Relief Device Stability Screening

For Spring Loaded API STD 526 Valves

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AGENDA

- Introduction
- Background
- Goals of the screening method
- Methodology
- Sample problems
- Review compared to known data
- Recommendations for any future work
- Discussion

INTRODUCTION

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BACKGROUND - Problem

- There are known chatter incidents that resulted in a “loss of containment”
- Relatively rare occurrence
- Industry // regulatory difference of opinion on “Relaxing” the 3% rule

Historically, un-managed (or studied) change leads to increased problems

GOAL OF THE SCREENING METHODOLOGY

1. Focused on vapor / gas systems
2. Categorize installations into two buckets
   - Free from chatter
   - May chatter
3. Equations that can be done by hand
4. Relies on minimal valve specific information
5. ***All criteria must be passed***

The methodology does not predict chatter intensity, or frequency

Methodology Basis

- Based on known work
  - 80's ASME / EPRI Research
  - 99-02 Research (From Germany)

- Validated (to date)
  - Published API Perf Data
  - Zahorsky's ASME/ EPRI Data

Mechanisms of Chatter – Literature Review

1. Inlet line length
2. Excessive inlet pressure losses
3. Standing waves
4. Oversized relief devices
5. Improper relief device installation

All criteria <u>must</u> be met to be considered acceptable

Inlet Line Length – Literature Review

1. Theory
    1. Valve opens
    2. Reduced pressure area forms
    3. Pressure wave travels to some point
    4. Gets reflected back and "Supports" the disk
2. Published equation basis (Source 9)

$$t_{open} > \frac{2L}{c}; \quad \Delta P \leq \frac{2t_{wave}}{t_{open}}; \quad L_{Allowable} = f\left(\Delta P_{Chosen}, t_{open}\right)$$

Inlet Line Length – Various Equations

1. Direct solution of the basis equation

$$L < 111.5 t_{open}\sqrt{\frac{kT}{MW}}; \quad t_{open} > \frac{2L}{c}; \quad c = 223\sqrt{\frac{kT}{MW}}$$

2. Frommann & Friedel (1998, Source 6)

$$L_i < 9{,}078\frac{d_i^2}{w_{\%O}}\left(P_s - P_B\right)t_o$$

Assumes a 20% sudden pressure loss is acceptable

Inlet Line Length – Various Equations

3. Frommann & Friedel (1998, Source 6)

$$L_i < 45{,}390\,\frac{d_i^2}{w_{\%O}}\left(\frac{P_s - P_{rc}}{P_s}\right)(P_s - P_B)\,t_o$$

Assumes sudden pressure loss is limited by blowdown

4. Cremers, Friedel, Pallaks (2001, Source 9)

My implementation was not substantiated by the 99-05 PERF PRV Stability Project

Inlet Pressure Losses– Literature Review

1. Theory (EPRI / ASME)
   1. Valve opens
   2. Pressure develops (both acoustic and frictional)
   3. Valve closes (repeat)
2. Published equations (Source 32)

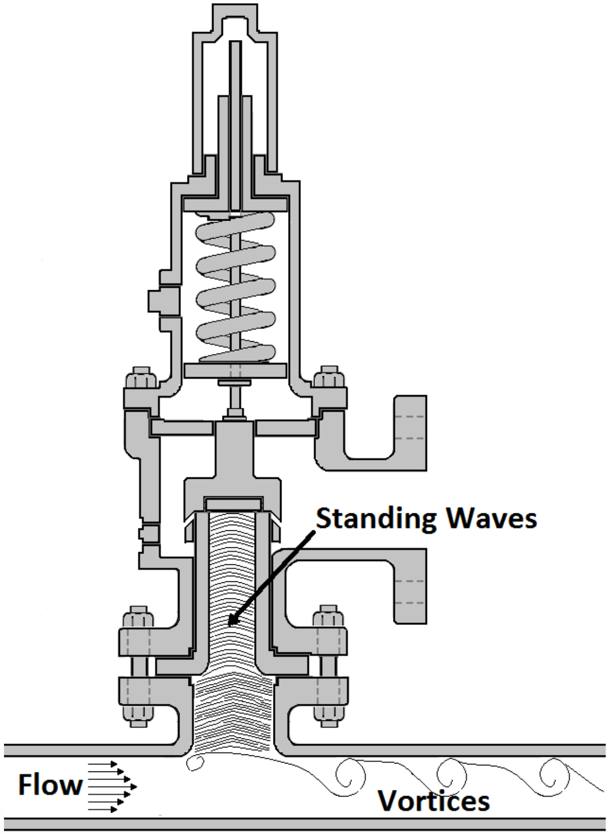
$$P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Acoustic}$$

$$\Delta P_{Acoustic} = \frac{L w_{PSV}}{12.6 d_i^2 t_O} + \frac{1}{10.5\rho}\left(\frac{w_{PSV} L}{c d_i t_O}\right)^2$$

Standing Waves – Literature Review

1. Theory
   1. High process flow velocity
   2. Vortex Shedding occurs at the tie-in point
   3. Standing waves form
2. Published equations (Source 10)

$$L_i < \frac{d_i c}{2.4U}$$



It has been speculated that Helmholtz resonance may occur (34) but generally is not considered to cause destructive chatter (35, 36).

Oversized relief devices

1. Conventional wisdom – concern when the capacity is less than 25% (Sources 22, 29)
2. Valve operation
    1. Pressure in vessel increases
    2. Valve opens, capacity depends on inlet/outlet conditions
    3. If flow to vessel is more than capacity pressure increases if not it decreases.
    4. Cycle time related to flow and volume (not only rate)

Oversized relief devices

1. If destructive chatter was caused by oversize devices:
   1. Problem would be extensive
   2. No solution
2. High frequency chatter > 1 hz (per manufacturers)

$$w_{PSV} > 4w_{required}$$

And,

$$1 > t_{cycle} = t_{P_{Blowdown} \to P_{Set}} + t_{P_{set} \to P_{Blowdown}}$$

Installation Guidelines

1. No inlet restrictions [UG-135(b)(1), Source 15]
2. No outlet restrictions / backpressure issues (Sources, 3, 9, 12, 23 ,25)
3. Balanced Bellows vents open (Source 24)
4. Pocketed outlet piping (Source 1)

Supporting Equations // Assumptions

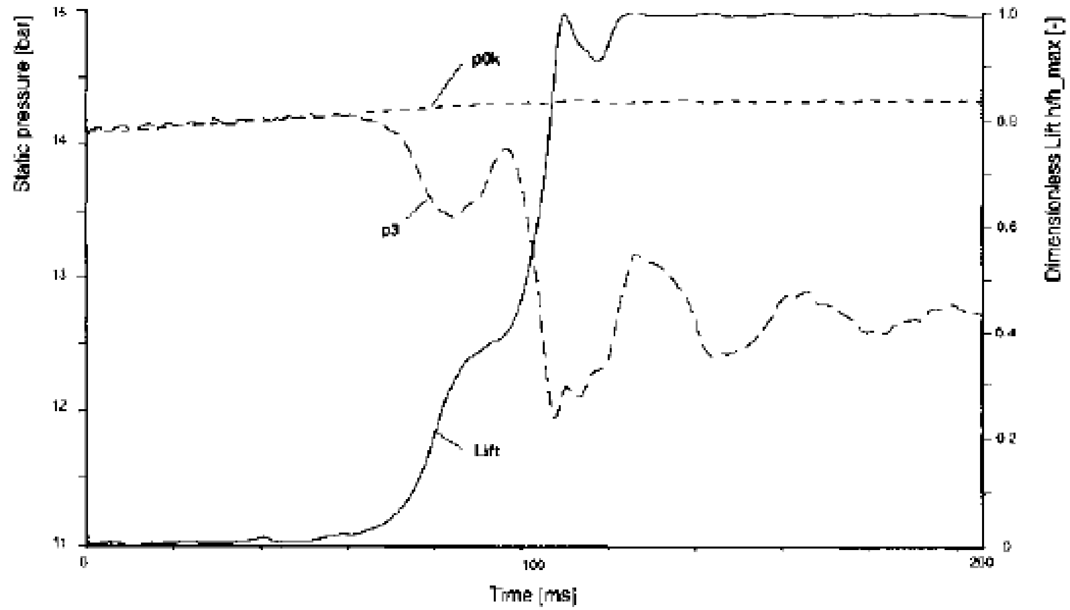
1. Relief valve opening time [Source 9]

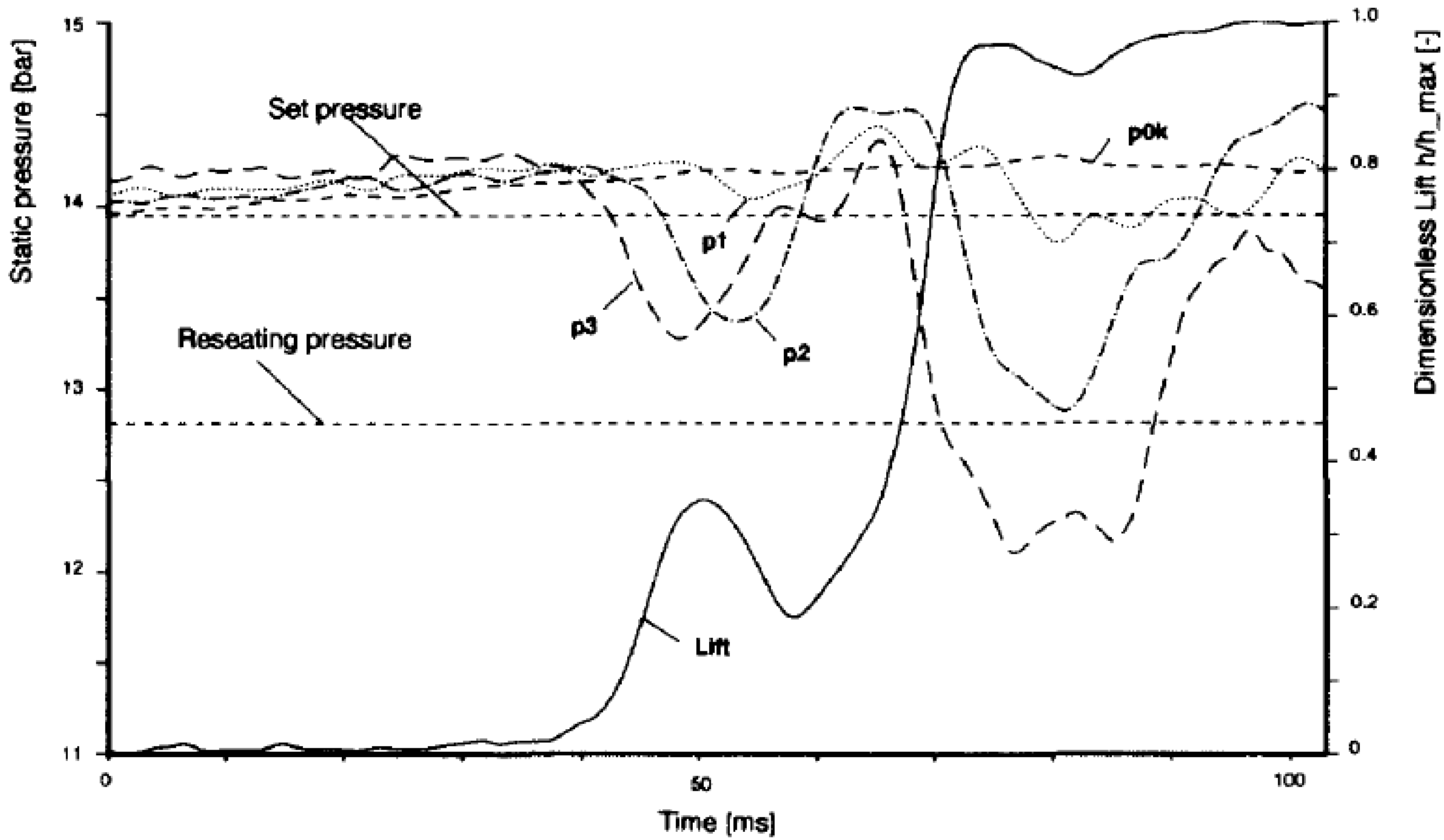
$$t_O \approx \left(0.015 + 0.02\frac{\sqrt{2d_{PSVi}}}{\left(P_s / P_{ATM}\right)^{2/3}\left(1 - P_{ATM}/P_s\right)^2}\right)\left(\frac{h}{h_{\max}}\right)^{0.7}$$

2. Speed of sound in a perfect gas (Source 29)

$$C = 223\sqrt{\frac{kT}{MW}}$$

3. Valve “pops” to about 60% open (Source 6)





Static pressure [bar]
15
14
13
12
11
Set pressure
Reseating pressure
p0k
p1
p2
p3
Lift
0
50
100
Time [ms]
1.0
0.8
0.6
0.4
0.2
0
Dimensionless Lift h/h_max [-]

Sample Problems (Criteria 1.1 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L < 111.5 t_0 \sqrt{\frac{kT}{MW}} < 111.5\left[\left(0.015 + 0.02\frac{\sqrt{2d_{PSVi}}}{(P_s/P_{ATM})^{2/3}(1-P_{ATM}/P_s)^2}\right)\left(\frac{h}{h_{\max}}\right)^{0.7}\right]\sqrt{\frac{kT}{MW}}$$

$$L < 111.5\left[\left(0.015 + 0.02\frac{\sqrt{2\times 2.1}}{(64.7/14.7)^{2/3}(1-14.7/64.7)^2}\right)(0.6)^{0.7}\right]\sqrt{\frac{1.4(85+460)}{28.8}}$$

$$L < 111.5[0.028]\sqrt{\frac{1.4(545)}{28}} < 16.1\, ft$$

Sample Problems (Criteria 1.1 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L < 111.5\left(0.015 + 0.02\frac{\sqrt{2d_{PSVi}}}{\left(P_s/P_{ATM}\right)^{2/3}\left(1-P_{ATM}/P_s\right)^2}\right)\left(\frac{h}{h_{\max}}\right)^{0.7}\sqrt{\frac{kT}{MW}}$$

$$L < 111.5\left(0.015 + 0.02\frac{\sqrt{2\times 0.957}}{\left(264.7/14.7\right)^{2/3}\left(1-14.7/264.7\right)^2}\right)(0.6)^{0.7}\sqrt{\frac{1.4(85+460)}{28.8}}$$

$$L < 111.5(0.014)\sqrt{\frac{1.4(545)}{28.8}} \quad < 8.0\, ft$$

Sample Problems (Criteria 1.2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L_i < 9{,}078\frac{d_i^2}{w_{\%O}}\left(P_s - P_B\right)t_o < 9{,}078\frac{2.1^2}{7{,}060\times 0.6}\left(50-4\right)0.028$$

$$L < 12.2\ ft$$

Sample Problems (Criteria 1.2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L_i < 9{,}078 \frac{d_i^2}{w_{\%O}} \left(P_s - P_B\right) t_o < 9{,}078 \frac{0.957^2}{4{,}470 \times 0.6} \left(250 - 20\right) 0.014$$

$$L < 10\ ft$$

Sample Problems (Criteria 1.3 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L_i < 45{,}390\frac{d_i^2}{w_{\%O}}\left(\frac{P_s - P_{rc}}{P_s}\right)(P_s - P_B)\,t_o \quad < 45{,}390\frac{2.1^2}{7{,}060 \times 0.6}(0.08)(50-4)\,0.028$$

$$Where, \quad blowdown = \left(\frac{P_s - P_{rc}}{P_s}\right) = 8\%$$

$$L < 4.9\ ft$$

Sample Problems (Criteria 1.3 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$L_i < 45{,}390 \frac{d_i^2}{w_{\%O}} \left(\frac{P_s - P_{rc}}{P_s} \right) (P_s - P_B) t_o < 45{,}390 \frac{0.957^2}{4{,}470 \times 0.6} (0.025)(250 - 20) 0.014$$

$$L < 1.25\, ft$$

Sample Problems (Criteria 2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Accustic}, \quad \Delta P_{Accustic} = \frac{L w_{PSV}}{12.6 d_i^2 t_O} + \frac{1}{10.5\rho}\left(\frac{w_{PSV} L}{c d_i t_O}\right)^2$$

$$C = 223\sqrt{\frac{kT}{MW}} = 223\sqrt{\frac{1.4(85+460)}{28.8}} = 1150\frac{ft}{s}, \quad \rho = \frac{P_{Set} MW}{RT} = \frac{64.7\times 28.8}{10.73\times 545} = 0.32\frac{lb}{ft^3}$$

$$\Delta P_{Accustic} = \frac{2\times 1.17}{12.6\times 2.1^2\times 0.028} + \frac{1}{10.5\times 0.32}\left(\frac{1.17\times 2}{1{,}150\times 2.1\times 0.028}\right)^2, w_{PSV} = \left(\frac{7{,}060\times 0.6}{3{,}600}\right) = 1.17\frac{lb}{s}$$

Sample Problems (Criteria 2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$\Delta P_{Accustic} = \frac{Lw_{PSV}}{12.6 d_i^2 t_O} + \frac{1}{10.5\rho}\left(\frac{w_{PSV}L}{cd_i t_O}\right)^2 = 2.512 + 0.00036 = 2.5\,psi, \quad \Delta P_{Friction} = 5.1\,psi\,(measured)$$

$$P_S \times BD = P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Accustic}, \quad 50 \times 0.08 > 5.1 + 2.5$$

$$P_S \times BD > \Delta P_{Frictional} + \Delta P_{Accustic}, \quad 9\ psi > 7.6\ psi$$

Sample Problems (Criteria 2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
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$$P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Accustic}, \quad \Delta P_{Accustic} = \frac{Lw_{PSV}}{12.6 d_i^2 t_O} + \frac{1}{10.5\rho}\left(\frac{w_{PSV} L}{c d_i t_O}\right)^2$$

$$C = 223\sqrt{\frac{kT}{MW}} = 223\sqrt{\frac{1.4(85+460)}{28.8}} = 1150\frac{ft}{s}, \quad \rho = \frac{P_{Set} MW}{RT} = \frac{264.7\times 28.8}{10.73\times 545} = 1.3\frac{lb}{ft^3}$$

$$\Delta P_{Accustic} = \frac{2\times 0.745}{12.6\times 0.92^2\times 0.014} + \frac{1}{10.5\times 1.3}\left(\frac{0.745\times 2}{1{,}150\times 0.96\times 0.014}\right)^2, w_{PSV} = \left(\frac{4{,}470\times 0.6}{3{,}600}\right) = 0.745\frac{lb}{s}$$

Sample Problems (Criteria 2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
PSV-3 (2J3)	7,060	60%	2	50.0	4	85	28.8
PSV-8 (1E2)	4,470	60%	2	250.0	20	85	28.8

$$\Delta P_{Accustic} = \frac{L w_{PSV}}{12.6 d_i^2 t_O} + \frac{1}{10.5\rho}\left(\frac{w_{PSV} L}{c d_i t_O}\right)^2 = 15.37 + 0.001 = 15.4\,psi, \quad \Delta P_{Friction} = 22.5\,psi\,(measured)$$

$$P_S \times BD = P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Accustic}, \quad 250 \times 0.025 > 15.4 + 22.5$$

$$P_S \times BD > \Delta P_{Frictional} + \Delta P_{Accustic}, \quad 31.3\ psi > 37.9\ psi$$

Sample Problems (Criteria 2 – Line Length)

Tag Number	PSV Capacity (lb/hr)	Initial Lift (%)	Inlet Pipng (ft)	P_{Set} (PSIG)	P_{Back} (PSIG)	T_{inlet} (°F)	MW
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$$P_S \times BD = P_S - P_{RC} > \Delta P_{Total} = \Delta P_{Frictional} + \Delta P_{Accustic}, \quad 250 \times 0.025 > 15.4 + 22.5$$

$$P_S \times BD > \Delta P_{Frictional} + \Delta P_{Accustic}, \quad \cancel{31.3\ psi > 37.9\ psi}$$

Sample Problems – Summary Results

Tag Number	Eq. 1.1	Eq. 1.2	Eq. 1.3	Eq. 2.0	PERF Exp. Between
PSV-3 (2J3)	16.1	12.2	4.8	2 – 4	4 - 6
PSV-8 (1E2)	8.0	10.0	1.2	< 2	2 - 4

1. Equations 1.1 and 1.2 are "optimistic"

$$L < 111.5 t_{open} \sqrt{\frac{kT}{MW}}, Eq\,1.1;\; L_i < 9{,}078 \frac{d_i^2}{w_{\%O}} (P_s - P_B) t_o, Eq\,1.2$$

2. Eq. 1.3 is most "accurate" $L_i < 45{,}390 \frac{d_i^2}{w_{\%O}} \left(\frac{P_s - P_{rc}}{P_s} \right) (P_s - P_B) t_o$

3. Eq. 2.0 (Acoustic & Friction ΔP) conservative

Experimental Validation

Comparison to API PERF Study (Source 15)

Model Correlation	PERF Results	Model Prediction	Eq. 1.3	Eq. 2.0	No. Of Cases
Agreement	Chatter	Chatter	9	9	9
Agreement	Stable	Stable	26	14	14
False Negative	**Chatter**	**Stable**	**0**	**0**	**0**
False Positive	Stable	Chatter	12	24	24
Agreement[1]	Not Tested	Chatter	7	7	7
		Percent Correlation %	74 (78)	49 (56)	

Note 1: *There are a number of cases that were not tested, but were assumed to chatter as the reason for not being tested was not included but assumed to be damage from previous runs.*

Experimental Validation

Comparison to the Zahorsky Data (Source 31)

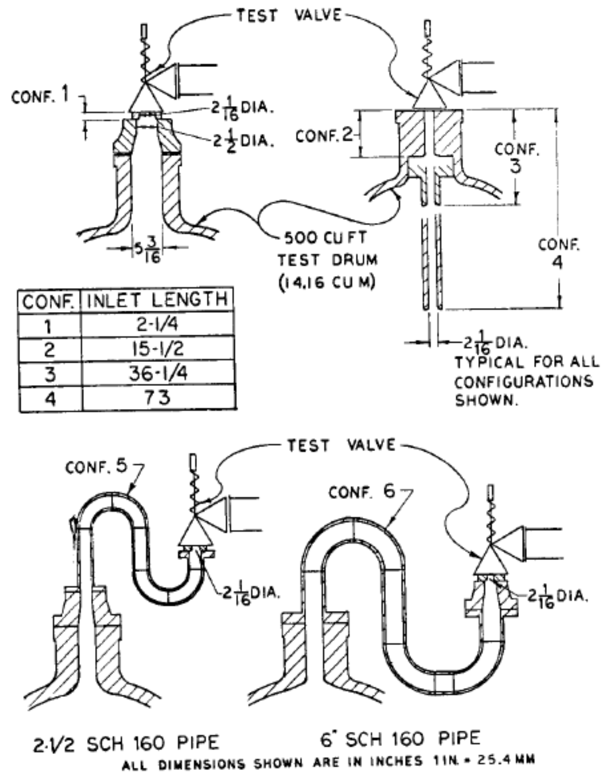

Figure 2. Schematic of Inlet Piping Configurations

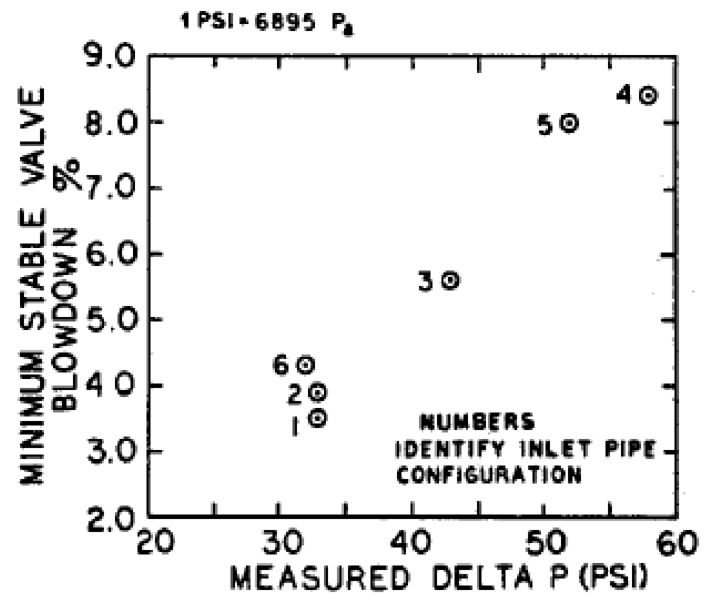

Figure 8. Relationship of Inlet Pressure Drop to Minimum Obtainable Valve Blowdown on Various Inlet Pipe Configurations

Comparison to the Zahorsky Data (Source 31)

Run	Exp. Determined Blowdown	Predicted Blowdown[1]	Δ Blowdown (Pred. – Exp)
1	3.9%	4.0% (0.3 / 4.0)	0.1%
2	3.9%	5.6% (2.0 / 5.6)	1.7%
3	5.6%	9.7% (4.7 / 9.7)	4.1%
4	8.4%[2]	16.7% (9.4 / 16.7)	***8.3%***
5	8.3%	12.6% (6.3 / 12.6)	4.3%
6	4.3%	5.3% (0.3 / 5.3)	1.0%

Note 1: *The values are (Eq. 1.3 / Eq. 2.0) in percent.*

2: *The only case with agreement for Eq. 1.3*

Recommendations For PERF-II

1. Is increasing PSV blowdown enough?
2. How do pipe diameter changes affect stability…

$$R_\pi = \frac{(A_1 - A_2)^2}{(A_1 + A_2)^2} > {}^2/_3,$$ Reflection for acoustic boundary

$$T_\pi = \frac{4A_1A_2}{(A_1 + A_2)^2},$$ Transmission of acoustic losses

3. Do acoustic losses degrade with distance?
4. What is the opening time relevant to chatter?
5. Do the valves pop to XX% open?
6. Does backpressure affect chatter? For bellows?
7. This is generic, is it conservative enough?