Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

DRAFT Proceedings of the ASME 2021 Pressure Vessels & Piping Conference
PVP2021
July 12, 2021

PVP2021-67230

COMPARISON OF VALVE FAILURE RATES ESTIMATED FROM FIELD FAILURE DATA TO THOSE PREDICTED BY CALIBRATED FMEDA

Julia V. Bukowski
Villanova University
Villanova, PA USA
julia.bukowski@villanova.edu

William M. Goble
exida, LLC
Sellersville, PA USA
wgoble@exida.com

Stephen P. Harris
Savannah River National Laboratory
Aiken, SC USA
stephen.harris@srnl.doe.gov

ABSTRACT

This paper presents the results of three comparative studies. In each study the failure rate of one specific valve at one specific facility is estimated from field failure data (FFD). Each estimate is compared to the failure rate predicted for that valve by the Calibrated FMEDA technique. The predicted failure rates consider the failure rate variations due to valve application, to fluid service, and to each specific facility's Site Safety Index (SSI) which accounts for various aspects of safety culture. The results show that the predictions are quite good, i.e., all predictions lie within a 70% confidence interval constructed from each valve's FFD and near the estimated mean failure rate for each valve.

INTRODUCTION

Pressure relief valves (PRV), along with other types of valves, play critical roles in the safe operation of many industrial processes. Valve failure rates determine not only their reliability but also their safety performance with respect to safety integrity level. Failure rates can be estimated from FFD or predicted by several techniques. While FFD is the best source for determining failure rates, it is often the case that there is insufficient quality FFD to estimate failure rates for all equipment of interest. Predictive methods (FMEA, FMEDA [1], Calibrated FMEDA [2]) provide an alternative solution to determining failure rates *provided that*, for some valves, the predictions can be validated against actual FFD.

There have been numerous studies comparing equipment failure rates estimated from FFD to predicted failure rates for similar equipment [3, 4, 5, 6, 7, 8, 9, 10]. The studies reported here differ from the previous studies in some important respects. To include enough FFD for reasonable estimates, previous studies often grouped failure data for similar equipment from several manufacturers/models. While in some cases, this grouped FFD came from a single facility, in others, the FFD came from more than one facility. This is significant because it is known that the failure rates achieved in use depend in part on the safety culture of the facility [11, 12] and that even at a single facility, the safety culture can change over time [13]. The current studies rely on FFD for three specific valves. Each valve is specified as to manufacturer and model. Furthermore, each valve's estimated failure rate is based on FFD from only a single facility. This is the most precise estimation of achieved failure rate that can be computed.

Finally, previous studies predicted failure rates anticipated to be achieved given some "average" safety culture. In this study, knowledge of each facility's practices over the timeframe of data collection was available. Thus, it is possible to assess each facility's SSI and incorporate this into the prediction of failure rate achieved at that facility creating a more precise comparison between estimated and predicted failure rates.

Following a Nomenclature section, this paper:

- describes the valves and data sources for this study, and summarizes the FFD data,
- describes the method for constructing confidence intervals and estimating mean failure rate based on the FFD,
- summarizes the results of analysis of FFD,
- describes the Calibrated FMEDA predictive method and the concept of SSI,
- summarizes the Calibrated FMEDA predicted failure rates,
- compares the estimated and predicted failure rates,
- discusses the findings and conclusions.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
COT	close-on-trip
df	degrees of freedom
FFD	field failure data
FITS	1failure / 10^9 hours
n	number of failures
OOT	open-on-trip
PRV	pressure relief valve
SRS	Savannah River Site
SRNS	Savannah River Nuclear Services
SSI	site safety index
$z(p,df)$	*upper p* percentile of χ^2 distribution
λ	estimated mean failure rate
τ	total operating hours
χ^2	Chi Square

VALVES AND DATA SOURCES

Soft Seat PRV

The soft seat PRV is spring operated**.** Its FFD comes from Savannah River Site (SRS) in Aiken, SC. SRS tests all PRV at its single facility in its own ASME National Board-certified valve shop. SRS maintains an extensive computerized maintenance database. Further, it performs root cause analysis on all failed valves and uses the information for systematic improvement of many aspects of its maintenance programs. Additional information about SRS and its testing procedures can be found in Ref. 14. The soft seat PRV FFD data used in this study were collected from 271 valves from the same manufacturer and series/model over a period of 15 years totalling 9,259,853 operating hours. It is believed that the data cover two separate timeframes during which SRS safety culture would be characterized by two different SSI. These two timeframes are analyzed separately.

Hard Seat PRV

The hard seat PRV is an actuated valve manufactured as a combined actuator and PRV. Its FFD comes from a US facility of company A. This equipment had some testing performed on site but PRV proof testing was sourced to a third-party valve shop. The maintenance/test records consist of pdf files of scanned paper documents. The hard seat PRV FFD used in this study were collected from eight identical actuator-valve combinations identified by serial numbers in the test records. The data cover a period of 26 years and 1,418,304 operating hours. Based on maintenance/test records and additional knowledge of Company A, it is believed that all FFD data from Company A are characterized by a single SSI.

Gate Valve

The gate valve is a slab style gate valve. Its FFD was generated from results of testing performed in situ on gate valves on a single North Sea oil/gas production platform and recorded in the database of the OREDA project [15]. The gate valve FFD used in this study were collected from 60 valves over a period of two years covering 1,051,200 operating hours. Based on extensive maintenance records which record "functional testing, lubrication, inspection" every six months, it is believed that all FFD data for this gate valve are characterized by a single SSI.

SUMMARY OF FFD DATA FOR THIS STUDY

Table 1 summarizes the data for this study.

Table 1. Summary of FFD Available for Failure Rate Estimation

Valve Type	# Valves	n # failures	τ - Total Operating Hours
Soft Seat PRV	131	1	3,726,288
Soft Seat PRV	140	0	5,533,565
Hard Seat PRV	8	1	1,418,304
Gate Valve	60	0	1,051,200

CONSTRUCTING CONFIDENCE INTERVALS & ESTIMATING MEAN FAILURE RATES FROM FFD

The equation for computing a two-sided (100)x% confidence interval is [16]

(100)x% confidence interval = [lower bound, upper bound] (1)

$$= [\frac{1}{2\tau} z((1+x)/2, 2n+2), \frac{1}{2\tau} z\ ((1-x)/2, 2n+2)))]$$

where $z(p, df)$ represents the *upper p* percentile, of the χ^2 distribution with *df* degrees of freedom which can be computed in Excel using the function chiinv(p, df), n is the number of observed failures, and τ is the total operating time. Note that Eqn. 1 is the same as that used by OREDA [17] for data comprising a homogeneous sample (which is the case with data from a single facility) with one exception. In Eqn. 1, df for the lower limit is $2n+2$ where as OREDA gives the df for the lower limit as $2n$. In Eqn. 1, the df of $2n+2$ not only permits computation of a lower limit when n is zero, but also provides for a larger and, therefore, more conservative lower limit.

The estimated mean failure rate. λ, is given by

$$\lambda = n/\tau. \qquad (2)$$

When n is zero, meaning no failures were observed, then, strictly speaking, an estimate of λ is not statistically defined. Nevertheless, with zero observed failures it is common to estimate λ. For this purpose, the authors use Eqn. (3) per [18]

$$\lambda = 0.55/\tau. \qquad (3)$$

SUMMARY OF RESULTS OF FDD ANALYSIS

Table 2 summaries the results of the FFD analysis indicating the bounds of the 70% confidence interval using Eqn. (1) and the estimated mean failure rates as given by Eqns.

(2) or (3) depending on the value of *n*. Failure rates are given in FITS which equals 1 failure/10^9 hours.

Table 2. Summary of Results of FFF Analysis Showing 70% Confidence Interval Bounds and Estimated Mean Failure Rates

Valve Type	Soft Seat PRV (FITS)	Soft Seat PRV (FITS)	Hard Seat PRV (FITS)	Gate Valve (FITS)
upper bound	905	343	2378	1850
λ	268	99	705	523
Lower bound	183	29	115	155

CALIBRATED FMEDA METHOD

The Calibrated FMEDA technique is performed on a specific device (e.g., PRV, gate valve, pressure transmitter, temperature sensor, electronic module, etc.) specified down to the manufacturer and series/model. Based on the specifics of the design, the parts used to execute the design, the design margins, any automatic diagnostics, the specific use and the environment in which the device will be deployed, the Calibrated FMEDA produces predictions for the dangerous detected and undetected failure rates, the safe detected and undetected failure rates, the diagnostic annunciation failure rates, the no effect failure rates, the dangerous and safe diagnostic coverages (for devices with self-diagnostic capabilities), the useful life, and in the case where external leakage can occur, the external leakage failure rate. The analysis is application specific because a particular failure mode may be dangerous in one application but safe in a different application; for example, consider the difference when a valve responds automatically to a demand by opening vs responding automatically to a demand by closing.

Calibrated FMEDA analysis requires a validated database of failure modes and failure rates for the parts which comprise the various devices [3,4]. Originally, it was thought that the Calibrated FMEDA parts database did not account for the effects of site-specific end-user activities. However, through numerous comparison studies, it has become clear that, because of the way in which the parts database was developed, the Calibrated FMEDA predicted device failure rates routinely account for the effects of some average level of site-specific activities. Essentially Calibrated FMEDA predicts the failure rates of a specific product in a specific application and environment assuming that the devices will be used on a site with an average safety culture and average level of maintenance capability. This baseline prediction is designated SSI 2. Recently, Calibrated FMEDA has been augmented to predict failure rates under five levels of site-specific operations and maintenance activities, viz., SSI 0 through SSI 4 (best case). While it is easy to think about SSI levels with respect to maintenance activities, SSI encompasses much more about safety culture. SSI level can be assessed approximately via a questionnaire about many aspects of safety culture and more precisely by an on-site audit.

Over the years, many devices have been subjected to Calibrated FMEDA analysis and all Calibrated FMEDA results have been collected and retained in a Calibrated FMEDA master database (separate and different from the validated parts failure mode and rate database used by Calibrated FMEDA). The device results in the database are continuously calibrated against FFD as such data become available. Calibrated FMEDA's are updated if the parts database changes significantly. The results of device Calibrated FMEDA are stored in the database of exida's exSILentia® [2] tool set which is updated quarterly.

Calibrated FMEDA Failure Rate Prediction

Given the specifications of the three valves for which FFD were available and given additional information regarding the valve applications (i.e., close-on-trip (COT) or open-on-trip (OOT)), the type of fluid service involved, along with an assessment of the SSI level of each facility providing data, a Calibrated FMEDA analysis was performed. Recall that the soft seat PRV covered timeframes with two different SSI levels for that facility. The predicted failure rates include safe and dangerous failure rates and the failure rate for external leakage where applicable. Table 3 summarizes the results of the predictive analysis.

Table 3. Summary of Calibrated FMEDA Predicted Failure Rates Including Effects of Application, Working Fluid, & SSI for Each Facility and Timeframe.

Valve Type	Application	Fluid Service	SSI Level	Predicted λ (FITS)
Soft Seat PRV	OOT	Clean	1	226
Soft Seat PRV	OOT	Clean	2	87
Hard Seat PRV	OOT	Clean	2	661
Gate Valve	COT	Severe	3	554

COMPARISON OF ESTIMATED AND PREDICTED FAILURE RATES

Figure 1 compares the estimated and predicted failure rates.

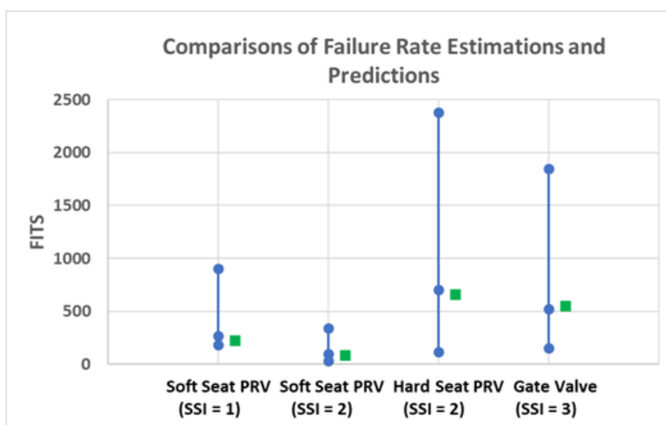

Figure 1. Comparison of 70% Confidence Interval and Failure Rate Estimation from FFD (blue circles

and lines) with Calibrated FMEDA Predicted Failure Rates (green squares).

CONCLUSIONS

The three studies reported here strongly support the validity of the Calibrated FMEDA failure rate predictions and, consequently, the Calibrated FMEDA method and supporting databases for component failure modes and failure rates. The equipment examples cover different equipment types, viz., soft seat spring operated PRV, hard seat actuated PRV, and slab style gate valves, and all equipment FFD exceed 1,000,000 operating hours. While FFD with larger number of operating hours leads to narrower confidence intervals, it is noteworthy that not only do *all* the predicted failure rates lie within the 70% confidence intervals of their respective equipment, but also, the predicted failure rates lie *remarkably close* to the estimated mean failure rates. Calibrated FMEDA predicted failure rates provide a reliable alternative to estimated failure rates and are especially useful in the absence of FFD of sufficient quality and quantity to make estimations possible. Furthermore, for a specific facility, comparisons between estimations of equipment mean failure rates from FFD at that facility and Calibrated FMEDA predictions for the same equipment at that facility provide a means of measuring the SSI of the facility.

ACKNOWLEDGMENTS

The authors wish to acknowledge with gratitude the following individuals who have been involved in and/or have supported the SRS PRV data collection and RCA analyses: Robert Gross, Sr. Fellow Engineer with SRNS (retired), James Fulmer and Chester Enlow, SRS Valve Shop Mechanics; Duane Edington and Albert (Chip) Jenison, SRS Valve Shop Management; Bob Davis and Jim Broome, Site Services SOPRV Coordinators; SRS Pressure Protection Committee Members.

The authors also wish to acknowledge with gratitude the gracious support of the OREDA organization which provided detailed data for gate valve assemblies from its database and for its efforts in reviewing the research results. We wish to thank Nicolas Clavé of Total (Total's Representative to OREDA and Steering Committee Chairman), our point of first contact with OREDA who reviewed our results and provided thoughtful comments and suggestions, Siegfried Eisinger of DNVGL (OREDA Project Management team leader) who shepherded our project proposal through the necessary approvals, set up the mechanisms for data sharing and also reviewed our results and provided thoughtful comments and suggestions, and Stian Sætre of DNVGL who performed the database queries to provide the data required for this study.

REFERENCES

1. Goble, W. M., and Brombacher, A. C., "Using a Failure Modes, Effects and Diagnostic Analysis (FMEDA) to Measure Diagnostic Coverage in Programmable Electronic Systems," *Reliability Engineering and System Safety,* Vol. 66, No. 2, November 1999.
2. *exSILentia*® version 4.0*,* exida.com, LLC, Sellersville, PA, 2020.
3. Bukowski, J. V. and Goble, W. M., "Validation of a Mechanical Component Constant Failure Rate Database," 2009 *Proceedings Annual Reliability and Maintainability Symposium*, Fort Worth, TX, January 2009, 338-343.
4. Bukowski, J. V. and Goble, W. M., "Properly Assessing Mechanical Component Failure Rates," *2012 Proceedings Annual Reliability and Maintainability Symposium*, Reno, NV, January 2012, pp. 1-7.
5. Bukowski, J. V., Stewart, L. and Lee, D., "Understanding the Similarities and Differences of OREDA and FMEDA Data Analysis," *Proceedings AIChE 2nd CCPS Global Summit on Process Safety*, Malaysia, November 2015.
6. Bukowski, J. V. and Stewart, L., "FMEDA Predictions and OREDA Estimations for Mechanical Failure Rates: Explaining the Differences," *Proceedings ISA Process Control and Safety Symposium*, Houston, TX, November 2015.
7. Bukowski, J. V. and Stewart, L., "Comparing Failure Rates for Safety Devices: FMEDA Prediction vs OREDA Estimation," Presented at 2015 Wilmington ISA Show & Technical Conference November 18, 2015.
8. Bukowski, J. V., Goble, W. M., and van Beurden, I., "Product Failure Rates vs Total Failure Rates at Specific Sites: Implications for Safety," *Proceedings AIChE 11th Annual Global Conf on Process Safety – Process Plant Safety Symposium*, Austin, TX, April 2015.
9. Bukowski, J. V. and Stewart, L., "Explaining the Differences in Mechanical Failure Rates: exida FMEDA predictions and OREDA Estimations," Version 1.2 October 2017, (originally published September 2015), whitepaper available at www.exida.com under whitepaper categories Failure Rate Data and FMEDA and listed as posted on 2015-09-11.
10. Goble, W. M., Bukowski, J. V. and Stewart, L, "Comparing FMEDA Predicted Failure Rates to OREDA Estimated Failure Rates for Sensor and Valve Assemblies", Version 1.1 September 2019, (originally published March 2016), whitepaper available at www.exida.com under whitepaper categories Failure Rate Data and FMEDA as "Comparing FMEDA Predicted Failure Rates to OREDA" posted 2016-04-11.
11. Bukowski, J. V. and Chastain-Knight, D., "Assessing Safety Culture via the Site Safety Index™," *Proceedings AIChE 12th Annual Global Conf on Process Safety – Process Plant Safety Symposium*, Houston, TX, April 2016.
12. Bukowski, J. V. and Stewart, L., "Quantifying the Impacts of Human Factors on Functional Safety," *Proceedings AIChE 12th Annual Global Conf on Process Safety – Process Plant Safety Symposium*, Houston, TX, April 2016.
13. Bukowski, J. V., Gross, R. E., Harris, S. P., and Goble, W. M., "Analysis of Spring Operated Pressure Relief Valve

Proof Test Data: Findings and Implications," *Process Safety Progress,* V37, N4, 2018, pp.467-477; doi:10.1002/prs.12006.
14. Gross, R., "Reliability Testing of Pressure Relief Valves," ASME PVP2004-2610, *Proceedings of the ASME 2013 Pressure Vessels and Piping Division Conference*, San Diego, CA, July 2004.
15. OREDA Data Release 11.2, OREDA Organization, 2020.
16. "Reliability Estimations for the Exponential Life," START, Selected Topics in Assurance Related Technologies, DOD Reliability Analysis Center, Vol. 10, No. 7.
17. SINTEF, *OREDA Offshore and Onshore Reliability Data Handbook, Vol 1. – Topside Equipment* 6th Ed, OREDA Participants, 2015.
18. Williams, M. M. R. and Thorne, M. C., "The estimation of failure rates for low probability events," *Progress in Nuclear Energy*, Vol 31, Issue 4, 1997, pp. 373-476.