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Enhanced Component Performance Study: Motor-Operated Valves 1998–2022

July 2023

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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 2022 as reported in the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS). The MOV failure modes considered are fail to open or close (FTOC), fail to operate or control (FTOP), and spurious operation (SO). 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.

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

- Low-demand MOV frequency of FTOC demands (demands per reactor year).

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

- Low-demand MOV FTOC failure probability
- Low-demand MOV frequency of FTOC events (failures per reactor year).

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FIGURES

TABLES

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ACRONYMS

AFW	Auxiliary feed water
AOV	air-operated valve
BWR	boiling water reactor
CCF	common-cause failure
CCW	component cooling water
CNID	constrained noninformative prior distribution
CRD	control rod drive
CSR	containment spray recirculation
CVC	chemical and volume control
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
ESF	engineered safety feature
FTOC	fail to open or close
FTOP	fail to operate or control
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
LPCI	low-pressure coolant injection
LPCS	low-pressure core spray
LPSI	low-pressure safety injection
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
NRC	Nuclear Regulatory Commission
OLS	ordinary least squares
PMT	post maintenance testing
PRA	probabilistic risk assessment
PWR	pressurized water reactor
RCIC	reactor core isolation cooling

RCS	reactor coolant
RHR	residual heat removal
SO	spurious operation
SPAR	standardized plant analysis risk
SWN	normally running service water
SWS	standby service water
TDP	turbine-driven pump
UA	unavailability
VSS	vapor suppression

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Enhanced Component Performance Study: Motor-Operated Valves 1998–2022

1. INTRODUCTION

This report presents an enhanced performance evaluation of motor-operated valves (MOVs) at U.S. commercial nuclear power plants from 1998 through 2022. 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 instead of the federal fiscal year, 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/RPT-22-66600, *Enhanced Component Performance Study: Motor-Operated Valves 1998-2020* [2]. The Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases webpage provides the link to the historical and current results of component performance studies (http://nrcoe.inl.gov/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 from https://nrcoe.inl.gov/.

The data used in this study are based on the operating experience failure reports from Institute of Nuclear Power Operations (INPO) *Industry Reporting and Information System (IRIS)* [4], formerly the Equipment Performance and Information Exchange Database (EPIX) and INPO Consolidated Events Database (ICES) [5]. Maintenance unavailability (UA) performance data came from the Reactor Oversight Process program's Mitigating Systems Performance Index (MSPI) program [6] and IRIS. Previously, the study relied on operating experience obtained from licensee event reports, Nuclear Plant Reliability Data System, and EPIX. The IRIS database (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.

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 fail to open or close (FTOC), fail 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) or Standardized Plant Analysis Risk (SPAR) models. The *2020 Parameter Update* documented in INL/EXT-21-65055 [7] is the most recent update to NUREG/CR-6928, *Industry-Average Performance for Components and Initiating Events at U.S Commercial Nuclear Power Plants* [8], using data through 2020 and provides component unreliability estimates for SPAR models. Estimates from that report are included herein for comparison. Those estimates are labelled "SPAR 2020" in the associated tables and figures.

Section 2 of this report presents the summary of findings from the study, with particular emphasis on the existence of any statistically significant increasing or decreasing trends in component performances. Section 3 provides the 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 MOVs 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: subcomponent, 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

- Extremely statistically significant **increasing trend** was identified in the **frequency of FTOC demands** (demands per reactor year) estimates for low-demand MOV with a p-value of 0.0000 (see Figure 7). This trend was observed in the *2020 MOV Update* study [2].

2.1.2 Highly Statistically Significant

- None.

2.1.3 Statistically Significant

- None.

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- Extremely statistically significant **decreasing trend** was identified in the **low-demand MOV FTOC failure probability** estimates with a p-value of 0.0001 (see Figure 1). This same trend was observed in the *2020 MOV Update* study.
- Extremely statistically significant **decreasing trend** was identified in the **frequency of FTOC events** (failures per reactor year) estimates for low-demand MOV with a p-value of 0.0001 (see Figure 9). This same trend was observed in the *2020 MOV Update* study.

2.2.2 Highly Statistically Significant

- None.

2.2.3 Statistically Significant

- None.

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[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 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 IRIS 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 *2020 Parameter Update* [7]. Note that only low-demand MOVs were included in [7] for parameter estimation in order to match the types of valves typically included in the SPAR models. There are no 2020 parameter update results for high-demand MOVs in [7]. The *2020 Parameter 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 *2020 Parameter 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 any time during the study period. 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 (ESF) demands. Non-test demands are actual plant demands that are not ESF demands.

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

System	Description	MOV Count		
		Total	Low Demand	High Demand
AFW	Auxiliary feedwater	677	580	97
CCW	Component cooling water	877	757	120
CRD	Control rod drive	25	25	
CSR	Containment spray recirculation	362	351	11
CVC	Chemical and volume control	13	13	
HPCI	High-pressure coolant injection	313	289	24
HPCS	High-pressure core spray	52	35	17
HPSI	High-pressure safety injection	1180	1106	74
ISO	Isolation condenser	20	14	6
LPCS	Low-pressure core spray	235	208	27
RCIC	Reactor core isolation cooling	376	343	33
RCS	Reactor coolant	114	109	5
RHR	Residual heat removal (LPCI in BWRs; LPSI in PWRs)	2268	1972	296

System	Description	MOV Count		
		Total	Low Demand	High Demand
SWN	Normally operating service water	1019	762	257
SWS	Standby service water	362	258	104
VSS	Vapor suppression	14	14	
	Total	7907	6836	1071

Table 2. Industry-wide distributions of p (failure probability) and λ (hourly rate) in the *2020 Parameter Update* for low-demand MOVs [7].

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTOC	1.42E-4	5.54E-4	6.40E-4	1.43E-3	Beta	2.43	3.80E+03
FTOP	9.42E-10	2.17E-8	3.47E-8	1.13E-7	Gamma	0.80	2.30E+07
SO	1.93E-8	2.53E-8	2.54E-8	3.23E-8	Gamma	41.50	1.63E+09

3.2 MOV Failure Probability and Failure Rate Trends

This section estimates industry-wide annual failure probabilities and failure rates for MOVs in the entire study period which covers 1998 through 2022. 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 noninformative prior distribution (CNID), which has wide bounds [3, 9]. 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 do 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 (α) is a constant number of 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 distribution, 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 [9]). The posterior distribution mean for the ith year (μ_i) can be calculated as:

$$\mu_i = \frac{f_i + \alpha}{\frac{\alpha}{\mu} + D_i} \tag{4}$$

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, therefore, suggest a trend does exist. P-values of less than or equal to 0.05 indicate strong evidence 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) that 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 method 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* [3].

A final feature of the trend graphs is that the baseline industry values from the *2020 Parameter Update* (Table 2) are shown as "SPAR 2020" in the graphs 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 MOV failure probabilities/rates for FTOC, FTOP, and SO events in the most recent 10-year period:

- **Decreasing trend** in the **low-demand MOV FTOC failure probability** estimates, which is extremely statistically significant with a p-value of 0.0001 (see Figure 1). The same trend was observed in the *2020 MOV Update* study [2].

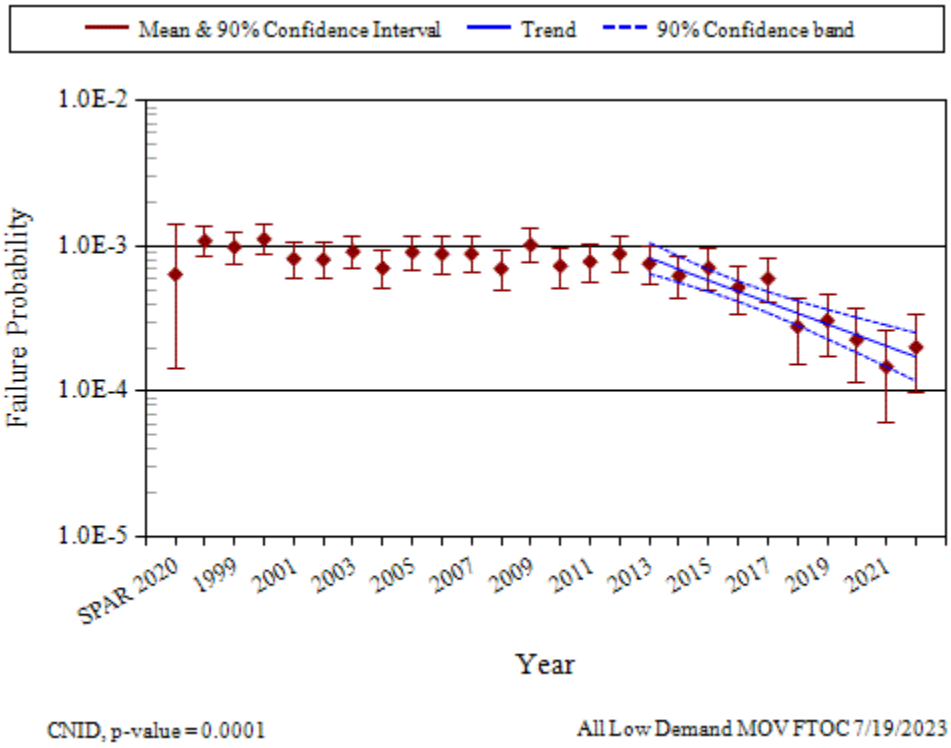

Figure 1. Failure probability estimate trend for low-demand MOV FTOC.

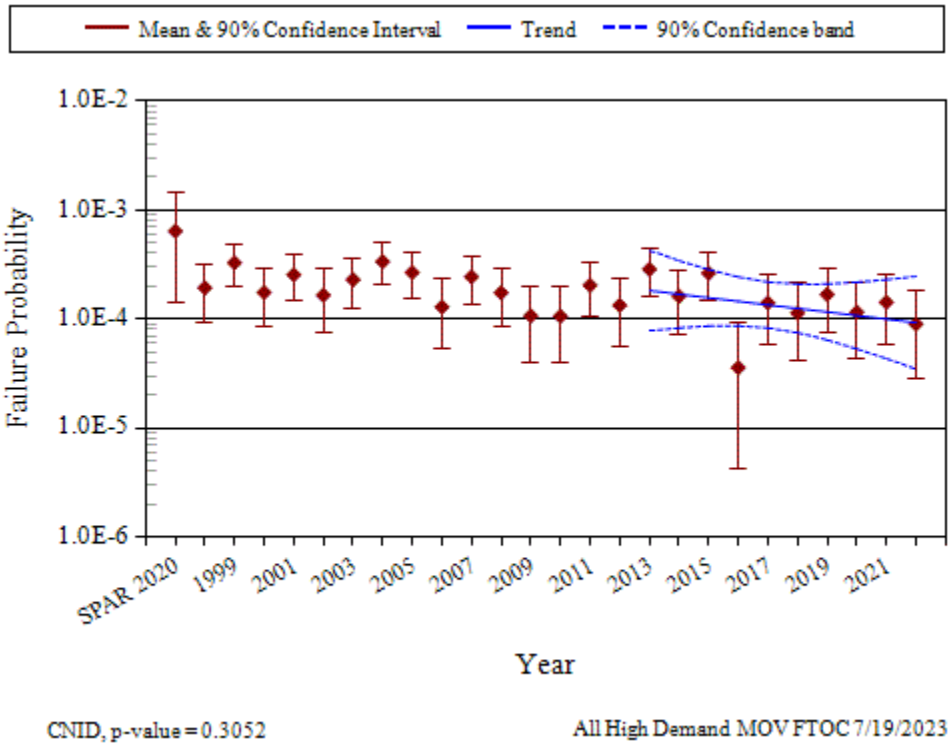

Figure 2. Failure probability estimate trend for high-demand MOV FTOC.

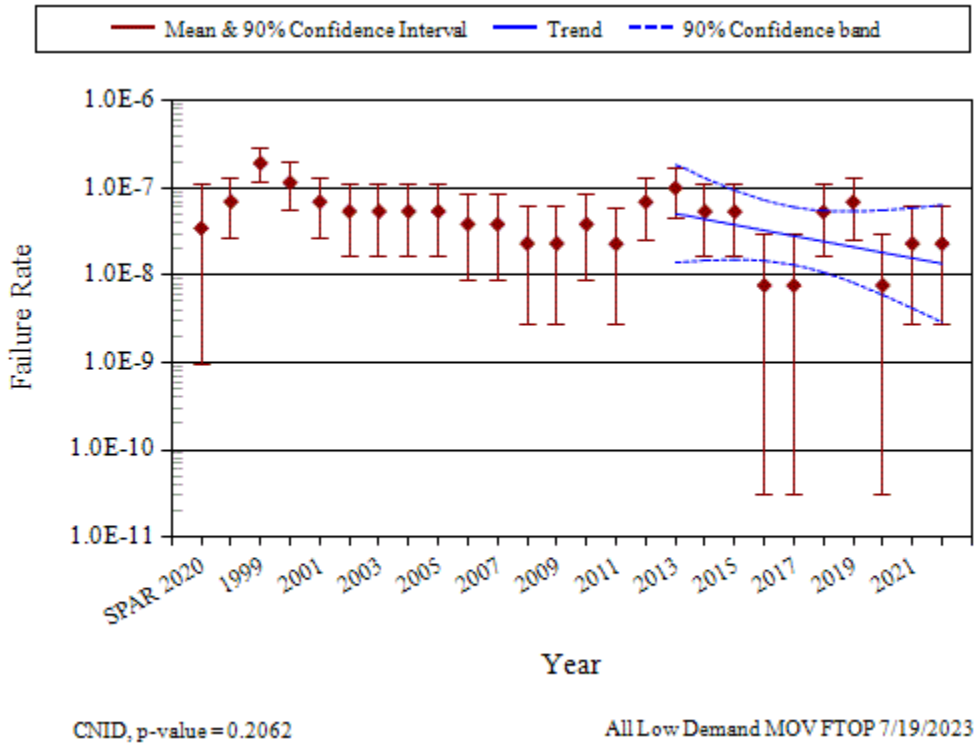

Figure 3. Failure rate estimate trend for low-demand MOV FTOP.

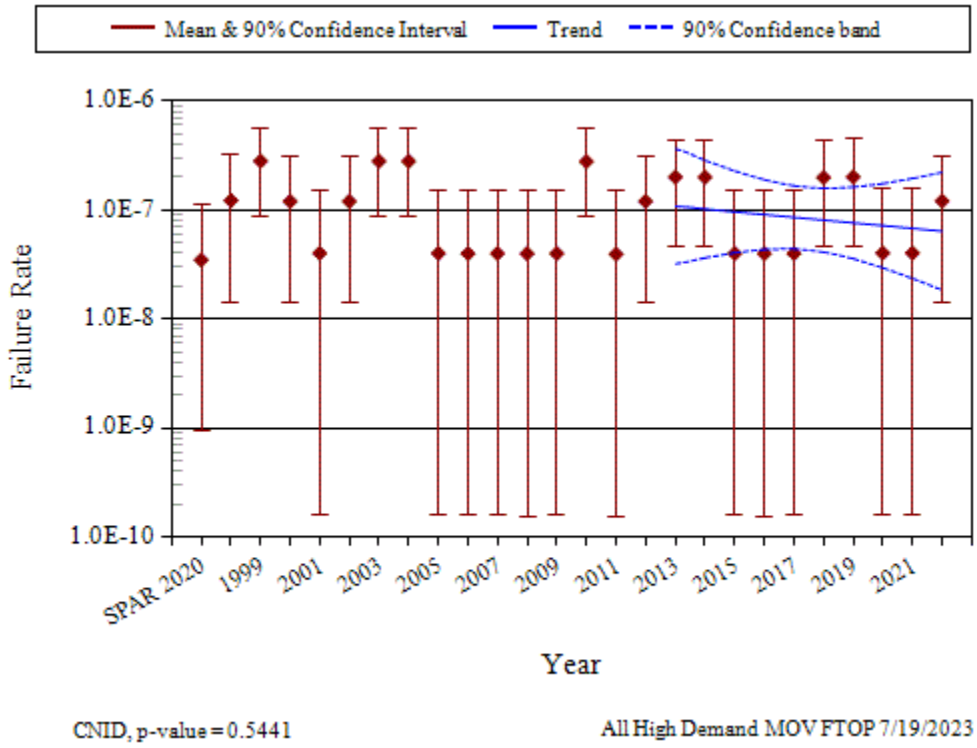

Figure 4. Failure rate estimate trend for high-demand MOV FTOP.

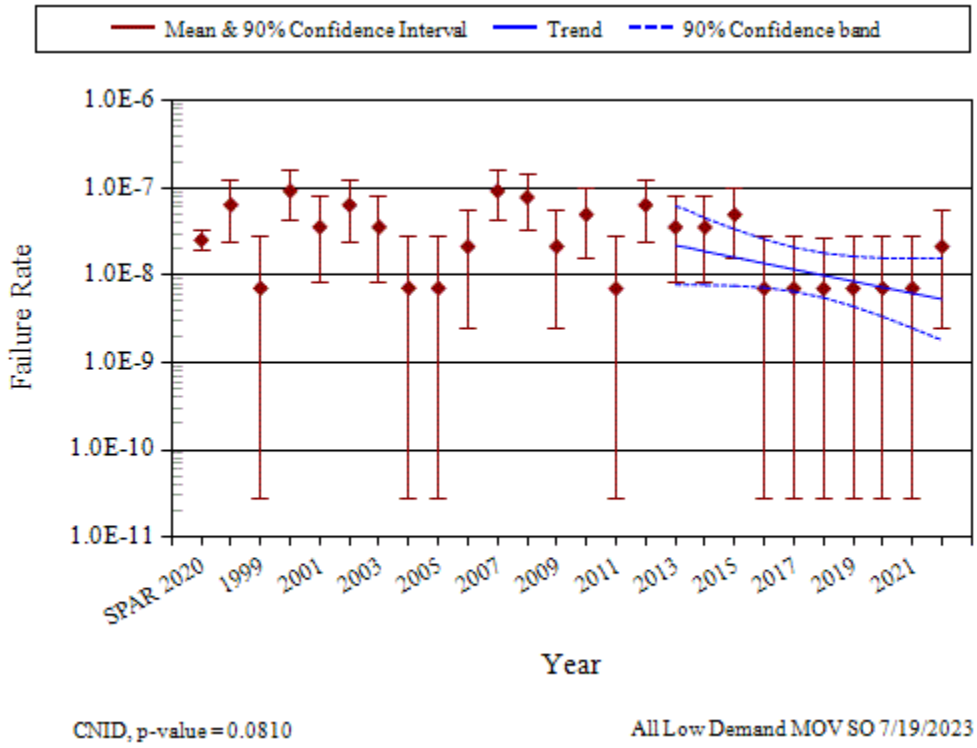

Figure 5. Failure rate estimate trend for low-demand MOV SO.

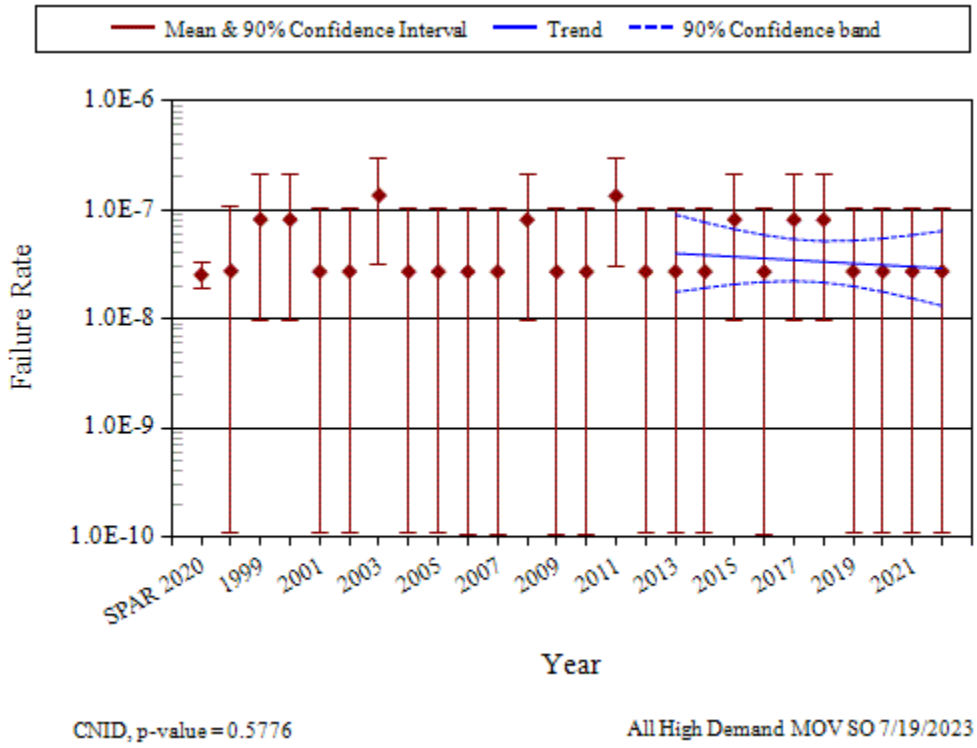

Figure 6. Failure rate estimate trend for high-demand MOV SO.

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 figures listed above are provided in Section 6. The systems from Table 1 are trended together for each figure. The rate methods described in Section 2 of *Overview and Reference* [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 MOV frequency of demands or events in the most recent 10-year period:

- **Increasing trend** in the **low-demand MOV frequency of FTOC demands** (demands per reactor year), which is extremely statistically significant with a p-value of 0.0000 (see Figure 7). The same trend was observed in the *2020 MOV Update* study [2]
- **Decreasing trend** in the **low-demand MOV frequency of FTOC events** (failures per reactor year), which is extremely statistically significant with a p-value of 0.0001 (see Figure 9). The same trend was observed in the *2020 MOV Update* study.

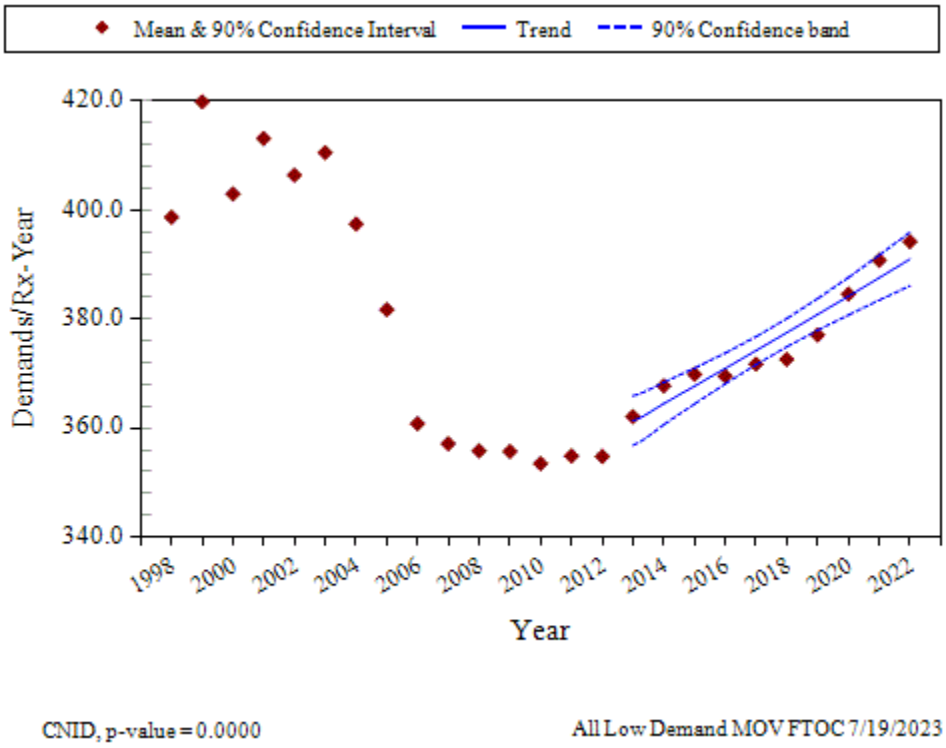

Figure 7. Frequency of FTOC demands (demands per reactor year) for low-demand MOVs.

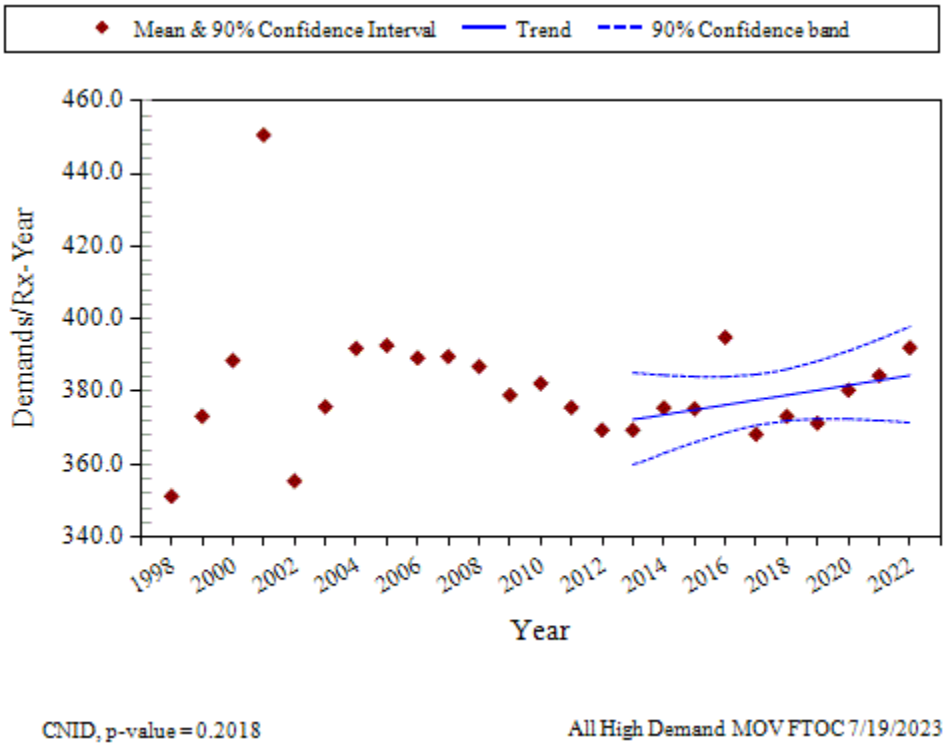

Figure 8. Frequency of FTOC demands (demands per reactor year) for high-demand MOVs.

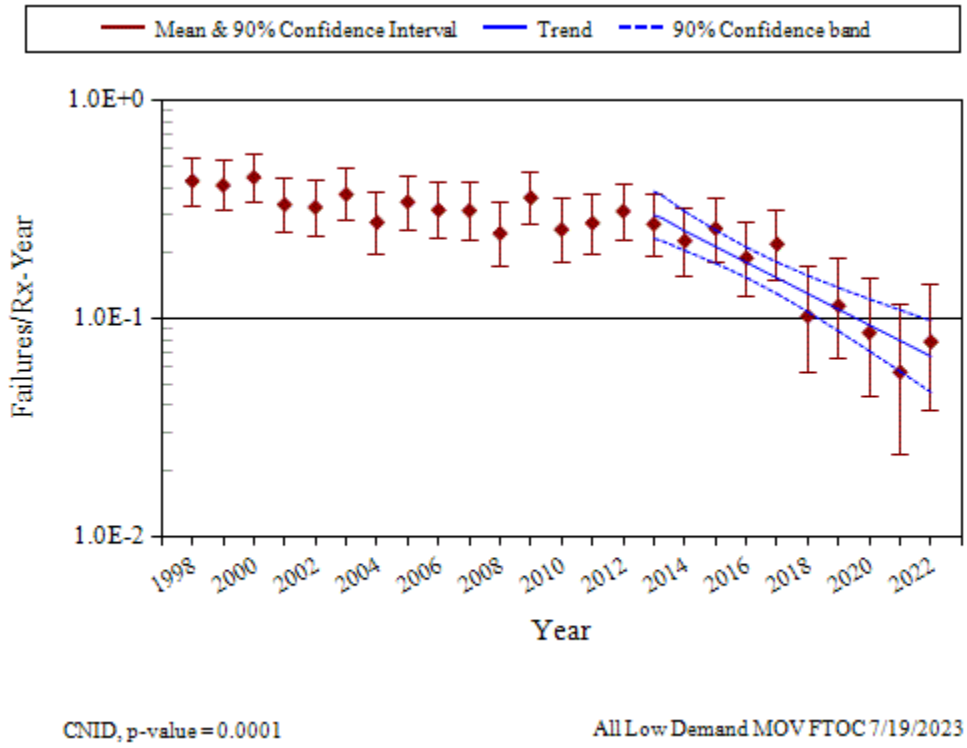

Figure 9. Frequency of FTOC events (failures per reactor year) for low-demand MOVs.

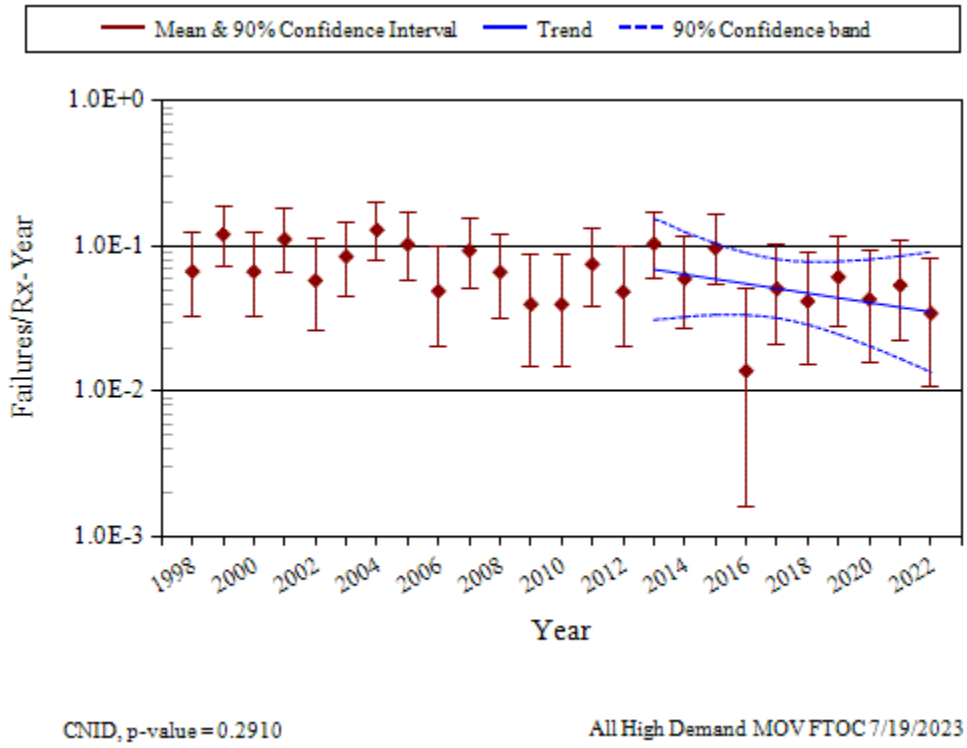

Figure 10. Frequency of FTOC events (failures per reactor year) for high-demand MOVs.

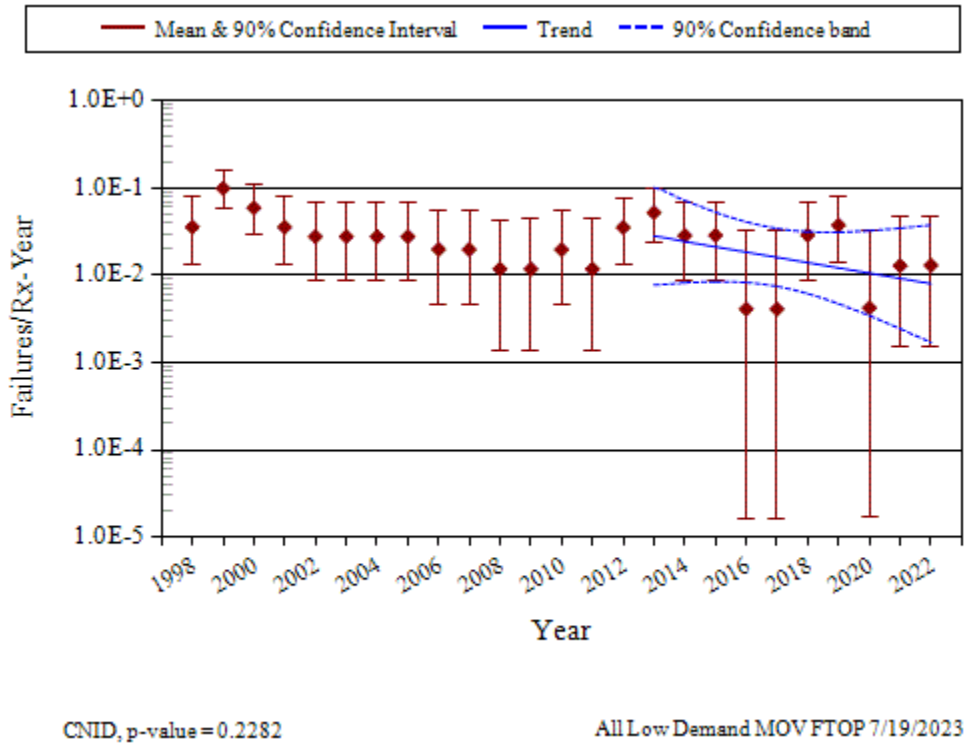

Figure 11. Frequency of FTOP events (failures per reactor year) for low-demand MOVs.

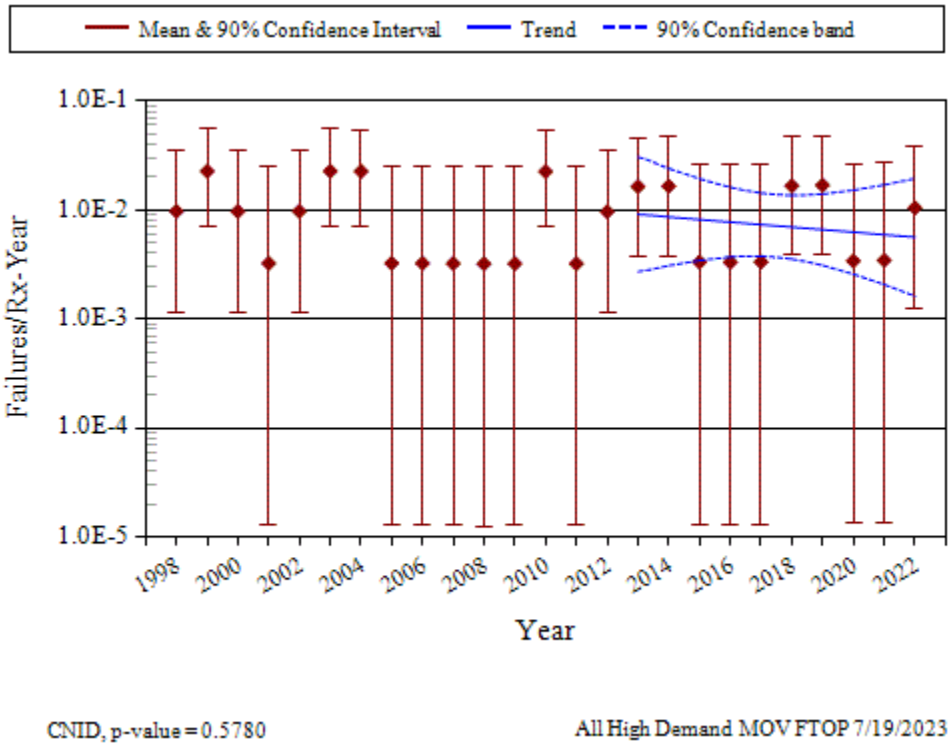

Figure 12. Frequency of FTOP events (failures per reactor year) for high-demand MOVs.

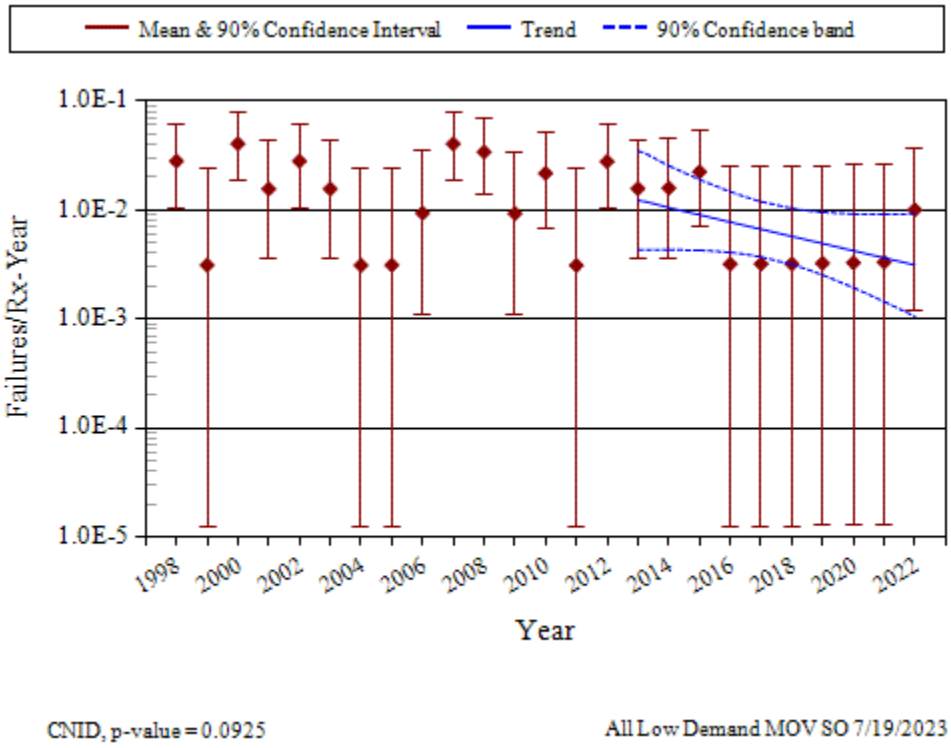

Figure 13. Frequency of SO events (failures per reactor year) for low-demand MOVs.

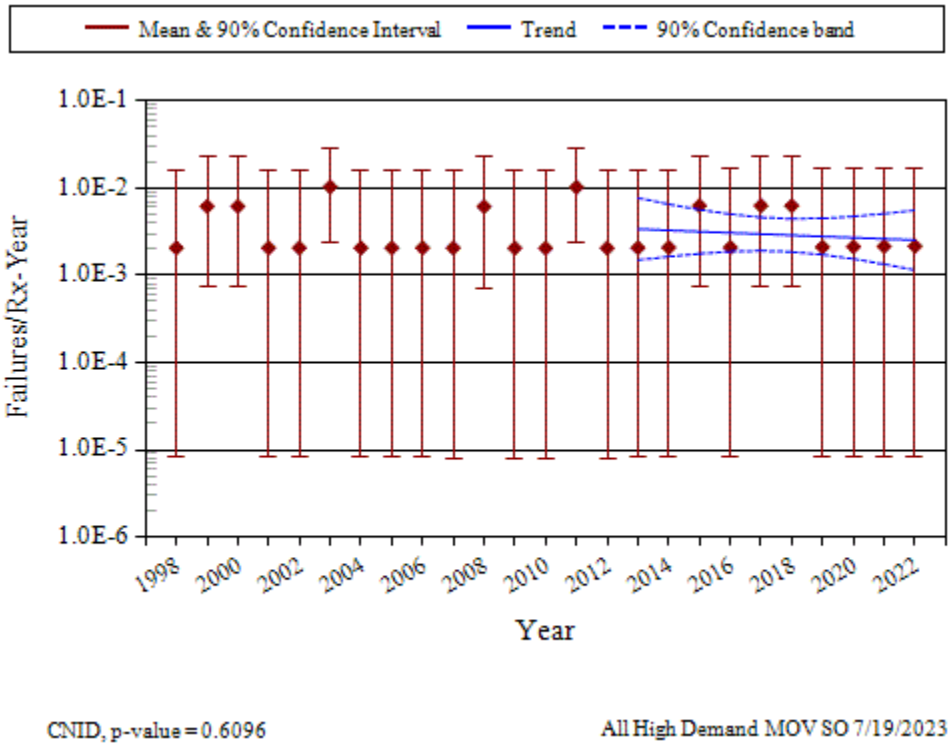

Figure 14. Frequency of SO events (failures per reactor year) for high-demand MOVs.

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

System	Valve Count	Valve Percent	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	580	8.5%	4	4	5	3		1	2				19	11.9%
CCW	757	11.1%	3	1	5	4	2	2	1	2			20	12.6%
CRD	25	0.4%											0	0.0%
CSR	351	5.1%		3	3	1				1		2	10	6.3%
CVC	13	0.2%											0	0.0%
HCI	289	4.2%	1	1	1	1	1						5	3.1%
HCS	35	0.5%					1						1	0.6%
HPI	1106	16.2%	2	5	1				1			1	10	6.3%
ISO	14	0.2%											0	0.0%
LCS	208	3.0%	1				2	1				1	5	3.1%
RCI	343	5.0%	3		3		2	1	3	1	2		15	9.4%
RCS	109	1.6%	1			1		1				1	4	2.5%
RHR	1972	28.8%	5	7	5	6	9	3	1	3	3	2	44	27.7%
SWN	762	11.1%	7	2	3	1	3	1	1	1			19	11.9%
SWS	258	3.8%				2	2		2				6	3.8%
VSS	14	0.2%	1										1	0.6%
Total	6836	100.0%	28	23	26	19	22	10	11	8	5	7	159	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	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	580	8.5%	1					1				1	3	14.3%
CCW	757	11.1%			1				1				2	9.5%
CRD	25	0.4%											0	0.0%
CSR	351	5.1%											0	0.0%
CVC	13	0.2%											0	0.0%
HCI	289	4.2%	1		1						1		3	14.3%
HCS	35	0.5%											0	0.0%
HPI	1106	16.2%						1					1	4.8%
ISO	14	0.2%											0	0.0%
LCS	208	3.0%											0	0.0%
RCI	343	5.0%			1				1				2	9.5%
RCS	109	1.6%		1									1	4.8%
RHR	1972	28.8%	2						2				4	19.0%
SWN	762	11.1%	2	1				1					4	19.0%
SWS	258	3.8%											0	0.0%

System	Valve Count	Valve Percent	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
VSS	14	0.2%		1									1	4.8%
Total	6836	100.0%	6	3	3	0	0	3	4	0	1	1	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	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	580	8.5%			1								1	12.5%
CCW	757	11.1%											0	0.0%
CRD	25	0.4%											0	0.0%
CSR	351	5.1%											0	0.0%
CVC	13	0.2%											0	0.0%
HCI	289	4.2%		1								1	2	25.0%
HCS	35	0.5%											0	0.0%
HPI	1106	16.2%											0	0.0%
ISO	14	0.2%											0	0.0%
LCS	208	3.0%											0	0.0%
RCI	343	5.0%	1										1	12.5%
RCS	109	1.6%											0	0.0%
RHR	1972	28.8%	1	1	2								4	50.0%
SWN	762	11.1%											0	0.0%
SWS	258	3.8%											0	0.0%
VSS	14	0.2%											0	0.0%
Total	6836	100.0%	2	2	3	0	0	0	0	0	0	1	8	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	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	97	9.1%	3	2	2			2	2				11	20.0%
CCW	120	11.2%									1		1	1.8%
CSR	11	1.0%			1								1	1.8%
HCI	24	2.2%		1			1						2	3.6%
HCS	17	1.6%									1		1	1.8%
HPI	74	6.9%	1										1	1.8%
ISO	6	0.6%											0	0.0%
LCS	27	2.5%											0	0.0%
RCI	33	3.1%	1					1					2	3.6%
RCS	5	0.5%											0	0.0%
RHR	296	27.6%	3	2	3		3	1	2	3		1	18	32.7%
SWN	257	24.0%	1		3		1		1	1	2	2	11	20.0%
SWS	104	9.7%	2	1	1	1			1		1		7	12.7%
Total	1071	100.0%	11	6	10	1	5	4	6	4	5	3	55	100.0%

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

System	Valve Count	Valve Percent	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	97	9.1%							1				1	11.1%
CCW	120	11.2%		2									2	22.2%
CSR	11	1.0%											0	0.0%
HCI	24	2.2%											0	0.0%
HCS	17	1.6%											0	0.0%
HPI	74	6.9%											0	0.0%
ISO	6	0.6%											0	0.0%
LCS	27	2.5%											0	0.0%
RCI	33	3.1%											0	0.0%
RCS	5	0.5%											0	0.0%
RHR	296	27.6%	1									1	2	22.2%
SWN	257	24.0%	1					2					3	33.3%
SWS	104	9.7%							1				1	11.1%
Total	1071	100.0%	2	2	0	0	0	2	2	0	0	1	9	100.0%

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

System	Valve Count	Valve Percent	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total	Percent of Failures
AFW	97	9.1%											0	0.0%
CCW	120	11.2%											0	0.0%
CSR	11	1.0%											0	0.0%
HCI	24	2.2%											0	0.0%
HCS	17	1.6%			1								1	33.3%
HPI	74	6.9%											0	0.0%
ISO	6	0.6%											0	0.0%
LCS	27	2.5%											0	0.0%
RCI	33	3.1%											0	0.0%
RCS	5	0.5%											0	0.0%
RHR	296	27.6%					1	1					2	66.7%
SWN	257	24.0%											0	0.0%
SWS	104	9.7%											0	0.0%
Total	1071	100.0%	0	0	1	0	1	1	0	0	0	0	3	100.0%

4.2 MOV Engineering Analysis by Failure Modes

The engineering analysis of the MOV failure breakdown by failure mode and other factors such as subcomponents, failure causes, detection methods, and recovery possibility are presented in this section. First, each analysis 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). Then the events are further divided by the failure modes and factors such as subcomponents, failure causes, detection methods, and recovery possibility. The failure modes are determined as a result of the IRIS data review by the Idaho National Laboratory (INL) staff. See Section 5 for further description of failure modes.

MOV subcomponent contributions to the three failure modes are presented in Figure 15. The subcomponent categories are similar to those used in the common-cause failure (CCF) database. For all three failure modes, the **actuator** is the largest contributor to the failure rates/probabilities.

MOV failure cause group contributions to the three failure modes are presented in Figure 16. The cause groups are similar to those 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 key causes that contributed to MOV failures are presented below.

- The **Component** cause group is the most likely cause group 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 earlier studies.
- 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 group 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.

MOV failure detection methods for the three failure modes are presented in Figure 17. A failure can be detected during inspection, testing, post maintenance testing (PMT), non-testing, or ESF demand.

- Overall, the most likely detection method for all three failure modes is **test 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 **test demand**, the detection method for **high-demand MOVs** is dominated by **non-test demand**.

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

Table 9. Component failure cause groups.[b]

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 an 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.

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

	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.

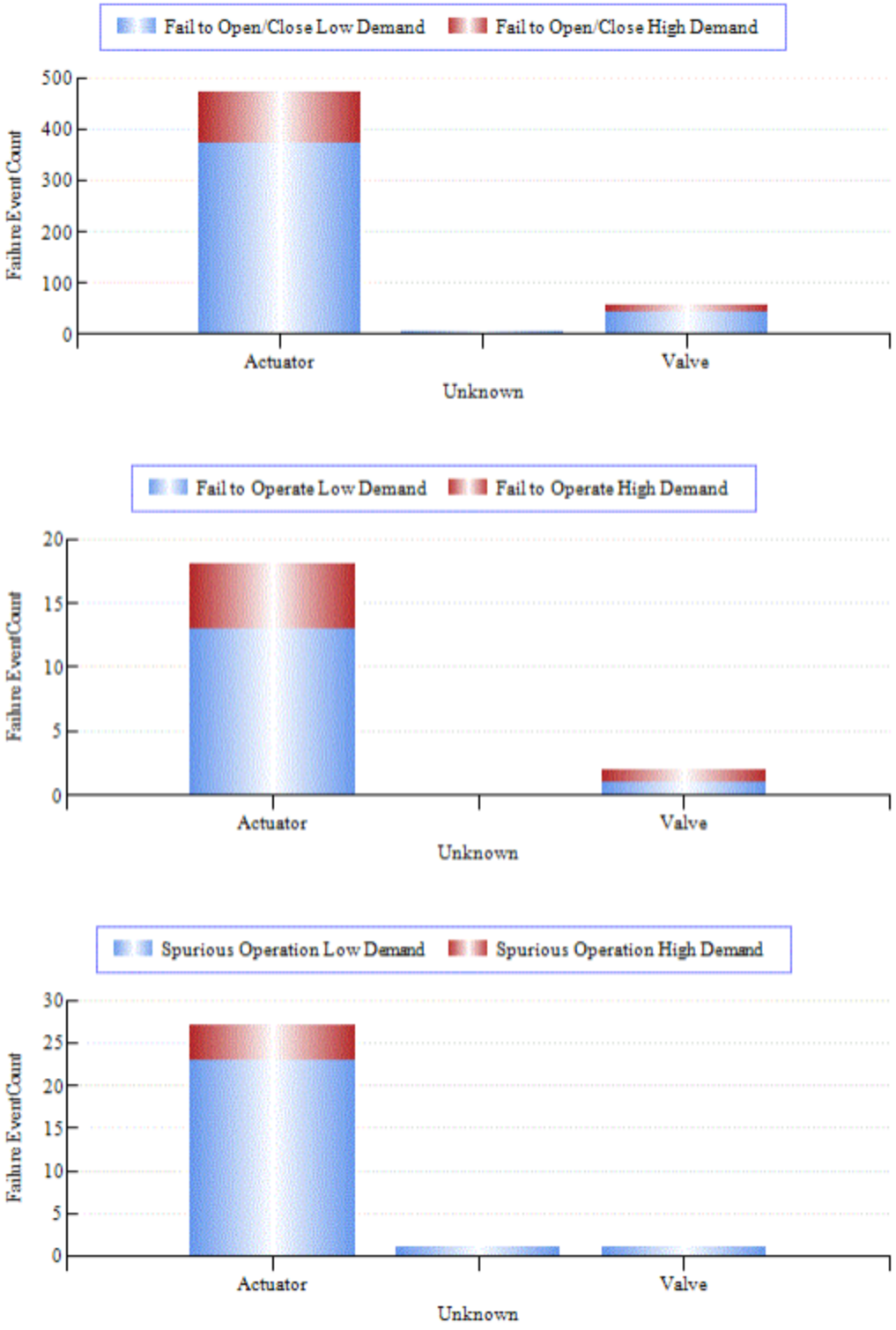

Figure 15. MOV failure event breakdown by subcomponent, failure mode, and demand rate.

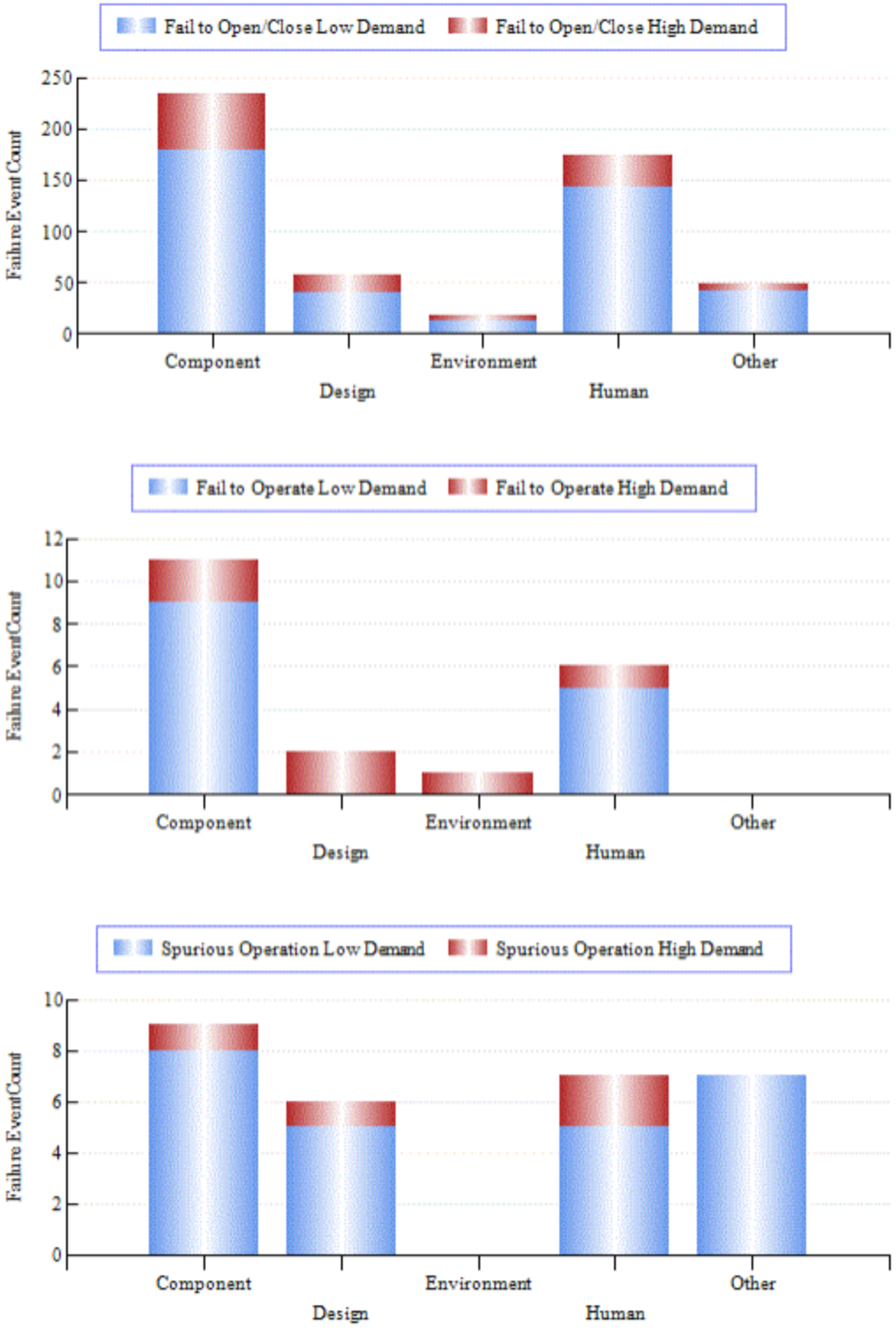

Figure 16. MOV failure event breakdown by cause group, failure mode, and demand rate.

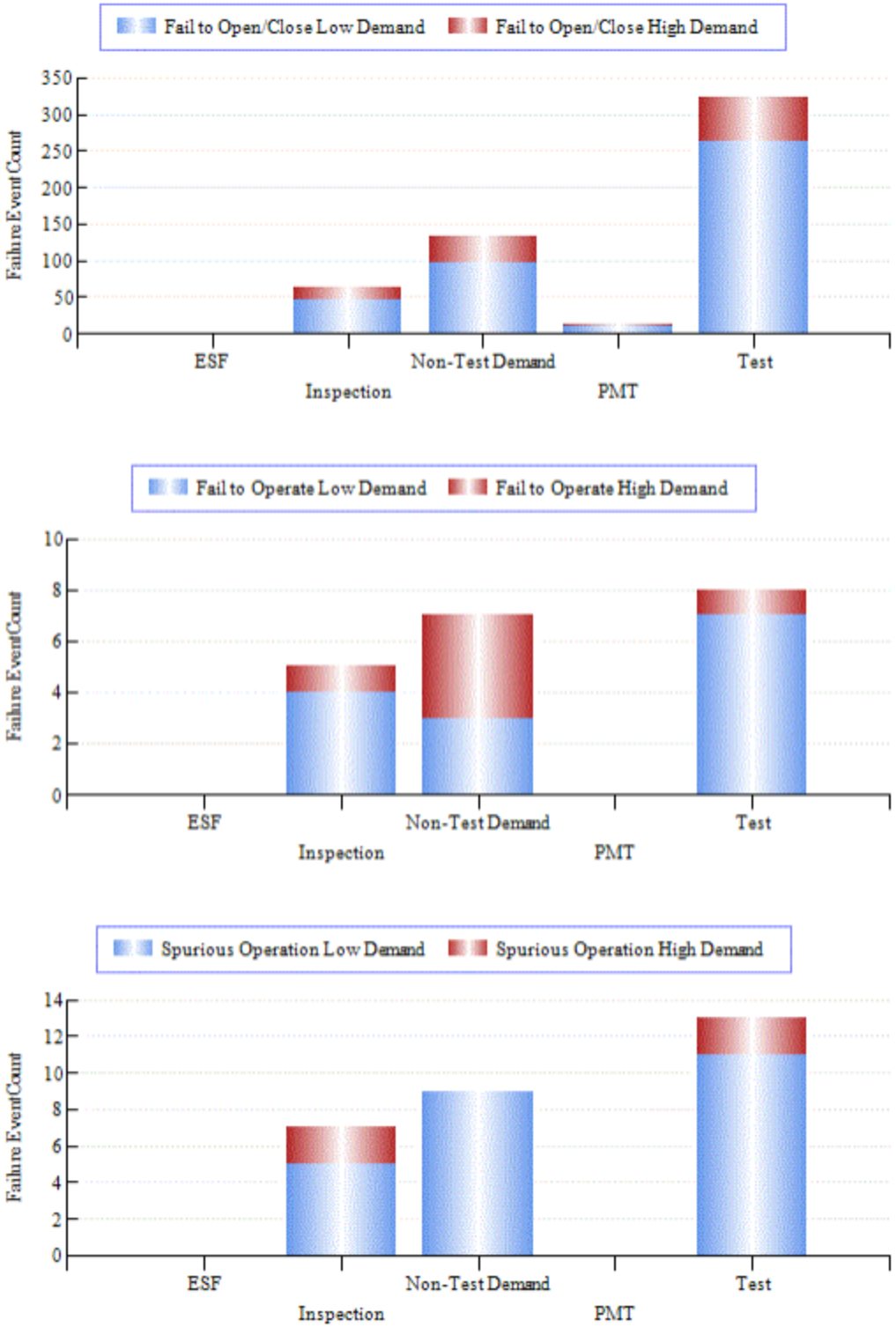

Figure 17. MOV failure event breakdown by method of detection, failure mode, and demand rate.

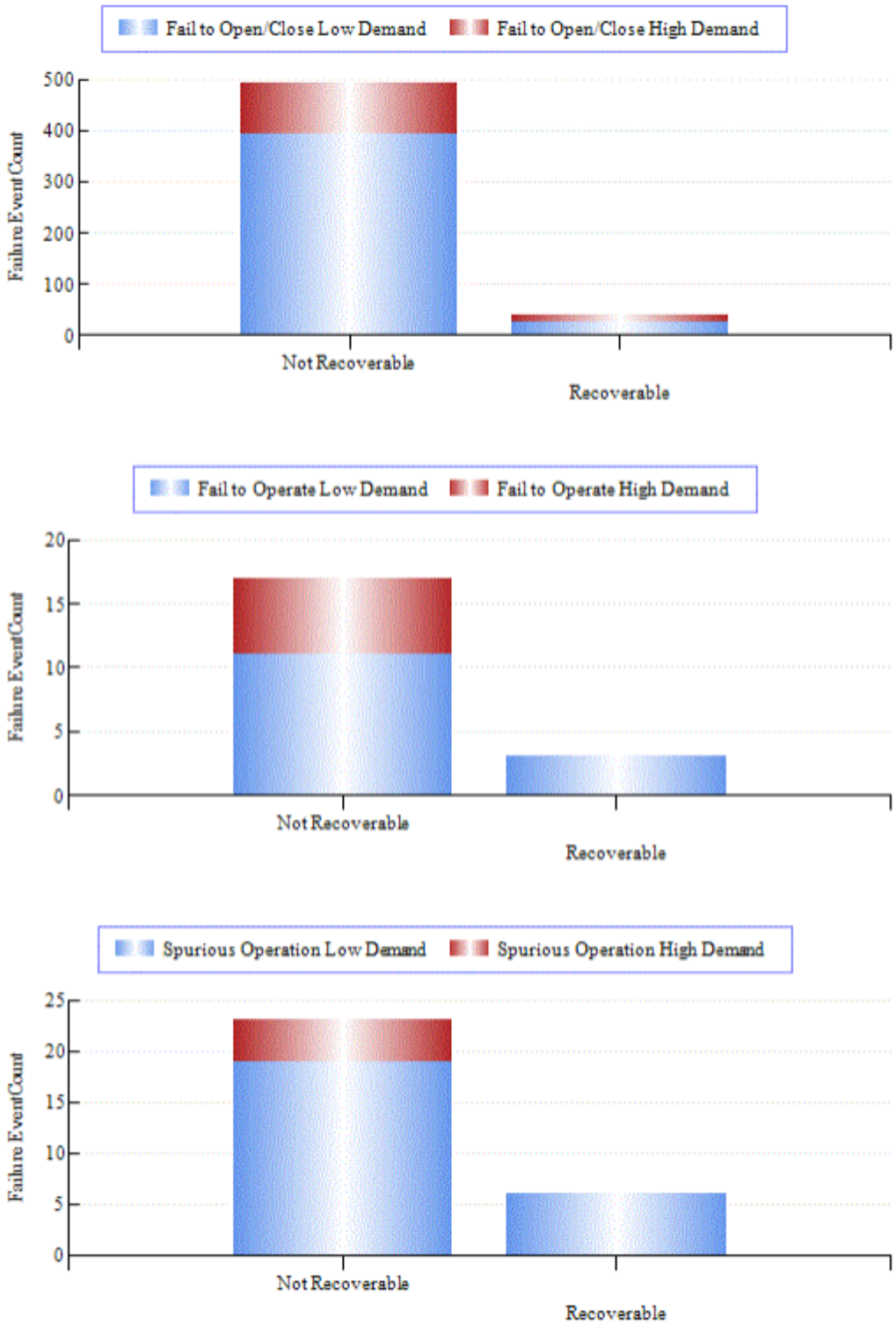

Figure 18. MOV failure event breakdown by recoverability, failure mode, and demand rate.

5. MOV ASSEMBLY DESCRIPTION

A MOV assembly consists of a valve body and motor-operated subcomponents (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 fail to control for a flow/temperature control device and any other rate-based failure modes except for SO
- 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
SPAR 2020		--	--	--	--	1.42E-04	1.43E-03	6.40E-04
1998	45	41,062	--	--	--	8.37E-04	1.37E-03	1.09E-03
1999	43	43,242	--	--	--	7.56E-04	1.25E-03	9.89E-04
2000	47	41,615	--	--	--	8.68E-04	1.40E-03	1.12E-03
2001	35	42,550	--	--	--	6.08E-04	1.06E-03	8.20E-04
2002	34	41,857	--	--	--	5.97E-04	1.05E-03	8.10E-04
2003	39	42,283	--	--	--	6.92E-04	1.17E-03	9.18E-04
2004	29	41,044	--	--	--	5.07E-04	9.33E-04	7.06E-04
2005	36	39,316	--	--	--	6.78E-04	1.17E-03	9.11E-04
2006	33	37,160	--	--	--	6.49E-04	1.15E-03	8.84E-04
2007	33	37,003	--	--	--	6.52E-04	1.15E-03	8.88E-04
2008	26	37,106	--	--	--	4.93E-04	9.38E-04	7.01E-04
2009	38	36,993	--	--	--	7.66E-04	1.31E-03	1.02E-03
2010	27	36,760	--	--	--	5.20E-04	9.78E-04	7.34E-04
2011	29	36,906	--	--	--	5.63E-04	1.04E-03	7.84E-04
2012	33	37,000	--	--	--	6.52E-04	1.15E-03	8.88E-04
2013	28	36,776	8.22E-04	6.42E-04	1.05E-03	5.42E-04	1.01E-03	7.60E-04
2014	23	36,772	6.92E-04	5.63E-04	8.49E-04	4.30E-04	8.53E-04	6.27E-04
2015	26	36,615	5.82E-04	4.89E-04	6.93E-04	4.99E-04	9.51E-04	7.10E-04
2016	19	36,664	4.90E-04	4.17E-04	5.75E-04	3.44E-04	7.30E-04	5.22E-04
2017	22	36,800	4.12E-04	3.48E-04	4.87E-04	4.08E-04	8.22E-04	6.00E-04
2018	10	36,792	3.46E-04	2.85E-04	4.21E-04	1.55E-04	4.36E-04	2.80E-04
2019	11	36,574	2.92E-04	2.31E-04	3.68E-04	1.76E-04	4.72E-04	3.08E-04
2020	8	36,634	2.45E-04	1.86E-04	3.24E-04	1.16E-04	3.69E-04	2.28E-04
2021	5	36,471	2.06E-04	1.48E-04	2.87E-04	6.15E-05	2.65E-04	1.48E-04
2022	7	36,427	1.74E-04	1.18E-04	2.55E-04	9.78E-05	3.37E-04	2.02E-04
Total	686	958,420	--	--	--	--	--	--

Table 11. Plot data for Figure 2, failure probability estimate trend for high-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
SPAR 2020		--	--	--	--	1.42E-04	1.43E-03	6.40E-04
1998	7	36,174	--	--	--	9.33E-05	3.21E-04	1.93E-04
1999	13	38,442	--	--	--	1.96E-04	4.87E-04	3.28E-04
2000	7	40,132	--	--	--	8.47E-05	2.92E-04	1.75E-04
2001	12	46,416	--	--	--	1.49E-04	3.83E-04	2.54E-04
2002	6	36,607	--	--	--	7.49E-05	2.84E-04	1.65E-04
2003	9	38,709	--	--	--	1.22E-04	3.64E-04	2.29E-04
2004	14	40,474	--	--	--	2.05E-04	4.92E-04	3.36E-04
2005	11	40,447	--	--	--	1.52E-04	4.07E-04	2.66E-04
2006	5	40,095	--	--	--	5.34E-05	2.30E-04	1.28E-04
2007	10	40,373	--	--	--	1.34E-04	3.79E-04	2.44E-04
2008	7	40,352	--	--	--	8.43E-05	2.90E-04	1.74E-04
2009	4	39,420	--	--	--	3.95E-05	2.01E-04	1.07E-04
2010	4	39,757	--	--	--	3.91E-05	1.99E-04	1.06E-04
2011	8	39,066	--	--	--	1.04E-04	3.30E-04	2.03E-04
2012	5	38,528	--	--	--	5.55E-05	2.38E-04	1.33E-04
2013	11	37,521	1.82E-04	7.84E-05	4.21E-04	1.63E-04	4.37E-04	2.86E-04
2014	6	37,555	1.69E-04	8.30E-05	3.42E-04	7.31E-05	2.78E-04	1.61E-04
2015	10	37,152	1.56E-04	8.62E-05	2.84E-04	1.45E-04	4.10E-04	2.63E-04
2016	1	39,187	1.45E-04	8.66E-05	2.43E-04	4.20E-06	9.32E-05	3.58E-05
2017	5	36,458	1.35E-04	8.28E-05	2.19E-04	5.84E-05	2.51E-04	1.40E-04
2018	4	36,854	1.25E-04	7.47E-05	2.09E-04	4.20E-05	2.14E-04	1.14E-04
2019	6	36,017	1.16E-04	6.41E-05	2.10E-04	7.60E-05	2.89E-04	1.68E-04
2020	4	36,237	1.08E-04	5.32E-05	2.17E-04	4.27E-05	2.17E-04	1.16E-04
2021	5	35,875	9.98E-05	4.33E-05	2.30E-04	5.93E-05	2.55E-04	1.43E-04
2022	3	36,235	9.26E-05	3.48E-05	2.46E-04	2.78E-05	1.81E-04	8.98E-05
Total	177	964,082	--	--	--	--	--	--

Table 12. Plot data for Figure 3, failure rate estimate trend for low-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
SPAR 2020		--	--	--	--	9.42E-10	1.13E-07	3.47E-08
1998	4	55,004,040	--	--	--	2.58E-08	1.31E-07	6.99E-08
1999	12	55,117,920	--	--	--	1.13E-07	2.92E-07	1.94E-07
2000	7	55,179,240	--	--	--	5.62E-08	1.93E-07	1.16E-07
2001	4	55,144,200	--	--	--	2.58E-08	1.31E-07	6.97E-08
2002	3	55,135,440	--	--	--	1.68E-08	1.09E-07	5.42E-08
2003	3	55,144,200	--	--	--	1.68E-08	1.09E-07	5.42E-08
2004	3	55,109,160	--	--	--	1.68E-08	1.09E-07	5.42E-08
2005	3	55,152,960	--	--	--	1.68E-08	1.09E-07	5.42E-08
2006	2	55,249,320	--	--	--	8.86E-09	8.56E-08	3.87E-08
2007	2	55,310,640	--	--	--	8.85E-09	8.55E-08	3.86E-08
2008	1	55,205,520	--	--	--	2.72E-09	6.05E-08	2.32E-08
2009	1	55,196,760	--	--	--	2.72E-09	6.05E-08	2.32E-08
2010	2	55,407,000	--	--	--	8.83E-09	8.54E-08	3.86E-08
2011	1	55,880,040	--	--	--	2.69E-09	5.98E-08	2.30E-08
2012	4	55,371,960	--	--	--	2.57E-08	1.31E-07	6.95E-08
2013	6	55,363,200	5.08E-08	1.40E-08	1.84E-07	4.55E-08	1.73E-07	1.00E-07
2014	3	55,310,640	4.39E-08	1.48E-08	1.30E-07	1.67E-08	1.09E-07	5.41E-08
2015	3	55,678,560	3.79E-08	1.52E-08	9.46E-08	1.66E-08	1.08E-07	5.38E-08
2016	0	55,862,520	3.27E-08	1.47E-08	7.28E-08	3.01E-11	2.94E-08	7.66E-09
2017	0	55,704,840	2.83E-08	1.32E-08	6.06E-08	3.02E-11	2.95E-08	7.68E-09
2018	3	56,125,320	2.44E-08	1.08E-08	5.52E-08	1.65E-08	1.07E-07	5.34E-08
2019	4	55,643,520	2.11E-08	8.24E-09	5.41E-08	2.56E-08	1.30E-07	6.92E-08
2020	0	55,529,640	1.82E-08	5.96E-09	5.58E-08	3.03E-11	2.96E-08	7.70E-09
2021	1	55,371,960	1.58E-08	4.19E-09	5.93E-08	2.72E-09	6.03E-08	2.32E-08
2022	1	55,424,520	1.36E-08	2.89E-09	6.41E-08	2.71E-09	6.03E-08	2.31E-08
Total	73	1,384,623,120	--	--	--	--	--	--

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
SPAR 2020		--	--	--	--	9.42E-10	1.13E-07	3.47E-08
1998	1	8,164,320	--	--	--	1.43E-08	3.18E-07	1.22E-07
1999	3	8,348,280	--	--	--	8.70E-08	5.64E-07	2.81E-07
2000	1	8,374,560	--	--	--	1.41E-08	3.13E-07	1.20E-07
2001	0	8,357,040	--	--	--	1.58E-10	1.54E-07	4.01E-08
2002	1	8,374,560	--	--	--	1.41E-08	3.13E-07	1.20E-07
2003	3	8,365,800	--	--	--	8.68E-08	5.64E-07	2.80E-07
2004	3	8,400,840	--	--	--	8.66E-08	5.62E-07	2.80E-07
2005	0	8,409,600	--	--	--	1.57E-10	1.53E-07	3.99E-08
2006	0	8,418,360	--	--	--	1.57E-10	1.53E-07	3.99E-08
2007	0	8,427,120	--	--	--	1.57E-10	1.53E-07	3.99E-08
2008	0	8,470,920	--	--	--	1.56E-10	1.53E-07	3.97E-08
2009	0	8,444,640	--	--	--	1.57E-10	1.53E-07	3.98E-08
2010	3	8,462,160	--	--	--	8.62E-08	5.59E-07	2.78E-07
2011	0	8,584,800	--	--	--	1.55E-10	1.51E-07	3.94E-08
2012	1	8,400,840	--	--	--	1.41E-08	3.12E-07	1.20E-07
2013	2	8,374,560	1.08E-07	3.21E-08	3.64E-07	4.59E-08	4.43E-07	2.00E-07
2014	2	8,383,320	1.02E-07	3.65E-08	2.85E-07	4.58E-08	4.43E-07	2.00E-07
2015	0	8,418,360	9.62E-08	4.05E-08	2.28E-07	1.57E-10	1.53E-07	3.99E-08
2016	0	8,479,680	9.07E-08	4.34E-08	1.90E-07	1.56E-10	1.53E-07	3.97E-08
2017	0	8,435,880	8.56E-08	4.38E-08	1.67E-07	1.57E-10	1.53E-07	3.98E-08
2018	2	8,497,200	8.07E-08	4.11E-08	1.59E-07	4.54E-08	4.39E-07	1.98E-07
2019	2	8,339,520	7.61E-08	3.58E-08	1.62E-07	4.60E-08	4.44E-07	2.01E-07
2020	0	8,304,480	7.18E-08	2.95E-08	1.75E-07	1.58E-10	1.55E-07	4.03E-08
2021	0	8,304,480	6.77E-08	2.36E-08	1.95E-07	1.58E-10	1.55E-07	4.03E-08
2022	1	8,304,480	6.39E-08	1.84E-08	2.22E-07	1.42E-08	3.15E-07	1.21E-07
Total	25	209,845,800	--	--	--	--	--	--

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

Year/ Source	Failures	Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	1.93E-08	3.23E-08	2.54E-08
1998	4	55,004,040	--	--	--	2.38E-08	1.21E-07	6.44E-08
1999	0	55,117,920	--	--	--	2.81E-11	2.74E-08	7.14E-09
2000	6	55,179,240	--	--	--	4.20E-08	1.60E-07	9.28E-08
2001	2	55,144,200	--	--	--	8.18E-09	7.90E-08	3.57E-08
2002	4	55,135,440	--	--	--	2.37E-08	1.21E-07	6.43E-08
2003	2	55,144,200	--	--	--	8.18E-09	7.90E-08	3.57E-08
2004	0	55,109,160	--	--	--	2.81E-11	2.74E-08	7.14E-09
2005	0	55,152,960	--	--	--	2.81E-11	2.74E-08	7.14E-09
2006	1	55,249,320	--	--	--	2.51E-09	5.57E-08	2.14E-08
2007	6	55,310,640	--	--	--	4.20E-08	1.59E-07	9.26E-08
2008	5	55,205,520	--	--	--	3.26E-08	1.40E-07	7.85E-08
2009	1	55,196,760	--	--	--	2.51E-09	5.58E-08	2.14E-08
2010	3	55,407,000	--	--	--	1.54E-08	1.00E-07	4.98E-08
2011	0	55,880,040	--	--	--	2.78E-11	2.71E-08	7.07E-09
2012	4	55,371,960	--	--	--	2.37E-08	1.20E-07	6.40E-08
2013	2	55,363,200	2.20E-08	7.79E-09	6.22E-08	8.15E-09	7.88E-08	3.56E-08
2014	2	55,310,640	1.88E-08	7.78E-09	4.54E-08	8.16E-09	7.89E-08	3.56E-08
2015	3	55,678,560	1.60E-08	7.63E-09	3.38E-08	1.54E-08	9.97E-08	4.96E-08
2016	0	55,862,520	1.37E-08	7.24E-09	2.59E-08	2.78E-11	2.71E-08	7.07E-09
2017	0	55,704,840	1.17E-08	6.54E-09	2.09E-08	2.79E-11	2.72E-08	7.08E-09
2018	0	56,125,320	1.00E-08	5.54E-09	1.80E-08	2.77E-11	2.70E-08	7.04E-09
2019	0	55,643,520	8.54E-09	4.42E-09	1.65E-08	2.79E-11	2.72E-08	7.09E-09
2020	0	55,529,640	7.29E-09	3.36E-09	1.58E-08	2.79E-11	2.73E-08	7.10E-09
2021	0	55,371,960	6.23E-09	2.49E-09	1.56E-08	2.80E-11	2.73E-08	7.12E-09
2022	1	55,424,520	5.32E-09	1.81E-09	1.56E-08	2.50E-09	5.56E-08	2.13E-08
Total	46	1,384,623,120	--	--	--	--	--	--

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

Year/ Source	Failures	Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020		--	--	--	--	1.93E-08	3.23E-08	2.54E-08
1998	0	8,164,320	--	--	--	1.08E-10	1.06E-07	2.75E-08
1999	1	8,348,280	--	--	--	9.59E-09	2.13E-07	8.18E-08
2000	1	8,374,560	--	--	--	9.58E-09	2.13E-07	8.17E-08
2001	0	8,357,040	--	--	--	1.07E-10	1.05E-07	2.72E-08
2002	0	8,374,560	--	--	--	1.07E-10	1.05E-07	2.72E-08
2003	2	8,365,800	--	--	--	3.12E-08	3.02E-07	1.36E-07
2004	0	8,400,840	--	--	--	1.07E-10	1.04E-07	2.72E-08
2005	0	8,409,600	--	--	--	1.07E-10	1.04E-07	2.72E-08
2006	0	8,418,360	--	--	--	1.07E-10	1.04E-07	2.72E-08
2007	0	8,427,120	--	--	--	1.07E-10	1.04E-07	2.71E-08
2008	1	8,470,920	--	--	--	9.53E-09	2.12E-07	8.12E-08
2009	0	8,444,640	--	--	--	1.07E-10	1.04E-07	2.71E-08
2010	0	8,462,160	--	--	--	1.07E-10	1.04E-07	2.71E-08
2011	2	8,584,800	--	--	--	3.08E-08	2.98E-07	1.35E-07
2012	0	8,400,840	--	--	--	1.07E-10	1.04E-07	2.72E-08
2013	0	8,374,560	3.99E-08	1.77E-08	8.99E-08	1.07E-10	1.05E-07	2.72E-08
2014	0	8,383,320	3.85E-08	1.93E-08	7.68E-08	1.07E-10	1.05E-07	2.72E-08
2015	1	8,418,360	3.72E-08	2.08E-08	6.65E-08	9.56E-09	2.12E-07	8.15E-08
2016	0	8,479,680	3.59E-08	2.20E-08	5.88E-08	1.06E-10	1.04E-07	2.71E-08
2017	1	8,435,880	3.47E-08	2.23E-08	5.39E-08	9.55E-09	2.12E-07	8.14E-08
2018	1	8,497,200	3.35E-08	2.17E-08	5.18E-08	9.51E-09	2.11E-07	8.11E-08
2019	0	8,339,520	3.24E-08	2.00E-08	5.24E-08	1.07E-10	1.05E-07	2.73E-08
2020	0	8,304,480	3.13E-08	1.78E-08	5.49E-08	1.07E-10	1.05E-07	2.73E-08
2021	0	8,304,480	3.02E-08	1.54E-08	5.90E-08	1.07E-10	1.05E-07	2.73E-08
2022	0	8,304,480	2.91E-08	1.32E-08	6.43E-08	1.07E-10	1.05E-07	2.73E-08
Total	10	209,845,800	--	--	--	--	--	--

Table 16. Plot data for Figure 7, frequency of FTOC demands (demands per reactor year) for low-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	41,062	103.0	--	--	--	3.95E+02	4.02E+02	3.99E+02
1999	43,242	103.0	--	--	--	4.17E+02	4.23E+02	4.20E+02
2000	41,615	103.3	--	--	--	4.00E+02	4.06E+02	4.03E+02
2001	42,550	103.0	--	--	--	4.10E+02	4.16E+02	4.13E+02
2002	41,857	103.0	--	--	--	4.03E+02	4.10E+02	4.06E+02
2003	42,283	103.0	--	--	--	4.07E+02	4.14E+02	4.11E+02
2004	41,044	103.3	--	--	--	3.94E+02	4.01E+02	3.97E+02
2005	39,316	103.0	--	--	--	3.79E+02	3.85E+02	3.82E+02
2006	37,160	103.0	--	--	--	3.58E+02	3.64E+02	3.61E+02
2007	37,003	103.6	--	--	--	3.54E+02	3.60E+02	3.57E+02
2008	37,106	104.3	--	--	--	3.53E+02	3.59E+02	3.56E+02
2009	36,993	104.0	--	--	--	3.53E+02	3.59E+02	3.56E+02
2010	36,760	104.0	--	--	--	3.50E+02	3.57E+02	3.53E+02
2011	36,906	104.0	--	--	--	3.52E+02	3.58E+02	3.55E+02
2012	37,000	104.3	--	--	--	3.52E+02	3.58E+02	3.55E+02
2013	36,776	101.6	3.61E+02	3.57E+02	3.66E+02	3.59E+02	3.65E+02	3.62E+02
2014	36,772	100.0	3.64E+02	3.61E+02	3.68E+02	3.65E+02	3.71E+02	3.68E+02
2015	36,615	99.0	3.68E+02	3.64E+02	3.71E+02	3.67E+02	3.73E+02	3.70E+02
2016	36,664	99.2	3.71E+02	3.68E+02	3.74E+02	3.66E+02	3.73E+02	3.70E+02
2017	36,800	99.0	3.74E+02	3.72E+02	3.77E+02	3.69E+02	3.75E+02	3.72E+02
2018	36,792	98.7	3.78E+02	3.75E+02	3.80E+02	3.69E+02	3.76E+02	3.73E+02
2019	36,574	97.0	3.81E+02	3.78E+02	3.84E+02	3.74E+02	3.80E+02	3.77E+02
2020	36,634	95.3	3.84E+02	3.81E+02	3.88E+02	3.81E+02	3.88E+02	3.85E+02
2021	36,471	93.3	3.88E+02	3.83E+02	3.92E+02	3.87E+02	3.94E+02	3.91E+02
2022	36,427	92.4	3.91E+02	3.86E+02	3.96E+02	3.91E+02	3.98E+02	3.94E+02
Total	958,420	2,527.3	--	--	--	--	--	--

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	36,174	103.0	--	--	--	3.48E+02	3.54E+02	3.51E+02
1999	38,442	103.0	--	--	--	3.70E+02	3.76E+02	3.73E+02
2000	40,132	103.3	--	--	--	3.85E+02	3.92E+02	3.89E+02
2001	46,416	103.0	--	--	--	4.47E+02	4.54E+02	4.51E+02
2002	36,607	103.0	--	--	--	3.52E+02	3.58E+02	3.55E+02
2003	38,709	103.0	--	--	--	3.73E+02	3.79E+02	3.76E+02
2004	40,474	103.3	--	--	--	3.89E+02	3.95E+02	3.92E+02
2005	40,447	103.0	--	--	--	3.89E+02	3.96E+02	3.93E+02
2006	40,095	103.0	--	--	--	3.86E+02	3.92E+02	3.89E+02
2007	40,373	103.6	--	--	--	3.86E+02	3.93E+02	3.90E+02
2008	40,352	104.3	--	--	--	3.84E+02	3.90E+02	3.87E+02
2009	39,420	104.0	--	--	--	3.76E+02	3.82E+02	3.79E+02
2010	39,757	104.0	--	--	--	3.79E+02	3.85E+02	3.82E+02
2011	39,066	104.0	--	--	--	3.73E+02	3.79E+02	3.76E+02
2012	38,528	104.3	--	--	--	3.66E+02	3.73E+02	3.69E+02
2013	37,521	101.6	3.72E+02	3.60E+02	3.85E+02	3.66E+02	3.73E+02	3.69E+02
2014	37,555	100.0	3.74E+02	3.63E+02	3.85E+02	3.72E+02	3.79E+02	3.76E+02
2015	37,152	99.0	3.75E+02	3.66E+02	3.84E+02	3.72E+02	3.78E+02	3.75E+02
2016	39,187	99.2	3.76E+02	3.69E+02	3.84E+02	3.92E+02	3.98E+02	3.95E+02
2017	36,458	99.0	3.78E+02	3.71E+02	3.85E+02	3.65E+02	3.71E+02	3.68E+02
2018	36,854	98.7	3.79E+02	3.72E+02	3.86E+02	3.70E+02	3.76E+02	3.73E+02
2019	36,017	97.0	3.80E+02	3.73E+02	3.88E+02	3.68E+02	3.75E+02	3.71E+02
2020	36,237	95.3	3.82E+02	3.72E+02	3.91E+02	3.77E+02	3.84E+02	3.80E+02
2021	35,875	93.3	3.83E+02	3.72E+02	3.94E+02	3.81E+02	3.88E+02	3.84E+02
2022	36,235	92.4	3.84E+02	3.71E+02	3.98E+02	3.89E+02	3.95E+02	3.92E+02
Total	964,082	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	45	103.0	--	--	--	3.30E-01	5.49E-01	4.29E-01
1999	43	103.0	--	--	--	3.13E-01	5.28E-01	4.10E-01
2000	47	103.3	--	--	--	3.46E-01	5.69E-01	4.47E-01
2001	35	103.0	--	--	--	2.48E-01	4.43E-01	3.35E-01
2002	34	103.0	--	--	--	2.40E-01	4.32E-01	3.25E-01
2003	39	103.0	--	--	--	2.81E-01	4.86E-01	3.72E-01
2004	29	103.3	--	--	--	1.99E-01	3.77E-01	2.77E-01
2005	36	103.0	--	--	--	2.56E-01	4.54E-01	3.44E-01
2006	33	103.0	--	--	--	2.32E-01	4.21E-01	3.16E-01
2007	33	103.6	--	--	--	2.30E-01	4.19E-01	3.14E-01
2008	26	104.3	--	--	--	1.74E-01	3.41E-01	2.47E-01
2009	38	104.0	--	--	--	2.70E-01	4.71E-01	3.60E-01
2010	27	104.0	--	--	--	1.82E-01	3.53E-01	2.57E-01
2011	29	104.0	--	--	--	1.98E-01	3.75E-01	2.76E-01
2012	33	104.3	--	--	--	2.29E-01	4.16E-01	3.12E-01
2013	28	101.6	2.99E-01	2.33E-01	3.83E-01	1.94E-01	3.72E-01	2.72E-01
2014	23	100.0	2.53E-01	2.06E-01	3.11E-01	1.57E-01	3.22E-01	2.28E-01
2015	26	99.0	2.15E-01	1.80E-01	2.56E-01	1.83E-01	3.59E-01	2.60E-01
2016	19	99.2	1.82E-01	1.55E-01	2.13E-01	1.26E-01	2.78E-01	1.91E-01
2017	22	99.0	1.54E-01	1.30E-01	1.82E-01	1.50E-01	3.14E-01	2.20E-01
2018	10	98.7	1.31E-01	1.08E-01	1.58E-01	5.69E-02	1.73E-01	1.03E-01
2019	11	97.0	1.11E-01	8.80E-02	1.39E-01	6.54E-02	1.88E-01	1.15E-01
2020	8	95.3	9.38E-02	7.12E-02	1.23E-01	4.41E-02	1.53E-01	8.65E-02
2021	5	93.3	7.95E-02	5.74E-02	1.10E-01	2.37E-02	1.16E-01	5.71E-02
2022	7	92.4	6.74E-02	4.62E-02	9.83E-02	3.80E-02	1.44E-01	7.86E-02
Total	686	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	7	103.0	--	--	--	3.25E-02	1.23E-01	6.71E-02
1999	13	103.0	--	--	--	7.22E-02	1.90E-01	1.21E-01
2000	7	103.3	--	--	--	3.24E-02	1.23E-01	6.69E-02
2001	12	103.0	--	--	--	6.54E-02	1.79E-01	1.12E-01
2002	6	103.0	--	--	--	2.64E-02	1.12E-01	5.81E-02
2003	9	103.0	--	--	--	4.53E-02	1.46E-01	8.50E-02
2004	14	103.3	--	--	--	7.90E-02	2.01E-01	1.29E-01
2005	11	103.0	--	--	--	5.86E-02	1.68E-01	1.03E-01
2006	5	103.0	--	--	--	2.05E-02	1.00E-01	4.92E-02
2007	10	103.6	--	--	--	5.16E-02	1.56E-01	9.34E-02
2008	7	104.3	--	--	--	3.21E-02	1.22E-01	6.63E-02
2009	4	104.0	--	--	--	1.47E-02	8.72E-02	3.99E-02
2010	4	104.0	--	--	--	1.47E-02	8.72E-02	3.99E-02
2011	8	104.0	--	--	--	3.84E-02	1.34E-01	7.54E-02
2012	5	104.3	--	--	--	2.02E-02	9.89E-02	4.86E-02
2013	11	101.6	6.90E-02	3.11E-02	1.53E-01	5.93E-02	1.71E-01	1.04E-01
2014	6	100.0	6.41E-02	3.27E-02	1.25E-01	2.71E-02	1.15E-01	5.97E-02
2015	10	99.0	5.95E-02	3.38E-02	1.05E-01	5.38E-02	1.63E-01	9.74E-02
2016	1	99.2	5.52E-02	3.38E-02	9.02E-02	1.63E-03	5.12E-02	1.39E-02
2017	5	99.0	5.12E-02	3.22E-02	8.17E-02	2.12E-02	1.04E-01	5.10E-02
2018	4	98.7	4.76E-02	2.89E-02	7.82E-02	1.55E-02	9.15E-02	4.18E-02
2019	6	97.0	4.42E-02	2.48E-02	7.85E-02	2.78E-02	1.18E-01	6.14E-02
2020	4	95.3	4.10E-02	2.07E-02	8.13E-02	1.60E-02	9.46E-02	4.33E-02
2021	5	93.3	3.81E-02	1.69E-02	8.58E-02	2.24E-02	1.09E-01	5.39E-02
2022	3	92.4	3.53E-02	1.36E-02	9.15E-02	1.07E-02	8.36E-02	3.46E-02
Total	177	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4	103.0	--	--	--	1.32E-02	7.83E-02	3.58E-02
1999	12	103.0	--	--	--	5.81E-02	1.60E-01	9.95E-02
2000	7	103.3	--	--	--	2.88E-02	1.09E-01	5.95E-02
2001	4	103.0	--	--	--	1.32E-02	7.83E-02	3.58E-02
2002	3	103.0	--	--	--	8.62E-03	6.73E-02	2.78E-02
2003	3	103.0	--	--	--	8.62E-03	6.73E-02	2.78E-02
2004	3	103.3	--	--	--	8.60E-03	6.72E-02	2.78E-02
2005	3	103.0	--	--	--	8.62E-03	6.73E-02	2.78E-02
2006	2	103.0	--	--	--	4.56E-03	5.60E-02	1.99E-02
2007	2	103.6	--	--	--	4.53E-03	5.57E-02	1.98E-02
2008	1	104.3	--	--	--	1.39E-03	4.36E-02	1.18E-02
2009	1	104.0	--	--	--	1.39E-03	4.37E-02	1.18E-02
2010	2	104.0	--	--	--	4.52E-03	5.55E-02	1.97E-02
2011	1	104.0	--	--	--	1.39E-03	4.37E-02	1.18E-02
2012	4	104.3	--	--	--	1.31E-02	7.75E-02	3.54E-02
2013	6	101.6	2.80E-02	7.73E-03	1.01E-01	2.37E-02	1.01E-01	5.23E-02
2014	3	100.0	2.44E-02	8.24E-03	7.21E-02	8.83E-03	6.90E-02	2.85E-02
2015	3	99.0	2.12E-02	8.50E-03	5.29E-02	8.91E-03	6.95E-02	2.88E-02
2016	0	99.2	1.85E-02	8.31E-03	4.10E-02	1.61E-05	3.21E-02	4.10E-03
2017	0	99.0	1.61E-02	7.50E-03	3.44E-02	1.62E-05	3.21E-02	4.11E-03
2018	3	98.7	1.40E-02	6.19E-03	3.16E-02	8.92E-03	6.97E-02	2.88E-02
2019	4	97.0	1.22E-02	4.74E-03	3.13E-02	1.39E-02	8.22E-02	3.76E-02
2020	0	95.3	1.06E-02	3.46E-03	3.25E-02	1.67E-05	3.31E-02	4.24E-03
2021	1	93.3	9.22E-03	2.44E-03	3.48E-02	1.52E-03	4.77E-02	1.29E-02
2022	1	92.4	8.03E-03	1.70E-03	3.79E-02	1.53E-03	4.81E-02	1.30E-02
Total	73	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	1	103.0	--	--	--	1.14E-03	3.59E-02	9.72E-03
1999	3	103.0	--	--	--	7.02E-03	5.48E-02	2.27E-02
2000	1	103.3	--	--	--	1.14E-03	3.58E-02	9.70E-03
2001	0	103.0	--	--	--	1.27E-05	2.53E-02	3.24E-03
2002	1	103.0	--	--	--	1.14E-03	3.59E-02	9.72E-03
2003	3	103.0	--	--	--	7.02E-03	5.48E-02	2.27E-02
2004	3	103.3	--	--	--	7.01E-03	5.47E-02	2.26E-02
2005	0	103.0	--	--	--	1.27E-05	2.53E-02	3.24E-03
2006	0	103.0	--	--	--	1.27E-05	2.53E-02	3.24E-03
2007	0	103.6	--	--	--	1.27E-05	2.52E-02	3.23E-03
2008	0	104.3	--	--	--	1.26E-05	2.51E-02	3.21E-03
2009	0	104.0	--	--	--	1.27E-05	2.52E-02	3.22E-03
2010	3	104.0	--	--	--	6.98E-03	5.45E-02	2.25E-02
2011	0	104.0	--	--	--	1.27E-05	2.52E-02	3.22E-03
2012	1	104.3	--	--	--	1.13E-03	3.56E-02	9.64E-03
2013	2	101.6	9.09E-03	2.71E-03	3.04E-02	3.75E-03	4.60E-02	1.63E-02
2014	2	100.0	8.61E-03	3.09E-03	2.40E-02	3.78E-03	4.65E-02	1.65E-02
2015	0	99.0	8.17E-03	3.45E-03	1.93E-02	1.31E-05	2.60E-02	3.33E-03
2016	0	99.2	7.74E-03	3.71E-03	1.62E-02	1.31E-05	2.60E-02	3.32E-03
2017	0	99.0	7.34E-03	3.77E-03	1.43E-02	1.31E-05	2.60E-02	3.33E-03
2018	2	98.7	6.96E-03	3.55E-03	1.37E-02	3.82E-03	4.69E-02	1.67E-02
2019	2	97.0	6.60E-03	3.11E-03	1.40E-02	3.86E-03	4.74E-02	1.69E-02
2020	0	95.3	6.26E-03	2.58E-03	1.52E-02	1.34E-05	2.67E-02	3.41E-03
2021	0	93.3	5.93E-03	2.07E-03	1.70E-02	1.36E-05	2.70E-02	3.46E-03
2022	1	92.4	5.62E-03	1.62E-03	1.95E-02	1.22E-03	3.85E-02	1.04E-02
Total	25	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	4	103.0	--	--	--	1.04E-02	6.13E-02	2.81E-02
1999	0	103.0	--	--	--	1.23E-05	2.44E-02	3.12E-03
2000	6	103.3	--	--	--	1.83E-02	7.78E-02	4.05E-02
2001	2	103.0	--	--	--	3.57E-03	4.39E-02	1.56E-02
2002	4	103.0	--	--	--	1.04E-02	6.13E-02	2.81E-02
2003	2	103.0	--	--	--	3.57E-03	4.39E-02	1.56E-02
2004	0	103.3	--	--	--	1.22E-05	2.43E-02	3.11E-03
2005	0	103.0	--	--	--	1.23E-05	2.44E-02	3.12E-03
2006	1	103.0	--	--	--	1.10E-03	3.45E-02	9.35E-03
2007	6	103.6	--	--	--	1.83E-02	7.76E-02	4.04E-02
2008	5	104.3	--	--	--	1.41E-02	6.92E-02	3.40E-02
2009	1	104.0	--	--	--	1.09E-03	3.43E-02	9.29E-03
2010	3	104.0	--	--	--	6.72E-03	5.24E-02	2.17E-02
2011	0	104.0	--	--	--	1.22E-05	2.42E-02	3.10E-03
2012	4	104.3	--	--	--	1.03E-02	6.08E-02	2.78E-02
2013	2	101.6	1.22E-02	4.30E-03	3.46E-02	3.60E-03	4.42E-02	1.57E-02
2014	2	100.0	1.05E-02	4.33E-03	2.54E-02	3.64E-03	4.47E-02	1.59E-02
2015	3	99.0	9.01E-03	4.27E-03	1.90E-02	6.93E-03	5.41E-02	2.24E-02
2016	0	99.2	7.75E-03	4.08E-03	1.47E-02	1.26E-05	2.49E-02	3.19E-03
2017	0	99.0	6.66E-03	3.71E-03	1.19E-02	1.26E-05	2.50E-02	3.20E-03
2018	0	98.7	5.72E-03	3.16E-03	1.03E-02	1.26E-05	2.50E-02	3.20E-03
2019	0	97.0	4.92E-03	2.54E-03	9.54E-03	1.27E-05	2.53E-02	3.24E-03
2020	0	95.3	4.23E-03	1.94E-03	9.20E-03	1.29E-05	2.56E-02	3.28E-03
2021	0	93.3	3.63E-03	1.45E-03	9.13E-03	1.30E-05	2.59E-02	3.32E-03
2022	1	92.4	3.12E-03	1.06E-03	9.22E-03	1.17E-03	3.70E-02	1.00E-02
Total	46	2,527.3	--	--	--	--	--	--

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

Year	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	0	103.0	--	--	--	8.11E-06	1.61E-02	2.06E-03
1999	1	103.0	--	--	--	7.26E-04	2.28E-02	6.19E-03
2000	1	103.3	--	--	--	7.25E-04	2.28E-02	6.18E-03
2001	0	103.0	--	--	--	8.11E-06	1.61E-02	2.06E-03
2002	0	103.0	--	--	--	8.11E-06	1.61E-02	2.06E-03
2003	2	103.0	--	--	--	2.36E-03	2.90E-02	1.03E-02
2004	0	103.3	--	--	--	8.10E-06	1.61E-02	2.06E-03
2005	0	103.0	--	--	--	8.11E-06	1.61E-02	2.06E-03
2006	0	103.0	--	--	--	8.11E-06	1.61E-02	2.06E-03
2007	0	103.6	--	--	--	8.09E-06	1.61E-02	2.06E-03
2008	1	104.3	--	--	--	7.22E-04	2.27E-02	6.16E-03
2009	0	104.0	--	--	--	8.08E-06	1.61E-02	2.05E-03
2010	0	104.0	--	--	--	8.08E-06	1.61E-02	2.05E-03
2011	2	104.0	--	--	--	2.35E-03	2.89E-02	1.03E-02
2012	0	104.3	--	--	--	8.07E-06	1.60E-02	2.05E-03
2013	0	101.6	3.38E-03	1.50E-03	7.63E-03	8.16E-06	1.62E-02	2.08E-03
2014	0	100.0	3.28E-03	1.64E-03	6.54E-03	8.21E-06	1.63E-02	2.09E-03
2015	1	99.0	3.17E-03	1.78E-03	5.67E-03	7.38E-04	2.32E-02	6.29E-03
2016	0	99.2	3.07E-03	1.88E-03	5.03E-03	8.24E-06	1.64E-02	2.10E-03
2017	1	99.0	2.98E-03	1.92E-03	4.63E-03	7.38E-04	2.32E-02	6.29E-03
2018	1	98.7	2.88E-03	1.87E-03	4.46E-03	7.39E-04	2.32E-02	6.30E-03
2019	0	97.0	2.79E-03	1.73E-03	4.52E-03	8.32E-06	1.65E-02	2.12E-03
2020	0	95.3	2.71E-03	1.54E-03	4.75E-03	8.38E-06	1.67E-02	2.13E-03
2021	0	93.3	2.62E-03	1.34E-03	5.11E-03	8.45E-06	1.68E-02	2.15E-03
2022	0	92.4	2.54E-03	1.15E-03	5.59E-03	8.48E-06	1.69E-02	2.16E-03
Total	10	2,527.3	--	--	--	--	--	--

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