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A QUANTITATIVE APPROACH TO A RISK-BASED INSPECTION METHODOLOGY OF MAIN STEAM AND HOT REHEAT PIPING SYSTEMS (*)

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ABSTRACT

This paper presents an evaluation of the failure probability and cost of high energy piping (HEP) failures. Using a conventional definition of risk as the product of failure probability and failure consequence, we propose in this paper a dollar value of consequence in order to develop a quantitative approach to risk-based inspection (RBI) methodology. A 16-year historical database of probability and consequence was evaluated as an RBI methodology for devising a life management strategy for welds in main steam and hot reheat piping systems. This evaluation provides us the raw data necessary for producing a concrete example of this new Richter-scale-like approach. Uncertainty in consequence and probability estimates is also provided in plotting (a) a static consequence vs. likelihood diagram at a specific time for comparing the relative severity of a variety of potential failures, and (b) a dynamic risk vs. time diagram for a specific hardware under continuous monitoring where the effect of life management decisions over a period of time is quantitatively displayed. Significance of this new approach to risk-based inspection strategy for advancing the state-of-the-art of managing aging structures is discussed.

Keywords: Clamshell weld; consequence; design of experiments; duration histogram; fractional factorial design; girth weld; high energy piping; high impact low probability events; hot reheat piping systems; main steam piping systems; NERC-GADS; probability; risk-based inspection; seam weld; statistical data analysis; uncertainty estimation.

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INTRODUCTION

The risk-based inspection (RBI) methodology is based on an evaluation of the failure probability and consequence of a specified type of event. In this paper, a database of piping failures in main steam (MS) and hot reheat (HRH) piping systems were evaluated. This RBI study considered the large set of data in the Generating Availability Data System (GADS)

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obtained by the North American Electric Reliability Corporation (NERC) to develop realistic quantitative values of probabilities and consequence.

For this paper, the NERC-GADS 1982 through 1997 industry-wide data [1] for MS and HRH piping incidents with forced outages of at least 350 hours were considered. These incidents are described as High Impact Low Probability (HILP) events. The MS and HRH piping systems were considered in this analysis because they are recognized as a major portion of the fossil power plant HEP systems subject to significant forced outages.

Cohn wrote a paper in 2007 [2] illustrating the risk analysis evaluation of a HRH piping system. This piping system has a design pressure of 575 psig (3.96 MPa) and typically operates at 430 psig (2.96 MPa). The design temperature is 955°F (513°C) and the operating temperature ranges from 940°F (504°C) to 950°F (510°C). An isometric of the piping system, including weld designations, is illustrated in Figure 1. This example includes girth welds (designated as 1 through 23), clamshell welds (designated as E1 through E9), and seam welds (designated as L1 through L18).

As described in the 2007 paper, the specific risk matrix is shown in Figure 2. This was an example of a qualitative risk matrix, illustrating that 1) the girth weld failures are high likelihood with medium consequence, 2) the clamshell weld failures are medium likelihood with high consequence, and 3) the seam weld failures are very low to low likelihood with very high consequence.

This paper augments the 2007 paper, providing quantitative risk information based on an empirical database of MS and HRH piping systems. Statistical evaluations were performed to determine the failure frequencies and failure consequences of 1) all reported incidents, 2) girth weld failures, 3) clamshell weld failures, and 4) seam weld failures. The major statistical tools used were "survival analysis" and "Monte Carlo simulation," as implemented using the computer program Stata [3]. Survival analysis [4-7] is a form of regression analysis designed to fit what Statisticians call "event history" data, such as the time-to-failure random variable for welds. Monte Carlo simulation [8-9] is a powerful numerical technique to implement complex statistical models that might otherwise be intractable. For example in this paper we treat a model with five random variables, the most important of which are weld time to failure in years, forced outage duration in hours, and forced outage replacement power cost in USD per MWhr. Evaluations of simulation results can be used to estimate the likelihood and consequence of a HILP event during the remaining life of a fossil power plant unit.

A two-level fractional factorial design of experiments analysis was used as described by Box, et.al. [10] and Montgomery [11]. This evaluation was performed for a HRH piping system failure at a specific fossil power plant. In this example, the perturbations of five attributes (age, personnel response, piping stress, injuries, and prior examinations) were considered to determine the governing outage duration cost parameters.

MS AND HRH PIPING SYSTEMS – ALL WELDS

The evaluation of the NERC-GADS industry-wide data revealed that there were 40 incidents of HILP forced outages of at least 350 hours (about ½ month) reported during the period of 1982 through 1997. A histogram of the age distribution of the 1998 NERC-GADS reporting fossil units is illustrated in Figure 3. Most of the units were between 20 and 50 years of age.

Several steps were used to estimate failure frequencies and severities. The first two steps were to build statistical models of failure ages and the duration of HEP HILP events.

The failure ages were developed using a technique called survival analysis of the age-at-failure data. An evaluation of the data revealed that the failure rate of the piping systems was relatively constant after several years of operation. This evaluation also indicated that there is no evidence of very early "infant mortality" failures or an accelerated "wear out" pattern for the older units. There is no indication of a time-dependent "bathtub" curve in the piping failure data.

The piping failure outage durations were modeled as a random variable by similar statistical techniques. Outage durations were modeled with the best fitting of several parametric distributions. In most cases, the generalized gamma model was used, which includes both lognormal and Weibull models as special cases. A duration distribution example is illustrated below in the section discussing girth welds.

The resulting simulated future outage durations were converted to present dollars consequence in a series of steps and assumptions. The cost of very long outages is typically dominated by the cost to replace lost power. It is assumed that the simulated 400 MW unit is baseloaded, efficient, and generally significantly less expensive than other replacement power alternatives. Based on a composite of our experience regarding power replacement economic analyses for such units, the power replacement cost distribution in Figure 4 was assumed. A composite distribution to model the discount rate as a random variable was constructed by assuming a median annual discount rate of 9% and a lognormal distribution with a coefficient of variation (standard deviation/mean) of 0.15.

The NERC-GADS piping failure data were used to simulate the probability and consequence of pipe failure for a 400 MW 40-year old fossil unit. The above methodology was implemented using the computer software Stata Version 10 [5], a "data analysis and statistical software package for research professionals." As a result of a million simulations, the frequency and severity of piping HILP outages exceeding $100,000 is illustrated in Figure 5. The confidence bound curves illustrate the aggregated effects of uncertainties, which are dominated by the outage duration and failure age. This figure applies only to the unlucky 5.66% of the 400 MW units having an HILP incident sometime in their remaining lives.

As an example, this plot can be used to answer the following questions:

1. What are the chances of suffering a greater than $20 million (present value) piping HILP catastrophe during the remaining life of a NERC-member 40-year old fossil unit? The best estimate is about 4.5 chances in 10,000 and the confidence interval on that estimate is 1/10,000 to 10/10,000.

2. What is the present valued cost of the worst-in-100 units HILP piping event? The best estimate is about $3.4 million and the confidence interval on that estimate is $2.3 million to $5.0 million.

For this case, the statistical analysis revealed that given a HILP incident, the durations and the 95% confidence bounds {-,+} are:

- Mean duration is 1286 hours {1014, 1482}
- Median duration is 816 hours {559, 939}

For this case, the statistical analysis revealed that given a HILP incident, the costs in $1,000,000 and the 95% confidence bounds {-,+} are:

- Mean cost is $2.07 {1.59, 2.43}
- Median cost is $0.72 {0.58, 0.77}

MS AND HRH PIPING SYSTEMS – GIRTH WELDS

The event description for each of the NERC-GADS list of 40 HILP incidents was reviewed. It was determined that 31 of the incidents were associated with girth weld failures. For this set of data, the mean age of the girth weld failures was 24.5 years and the mean duration was 744 hours.

Based on the NERC-GADS data, a simulation of remaining lives for 1,000,000 400 MW 40-year old fossil units was performed. It was estimated that 4.83% of the units suffered forced outages of greater than 350 hours duration. The histogram of frequency versus outage duration is illustrated in Figure 6. This histogram drops quickly from an outage duration of 1/2 month to 3 months.

As a result of a million simulations, the frequency and severity of piping girth weld HILP outages exceeding $100,000 is illustrated in Figure 7. This figure applies only to the unlucky 4.83% of the 400 MW units having a girth weld HILP incident sometime in their remaining lives. This plot excludes about 19% of the girth weld HILP events costing less than $100,000. The figure is similar to Figure 5, with slightly lower curves below $2M and a much lower probability of outage costs beyond $10M.

For this case, the statistical analysis revealed that given a girth weld HILP incident, the durations and the 95% confidence bounds {-,+} are:

- Mean duration is 762 hours {630, 923}
- Median duration is 675 hours {464, 877}

For this case, the statistical analysis revealed that given a girth weld HILP incident, the costs in $1,000,000 and the 95% confidence bounds {-,+} are:

- Mean cost is $1.36 {1.15, 1.70}
- Median cost is $0.55 {0.50, 0.58}

MS AND HRH PIPING SYSTEMS – CLAMSHELL WELDS

The event description for each of the NERC-GADS list of 40 HILP incidents was reviewed. It was determined that 3 of the incidents were associated with clamshell weld failures. For this set of data, the mean age of the clamshell weld failures was 34 years and the mean duration was 1680 hours.

In the 1990s, nearly all MS piping systems did not have clamshell welds and many HRH piping systems did not have clamshell welds. Therefore, the frequency values, measured in failures per unit with clamshell welds, may be a factor of 4 to 5 times higher than the 3/1573 HILP events per NERC-reported fossil unit cited in this study.

As a result of a million simulations, the frequency and severity of clamshell piping HILP outages exceeding $100,000 is illustrated in Figure 8. This plot excludes about 0.1% of the clamshell HILP events costing less than $100,000. The figure is similar in format to Figure 5, with much lower curves reflecting the order of magnitude decrease in failure frequency.

For this case, the statistical analysis revealed that given a clamshell HILP incident, the durations and the 95% confidence bounds {-,+} are:

- Mean duration is 1700 hours {1619, 1781}
- Median duration is 1631 hours {1545, 1701}

It is interesting that there is relatively low scatter in the outage durations, as revealed by nearly identical mean and median durations.

For this case, the statistical analysis revealed that given a clamshell weld HILP incident, the costs in $1,000,000 and the 95% confidence bounds {-,+} are:

- Mean cost is $2.66 {2.06, 3.39}
- Median cost is $1.16 {1.03, 1.55}

MS AND HRH PIPING SYSTEMS – SEAM WELDS

The event description for each of the NERC-GADS list of 40 HILP incidents was reviewed. It was determined that 6 of the incidents were associated with seam weld failures. For this set of data, the mean age of the seam weld failures was 18 years and the mean duration was 3284 hours.

In the 1990s, all MS piping systems should not have had seam welds because this material is not acceptable for use on boiler external piping [12], such as MS piping systems. Many of the HRH piping systems did not have seam welds. Therefore, the frequency values, measured in failures per unit with seam welds, may be a factor of 4 to 5 times higher than the 6/1573 HILP failures per NERC-reported fossil unit cited in this study.

As a result of a million simulations, the frequency and severity of seam weld piping HILP outages exceeding $100,000 is illustrated in Figure 9. This plot excludes about 0.2% of the seam weld HILP events costing less than $100,000. Again, the figure is similar to Figure 5, with a factor of 5 lower curves at all but the very largest costs.

For this case, the statistical analysis revealed that given a seam weld HILP incident, the durations and the 95% confidence bounds {-,+} are:

- Mean duration is 1916 hours {1378, 2727}
- Median duration is 802 hours {609, 1 108}

For this case, the statistical analysis revealed that given a seam weld HILP incident, the costs in $1,000,000 and the 95% confidence bounds {-,+} are:

- Mean cost is $2.56 {1.88, 3.80}
- Median cost is $0.78 {0.68, 1.07}

At extreme costs approaching $50M, the probabilities in Figures 5 and 9 are virtually identical. This indicates that almost all of the very largest outages involve seam welds. Note the enormous scatter in outage duration and that the mean duration is more than twice the median duration.

It is interesting that the clamshell mean outage duration is slightly less than the seam weld mean outage duration, yet the clamshell mean cost is slightly greater than the seam weld mean cost. This can be explained due to the fact that the average costs depend on several factors in addition to the average outage duration, such as the entire shape of the duration and failure age random variables. As described above, the duration outage distributions for the clamshell and seam weld failures are dramatically different.

FRACTIONAL FACTORIAL DESIGN OF HEP OUTAGE DURATION COSTS FOR A SINGLE UNIT

In this case, the median cost of a specific unit HRH piping system failure was estimated. In contrast to the global analysis above, it is assumed that much more information is available for this unit, so the uncertainties for the single unit are less than for a randomly selected unit.

Then, five applicable attributes that could impact the cost were selected. With this information, the problem was to determine the most governing attributes which would have significant impact on the cost of the forced outage.

The solution to this problem used a two-level fractional factorial design of experiments methodology and a public domain statistical data analysis software package named DATAPLOT [13]. Croarkin et al. has written a tutorial on two-level fractional design [14] and Fong et al. has recently provided two example applications of the fractional factorial [15]. In this example, a HRH piping system was selected that had girth welds, clamshell welds, and seam welds. The selected piping system has 21 years of commercial operation and high weldment stresses (10,000 psi). This HRH piping system had two previous examinations that included only a few welds. It was estimated that the mean cost of a forced outage would be $3,090,000, with an upper 95% confidence bound of $3,690,000 and a lower 95% confidence bound of $2,480,000.

The five selected attributes for perturbation were 1) age, 2) plant response, 3) on line weldment multiaxial stress, 4) number of injuries from the hypothetical accident, and 5) prior examinations.

Subsequently, the 95% uncertainty bounds were estimated for each of the five variable attributes. The operating years (X1) had uncertainty bounds of +/- 10%. The level of plant response (X2) varied from a level of 2 to 6. The applied weldment multiaxial stresses (X3) varied from 9,500 psi to 10,500 psi. Injuries (X4) varied from 1 to 3. Prior examinations (X5) varied from 1 to 3.

The ordered data plot is illustrated in Figure 10. This describes the forced outage costs for the matrix of interactions among variables X1 through X5. Applying the upper and lower confidence limits for various combinations of the selected variables, the forced outage cost range is about $2,600,000 to $4,300,000.

The effects plot is illustrated in Figure 11. This figure indicates that the top three rankings of the five variables, based on a plot of the absolute values of the coefficients of a first order linear model of the power outage duration cost as a function of five factors, are as follows:

- Rank 1 – Plant response
- Rank 2 – Number of injuries
- Rank 3 – Interaction of the plant response and maximum applied multiaxial weldment stress

DISCUSSION

As illustrated in Cohn's 2007 paper [2], it was qualitatively indicated that 1) the girth weld failures are high likelihood with medium consequence, 2) the clamshell weld failures are medium likelihood with high consequence, and 3) the seam weld failures are very low to low likelihood with very high consequence.

The all-welds frequency and severity curves (Figure 5) are quite reasonably consistent with the summation of the individual results for the three weld types (Figures 7, 8, and 9). Each individual weld type was evaluated independently and the results are dependent on both the interpolation and extrapolation of statistical models, as reflected in the uncertainty bounds of Figures 5, 7, 8, and 9.

A comparison of the plots in Figures 7, 8 and 9 confirm that the likelihood of girth weld failures is substantially greater than clamshell and seam weld failures at outage cost values of $1 and $5 million. However, at an outage cost of $20 million, the seam weld failure probability is much greater than the girth weld and clamshell weld failure probabilities.

Based on discussions with utility personnel, the frequency of HEP girth weld failures seems to be anecdotally more than an order of magnitude greater than clamshell or seam weld failures. This discrepancy may be due to 1) under reporting the girth weld failures in the NERC-GADS database and 2) over the past 20 years, many of the clamshell fittings and longitudinal seam welded pipe have been replaced with seamless pipe.

Recent discussions with fossil power plant personnel have revealed that the outage duration from an HEP forced outage may be much longer than initially expected. If the plant has had no inspections or very cursory inspections of the applicable piping system, the piping failure incident may result in extensive weldment inspections of a multitude of weldments prior to startup because of personnel safety concerns. On the other hand, if the plant has had a proactive HEP inspection program, it is more likely that only the specific weldment is repaired, the outage duration is much shorter, and the resulting cost of the incident is much less. These variations in inspection programs and perceived safety issues are probably responsible for much of the wide variability in the NERC-reported outage durations.

This paper has provided quantitative frequency and consequence values that can be used in RBI studies of MS and HRH piping failures, especially if unit specific frequencies and consequences are developed.

The fractional factorial design of HEP outage costs is a relatively quick methodology to determine governing attributes of a response variable. In the example of HEP outage costs for a single well-analyzed unit, it was determined that the plant response, number of injuries, and maximum applied multiaxial weldment stress governed the outage costs.

CONCLUSIONS

There is a need to develop and apply an RBI methodology as part of a proactive cost effective strategy for the examination of critical HEP weldments. To provide additional support for an RBI methodology, the authors have presented statistical analyses of NERC-GADS industry-wide HEP failure data. Furthermore, the failure data were partitioned into girth weld failures, clamshell weld failures, and seam weld failures. The frequency and severity of HEP HILP outages exceeding $100,000 were evaluated for 1) all welds, 2) girth welds, 3) clamshell welds, and 4) seam welds. The resulting plots quantitatively illustrate that the comparison of girth weld to seam weld failures reveals that the girth welds have a higher likelihood with lower consequence events while seam welds have a lower likelihood with higher consequence events. This quantitative RBI methodology is particularly useful when applied to unit-specific parameters.

The fractional factorial design methodology was used to evaluate the governing parameters of HEP outage costs given a HILP incident at a well-characterized unit. In this example, it was determined that outage costs were mostly governed by plant personnel response, number of injuries, and the interaction of the plant personnel response and the weldment stress.

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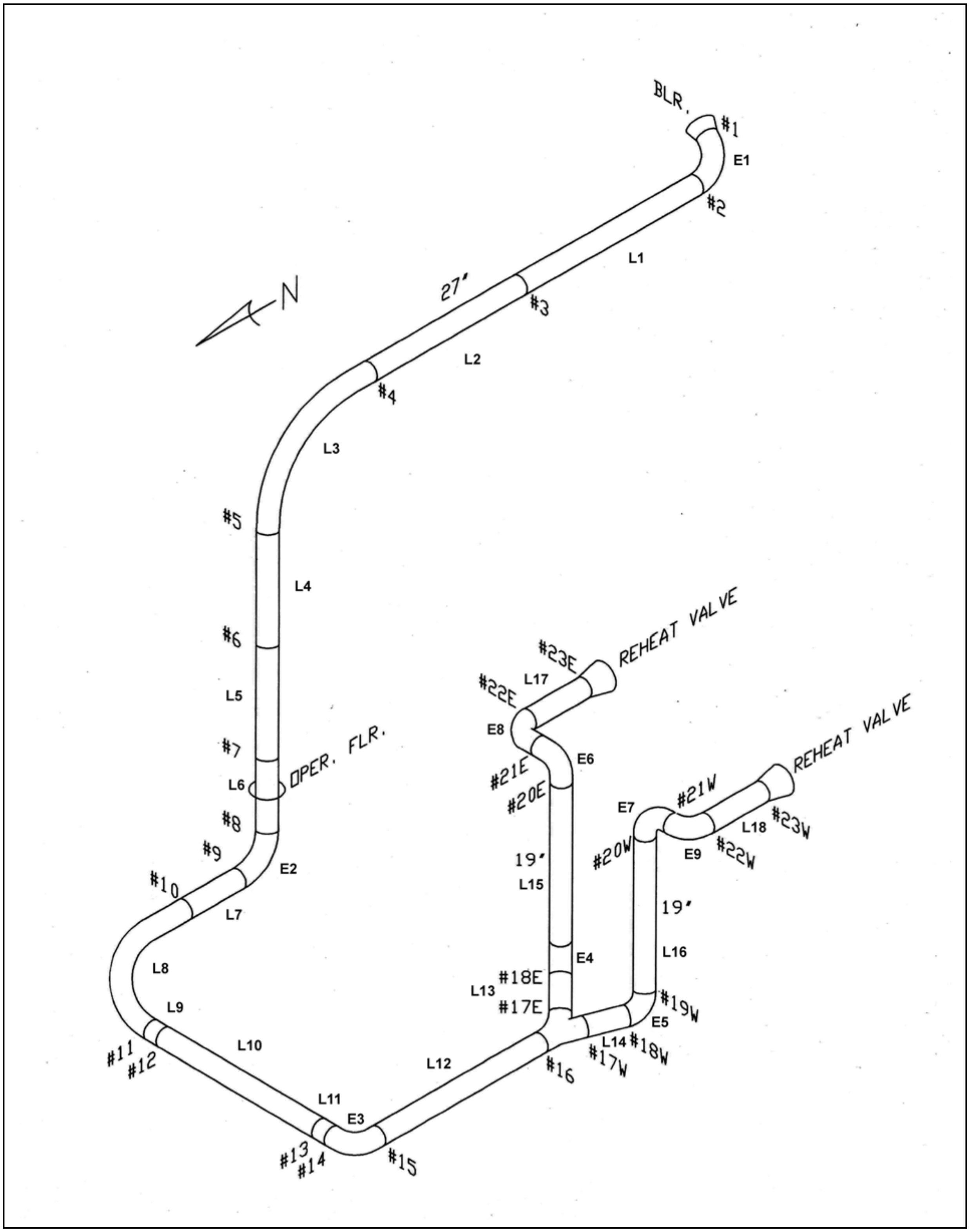
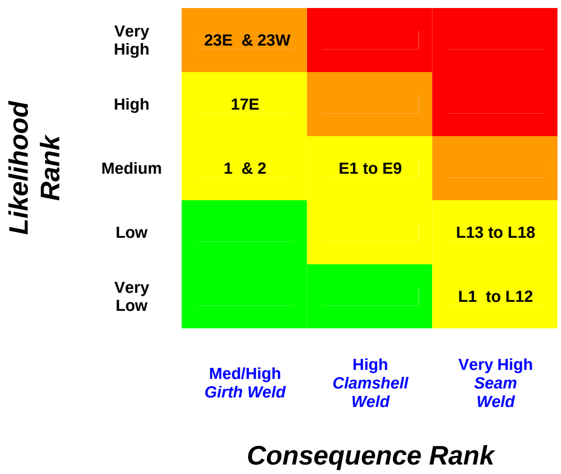


Figure 1 — HRH Piping System – Weld Designations



Likelihood Rank	Med/High Girth Weld	High Clamshell Weld	Very High Seam Weld
Very High	🟧 23E & 23W	🟥	🟥
High	🟨 17E	🟧	🟥
Medium	🟨 1 & 2	🟨 E1 to E9	🟧
Low	🟩	🟨	🟨 L13 to L18
Very Low	🟩	🟩	🟨 L1 to L12

Figure 2 — Specific Qualitative Risk Matrix for a Hot Reheat Piping System

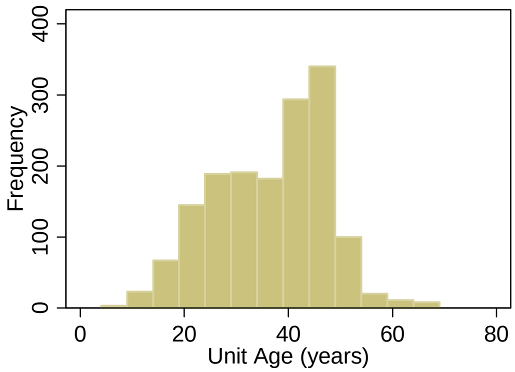


Figure 3 — Age Distribution of the Fossil Units in the 1998 NERC-GADS Database

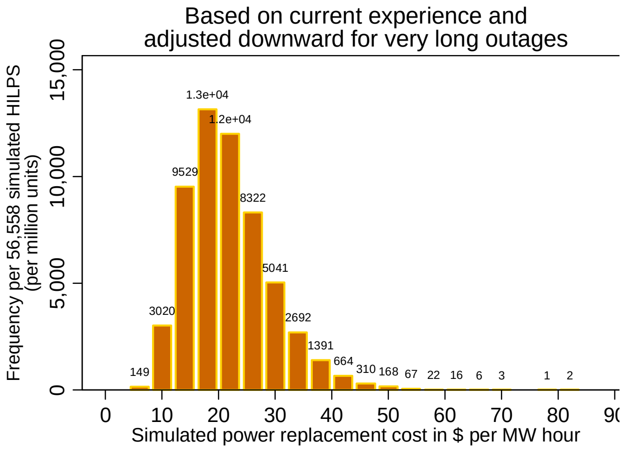
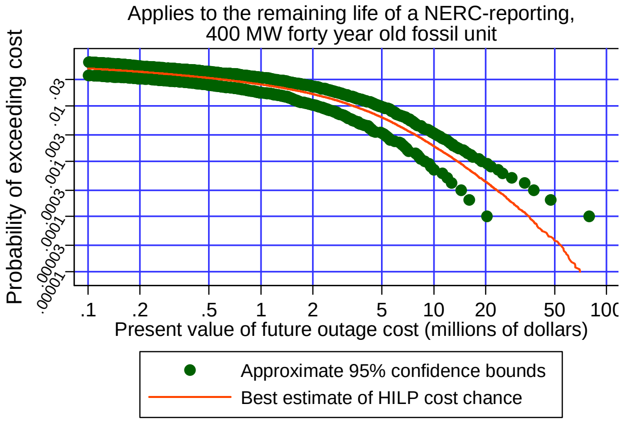
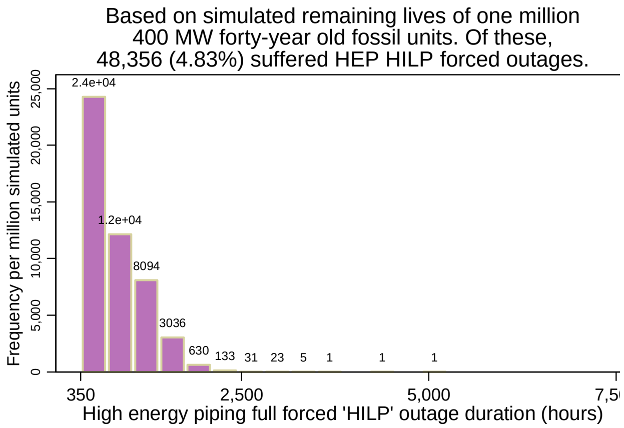


Figure 4 — Simulated HILP Outage Power Replacement Costs



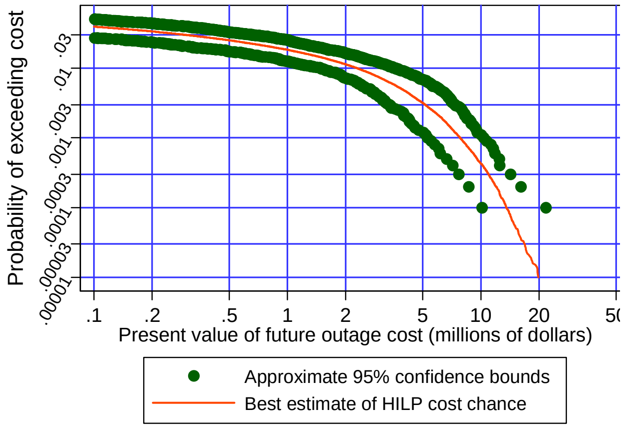
This plot excludes the ~15% of HILPS costing less than $100K

Figure 5 — Frequency and Severity of Piping HILP Outages Exceeding $100,000 (All Welds)


Based on simulated remaining lives of one million 400 MW forty-year old fossil units. Of these, 48,356 (4.83%) suffered HEP HILP forced outages.

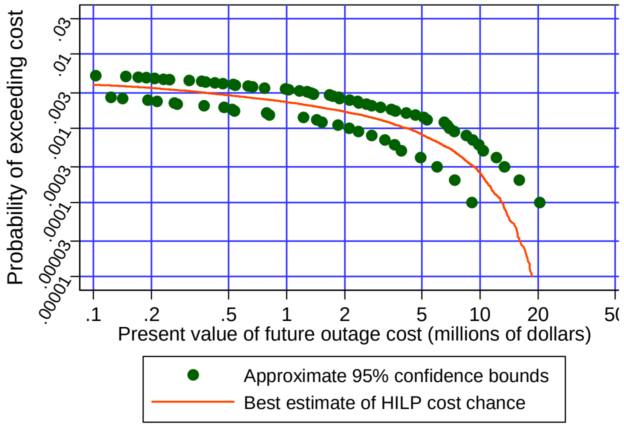
Simulated HILP durations limited to two years

Figure 6 — Duration of HEP HILP Girth Weld Outages



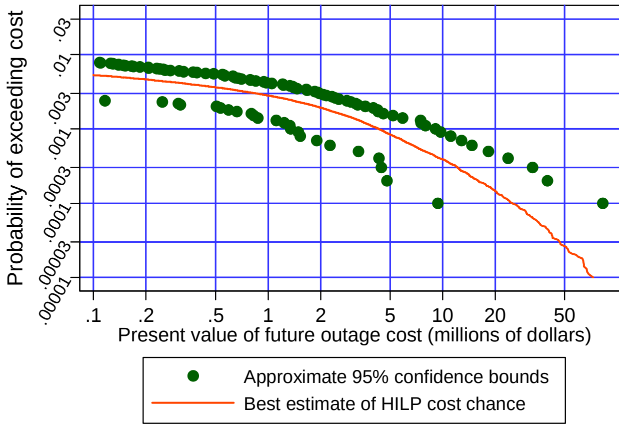
This plot excludes the ~19% of HILPS costing less than $100K

Figure 7 — Frequency and Severity of Piping HILP Outages Exceeding $100,000 (Girth welds)



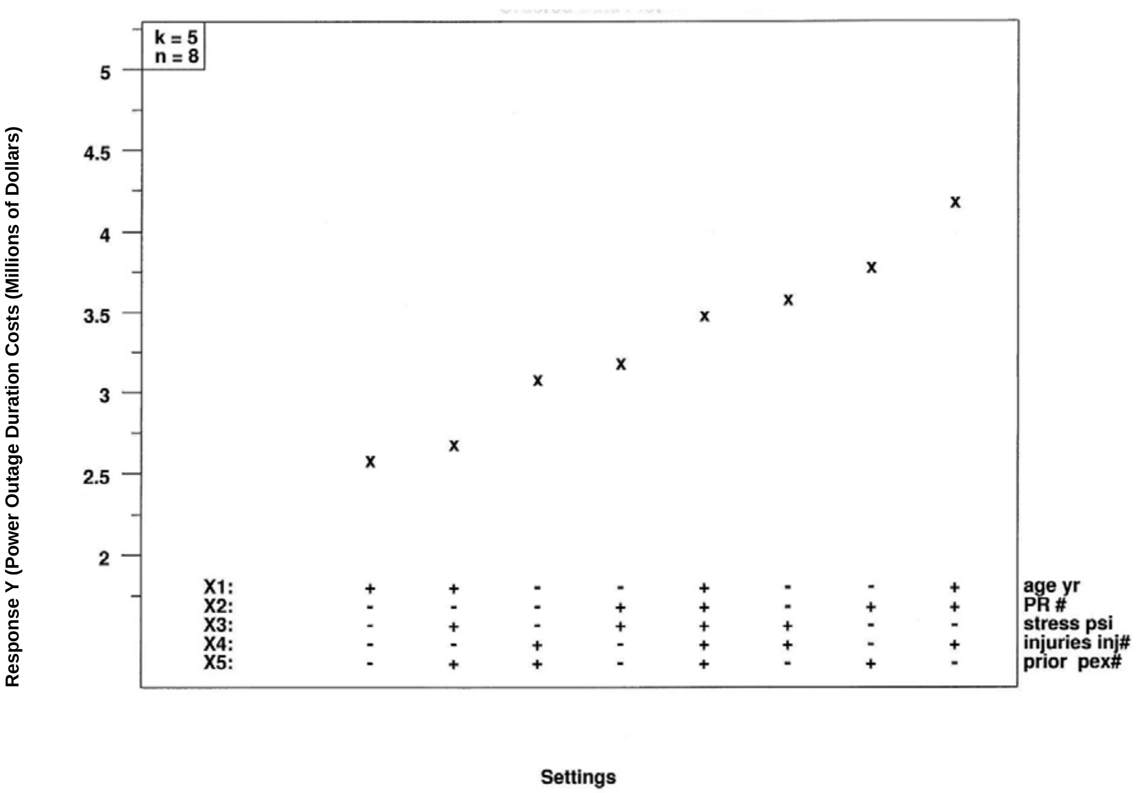
This plot excludes the 0.08% of HILPS costing less than $100K

Figure 8 — Frequency and Severity of Piping HILP Outages Exceeding $100,000 (Clamshell Welds)



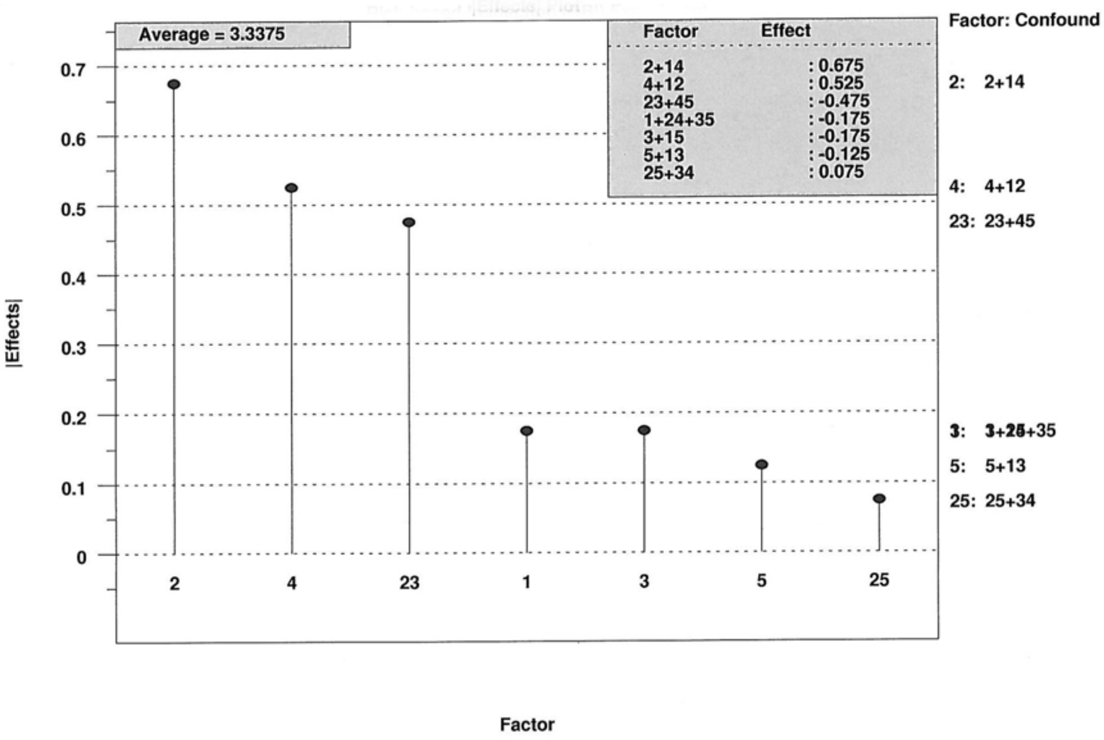
This plot excludes the 0.15% of HILPS costing less than $100K

Figure 9 — Frequency and Severity of Piping HILP Outages Exceeding $100,000 (Seam Welds)



X1:	+	+	-	-	+	-	-	+	age yr
X2:	-	-	-	+	+	-	+	+	PR #
X3:	-	+	-	+	+	+	-	-	stress psi
X4:	-	-	+	-	+	+	-	+	injuries inj#
X5:	-	+	+	-	+	-	+	-	prior pex#

Figure 10 — Ordered Data Plot



Factor	Effect
2+14	: 0.675
4+12	: 0.525
23+45	: -0.475
1+24+35	: -0.175
3+15	: -0.175
5+13	: -0.125
25+34	: 0.075

Figure 11 — Effects Plot