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Business Confidential Document

Screening for PRV Stability – Inlet Pressure Drop and The 3 % Rule

by

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78th API Refining and Equipment Standards Meeting

April 20-27, 2013

Las Vegas

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We can conclude the following based on the reasoning presented in this paper

- Chatter is most likely in vapor service - Damage will most likely be due to large mechanical forces caused by the rapid valve closure and/or by PRV reduced flow capacity due to PRV damage. This is especially true for large valves and/or for valves in high pressure service
- Chatter is least likely in flashing two-phase***** flow service and/or in liquid service
- Flutter will almost always occur in liquid service with fast opening or pop action valves
- Cycling is most likely to occur in flashing two-phase flow service
- Piping damage is most likely in liquid service due to the large magnitude of the water hammer pressure waves propagated upstream during rapid valve closure (full or partial), i.e. during chatter or during flutter
- The 3 % inlet pressure is not sufficient to guarantee PRV stability. Stability may need to be assessed and confirmed for all credible scenarios and not necessarily just the one with the highest required flow rate

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All models have limitations, some models are more useful than others

The design and evaluation of relief systems is highly constrained

- The relief system should prevent the failure of the vessel due to overpressure or underpressure
- Damage to vessel, piping, and valve can be prevented by design
  - Fluid reaction forces, steady and dynamic loading
  - Vibration risk, especially to discharge piping
  - Fatigue failure caused by PRV chatter to valve, piping, and piping components
  - Large pressure fluctuations caused by acoustic resonance
  - Vortex shedding (singing relief valve problem) for some specific installations
- If we can address all the above requirements, we also need to properly handle and treat the effluent
- Finally we need to properly document the design and keep the documentation up to date and easily accessible

Typical causes of chatter include

- Excessive inlet pressure loss
- Excessive backpressure
- Oversized valve
- Bad installation

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To determine if a "relief system" will operate in a stable manner (chatter and flutter free) we need to consider important system time constants and how they interact

- Valve time constant
  - How fast does a pressure relief device close and open?
- Vessel or pressure source time constant
  - How fast does a vessel de-pressure and re-pressure after a pressure relief device opens and re-seats?
- Inlet line time constant
  - How long does it take for a pressure wave to propagate upstream from a pressure relief device to the pressure source and back?
- Outlet line time constant
  - Acoustic barriers may be established due to "body bowl choking"
  - Note that acoustic barriers, such as the presence of control valves, change in diameter, etc. can cause standing waves that can lead to acoustic coupling or resonance with relief systems components

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How can we <u>simply</u> establish if PRV stability is an issue for a specific installation?

- It has been shown that very long inlet lines will result in stable PRV operation
- It has been shown that a PRV will go through a short period of instability during closing and by inference during opening as the valve gets to full lift
- During valve closing, if the inlet line is short enough, the returning compression wave can keep the valve open
- It is expected that the coefficient of restitution and sticktion force can change the calculated valve response
- A slower valve may be better
- Low flow rates cause less damping for the relief system and are more problematic
- Resonance amplification factors can be very large, 50 to 100 times
- Stable PRV installations are required/implied by ASME and API

The 3 % inlet pressure loss rule is not sufficient to guarantee PRV stability

- More is needed to confirm a stable installation…
  - The inlet line/fluid fundamental frequency should be sufficiently decoupled from the valve frequency to prevent resonance/harmonics
  - The total pressure drop, wave and frictional, should be less than the valve blowdown
  - The valve blowdown should be carefully established and verified
- Reduced flow rates due to excessive pressure drop must still provide sufficient relief capacity
- The impact of longer relief durations on dispersion, fire, and explosion risk needs to be evaluated
- The analysis in this presentation is restricted to inlet pressure loss at constant conditions. Dynamics need to be considered as source pressure increases from P_{set} to full open pressure (see earlier presentations on dynamics).

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First, some key assumptions…

- Fast opening and/or pop action valve
- PRV opening time can be different from closing time
- Mass flow rate is at stable open position – 10 % overpressure for example
- Mass flow rate varies linearly with time
- Mass flow rate during PRV closing is 80 % of mass flow rate during opening
- Largest upstream pressure fluctuations occur during valve opening or closure
- Rigid piping supports, i.e. piping supports do not influence speed of sound
- Backpressure is within normal limits, i.e. does not influence stability
- Valve blowdown is known or can be verified

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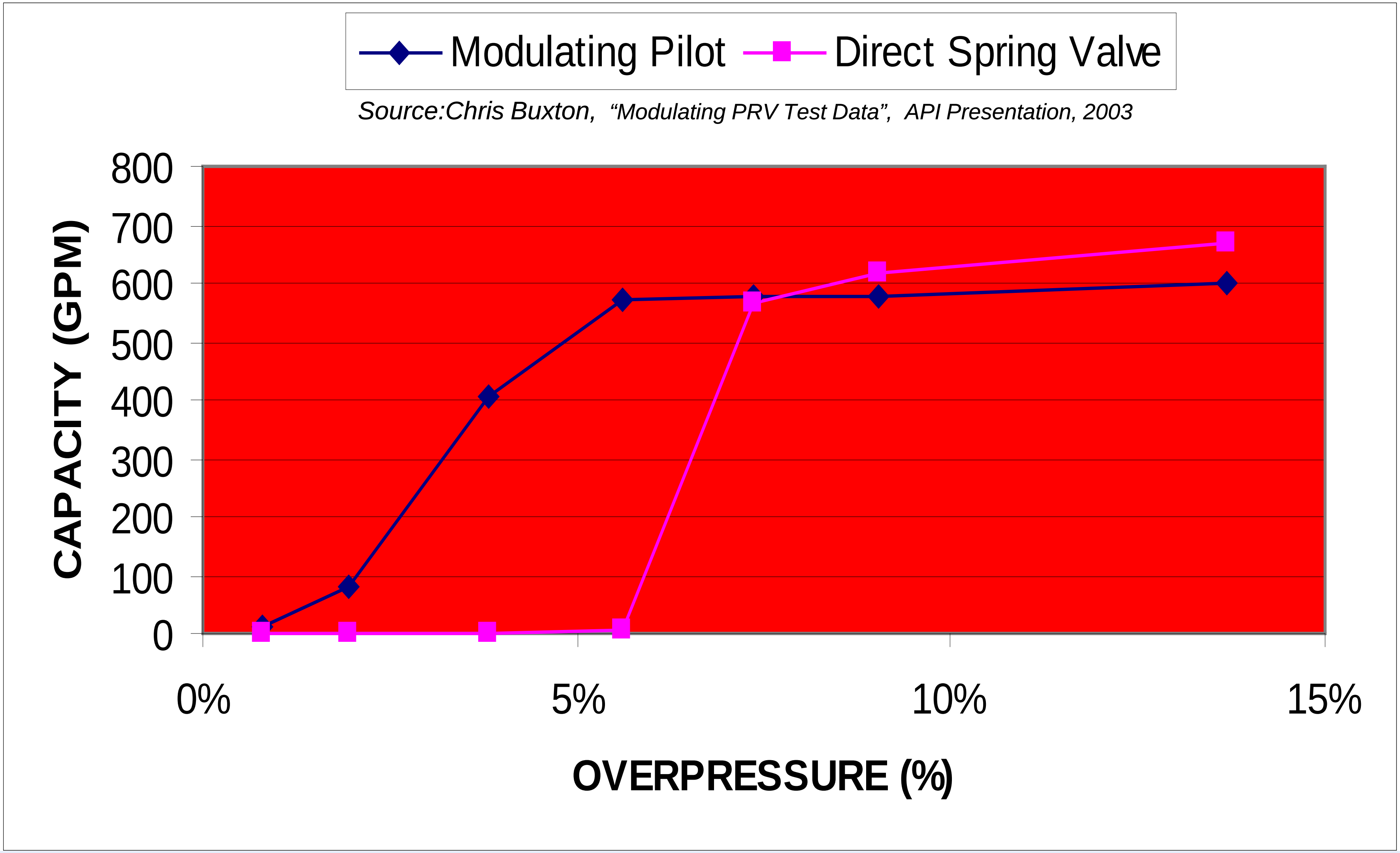
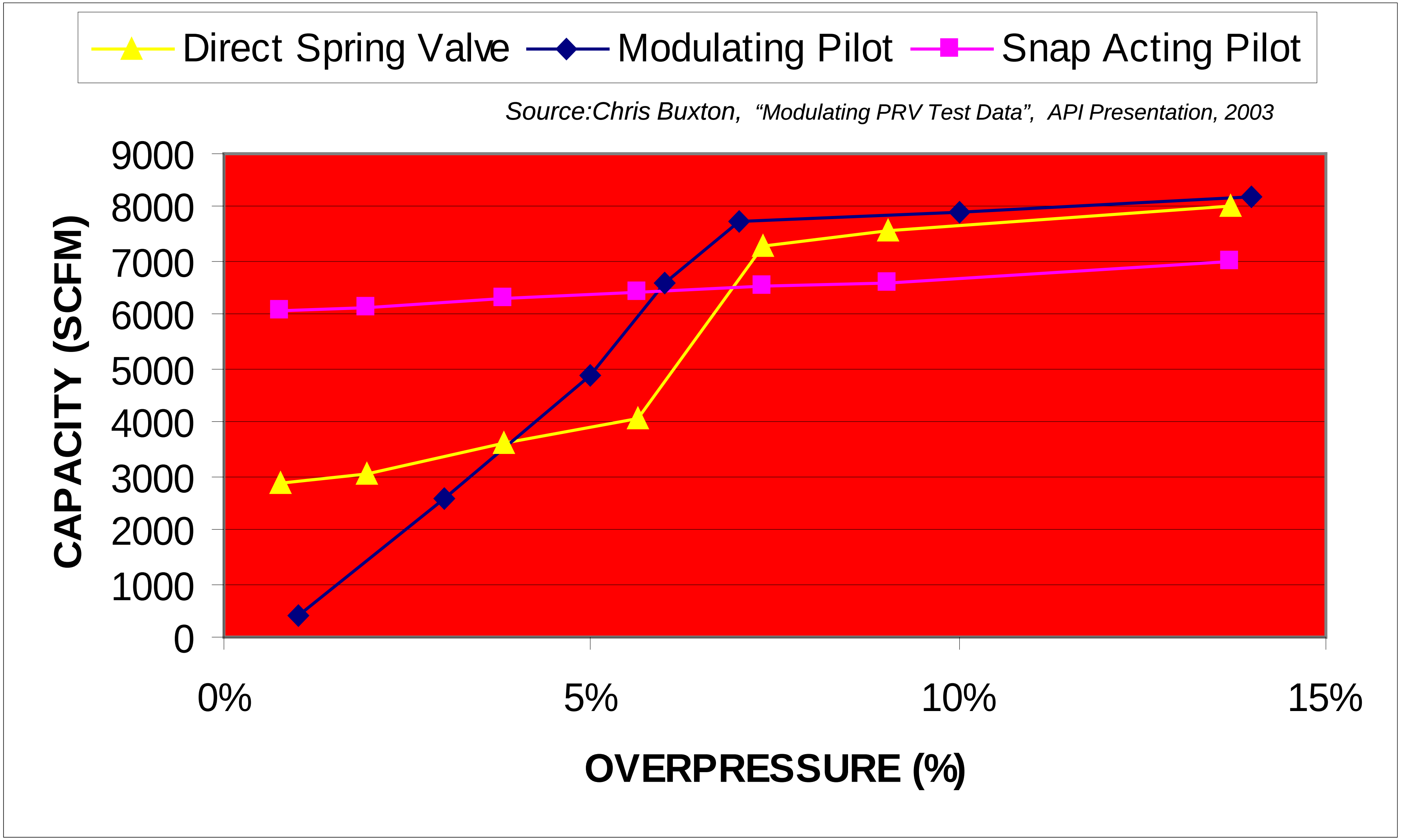
Liquid opening test results - 2J3 (250 psig set)



Gas opening test results - 2J3 (250 psig set)



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How does one estimate the valve opening and closing times?

- Typically ranges from 25 to 50 milliseconds
- Get it from the manufacturer
- Get total valve weight from manufacturer catalogue and then estimate the disk and spring mass in motion using simple equations
- Calculate valve ideal opening / closing time
- Use computational PRV test bench to simulate opening and closing of PRV
  - SuperChems
  - API/PERF model
  - ?
- Literature correlations

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Estimate the weight in motion of PRV spring/disk system

$$m = \text{disk mass} + \text{spring mass} / 3$$

$$\approx \frac{\left[1.8 + 0.022 \times W\right] \times W}{100} \text{ yields m in lbs}$$

W = PRV body weight with 150 psi flange in lbs

Source: M. A. Grolmes, "DIERS Odds and Ends – PRV Stability", Parts 1 through 5, Multiple DIERS Users Group Meetings

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Establish the PRV spring constant

$$k \approx \left[\frac{A_d}{A_n}\right]\left[\frac{P_{open}}{P_{set}}\right]\frac{P_{set}A_n}{X_{\max}} \approx \frac{1.1P_{set}A_d}{X_{\max}}$$ yields k in force/length

One can also use the equation proposed by Grolmes

$$k \approx 5.15P_{set}\sqrt{A_{API}}$$ yields k in lbf/in, P_{set} in psig, A_{API} in in^2

Note:

Spring constant varies linearly with axial distance and does not change with temperature. Gravity force ignored.

A_d	=	*Disk area*
A_n	=	*Nozzle area*
P_{open}	=	*PRV full open pressure, 1.1xP_{set}*
X_{max}	=	*Maximum lift*

Source: M. A. Grolmes, "DIERS Odds and Ends – PRV Stability", Parts 1 through 5, Multiple DIERS Users Group Meetings

Approximate the valve opening and closing times based on the spring constant and the spring/disk mass in motion

$$f_{nat} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \text{ yields } \mathrm{f}_{\mathrm{nat}} \text{ in Hz (cycles/second)}$$

$$t_{open} \simeq \frac{\sqrt{\dfrac{2}{\dfrac{A_d}{A_n}-1}}}{2\pi}\left[\frac{1}{f_{nat}}\right] \text{ yields time in seconds}$$

Source: M. A. Grolmes, “DIERS Odds and Ends – PRV Stability”, Parts 1 through 5, Multiple DIERS Users Group Meetings

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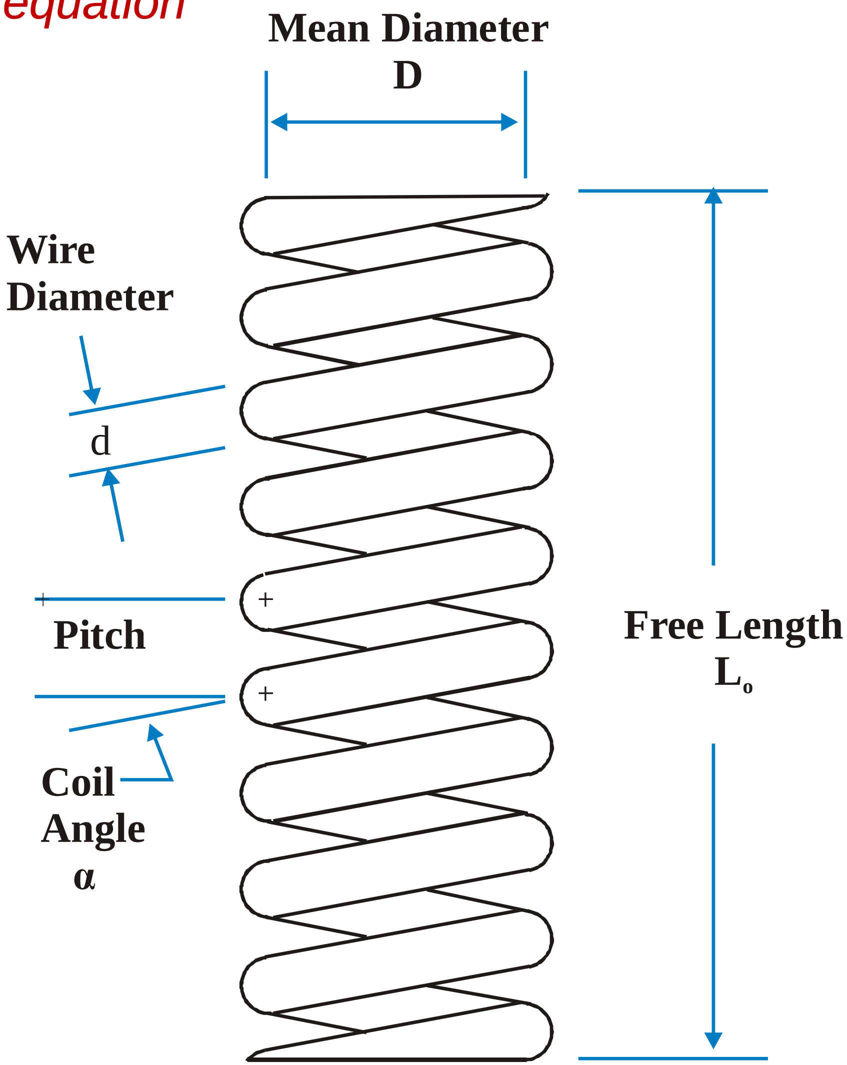
The spring constant can also be calculated for a helical spring using a more detailed equation



$$k = \frac{G\,d}{8\,C^3\,N_a}$$

N_a is the number of active coils

G is the modulus of torsion or rigidity

C is the diameter modulus; C = D/d

D is the mean diameter

d is the coil diameter

Source: M. A. Grolmes, "DIERS Odds and Ends – PRV Stability", Parts 1 through 5, Multiple DIERS Users Group Meetings

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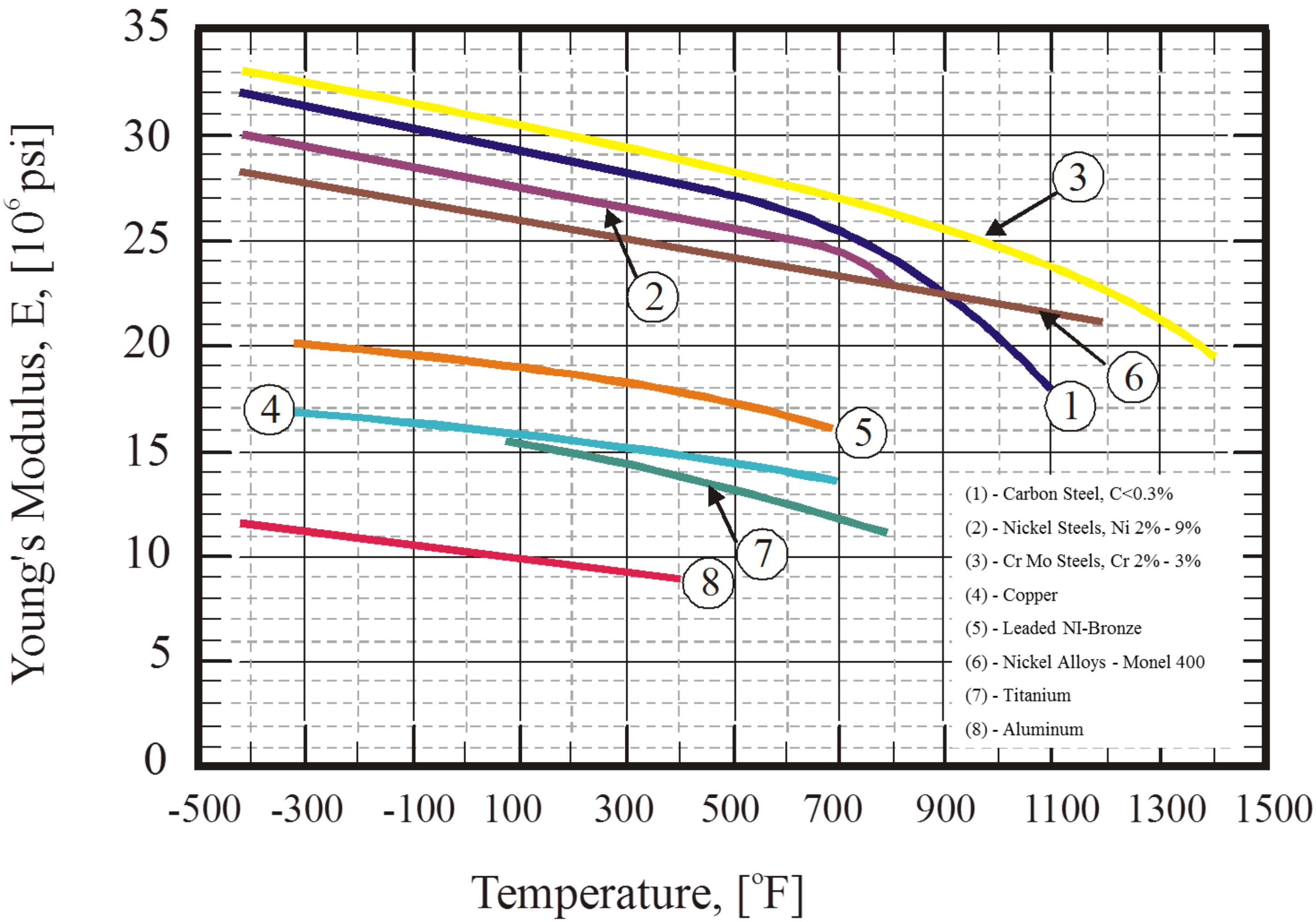
Typical properties of materials from the literature can be used

Material	E (GPa)	Poisson's Ratio ν	$K = \frac{1}{\kappa}$ (GPa)	ρ in kg/m3
Aluminum	69	0.33		
Brass	78-110	0.36		
Carbon steel	202	0.303		
Cast iron	90-160	0.25		
Concrete	20-30	0.15		
Copper	117	0.36		
Ductile iron	172	0.30		
Fibre cement	24	0.17		
High carbon steel	210	0.295		
Inconel	214	0.29		
Mild steel	200-212	0.27		
Nickel steel	213	0.31		
Plastic / Perspex	6.0	0.33		
Plastic / Polyethylene	0.8	0.46		
Plastic / PVC rigid	2.4-2.75			
Stainless steel 18-8	201	0.30		
Water - fresh			2.19	999 at 20 C
Water - sea			2.27	1025 at 15 C

E is typically referred to as Young's modulus of elasticity
G is typically referred to as modulus of torsion, $G = \frac{1}{2}\frac{E}{1+\nu}$

Source: SuperChems v7

Note that the valve materials properties change with temperature



Source: M. A. Grolmes, "DIERS Odds and Ends – PRV Stability", Parts 1 through 5, Multiple DIERS Users Group Meetings

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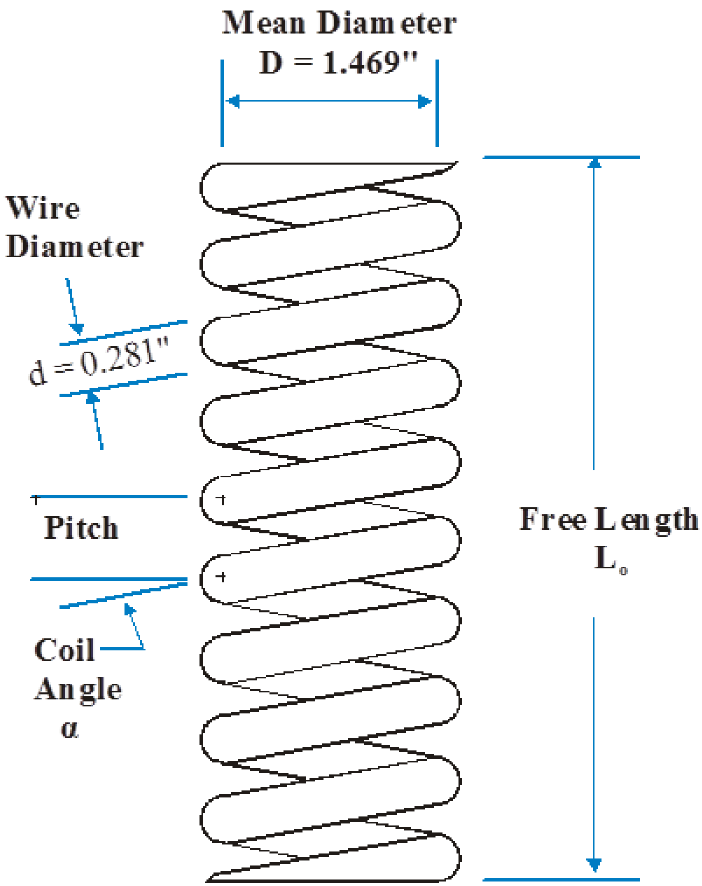
An example – spring from Farris 26 FA 10 – 120. P_{set} = 180 psig



$$N_a = 8$$

$$C = \frac{D}{d} = 5.288$$

$$E = 205 \times 10^9 \text{ GPa}$$

$$\nu = 0.31$$

$$G = 78.2 \times 10^9 \text{ GPa}$$

Spring Weight = 360 g

Other Parts in Motion Weight = 435 g

Total Weight in Motion = 435 + 360 / 3 = 555 g

$$k = \frac{G\,d}{8C^3 N_a}$$

$$k = \frac{11.35 \times 10^6 \times 0.281}{8 \times 5.288^3 \times 8} = 349 \frac{lbf}{in} \text{ or } 61294 \text{ N/m}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{61294}{0.555}} = 53\,\text{Hz}$$

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4P6 Farris data reported by Grolmes and later analyzed by Melhem

27	Minimum lift. in	0		
28	Maximum lift. in	0.901		
29				
30	Inlet line nominal pipe size	4	4	
31	Inlet line piping schedule	40		
32	Inlet flange pressure rating and class. bara	11.3554	ANSI	
33				
34	Outlet line nominal pipe size	6	6	
35	Outlet line piping schedule	40		
36	Outlet flange pressure rating and class. bara	11.3554	ANSI	
37				
38	Flow Type	Gas / Vapor	Liquid	Two Phase
39	Discharge Coefficient	0.95000	0.65000	0.95000
40	Slip ratio multiplier zeta			1.00000
41	Slip ratio exponent eta			0.00010
42	Actual orifice flow area. in2	6.41080		
43	Design orifice flow area. in2	6.41080	Design/Actual >>>	1.0000
44	Letter	P	Beta ratio >>>	0.7096
45	Flow Area Basis	Red Book		
46	Set pressure. bara	4.4606	Will first open at >>>	4.8054 bara
47	Reset pressure. bara	4.2193		
48	Maximum blowdown. %	14.000	Actual blowdown >>>	7.000 %
49				

Source: SuperChems v7

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4P6 Farris data reported by Grolmes and later analyzed by Melhem

61	Valve dynamics parameters [Advanced users only]	
62		
63	Flow area at the inner seat / minimum flow area	1.000
64	Disk backpressure area / minimum flow area	1.300
65	Disk area enclosed by bellows / minimum flow area	0.000
66		
67	Valve mass in motion. lb	11.54
68	Spring constant. lbf/in	571.96
69	Critical damping ratio	0.200
70	Coefficient of restitution	0.010
71		
72	Fluid exit angle (from vertical) at full lift. degrees	20.00
73	Force conversion efficiency for valve seat top surface pressure	0.60
74	Discharge coefficient factor	0.25
75		
76	Undamped natural period. s	0.0454
77	Undamped natural frquency. Hz	22.0173
78		
79	User defined opening time. ms	27.0000
80	User defined closing time. ms	38.0000
81		

Source: SuperChems v7

Calculate the 4P6 spring/mass data using the simple equations outlined earlier

W = 190 lb from catalogue

$$m = \frac{\left[1.8 + 0.022 \times 190\right] \times 190}{100} = 11.36 \text{ lb or } 5.15 \text{ kg}$$

$$\left[\frac{A_d}{A_n}\right] \approx 1.30, \; X_{max} = 0.90 \text{ in and } A_n = 7.087 \text{ in}^2 \text{ from Red Book}$$

$$k = \frac{1.1 P_{set} A_d}{X_{max}} = \frac{1.1 \times 4.46 \times 10^5 \times 1.3 \times 0.004572}{0.9 \times 0.0254} = 127{,}556 \text{ N/m or } 728 \text{ lbf/in}$$

$$\approx 5.15 P_{set} \sqrt{A_{API}} \approx 5.15 \times 50 \times \sqrt{6.48} = 655 \text{ lbf/in}$$

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Calculate the 4P6 frequency using the simple spring/mass equations outlined earlier

$$f_{nat} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{127{,}556}{5.15}} = 25\,\mathrm{Hz}$$

$$t_{open} \approx \frac{\sqrt{\dfrac{2}{\dfrac{A_d}{A_n}-1}}}{2\pi}\left[\frac{1}{f_{nat}}\right] \approx \frac{\sqrt{\dfrac{2}{1.3-1}}}{2\pi}\left[\frac{1}{25}\right] = 0.0164\ \mathrm{s}$$

$$t_{close} \approx t_{open} = 16.5\ \text{milliseconds}$$

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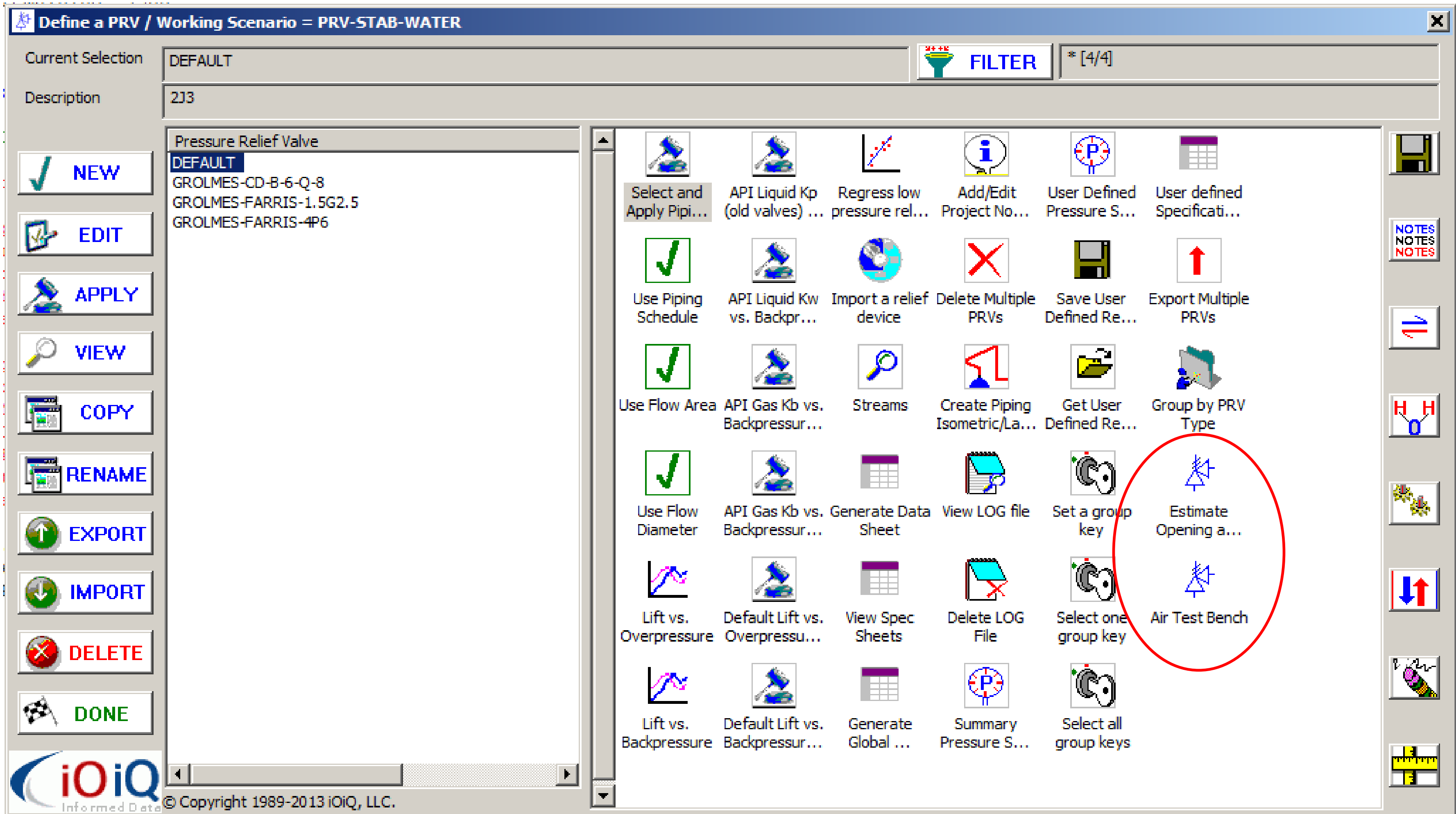
The SuperChems PRV object includes two useful tools



Source: SuperChems v7

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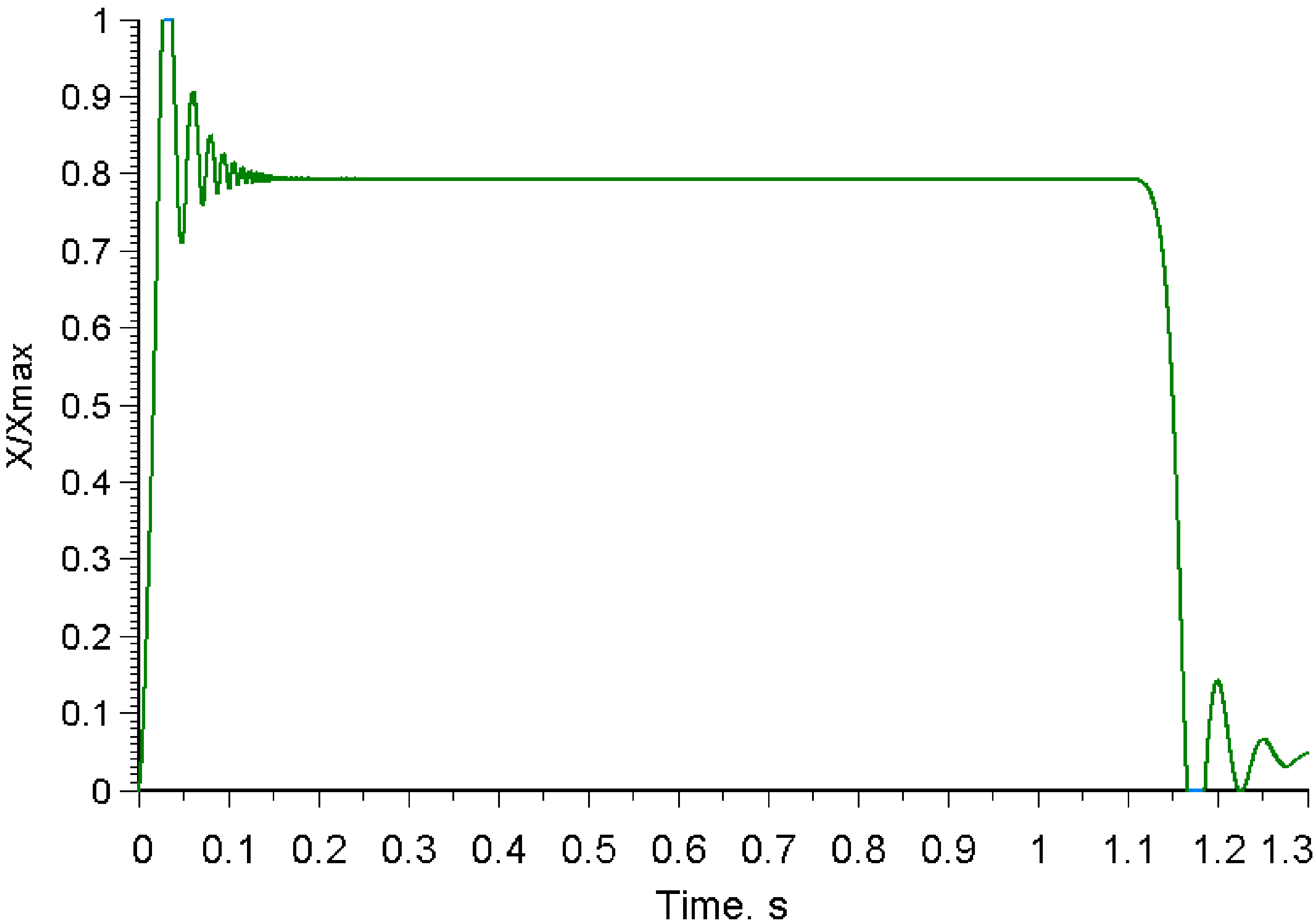
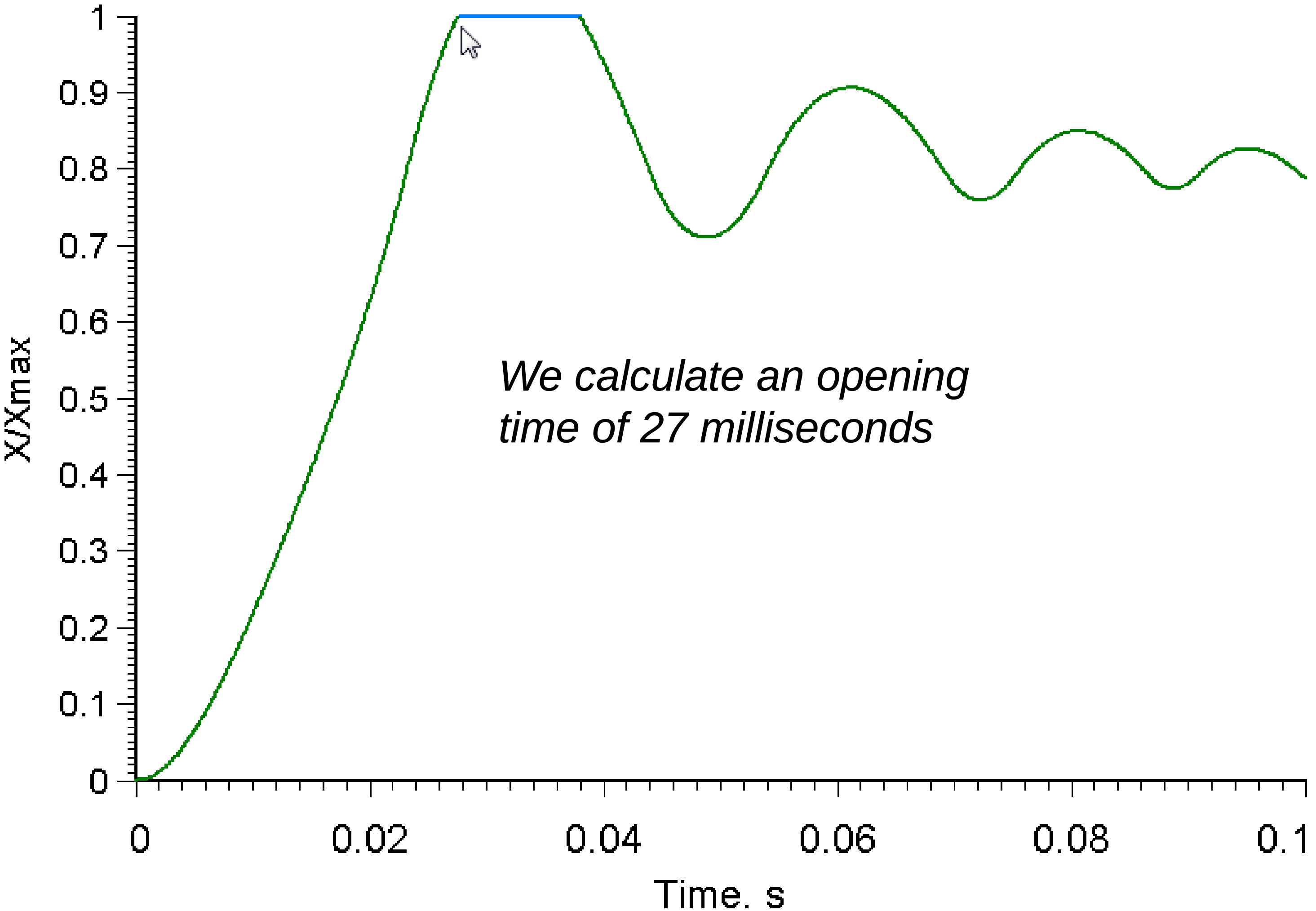
Use the PRV test bench in SuperChems to calculate the opening and closing times starting at a pressure of 1.1xPset



Source: SuperChems v7

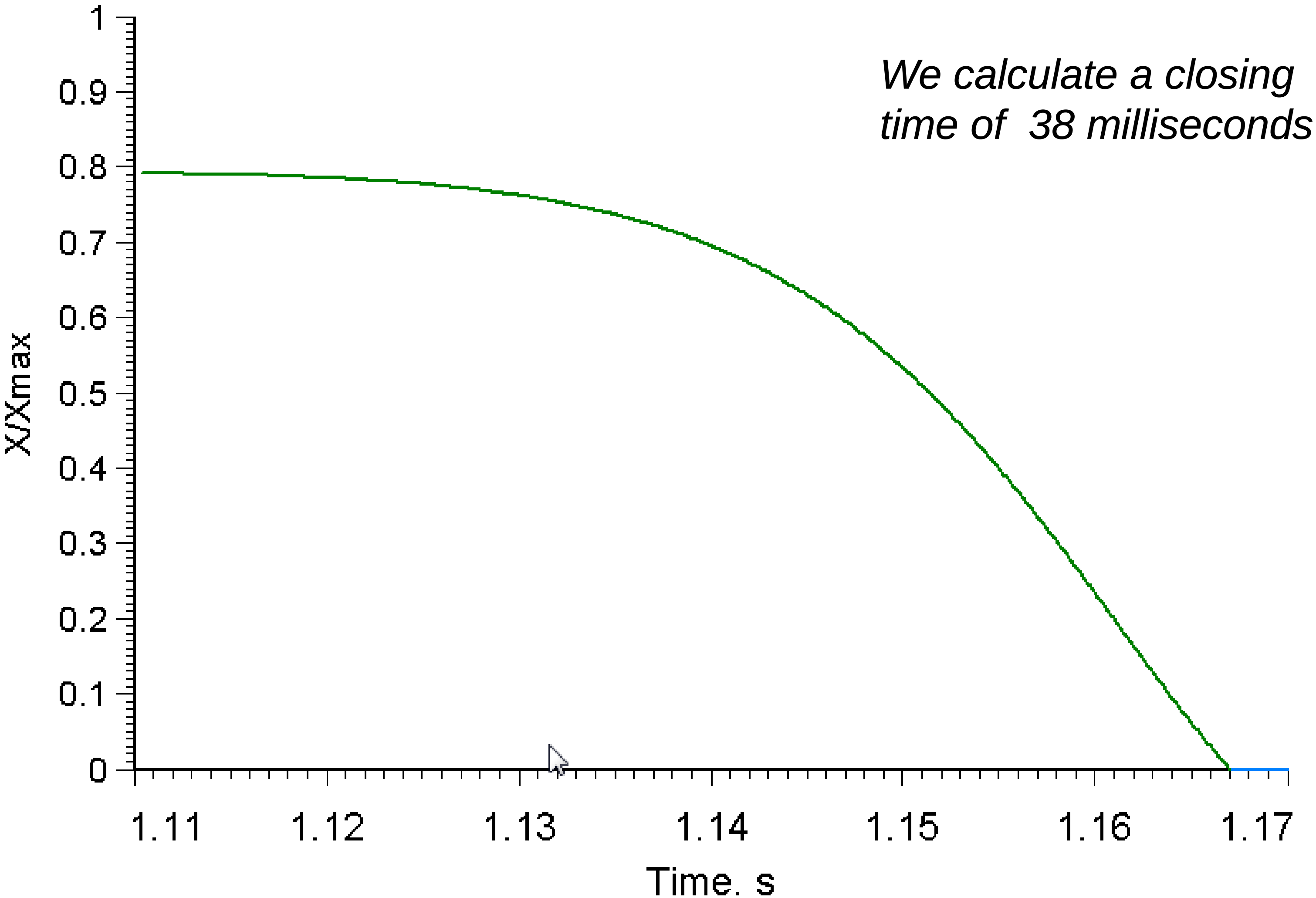
Use the PRV test bench in SuperChems to calculate the opening and closing times



We calculate an opening time of 27 milliseconds

Source: SuperChems v7

Use the PRV test bench in SuperChems to calculate the opening and closing times



Source: SuperChems v7

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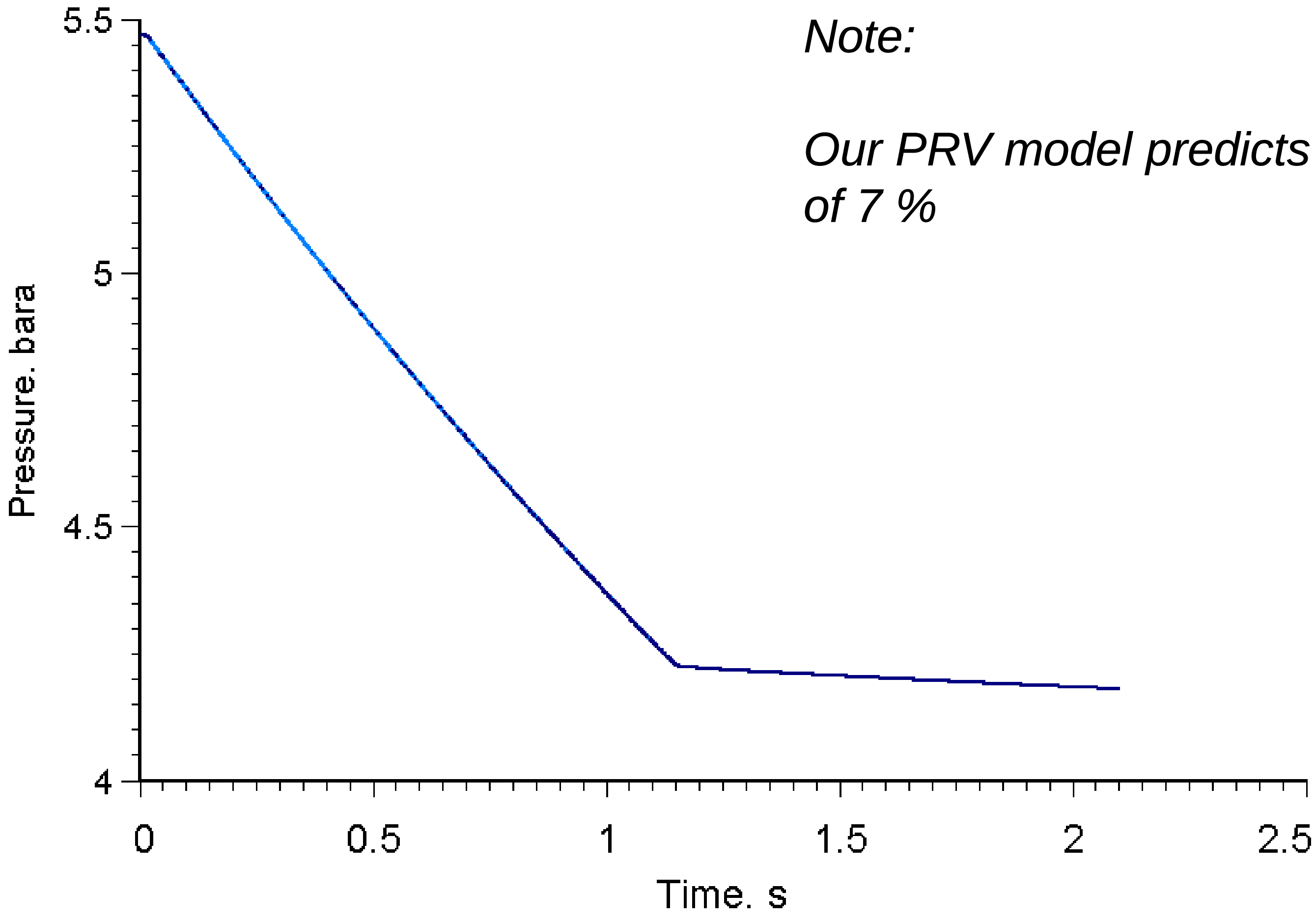
Use the PRV test bench in SuperChems to confirm the valve blowdown



Note:

Our PRV model predicts a blowdown of 7 %

Source: SuperChems v7

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When a PRV opens or closes, we need to approximate the pressure drop caused by the expansion / compression wave in addition to any irrecoverable pressure drop

$$t_{wave} = 2\frac{L_p}{c_0}$$

$$\tau = \min\left[\frac{t_{wave}}{t_{valve}}, 1\right] \text{ where } t_{valve} \text{ is the opening or closing time}$$

$$\Delta P_{wave} = \tau\frac{c_0 \dot{M}}{A_p} + \tau^2 \frac{\dot{M}^2}{2\rho_0 A_P^2} \text{ where } 0 \le \tau \le 1$$

$$\Delta P_{f,wave} = \tau^2 \Delta P_f \text{ where } 0 \le \tau \le 1$$

Source: Singh, ASME, 1983

Use the 4P6 PRV we considered earlier in a simple relief line arrangement

- 4 inch inlet line, 1 meter long, ½ velocity head loss for entrance
- 6 inch discharge line, 5 meters long, 1 velocity head loss for exit
- Vapor flow
  - P = 1.1xPset, T= 25 C, Methane
- Liquid Flow
  - P = 1.1xPset, T=25 C, Water
- Two Phase Flow
  - P = 1.1xPset, T=Saturation, Quality = 0.001, Water

All Vapor Flow Solution, L = 1 m

33			
34	Relief device found at segment 2	GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase	
35	Last iteration Kb correction	1.00	
36	Pressure at device inlet. bara	4.64	
37	% inlet pressure drop relative to actual set point	4.94	
38	% irreversible inlet pressure drop relative to actual set point	4.46	** WARNING: Inlet pressure drop exceeds 3.0 percent
39	% back pressure relative to actual set point	6.63	
40			

41	Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
42	001, Piping Segment, 4 INCH INLET	0.0000	0.0000	39.3701	4.0260	12.7303
43	002, Pressure Relief Valve (orifice), GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
44	003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903
45						

46	PRV Inlet Pressure Drop Stability Analysis	Opening	Closing
47	Pressure required for. bara	4.461	4.219
48	Blowdown. bara	0.241	0.241
49	Blowdown in %	7.000	7.000
50	Acoustic pressure drop during. bara	0.287	0.162
51	Irreverisble pressure drop during. bara	0.004	0.001
52	Total pressure drop during. bara	0.292	0.163
53	Blowdown required for stable operation in % during	8.457	4.731
54	Pressure at PRV inlet during. bara	4.514	4.642
55	Time required for. milliseconds	27.000	38.000
56	Wave time during. milliseconds	4.492	4.492
57	Wave time / time required for	0.166	0.118
58	Resonance/Harmonics during	Not Likely	Not Likely
59	Chatter, flutter, or cycle during	Not Likely	Not Likely
60			

61	Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?

Source: SuperChems v7

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All Liquid Flow Solution, L = 1 m

28			
29	Relief device found at segment 2		GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase
30	Last iteration Kb correction	1.00	
31	Pressure at device inlet. bara	4.58	
32	% inlet pressure drop relative to actual set point	6.44	
33	% irreversible inlet pressure drop relative to actual set point	6.44	** WARNING: Inlet pressure drop exceeds 3.0 percent
34	% back pressure relative to actual set point	1.53	
35			

	Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
36						
37	001, Piping Segment, 4 INCH INLET	0.0000	0.0000	39.3701	4.0260	12.7303
38	002, Pressure Relief Valve, (orifice) GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
39	003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903
40						

41	PRV Inlet Pressure Drop Stability Analysis	Opening	Closing
42	Pressure required for. bara	4.461	4.219
43	Blowdown. bara	0.241	0.241
44	Blowdown in %	7.000	7.000
45	Acoustic pressure drop during. bara	6.035	3.431
46	Irreverisble pressure drop during. bara	0.000	0.000
47	Total pressure drop during. bara	6.035	3.431
48	Blowdown required for stable operation in % during	175.072	99.513
49	Pressure at PRV inlet during. bara	-1.230	1.375
50	Time required for. milliseconds	27.000	38.000
51	Wave time during. milliseconds	0.533	0.533
52	Wave time / time required for	0.020	0.014
53	Resonance/Harmonics during	Not Likely	Not Likely
54	Chatter, flutter, or cycle during	Flutter Likely	Flutter Likely
55			

	Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?
56						

Source: SuperChems v7

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Two-Phase Flow Solution, L = 1 m

36	Relief device found at segment 2	GROLMES-FARRIS-4P6: NOT SPECIFIED; Bellows; Svc= Twophase				
37	Last iteration Kb correction	1.00				
38	Pressure at device inlet. bara	4.78				
39	% inlet pressure drop relative to actual set point	0.63				
40	% irreversible inlet pressure drop relative to actual set point	0.52				
41	% back pressure relative to actual set point	20.21				
42						
43	Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
44	001, Piping Segment, 4 INCH INLET	0.0000	0.0000	39.3701	4.0260	12.7303
45	002, Pressure Relief Valve, (orifice) GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
46	003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903
47						
48	PRV Inlet Pressure Drop Stability Analysis	Opening	Closing			
49	Pressure required for. bara	4.461	4.219			
50	Blowdown. bara	0.241	0.241			
51	Blowdown in %	7.000	7.000			
52	Acoustic pressure drop during. bara	0.129	0.099			
53	Irreverisble pressure drop during. bara	0.018	0.011			
54	Total pressure drop during. bara	0.147	0.111			
55	Blowdown required for stable operation in % during	4.258	3.219			
56	Pressure at PRV inlet during. bara	4.659	4.694			
57	Time required for. milliseconds	27.000	38.000			
58	Wave time during. milliseconds	320.102	320.102			
59	Wave time / time required for	1.000	1.000			
60	Resonance/Harmonics during	Not Likely	Not Likely			
61	Chatter, flutter, or cycle during	Not Likely	Not Likely			
62						
63	Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?

Source: SuperChems v7

Let's make the valve chatter!

- Increase inlet line length to 5 m

Vapor Flow Solution, L = 5 m

Relief device found at segment 2		GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase
Last iteration Kb correction	1.00	
Pressure at device inlet. bara	4.49	
% inlet pressure drop relative to actual set point	9.27	
% irreversible inlet pressure drop relative to actual set point	8.40	** WARNING: Inlet pressure drop exceeds 3.0 percent
% back pressure relative to actual set point	6.16	

Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
001, Piping Segment, 4 INCH INLET	0.0000	0.0000	196.8504	4.0260	12.7303
002, Pressure Relief Valve (orifice), GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903

PRV Inlet Pressure Drop Stability Analysis	Opening	Closing
Pressure required for. bara	4.461	4.219
Blowdown. bara	0.241	0.241
Blowdown in %	7.000	7.000
Acoustic pressure drop during. bara	1.514	0.823
Irreverisible pressure drop during. bara	0.200	0.065
Total pressure drop during. bara	1.714	0.888
Blowdown required for stable operation in % during	49.731	25.750
Pressure at PRV inlet during. bara	3.091	3.918
Time required for. milliseconds	27.000	38.000
Wave time during. milliseconds	22.461	22.461
Wave time / time required for	0.832	0.591
Resonance/Harmonics during	Likely	Not Likely
Chatter, flutter, or cycle during	Chatter Likely	Flutter Likely

Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?

Source: SuperChems v7

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Liquid Flow Solution, L = 5 m

Relief device found at segment 2		GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase
Last iteration Kb correction	1.00	
Pressure at device inlet. bara	4.39	
% inlet pressure drop relative to actual set point	12.14	
% irreversible inlet pressure drop relative to actual set point	12.14	** WARNING: Inlet pressure drop exceeds 3.0 percent
% back pressure relative to actual set point	1.42	

Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
001, Piping Segment, 4 INCH INLET	0.0000	0.0000	196.8504	4.0260	12.7303
002, Pressure Relief Valve, (orifice) GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903

PRV Inlet Pressure Drop Stability Analysis	Opening	Closing
Pressure required for. bara	4.461	4.219
Blowdown. bara	0.241	0.241
Blowdown in %	7.000	7.000
Acoustic pressure drop during. bara	29.342	16.678
Irreveristble pressure drop during. bara	0.004	0.001
Total pressure drop during. bara	29.346	16.679
Blowdown required for stable operation in % during	851.248	483.816
Pressure at PRV inlet during. bara	-24.540	-11.874
Time required for. milliseconds	27.000	38.000
Wave time during. milliseconds	2.663	2.663
Wave time / time required for	0.099	0.070
Resonance/Harmonics during	Not Likely	Not Likely
Chatter, flutter, or cycle during	Flutter Likely	Flutter Likely

Segment #, Type, Name	D/t	Maximum SPL.	Limit SPL. dB	SPL	Vibration

Source: SuperChems v7

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Two-Phase Flow Solution, L = 5 m

36	Relief device found at segment 2	GROLMES-FARRIS-4P6: NOT SPECIFIED; Bellows; Svc= Twophase				
37	Last iteration Kb correction	1.00				
38	Pressure at device inlet. bara	4.75				
39	% inlet pressure drop relative to actual set point	1.57				
40	% irreversible inlet pressure drop relative to actual set point	1.30				
41	% back pressure relative to actual set point	19.46				
42						
43	Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
44	001, Piping Segment, 4 INCH INLET	0.0000	0.0000	196.8504	4.0260	12.7303
45	002, Pressure Relief Valve, (orifice) GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
46	003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903
47						
48	PRV Inlet Pressure Drop Stability Analysis	Opening	Closing			
49	Pressure required for. bara	4.461	4.219			
50	Blowdown. bara	0.241	0.241			
51	Blowdown in %	7.000	7.000			
52	Acoustic pressure drop during. bara	0.134	0.103			
53	Irreverisble pressure drop during. bara	0.045	0.029			
54	Total pressure drop during. bara	0.179	0.132			
55	Blowdown required for stable operation in % during	5.183	3.831			
56	Pressure at PRV inlet during. bara	4.627	4.673			
57	Time required for. milliseconds	27.000	38.000			
58	Wave time during. milliseconds	1516.026	1516.026			
59	Wave time / time required for	1.000	1.000			
60	Resonance/Harmonics during	Not Likely	Not Likely			
61	Chatter, flutter, or cycle during	Not Likely	Not Likely			
62						
63	Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?

Source: SuperChems v7

Let’s make the valve chatter even when we meet the 3 % rule

- Inlet line is 5 m long
- Increase inlet line diameter to 5 inches

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All Vapor Solution, L = 5 m, Enlarged Inlet Pipe Diameter to 5 inches

33						
34	Relief device found at segment 2	GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase				
35	Last iteration Kb correction	1.00				
36	Pressure at device inlet. bara	4.69				
37	% inlet pressure drop relative to actual set point	3.24				
38	% irreversible inlet pressure drop relative to actual set point	3.11	** WARNING: Inlet pressure drop exceeds 3.0 percent			
39	% back pressure relative to actual set point	6.89				
40						
41	Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
42	001, Piping Segment, 4 INCH INLET	0.0000	0.0000	196.8504	5.0470	20.0058
43	002, Pressure Relief Valve (orifice), GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
44	003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903
45						
46	PRV Inlet Pressure Drop Stability Analysis	Opening	Closing			
47	Pressure required for. bara	4.461	4.219			
48	Blowdown. bara	0.241	0.241			
49	Blowdown in %	7.000	7.000			
50	Acoustic pressure drop during. bara	0.972	0.536			
51	Irreverisble pressure drop during. bara	0.074	0.024			
52	Total pressure drop during. bara	1.046	0.560			
53	Blowdown required for stable operation in % during	30.336	16.243			
54	Pressure at PRV inlet during. bara	3.760	4.245			
55	Time required for. milliseconds	27.000	38.000			
56	Wave time during. milliseconds	22.456	22.456			
57	Wave time / time required for	0.832	0.591			
58	Resonance/Harmonics during	Likely	Not Likely			
59	Chatter, flutter, or cycle during	Chatter Likely	Not Likely			
60						
61	Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?

Source: SuperChems v7

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All Vapor Solution, L = 5 m, Enlarged Inlet Pipe Diameter to 6 inches

Relief device found at segment 2	GROLMES-FARRIS-4P6: NOT SPECIFIED. Bellows. Service= Twophase
Last iteration Kb correction	1.00
Pressure at device inlet. bara	4.76
% inlet pressure drop relative to actual set point	1.38
% irreversible inlet pressure drop relative to actual set point	1.36
% back pressure relative to actual set point	7.08

Segment #, Type, Name	Start Elevation. in	End Elevation. in	Length. in	Exit Diameter. in	Exit/Flow Area. in2
001, Piping Segment, 4 INCH INLET	0.0000	0.0000	196.8504	6.0650	28.8903
002, Pressure Relief Valve (orifice), GROLMES-FARRIS-4P6	0.0000	19.8750	19.8750	2.8570	6.4108
003, Piping Segment, 6 INCH OUTLET	19.8750	19.8750	5.0000	6.0650	28.8903

PRV Inlet Pressure Drop Stability Analysis	Opening	Closing
Pressure required for. bara	4.461	4.219
Blowdown. bara	0.241	0.241
Blowdown in %	7.000	7.000
Acoustic pressure drop during. bara	0.668	0.372
Irreverisible pressure drop during. bara	0.032	0.010
Total pressure drop during. bara	0.700	0.382
Blowdown required for stable operation in % during	20.311	11.083
Pressure at PRV inlet during. bara	4.105	4.423
Time required for. milliseconds	27.000	38.000
Wave time during. milliseconds	22.455	22.455
Wave time / time required for	0.832	0.591
Resonance/Harmonics during	Likely	Not Likely
Chatter, flutter, or cycle during	Chatter Likely	Not Likely

Segment #, Type, Name	D/t	Maximum SPL. dB	Limit SPL. dB	SPL Difference. dB	Vibration Risk?
001, Piping Segment, 4 INCH INLET	21.66	85.40	176.34	-90.94	Not Likely

Source: SuperChems v7

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The acoustic velocity estimates can be subject to uncertainties

- This is most significant for liquids
- Pipe flexibility can lower the value of the acoustic velocity
- The presence of minute amounts of entrained gas in liquids can reduce the acoustic velocity
- Adding a small amount of air, say 0.1 % by volume can reduce the value of the acoustic velocity for a liquid-air system by a factor of 1/2

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The acoustic velocity of a traveling wave can be calculated based on the fluid properties and the flexibility of the piping supports

$$u_{ac} = \eta u_{sonic} = \frac{1}{\sqrt{1 + \frac{K}{E}\psi}} u_{sonic}$$

$$u_{sonic} = \sqrt{\frac{C_p}{C_v}\frac{1}{\kappa\rho}} = \sqrt{\left[\frac{\partial P}{\partial \rho}\right]_S} = \sqrt{\frac{1}{\kappa_S \rho}}$$

Pipe condition	ψ
Rigid	0
Anchored against longitudinal movement through its length	$\frac{d}{\delta}(1 - \nu^2)$
Anchored against longitudinal movement at the upper end	$\frac{d}{\delta}(1.25 - \nu)$
Frequent expansion joints present	$\frac{d}{\delta}$

Let's consider the impact of piping flexibility on acoustic velocity reduction

Material	Piping Schedule US	$K = 1/\kappa$ GPa	d/δ	η
Liquid Water	5	2.19	52.2	0.799
Liquid Water	10	2.19	35.5	0.850
Liquid Water	40	2.19	13.4	0.934
Liquid Water	80	2.19	11.3	0.944
Liquid Water	160	2.19	6.47	0.967
Liquid Propane	5	0.11	52.2	0.986
Liquid Propane	10	0.11	35.5	0.991
Liquid Propane	40	0.11	13.4	0.996
Liquid Propane	80	0.11	11.3	0.997
Liquid Propane	160	0.11	6.47	0.998
Vapor Propane	5	6.80E-04	52.2	1.000
Vapor Propane	10	6.80E-04	35.5	1.000
Vapor Propane	40	6.80E-04	13.4	1.000
Vapor Propane	80	6.80E-04	11.3	1.000
Vapor Propane	160	6.80E-04	6.47	1.000

Propane data at 293 K and 8.35 bara

Piping flexibility is most important for liquids that are highly incompressible where thin wall piping is used

It is well established that small amounts of vapor can reduce the two-phase mixture speed of sound

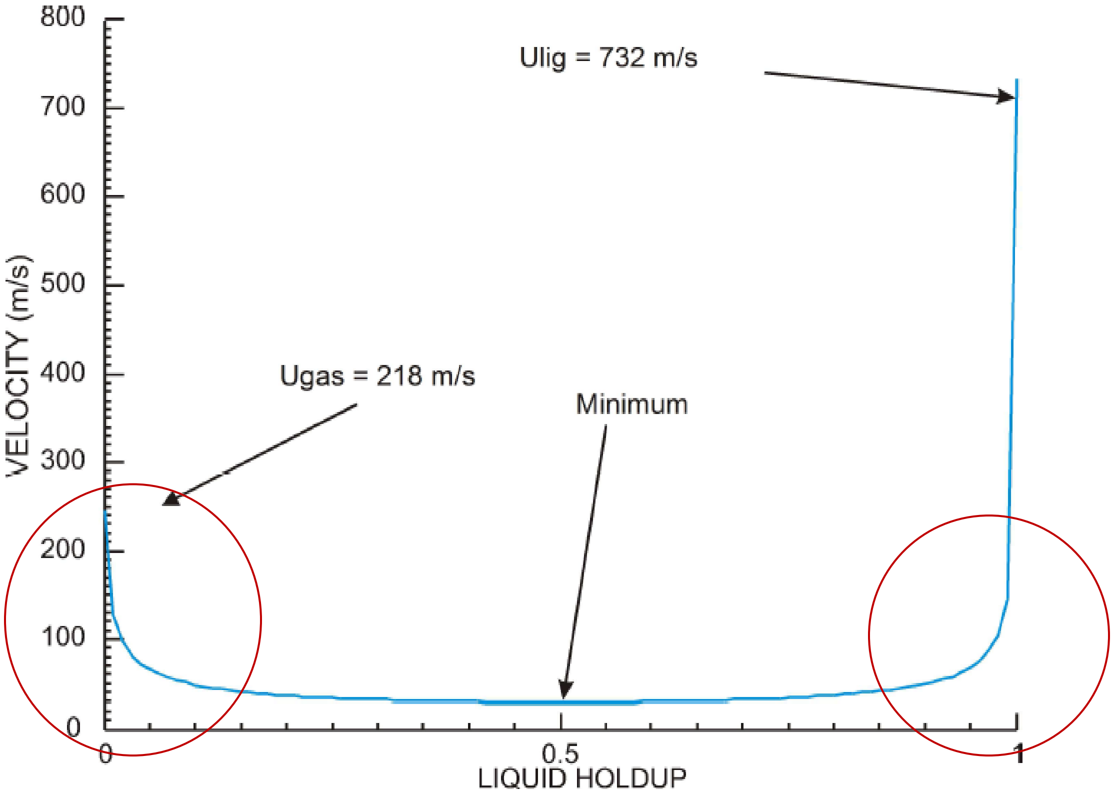

Table 2.1: Propane properties at 293 K and 8.35×10^5 Pa.

Property	Liquid	Vapor
Density, kg/m^3	523	18.1
κ, Pa^{-1}	9.18×10^{-9}	1.47×10^{-6}
β, K^{-1}	0.00408	0.00558
u_{max}, m/s	733	218

Table 2.2: Calculated propane mixture maximum velocities

ϵ_l	$u_{m,max}$ in (m/s)	ϵ_l	$u_{m,max}$ in (m/s)
0.00	218	0.60	81.7
0.05	145	0.70	87.6
0.10	118	0.80	100
0.20	95	0.90	133
0.30	85.1	0.95	181
0.40	80.7	0.99	357
0.50	79.7	1.00	732

$$u_m^2 = \frac{1}{\frac{\alpha}{u_{g,max}^2} + \frac{1-\alpha}{u_{l,max}^2} + (\rho_g - \rho_l)\left[\frac{\partial \alpha}{\partial P}\right]_s}$$

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We can conclude the following based on the reasoning presented in this paper

- Chatter is most likely in vapor service - Damage will most likely be due to large mechanical forces caused by the rapid valve closure and/or by PRV reduced flow capacity due to PRV damage. This is especially true for large valves and/or for valves in high pressure service

- Chatter is least likely in flashing two-phase***** flow service and/or in liquid service

- Flutter will almost always occur in liquid service with fast opening or pop action valves

- Cycling is most likely to occur in flashing two-phase flow service

- Piping damage is most likely in liquid service due to the large magnitude of the water hammer pressure waves propagated upstream during rapid valve closure (full or partial), i.e. during chatter or during flutter

- The 3 % inlet pressure is not sufficient to guarantee PRV stability. Stability may need to be assessed and confirmed for all credible scenarios and not necessarily just the one with the highest required flow rate

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- [1] G. A. Melhem, “PRV Stability Requirements”, Fall DIERS Users Group Meeting, Boston, October 2012
- [2] M. Grolmes, “DIERS Odds and Ends – PRV Stability”, Parts 1 through 5, Multiple DIERS Users Group Meetings
- [3] W. W. Powell, “A Study of Resonant Phenomena in Pilot Operated Safety Relief Valves”, Anderson Greenwood Report Number 2-0175-51, 1971
- [4] “Pressure Drop Considerations on Pressure Relief Valve Inlets”, Consolidated Safety Valves Report Number CON/PI-10, March 1988
- [5] “Interim Research Report on Safety Relief Valve Stability and Piping Vibration Risk”, 2003-2012, DIERS Users Group Report

*: *Note that condensation shocks are possible for two-phase flashing flows*

It is common to install relief devices on column overhead and process lines

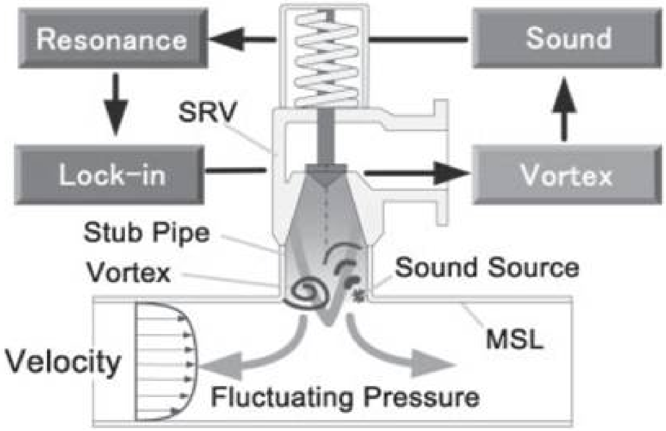
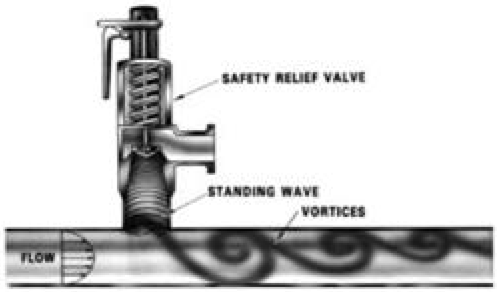
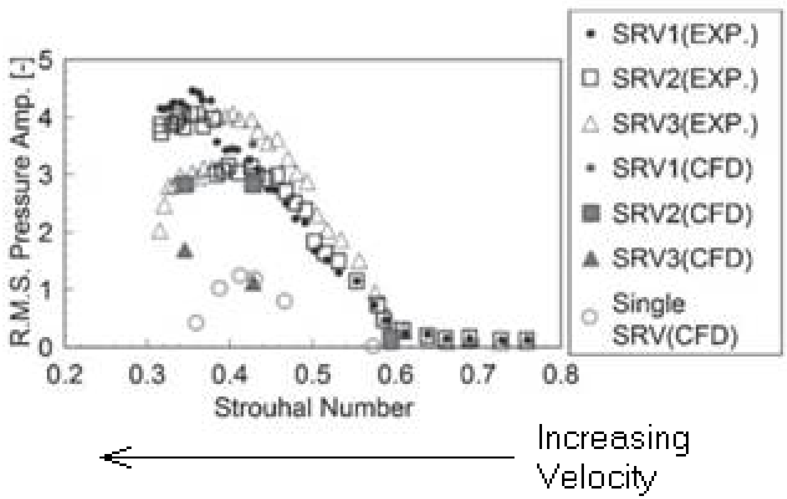


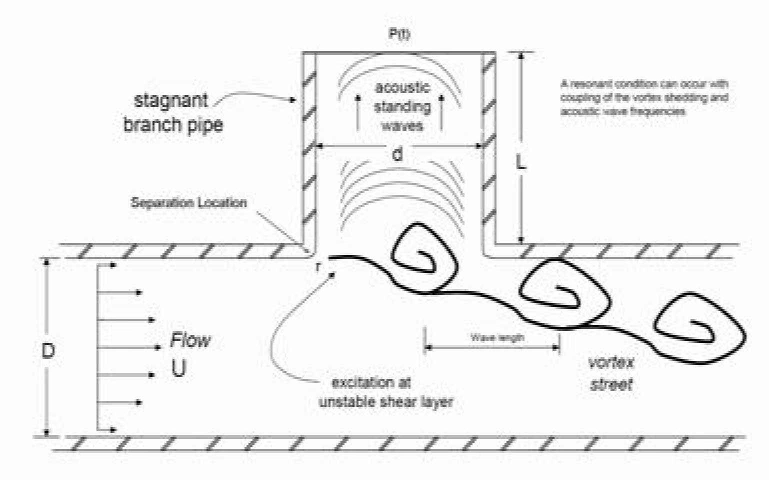
Fig. 4 Flow-induced acoustic resonance of SRVs in MSL

"Singing" Safety Relief Valve



Reference: Hambric, S.A., Mulcahy, T.M., Shah, V.N., et. al., "Flow-Induced Vibration Effects on Nuclear Power Plant Components Due to Main Steam Line Valve Singing," Proceedings of the Ninth NRC/ASME Symposium on Valves, Pumps, and Inservice Testing, NUREG/CP-0152, Vol. 6, pp. 3B 49-3B 69, July 2006





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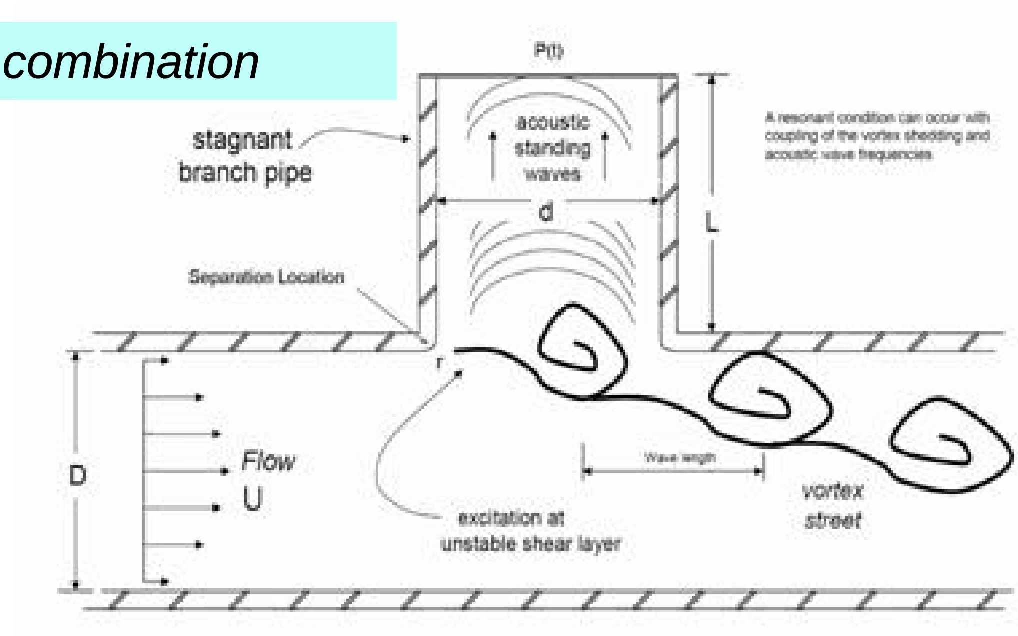
Resonance occurs when the vortex shedding frequency coincides with the acoustic frequency of the standpipe

Natural frequency of standpipe / valve combination

$$f_a = \left(\frac{2n-1}{4}\right)\frac{c_0}{L+L_e}$$

n = 1 for 1st mode, 2 for 3rd mode, etc., c_0 = fluid speed of sound, and
r = radius of inlet chamfer
L_e = End correction corresponding to Rayleigh's upper limit = 0.425 d



Frequency of pressure oscillations (sound) created by vortex shedding

Vortex shedding creates pressure oscillations – the energy source for standing waves

$$N_{St} = \frac{f_s}{U}(d+r)$$

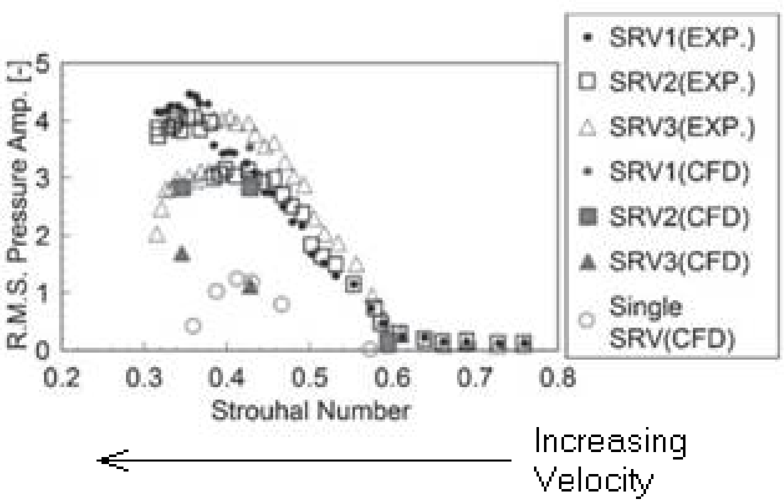
N_{St} = Strouhal Number where 0.63 >= N_{St} >= 0.3

Resonance can cause fatigue failure from cyclic loads and can cause leaking and chatter of the valve

$$f_s = N_{St}\left(U/D\right) \approx 0.33\left(n-0.25\right)\left(U/D\right)$$

For n = 1

$$U = \frac{f_s}{N_{St}}\left(d+r\right) = \frac{1}{4}\left(\frac{c_0}{L+L_e}\right)\left(\frac{d+r}{N_{St}}\right)$$



N_{St} = Strouhal Number where 0.63 $\geq N_{St} \geq$ 0.3
Peak oscillations occur around N_{St} = 0.4
RMS is the ratio of pressure oscillations divided by dynamic pressure = ½ ρu^2
RMS begins increasing at a specific onset Strouhal Number and flow velocity depending on acoustic speed, pipe diameter, and pipe length, reaches a peak value and then decreases

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ioMosaic Corporation is the leading provider of safety and risk management consulting services, training, and software solutions. Whether you need pressure relief system design services, quantitative risk assessments, onsite training, or the latest in software technology, ioMosaic has the knowledge, experience, and resources to address your unique needs. At ioMosaic, we are delivering practical solutions for safety, risk, and business challenges facing our clients.

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