ASME Pressure Relief Valve Failure Predictions

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https://youtu.be/ovaJNTwaCDc

Project Overview

- **Top-Level goal**
  - **Evaluate pressure relief valve pre-installation test failure rates:**
    - **On a per-vendor basis**
    - **On a per-medium basis**
    - **As a predictor for future orders and installation**
- Implementation
  - Multilevel Bayesian model (partial pooling) used to estimate failure rate parameter

Terminology

Acronym / Phrase	Definition
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
PRV / PRD	Pressure Relief Valve / Pressure Relief Device
PTC	Performance Test Code
Service medium	Type of process fluid specified for a given PRV (water, steam, etc.)
Set pressure	Given pressure at which a PRV opens (relieves)

Background

- ASME BPVC Section VIII specifies the requirements for pressure vessel PRVs
    - PRV set pressures are controlled to strict tolerance
    - Deviation from set pressures necessitates removal and replacement of the PRV
- Consequences of set pressure deviation
    - PRV relieves under set pressure
        - Process functionality impacted
            - Inability to run at design pressure
            - Excessive loss of process medium
    - PRV relieves over set pressure
        - **Worst case scenario**
        - Process pressure may exceed vessel design limits and cause damage, injury, or death
- **PRVs are the final line of defense against dangerous process conditions**

Background (cont.)

- Not all ASME-certified PRVs are created equal
  - PRVs may fail pressure testing even after certification
  - Valves from different vendors may have differing levels of reliability
- PRV testing good practice
  - Pressure test new PRVs prior to installation on process lines
  - Re-test PRVs regularly
- **PRV failures should be minimized**
  - Removal, replacement, and re-installation costs time and money
    - Long vendor lead times
    - Facility down time
  - Picking the proper vendor and estimating the amount of spare valves needed on-hand is key
    - Determining the expected proportion of failed valves allows for proper planning

Data

- Dataset taken from Savannah River Site survey of PRV tests
  - Weber, J. (2004). ASME Section VIII Pressure Relief Valves -- as-arrived test data for new valves from stores [Dataset]. ASME.
- Top-level summary
  - 560 total valves tested
  - 70 valves rejected after pre-installation testing
  - 18 distinct vendors in total supplied population of valves
  - 5 service media considered

Data (cont.)

Results of New Valve Tests

% Rejected	Rejected for
4.6%	leaking
4.3%	high pop
2.5%	low pop
1.1%	stamped wrong
0.5%	no seel
0.4%	wrong valve
0.4%	bad lever
0.4%	no oxygen cleen report(?)
14.2%	Total
79.52	Number of units rejected

	Vendor	Population	Rejected	High Pop	% Over Set	% Over Limit	Set Pressure	Service
	a	9	2	1	10.0%	4.3%	35	steam
	b	13	0	0	0.0%	0.0%		air
	c	85	1	1	13.0%	9.7%	175	steam
	d	108	21	4	4.5%	1.5%	350	air
	e	1	0	0	0.0%	0.0%		na
	f	55	9	2	5.5%	2.5%	400	liquid
	g	41	5	2	6.7%	3.3%	165	steam
	h	2	0	0	0.0%	0.0%		air
	z	40	6	1	24.0%	20.0%	165	steam
	k	1	0	0	0.0%	0.0%		steam
	y	66	4	4	6.0%	3.0%	100	air
	m	54	6	1	27.0%	24.0%	75	air/liquid
	m	14	7	3	10.0%	3.0%	80	steam
	n	1	0	0	0.0%	0.0%		na
	o	3	0	0	0.0%	0.0%		air
	p	3	0	0	0.0%	0.0%		liquid
	r	38	7	1	6.8%	4.0%	250	liquid
	s	8	0	0	0.0%	0.0%		air
	x	18	2	1	6.3%	1.2%	175	air
Total		560	70	21	6.3%	4.0%		
					average	average		

Statistical Background

- Multilevel, varying intercepts model used to partially pool data from each vendor
  - Since all valves are constructed to ASME BPVC Section VIII standards, there is implicit commonality between valves made by different vendors
  - Effects not accounted for in ASME standard are captured by varying intercepts model
    - Storage or transport conditions
    - Specific machining operations
    - Specific material selection (beyond general guidelines)
    - Etc.
- Valves sorted by service medium due to inherent differences in construction
  - Apples-to-apples comparison

Statistical Background (cont.)

- Multilevel Modeling Overview
  - Bayes' Theorem: $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$
  - *P(A)* is the prior probability distribution, or *prior*
  - **Single level model**
    - Prior is a defined distribution with set parameters
  - **Multilevel Model**
    - Prior distribution is defined by hyperparameters
    - Hyperparameters themselves defined by their own prior distributions

Statistical Model

- $Valve\ Failures \sim Binomial(n, f)$
  - ***n:*** total valves tested
  - *f*: probability of failure
    - Parameter of interest
    - $$f = \frac{1}{1 + e^{-\mu}}$$
- $\mu \sim Normal(\bar{\mu}, \sigma)$
- $\bar{\mu} \sim Normal(-2, 2)$
- $\sigma \sim Exponential(0.5)$

Hyper Parameters

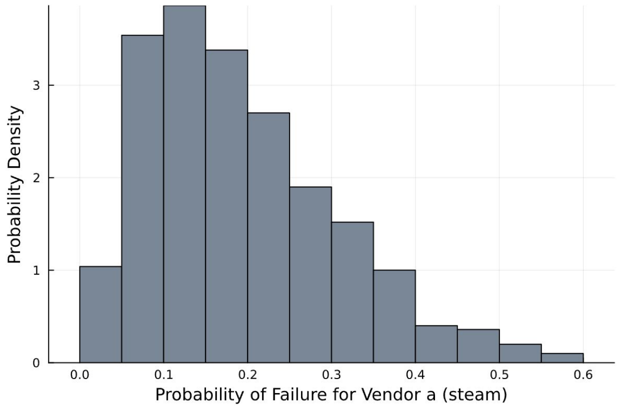
Statistical Model (cont.)

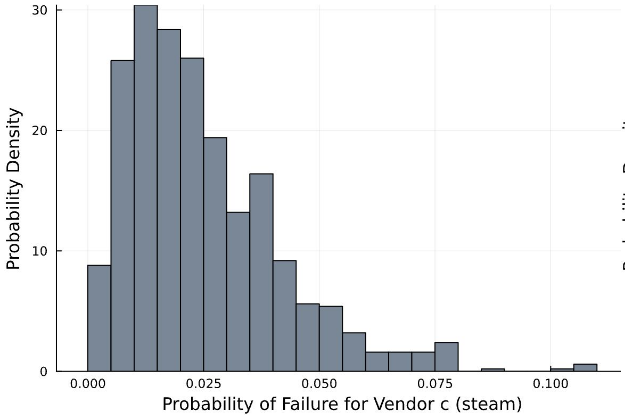
- Choice of distribution $Valve\ Failures \sim Binomial(n, f)$
  - Binomial distribution chosen as PRV tests can be considered independent tests with only pass/fail results
- Logistic function $f = \dfrac{1}{1 + e^{-\mu}}$
  - Used for logistic regression
  - Converts log-odds into probability ($0<f<1$)

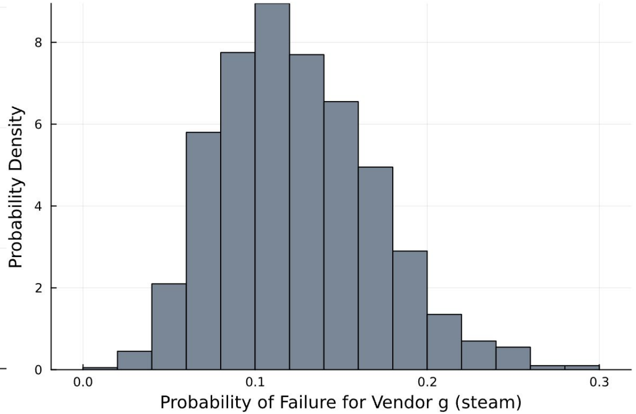
Statistical Model (cont.)

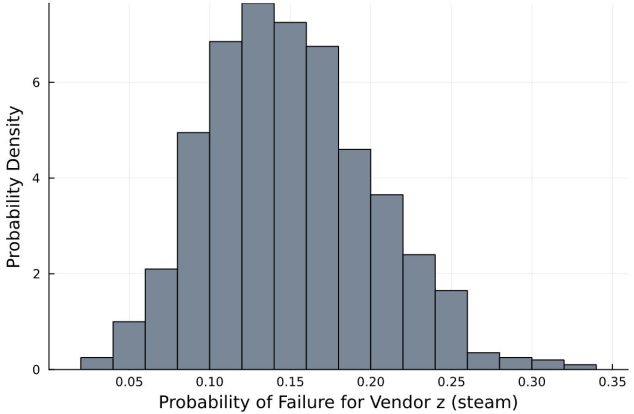
- Prior $\mu \sim Normal(\bar{\mu}, \sigma)$
  - Assume that the log-odds are normally distributed
  - Prior adapts information taken from each specific vendor by way of hyperparameters
- Hyper Parameters / Hyper Priors
  - $\bar{\mu} \sim Normal(-2, 2)$
    - Initially assume that all valves have a relatively low probability of failure
    - Assume normal distribution has a relatively large width
  - $\sigma \sim Exponential(0.5)$
    - Allow for variance of μ to take a wide variety of values, biased towards being relatively small

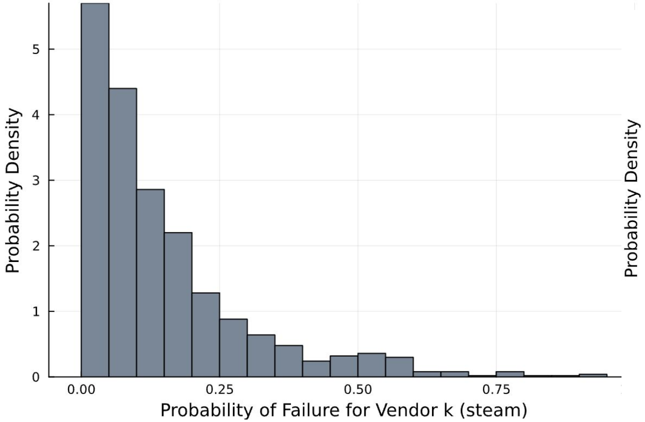
Results by Vendor, Steam PRVs

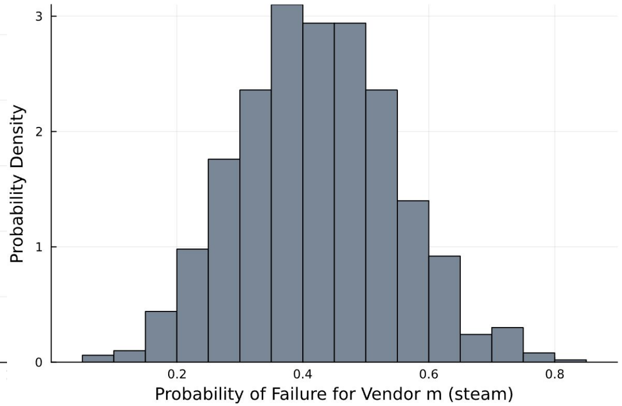




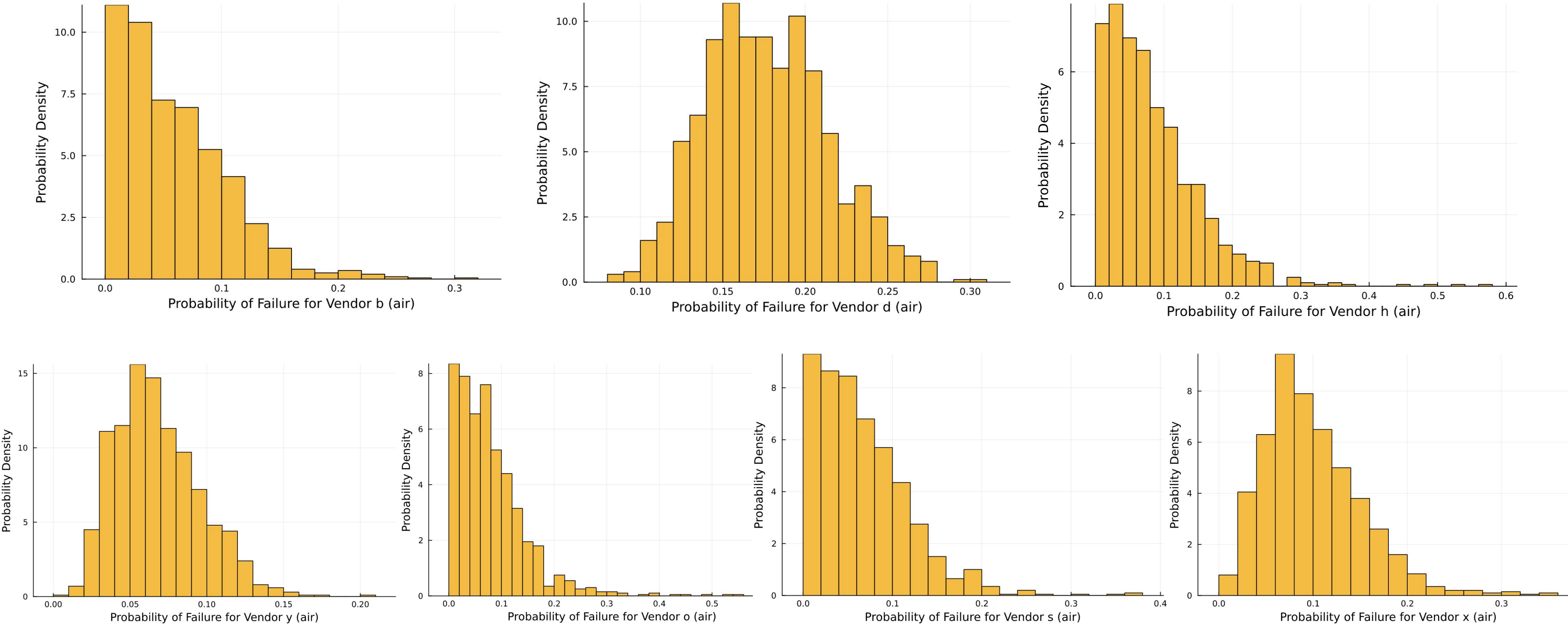




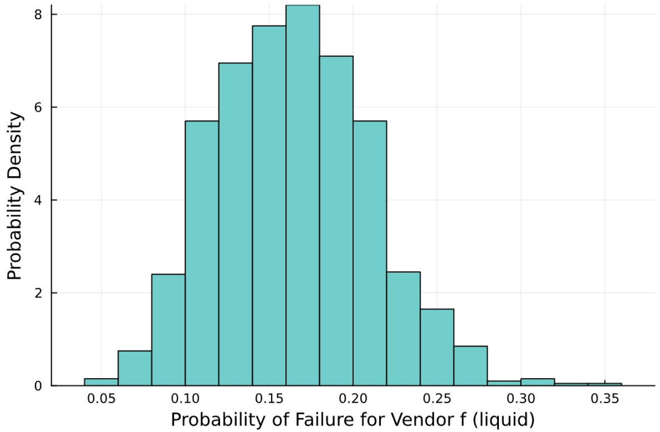


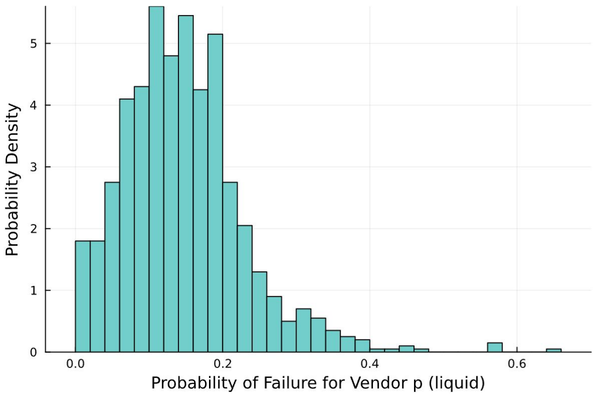


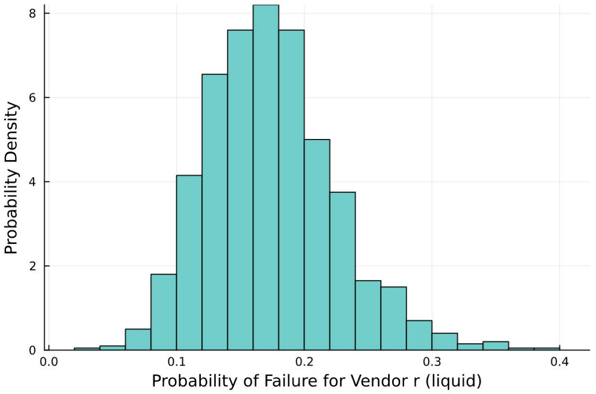
Results by Vendor, Air PRVs



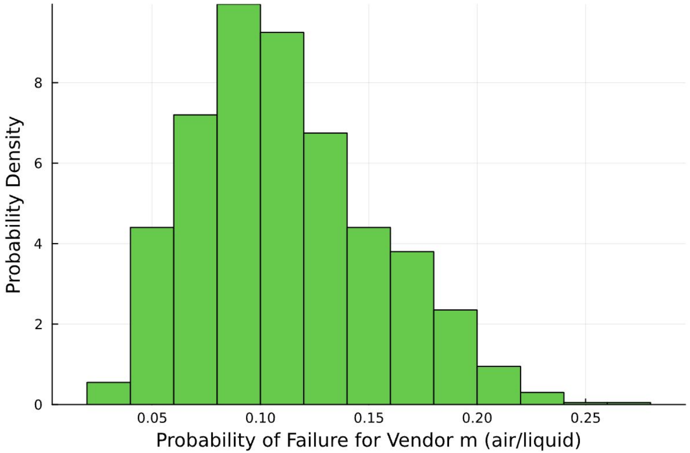
Results by Vendor, Liquid PRVs

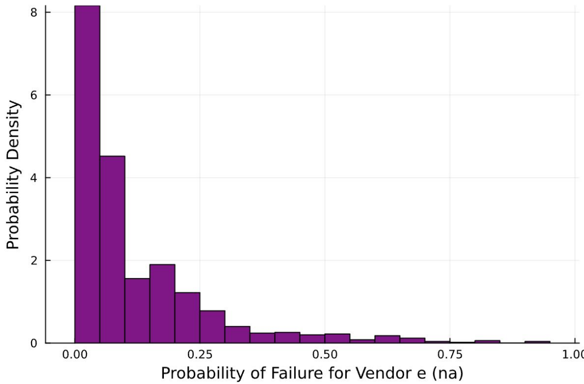


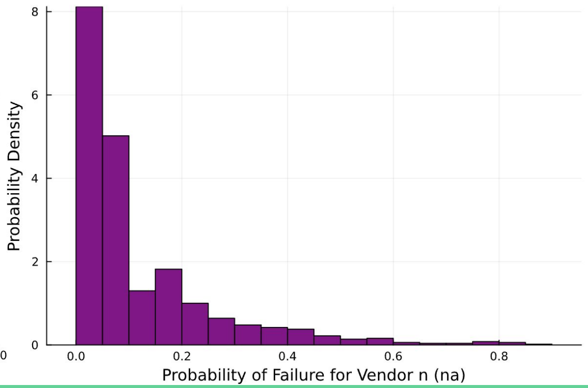




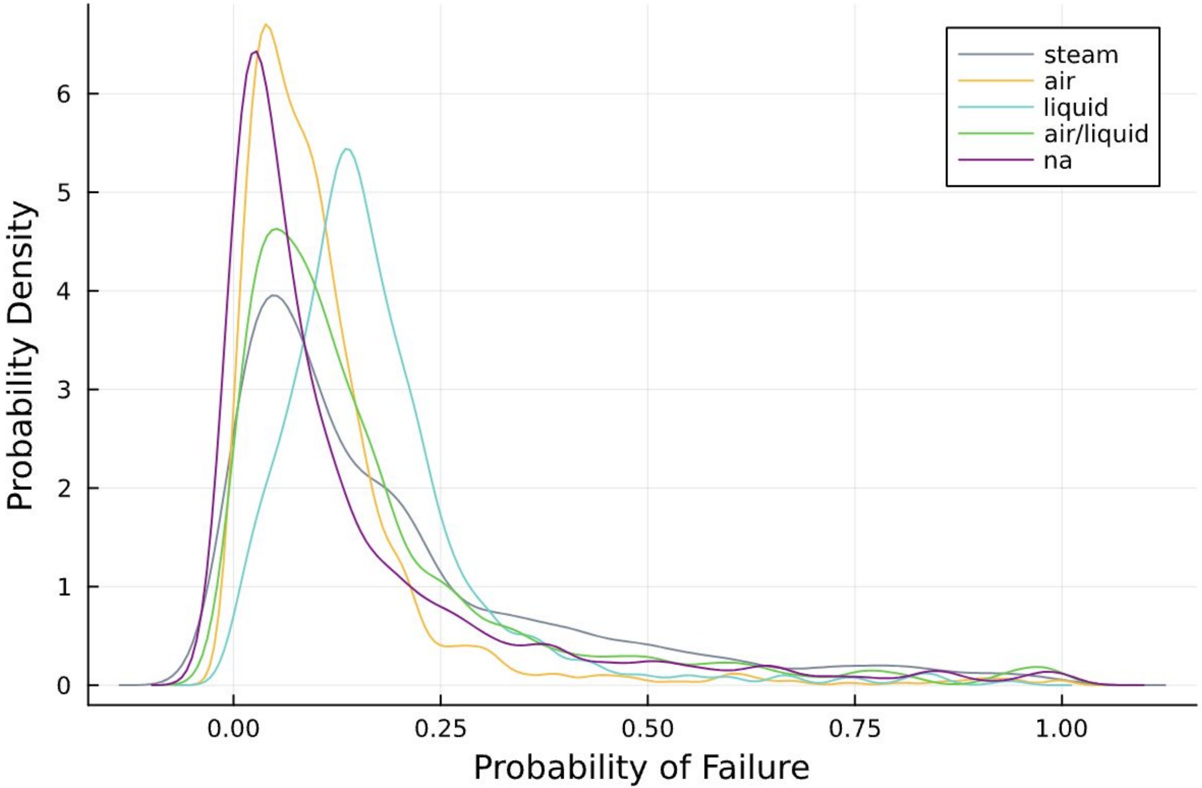
Results by Vendor, Other Service media







Partial-Pooling Results



Discussion

- Based on available data, most reliable vendor can be chosen for each service medium
  - Steam
    - Vendor C exhibits highest PRV reliability (MAP point estimate = 0.075, 95% CI from 0.0037-0.068)
    - Vendor M exhibits lowest PRV reliability (MAP point estimate = 0.24, 95% CI from 0.19-0.66)
  - Air
    - Vendor O exhibits highest PRV reliability (MAP point estimate = 0.088, 95% CI from 0.0034-0.24)
    - Vendor D exhibits lowest PRV reliability (MAP point estimate = 0.15, 95% CI from 0.11-0.25)
  - Liquid
    - Vendor P exhibits highest PRV reliability (MAP point estimate = 0.14, 95% CI from 0.013-0.33)
    - Vendor F exhibits lowest PRV reliability (MAP point estimate = 0.20, 95% CI from 0.083-0.25)
  - Other media
    - These media had very limited PRV population in set
    - Current statistical model should be bolstered with additional PRV testing data to give a more realistic distribution

Discussion (cont.)

- Predictions can also be made as to the overall posterior distribution of failure probability for each service medium
- From given data, MAP estimates of failure probability differ only slightly between media
  - Liquid medium valves fail at a slightly higher rate
  - Note the increased variance in steam valves compared to other media
- Close agreement between distributions may be due to strict ASME PRV characteristics that are common between service media

Applications of Results

- Cost of process downtime caused by PRV failure can easily exceed cost of buying/storing PRV spares
    - Statistical model can be used to estimate amount of spares required on-hand, with 95% confidence
        - Assuming vendor, service medium known
        - Risk analysis generally favors “cheap” PRVs vs “expensive” process downtime or potential damage/injury
        - Limited risk of overbuying PRVs due to confidence interval giving an extreme ceiling for failure probability

Applications of Results (cont.)

- Consider a situation:
  - Probability of failure of a particular vendor's PRV is estimated to be 10%
  - Analysis shows 95% CI placing bounds at 0% and 40%
  - 3 identical PRVs are required
- Assume worst-case, $f = 0.4$
  - Buying 8 valves gives a >95% probability that 3 will pass the pre-installation test
    - Minimal cost (PRVs are cheap) to ensure protection against downtime
    - Minimal over-buying of valves
      - Also minimizes storage space, which can be a premium in lab environments
- For non-safety-critical PRVs, MAP estimate can be used
  - Lower risk, even if failure occurs
  - Further minimize over-ordering of PRVs
- **Statistical model gives insight into PRV behavior and downstream impact on process financials**

Improvements

- Data set size
  - Data set is limited for certain media
  - Training data should be updated based on more recent PRV pre-installation tests
  - Service media should be expanded for further industry reach
    - GN2, LN2, H2, O2, He, etc
- Confidence Interval Estimation
  - 95% CI based on probability distribution of valve failure parameter
  - CI can be better estimated prior to logistic transform, on log-odds scale
    - More complicated / conservative CI estimates can be constructed e.g. Jeffreys Interval
- Parameter consideration & additional levels
  - If data-set can be constructed that considers PRV material (for example), further inferences can be drawn on probability of failure
  - Opportunities to increase number of levels in multilevel model
  - Consider the more dangerous subset of failures (overpressure deviations)

Conclusion

- Statistical model developed that can be used for PRV failure rate prediction
  - Multilevel model can draw inferences based on vendor performance, as well as pool information to get a distribution for failure rate based on overall service medium
- Considerable financial impacts when applied to real engineering problems
  - Minimize process downtime by stocking adequate amount of PRV spares
  - Minimize overstock of PRVs by estimating worst-case failure rates
- Vendors can be down-selected based on existing PRV failure data
- Proposed improvements can be rolled into later iterations

Proper PRV evaluation is key to protecting life, property, and process with minimal financial impact

Contributions (Addendum)

Ari	Alex
Refactor code	Build initial model
Results generation (numerical)	Statistical background
Graph generation and Bug fixes	Graph generation
Presentation	Bug fixes
Video and Audio Editing	Presentation