SAND2019-4234C

Sodium Pump Performance in the NaSCoRD Database

Zachary K. Jankovsky*, Zach Stuart*, Matthew R. Denman†

*Sandia National Laboratories, Albuquerque, New Mexico, Zachary.Jankovsky@sandia.gov
†Sandia National Laboratories (currently Kairos Power, Alameda, California)

Sodium-cooled Fast Reactors (SFRs) have an extended operational history that can be leveraged to accelerate the licensing process for modern designs. Sandia National Laboratories has recently reconstituted the United States SFR data from the Centralized Reliability Data Organization (CREDO) into a new modern database called the Sodium System Component Reliability Database (NaSCoRD). NaSCoRD contains a record of 117 pumps, 60 with a sodium working fluid, that have operated in EBR-II, FFTF, and test loops including those operated by both Westinghouse and the Energy Technology Engineering Center. This paper will present sodium pump failure probabilities for various conditions allowable from the U.S. facility CREDO data that has been recovered under NaSCoRD. The current sodium pump reliability estimates will be presented in comparison to estimates provided in historical studies. The impacts of the suggested corrections from an EG&G Idaho report and various prior distributions on these reliability estimates will also be presented.

I INTRODUCTION

Recent efforts undertaken at Sandia National Laboratories (SNL) have focused on gathering reliability insights for systems used in Sodium-cooled Fast Reactors (SFRs) using a portion of the Centralized Reliability Data Organization (CREDO) database[1]. The overall effort, dubbed the Sodium System Component Reliability Database (NaSCoRD), combines CREDO data with independently-gathered documents to validate records and provide richer context[2]. It is the aim of this paper to explore CREDO data in the context of mechanical and Electro-Magnetic (EM) pump reliability. A previous study by CREDO found that mechanical pumps dominated plant unavailability at three SFRs[3].

CREDO collected reliability information from US SFRs and sodium test facilities from 1977 until 1993 when funding was eliminated. The database was used to inform Probabilistic Risk Assessment (PRA) for new SFR designs. During that time, the Japan Atomic Energy Agency (JAEA) contributed data relating to Japanese reactors and test facilities to produce a combined database that is herein referred to as CREDO. The US subsequently lost access to the data until 2016 when JAEA provided a copy of the US data, which is referred to in this paper as CREDO-I as shown in Figure 1. CREDO-II was an effort begun in 2013 to build a reliability database and analysis capability from historical documents including run logs and unusual occurrence reports in the event that none of the original CREDO data could be recovered. CREDO-II is now used for confirmation of values and enrichment of the CREDO-I data by providing additional narratives for numerous events and periods of operation. Interpretation and correction of the CREDO-I data have been accomplished independently (see Reference[2]) and with consultation from JAEA[a]. Because access to the database was lost abruptly and for several decades, it is important to understand which data correction steps had been taken by CREDO (and thus were reflected in previously-published analyses) and which steps were performed later by JAEA.

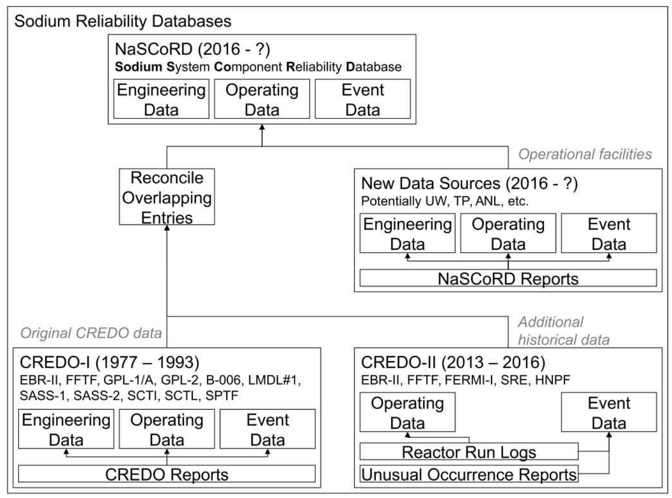

Fig. 1. Current and Anticipated NaSCoRD Data Sources

The partial return of the CREDO data along with the capability to effectively mine it will accelerate efforts by United States Department of Energy (USDOE) and the SFR industry to develop future systems by providing insights into the performance of historical systems. The NaSCoRD effort helps resolve issues of knowledge management and preservation which were identified in Reference[4]. This is a companion paper to Reference[5] which applied a similar methodology to valve reliability. It is desired that NaSCoRD will eventually be augmented with reliability data from new facilities. A portal (`www.sandia.gov/NaSCoRD`) with a set of reports has been established to allow external users to draw insights from the data.

This paper calculates estimates of pump reliability using NaSCoRD data and evaluates the robustness of those estimates. Section II discusses the methodologies applied in previous

[a] An example is copied with light editing from Reference[2]: "The value given in CREDO-I for the most suspect point was 72960 MWe-hr. CREDO-II daily history was available for the days in the time period covered by the suspect entry in CREDO-I. The daily histories sum to 7296 MWe-hr, which strongly suggests that a simple order of magnitude error was present in the CREDO-I data. The value was corrected in the database and a note was added to explain the change in the CREDO-I database."

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CREDO reliability studies as well as the current NaSCoRD work. Section III presents results from a study of pump reliability using various priors and Bayesian updating using NaSCoRD data. Different dimensions of the data are examined such as pump types and failure modes. Finally, Section IV contains closing remarks on this analysis and the future of NaSCoRD.

II METHODOLOGY

The purpose for this study and the extent of its applicability are explained in Sections II.A and II.B, respectively. The Bayesian failure rate estimation method applied to the data is detailed in Section II.C. This process is similar to that followed in companion paper Reference[5] which examined valve failure rates.

II.A Motivation

The historical analyses performed using CREDO included data for Japanese facilities which are not available in NaSCoRD. This has the potential to cause discrepancies in reliability estimates using NaSCoRD due to both genuine facility-dependent differences and the size of the data set. To quantify deviations in reliability estimates, values obtained using NaSCoRD are compared to historical analyses. An informal EG&G Idaho report that included analyses using the CREDO data is used as a reference for previous reliability estimates[6]. The goal of this analysis is to determine, using the same prior assumptions as the EG&G Idaho work, how NaSCoRD estimates and insights may be affected by the exclusion of the Japanese facility data.

CREDO input forms offered some flexibility in event reporting and the EG&G Idaho report determined that some CREDO events are not applicable for PRA applications. The EG&G Idaho report compiled a list of recommended changes for events to be reclassified or excluded when performing reliability calculations. For example, CREDO included numerous events which required repair at the next outage but did not lead to a loss of function in the meantime. In this paper, failure rate estimates are calculated both with and without the recommended changes to determine sensitivity to such changes. The changes from Reference[6] are summarized for mechanical pumps:

- Nineteen "NORUN" events, five "SPURIOUS" events, and seven "ABNORMOP" events are reclassified as "Failure to Run" events
- Sixty-seven of 105 CREDO events are removed

The changes from Reference[6] for EM pumps are:

- Thirty-eight "NORUN" events, five "SPURIOUS" events, and two "ABNORMOP" events are reclassified as "Failure to Run" events
- Two "PRIMLEAK" events and five "LEAK" events are reclassified as "External Leakage" events
- Twenty-three of eighty-five CREDO events are removed

Prior assumptions may have a significant impact on reliability estimates for a relatively small data set such as NaSCoRD. Failure rate estimates are produced with multiple prior assumptions to explore this sensitivity. Informative prior distributions for failure rates are used directly from the EG&G Idaho report. That report focused on providing estimates for power reactors rather than the test facilities that contributed data to CREDO and so some differences in the mean and variance of component failure rates are expected. A non-informative prior is applied against NaSCoRD data to determine the impact of the assumptions made by the EG&G Idaho report in informing prior distributions.

II.B Scope

Only the US data from CREDO was available for this study. This data covered two SFRs and ten sodium test facilities whose periods of operation spanned from 1964 to 1992. Two types of pumps, mechanical and EM, were included in CREDO and both are included in this study. Only pumps with sodium as the working fluid are included.

CREDO provided fine granularity of failure modes, some of which would be combined for general PRA applications. The EG&G Idaho report provided a recommended means of combining failure modes in Appendix A[6]. For example, "Failure to Run", "Spurious Operation", and "Abnormal Operation" are all gathered under "Failure to Run" for the purposes of the EG&G Idaho report and the present study. It should be noted that both of the prior distributions from the EG&G Idaho report (used in Section III.A) use the recommended combined failure modes. Failure modes in the NaSCoRD database were combined in the same way for the purposes of this study. This study provides estimates of the overall failure rates of the pumps as well as two specific failure modes, "Failure to Run" and "External Leakage", which are likely to be of interest to designers of future components.

II.C Bayesian Failure Rate Estimation

A Bayesian updating approach was used to generate failure rate estimates with uncertainty for sodium pumps. It was assumed that the time until failure followed an exponential distribution which is common for estimating time to failure in PRA[7]. Figure 2 helps to illustrate the Bayesian updating process. The prior distribution (see Section II.C.1) is updated with data from the database (see Section II.C.2) to produce the posterior distribution (see Section II.C.3).

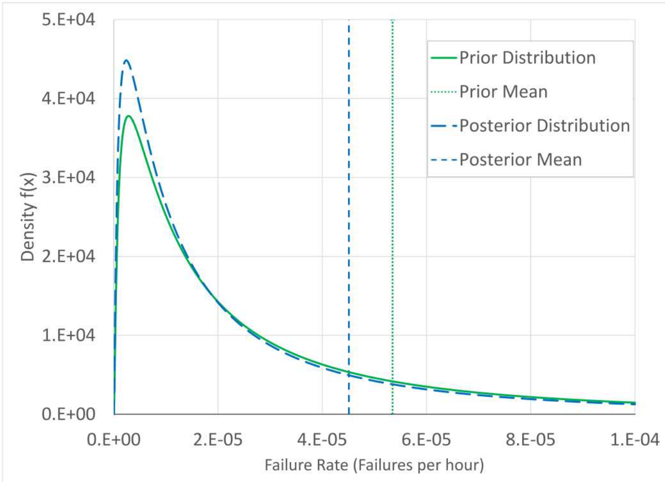

Fig. 2. Example of Bayesian Updating of Total Failure Rate for Mechanical Pumps

II.C.1 Definition of Prior Distributions

A sensitivity analysis was used to examine the influence of informative priors. Three different distributions were used to represent the prior assumption of failure rates:

- An informed prior defined as a lognormal distribution parameterized by the mean and error factor recommended by the EG&G Idaho report
- An informed prior defined as a lognormal distribution parameterized by the mean aggregated from outside sources in the EG&G Idaho report combined with the report's recommended error factor
- A non-informed prior defined as the Jeffreys prior for the exponential distribution[8]

The two informative priors produced using the EG&G Idaho report followed a lognormal distribution as shown in Equation 1 with parameters from Reference[6]:

$$p(\lambda|\sigma^2,\mu) = \frac{1}{\lambda\sqrt{2\pi\sigma^2}}\exp(\frac{-(ln\lambda-\mu)^2}{2\sigma^2}) \qquad (1)$$

Where:

- $p(\lambda|\sigma^2,\mu)$ = The informed, lognormally distributed prior distribution of λ given parameters σ and μ
- λ = The pump failure rate (failures/hour), $\lambda > 0$
- $\sigma^2 = (\frac{ln(EF)}{1.645})^2$
- EF = The error factor
- $\mu = ln(expected\ failure\ rate) - \frac{\sigma^2}{2}$

The final, non-informative, prior was used to explore the influence of the information assumed by the first two priors. An uninformative prior recognizes a lack of knowledge by balancing outcomes, for example by assuming half a failure in one trial. The Jeffreys prior for exponential data was used to model the prior knowledge of the failure rate. The gamma distribution (Equation 2) is used with parameters $\alpha = 0$ and $\beta = 0$ for this case of the exponential distribution[9].

$$p(\lambda|\alpha=0,\beta=0) = \frac{\beta^\alpha\lambda^{\alpha-1}e^{-\beta\lambda}}{\Gamma(\alpha)} = \lambda^{-1} \qquad (2)$$

Where:

- $p(\lambda|\alpha=0,\beta=0)$ = Jeffreys prior distribution of the failure rate λ
- λ = The pump failure rate (failures/hour), $\lambda > 0$
- α and β = Shape parameters for the gamma distribution
- $\Gamma(\alpha)$ = The gamma function evaluated at α

II.C.2 Data Likelihood Distribution

An exponential distribution was used to determine the probability of experiencing the NaSCoRD data set given a failure rate. Future NaSCoRD work may incorporate additional uncertainty distributions as justified. There is reason to believe that many pump failure times in the CREDO and NaSCoRD databases are censored. This censoring has two primary causes:

- The system ceased operation before the pump experienced a failure. The test facilities included in the data set ran for as little as two years and some were abruptly closed in the early 1990s.
- A portion of the pump failed and was repaired or replaced without leading to a traditional PRA failure.

The failure rate in an exponential distribution remains constant regardless of survival time and so it is relatively simple to account for censored data[10]. The exponential likelihood distribution is given as Equation 3:

$$f(\underline{y}|\lambda) = \prod_{i=1}^{n}(\frac{1}{\lambda}exp(\frac{y_i}{\lambda}))\prod_{j=1}^{m}(exp(\frac{y_j}{\lambda})) \qquad (3)$$

Where:

- $f(\underline{y}|\lambda)$ = The likelihood distribution for data vector $\underline{y}$ given pump failure rate λ
- $\underline{y}$ = A vector of observed times until failure or censorship
- n = The number of uncensored observations
- m = The number of censored observations
- $(\lambda, y_i, y_j) > 0$

The maximum likelihood estimate of λ may be found by maximizing the distribution in Equation 3 with respect to λ given the data observed in NaSCoRD[10]. Failure rates of components are commonly inferred through the consideration of operating time and number of failures[11]. This inference structure suggests that a Poisson distribution may be appropriate for sampling failure event counts[10]. Because the interval between Poisson-distributed events is itself exponentially distributed[10], the estimation of failure rates based on a pump's time until failure using the exponential distribution will be equivalent to the rate of failures for a Poisson model. This process accounts for censored events as seen in Equation 3. Time until failure was used rather than failure counts to allow flexibility for future analyses. If likelihood distributions are chosen in which the failure rate is not assumed to be constant over time, the Poisson assumption no longer applies.

II.C.3 Posterior Distribution

The assumed prior distribution is combined with the distribution of the present evidence (NaSCoRD failure rates) to form a posterior distribution which acts as a weighted average of the two distributions. This is performed using Bayes' theorem as represented in Equation 4:

$$p(\lambda|\underline{y}) \propto f(\underline{y}|\lambda)p(\lambda) \tag{4}$$

Where:

- $p(\lambda|\underline{y})$ = The posterior distribution of the failure rate given data vector $\underline{y}$
- $f(\underline{y}|\lambda)$ = The likelihood distribution for data vector $\underline{y}$ given pump failure rate λ
- $p(\lambda)$ = The prior distribution of the failure rate

The product of the prior and likelihood distributions in Equation 4 is only proportional to the posterior distribution. By sampling from the prior and likelihood distributions using a simulation method such as Markov Chain Monte Carlo, inferences may be produced from the posterior distribution.

III ANALYSIS

This section discusses the reliability analyses for sodium pumps using the methodology developed in Section II. Section III.A develops the parameters for the prior distributions. Section III.B presents the results of the Bayesian update process.

III.A Prior Distribution Values

The parameters for the prior distributions presented in Section II.C.1 are developed here and presented in Table I. The first informative prior distribution ("EG&G Idaho Prior Mean" in Table I) was based on the recommended parameters provided in Reference[6]. The recommended failure rates were assumed to have a lognormal distribution and so the informed priors were assumed to be lognormally-distributed. The error factors provided in Reference[6] are used to characterize the variance of the prior distributions. The error factor is defined as the ratio of the 5th percentile value to the 95th percentile value of the lognormal distribution. The recommended error factors determined in Reference[6] used some information from the CREDO database, introducing the potential for circular reasoning because some data used to generate the prior distribution was also used in the likelihood estimate.

The second informative prior distribution uses failure rates from historical SFR risk studies including sources from LMEC[12], LYON[13], CRBRP-4[14], and GEFR-00554[15]. Failure rates from these sources were aggregated to generate a point estimate of the mean of the prior distribution. Because these rates were presented without associated uncertainties, the EG&G Idaho recommended error factors (which were also used in the first informative prior) were assigned to the second prior ("Aggregated Prior Mean" in Table I).

III.B Posterior Failure Rate Results

For these analyses, the posterior distribution is treated as the result of normalized multiplication of the prior distribution and the likelihood distribution (see Equation 4). The first analysis concerned the NaSCoRD data as received from JAEA. After examining the database for robustness to differing prior assumptions, data correction recommendations from SNL[2] and reclassification recommendations from EG&G Idaho[6] were applied to the database. Failure rate estimates were then developed for each pump type and failure mode. The NaSCoRD pump data set has dimensions as shown under "Evidence" in Table II.

Pump failure rate estimates were developed from the NaSCoRD database using a variety of prior distributions as shown in Figure 3. The middle 95% of the posterior distributions largely overlap for both pump types indicating that there is not a large dependence on the choice of prior distribution. There appears to be sufficient information in the database for the posterior distribution to not be overly influenced by the prior distribution.

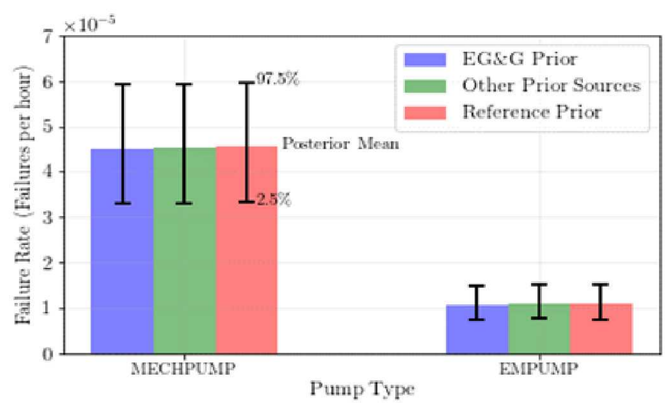

Fig. 3. Sodium Pump Failure Rates by Prior Assumption, Original NaSCoRD Data Set

The effects of data reclassification may be significant, particularly if the data set is relatively small. Viewed on a log scale using only the EG&G Idaho recommended prior, Figure 4 shows the effect of data reclassification recommendations from Reference[6]. The posterior mean shifts higher for mechanical pumps (Figure 4 top) but the posterior distributions remain similar. With EM pumps (Figure 4 bottom), however, posteriors differ to the point that the middle 95% ranges of the means do not overlap at all. This is explained by the data reclassification recommendations in

TABLE I. Prior Distributions for Sodium Pump Failure Rates (rates in failures/hour)[6]

Pump Type	Failure Mode	EG&G Idaho Prior Mean	Aggregated Prior Mean	Error Factor
Mechanical	Failure to Run	5.0E-5	9.0E-5	10
	External Leakage	3.0E-6	3.3E-5	10
	Total	5.4E-5	1.1E-4	10
EM	Failure to Run	1.0E-5	6.8E-5	10
	External Leakage	3.0E-6	4.4E-6	10
	Total	1.3E-5	7.2E-5	10

Appendix A of Reference[6]. Numerous EM pump events which were originally classified as demand-type failures (e.g., "Failure to Start") were reclassified as running failures (e.g., "Failure to Run"), which significantly raised the overall failure rate for events considered in this analysis. These data reclassification recommendations have not been permanently applied to the NaSCoRD database (unlike some other corrections detailed in Reference[2]) but rather are applied as a set of changes for analyses where it is preferred to use them. In the future, they may be evaluated on a case-by-case basis for permanent inclusion with an explanatory comment on each relevant event.

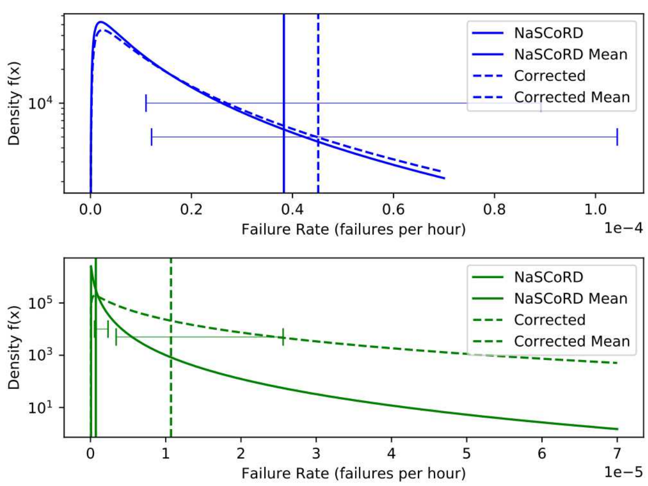

Fig. 4. Sodium Pump Failure Rates, EG&G Idaho Updated NaSCoRD Data Set. Top: Mechanical Pumps, Bottom: EM Pumps

The following results used NaSCoRD data set after incorporating the reclassifications recommended in Reference[6]. Failure rate estimates broken down by failure mode are shown in Figure 5 for mechanical pumps and in Figure 6 for EM pumps. Table II provides a summary of the reliability study results. The posterior mean for "Failure to Run" for mechanical pumps (2.6E-5) did not shift significantly from the prior (5.0E-5) but the variance was reduced significantly (from 1.5E-8 to 2.4E-11), indicating that NaSCoRD provided a heavily-weighted body of evidence clustered around a similar mean to the prior. This is also apparent when viewing "External Leakage" for mechanical pumps as the NaSCoRD data set caused the posterior mean (1.4E-5) to deviate from the prior mean (3.0E-6) to a large degree while also significantly reducing the variance.

The EM pump reliability estimates in Figure 6 reveal similar insights. A large variance reduction occurs in each category with the inclusion of the NaSCoRD data set. The "External Leakage" failure mode shifts from a prior mean of 3.0E-6 to a posterior mean of 5.1E-7 after updating using NaSCoRD. Reference[6] includes forty-five "Failure to Run" events and seven "External Leakage" events for EM pumps up to approximately 1990, with many of them occurring at Joyo, which is not included in NaSCoRD. By comparison, NaSCoRD includes (see Table II) twenty-seven "Failure to Run" events and one "External Leakage" event for EM pumps.

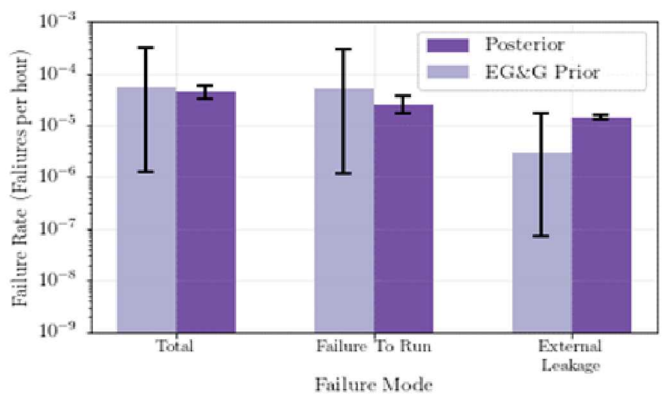

Fig. 5. Mechanical Sodium Pump Failure Rates by Failure Mode

TABLE II. Sodium Pump Failure Rates (rates in failures/hour)

Pump Type	Failure Mode	EG&G Idaho Prior Mean	Evidence (Hours, Failures)	Posterior Mean	95% Prob. Interval
Mechanical	Failure to Run	5.0E-5	(1.0E6, 26)	2.6E-5	(1.7E-5, 3.6E-5)
	External Leakage	3.0E-6	(1.0E6, 15)	1.4E-5	(1.3E-5, 1.6E-5)
	Total	5.4E-5	(1.0E6, 46)	4.5E-5	(3.3E-5, 6.0E-5)
EM	Failure to Run	1.0E-5	(2.9E6, 27)	9.1E-6	(6.0E-6, 1.3E-5)
	External Leakage	3.0E-6	(2.9E6, 1)	5.1E-7	(8.1E-8, 1.6E-6)
	Total	1.3E-5	(2.9E6, 32)	1.1E-5	(7.3E-6, 1.5E-5)

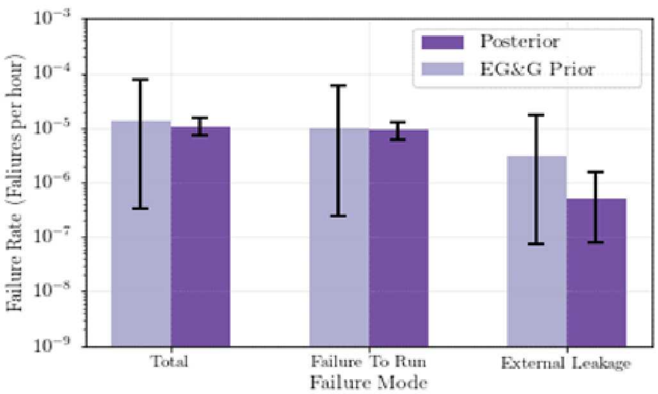

Fig. 6. EM Sodium Pump Failure Rates by Failure Mode

IV CONCLUSIONS

This analysis developed posterior failure rate estimates for SFR pumps for a variety of pump types and failure modes using the NaSCoRD database, which contains a subset of the historical CREDO database. Some interesting deviations were observed when compared to failure rates produced using the CREDO data prior to approximately 1990[6]. Factors such as the assumption of a prior distribution and cleaning of the data were tested for their impact on failure rates and potentially PRA insights. The NaSCoRD data was found to overwhelm any of the chosen prior distributions but a deviation was found in the overall failure rate for EM pumps after cleaning the data according to recommendations in a recent SNL report[2] and an EG&G Idaho report[6]. Numerous EM pump events were reclassified in the EG&G Idaho report which may have a significant effect on the reliability estimates and insights that may be taken from NaSCoRD. Future work may investigate the effect of the EG&G Idaho report data cleaning recommendations on other important components.

Deviations were also found for both pump types for the specific failure mode "External Leakage". CREDO includes a large number of EM pump failures from Japanese facilities which are not included in NaSCoRD. By contrast, the estimate for "External Leakage" for mechanical pumps in NaSCoRD is higher than that from the EG&G Idaho report. It is possible that the inclusion of JAEA data would shift the mechanical pump external leakage estimate down and the EM pump external leakage estimate up. Reference[3] found pumps of both types to be critical to unavailability at SFRs in both the US and Japan.

Although the data are generally robust, there are significant aspects of NaSCoRD that are yet to be explored for the accuracy, reliability, and usefulness for producing inferences. The understanding of component demand rates in CREDO (and, by extension, NaSCoRD) must be improved before demand-based failure modes, such as "Failure to Start", may be evaluated.

V ACKNOWLEDGMENTS

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper has been assigned number SAND2019-XXXXC.

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