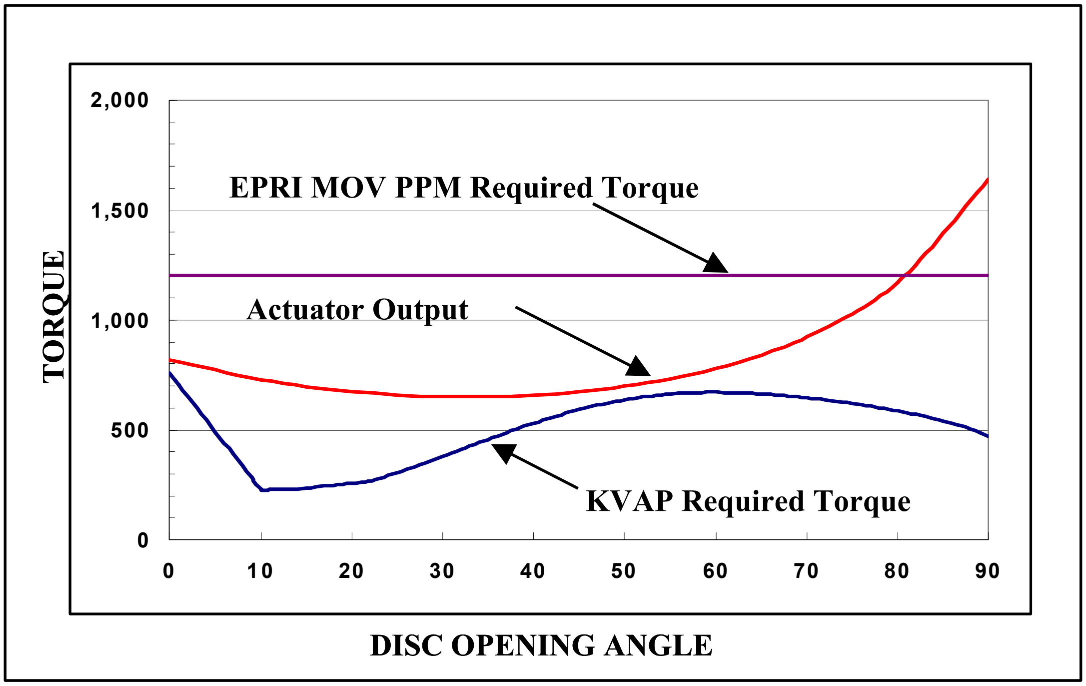
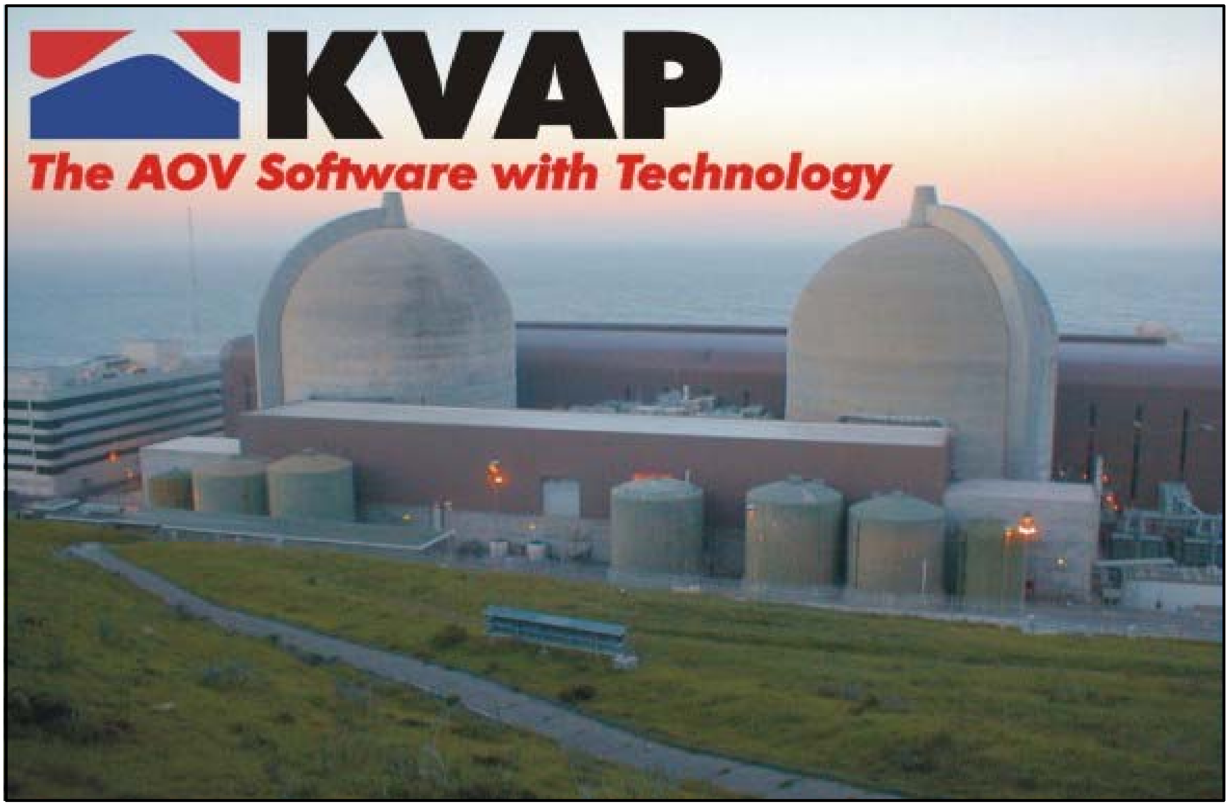


Figure 15: Margin improvement achieved by use of KVAP models in a compressible flow (containment purge) application at a plant.


KVAP
The AOV Software with Technology