Evaluation of SRV Pipe Failure Rates Via Probabilistic Mechanical Design

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Abstract

For a risk assessment analysis of the postulated failure of the vapor suppression system in Mark I and Mark II containments during anticipated transients a pipe failure rate for safety relief valve (SRV) piping located in the wetwell air space of the containment was needed. The stress-strength overlap method was chosen to predict this failure rate. In this method the amount of overlap of the probabilistic stress and strength distribution of the pipe is used as a measure of failure probability. If these distributions are known, the probability of failure can be computed in a straightforward manner.

To obtain the distribution of stresses experienced in an SRV line during a transient, the values measured during SRV actuation in the early stages of operation of the Mark II plant at Caorso, Italy were used. In order to obtain strength parameters the material properties and their variability had to be established for the Caorso SRV piping and a choice had to be made regarding failure strength, i.e., the plastic collapse load. A reasonable value to assign to the failure strength was judged to be the average of the yield and ultimate strengths. This choice agreed with the plastic collapse load chosen by General Electric for a generic evaluation of Mark I SRV discharge line integrity and is consistent with the philosophy for choosing containment failure criteria expressed in WASH-1400.

Assuming normally distributed variables, stress and strength distributions were found: the stress distribution from the values measured in the Caorso plant, the strength distributions from the results of material testing found in the literature.

A failure probability for a newly installed SRV pipe was calculated and estimates were made of the effects of fatigue and corrosion on this value. Fatigue was accounted for by applying a stress range reduction factor as found in the ASME Boiler and Pressure Vessel Code to the mean value of the strength, while corrosion was considered by modifying the applied stresses consistent with a reduction in pipe wall thickness found in a corroded pipe.

Sensitivity studies were also conducted regarding the assumed distribution shapes and distribution parameter values.
1. Introduction and Description

For a risk assessment analysis of the postulated failure of the vapor suppression system in Mark I and Mark II containments during anticipated transients, a pipe failure rate for safety relief valve (SRV) piping located in the wetwell air space of the containment was needed. Two methods were used to obtain failure rates. One was an evaluation based on existing generating experience, the other was by use of so-called Probabilistic Mechanical Design (PMD) methods. It is application of the PMD method with which this paper is concerned. Specifically, a failure rate is predicted from the amount of overlap of the probabilistic stress and strength distributions of the pipe.

The concept of a safety factor in design implies that there is a certain separation of the strength of a particular component from the stresses applied to that component. What must be remembered is that the strength and stress in question are mean values (or conservative estimates of mean values) of a complete strength and stress distribution. For any reasonable distribution, including the normal, an overlap of stress and strength, however small, is unavoidable (Figure 1). Rather than use a safety factor, the adequacy of a component for which strength and stress distributions are known can be determined from the probability that strength exceeds stress (reliability), or the probability that strength is less than stress (failure). By definition, reliability equals one minus the failure probability. Given the variable nature of the parameters encountered in the physical sciences, the probabilistic approach to design is a natural choice.

The amount of overlap of the strength and stress distribution is a measure of the probability of failure. If the distributions are known, the reliability or, alternately, probability of failure, can be computed. As described in Haugen [1], the salient points in the calculation are the following:

Let \( s \), the stress, and \( S \), the strength, be normally distributed random variables with density functions \( f(s) \) and \( f(S) \). Let \( \delta = S - s \). Since \( f(s) \) and \( f(S) \) are normally distributed, so is \( f(\delta) \). Therefore,

\[
f(\delta) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\delta - \bar{\delta}}{\sigma_\delta} \right)^2 \right]
\]

where

\[
\bar{\delta} = \bar{S} - \bar{s} \quad \text{and} \quad \sigma_\delta = \sqrt{\sigma_S^2 + \sigma_s^2}
\]

A bar indicates the mean and \( \sigma \) the standard deviation (or standard deviation estimator) of the variables indicated.

Figure 2 shows a sketch of \( f(\delta) \). The density of \( \delta \) to the right of zero is the reliability, while the failure density is represented by the portion less than zero. In other words, the reliability \( R \) is the probability that \( \delta > 0 \) and so \( R = \int_0^\infty f(\delta) \, d\delta \) and the failure probability \( P_f \) is given by \( 1 - R \) or \( P_f = \int_0^\infty f(\delta) \, d\delta \). To evaluate either of these integrals, one has only to make the transformation which relates \( \delta \) to the standardized normal
variable $Z$ and look up the integral values which are tabulated in standard tables of normal functions. The transformation is given by $Z = \frac{\delta - \bar{s}}{\sigma_s}$. Since the $Z$ coordinate of interest is the one where $\delta = 0$

$$Z = \frac{\bar{s} - \bar{s}}{\sigma_s} = \left| \bar{s} - \bar{s} \right| \sqrt{1 + \frac{\sigma_s^2}{\sigma_s^2}}$$

or

$$Z = \frac{|\bar{s} - \bar{s}|}{\sqrt{\sigma_s^2 + \sigma_s^2}}$$

Therefore, if the distributions of $S$ and $s$ are known, $Z$ can be computed and the reliability or failure probability found from tables of the standard normal function. (See [1] for a more detailed discussion.)

2. Obtaining Parameter Values

If stress and strength are assumed to be normally distributed, then the mean and standard deviations for each must be found to compute the probability of failure.

The stress data for this study was obtained from measurements made in the SRV lines of the Caorso nuclear plant in Italy during SRV discharge tests. Details of measurement location, strain gage arrangement and data interpretation can be found in Reference [2]. Although many measurements were made, Reference [2] cites only 7 data points for which all stresses, i.e. pressure, thermal, etc., are given. Two additional data points can be found in Reference [3]. These nine values lead to a mean stress of 23,727 psi, with a standard deviation of 2561 psi. Implicit in the use of this data to determine failure rates for the present purpose is the assumption that the strain gages in Caorso were located on the most highly stressed part of the SRV line.

To obtain the strength parameters, the SRV pipe material properties and their variability must be established. In the wetwell, the Caorso SRV piping is 10-inch, Schedule 80. The material is specified as A106, Grade B, carbon steel. The yield strength for this material is listed as 35 KSI, while the ultimate strength is given as 60 KSI. These values were taken to be conservative estimates of the means of the assumed normal yield and ultimate strength distributions. A fairly exhaustive search was made for strength variability data on A106 Grade B but no statistical information for this particular piping material could be found. In order to obtain a reasonable estimate of the standard deviation, data which was available for other carbon steels was used as described in the following: In Appendix 10.4 of Haugen [4], data on eighteen carbon steels of various kinds are listed. Mean, standard deviation and sample size are given for ultimate tensile strength and tensile yield strength. A weighted average standard deviation as a percentage of tensile or yield strength was found from averaging this data and weighting it by the sample size for each entry. It was found that for the ultimate tensile strength the weighted average standard deviation was 4.6% of the mean, while for the tensile yield strength the weighted average standard deviation was 6.6% of the mean.

A choice must be made regarding the value assigned to the strength at failure, $\bar{S}$, i.e., the plastic collapse load. Choosing the yield strength would be overly conservative, since the carbon steel pipe can be assumed to be quite ductile and therefore can undergo substantial plastic deformation before rupture failure. Construction quality can also be considered high since these pipes are designed and fabricated to certain code requirements. One
may be led to conclude that the ultimate strength would be an appropriate choice for \( \hat{S} \). This would be too optimistic an assumption however, since the potential failure at smaller loads due to weldment imperfections or other stress concentrations must be recognized. Therefore, a reasonable value for failure strength \( \hat{S} \) is judged to be a stress level halfway between the yield and ultimate strength of A106 Grade B. This choice of \( \hat{S} \) agrees with the plastic collapse load chosen by General Electric for a generic evaluation of Mark I SRV discharge line integrity [5]. The philosophy behind choosing this average of yield and ultimate stress is the same as that expressed for BMR containment failure criteria in [6].

Therefore, if \( \tilde{S} = (\text{ultimate stress} + \text{yield stress})/2 \), the corresponding standard deviation \( \sigma_S \) is then computed from:

\[ \sigma_S = \sqrt{\frac{\sigma_y^2 + \sigma_u^2}{2}} \]

In terms of percent of the mean \% \( \sigma_S = \sqrt{(4.6\%)^2 + (6.6\%)^2} = 8.0\% \) of \( \tilde{S} \). For instance, if the values for tensile and yield strength of A106 Grade B carbon steel cited above are used, \( \tilde{S} = \frac{35000 + 60000}{2} = 47,500 \) psi and \( \sigma_S = 0.080 \times 47,500 = 3,800 \) psi.

To get additional insight, standard deviations corresponding to the highest and lowest percent of mean value in Appendix 10.A of Reference [4] were also computed. For \( \sigma_S \) these were calculated to be 12.7\% and 3.5\% of \( \tilde{S} \), respectively.

3. Sample Calculation

To illustrate how a particular probability value is computed, consider the case of the Caqro SRV lines again where the stress parameters, as indicated earlier, are given by

\[ (\tilde{S},\sigma_S) = (23727, 2561) \]

and the strength was found to be \( (\tilde{S},\sigma_S) = (47500, 3800) \). Then

\[ Z = \frac{23727 - \tilde{S}}{\sigma_S} = \sqrt{\frac{2561^2 + 3800^2}{2}} = 5.19 \]

From a standard table for \( \int f(Z)\)dZ the probability of failure is found to be \( P_f = 1.07 \times 10^{-7} \).

4. Fatigue and Corrosion Considerations

The USNRC requires that SRV piping must be evaluated in accordance with U.S. ASME Class 2 Rules. The ASME Class 2 Fatigue requirements provide for a stress range reduction factor which is a function of the number of alternating stress cycles as shown in Table NC-3611.2(e)-1 of the 1977 ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NC. Use of this table provides one way of considering fatigue when estimating the failure rate of SRV piping.

 Conservatively assuming that the entire applied stress can alternate, one can get an estimate of the effect of fatigue on the failure probabilities by applying the stress range reduction factor directly to the mean value of the strength, \( \tilde{S} \). For example, using values from the Table cited above and the "as built" value for \( \tilde{S} \) of 47.5 kips for A106 Grade B carbon steel, between 7,000 and 14,000 cycles \( \tilde{S} = 0.9x47.5 \) kips or 42.75 kips. Between 14,000 and

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22,000 cycles \( \frac{\sigma}{5} = 0.8 \times 47.5 \) kips or 38.0 kips. Taking the strength standard deviation \( \sigma_s \) as a fixed percentage of \( \frac{\sigma}{5} \), e.g. 8.0% as discussed earlier, one can now calculate a failure probability taking into account fatigue by using the modified strength values and the previously used applied stresses. Figure 3 shows the variation of the demand failure rate with strength \( \frac{\sigma}{5} \).

Corrosion can be accounted for by assuming a certain reduction in pipe thickness during the life of the plant. Using a general rule of conventional design practice, one can assume a 1/6 reduction in pipe thickness due to corrosion over 40 plant years. This change in wall thickness will modify the applied stress values obtained from References [2] and [3]. For a thin walled cylinder, like the SRV pipe, thermal stresses are relatively unaffected by thickness, while pressure and bending stresses are inversely proportional to the wall thickness. Modifying the stress components from References [2] and [3] appropriately then leads to a mean stress value \( \frac{\sigma}{5} = 25,126 \) psi and a \( \sigma_s = 2,691 \) psi. Now a demand failure rate accounting for corrosion can be found by using the modified stress parameters and the original strength parameters.

Obviously, one can evaluate failure rates using both modified stress and modified strength parameters thus accounting for both corrosion as well as fatigue at the same time. The values for several cases are given in Table I.

5. Comments on Assumptions and Accuracy

Any discussion of the stress-strength overlap method would be incomplete without mentioning its sensitivity to the assumptions regarding distribution shapes and parameter values.

The high sensitivity of the failure probability to variations in the standard deviation is shown in Figure 3. Three different strength standard deviations taken as 3.5, 8.0 and 12.7% of the mean failure strength give vastly different failure probabilities as shown in the figure. That such small variations in the standard deviation \( \sigma \) lead to such large differences in the failure probabilities is not so surprising since only the extreme tails of the distributions overlap to determine the probabilities and these tails are sensitive to \( \sigma \). While Figure 3 shows the effect of varying the standard deviation of the strength, a similar effect would be achieved by varying the stress standard deviation.

So far, only a normal distribution has been considered. The sensitivity of the probabilities to distribution shape is obviously also great since it is the extreme tails of the distributions which determine the probabilities. Even if a distribution appears close to normal for moderate distances away from the mean, the shape of the extreme tails may differ greatly, thereby greatly changing the probability from one predicted using a normal distribution assumption.

An interesting and thorough discussion of the failure probability's sensitivity to assumptions of distribution shape and parameters can be found in Bari, et al. [7].

The assumptions made in the present paper were based on best estimates made from the available data. That this data is much more sparse than is desirable cannot be disputed. It would be very helpful to have many more data points for the stress distribution which an SRV line is subjected to at its critical point. Much more material testing is needed to conclude with confidence that the strength distribution of A106 Grade B is normal and what the distribution parameters are.
References


Table I Pipe Failure Rates

<table>
<thead>
<tr>
<th>Failure Rate (per demand)</th>
<th>Load Cycles</th>
<th>Corrosion</th>
<th>Remarks</th>
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</thead>
<tbody>
<tr>
<td>1.0E-7</td>
<td>0</td>
<td>No</td>
<td>&quot;As Built&quot; Best Estimate</td>
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<tr>
<td>3.0E-6</td>
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<td>Strength Reduced 10%</td>
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<tr>
<td>1.0E-4</td>
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<tr>
<td>2.6E-5</td>
<td>7001</td>
<td>Yes</td>
<td>40 Plant-Years</td>
</tr>
</tbody>
</table>
Figure 1 Normal Distributions Showing Overlap

Figure 2 Difference Distribution

Figure 3 Pipe Failure Rates Estimated by Stress-Strength Overlap Method