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

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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.

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NOMENCLATURE
ASME American Society of Mechanical Engineers
COT close-on-trip
\( df \) degrees of freedom
FFD field failure data
FITS 1 failure / 10^6 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 \( \chi^2 \) distribution
\( \lambda \) estimated mean failure rate
\( \tau \) total operating hours
\( \chi^2 \) 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>
<thead>
<tr>
<th>Valve Type</th>
<th># Valves</th>
<th># Failures</th>
<th>( \tau ) - Total Operating Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Seat PRV</td>
<td>131</td>
<td>1</td>
<td>3,726,288</td>
</tr>
<tr>
<td>Soft Seat PRV</td>
<td>140</td>
<td>0</td>
<td>5,333,565</td>
</tr>
<tr>
<td>Hard Seat PRV</td>
<td>8</td>
<td>1</td>
<td>1,418,304</td>
</tr>
<tr>
<td>Gate Valve</td>
<td>60</td>
<td>0</td>
<td>1,051,200</td>
</tr>
</tbody>
</table>

CONSTRUCTING CONFIDENCE INTERVALS & ESTIMATING MEAN FAILURE RATES FROM FFD
The equation for computing a two-sided (100)x% confidence interval is [16]

\[
(100)x\% \text{ confidence interval } = [\text{lower bound}, \text{upper bound}] \quad (1)
\]

\[
= \left[ \frac{1}{2z} \left( \frac{\chi^2}{2} - \frac{1}{2z} \chi^2 \left( \frac{1}{2} \right) \right), \frac{1}{2z} \chi^2 \left( \frac{1}{2} \right) \right]
\]

where \( z(p, df) \) represents the upper \( p \) percentile, of the \( \chi^2 \) distribution with \( df \) degrees of freedom which can be computed in Excel using the function \( \text{chiinv}(p, df) \), \( n \) is the number of observed failures, and \( \tau \) 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, \( \lambda \), is given by

\[
\lambda = \frac{n}{\tau}. \quad (2)
\]

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

\[
\lambda = 0.55/\tau. \quad (3)
\]

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 $1 \text{ failure/10}^6 \text{ hours}$.

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

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Soft Seat PRV (FITS)</th>
<th>Soft Seat PRV (FITS)</th>
<th>Hard Seat PRV (FITS)</th>
<th>Gate Valve (FITS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper bound</td>
<td>905</td>
<td>343</td>
<td>2378</td>
<td>1850</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>268</td>
<td>99</td>
<td>705</td>
<td>523</td>
</tr>
<tr>
<td>Lower bound</td>
<td>183</td>
<td>29</td>
<td>115</td>
<td>155</td>
</tr>
</tbody>
</table>

**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 announcement 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.**

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Application</th>
<th>Fluid Service</th>
<th>SSI Level</th>
<th>Predicted $\lambda$ (FITS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Seat PRV</td>
<td>OOT</td>
<td>Clean</td>
<td>1</td>
<td>226</td>
</tr>
<tr>
<td>Soft Seat PRV</td>
<td>OOT</td>
<td>Clean</td>
<td>2</td>
<td>87</td>
</tr>
<tr>
<td>Hard Seat PRV</td>
<td>OOT</td>
<td>Clean</td>
<td>2</td>
<td>661</td>
</tr>
<tr>
<td>Gate Valve</td>
<td>COT</td>
<td>Severe</td>
<td>3</td>
<td>554</td>
</tr>
</tbody>
</table>

**COMPARISON OF ESTIMATED AND PREDICTED FAILURE RATES**

Figure 1 compares the estimated and predicted failure rates.

![Comparisons of Failure Rate Estimations and Predictions](image)

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.

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