INL/EXT-19-54611

Enhanced Component Performance Study: Motor-Operated Valves 1998–2018

Zhegang Ma

September 2019

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-19-54611

Enhanced Component Performance Study: Motor-Operated Valves 1998–2018

Zhegang Ma

Update Completed September 2019

Idaho National Laboratory
Risk Assessment and Management Services Department
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC Agreement Number NRC-HQ-60-14-D-0018

ABSTRACT

This report presents an enhanced performance evaluation of motor-operated valves (MOVs) at U.S. commercial nuclear power plants. The data used in this study are based on the operating experience failure reports from calendar year 1998 through 2018 as reported in the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). The MOV failure modes considered are failure to open/close, failure to operate or control, and spurious operation. The component reliability estimates and the reliability data are trended for the most recent 10-year period while yearly estimates for reliability are provided for the entire study period.

One highly significant increasing trend was observed for the frequency of fail-to-open or close demands per reactor year for low-demand (≤ 20 demands per year) valves. Two highly statistically significant decreasing trends were observed in the data: the failure probability estimate for valve fail-to-open/close for low-demand valves, and the frequency of fail-to-open or close events per reactor year for low-demand valves.

CONTENTS

FIGURES

TABLES

ACRONYMS

AFW	Auxiliary feed water
AOV	air-operated valve
CCW	component cooling water
CNID	constrained non-informative prior distribution
CRD	control rod drive
CSR	containment spray recirculation
CVC	chemical and volume control
CY	calendar year
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
FTOC	failure-to-open/close
FTOP	failure to operate or control
FY	fiscal year
HPCI	high-pressure coolant injection
HPCS	high-pressure core spray
HPSI	high-pressure safety injection
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
ISO	isolation condenser
LPCS	low-pressure core spray
LPSI	low-pressure safety injection
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
OLS	ordinary least squares
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling
RCS	reactor coolant
RHR	residual heat removal
SO	spurious operation
SWN	normally running service water
SWS	standby service water
TDP	turbine-driven pump

UA	unavailability
VSS	vapor suppression

Enhanced Component Performance Study: Motor-Operated Valves 1998–2018

1. INTRODUCTION

This report presents a performance evaluation of motor-operated valves (MOVs) at U.S. commercial nuclear power plants from 1998 through 2018. The objective of the updated component performance studies is to obtain annual performance trends of failure rates and probabilities and to present an analysis of factors that could influence the component trends. This year's update continues with the two changes implemented in the 2016 update that are different from earlier updates: (1) the update results are based on calendar year (CY) instead of the federal fiscal year (FY), and (2) The failure events included in the update are "hard" failures, i.e., the p-values indicating the likelihood the component would have failed during a 24-hour mission are 1.0. Previous updates (2015 and before) include lesser p-values indicating a degraded condition that probably would have caused failure during a 24-hour mission but were not quite hard failures at their outset.

The enhanced component performance studies are conducted for the following component types: air-operated valves (AOVs), emergency diesel generators (EDGs), motor-driven pumps (MDPs), MOVs, and turbine-driven pumps (TDPs). The MOV performance analysis was originally published as NUREG-1715, Volume 4 in July 2001 [1] and then updated annually in a series of reports, with the last one being documented in INL/LTD-17-44123, *Enhanced Component Performance Study: Motor-Operated Valves 1998-2016* [2]. The Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page provides the links to the historical and current results of component performance studies (http://nrcoe.inl.gov/resultsdb/CompPerf). An overview of the trending methods, glossary of terms, and abbreviations is documented in the paper Overview and Reference [3] that can also be found on that web page.

The data used in this study are based on the operating experience failure reports from Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES) [4], formerly the Equipment Performance and Information Exchange Database (EPIX) and now upgraded again to IRIS, the Industry Reporting and Information System. Previously, the study relied on operating experience obtained from licensee event reports, Nuclear Plant Reliability Data System (NPRDS), and ICES. The ICES database, now IRIS, (which includes the MSPI designated devices as a subset) has matured to the point where both component availability and reliability can be estimated with a high degree of accuracy. In addition, the population of data in current ICES database is much larger than the population available in the previous study.

MOVs are categorized as low-demand MOVs (with less than or equal to 20 demands/year) and high-demand MOVs (with greater than 20 demands/year) in this study. The MOV failure modes considered are failure-to-open/close (FTOC), failure to operate or control (FTOP), and spurious operation (SO). Annual failure probabilities (failures per demand) are provided for FTOC events and annual failure rates (failures per valve hour) are provided for FTOP and SO events. The estimates are trended for the most recent 10-year period while yearly estimates are provided for the entire study period.

While this report provides an overview of operational data and evaluate component performance over time, it makes no attempt to estimate values for use in probabilistic risk assessments (PRAs). The 2015 Component Reliability Update [6], which is an update to NUREG/CR-6928, *Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants* [7], reports component unreliability estimates for use in PRAs. Estimates from that report are included herein, for comparisons. Those estimates are labelled “2015 Update” (or “Update 2015”) in the associated tables and figures.

Section 2 of this report presents the summary of findings from the study, with particular interest in the existence of any statistically significant increasing or decreasing trends in component performances. Section 3 provides annual estimates of failure probabilities and rates related to MOVs as well as the trending of the estimates. Section 4 presents engineering analyses performed for MOV with respect to time period and failure modes. Section 4.1 estimates overall failure frequencies per plant reactor year using the same failures listed in Section 3. Frequencies of demands per plant reactor year for both groupings of MOVs are also provided for each year. As in Section 3, each of the estimates is trended for the most recent 10-year period. The frequencies show general industry performance and are not based on the number of valves at each plant. Section 4.2 provides breakdowns of the failures for each failure mode for each valve grouping. The analyses are based on the following factors: sub-component, failure cause, detection method, and recovery. Section 5 provides the MOV assembly information. Section 6 presents the plot data for various figures in previous sections.

2. SUMMARY OF FINDINGS

The results of this study are summarized in this section. Of particular interest is the existence of any statistically significant[a] increasing trends.

2.1 Increasing Trends

2.1.1 Extremely Statistically Significant

- None.

2.1.2 Highly Statistically Significant

- Highly statistically significant **increasing trend** was identified for the **frequency of FTOC demands** (demands per reactor year) for **low-demand MOV** with a p-value of 0.0047 (see Figure 7). The same trend has been identified in the 2016 MOV update study [2].

2.1.3 Statistically Significant

- None.

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- None.

2.2.2 Highly Statistically Significant

- Highly statistically significant **decreasing trend** was identified for the **failure probability of low-demand MOV FTOC** with a p-value of 0.0037 (see Figure 1). This same trend was observed as statistically significant in the 2016 MOV update study.
- Highly statistically significant **decreasing trend** was identified for the **frequency of FTOC events** (failures per reactor year) for **low-demand MOV** with a p-value of 0.0054 (see Figure 9). The same trend was observed in the 2016 MOV update study.

2.2.3 Statistically Significant

- None.

a. Statistical significance is defined in terms of the ‘p-value.’ A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values of less than or equal to 0.05 indicate that we are 95% confident that there is a trend in the data (reject the null hypothesis of no trend.) By convention, we use the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

3. FAILURE PROBABILITIES AND FAILURE RATES

3.1 Overview

Trends of industry-wide failure probabilities and failure rates of MOVs have been calculated from the operating experience for the FTOC, FTOP, and SO failure modes. The MOV data set obtained from ICES was partitioned to low-demand MOVs (those with less than or equal to 20 demands/year) and high-demand MOVs (those with greater than 20 demands/year). The data set includes MOVs in the systems listed in Table 1.

Table 2 shows industry-wide failure probability and failure rate results for low-demand MOV from Reference [6], or the 2015 Update. No 2015 Update results are shown for high-demand MOVs because Reference [6] does not provide them. The 2015 Update results are provided for comparison purposes and are important because they are intended for use in PRA. The results in this section demonstrate the extent to which the 2015 Update results remain suitable estimates for use in PRA.

The MOVs are assumed to operate both when the reactor is critical and during shutdown periods. The number of MOVs in operation is the number that have been in operation at some time during the study period. So new devices put in service during the period are included, as are devices that were in service at one time but have since been removed from service. All demand types are considered—testing, non-testing, and, as applicable, engineered safety feature demands.

Table 1. Summary of MOV counts in the systems in which they are found.

		MOV Count		
System	**Description**	**Total**	**Low Demand**	**High Demand**
AFW	Auxiliary feedwater	638	461	177
CCW	Component cooling water	859	620	239
CRD	Control rod drive	25	8	17
CSR	Containment spray recirculation	351	328	23
CVC	Chemical and volume control	13	13	0
HPCI	High pressure coolant injection	291	267	24
HPCS	High pressure core spray	49	30	19
HPSI	High pressure safety injection	1132	1011	121
ISO	Isolation condenser	20	14	6
LPCS	Low pressure core spray	235	199	36
RCIC	Reactor core isolation	354	317	37
RCS	Reactor coolant	111	104	7
RHR	Residual Heat Removal (LPCI in BWRs; LPSI in PWRs)	2189	1859	330
SWN	Normally operating service water	1013	740	273
SWS	Standby service water	316	215	101
VSS	Vapor suppression	14	14	
	Total	7610	6200	1410

Table 2. 2015 Update industry-wide distributions of p (failure probability) and λ (hourly rate) for low-demand MOVs.

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTOC	2.13E-4	7.28E-4	8.23E-4	1.75E-3	Beta	2.84	3.45E+03
FTOP	7.40E-9	4.76E-8	5.98E-8	1.54E-7	Gamma	1.55	2.59E+07
SO	2.90E-10	1.69E-8	3.24E-8	1.17E-7	Gamma	0.59	1.83E+07

3.2 MOV Failure Probability and Failure Rate Trends

This section estimates all systems, industry-wide, annual failure probabilities (failures per demand) for FTOC events and annual failure rates (failures per valve hour) for FTOP and SO events for the entire study period which covers 1998 through 2018. The estimates are trended for the most recent 10-year period.

The failure probability and failure rate estimates in this section were obtained from a Bayesian update process. The means from the posterior distributions were plotted for each year. The 5th and 95th percentiles from the posterior distributions are also provided and give an indication of the relative uncertainty in the estimated parameters from year to year. When there are no failures, the interval is larger than the interval for years when there are one or more failures because of the form of the posterior variance. Each update utilizes a relatively "flat" constrained non-informative prior distribution (CNID), which has wide bounds, see [3] and NUREG/CR-6823 [8]. CNID is a compromise between an informative prior and the Jeffreys noninformative prior. The mean of the CNID uses prior belief and is based on a pooling of the component or event type data for the years going into the plot (i.e., the most recent 10-year period), but the dispersion is defined to correspond to little information (i.e., relatively flat by set) so that the prior distributions did not create large changes in the data.

For **failure rates** or Poisson data, the CNID is a gamma distribution, with the mean (μ) given by prior belief and calculated as:

$$\mu = \frac{\sum f_i + 0.5}{\sum T_i} \tag{1}$$

where f_i and T_i are the failures and operating/standby time for the ith year, respectively. The CNID shape parameter = 0.5. The posterior distribution mean for the ith year (μ_i) can be calculated as:

$$\mu_i = \frac{f_i + 0.5}{\frac{0.5}{\mu} + T_i} \tag{2}$$

For **failure probabilities** or binomial data, the CNID is a beta approximation, with the mean given by prior belief and calculated as:

$$\mu = \frac{\sum f_i + 0.5}{\sum D_i + 1} \tag{3}$$

where f_i and D_i are the failures and demands for the ith year, respectively. The CNID shape parameter (α) is a number between 0.3 and 0.5 based on the mean μ (see Table C.8 of [8]). The posterior distribution mean for the ith year (μ_i) can be calculated as:

$$\mu_i = \frac{f_i + \alpha}{\frac{\alpha}{\mu} + D_i} \quad (4)$$

The horizontal curves plotted around the regression lines in the graphs form 90% simultaneous confidence bands for the fitted lines. The bounds are larger than ordinary confidence bands for the individual coefficients because they form a confidence band for the entire line. In the lower left hand corner of the trend figures, the regression p-values are reported. They come from a statistical test to assess evidence against the slope of the regression line being zero. Low p-values indicate strong evidence that the slopes are not zero, and suggest a trend does exist. P-values of less than or equal to 0.05 indicate that we are 95% confident that there is a trend in the data (reject the null hypothesis of no trend.) By convention, this study uses the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

The regression methods are all based on “ordinary least squares” (OLS), which minimizes the residuals, or the square of the vertical distance between the annual data points and the fitted regression line. The p-values assume normal distributions for the residuals, with the same variability in the residuals across the years. In the case where the data involve failure counts, the iterative reweighted least squares is used to account for the fact that count data are not expected to have a constant variance (for example, the variance for Poisson-distributed counts is equal to the expected number of counts, which is expected to vary proportionally to the expected number of counts). Further information on the trending methods is provided in Section 2 of the Overview and Reference document [3].

A final feature of the trend graphs is that the 2015 Update baseline industry values from Table 2 are shown for comparison.

Figure 1 to Figure 6 provide the plots for all systems, industry-wide failure probabilities/rates of MOV FTOC, FTOP, and SO events. The data for these plots are provided in Section 6.

- Figure 1 and Figure 2 show the failure probability estimate trends for MOV FTOC events for low-demand and high-demand MOVs, respectively.
- Figure 3 and Figure 4 show the failure probability estimate trends for MOV FTOP events for low-demand and high-demand MOVs, respectively.
- Figure 5 and Figure 6 show the failure probability estimate trends for MOV SO events for low-demand and high-demand MOVs, respectively.

The following trend was identified for the most recent 10-year period:

- Highly statistically significant **decreasing trend** for the **failure probability of low-demand MOV FTOC**, with a p-value of 0.0037 (see Figure 1). This same trend was observed as statistically significant in the 2016 MOV update study [2].

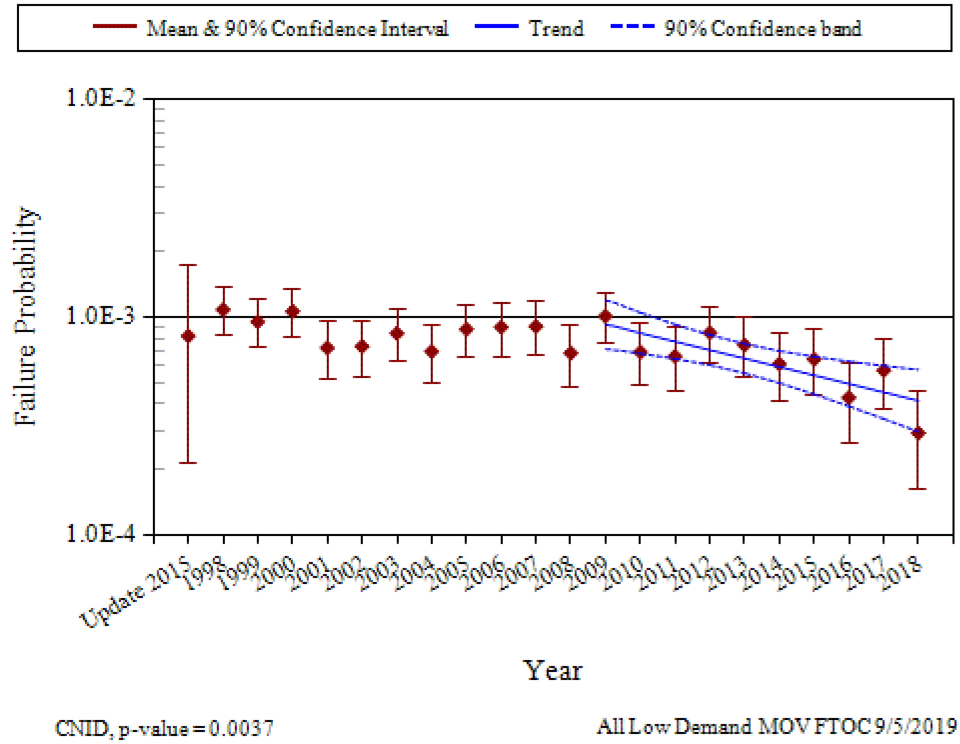

Figure 1. Failure probability estimate trend for low-demand MOV FTOC.

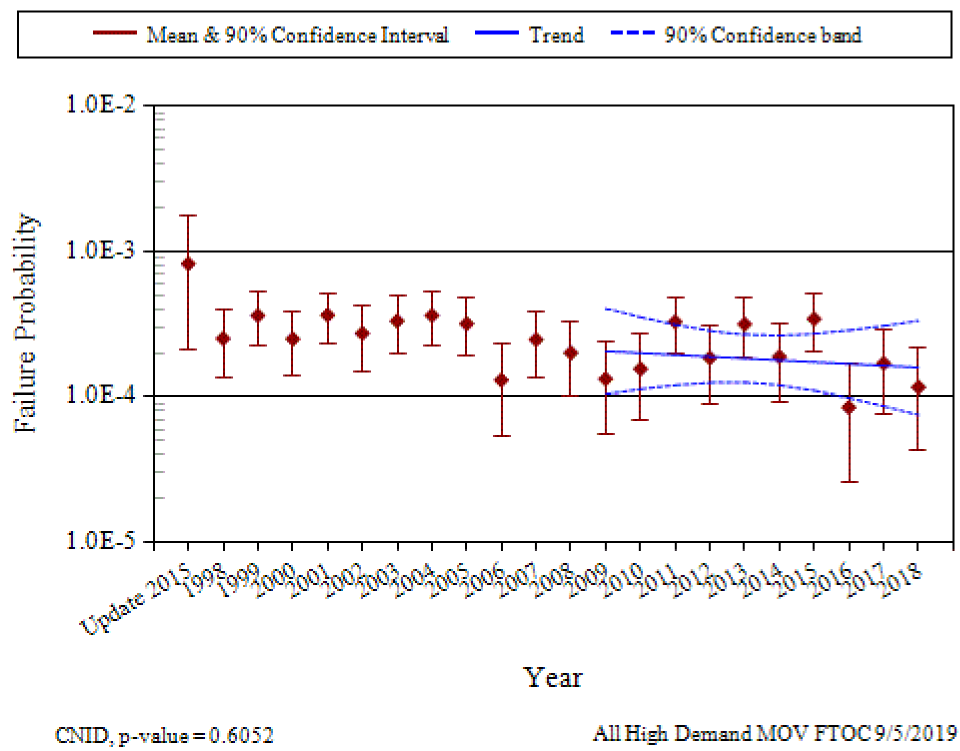

Figure 2. Failure probability estimate trend for high-demand MOV FTOC.

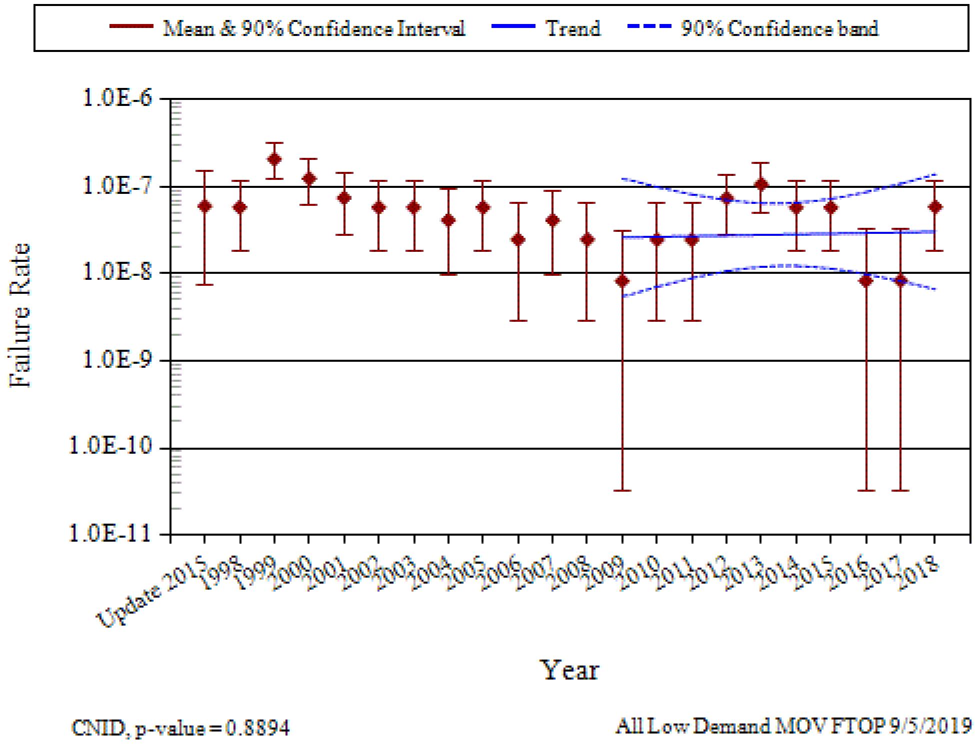

Figure 3. Failure rate estimate trend for low-demand MOV FTOP.

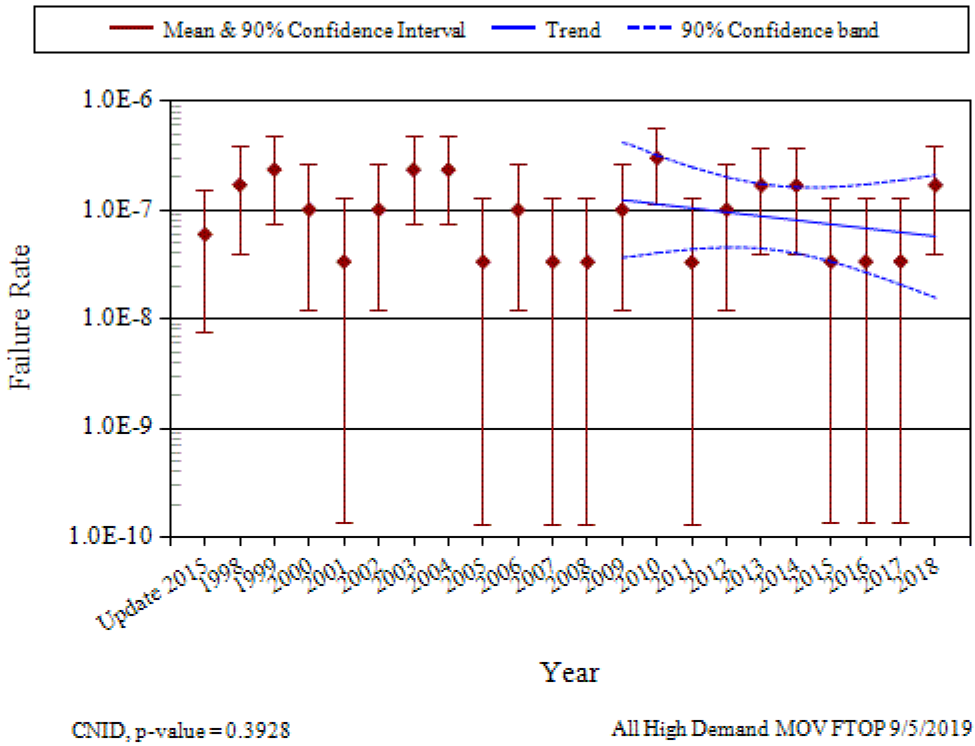

Figure 4. Failure rate estimate trend for high-demand MOV FTOP.

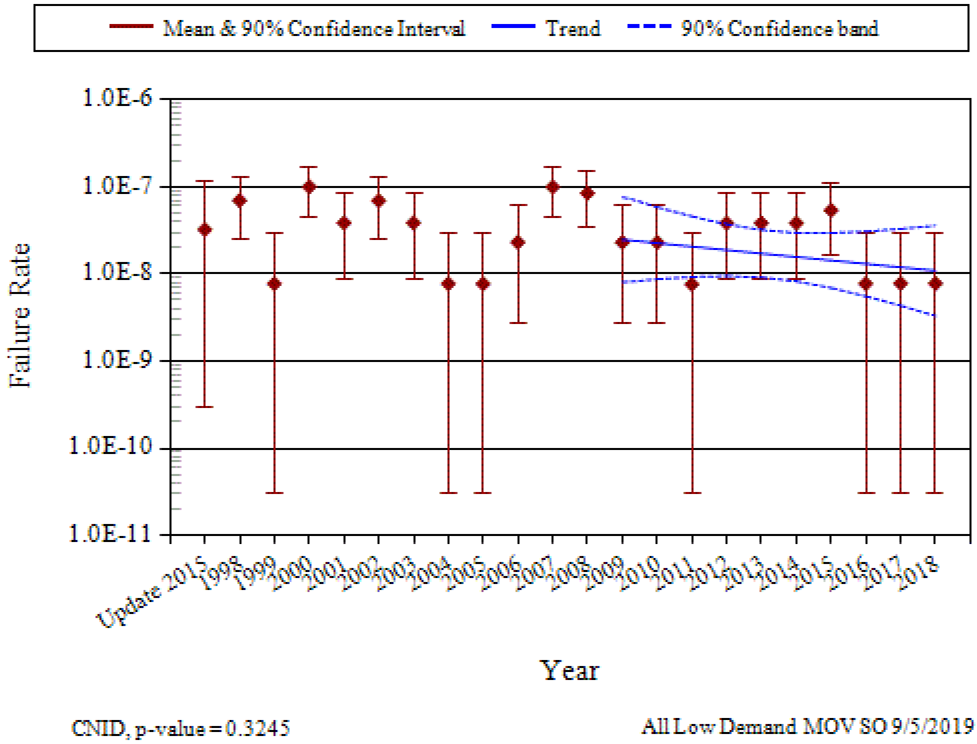

Figure 5. Failure rate estimate trend for low-demand MOV SO.

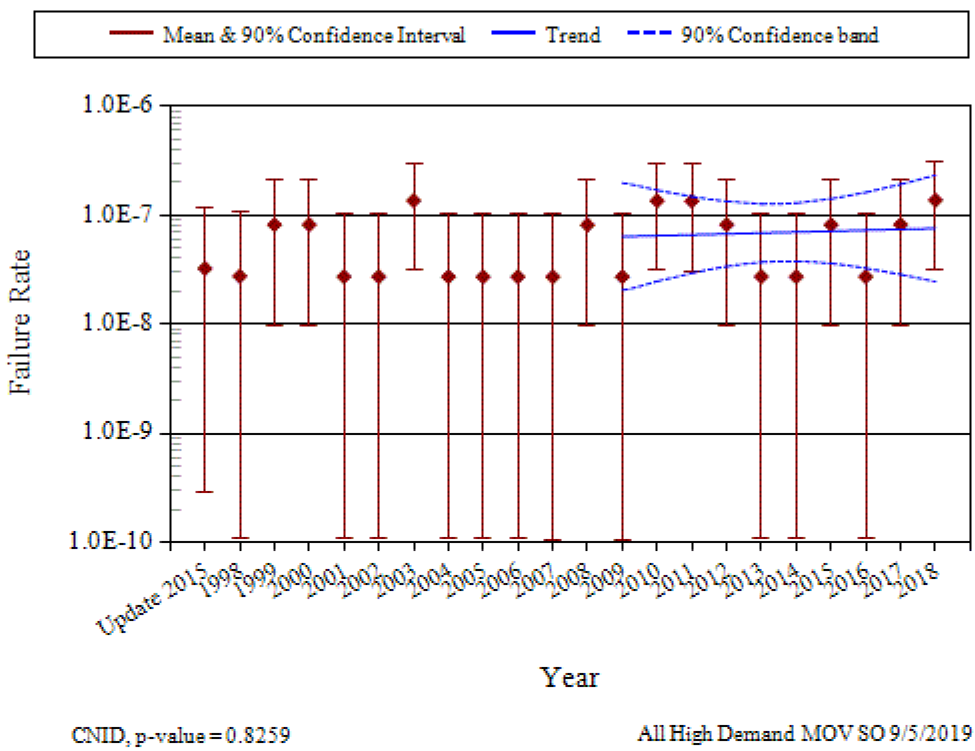

Figure 6. Failure rate estimate trend for high-demand MOV SO.

4. ENGINEERING ANALYSIS

4.1 Engineering Trends

This section presents frequency trends for MOV failures and demands. The data are normalized by reactor year for plants that report data for the equipment being trended. The trends provide an overview of the demand counts and failure counts associated with each failure mode across the years.

Figure 7 to Figure 14 provide the plot for frequency (per reactor year) of MOV demands, FTOC events, FTOP events, and SO events.

- Figure 7 and Figure 8 show the trends for total industry MOV demands for low-demand and high-demand MOVs, respectively.
- Figure 9 and Figure 10 show the trends in failure events for the FTOC mode for low-demand and high-demand MOVs, respectively.
- Figure 11 and Figure 12 show the trends in failure events for the FTOP mode for low-demand and high-demand MOVs, respectively.
- Figure 13 and Figure 14 show the trends in failure events for the SO mode for low-demand and high-demand MOVs, respectively.

The data for the above figures are provided in Section 6. The systems from Table 2 are trended together for each figure. The rate methods described in Section 2 of the Overview and Reference document [3] are used.

Table 3 to Table 8 provide a summary of the FTOC, FTOP, and SO failure counts by system and year during the most recent 10-year period.

- Table 3 presents the FTOC failure counts by system and year for low-demand MOVs.
- Table 4 presents the FTOP failure counts by system and year for low-demand MOVs.
- Table 5 presents the SO failure counts by system and year for low-demand MOVs.
- Table 6 presents the FTOC failure counts by system and year for high-demand MOVs.
- Table 7 presents the FTOP failure counts by system and year for high-demand MOVs.
- Table 8 presents the SO failure counts by system and year for high-demand MOVs.

The following trends were identified for the most recent 10-year period:

- Highly statistically significant **increasing trend** for the **frequency of FTOC demands** (demands per reactor year) for **low-demand MOV**, with a p-value of 0.0047 (see Figure 7). The same trend has been identified in the 2016 MOV update study [2].
- Highly statistically significant **decreasing trend** for the **frequency of FTOC events** (failures per reactor year) for **low-demand MOV**, with a p-value of 0.0054 (see Figure 9). The same trend has been identified in the 2016 MOV update study.

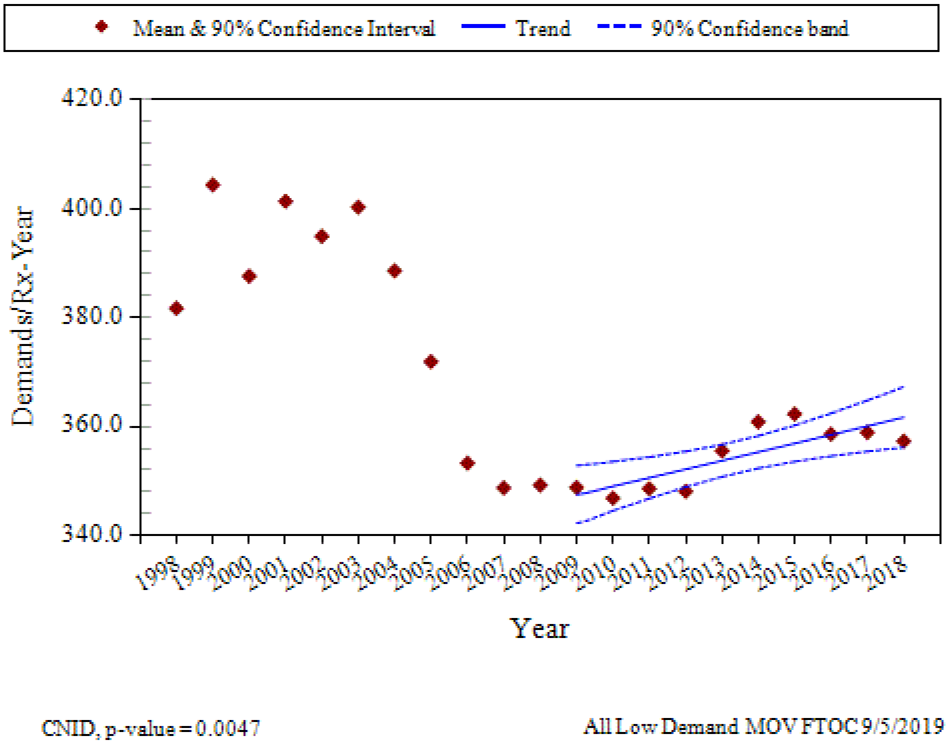

Figure 7. Frequency of FTOC demands (demands per reactor year) for low-demand MOVs.

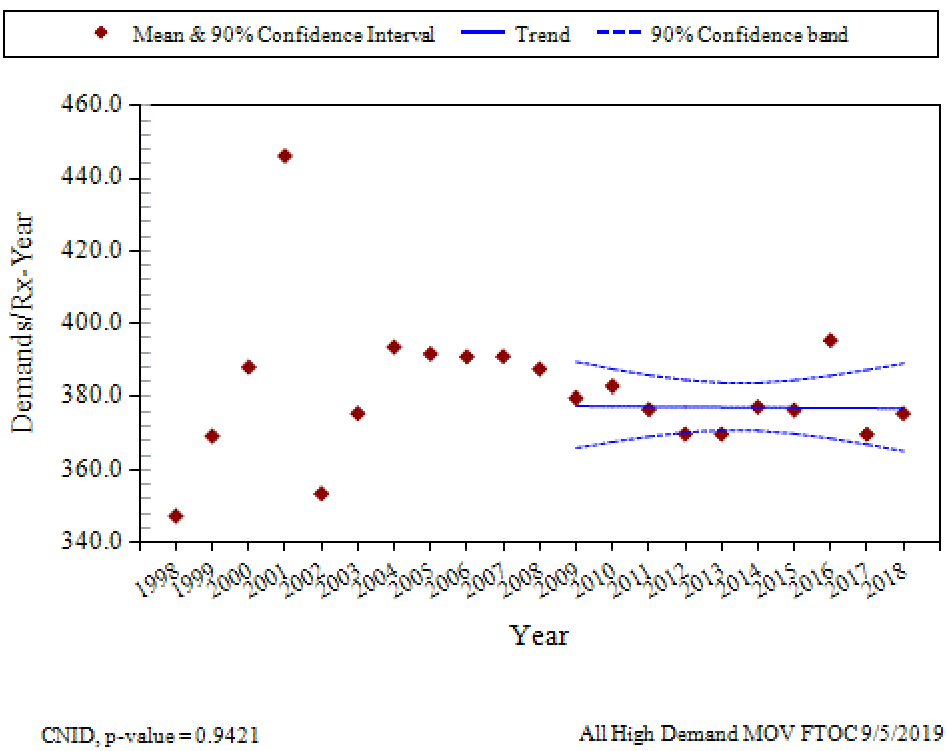

Figure 8. Frequency of FTOC demands (demands per reactor year) for high-demand MOVs.

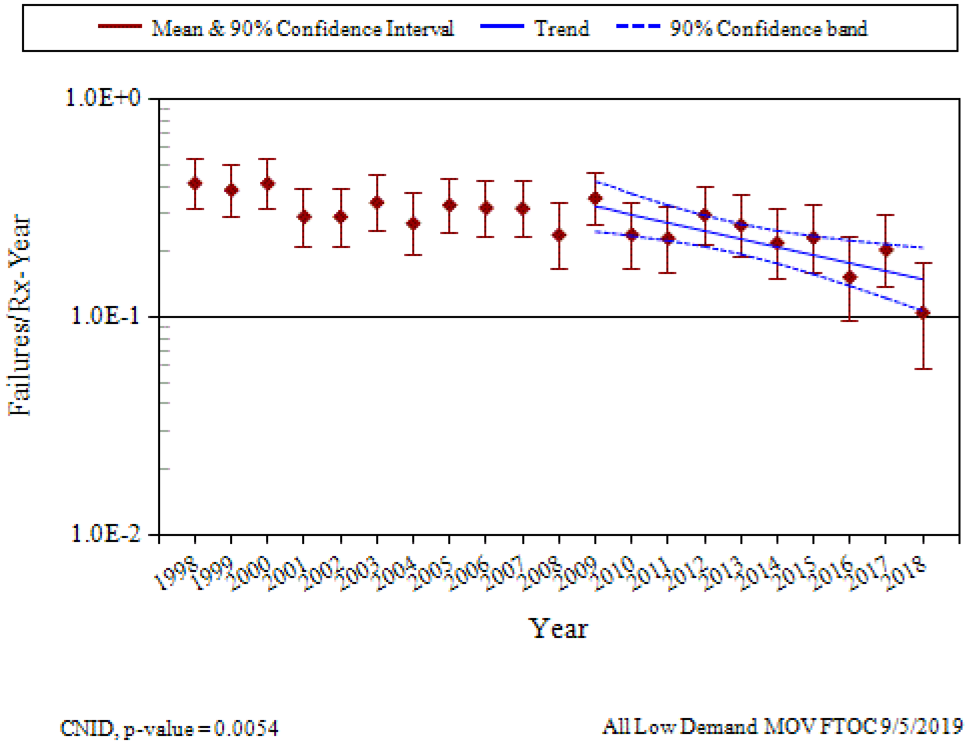

Figure 9. Frequency of FTOC events (failures per reactor year) for low-demand MOVs.

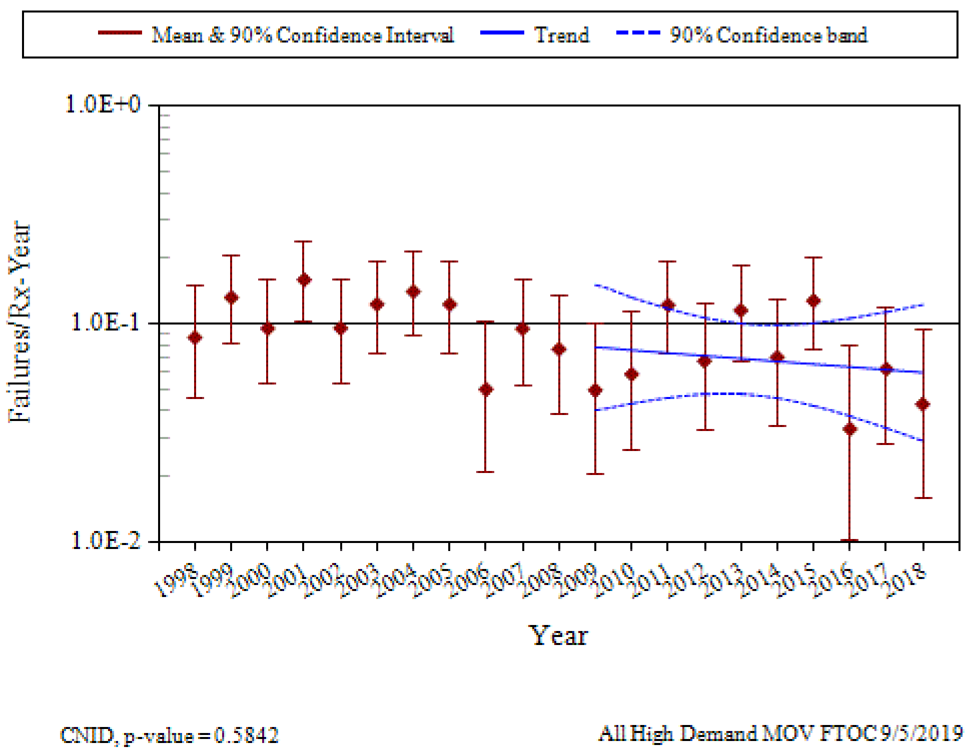

Figure 10. Frequency of FTOC events (failures per reactor year) for high-demand MOVs.

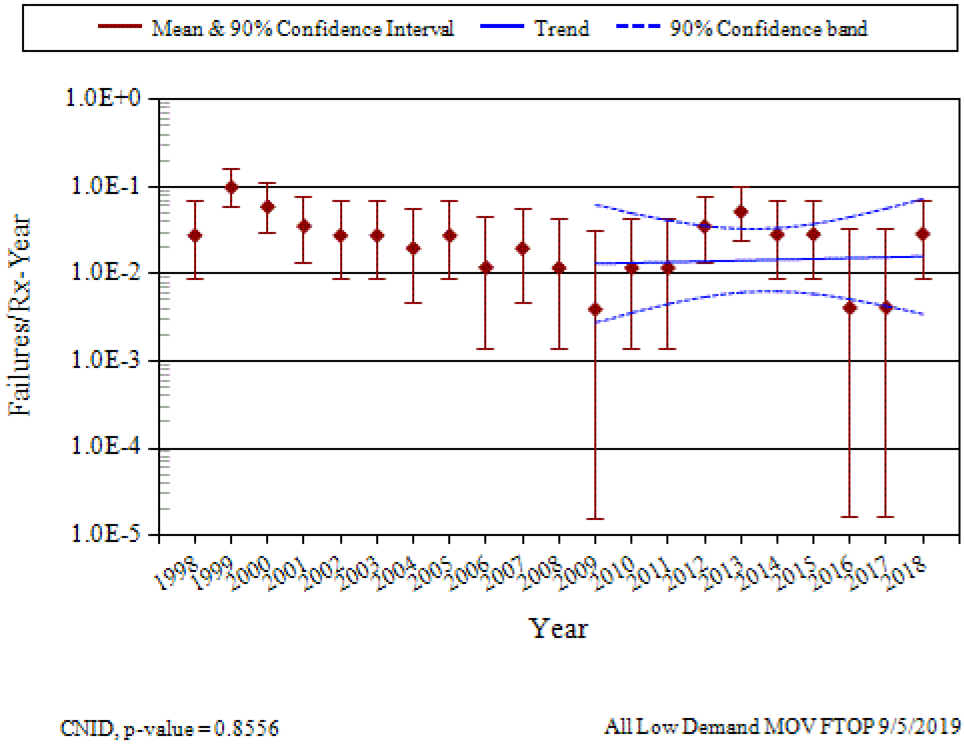

Figure 11. Frequency of FTOP events (failures per reactor year) for low-demand MOVs.

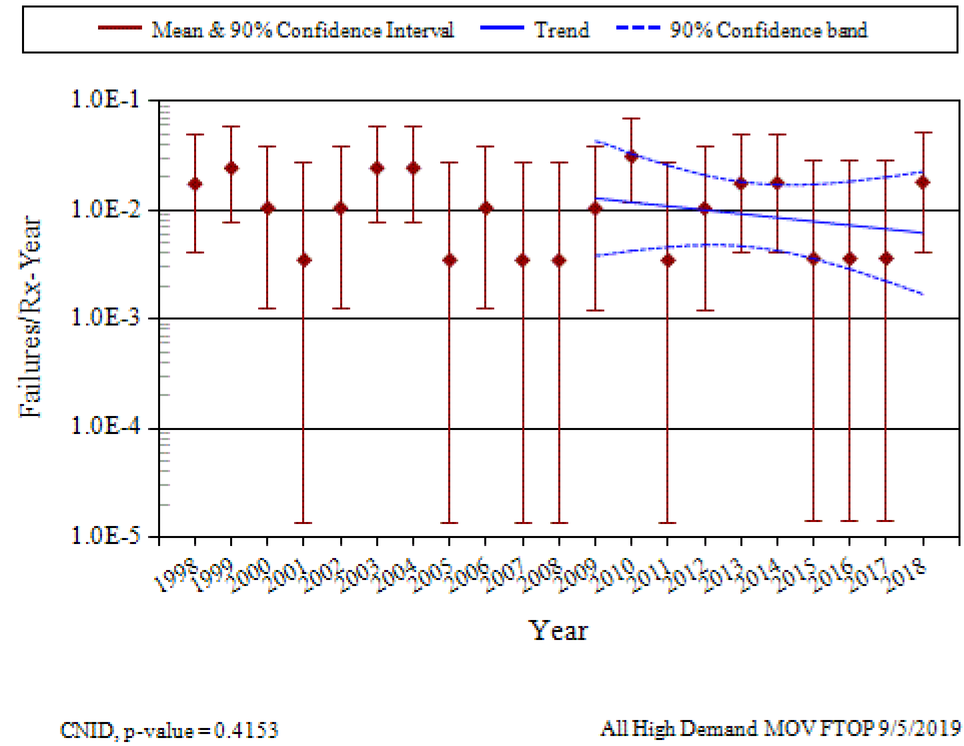

Figure 12. Frequency of FTOP events (failures per reactor year) for high-demand MOVs.

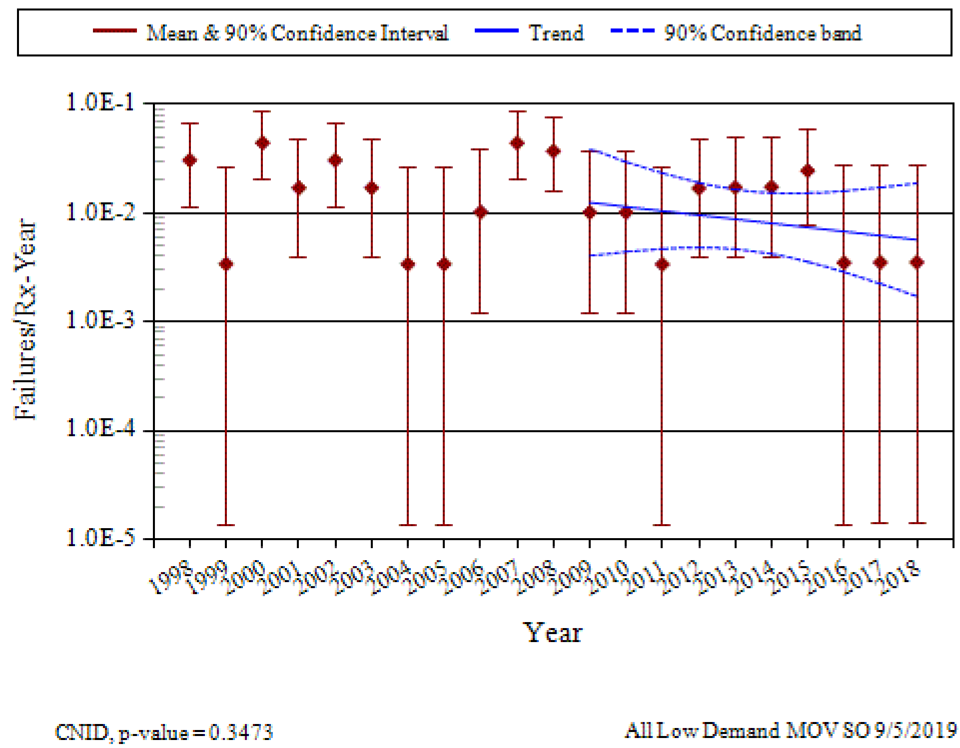

Figure 13. Frequency of SO events (failures per reactor year) for low-demand MOVs.

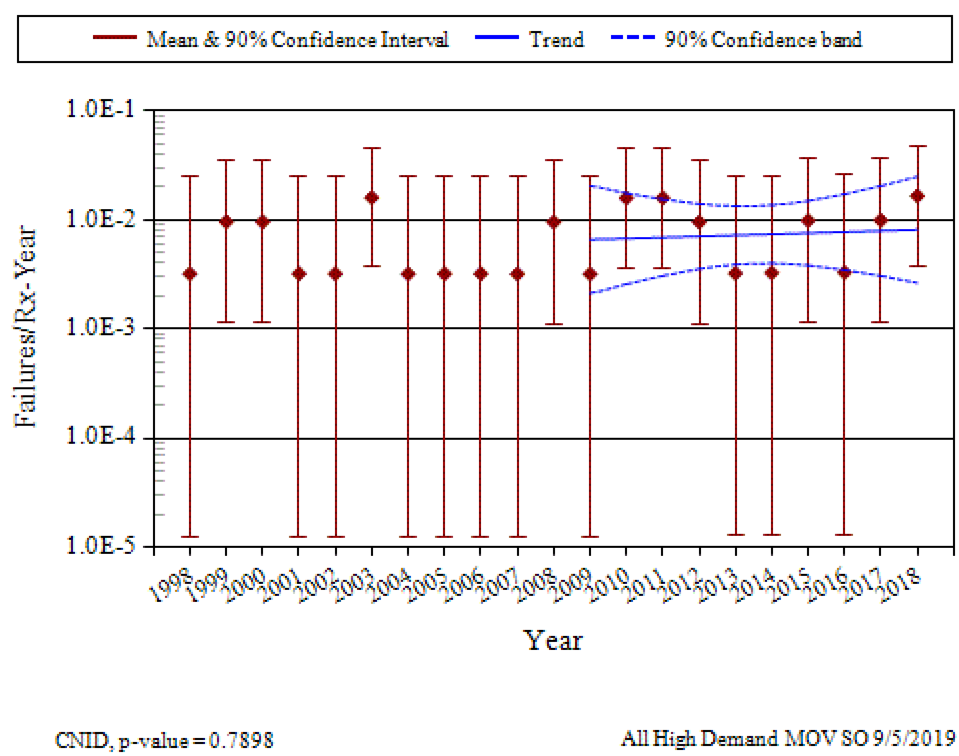

Figure 14. Frequency of SO events (failures per reactor year) for high-demand MOVs.

Table 3. Summary of low-demand MOV failure counts for the FTOC failure mode over time by system.

System	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	461	7.4 %	5	5	4		3	4	4	2		1	28	12.0 %
CCW	620	10.0 %	2	2	2	1	3	1	3	2	2	2	20	8.5 %
CRD	8	0.1 %											0	0.0 %
CSR	328	5.3 %	1	1	2	1		2	3	1			11	4.7 %
CVC	13	0.2 %											0	0.0 %
HPCI	267	4.3 %	4	1		3	1	1	1	1	1		13	5.6 %
HPCS	30	0.5 %									1		1	0.4 %
HPSI	1011	16.3 %	4	3	2	2	2	5	1				19	8.1 %
ISO	14	0.2 %			1								1	0.4 %
LPCS	199	3.2 %			2	3	1				2	1	9	3.8 %
RCIC	317	5.1 %		2	1	6	3		3		1	1	17	7.3 %
RCS	104	1.7 %	1			2	1			1		1	6	2.6 %
RHR	1859	30.0 %	15	10	5	9	5	7	5	6	9	3	74	31.6 %
SWN	740	11.9 %	4	1	3	4	7	2	3	1	2	1	28	12.0 %
SWS	215	3.5 %	1		2					1	2		6	2.6 %
VSS	14	0.2 %					1						1	0.4 %
Total	6200	100.0%	37	25	24	31	27	22	23	15	20	10	234	100.0%

Table 4. Summary of low-demand MOV failure counts for the FTOP failure mode over time by system.

System	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	461	7.4 %		1		1	1					1	4	19.0 %
CCW	620	10.0 %							1				1	4.8 %
CRD	8	0.1 %											0	0.0 %
CSR	328	5.3 %											0	0.0 %
CVC	13	0.2 %											0	0.0 %
HPCI	267	4.3 %					1		1				2	9.5 %
HPCS	30	0.5 %											0	0.0 %
HPSI	1011	16.3 %			1	1						1	3	14.3 %
ISO	14	0.2 %											0	0.0 %
LPCS	199	3.2 %											0	0.0 %
RCIC	317	5.1 %							1				1	4.8 %
RCS	104	1.7 %						1					1	4.8 %
RHR	1859	30.0 %				1	2						3	14.3 %
SWN	740	11.9 %				1	2	1				1	5	23.8 %
SWS	215	3.5 %											0	0.0 %
VSS	14	0.2 %						1					1	4.8 %
Total	6200	100.0%	0	1	1	4	6	3	3	0	0	3	21	100.0%

Table 5. Summary of low-demand MOV failure counts for the SO failure mode over time by system.

System	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	461	7.4 %							1				1	9.1 %
CCW	620	10.0 %											0	0.0 %
CRD	8	0.1 %											0	0.0 %
CSR	328	5.3 %											0	0.0 %
CVC	13	0.2 %											0	0.0 %
HPCI	267	4.3 %		1				1					2	18.2 %
HPCS	30	0.5 %											0	0.0 %
HPSI	1011	16.3 %											0	0.0 %
ISO	14	0.2 %											0	0.0 %
LPCS	199	3.2 %											0	0.0 %
RCIC	317	5.1 %	1			2	1						4	36.4 %
RCS	104	1.7 %											0	0.0 %
RHR	1859	30.0 %					1	1	2				4	36.4 %
SWN	740	11.9 %											0	0.0 %
SWS	215	3.5 %											0	0.0 %
VSS	14	0.2 %											0	0.0 %
Total	6200	100.0%	1	1	0	2	2	2	3	0	0	0	11	100.0%

Table 6. Summary of high-demand MOV failure counts for the FTOC failure mode over time by system.

System	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	177	12.6 %	1	1	5		4	2	3			2	18	23.7 %
CCW	239	17.0 %			2				2	2			6	7.9 %
CRD	17	1.2 %											0	0.0 %
CSR	23	1.6 %						1	1				2	2.6 %
HPCI	24	1.7 %		1	1			1			1		4	5.3 %
HPCS	19	1.3 %											0	0.0 %
HPSI	121	8.6 %			1		1						2	2.6 %
ISO	6	0.4 %											0	0.0 %
LPCS	36	2.6 %		1		1							2	2.6 %
RCIC	37	2.6 %			1	1	1					1	4	5.3 %
RCS	7	0.5 %											0	0.0 %
RHR	330	23.4 %	3	3	2	3	3	2	3		3	1	23	30.3 %
SWN	273	19.4 %	1			2	1		3		2		9	11.8 %
SWS	101	7.2 %			1		2	1	1	1			6	7.9 %
Total	1410	100.0%	5	6	13	7	12	7	13	3	6	4	76	100.0%

Table 7. Summary of high-demand MOV failure counts for the FTOP failure mode over time by system.

System Code	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	177	12.6 %		1									1	8.3 %
CCW	239	17.0 %		1				2					3	25.0 %
CRD	17	1.2 %											0	0.0 %
CSR	23	1.6 %											0	0.0 %
HPCI	24	1.7 %											0	0.0 %
HPCS	19	1.3 %											0	0.0 %
HPSI	121	8.6 %											0	0.0 %
ISO	6	0.4 %											0	0.0 %
LPCS	36	2.6 %											0	0.0 %
RCIC	37	2.6 %											0	0.0 %
RCS	7	0.5 %											0	0.0 %
RHR	330	23.4 %	1	1			1						3	25.0 %
SWN	273	19.4 %				1	1					2	4	33.3 %
SWS	101	7.2 %		1									1	8.3 %
Total	1410	100.0%	1	4	0	1	2	2	0	0	0	2	12	100.0%

Table 8. Summary of high-demand MOV failure counts for the SO failure mode over time by system.

System Code	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	177	12.6 %										1	1	11.1 %
CCW	239	17.0 %											0	0.0 %
CRD	17	1.2 %											0	0.0 %
CSR	23	1.6 %											0	0.0 %
HPCI	24	1.7 %											0	0.0 %
HPCS	19	1.3 %							1				1	11.1 %
HPSI	121	8.6 %											0	0.0 %
ISO	6	0.4 %											0	0.0 %
LPCS	36	2.6 %											0	0.0 %
RCIC	37	2.6 %		2		1							3	33.3 %
RCS	7	0.5 %											0	0.0 %
RHR	330	23.4 %			2						1	1	4	44.4 %
SWN	273	19.4 %											0	0.0 %
SWS	101	7.2 %											0	0.0 %
Total	1410	100.0%	0	2	2	1	0	0	1	0	1	2	9	100.0%

4.2 MOV Engineering Analysis by Failure Modes

This section presents the engineering analysis of MOV failure sub-components, causes, detection methods, and recovery. Each analysis first divides the events into two categories: low-demand MOVs (with less than or equal to 20 demands/year) and high-demand MOVs (with greater than 20 demands/year). The second division of the events is by the failure mode determined after ICES data review by the staff. See Section 5 for more description of failure modes.

Figure 15 shows the MOV sub-component contributions to the three failure modes (FTOC, FTOP, and SO). The sub-component categories are similar to those used in the CCF database. For all three failure modes, the actuator is the largest contributor to the failure rates/probabilities.

Figure 16 shows the MOV cause group contributions to the three failure modes. The cause groups have been re-arranged in this update study in order to align with those currently used in the CCF database. Table 9 shows the breakdown of the cause groups with the specific causes that were coded during the data collection.

- The Component cause group is the most likely cause for all three failure modes. The Component cause group includes the causes that were related to something internal to the component or an aging or worn out part, which were categorized as the Internal cause group in previous studies [2].
- The Human cause group, which now includes both the Human and the Procedure cause groups found in previous studies, is the second most likely cause for FTOC and FTOP, and also a key contributor to SO. The Human cause group is primarily influenced by maintenance and operating procedures and practices.
- The Other cause group, which now includes the specific cause of the state of other component, is the second most likely cause for SO.

Figure 17 shows the MOV detection methods for the three failure modes.

- Overall, the most likely detection method for all three failure modes is testing demand. Non-test demand and inspection are the two other main detection methods.
- For FTOP, while the most likely detection method for low-demand MOVs is still testing demand, the detection method for high-demand MOVs is dominated by non-testing demand.

Figure 18 shows the MOV recovery fractions for the three failure modes. The overall non-recovery to recovery ratio is approximately 12:1 meaning that 12 of every 13 failures were not recovered.

Table 9. Component failure cause groups.[2]

Group	Specific Cause	Description
Component	Internal to component, piece-part	Used when the cause of a failure is a non-specific result of a failure internal to the component that failed other than aging or wear.
	Set point drift	Used when the cause of a failure is the result of set point drift or adjustment.
	Age/Wear	Used when the cause of the failure is a non-specific aging or wear issue.
Design	Construction/installation error or inadequacy	Used when a construction or installation error is made during the original or modification installation. This includes specification of incorrect component or material.
	Design error or inadequacy	Used when a design error is made.
	Manufacturing error or inadequacy	Used when a manufacturing error is made during component manufacture.
Environment	Ambient environmental stress	Used when the cause of a failure is the result of an environmental condition from the location of the component.
	Internal environment	The internal environment led to the failure. Debris/Foreign material as well as an operating medium chemistry issue.
	Extreme environmental stress	Used when the cause of a failure is the result of an environmental condition that places a higher than expected load on the equipment and is transitory in nature.
Human	Accidental action (unintentional or undesired human errors)	Used when a human error (during the performance of an activity) results in an unintentional or undesired action.
	Human action procedure	Used when the correct procedure is not followed or the wrong procedure is followed. For example: when a missed step or incorrect step in a surveillance procedure results in a component failure.
	Inadequate maintenance	Used when a human error (during the performance of maintenance) results in an unintentional or undesired action.
	Inadequate procedure	Used when the cause of a failure is the result of an inadequate procedure operating or maintenance.
Other	State of other component	Used when the cause of a failure is the result of a component state that is not associated with the component that failed. An example would be the diesel failed due to empty fuel storage tanks.
	Other (stated cause does not fit other categories)	Used when the cause of a failure is provided but it does not meet any one of the descriptions.
	Unknown	Used when the cause of the failure is not known.

[2]. The cause groups have been re-arranged in order to align with those currently used in the CCF database.

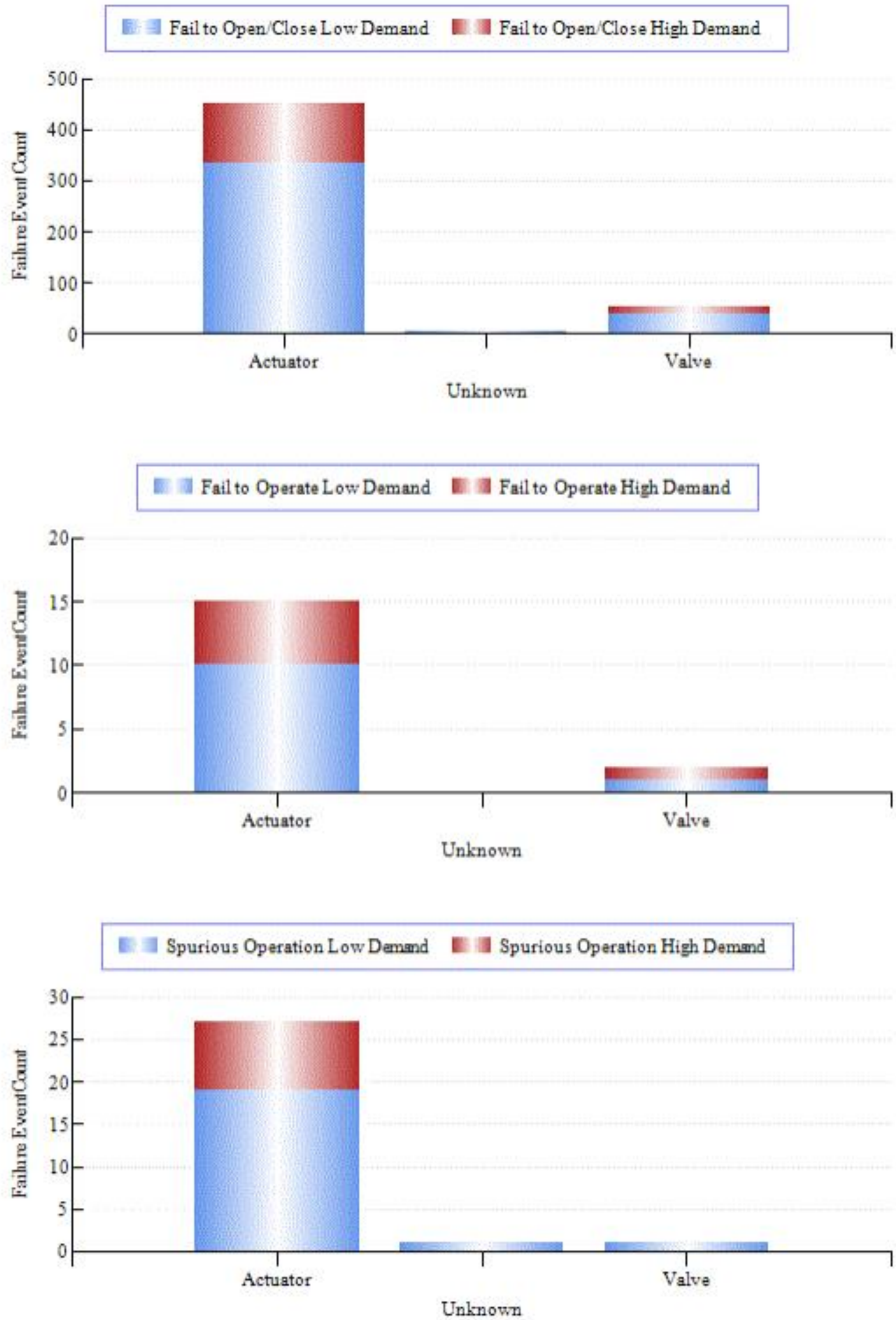

Figure 15. MOV failure event breakdown by subcomponent, failure mode, and demand rate.

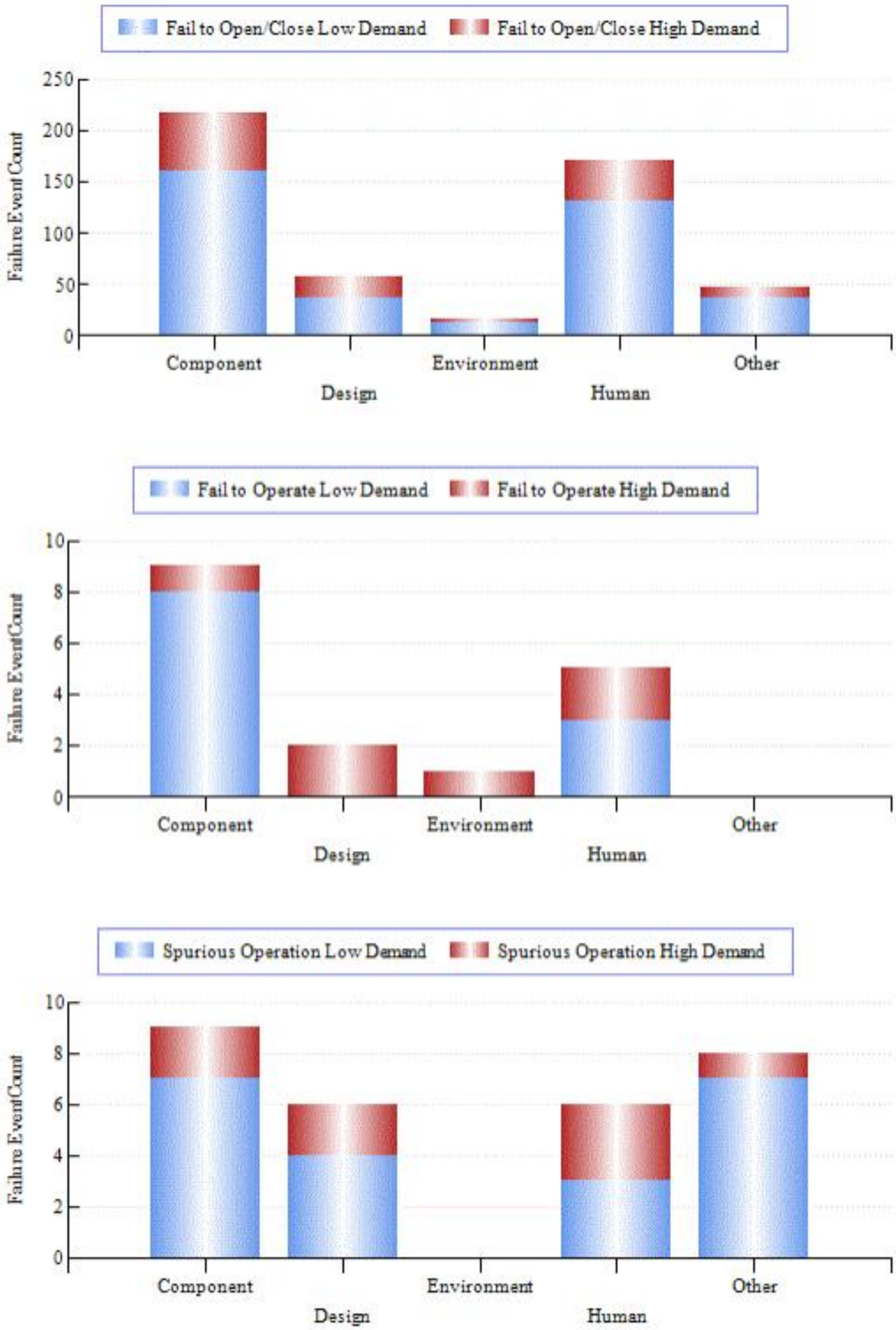

Figure 16. MOV failure event breakdown by cause group, failure mode, and demand rate.

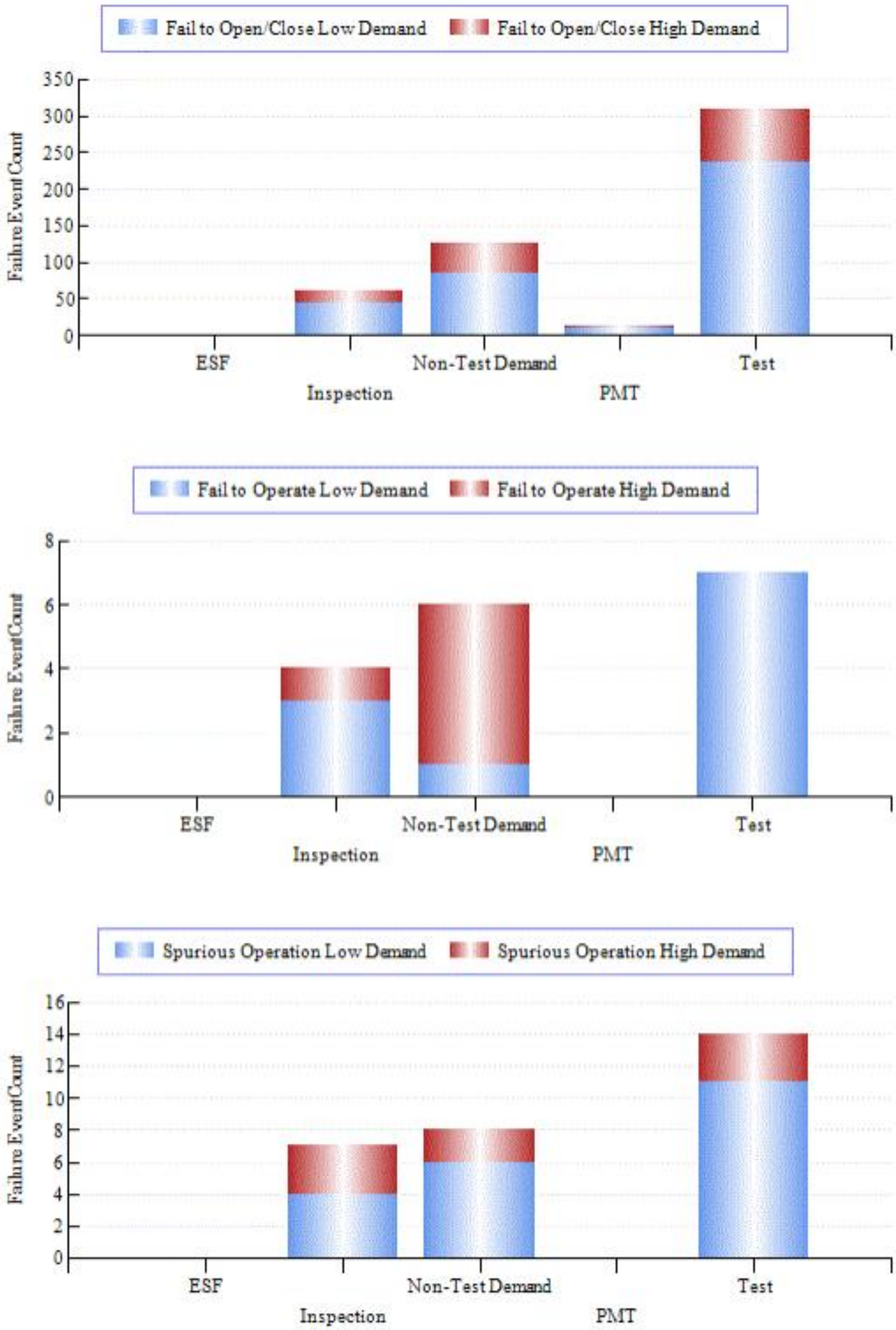

Figure 17. MOV failure event breakdown by method of detection, failure mode, and demand rate.

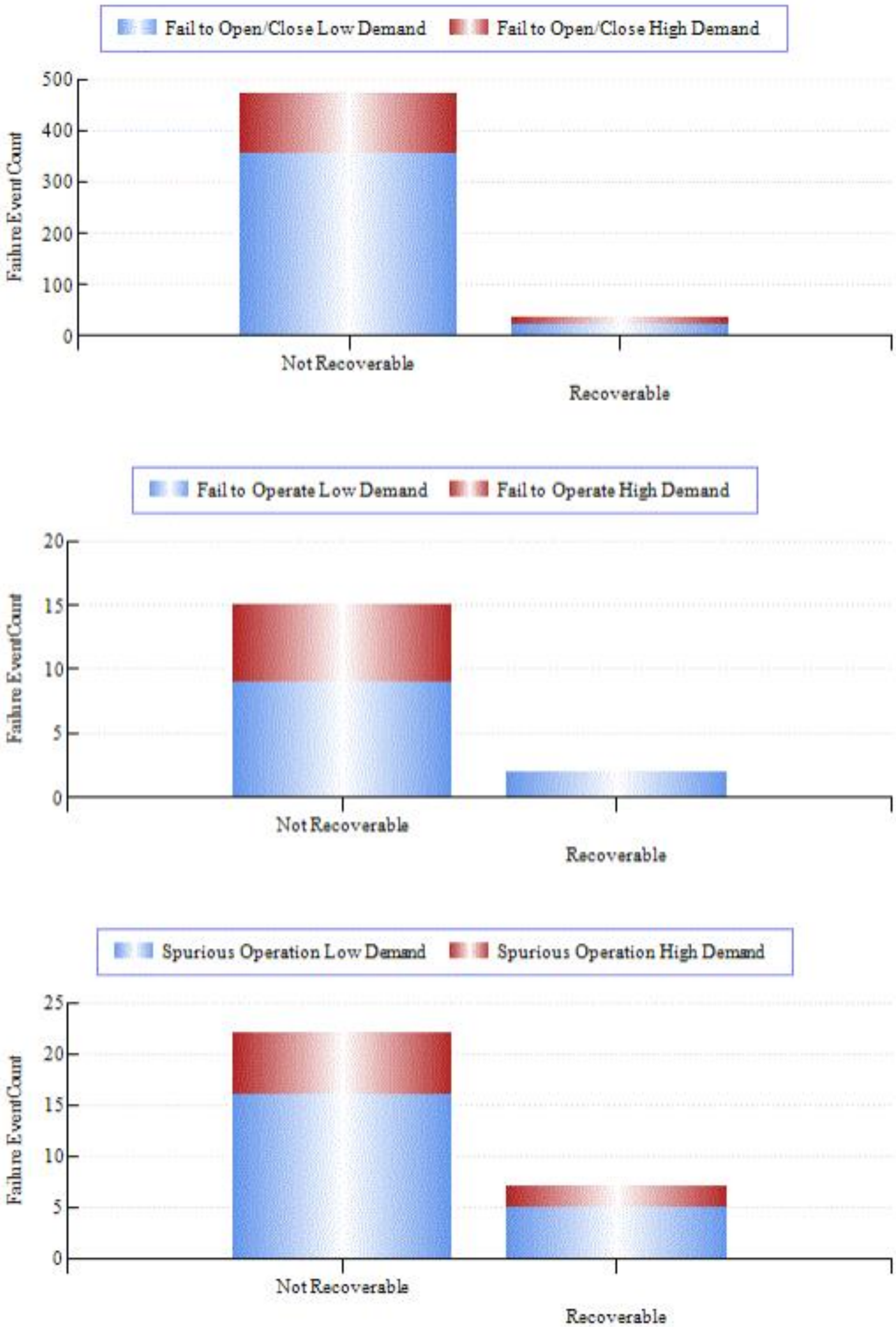

Figure 18. MOV failure event breakdown by recoverability, failure mode, and demand rate.

5. MOV ASSEMBLY DESCRIPTION

A MOV assembly consists of a valve body and motor-operated sub-components (including the circuit breaker). The valve body is generally a gate type. The motor-operator or ac/dc actuator is generally manufactured by Limitorque or Rotork.

The piece-parts of the valve body are the stem, packing, and internals. The motor-operator piece-parts include the torque switch, spring pack, limit switch, wiring/contacts, and motor internal and mechanical devices.

Failure modes for the MOV include

- FTOC, which combines the fail to open and fail to close failure modes into a single category;
- FTOP, which is a rate-based failure mode that includes FTC for a flow/temperature control device and any other rate-based failure modes except for SO, and
- SO, which includes spurious opening and spurious closing.

6. DATA TABLES

In this section, the plot data for Figure 1 to Figure 14 in previous sections are provided in Table 10 to Table 23, respectively.

Figure	Table	Analysis
Figure 1	Table 10	Failure probability estimate trend for low-demand MOV FTOC
Figure 2	Table 11	Failure probability estimate trend for high-demand MOV FTOC
Figure 3	Table 12	Failure rate estimate trend for low-demand MOV FTOP
Figure 4	Table 13	Failure rate estimate trend for high-demand MOV FTOP
Figure 5	Table 14	Failure rate estimate trend for low-demand MOV SO
Figure 6	Table 15	Failure rate estimate trend for high-demand MOV SO
Figure 7	Table 16	Frequency of FTOC demands (demands per reactor year) for low-demand MOVs
Figure 8	Table 17	Frequency of FTOC demands (demands per reactor year) for high-demand MOVs
Figure 9	Table 18	Frequency of FTOC events (failures per reactor year) for low-demand MOVs
Figure 10	Table 19	Frequency of FTOC events (failures per reactor year) for high-demand MOVs
Figure 11	Table 20	Frequency of FTOP events (failures per reactor year) for low-demand MOVs
Figure 12	Table 21	Frequency of FTOP events (failures per reactor year) for high-demand MOVs
Figure 13	Table 22	Frequency of SO events (failures per reactor year) for low-demand MOVs
Figure 14	Table 23	Frequency of SO events (failures per reactor year) for high-demand MOVs

Table 10. Plot data for Figure 1, failure probability estimate trend for low-demand MOV FTOC.

Year/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						2.13E-04	1.75E-03	8.23E-04
1998	43	39,316	--	--	--	8.30E-04	1.40E-03	1.09E-03
1999	40	41,653	--	--	--	7.22E-04	1.24E-03	9.55E-04
2000	43	40,033	--	--	--	8.15E-04	1.37E-03	1.07E-03
2001	30	41,341	--	--	--	5.23E-04	9.80E-04	7.24E-04
2002	30	40,678	--	--	--	5.31E-04	9.96E-04	7.36E-04
2003	35	41,228	--	--	--	6.26E-04	1.12E-03	8.45E-04
2004	28	40,135	--	--	--	4.97E-04	9.53E-04	6.97E-04
2005	34	38,307	--	--	--	6.51E-04	1.17E-03	8.83E-04
2006	33	36,385	--	--	--	6.62E-04	1.20E-03	9.02E-04
2007	33	36,131	--	--	--	6.66E-04	1.21E-03	9.08E-04
2008	25	36,418	--	--	--	4.79E-04	9.55E-04	6.86E-04
2009	37	36,274	9.28E-04	7.17E-04	1.20E-03	7.57E-04	1.33E-03	1.01E-03
2010	25	36,070	8.48E-04	6.84E-04	1.05E-03	4.83E-04	9.64E-04	6.92E-04
2011	24	36,251	7.76E-04	6.47E-04	9.30E-04	4.58E-04	9.27E-04	6.62E-04
2012	31	36,299	7.10E-04	6.05E-04	8.32E-04	6.17E-04	1.14E-03	8.50E-04
2013	27	36,109	6.49E-04	5.56E-04	7.58E-04	5.28E-04	1.03E-03	7.46E-04
2014	22	36,082	5.94E-04	5.01E-04	7.03E-04	4.15E-04	8.68E-04	6.11E-04
2015	23	35,865	5.43E-04	4.45E-04	6.62E-04	4.40E-04	9.05E-04	6.42E-04
2016	15	35,507	4.96E-04	3.92E-04	6.29E-04	2.66E-04	6.53E-04	4.27E-04
2017	20	35,171	4.54E-04	3.43E-04	6.01E-04	3.80E-04	8.25E-04	5.70E-04
2018	10	34,925	4.15E-04	2.99E-04	5.77E-04	1.62E-04	4.93E-04	2.94E-04
Total	608	790,175						

Table 11. Plot data for Figure 2, failure probability estimate trend for high-demand MOV FTOC.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year/ Source	**Failures**	**Demands**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2015 Update						2.13E-04	1.75E-03	8.23E-04
1998	9	35,766	--	--	--	1.32E-04	4.27E-04	2.48E-04
1999	14	38,033	--	--	--	2.18E-04	5.55E-04	3.58E-04
2000	10	40,070	--	--	--	1.36E-04	4.13E-04	2.47E-04
2001	17	45,956	--	--	--	2.32E-04	5.39E-04	3.61E-04
2002	10	36,401	--	--	--	1.49E-04	4.52E-04	2.70E-04
2003	13	38,677	--	--	--	1.96E-04	5.17E-04	3.28E-04
2004	15	40,646	--	--	--	2.23E-04	5.49E-04	3.59E-04
2005	13	40,338	--	--	--	1.89E-04	4.97E-04	3.15E-04
2006	5	40,255	--	--	--	5.35E-05	2.62E-04	1.29E-04
2007	10	40,508	--	--	--	1.35E-04	4.09E-04	2.44E-04
2008	8	40,409	--	--	--	1.01E-04	3.51E-04	1.98E-04
2009	5	39,484	2.05E-04	1.05E-04	4.03E-04	5.45E-05	2.66E-04	1.31E-04
2010	6	39,815	2.00E-04	1.13E-04	3.53E-04	6.96E-05	2.95E-04	1.54E-04
2011	13	39,163	1.94E-04	1.20E-04	3.13E-04	1.94E-04	5.11E-04	3.24E-04
2012	7	38,569	1.89E-04	1.25E-04	2.84E-04	8.84E-05	3.36E-04	1.83E-04
2013	12	37,559	1.83E-04	1.25E-04	2.68E-04	1.82E-04	5.01E-04	3.12E-04
2014	7	37,726	1.78E-04	1.20E-04	2.64E-04	9.03E-05	3.43E-04	1.86E-04
2015	13	37,266	1.73E-04	1.10E-04	2.71E-04	2.03E-04	5.35E-04	3.40E-04
2016	3	39,147	1.68E-04	9.87E-05	2.86E-04	2.60E-05	2.03E-04	8.41E-05
2017	6	36,237	1.63E-04	8.68E-05	3.08E-04	7.61E-05	3.23E-04	1.68E-04
2018	4	36,698	1.59E-04	7.55E-05	3.34E-04	4.24E-05	2.51E-04	1.15E-04
Total	200	818,722						

Table 12. Plot data for Figure 3, failure rate estimate trend for low-demand MOV FTOP.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year/ Source	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						7.40E-09	1.54E-07	5.98E-08
1998	3	51,561,360	--	--	--	1.70E-08	1.33E-07	5.50E-08
1999	12	51,692,760	--	--	--	1.15E-07	3.15E-07	1.96E-07
2000	7	51,754,080	--	--	--	5.69E-08	2.16E-07	1.18E-07
2001	4	51,719,040	--	--	--	2.61E-08	1.54E-07	7.06E-08
2002	3	51,701,520	--	--	--	1.70E-08	1.33E-07	5.49E-08
2003	3	51,710,280	--	--	--	1.70E-08	1.33E-07	5.49E-08
2004	2	51,675,240	--	--	--	8.99E-09	1.10E-07	3.92E-08
2005	3	51,719,040	--	--	--	1.70E-08	1.33E-07	5.49E-08
2006	1	51,815,400	--	--	--	2.76E-09	8.67E-08	2.35E-08
2007	2	51,876,720	--	--	--	8.96E-09	1.10E-07	3.91E-08
2008	1	51,780,360	--	--	--	2.76E-09	8.67E-08	2.35E-08
2009	0	51,789,120	2.62E-08	5.56E-09	1.23E-07	3.08E-11	6.12E-08	7.83E-09
2010	1	51,999,360	2.66E-08	7.14E-09	9.93E-08	2.75E-09	8.64E-08	2.34E-08
2011	1	52,472,400	2.71E-08	8.95E-09	8.19E-08	2.73E-09	8.58E-08	2.33E-08
2012	4	51,981,840	2.75E-08	1.08E-08	7.05E-08	2.60E-08	1.54E-07	7.03E-08
2013	6	51,911,760	2.80E-08	1.21E-08	6.49E-08	4.61E-08	1.95E-07	1.02E-07
2014	3	51,859,200	2.84E-08	1.23E-08	6.56E-08	1.70E-08	1.32E-07	5.48E-08
2015	3	51,841,680	2.89E-08	1.15E-08	7.29E-08	1.70E-08	1.32E-07	5.48E-08
2016	0	51,517,560	2.94E-08	9.94E-09	8.70E-08	3.09E-11	6.15E-08	7.87E-09
2017	0	51,132,120	2.99E-08	8.23E-09	1.09E-07	3.11E-11	6.19E-08	7.92E-09
2018	3	50,939,400	3.04E-08	6.63E-09	1.39E-07	1.72E-08	1.34E-07	5.56E-08
Total	62	1,086,450,240						

Table 13. Plot data for Figure 4, failure rate estimate trend for high-demand MOV FTOP.

Year/ Source	Failures	Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						7.40E-09	1.54E-07	5.98E-08
1998	2	10,450,680	--	--	--	3.89E-08	4.78E-07	1.70E-07
1999	3	10,617,120	--	--	--	7.28E-08	5.69E-07	2.35E-07
2000	1	10,643,400	--	--	--	1.18E-08	3.71E-07	1.01E-07
2001	0	10,625,880	--	--	--	1.32E-10	2.62E-07	3.36E-08
2002	1	10,643,400	--	--	--	1.18E-08	3.71E-07	1.01E-07
2003	3	10,634,640	--	--	--	7.28E-08	5.68E-07	2.35E-07
2004	3	10,669,680	--	--	--	7.26E-08	5.67E-07	2.34E-07
2005	0	10,678,440	--	--	--	1.32E-10	2.62E-07	3.35E-08
2006	1	10,687,200	--	--	--	1.18E-08	3.70E-07	1.00E-07
2007	0	10,695,960	--	--	--	1.31E-10	2.61E-07	3.34E-08
2008	0	10,739,760	--	--	--	1.31E-10	2.60E-07	3.33E-08
2009	1	10,704,720	1.24E-07	3.67E-08	4.18E-07	1.18E-08	3.70E-07	1.00E-07
2010	4	10,722,240	1.14E-07	4.06E-08	3.18E-07	1.11E-07	6.57E-07	3.00E-07
2011	0	10,844,880	1.04E-07	4.39E-08	2.48E-07	1.30E-10	2.59E-07	3.31E-08
2012	1	10,643,400	9.59E-08	4.56E-08	2.02E-07	1.18E-08	3.71E-07	1.01E-07
2013	2	10,608,360	8.80E-08	4.45E-08	1.74E-07	3.85E-08	4.73E-07	1.68E-07
2014	2	10,625,880	8.09E-08	4.02E-08	1.63E-07	3.85E-08	4.72E-07	1.68E-07
2015	0	10,660,920	7.43E-08	3.38E-08	1.63E-07	1.32E-10	2.62E-07	3.35E-08
2016	0	10,625,880	6.82E-08	2.69E-08	1.73E-07	1.32E-10	2.62E-07	3.36E-08
2017	0	10,564,560	6.26E-08	2.08E-08	1.89E-07	1.33E-10	2.64E-07	3.37E-08
2018	2	10,520,760	5.75E-08	1.57E-08	2.11E-07	3.87E-08	4.76E-07	1.69E-07
Total	26	223,607,760						

Table 14. Plot data for Figure 5, failure rate estimate trend for low-demand MOV SO.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year/ Source	**Failures**	**Hours**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
2015 Update						2.90E-10	1.17E-07	3.24E-08
1998	4	51,561,360	--	--	--	2.24E-08	1.33E-07	6.08E-08
1999	0	51,692,760	--	--	--	2.65E-11	5.27E-08	6.74E-09
2000	6	51,754,080	--	--	--	3.97E-08	1.68E-07	8.75E-08
2001	2	51,719,040	--	--	--	7.72E-09	9.48E-08	3.37E-08
2002	4	51,701,520	--	--	--	2.24E-08	1.33E-07	6.06E-08
2003	2	51,710,280	--	--	--	7.72E-09	9.48E-08	3.37E-08
2004	0	51,675,240	--	--	--	2.65E-11	5.27E-08	6.74E-09
2005	0	51,719,040	--	--	--	2.65E-11	5.26E-08	6.74E-09
2006	1	51,815,400	--	--	--	2.37E-09	7.45E-08	2.02E-08
2007	6	51,876,720	--	--	--	3.96E-08	1.68E-07	8.74E-08
2008	5	51,780,360	--	--	--	3.08E-08	1.51E-07	7.40E-08
2009	1	51,789,120	2.48E-08	8.07E-09	7.60E-08	2.37E-09	7.45E-08	2.02E-08
2010	1	51,999,360	2.26E-08	8.75E-09	5.84E-08	2.36E-09	7.43E-08	2.01E-08
2011	0	52,472,400	2.06E-08	9.28E-09	4.59E-08	2.62E-11	5.21E-08	6.67E-09
2012	2	51,981,840	1.88E-08	9.49E-09	3.74E-08	7.69E-09	9.44E-08	3.36E-08
2013	2	51,911,760	1.72E-08	9.18E-09	3.22E-08	7.70E-09	9.45E-08	3.36E-08
2014	2	51,859,200	1.57E-08	8.26E-09	2.99E-08	7.70E-09	9.46E-08	3.36E-08
2015	3	51,841,680	1.43E-08	6.94E-09	2.96E-08	1.46E-08	1.14E-07	4.71E-08
2016	0	51,517,560	1.31E-08	5.56E-09	3.08E-08	2.66E-11	5.28E-08	6.76E-09
2017	0	51,132,120	1.19E-08	4.33E-09	3.30E-08	2.67E-11	5.31E-08	6.79E-09
2018	0	50,939,400	1.09E-08	3.31E-09	3.60E-08	2.68E-11	5.32E-08	6.81E-09
Total	41	1,086,450,240						

Table 15. Plot data for Figure 6, failure rate estimate trend for high-demand MOV SO.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year/ Source	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						2.90E-10	1.17E-07	3.24E-08
1998	0	10,450,680	--	--	--	1.22E-10	2.43E-07	3.11E-08
1999	1	10,617,120	--	--	--	1.08E-08	3.41E-07	9.25E-08
2000	1	10,643,400	--	--	--	1.08E-08	3.41E-07	9.23E-08
2001	0	10,625,880	--	--	--	1.21E-10	2.41E-07	3.08E-08
2002	0	10,643,400	--	--	--	1.21E-10	2.40E-07	3.08E-08
2003	2	10,634,640	--	--	--	3.53E-08	4.33E-07	1.54E-07
2004	0	10,669,680	--	--	--	1.21E-10	2.40E-07	3.07E-08
2005	0	10,678,440	--	--	--	1.21E-10	2.40E-07	3.07E-08
2006	0	10,687,200	--	--	--	1.21E-10	2.40E-07	3.07E-08
2007	0	10,695,960	--	--	--	1.21E-10	2.40E-07	3.07E-08
2008	1	10,739,760	--	--	--	1.08E-08	3.39E-07	9.18E-08
2009	0	10,704,720	6.36E-08	2.05E-08	1.98E-07	1.21E-10	2.40E-07	3.07E-08
2010	2	10,722,240	6.48E-08	2.48E-08	1.70E-07	3.51E-08	4.31E-07	1.53E-07
2011	2	10,844,880	6.61E-08	2.94E-08	1.48E-07	3.48E-08	4.28E-07	1.52E-07
2012	1	10,643,400	6.73E-08	3.38E-08	1.34E-07	1.08E-08	3.41E-07	9.23E-08
2013	0	10,608,360	6.87E-08	3.70E-08	1.27E-07	1.21E-10	2.41E-07	3.08E-08
2014	0	10,625,880	7.00E-08	3.78E-08	1.30E-07	1.21E-10	2.41E-07	3.08E-08
2015	1	10,660,920	7.14E-08	3.61E-08	1.41E-07	1.08E-08	3.40E-07	9.22E-08
2016	0	10,625,880	7.27E-08	3.26E-08	1.62E-07	1.21E-10	2.41E-07	3.08E-08
2017	1	10,564,560	7.42E-08	2.86E-08	1.92E-07	1.09E-08	3.42E-07	9.28E-08
2018	2	10,520,760	7.56E-08	2.46E-08	2.33E-07	3.55E-08	4.36E-07	1.55E-07
Total	14	223,607,760						

Table 16. Plot data for Figure 7, frequency of FTOC demands (demands per reactor year) for low-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Demands	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	39,316	103.0	--	--	--	3.79E+02	3.85E+02	3.82E+02
1999	41,653	103.0	--	--	--	4.01E+02	4.08E+02	4.04E+02
2000	40,033	103.3	--	--	--	3.84E+02	3.91E+02	3.88E+02
2001	41,341	103.0	--	--	--	3.98E+02	4.05E+02	4.01E+02
2002	40,678	103.0	--	--	--	3.92E+02	3.98E+02	3.95E+02
2003	41,228	103.0	--	--	--	3.97E+02	4.04E+02	4.00E+02
2004	40,135	103.3	--	--	--	3.85E+02	3.92E+02	3.89E+02
2005	38,307	103.0	--	--	--	3.69E+02	3.75E+02	3.72E+02
2006	36,385	103.0	--	--	--	3.50E+02	3.56E+02	3.53E+02
2007	36,131	103.6	--	--	--	3.46E+02	3.52E+02	3.49E+02
2008	36,418	104.3	--	--	--	3.46E+02	3.52E+02	3.49E+02
2009	36,274	104.0	3.47E+02	3.42E+02	3.53E+02	3.46E+02	3.52E+02	3.49E+02
2010	36,070	104.0	3.49E+02	3.45E+02	3.54E+02	3.44E+02	3.50E+02	3.47E+02
2011	36,251	104.0	3.51E+02	3.47E+02	3.54E+02	3.46E+02	3.52E+02	3.49E+02
2012	36,299	104.3	3.52E+02	3.49E+02	3.55E+02	3.45E+02	3.51E+02	3.48E+02
2013	36,109	101.6	3.54E+02	3.51E+02	3.57E+02	3.52E+02	3.59E+02	3.56E+02
2014	36,082	100.0	3.55E+02	3.52E+02	3.58E+02	3.58E+02	3.64E+02	3.61E+02
2015	35,865	99.0	3.57E+02	3.54E+02	3.60E+02	3.59E+02	3.65E+02	3.62E+02
2016	35,507	99.0	3.58E+02	3.55E+02	3.62E+02	3.55E+02	3.62E+02	3.59E+02
2017	35,171	98.0	3.60E+02	3.55E+02	3.65E+02	3.56E+02	3.62E+02	3.59E+02
2018	34,925	97.7	3.62E+02	3.56E+02	3.67E+02	3.54E+02	3.60E+02	3.57E+02
Total	790,175	2,147.1						

Table 17. Plot data for Figure 8, frequency of FTOC demands (demands per reactor year) for high-demand MOVs.

Year	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	35,766	103.0	--	--	--	3.44E+02	3.50E+02	3.47E+02
1999	38,033	103.0	--	--	--	3.66E+02	3.72E+02	3.69E+02
2000	40,070	103.3	--	--	--	3.85E+02	3.91E+02	3.88E+02
2001	45,956	103.0	--	--	--	4.43E+02	4.50E+02	4.46E+02
2002	36,401	103.0	--	--	--	3.50E+02	3.56E+02	3.53E+02
2003	38,677	103.0	--	--	--	3.72E+02	3.79E+02	3.76E+02
2004	40,646	103.3	--	--	--	3.90E+02	3.97E+02	3.94E+02
2005	40,338	103.0	--	--	--	3.88E+02	3.95E+02	3.92E+02
2006	40,255	103.0	--	--	--	3.88E+02	3.94E+02	3.91E+02
2007	40,508	103.6	--	--	--	3.88E+02	3.94E+02	3.91E+02
2008	40,409	104.3	--	--	--	3.84E+02	3.91E+02	3.87E+02
2009	39,484	104.0	3.78E+02	3.66E+02	3.89E+02	3.77E+02	3.83E+02	3.80E+02
2010	39,815	104.0	3.77E+02	3.68E+02	3.87E+02	3.80E+02	3.86E+02	3.83E+02
2011	39,163	104.0	3.77E+02	3.69E+02	3.86E+02	3.73E+02	3.80E+02	3.77E+02
2012	38,569	104.3	3.77E+02	3.70E+02	3.84E+02	3.67E+02	3.73E+02	3.70E+02
2013	37,559	101.6	3.77E+02	3.71E+02	3.84E+02	3.67E+02	3.73E+02	3.70E+02
2014	37,726	100.0	3.77E+02	3.71E+02	3.84E+02	3.74E+02	3.80E+02	3.77E+02
2015	37,266	99.0	3.77E+02	3.70E+02	3.84E+02	3.73E+02	3.80E+02	3.76E+02
2016	39,147	99.0	3.77E+02	3.69E+02	3.86E+02	3.92E+02	3.99E+02	3.95E+02
2017	36,237	98.0	3.77E+02	3.67E+02	3.87E+02	3.67E+02	3.73E+02	3.70E+02
2018	36,698	97.7	3.77E+02	3.65E+02	3.89E+02	3.72E+02	3.79E+02	3.75E+02
Total	818,722	2,147.1						

Table 18. Plot data for Figure 9, frequency of FTOC events (failures per reactor year) for low-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	43	103.0	--	--	--	3.16E-01	5.33E-01	4.14E-01
1999	40	103.0	--	--	--	2.91E-01	5.01E-01	3.85E-01
2000	43	103.3	--	--	--	3.15E-01	5.31E-01	4.13E-01
2001	30	103.0	--	--	--	2.09E-01	3.92E-01	2.90E-01
2002	30	103.0	--	--	--	2.09E-01	3.92E-01	2.90E-01
2003	35	103.0	--	--	--	2.50E-01	4.47E-01	3.38E-01
2004	28	103.3	--	--	--	1.93E-01	3.70E-01	2.70E-01
2005	34	103.0	--	--	--	2.42E-01	4.36E-01	3.28E-01
2006	33	103.0	--	--	--	2.34E-01	4.25E-01	3.19E-01
2007	33	103.6	--	--	--	2.32E-01	4.23E-01	3.17E-01
2008	25	104.3	--	--	--	1.67E-01	3.33E-01	2.40E-01
2009	37	104.0	3.22E-01	2.47E-01	4.20E-01	2.64E-01	4.64E-01	3.53E-01
2010	25	104.0	2.96E-01	2.37E-01	3.70E-01	1.68E-01	3.34E-01	2.40E-01
2011	24	104.0	2.72E-01	2.26E-01	3.28E-01	1.60E-01	3.23E-01	2.31E-01
2012	31	104.3	2.50E-01	2.12E-01	2.94E-01	2.15E-01	3.98E-01	2.96E-01
2013	27	101.6	2.29E-01	1.96E-01	2.69E-01	1.88E-01	3.65E-01	2.65E-01
2014	22	100.0	2.11E-01	1.77E-01	2.50E-01	1.50E-01	3.13E-01	2.20E-01
2015	23	99.0	1.93E-01	1.58E-01	2.37E-01	1.59E-01	3.28E-01	2.32E-01
2016	15	99.0	1.78E-01	1.40E-01	2.26E-01	9.53E-02	2.34E-01	1.53E-01
2017	20	98.0	1.63E-01	1.23E-01	2.17E-01	1.36E-01	2.96E-01	2.05E-01
2018	10	97.7	1.50E-01	1.07E-01	2.09E-01	5.80E-02	1.76E-01	1.05E-01
Total	608	2,147.1						

Table 19. Plot data for Figure 10, frequency of FTOC events (failures per reactor year) for high-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	9	103.0	--	--	--	4.62E-02	1.49E-01	8.67E-02
1999	14	103.0	--	--	--	8.08E-02	2.05E-01	1.32E-01
2000	10	103.3	--	--	--	5.27E-02	1.60E-01	9.55E-02
2001	17	103.0	--	--	--	1.02E-01	2.38E-01	1.60E-01
2002	10	103.0	--	--	--	5.29E-02	1.60E-01	9.58E-02
2003	13	103.0	--	--	--	7.37E-02	1.94E-01	1.23E-01
2004	15	103.3	--	--	--	8.77E-02	2.16E-01	1.41E-01
2005	13	103.0	--	--	--	7.37E-02	1.94E-01	1.23E-01
2006	5	103.0	--	--	--	2.09E-02	1.02E-01	5.02E-02
2007	10	103.6	--	--	--	5.26E-02	1.60E-01	9.53E-02
2008	8	104.3	--	--	--	3.91E-02	1.36E-01	7.66E-02
2009	5	104.0	7.81E-02	4.04E-02	1.51E-01	2.07E-02	1.01E-01	4.97E-02
2010	6	104.0	7.58E-02	4.34E-02	1.32E-01	2.66E-02	1.13E-01	5.88E-02
2011	13	104.0	7.36E-02	4.61E-02	1.18E-01	7.30E-02	1.92E-01	1.22E-01
2012	7	104.3	7.15E-02	4.78E-02	1.07E-01	3.27E-02	1.24E-01	6.76E-02
2013	12	101.6	6.94E-02	4.79E-02	1.01E-01	6.75E-02	1.85E-01	1.16E-01
2014	7	100.0	6.74E-02	4.60E-02	9.88E-02	3.41E-02	1.29E-01	7.03E-02
2015	13	99.0	6.54E-02	4.24E-02	1.01E-01	7.65E-02	2.01E-01	1.28E-01
2016	3	99.0	6.35E-02	3.80E-02	1.06E-01	1.03E-02	8.01E-02	3.31E-02
2017	6	98.0	6.17E-02	3.35E-02	1.14E-01	2.82E-02	1.19E-01	6.21E-02
2018	4	97.7	5.99E-02	2.92E-02	1.23E-01	1.59E-02	9.43E-02	4.31E-02
Total	200	2,147.1						

Table 20. Plot data for Figure 11, frequency of FTOP events (failures per reactor year) for low-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	3	103.0	--	--	--	8.56E-03	6.69E-02	2.77E-02
1999	12	103.0	--	--	--	5.77E-02	1.59E-01	9.88E-02
2000	7	103.3	--	--	--	2.86E-02	1.09E-01	5.91E-02
2001	4	103.0	--	--	--	1.31E-02	7.78E-02	3.56E-02
2002	3	103.0	--	--	--	8.56E-03	6.69E-02	2.77E-02
2003	3	103.0	--	--	--	8.56E-03	6.69E-02	2.77E-02
2004	2	103.3	--	--	--	4.52E-03	5.55E-02	1.97E-02
2005	3	103.0	--	--	--	8.56E-03	6.69E-02	2.77E-02
2006	1	103.0	--	--	--	1.39E-03	4.37E-02	1.19E-02
2007	2	103.6	--	--	--	4.51E-03	5.53E-02	1.97E-02
2008	1	104.3	--	--	--	1.38E-03	4.33E-02	1.17E-02
2009	0	104.0	1.31E-02	2.78E-03	6.16E-02	1.54E-05	3.06E-02	3.92E-03
2010	1	104.0	1.34E-02	3.60E-03	4.98E-02	1.38E-03	4.34E-02	1.18E-02
2011	1	104.0	1.37E-02	4.53E-03	4.13E-02	1.38E-03	4.34E-02	1.18E-02
2012	4	104.3	1.40E-02	5.46E-03	3.57E-02	1.30E-02	7.70E-02	3.52E-02
2013	6	101.6	1.43E-02	6.16E-03	3.31E-02	2.36E-02	9.99E-02	5.20E-02
2014	3	100.0	1.46E-02	6.33E-03	3.37E-02	8.77E-03	6.85E-02	2.83E-02
2015	3	99.0	1.49E-02	5.91E-03	3.76E-02	8.84E-03	6.90E-02	2.86E-02
2016	0	99.0	1.52E-02	5.15E-03	4.51E-02	1.60E-05	3.19E-02	4.08E-03
2017	0	98.0	1.56E-02	4.29E-03	5.66E-02	1.62E-05	3.22E-02	4.11E-03
2018	3	97.7	1.59E-02	3.47E-03	7.29E-02	8.94E-03	6.98E-02	2.89E-02
Total	62	2,147.1						

Table 21. Plot data for Figure 12, frequency of FTOP events (failures per reactor year) for high-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	**Failures**	**Reactor Years**	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
1998	2	103.0	--	--	--	3.99E-03	4.90E-02	1.74E-02
1999	3	103.0	--	--	--	7.55E-03	5.90E-02	2.44E-02
2000	1	103.3	--	--	--	1.22E-03	3.85E-02	1.04E-02
2001	0	103.0	--	--	--	1.37E-05	2.72E-02	3.49E-03
2002	1	103.0	--	--	--	1.23E-03	3.86E-02	1.05E-02
2003	3	103.0	--	--	--	7.55E-03	5.90E-02	2.44E-02
2004	3	103.3	--	--	--	7.54E-03	5.88E-02	2.43E-02
2005	0	103.0	--	--	--	1.37E-05	2.72E-02	3.49E-03
2006	1	103.0	--	--	--	1.23E-03	3.86E-02	1.05E-02
2007	0	103.6	--	--	--	1.36E-05	2.71E-02	3.47E-03
2008	0	104.3	--	--	--	1.36E-05	2.70E-02	3.45E-03
2009	1	104.0	1.28E-02	3.81E-03	4.29E-02	1.22E-03	3.83E-02	1.04E-02
2010	4	104.0	1.18E-02	4.23E-03	3.29E-02	1.15E-02	6.81E-02	3.11E-02
2011	0	104.0	1.09E-02	4.59E-03	2.58E-02	1.36E-05	2.70E-02	3.46E-03
2012	1	104.3	1.00E-02	4.79E-03	2.10E-02	1.22E-03	3.82E-02	1.04E-02
2013	2	101.6	9.26E-03	4.69E-03	1.83E-02	4.03E-03	4.95E-02	1.76E-02
2014	2	100.0	8.54E-03	4.26E-03	1.71E-02	4.08E-03	5.01E-02	1.78E-02
2015	0	99.0	7.88E-03	3.59E-03	1.73E-02	1.41E-05	2.80E-02	3.59E-03
2016	0	99.0	7.27E-03	2.88E-03	1.84E-02	1.41E-05	2.80E-02	3.58E-03
2017	0	98.0	6.70E-03	2.23E-03	2.02E-02	1.42E-05	2.82E-02	3.61E-03
2018	2	97.7	6.18E-03	1.70E-03	2.26E-02	4.14E-03	5.09E-02	1.81E-02
Total	26	2,147.1						

Table 22. Plot data for Figure 13, frequency of SO events (failures per reactor year) for low-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4	103.0	--	--	--	1.13E-02	6.69E-02	3.06E-02
1999	0	103.0	--	--	--	1.34E-05	2.66E-02	3.40E-03
2000	6	103.3	--	--	--	2.00E-02	8.49E-02	4.41E-02
2001	2	103.0	--	--	--	3.90E-03	4.79E-02	1.70E-02
2002	4	103.0	--	--	--	1.13E-02	6.69E-02	3.06E-02
2003	2	103.0	--	--	--	3.90E-03	4.79E-02	1.70E-02
2004	0	103.3	--	--	--	1.34E-05	2.65E-02	3.40E-03
2005	0	103.0	--	--	--	1.34E-05	2.66E-02	3.40E-03
2006	1	103.0	--	--	--	1.20E-03	3.77E-02	1.02E-02
2007	6	103.6	--	--	--	2.00E-02	8.47E-02	4.40E-02
2008	5	104.3	--	--	--	1.54E-02	7.54E-02	3.71E-02
2009	1	104.0	1.24E-02	4.04E-03	3.82E-02	1.19E-03	3.74E-02	1.01E-02
2010	1	104.0	1.14E-02	4.40E-03	2.94E-02	1.19E-03	3.74E-02	1.01E-02
2011	0	104.0	1.04E-02	4.69E-03	2.32E-02	1.33E-05	2.64E-02	3.38E-03
2012	2	104.3	9.57E-03	4.82E-03	1.90E-02	3.86E-03	4.74E-02	1.69E-02
2013	2	101.6	8.78E-03	4.68E-03	1.65E-02	3.94E-03	4.83E-02	1.72E-02
2014	2	100.0	8.05E-03	4.23E-03	1.53E-02	3.98E-03	4.88E-02	1.74E-02
2015	3	99.0	7.38E-03	3.57E-03	1.53E-02	7.58E-03	5.92E-02	2.45E-02
2016	0	99.0	6.76E-03	2.87E-03	1.59E-02	1.37E-05	2.73E-02	3.50E-03
2017	0	98.0	6.20E-03	2.24E-03	1.72E-02	1.38E-05	2.75E-02	3.52E-03
2018	0	97.7	5.69E-03	1.72E-03	1.88E-02	1.39E-05	2.76E-02	3.53E-03
Total	41	2,147.1						

Table 23. Plot data for Figure 14, frequency of SO events (failures per reactor year) for high-demand MOVs.

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	0	103.0	--	--	--	1.26E-05	2.50E-02	3.20E-03
1999	1	103.0	--	--	--	1.13E-03	3.54E-02	9.60E-03
2000	1	103.3	--	--	--	1.12E-03	3.54E-02	9.58E-03
2001	0	103.0	--	--	--	1.26E-05	2.50E-02	3.20E-03
2002	0	103.0	--	--	--	1.26E-05	2.50E-02	3.20E-03
2003	2	103.0	--	--	--	3.67E-03	4.50E-02	1.60E-02
2004	0	103.3	--	--	--	1.26E-05	2.50E-02	3.19E-03
2005	0	103.0	--	--	--	1.26E-05	2.50E-02	3.20E-03
2006	0	103.0	--	--	--	1.26E-05	2.50E-02	3.20E-03
2007	0	103.6	--	--	--	1.25E-05	2.49E-02	3.19E-03
2008	1	104.3	--	--	--	1.12E-03	3.51E-02	9.52E-03
2009	0	104.0	6.57E-03	2.12E-03	2.04E-02	1.25E-05	2.48E-02	3.18E-03
2010	2	104.0	6.73E-03	2.58E-03	1.76E-02	3.64E-03	4.47E-02	1.59E-02
2011	2	104.0	6.89E-03	3.07E-03	1.54E-02	3.64E-03	4.47E-02	1.59E-02
2012	1	104.3	7.05E-03	3.55E-03	1.40E-02	1.12E-03	3.51E-02	9.52E-03
2013	0	101.6	7.22E-03	3.90E-03	1.34E-02	1.27E-05	2.52E-02	3.23E-03
2014	0	100.0	7.39E-03	3.99E-03	1.37E-02	1.28E-05	2.55E-02	3.26E-03
2015	1	99.0	7.56E-03	3.82E-03	1.50E-02	1.16E-03	3.64E-02	9.85E-03
2016	0	99.0	7.74E-03	3.47E-03	1.72E-02	1.29E-05	2.57E-02	3.28E-03
2017	1	98.0	7.92E-03	3.06E-03	2.05E-02	1.16E-03	3.66E-02	9.92E-03
2018	2	97.7	8.11E-03	2.64E-03	2.49E-02	3.79E-03	4.66E-02	1.66E-02
Total	14	2,147.1						

7. REFERENCES

[1] J. R. Houghton, "Component Performance Study – Motor-Operated Valves, 1987-1998," NUREG-1715, Vol. 4, U.S. Nuclear Regulatory Commission, September 2001.

[2] J. A. Schroeder, "Enhanced Component Performance Study: Motor-Operated Valves 1998-2016," INL/LTD-17-44123, Idaho National Laboratory, April 2018.

[3] C. D. Gentillion, "Overview and Reference Document for Operational Experience Results and Databases Trending," February 2016. [Online]. Available: https://nrcoe.inel.gov/resultsdb/publicdocs/Overview-and-Reference.pdf.

[4] J. C. Lane, "NRC Operating Experience (OpE) Programs," Office of Nuclear Regulatory Research, July 2015. [Online]. Available: http://pbadupws.nrc.gov/docs/ML1518/ML15189A345.pdf. [Accessed 2015].

[5] Nuclear Energy Institute, "Regulatory Assessment Performance Indicator Guideline," NEI 99-02, Revision 7, August 2013.

[6] United States Nuclear Regulatory Commission, "Component Reliability Data Sheets Update 2015," February 2017. [Online]. Available: http://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentReliabilityDataSheets2015.pdf.

[7] S. A. Eide, T. E. Wierman, C. D. Gentillon, D. M. Rasmuson and C. L. Atwood, "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants," NUREG/CR-6928, U.S. Nuclear Regulatory Commission, February 2007.

[8] C. L. Atwood, etc., "Handbook of Parameter Estimation for Probabilistic Risk Assessment," NUREG/CR-6823, U.S. Nuclear Regulatory Commission, September 2003.