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Analysis of Safety Relief Valve Proof Test Data to Optimize Lifecycle Maintenance Costs

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SUMMARY AND CONCLUSIONS

Proof test results were analyzed and compared with a proposed life cycle curve or hazard function and the limit of useful life.

Relief valve proof testing procedures, statistical modeling, data collection processes, and time-in-service trends are presented. The resulting analysis of test data allows for the estimation of the PFD. Extended maintenance intervals to the limit of useful life as well as methodologies and practices for improving relief valve performance and reliability are discussed. A generic cost-benefit analysis and an expected life cycle cost reduction concludes that $90 million maintenance dollars might be avoided for a population of 3000 valves over 20 years.

1 INTRODUCTION

Spring operated pressure relief valves perform an important safety function in the process industries by not allowing system pressures to exceed maximum system design pressure. Spring operated relief valves complying with ASME Boiler and Pressure Vessel Code (BPVC), Section I and Section VIII for fired and unfired pressure vessels are required to be inspected, tested and serviced on a periodic basis. Since a test period is not strictly specified, what typically establishes the maintenance interval is a company guidance document or past plant history. At most sites, system outage for safety relief valve maintenance is costly and may be performed as often as on an annual basis. But what if relief valves at the time of maintenance are still in proper working order and in good physical condition, in other words have remaining useful life? Could the valve be left in service for another year without a statistically significant increase in the probability of failure on demand (PFD)?

Maintenance intervals or valve useful life are best optimized by studying past reliability (performance) data. The Savannah River Site (SRS) joined a pressure relief valve reliability improvement group in 2005. Members of the chemical and gas industry share inventory and event data to quantify reliability based on "proof test" results. The proof test can also be considered the "as-found" condition or the expected lift pressure of the relief valve at the time it is removed from service. A ratio of proof test pressure to set pressure **(R)** of 1.5 or greater in the as-found condition is considered by industry to be failed high or *"stuck shut"* or the PFD meaning that the device would likely have failed on demand during an actual over pressure event. The ratio **(R)** of 1.1 gives an indication of the end of useful life since 10% is the maximum allowed overpressure by the BPVC.

Safely extending pressure relief valve test intervals when supported by quality test data, statistical tools, and failure analysis can provide significant reliability improvements and reduced costs over the lifetime of a valve. At most sites, system outages for safety relief valve maintenance is costly and may be performed as often as on an annual basis lacking data to support a longer service period. Without data and analyses to support test intervals, the relief valve may still be in acceptable working order when removed for maintenance. Any valve could be left in service longer, perhaps for another year if failure rates were not expected to increase over the period.[1] Quality test data and statistical tools are needed to support that statement as being credible.

2 HAZARD FUNCTION AND THE BATHTUB CURVE

The known distribution of spring operated relief valve failures seems to follow the classic bathtub curve[1]. What if relief valves at the time of maintenance are still in proper working order and in good physical condition, that is still in the intrinsic failure period? Could the valve be left in service for another year without a statistically significant increase in the probability of failure on demand? Conceptually, if the failure rate is flat or expected to be statistically the same next year then a facility could leave the pressure relief valve in service for another year at little additional risk.

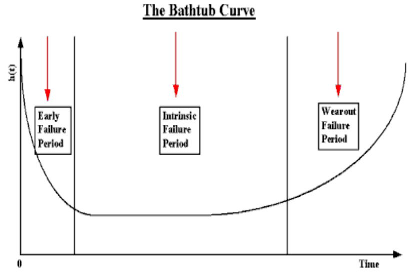
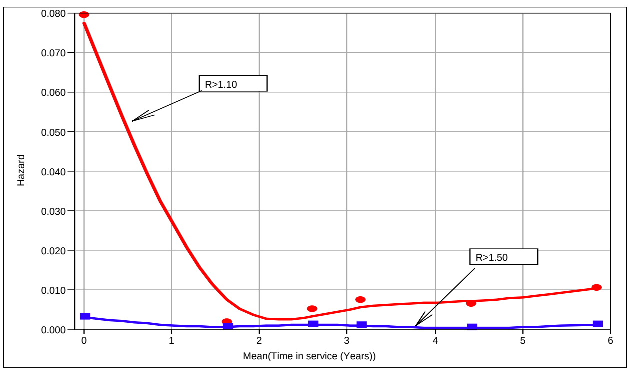


Figure 1 - The Traditional Bathtub Curve[4]

In Figure 1, note that infant mortality corresponds to the early failure period, ***useful life*** could be used to describe the intrinsic failure period where failures are random and occur at a relatively steady rate. We originally observed that the failure rate for pressure relief valves was "flat" or no-slope from 1 – 5 years in service. [2, 3] A significant amount of time-zero proof test data has been collected and compared with used proof test data for up to 10 years in service. Chart 1 is an accumulation of several quality data sets showing the hazard function related to time in service with the upturn between years 5 and 6. It is unclear at present what is happening in the early failure period because few if any valves are being removed from service in less than one year. What data we have as shown basically supports the bathtub curve quite well and suggests that day-one failure, or initial failures may be high; definitely cause for further study.

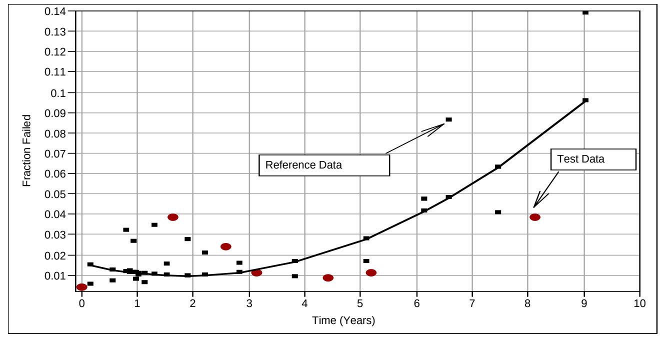
Chart 1- Hazard function vs. Time in Service (Years)



Two hazard functions are displayed in Chart 1 (Appendix Data), one for failure defined as R≥1.10 and the other for R≥1.50. There is not a significant difference in hazard between 1.6 years and 5.8 years for the R≥1.10 curve. However, the inflection point could potentially be between 5 and 6 years. Additional test data is needed to confirm this. The hazard function for R≥1.50 appears to be flat over the same range. However, the number of failures for R≥1.50 is sparse (N<5) for each of the time intervals over this range.

There are very few failures recorded for 6 - 10 years in service; this facility is hesitant to extend intervals beyond 6 years because that presents unknown risk. It is difficult to calculate or predict the end of the maintenance cycle without confirming the upward turning point on the wear out curve. One study reported probabilities of failure in clean gas service out to almost 10 years showing a strong upturn at year six as represented in Chart 2 (Appendix Data).[5] The test data falls within the same footprint as the reference when overlaid on this plot.

Chart 2 – The estimation of failure probabilities (R ≥1.5) Test Data vs. Referenced Publication Data



3 RELIEF VALVE PROOF TESTING PROCEDURES

At this site, valves from ¼ inch inlet to 8 inch inlet are removed from service in the field on a schedule from 1-5 years and in rare controlled situations 7 years. Valves are checked in to the qualified shop for inspection, test and repairs if needed. An as found condition or proof test is performed after visual examination of the valve body, the inlet and the outlet ports. The proof test is recorded and is considered to be the value at which the valve would have lifted in an actual demand. Failure to open prior to 1.5 times the cold set pressure (valve name plate) causes the proof test to be recorded as failure to open. The shop is authorized to increase the pressure to 2 times set pressure in an attempt pop the valve. *New* valves are also proof tested prior to installation just as if they had been in service. Root cause failure analysis is performed on all failed valves and the results characterized in site wide Bulletins.

4 DATA COLLECTION PROCESS

The valve must first pass an initial visual external inspection before testing. If the proof test is within 10% if the set pressure and the average are within 3% of the set point, then the valve has passed test and inspection without requiring further work. Any valve proof testing higher than 1.1 times set pressure is disassembled for "repair". Once the proof test is complete and the data recorded, the valve is tested three more times and the pop pressures recorded to provide an "average" pop pressure. Visual inspection of internals and parts replaced are then immediately recorded in the computerized maintenance management system.

Current Guidelines for Re test / Repair

Present guidelines for inspection are listed in Table 1.[5]

Service	Test or Inspect of Replacement or Reused Valves	Reuse or Replace	Frequency[1]
Gas	Test	Reuse or Replace	2 to 5 years
Steam (ASME Sec.I)	Test	Reuse or Replace	Yearly
Steam (ASME Sec.VIII)	Test	Reuse or Replace	1 to 3 years
Steam Pilot PRV	Test	Reuse or Replace	1 to 2 years[5]
Refrigerant (Henry, Superior)	Inspect	Replace	5 years
Domestic Water Heater	Test[2]	Replace	5 years
Dewar Vessel	Test	Replace	5 years
Oxygen (new valve)	Inspect	Replace	2 to 4 years
Oxygen (existing valve)	Test / Clean	Reuse	2 to 4 years
Rupture Disk (class 1)[4]	Inspect[3]	Reuse or Replace[3]	As required[3]
Rupture Disk (class 2)[4]	Inspect[3]	Reuse or Replace[3]	1 to 5 years
Non-Code soft-seated, inlet <3/4"	Test	Reuse or replace	1 to 2 years

Table 1 Pressure Relief Valve Inspection Guidelines (superscripts refer to Ref 5)

5 METHODS AND PRACTICES FOR IMPROVING RELIEF VALVE PERFORMANCE (RELIABILITY)

Lacking sufficient data on which to base a decision, it is often considered easiest to improve reliability by shortening the time in service. That however, is not cost effective over the life cycle and may

Figure – 2 New relief valve stored for 5 years

not even improve performance if the primary failure mode is not corrosion or high stress in service. The valve pictured in Figure 2 was stored in a warehouse where the temperature was to have been from 40-140 degrees Fahrenheit. Plastic stoppers were applied to the inlet and outlet at the factory to serve as foreign material exclusion. Shop performed the mandatory pre-installation test (proof test) but stopped at 2 times set pressure without the valve lifting. Corroded surfaces and corrosion debris were present on the outlet side of the valve. All the internals are stainless steel (SS); the body is carbon steel. The SS316 disc and SS316 nozzle seating area were stuck together by a film of undetermined oxides or metal-to-metal embedment. Pre-installation proof testing or day-zero verification of set pressure prior to service is an excellent way to improve performance. It has been found that two different corrosion-related failures occur over time. As in the situation above, the stainless steel disc bonds to the seat over time. That condition is also found after 3-5 years in the field.

The second failure cause is typical for stainless steel valves with carbon steel springs and carbon steel spring washers especially for those valves exposed to the elements. In this second case, carbon steel components rust and the corrosion products bind the spring washer inner diameters to the stainless steel valve stem. Once corrosion products have formed between washer and the stem, the stem can no longer slide upwards in the spring washers.

Consequently the disc cannot move off the seat, and the valve is stuck shut. In Figure 3 it can be seen that even after disassembly the carbon steel spring washers have not released their grip from the stainless

Figure 3 Compressor Cooling Water Relief Valve

steel valve stem. The stem is still held tightly in the two spring washers. For certain problem valves, our recommendation is to replace carbon steel with stainless steel spring washers. Most valve manufacturers now offer them. Exposure to the elements was mentioned earlier since corrosion on the discharge side will be accelerated by the presence of moisture or pooled water. Installing packed levers, bellows kits, closed caps, or rain hats will prevent intrusion of rain water. With the open cap design, the discharge side of the valve will fill to spring washer height or more. Humidity will cause corrosion too, but the damage to carbon steel parts has been found to be less severe and it seems to take a longer period of time to accumulate to failure. Drain or weep holes should be drilled in the upturned discharge pipe stub. The discharge pipe stub directs the valve discharge upwards away from personnel, but rainwater can again fill the pipe unless a drain hole at the bottom of the elbow is provided.

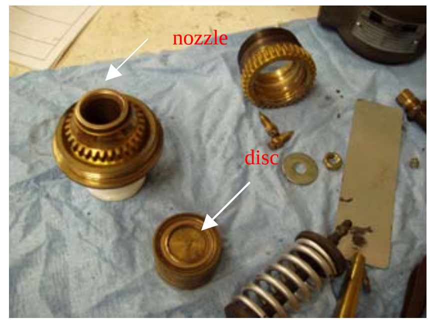


Figure 4 shows a frequent failure mode for reciprocating air compressors. The final discharge valve moves with the compressor discharge piping and the resulting accelerations cause the disc to beat

Figure 4 - Reciprocating Air Compressor Discharge

itself out against the nozzle. It can be seen in the photo that a ridge has worn in the disc, and the nozzle edges are rolled over (they both started out flat). The use of a more sturdy material (stainless steel) or isolation of the discharge piping from the compressor vibrations will increase valve life.

Soft Seated Valves

Of the distribution of relief valves failing high, (R) >/= 1.10 we find that 37% are small diameter (1/2 inch or less) with elastomer seats [145/388]. Compare that with 10% of the total valve population both hard and soft seat failing high. Of the soft seat relief valves, 13% were in service for 3 years or more and 83% [120/145] were new valves. Significant improvement can be made in overall reliability if the use of ¼, 3/8, and ½ inch inlet soft-seated valves is minimized.

6 COST-BENEFIT ESTIMATES

On the right side Table 2 summarizes the labor hours and associated costs for maintenance per valve. On the left side are shown the potential savings based on the number of valves listed in each case. Case 1 for example indicates that we have 31 relief valves at this plant that are now on a 2 year maintenance interval. Supported by statistical analysis of test and other performance data maintenance could be extended to 3 years with an annual savings of $11,772 for the 31 valves. If all the changes shown in the table could be justified, an annual savings of $520,278 in calendar year 2006 dollars would be realized for an average of $222.50 per valve-per year.

Expected Life Cycle Costs over a 20 year Service Life

In the example given above, an average of $4450 ($222.50 x 20) could be saved over a 20 year service life *for each valve*. For the

Each year extension provides a fraction of the $2274 cost as a savings per valve. Use the extension benefit factors from the following table to determine annual cost saving				Outage Evaluation: Estimated Valve Outage Costs per valve - Does not include materials	Estimated Man hours	Labor Rate	Cost
CASE	Factor	# of valves	Savings	1. Planning	5	$68.86	$344.30
1. Extend from 2 years to 3 factor 1/6	0.167	31	$11,772	2. Engineering	3	$68.86	$206.58
2. Extend from 1 years to 5 factor 4/5	0.800	7	$12,734	3. Work Control and Scheduling	4	$68.86	$275.44
3. Extend from 2 years to 5 factor 3/10	0.300	62	$42,296	4. Lockouts, write, review, approve, install and remove	12	$68.86	$826.32
4. Extend from 3 years to 5 factor 2/15	0.133	991	$299,720	5. Meetings POW, POD	3	$68.86	$206.58
5. Extend from 4 years to 5 factor 1/20	0.050	495	$56,282	6. Maintenance Wrench Time; remove, transport, reinstall, PMT	5.7	$51.80	$295.26
6. Extend from 5 years to 7 factor 2/35	0.057	752	$97,473	7. Valve Shop Time hours *	2.3	$51.80	$119.14
Potential cost reduction per year		**2338**	**$520,278**	8. Total outage time - Man hours	35		
Total ACTIVE PMs ~ 3500 Air, Liquid, Gas and Steam			CY 2006 Dollars	9. Total estimated cost per outage / lockout / valve			**$2,273.62**
9737 Relief Valve records				*Based on average of recent Work Orders and last year's average.			

Table 2 Analysis of potential savings for 2338 valves using CY 2006 labor expenditures and cost

entire group of 2338 valves a total of $10.4 million (2238 x $4450) would not be spent on unnecessary maintenance and testing. Another way to look at life cycle cost is to start with annual (1-year) maintenance at $2274 per valve for the first two maintenance cycles, then move to 3 year intervals for two maintenance cycles, and finally to 5 year intervals justifying extensions with test and inspection data. Tracking reliability all the way to ensure the PFD has not statistically changed by increasing the maintenance interval, we could assume the savings as follows over a 20 year life cycle: During the service life of this valve it would be tested 7 times including Day-0 or the pre-installation test for a total of $2274 x 7 = $15,920 not including parts. But, if the test interval had remained at 1 year, a total of $2274 x 20 = $45,480 would have been spent. The resulting savings over a 20 year life cycle not adjusted for future value would be close to $30,000 *per valve* if the same strategy of extension were applied. Using the assumed rates, $90 million maintenance dollars might be avoided for a population of 3000 valves over 20 years. Proof test records and maintenance history will also provide the owner with a documented improvement in valve reliability.

7 REFERENCES

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APPENDIX: DATA TABLES

Chart 1 Data

The hazard function is defined as the number of valves failing in the time interval divided by the number surviving the interval. Time (Years) is the average time over all valves within the time interval.

Time (Years)	N	# Failed R>1.10	# Failed R>1.50	Hazard R>1.10	Hazard R>1.50
0.00	2449	241	10	0.0797	0.0031
1.64	52	6	2	0.0020	0.0006
2.60	166	15	4	0.0052	0.0012
3.15	268	21	3	0.0074	0.0009
4.41	116	18	1	0.0064	0.0003
5.84	231	29	4	0.0105	0.0012
Total	3282	330	24		

Chart 2 Data

Reference Data: 1-19, Test Data 20-27

The estimate for the cumulative distribution function for time to failure (R≥1.50), qi, is estimated as (number of failures within the time interval)/(total number of tests within the time interval).

Group	Time (Years)	Fraction Failed	qi	-ln(1-qi)
1	**0.16**	0.0052	0.0052	0.0052
2	**0.57**	0.0072	0.0072	0.0072
3	**0.79**	0.0317	0.0317	0.0322
4	**0.88**	0.0120	0.0120	0.0120
5	**0.93**	0.0263	0.0263	0.0267
6	**0.98**	0.0080	0.0080	0.0080
7	**1.03**	0.0100	0.0100	0.0100
8	**1.13**	0.0061	0.0061	0.0061
9	**1.31**	0.0345	0.0345	0.0351
10	**1.53**	0.0154	0.0154	0.0155
11	**1.91**	0.0273	0.0273	0.0277
12	**2.21**	0.0205	0.0205	0.0207
13	**2.83**	0.0156	0.0156	0.0158
14	**3.83**	0.0089	0.0089	0.0090
15	**5.10**	0.0165	0.0165	0.0166
16	**6.15**	0.0472	0.0472	0.0483
17	**6.58**	0.0862	0.0862	0.0902
18	**7.46**	0.0407	0.0407	0.0415
19	**9.04**	0.1389	0.1389	0.1495
20	**0.00**	0.0042	0.0042	0.0042
21	**0.22**	0.0000	0.0000	0.0000
22	**1.64**	0.0385	0.0385	0.0392
23	**2.60**	0.0241	0.0241	0.0244
24	**3.15**	0.0112	0.0112	0.0113
25	**4.41**	0.0086	0.0086	0.0087
26	**5.18**	0.0112	0.0112	0.0112
27	**8.12**	0.0385	0.0385	0.0392

BIOGRAPHIES

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