INL/RPT-23-73953

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

July 2023

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Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC Agreement Number 31310019N0006
Task Order Number 31310019F0022

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ABSTRACT

This report presents an enhanced performance evaluation of air-operated valves (AOVs) 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 AOV 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 trends were identified for AOVs for the most recent 10-year period:

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

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

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

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FIGURES

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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
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 cooling injection
HPSI	high pressure safety injection
ICES	INPO Consolidated Events Database
INL	Idaho National Laboratory
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
NPRDS	Nuclear Plant Reliability Data System
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 system
RHR	residual heat removal
SO	spurious operation
SPAR	standardized plant analysis risk
SWN	normally operating service water
SWS	standby service water
TDP	turbine-driven pump

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

1. INTRODUCTION

This report presents an enhanced performance evaluation of air-operated valves (AOVs) 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) included failure events with lesser p-values indicating a degraded condition that probably would have caused failure during a 24-hour mission but were not hard failures at their outset.

The enhanced component performance studies are conducted for the following component types: AOVs, emergency diesel generators (EDGs), motor-driven pumps (MDPs), motor-operated valves (MOVs), and turbine-driven pumps (TDPs). The AOV performance analysis was originally published as NUREG-1715, Volume 3 in July 2001 [1] and then updated annually in a series of reports, with the last one being documented in INL/RPT-22-66461, *Enhanced Component Performance Study: Air-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]. Previously, the study relied on operating experience obtained from licensee event reports, Nuclear Plant Reliability Data System (NPRDS), and EPIX. The IRIS database (which includes the Mitigating Systems Performance Index [MSPI] designated devices [6] as a subset) has matured to the point where both component availability and reliability can be estimated with a high degree of accuracy.

AOVs are categorized as low-demand AOVs (with less than or equal to 20 demands/year) and high-demand AOVs (with greater than 20 demands/year) in this study. The AOV 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 evaluates 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 comparisons. 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 AOVs as well as the trending of the estimates. Section 4 presents engineering analyses performed for AOVs 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 AOVs 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 AOV 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 **low-demand AOV frequency of FTOC demands** (demands per reactor year) estimates with a p-value of 0.0005 (see Figure 7). The same trend was observed in the *2020 AOV Update* study [2].
- Extremely statistically significant **increasing trend** was identified in the **high-demand AOV frequency of FTOC demands** (demands per reactor year) estimates with a p-value of 0.0000 (see Figure 8). The same trend was observed in the *2020 AOV Update* study.

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 AOV FTOC failure probability** estimates with a p-value of 0.0006 (see Figure 1). This is a new trend that was not observed in the *2020 AOV Update* study.
- Extremely statistically significant **decreasing trend** was identified in the **low-demand AOV FTOP failure rate** estimates with a p-value of 0.0003 (see Figure 3). The same trend was observed in the *2020 AOV Update* study as highly statistically significant.
- Extremely statistically significant **decreasing trend** was identified in the **low-demand AOV frequency of FTOC events** (failures per reactor year) estimates with a p-value of 0.0008 (see Figure 9). This is a new trend that was not observed in the *2020 AOV Update* study.
- Extremely statistically significant **decreasing trend** was identified in the **low-demand AOV frequency of FTOP events** (failures per reactor year) estimates with a p-value of 0.0004 (see Figure 11). The same trend was observed in the *2020 AOV Update* study as highly statistically significant.

2.2.2 Highly Statistically Significant

- None

2.2.3 Statistically Significant

- None

a. Statistically significant 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 for AOVs have been calculated from the operating experience for the FTOC, FTOP, and SO failure modes. The AOV data set obtained from IRIS was partitioned to low-demand AOVs (those with less than or equal to 20 demands/year) and high-demand AOVs (those with greater than 20 demands/year). The data set includes AOVs in the systems listed in Table 1.

Table 2 shows industry-wide failure probability and failure rate results for low-demand AOVs from the *2020 Parameter Update* [7]. Note that only low-demand AOVs 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 AOVs 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 AOVs are assumed to operate both when the reactor is critical and during shutdown periods. The number of AOVs 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 AOV counts in the systems in which they are found.

		AOV Count		
System	Description	Total	Low Demand	High Demand
AFW	Auxiliary feedwater	409	340	69
CCW	Component cooling water	480	433	47
CRD	Control rod drive	122	110	12
CSR	Containment spray recirculation	38	38	0
HPCI	High pressure coolant injection	15	12	3
HPSI	High pressure safety injection	107	84	23
ISO	Isolation condenser	10	6	4
LPCS	Low pressure core spray	12	12	0
RCIC	Reactor core isolation cooling	10	10	0
RCS	Reactor coolant	123	105	18
RHR	Residual heat removal (LPCI in BWRs; LPSI in PWRs)	297	286	11
SWN	Normally operating service water	552	418	134
SWS	Standby service water	74	38	36
	Total	2249	1892	357

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

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTOC	1.73E-5	3.57E-4	5.58E-4	1.78E-3	Beta	0.83	1.49E+03
FTOP	1.50E-8	1.32E-7	1.75E-7	4.86E-7	Gamma	1.26	7.17E+06
SO	1.99E-9	3.79E-8	5.83E-8	1.85E-7	Gamma	0.86	1.47E+07

3.2 AOV Failure Probability and Failure Rate Trends

This section estimates industry-wide annual failure probabilities and failure rates for AOVs 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 *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 AOV 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 AOV FTOC events for low-demand and high-demand AOVs, respectively
- Figure 3 and Figure 4 show the failure rate estimate trends for AOV FTOP events for low-demand and high-demand AOVs, respectively
- Figure 5 and Figure 6 show the failure rate estimate trends for AOV SO events for low-demand and high-demand AOVs, respectively.

The following trends were identified for AOV failure probabilities/rates for FTOC, FTOP, and SO events in the most recent 10-year period:

- **Decreasing trend** in the **low-demand AOV FTOC failure probability** estimates, which is extremely statistically significant with a p-value of 0.0006 (see Figure 1). This is a new trend that was not observed in the *2020 AOV Update* study.
- **Decreasing trend** in the **low-demand AOV FTOP failure rate** estimates, which is extremely statistically significant with a p-value of 0.0003(see Figure 3). The same trend was observed in the *2020 AOV Update* study as highly statistically significant.

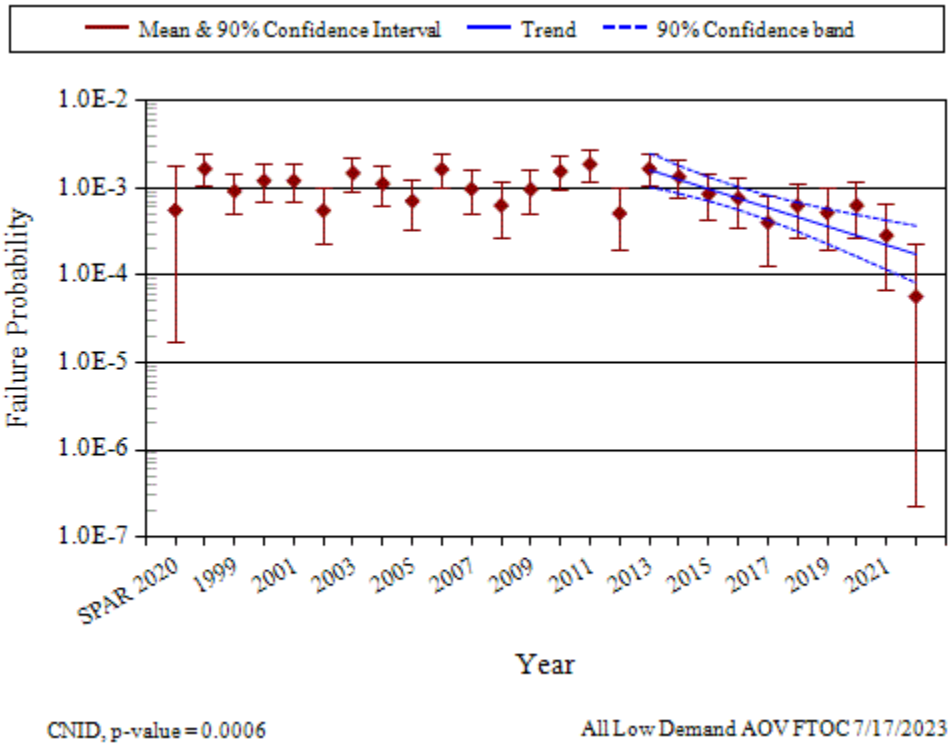

Figure 1. Failure probability estimate trend for low-demand AOV FTOC.

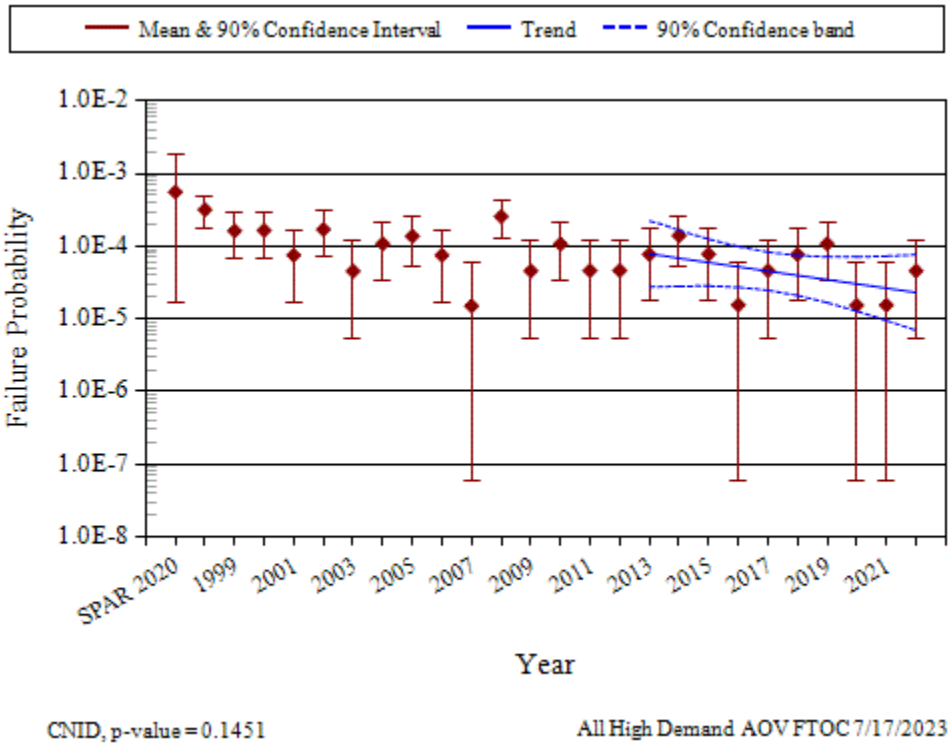

Figure 2. Failure probability estimate trend for high-demand AOV FTOC.

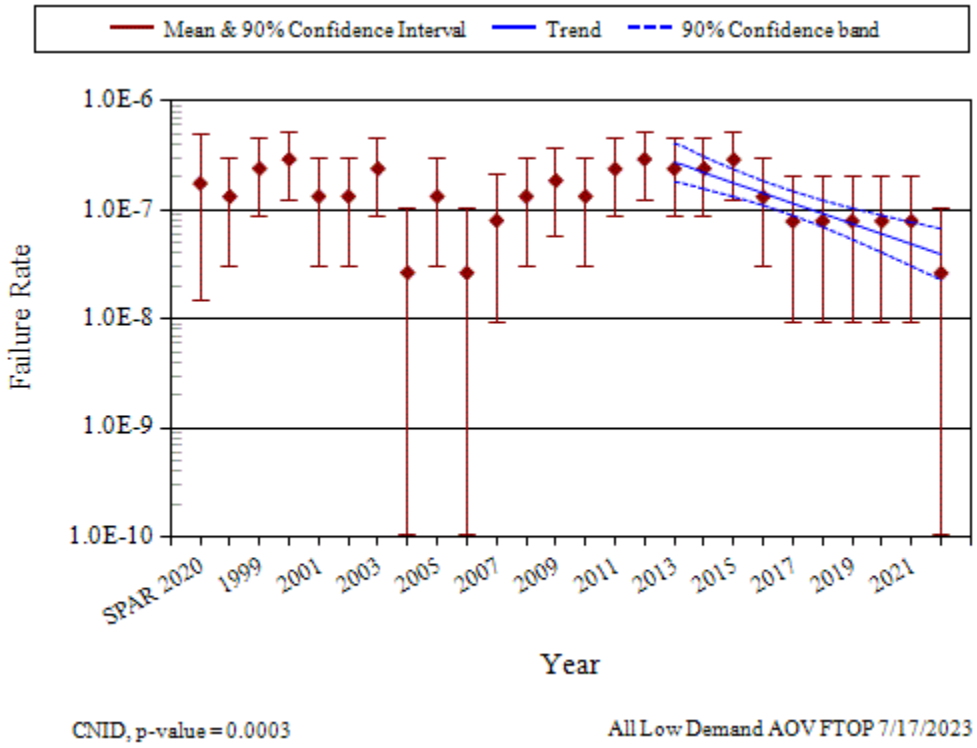

Figure 3. Failure rate estimate trend for low-demand AOV FTOP.

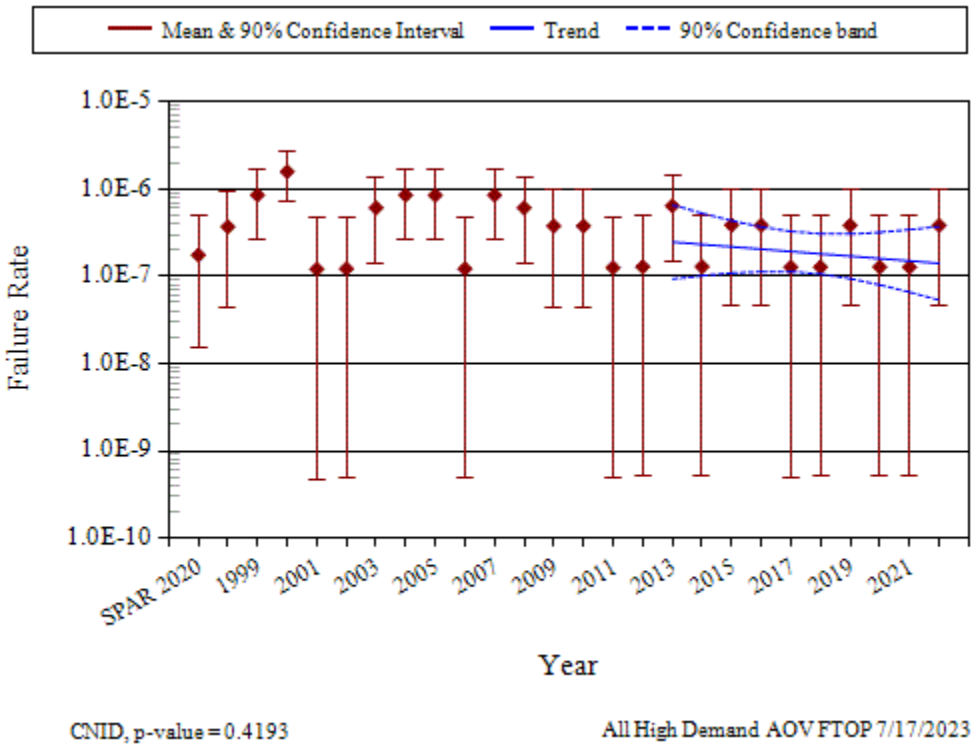

Figure 4. Failure rate estimate trend for high-demand AOV FTOP.

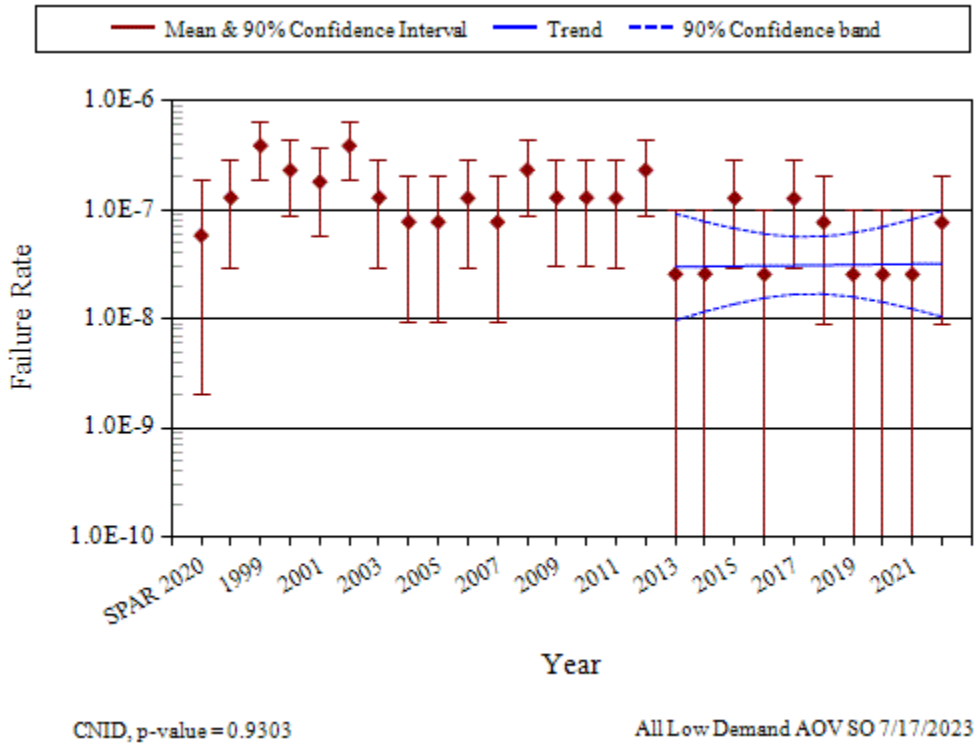

Figure 5. Failure rate estimate trend for low-demand AOV SO.

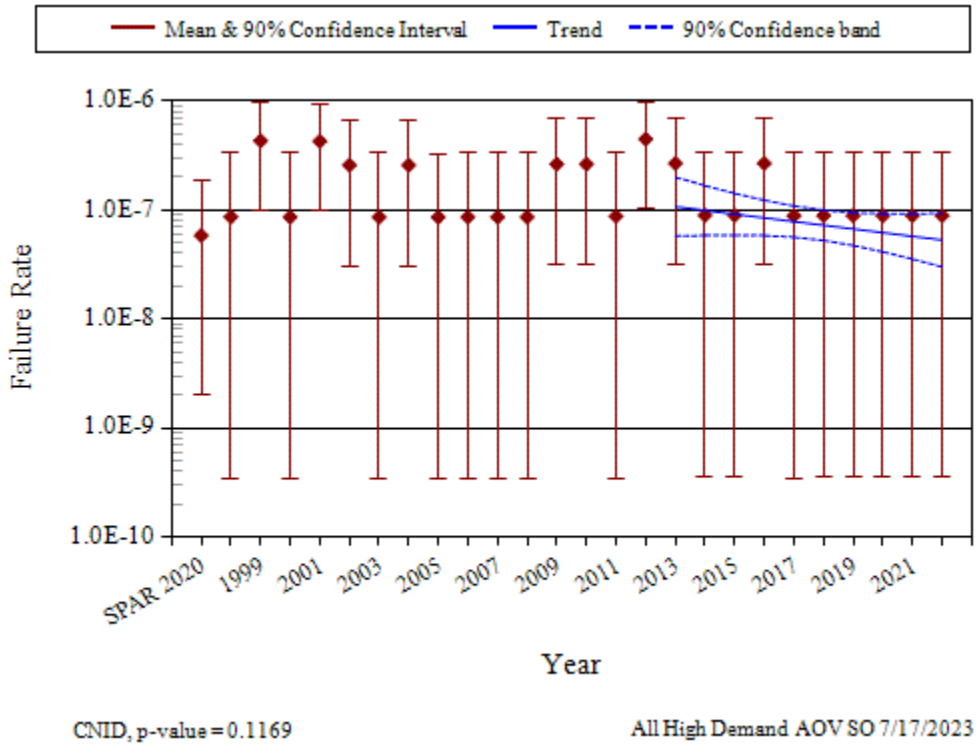

Figure 6. Failure rate estimate trend for high-demand AOV SO.

4. ENGINEERING ANALYSIS

4.1 Engineering Trends

This section presents frequency trends for AOV failure events 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 AOV demands, FTOC, FTOP, and SO events:

- Figure 7 and Figure 8 show the trends in frequency of FTOC demands (demands per reactor year) for low-demand and high-demand AOVs, respectively
- Figure 9 and Figure 10 show the trends in frequency of FTOC events (failures per reactor year) for low-demand and high-demand AOVs, respectively
- Figure 11 and Figure 12 show the trends in frequency of FTOP events (failures per reactor year) for low-demand and high-demand AOVs, respectively
- Figure 13 and Figure 14 show the trends in frequency of SO events (failures per reactor year) for low-demand and high-demand AOVs, 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 AOVs
- Table 4 presents the FTOP failure counts by system and year for low-demand AOVs
- Table 5 presents the SO failure counts by system and year for low-demand AOVs
- Table 6 presents the FTOC failure counts by system and year for high-demand AOVs
- Table 7 presents the FTOP failure counts by system and year for high-demand AOVs
- Table 8 presents the SO failure counts by system and year for high-demand AOVs.

The following trends were identified for AOV frequency of demands or events in the most recent 10-year period:

- **Increasing trend** in the **low-demand AOV frequency of FTOC demands** estimates, which is extremely statistically significant with a p-value of 0.0002 (see Figure 7). The same trend was observed in the *2020 AOV Update* study [2]
- **Increasing trend** in the **high-demand AOV frequency of FTOC demands** estimates, which is extremely statistically significant with a p-value of 0.0000 (see Figure 8). The same trend was observed in the *2020 AOV Update* study
- **Decreasing trend** in the **low-demand AOV frequency of FTOC events** estimates**,** which is extremely statistically significant with a p-value of 0.0008 (see Figure 9). This is a new trend that was not observed in the *2020 AOV Update* study.
- **Decreasing trend** in the **low-demand AOV frequency of FTOP events** estimates**,** which is extremely statistically significant with a p-value of 0.0004 (see Figure 11). The same trend was observed in the *2020 AOV Update* study as highly statistically significant.

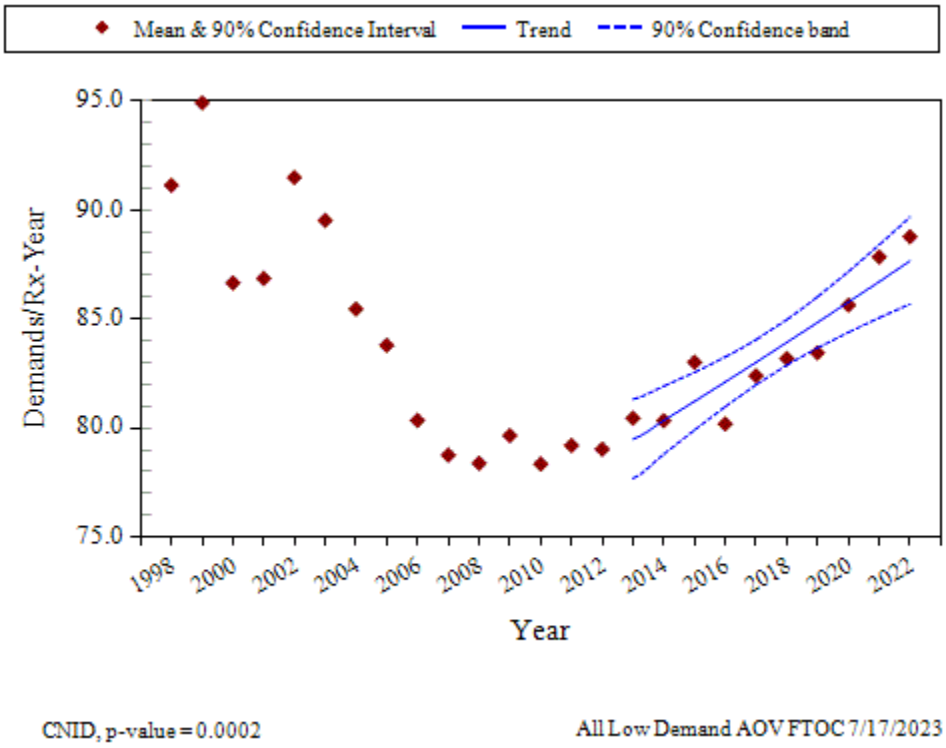

Figure 7. Frequency of FTOC demands (demands per reactor year) for low-demand AOVs.

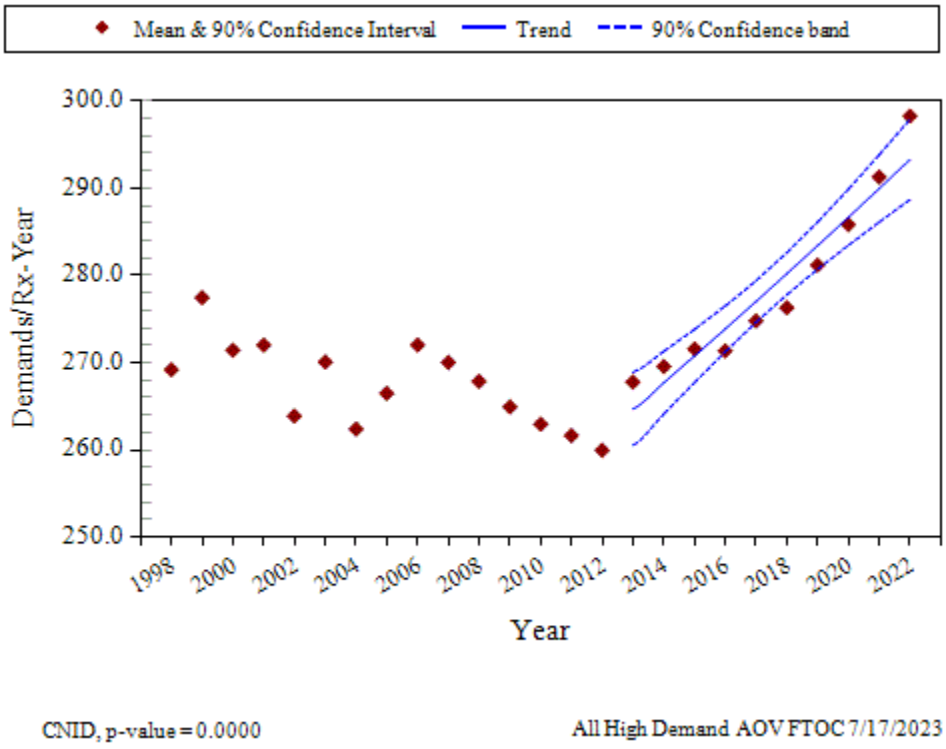

Figure 8. Frequency of FTOC demands (demands per reactor year) for high-demand AOVs.

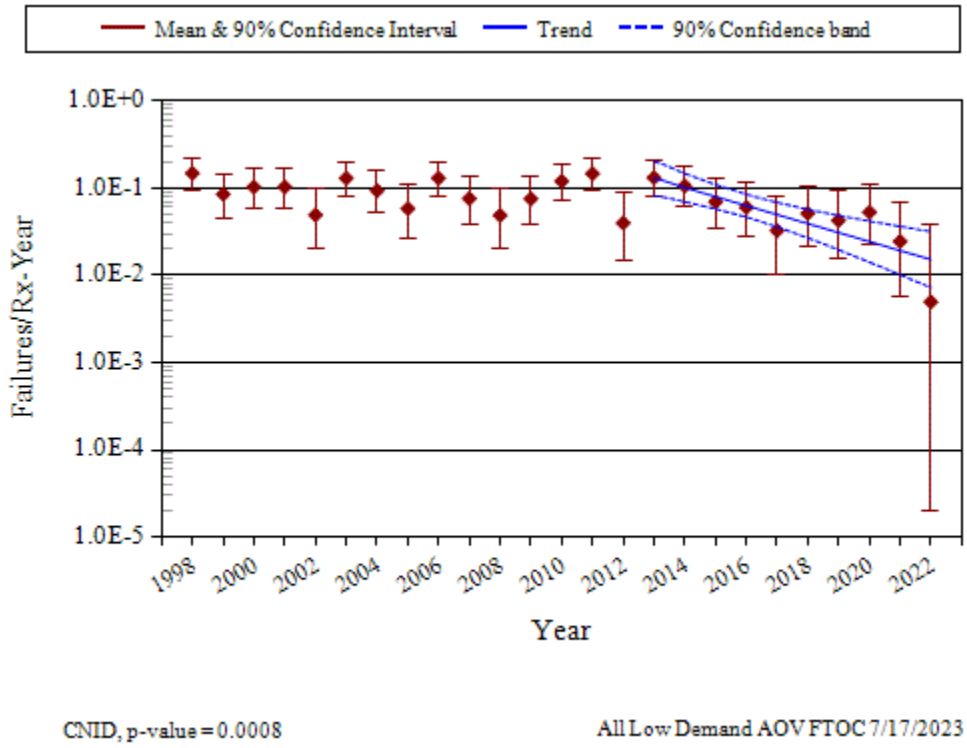

Figure 9. Frequency of FTOC events (failures per reactor year) for low-demand AOVs.

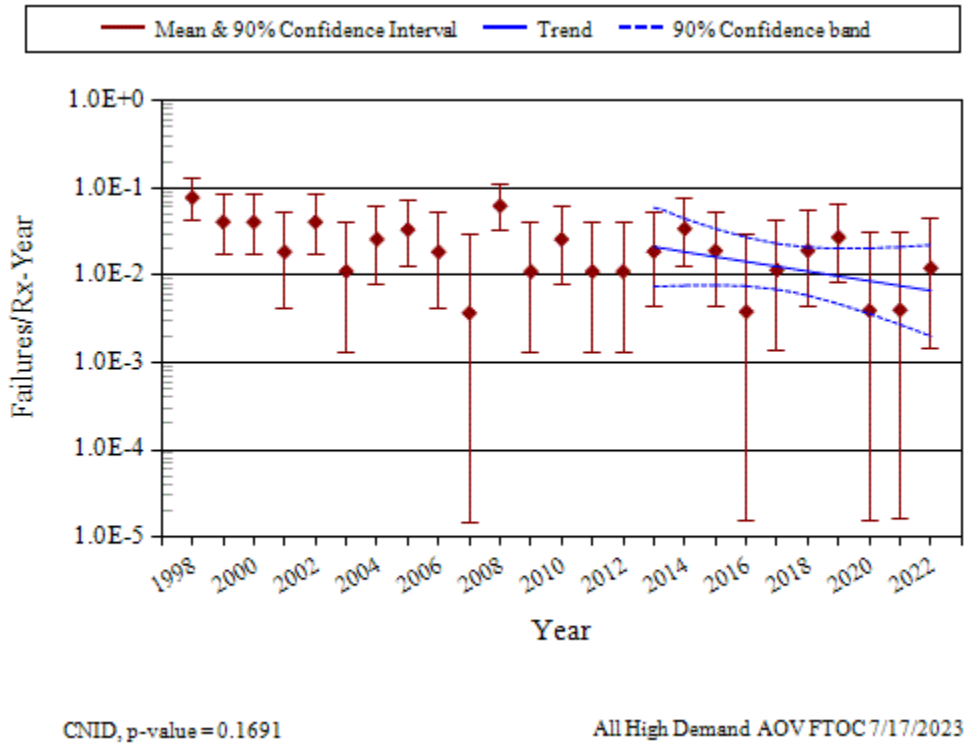

Figure 10. Frequency of FTOC events (failures per reactor year) for high-demand AOVs.

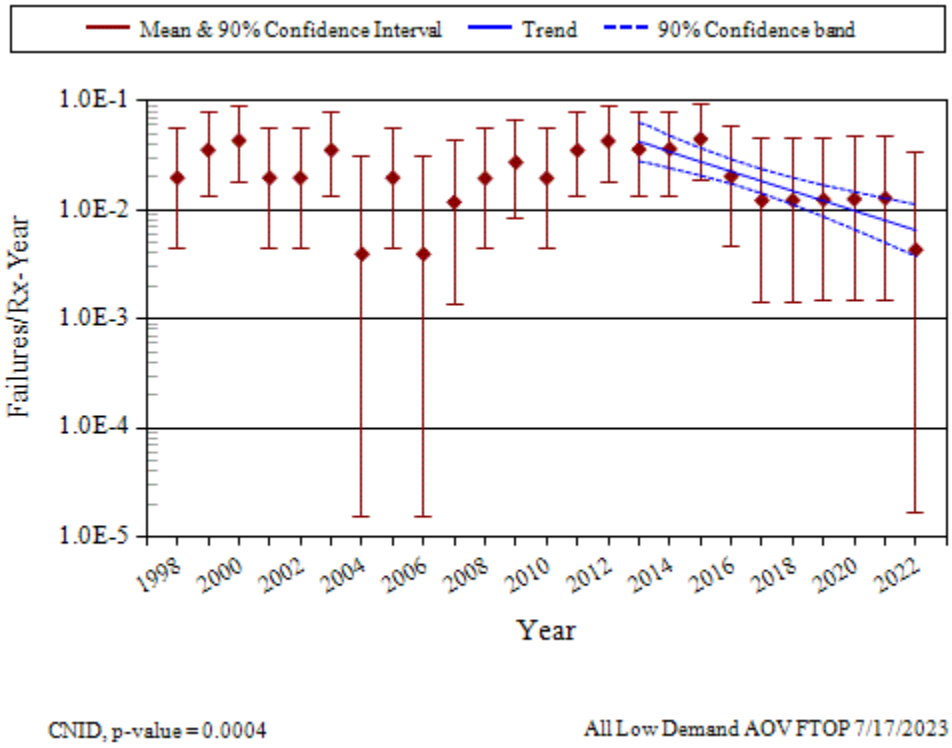

Figure 11. Frequency of FTOP events (failures per reactor year) for low-demand AOVs.

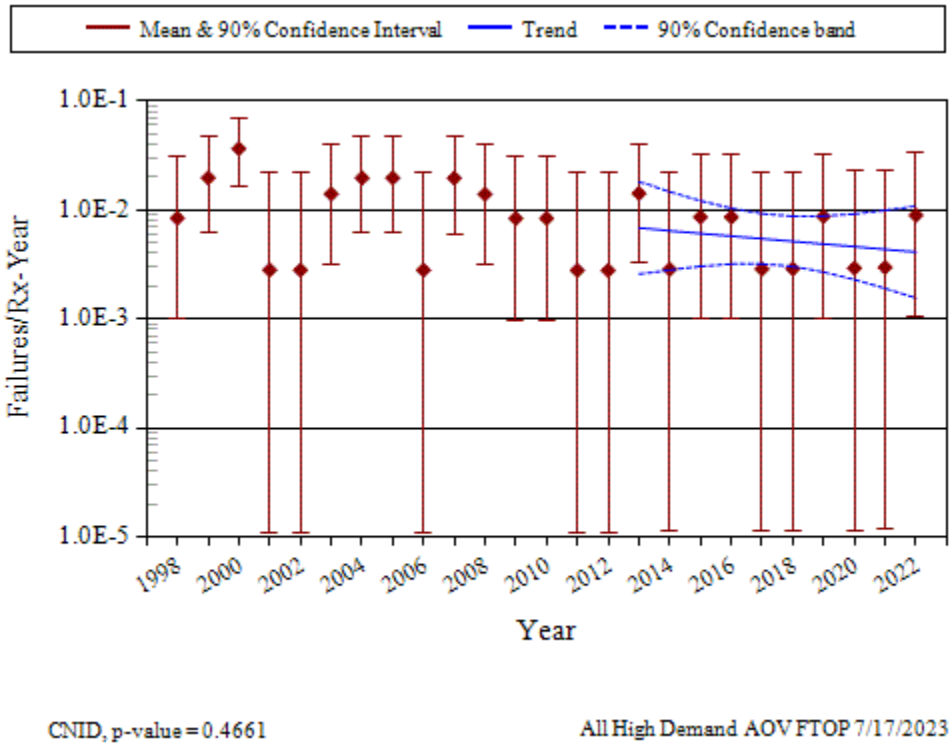

Figure 12. Frequency of FTOP events (failures per reactor year) for high-demand AOVs.

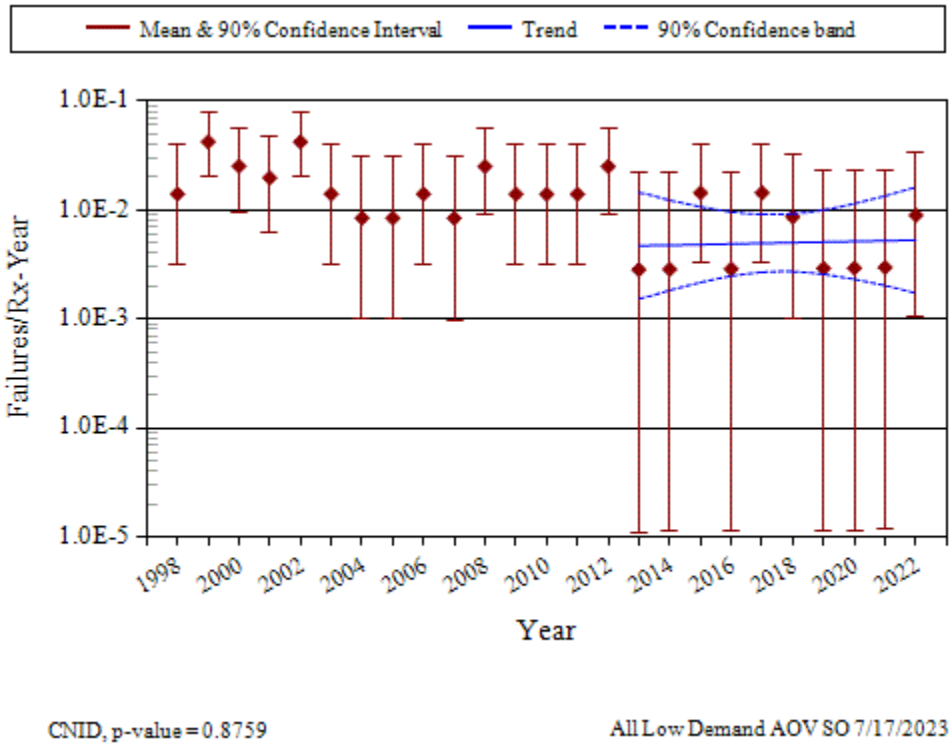

Figure 13. Frequency of SO events (failures per reactor year) for low-demand AOVs.

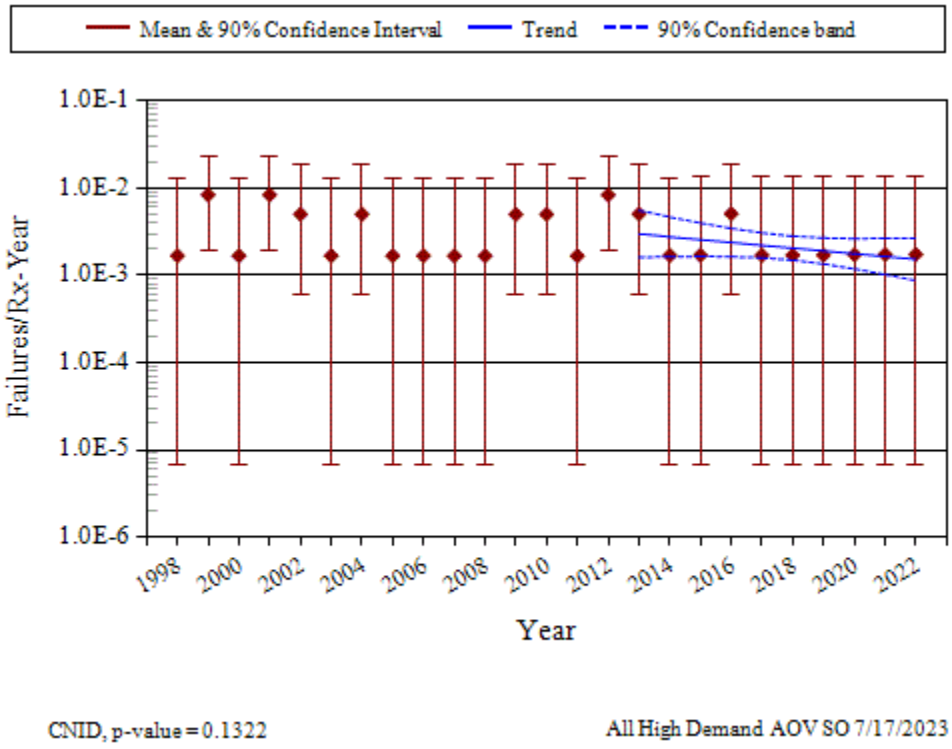

Figure 14. Frequency of SO events (failures per reactor year) for high-demand AOVs.

Table 3. Summary of low-demand AOV 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	340	18.0%	3	5	3		2	2	1				16	28.1%
CCW	433	22.9%	6	3	2					2			13	22.8%
CRD	110	5.8%	1						1				2	3.5%
CSR	38	2.0%											0	0.0%
HPCI	12	0.6%											0	0.0%
HPSI	84	4.4%		1									1	1.8%
ISO	6	0.3%											0	0.0%
LPCS	12	0.6%											0	0.0%
RCIC	10	0.5%											0	0.0%
RCS	105	5.5%				1			2				3	5.3%
RHR	286	15.1%	1	1	1	1		2		2			8	14.0%
SWN	418	22.1%	3	1		4	1	1		1	2		13	22.8%
SWS	38	2.0%			1								1	1.8%
Total	1892	100.0%	14	11	7	6	3	5	4	5	2	0	57	100.0%

Table 4. Summary of low-demand AOV 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	340	18.0%	4		3	1		1	1		1		11	55.0%
CCW	433	22.9%			1								1	5.0%
CRD	110	5.8%											0	0.0%
CSR	38	2.0%											0	0.0%
HPCI	12	0.6%											0	0.0%
HPSI	84	4.4%											0	0.0%
ISO	6	0.3%											0	0.0%
LPCS	12	0.6%											0	0.0%
RCIC	10	0.5%											0	0.0%
RCS	105	5.5%				1	1						2	10.0%
RHR	286	15.1%		1	1								2	10.0%
SWN	418	22.1%		3						1			4	20.0%
SWS	38	2.0%											0	0.0%
Total	1892	100.0%	4	4	5	2	1	1	1	1	1	0	20	100.0%

Table 5. Summary of low-demand AOV 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	340	18.0%			2		2						4	66.7%
CCW	433	22.9%											0	0.0%
CRD	110	5.8%											0	0.0%
CSR	38	2.0%											0	0.0%
HPCI	12	0.6%											0	0.0%
HPSI	84	4.4%											0	0.0%
ISO	6	0.3%											0	0.0%
LPCS	12	0.6%											0	0.0%
RCIC	10	0.5%											0	0.0%
RCS	105	5.5%											0	0.0%
RHR	286	15.1%										1	1	16.7%
SWN	418	22.1%						1					1	16.7%
SWS	38	2.0%											0	0.0%
Total	1892	100.0%	0	0	2	0	2	1	0	0	0	1	6	100.0%

Table 6. Summary of high-demand AOV 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	69	19.3%						1				1	2	13.3%
CCW	47	13.2%	1										1	6.7%
CRD	12	3.4%											0	0.0%
HPCI	3	0.8%											0	0.0%
HPSI	23	6.4%											0	0.0%
ISO	4	1.1%											0	0.0%
RCS	18	5.0%											0	0.0%
RHR	11	3.1%											0	0.0%
SWN	134	37.5%	1	4	2		1	1	3				12	80.0%
SWS	36	10.1%											0	0.0%
Total	357	100.0%	2	4	2	0	1	2	3	0	0	1	15	100.0%

Table 7. Summary of high-demand AOV 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	69	19.3%	1		1				1				3	50.0%
CCW	47	13.2%	1			1							2	33.3%
CRD	12	3.4%											0	0.0%
HPCI	3	0.8%											0	0.0%
HPSI	23	6.4%											0	0.0%
ISO	4	1.1%											0	0.0%
RCS	18	5.0%											0	0.0%
RHR	11	3.1%											0	0.0%
SWN	134	37.5%										1	1	16.7%
SWS	36	10.1%											0	0.0%
Total	357	100.0%	2	0	1	1	0	0	1	0	0	1	6	100.0%

Table 8. Summary of high-demand AOV 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	69	19.3%											0	0.0%
CCW	47	13.2%				1							1	50.0%
CRD	12	3.4%											0	0.0%
HPCI	3	0.8%											0	0.0%
HPSI	23	6.4%											0	0.0%
ISO	4	1.1%											0	0.0%
RCS	18	5.0%											0	0.0%
RHR	11	3.1%											0	0.0%
SWN	134	37.5%	1										1	50.0%
SWS	36	10.1%											0	0.0%
Total	357	100.0%	1	0	0	1	0	0	0	0	0	0	2	100.0%

4.2 AOV Engineering Analysis by Failure Modes

The engineering analysis of the AOV 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 AOVs (with less than or equal to 20 demands/year) and high-demand AOVs (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 after the IRIS data review by the Idaho National Laboratory (INL) staff. See Section 5 for further description of failure modes.

AOV 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.

AOV 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 AOV failures are presented below.

- The **Component** cause group is the most likely cause **for FTOC and FTOP**, and the second most likely cause for SO. 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 most likely cause **for FTOC** (same as the Component cause group), SO and also a key contributor to FTOP. The Human cause group is primarily influenced by maintenance and operating procedures and practices.
- The Design cause group, which is influenced by manufacturing, installation, and design issues, is a key contributor to all three failure modes.

AOV 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. The most likely detection method **for FTOC** is **test demand**. The most likely detection method **for FTOP** is **non-test demand**. The most likely detection method **for SO** is **inspection**.

AOV recovery fractions for the three failure modes are presented in Figure 18. The overall **non-recovery to recovery ratio** is approximately **7:1**, meaning that seven of every eight 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.
	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.

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

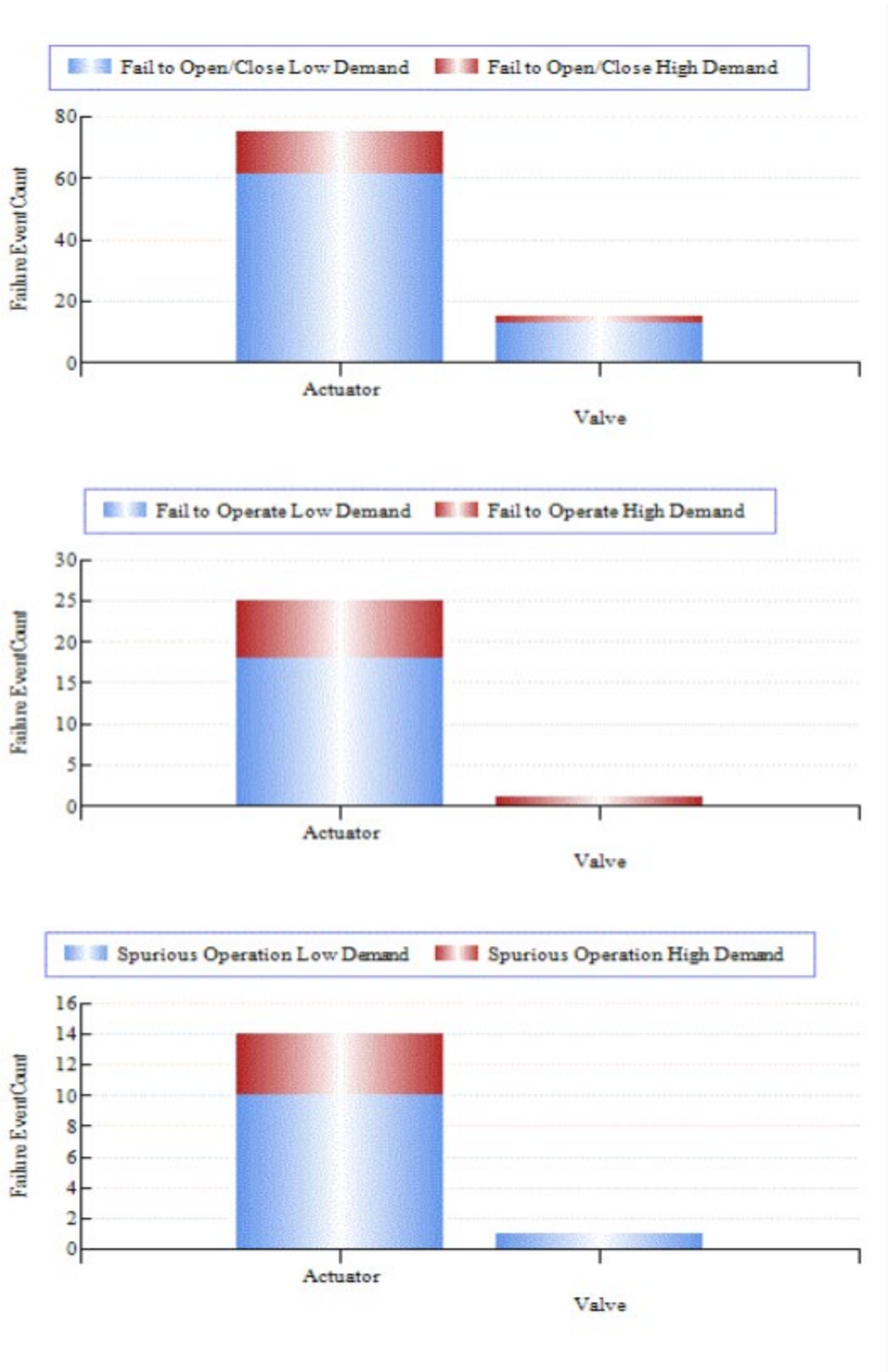

Figure 15. AOV failure event breakdown by subcomponent, failure mode, and demand rate

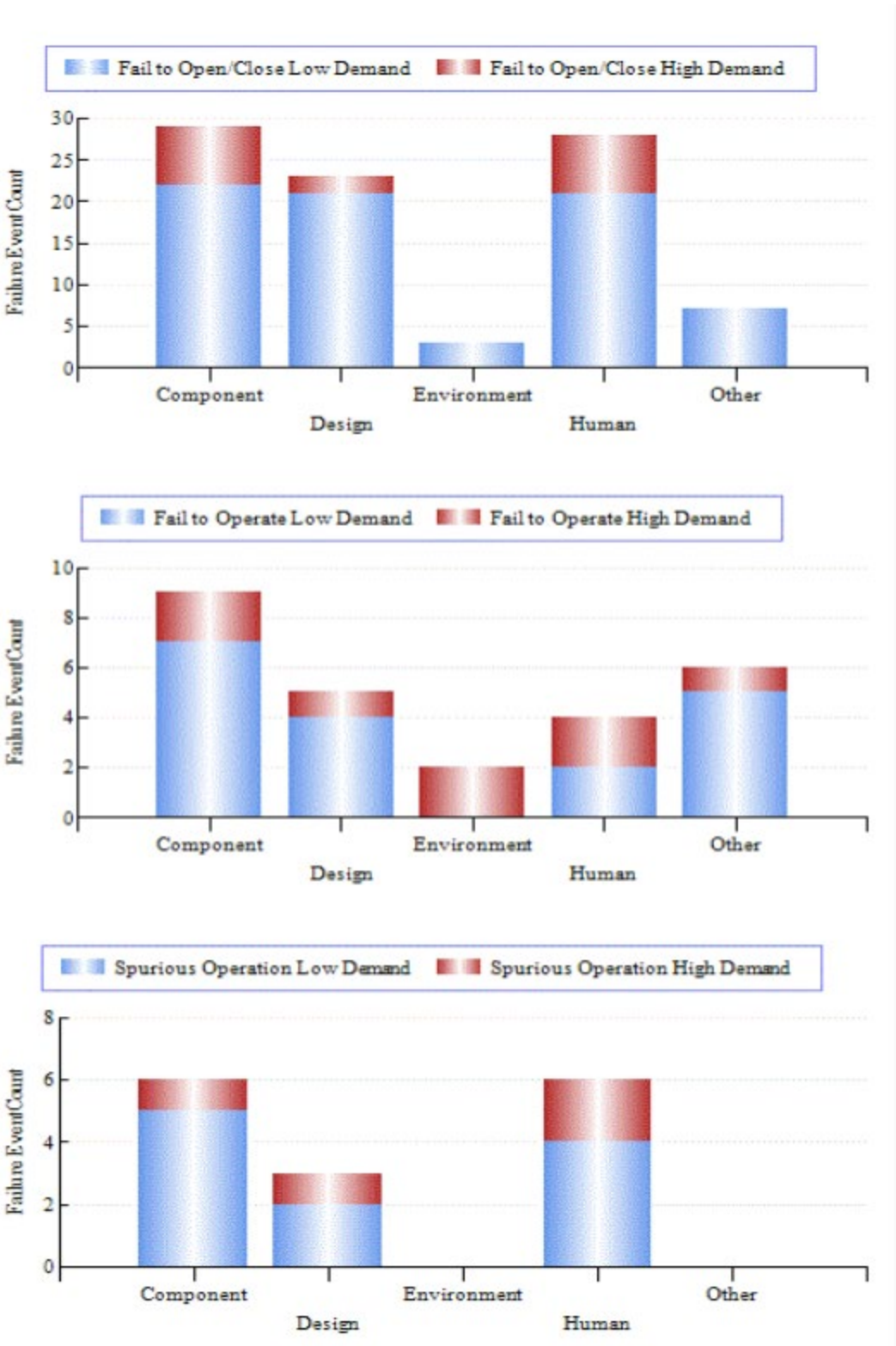

Figure 16. AOV failure event breakdown by cause group, failure mode, and demand rate

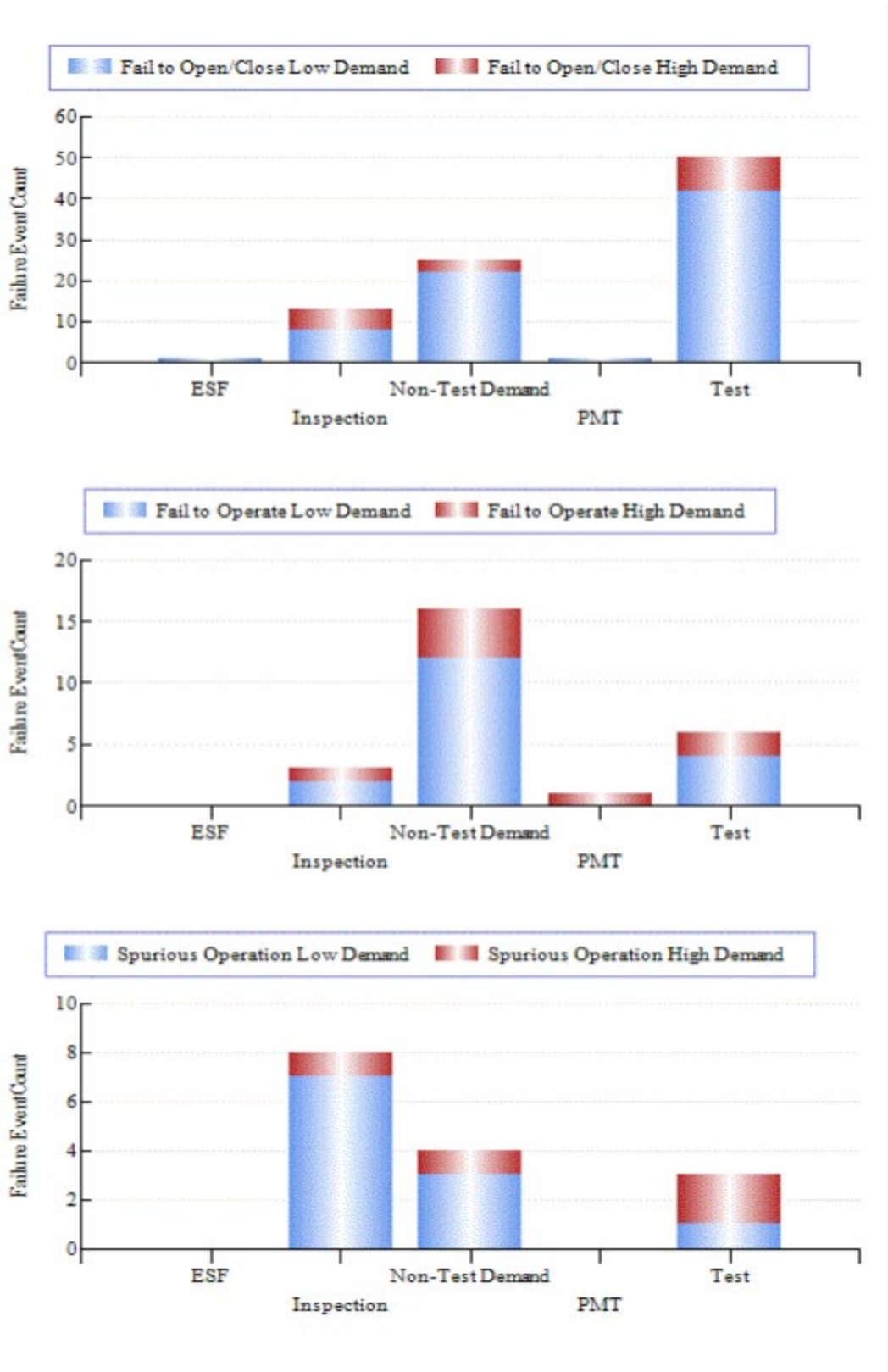

Figure 17. AOV failure event breakdown by method of detection, failure mode, and demand rate

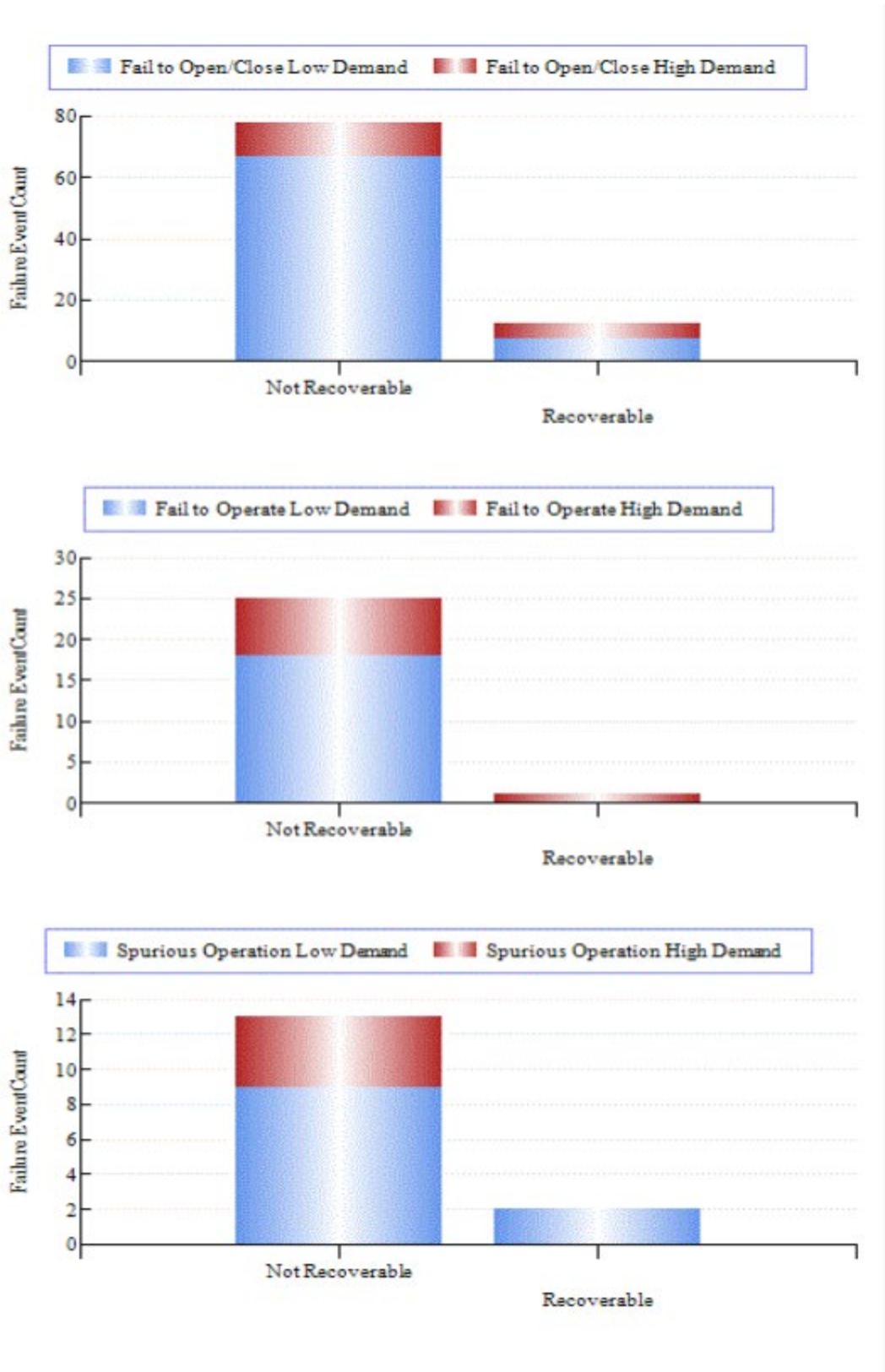

Figure 18. AOV failure event breakdown by recoverability, failure mode, and demand rate

5. AOV ASSEMBLY DESCRIPTION

An AOV assembly consists of a valve body and pneumatic operator subcomponents. The valve body is generally a globe or butterfly type. The pneumatic operator is generally a piston or diaphragm type actuator. Main steam isolation valves and power operated relief valves are excluded from the AOV study even though pneumatically operated, as these are valves with different design and operating features.

The piece-parts of the valve body are the stem, packing, and internals. The pneumatic operator piece-parts may include piston internals/seals or diaphragm, positioner, mechanical linkage, volume booster, pilot valve, bolting, air regulator, air line, and wiring/contacts. Failures associated with instrument air systems that are not integral to the AOV assembly (e.g., contamination from the instrument air system that failed the AOV) are excluded in the AOV analysis.

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

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Demands	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.73E-05	1.78E-03
1998	16	9,386	--	--	--	1.05E-03	2.39E-03	1.66E-03
1999	9	9,776	--	--	--	4.91E-04	1.46E-03	9.23E-04
2000	11	8,949	--	--	--	6.91E-04	1.86E-03	1.21E-03
2001	11	8,946	--	--	--	6.91E-04	1.86E-03	1.21E-03
2002	5	9,423	--	--	--	2.30E-04	9.90E-04	5.53E-04
2003	14	9,221	--	--	--	9.09E-04	2.18E-03	1.49E-03
2004	10	8,826	--	--	--	6.20E-04	1.75E-03	1.12E-03
2005	6	8,631	--	--	--	3.22E-04	1.22E-03	7.11E-04
2006	14	8,276	--	--	--	1.01E-03	2.42E-03	1.65E-03
2007	8	8,160	--	--	--	5.00E-04	1.59E-03	9.79E-04
2008	5	8,174	--	--	--	2.63E-04	1.13E-03	6.33E-04
2009	8	8,283	--	--	--	4.93E-04	1.57E-03	9.66E-04
2010	13	8,148	--	--	--	9.32E-04	2.31E-03	1.56E-03
2011	16	8,237	--	--	--	1.19E-03	2.70E-03	1.88E-03
2012	4	8,242	--	--	--	1.90E-04	9.66E-04	5.14E-04
2013	14	8,171	1.60E-03	1.03E-03	2.49E-03	1.02E-03	2.45E-03	1.67E-03
2014	11	8,033	1.25E-03	8.65E-04	1.80E-03	7.65E-04	2.06E-03	1.34E-03
2015	7	8,218	9.77E-04	7.13E-04	1.34E-03	4.16E-04	1.43E-03	8.58E-04
2016	6	7,956	7.64E-04	5.66E-04	1.03E-03	3.48E-04	1.32E-03	7.67E-04
2017	3	8,157	5.97E-04	4.32E-04	8.26E-04	1.25E-04	8.11E-04	4.04E-04
2018	5	8,214	4.67E-04	3.18E-04	6.85E-04	2.62E-04	1.13E-03	6.30E-04
2019	4	8,094	3.65E-04	2.30E-04	5.80E-04	1.93E-04	9.82E-04	5.23E-04
2020	5	8,158	2.85E-04	1.64E-04	4.96E-04	2.64E-04	1.13E-03	6.34E-04
2021	2	8,198	2.23E-04	1.16E-04	4.28E-04	6.57E-05	6.35E-04	2.87E-04
2022	0	8,204	1.74E-04	8.21E-05	3.71E-04	2.22E-07	2.20E-04	5.72E-05
Total	207	212,080	--	--	--	--	--	--

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

			Regression Curve Data Points			Plot Trend Error Bar Points		
Year	Failures	Demands	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.73E-05	1.78E-03
1998	10	27,725	--	--	--	1.76E-04	4.97E-04	3.19E-04
1999	5	28,576	--	--	--	6.78E-05	2.92E-04	1.63E-04
2000	5	28,032	--	--	--	6.89E-05	2.96E-04	1.66E-04
2001	2	28,016	--	--	--	1.73E-05	1.67E-04	7.53E-05
2002	5	27,179	--	--	--	7.07E-05	3.04E-04	1.70E-04
2003	1	27,816	--	--	--	5.33E-06	1.18E-04	4.55E-05
2004	3	27,098	--	--	--	3.36E-05	2.18E-04	1.08E-04
2005	4	27,446	--	--	--	5.10E-05	2.59E-04	1.38E-04
2006	2	28,017	--	--	--	1.73E-05	1.67E-04	7.53E-05
2007	0	27,976	--	--	--	5.92E-08	5.80E-05	1.51E-05
2008	8	27,931	--	--	--	1.31E-04	4.17E-04	2.57E-04
2009	1	27,552	--	--	--	5.38E-06	1.19E-04	4.58E-05
2010	3	27,345	--	--	--	3.33E-05	2.16E-04	1.08E-04
2011	1	27,210	--	--	--	5.43E-06	1.21E-04	4.63E-05
2012	1	27,108	--	--	--	5.45E-06	1.21E-04	4.65E-05
2013	2	27,197	7.83E-05	2.75E-05	2.23E-04	1.77E-05	1.71E-04	7.73E-05
2014	4	26,955	6.84E-05	2.83E-05	1.65E-04	5.18E-05	2.63E-04	1.40E-04
2015	2	26,884	5.97E-05	2.84E-05	1.26E-04	1.79E-05	1.73E-04	7.80E-05
2016	0	26,922	5.22E-05	2.74E-05	9.94E-05	6.12E-08	5.99E-05	1.56E-05
2017	1	27,204	4.56E-05	2.49E-05	8.34E-05	5.43E-06	1.21E-04	4.63E-05
2018	2	27,283	3.98E-05	2.11E-05	7.51E-05	1.77E-05	1.71E-04	7.70E-05
2019	3	27,271	3.47E-05	1.68E-05	7.19E-05	3.34E-05	2.17E-04	1.08E-04
2020	0	27,227	3.03E-05	1.28E-05	7.18E-05	6.06E-08	5.93E-05	1.54E-05
2021	0	27,184	2.65E-05	9.55E-06	7.36E-05	6.07E-08	5.94E-05	1.55E-05
2022	1	27,564	2.31E-05	7.00E-06	7.65E-05	5.37E-06	1.19E-04	4.58E-05
Total	66	686,718	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.50E-08	4.86E-07
1998	2	15,505,200	--	--	--	3.04E-08	2.94E-07	1.33E-07
1999	4	15,443,880	--	--	--	8.86E-08	4.51E-07	2.40E-07
2000	5	15,549,000	--	--	--	1.21E-07	5.21E-07	2.91E-07
2001	2	15,452,640	--	--	--	3.05E-08	2.95E-07	1.33E-07
2002	2	15,470,160	--	--	--	3.05E-08	2.95E-07	1.33E-07
2003	4	15,505,200	--	--	--	8.83E-08	4.49E-07	2.39E-07
2004	0	15,487,680	--	--	--	1.05E-10	1.02E-07	2.66E-08
2005	2	15,470,160	--	--	--	3.05E-08	2.95E-07	1.33E-07
2006	0	15,592,800	--	--	--	1.04E-10	1.02E-07	2.64E-08
2007	1	15,478,920	--	--	--	9.36E-09	2.08E-07	7.98E-08
2008	2	15,487,680	--	--	--	3.04E-08	2.94E-07	1.33E-07
2009	3	15,470,160	--	--	--	5.77E-08	3.74E-07	1.86E-07
2010	2	15,470,160	--	--	--	3.05E-08	2.95E-07	1.33E-07
2011	4	15,627,840	--	--	--	8.77E-08	4.46E-07	2.37E-07
2012	5	15,522,720	--	--	--	1.21E-07	5.22E-07	2.92E-07
2013	4	15,522,720	2.71E-07	1.81E-07	4.07E-07	8.82E-08	4.49E-07	2.39E-07
2014	4	15,461,400	2.19E-07	1.56E-07	3.07E-07	8.85E-08	4.50E-07	2.40E-07
2015	5	15,662,880	1.77E-07	1.32E-07	2.35E-07	1.20E-07	5.18E-07	2.90E-07
2016	2	15,671,640	1.42E-07	1.10E-07	1.84E-07	3.02E-08	2.91E-07	1.32E-07
2017	1	15,750,480	1.15E-07	8.90E-08	1.48E-07	9.22E-09	2.05E-07	7.86E-08
2018	1	15,636,600	9.26E-08	6.99E-08	1.23E-07	9.28E-09	2.06E-07	7.91E-08
2019	1	15,636,600	7.47E-08	5.37E-08	1.04E-07	9.28E-09	2.06E-07	7.91E-08
2020	1	15,636,600	6.02E-08	4.07E-08	8.92E-08	9.28E-09	2.06E-07	7.91E-08
2021	1	15,671,640	4.86E-08	3.05E-08	7.73E-08	9.26E-09	2.06E-07	7.90E-08
2022	0	15,671,640	3.92E-08	2.28E-08	6.72E-08	1.04E-10	1.01E-07	2.63E-08
Total	58	388,856,400	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.50E-08	4.86E-07
1998	1	2,925,840	--	--	--	4.33E-08	9.62E-07	3.69E-07
1999	3	2,943,360	--	--	--	2.66E-07	1.73E-06	8.58E-07
2000	6	2,960,880	--	--	--	7.19E-07	2.73E-06	1.59E-06
2001	0	2,995,920	--	--	--	4.76E-10	4.65E-07	1.21E-07
2002	0	2,960,880	--	--	--	4.80E-10	4.69E-07	1.22E-07
2003	2	2,960,880	--	--	--	1.40E-07	1.35E-06	6.11E-07
2004	3	2,960,880	--	--	--	2.65E-07	1.72E-06	8.55E-07
2005	3	2,969,640	--	--	--	2.64E-07	1.71E-06	8.53E-07
2006	0	2,952,120	--	--	--	4.81E-10	4.70E-07	1.22E-07
2007	3	2,952,120	--	--	--	2.65E-07	1.72E-06	8.57E-07
2008	2	2,960,880	--	--	--	1.40E-07	1.35E-06	6.11E-07
2009	1	2,838,240	--	--	--	4.43E-08	9.84E-07	3.78E-07
2010	1	2,838,240	--	--	--	4.43E-08	9.84E-07	3.78E-07
2011	0	2,855,760	--	--	--	4.93E-10	4.81E-07	1.25E-07
2012	0	2,750,640	--	--	--	5.06E-10	4.94E-07	1.29E-07
2013	2	2,750,640	2.47E-07	9.37E-08	6.51E-07	1.47E-07	1.42E-06	6.44E-07
2014	0	2,733,120	2.32E-07	1.02E-07	5.28E-07	5.08E-10	4.97E-07	1.29E-07
2015	1	2,741,880	2.18E-07	1.09E-07	4.36E-07	4.54E-08	1.01E-06	3.87E-07
2016	1	2,750,640	2.05E-07	1.14E-07	3.70E-07	4.53E-08	1.01E-06	3.86E-07
2017	0	2,785,680	1.93E-07	1.13E-07	3.28E-07	5.02E-10	4.90E-07	1.28E-07
2018	0	2,768,160	1.81E-07	1.07E-07	3.08E-07	5.04E-10	4.92E-07	1.28E-07
2019	1	2,768,160	1.70E-07	9.44E-08	3.07E-07	4.51E-08	1.00E-06	3.84E-07
2020	0	2,768,160	1.60E-07	8.00E-08	3.20E-07	5.04E-10	4.92E-07	1.28E-07
2021	0	2,768,160	1.50E-07	6.60E-08	3.43E-07	5.04E-10	4.92E-07	1.28E-07
2022	1	2,768,160	1.41E-07	5.35E-08	3.74E-07	4.51E-08	1.00E-06	3.84E-07
Total	31	71,429,040	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.99E-09	1.85E-07
1998	2	15,505,200	--	--	--	2.96E-08	2.86E-07	1.29E-07
1999	7	15,443,880	--	--	--	1.88E-07	6.48E-07	3.89E-07
2000	4	15,549,000	--	--	--	8.57E-08	4.36E-07	2.32E-07
2001	3	15,452,640	--	--	--	5.61E-08	3.64E-07	1.81E-07
2002	7	15,470,160	--	--	--	1.88E-07	6.47E-07	3.88E-07
2003	2	15,505,200	--	--	--	2.96E-08	2.86E-07	1.29E-07
2004	1	15,487,680	--	--	--	9.10E-09	2.02E-07	7.76E-08
2005	1	15,470,160	--	--	--	9.11E-09	2.02E-07	7.76E-08
2006	2	15,592,800	--	--	--	2.95E-08	2.85E-07	1.29E-07
2007	1	15,478,920	--	--	--	9.10E-09	2.02E-07	7.76E-08
2008	4	15,487,680	--	--	--	8.60E-08	4.37E-07	2.33E-07
2009	2	15,470,160	--	--	--	2.96E-08	2.87E-07	1.29E-07
2010	2	15,470,160	--	--	--	2.96E-08	2.87E-07	1.29E-07
2011	2	15,627,840	--	--	--	2.94E-08	2.84E-07	1.28E-07
2012	4	15,522,720	--	--	--	8.58E-08	4.37E-07	2.32E-07
2013	0	15,522,720	3.00E-08	9.84E-09	9.17E-08	1.01E-10	9.91E-08	2.58E-08
2014	0	15,461,400	3.03E-08	1.17E-08	7.80E-08	1.02E-10	9.95E-08	2.59E-08
2015	2	15,662,880	3.05E-08	1.38E-08	6.76E-08	2.94E-08	2.84E-07	1.28E-07
2016	0	15,671,640	3.07E-08	1.56E-08	6.05E-08	1.01E-10	9.84E-08	2.56E-08
2017	2	15,750,480	3.10E-08	1.68E-08	5.69E-08	2.92E-08	2.82E-07	1.28E-07
2018	1	15,636,600	3.12E-08	1.70E-08	5.74E-08	9.03E-09	2.01E-07	7.70E-08
2019	0	15,636,600	3.14E-08	1.60E-08	6.19E-08	1.01E-10	9.86E-08	2.57E-08
2020	0	15,636,600	3.17E-08	1.43E-08	7.02E-08	1.01E-10	9.86E-08	2.57E-08
2021	0	15,671,640	3.19E-08	1.24E-08	8.22E-08	1.01E-10	9.84E-08	2.56E-08
2022	1	15,671,640	3.21E-08	1.05E-08	9.82E-08	9.01E-09	2.00E-07	7.68E-08
Total	50	388,856,400	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Hours	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR 2020				--	--	--	1.99E-09	1.85E-07
1998	0	2,925,840	--	--	--	3.40E-10	3.32E-07	8.65E-08
1999	2	2,943,360	--	--	--	9.87E-08	9.54E-07	4.31E-07
2000	0	2,960,880	--	--	--	3.38E-10	3.30E-07	8.59E-08
2001	2	2,995,920	--	--	--	9.79E-08	9.46E-07	4.27E-07
2002	1	2,960,880	--	--	--	3.02E-08	6.72E-07	2.58E-07
2003	0	2,960,880	--	--	--	3.38E-10	3.30E-07	8.59E-08
2004	1	2,960,880	--	--	--	3.02E-08	6.72E-07	2.58E-07
2005	0	2,969,640	--	--	--	3.37E-10	3.30E-07	8.58E-08
2006	0	2,952,120	--	--	--	3.38E-10	3.31E-07	8.61E-08
2007	0	2,952,120	--	--	--	3.38E-10	3.31E-07	8.61E-08
2008	0	2,960,880	--	--	--	3.38E-10	3.30E-07	8.59E-08
2009	1	2,838,240	--	--	--	3.09E-08	6.86E-07	2.63E-07
2010	1	2,838,240	--	--	--	3.09E-08	6.86E-07	2.63E-07
2011	0	2,855,760	--	--	--	3.44E-10	3.36E-07	8.75E-08
2012	2	2,750,640	--	--	--	1.02E-07	9.87E-07	4.46E-07
2013	1	2,750,640	1.07E-07	5.78E-08	1.98E-07	3.14E-08	6.97E-07	2.67E-07
2014	0	2,733,120	9.88E-08	5.85E-08	1.67E-07	3.52E-10	3.44E-07	8.94E-08
2015	0	2,741,880	9.14E-08	5.88E-08	1.42E-07	3.51E-10	3.43E-07	8.93E-08
2016	1	2,750,640	8.46E-08	5.82E-08	1.23E-07	3.14E-08	6.97E-07	2.67E-07
2017	0	2,785,680	7.82E-08	5.63E-08	1.09E-07	3.48E-10	3.40E-07	8.86E-08
2018	0	2,768,160	7.24E-08	5.26E-08	9.96E-08	3.50E-10	3.41E-07	8.89E-08
2019	0	2,768,160	6.70E-08	4.74E-08	9.47E-08	3.50E-10	3.41E-07	8.89E-08
2020	0	2,768,160	6.19E-08	4.14E-08	9.27E-08	3.50E-10	3.41E-07	8.89E-08
2021	0	2,768,160	5.73E-08	3.55E-08	9.25E-08	3.50E-10	3.41E-07	8.89E-08
2022	0	2,768,160	5.30E-08	3.01E-08	9.34E-08	3.50E-10	3.41E-07	8.89E-08
Total	12	71,429,040	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Demands	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	9,386	103.0	--	--	--	8.96E+01	9.27E+01	9.11E+01
1999	9,776	103.0	--	--	--	9.33E+01	9.65E+01	9.49E+01
2000	8,949	103.3	--	--	--	8.51E+01	8.82E+01	8.66E+01
2001	8,946	103.0	--	--	--	8.54E+01	8.84E+01	8.69E+01
2002	9,423	103.0	--	--	--	8.99E+01	9.31E+01	9.15E+01
2003	9,221	103.0	--	--	--	8.80E+01	9.11E+01	8.95E+01
2004	8,826	103.3	--	--	--	8.40E+01	8.70E+01	8.55E+01
2005	8,631	103.0	--	--	--	8.23E+01	8.53E+01	8.38E+01
2006	8,276	103.0	--	--	--	7.89E+01	8.18E+01	8.03E+01
2007	8,160	103.6	--	--	--	7.73E+01	8.02E+01	7.88E+01
2008	8,174	104.3	--	--	--	7.70E+01	7.98E+01	7.84E+01
2009	8,283	104.0	--	--	--	7.82E+01	8.11E+01	7.96E+01
2010	8,148	104.0	--	--	--	7.69E+01	7.98E+01	7.83E+01
2011	8,237	104.0	--	--	--	7.78E+01	8.06E+01	7.92E+01
2012	8,242	104.3	--	--	--	7.76E+01	8.05E+01	7.90E+01
2013	8,171	101.6	7.95E+01	7.77E+01	8.13E+01	7.90E+01	8.19E+01	8.04E+01
2014	8,033	100.0	8.03E+01	7.88E+01	8.19E+01	7.89E+01	8.18E+01	8.03E+01
2015	8,218	99.0	8.12E+01	7.99E+01	8.26E+01	8.15E+01	8.45E+01	8.30E+01
2016	7,956	99.2	8.21E+01	8.10E+01	8.33E+01	7.87E+01	8.17E+01	8.02E+01
2017	8,157	99.0	8.30E+01	8.20E+01	8.41E+01	8.09E+01	8.39E+01	8.24E+01
2018	8,214	98.7	8.39E+01	8.29E+01	8.50E+01	8.17E+01	8.47E+01	8.32E+01
2019	8,094	97.0	8.48E+01	8.37E+01	8.60E+01	8.19E+01	8.50E+01	8.34E+01
2020	8,158	95.3	8.58E+01	8.44E+01	8.72E+01	8.41E+01	8.72E+01	8.56E+01
2021	8,198	93.3	8.67E+01	8.51E+01	8.84E+01	8.63E+01	8.95E+01	8.78E+01
2022	8,204	92.4	8.77E+01	8.57E+01	8.97E+01	8.72E+01	9.04E+01	8.88E+01
Total	212,080	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Demands	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	27,725	103.0	--	--	--	2.67E+02	2.72E+02	2.69E+02
1999	28,576	103.0	--	--	--	2.75E+02	2.80E+02	2.77E+02
2000	28,032	103.3	--	--	--	2.69E+02	2.74E+02	2.71E+02
2001	28,016	103.0	--	--	--	2.69E+02	2.75E+02	2.72E+02
2002	27,179	103.0	--	--	--	2.61E+02	2.67E+02	2.64E+02
2003	27,816	103.0	--	--	--	2.67E+02	2.73E+02	2.70E+02
2004	27,098	103.3	--	--	--	2.60E+02	2.65E+02	2.62E+02
2005	27,446	103.0	--	--	--	2.64E+02	2.69E+02	2.66E+02
2006	28,017	103.0	--	--	--	2.69E+02	2.75E+02	2.72E+02
2007	27,976	103.6	--	--	--	2.67E+02	2.73E+02	2.70E+02
2008	27,931	104.3	--	--	--	2.65E+02	2.70E+02	2.68E+02
2009	27,552	104.0	--	--	--	2.62E+02	2.68E+02	2.65E+02
2010	27,345	104.0	--	--	--	2.60E+02	2.66E+02	2.63E+02
2011	27,210	104.0	--	--	--	2.59E+02	2.64E+02	2.62E+02
2012	27,108	104.3	--	--	--	2.57E+02	2.63E+02	2.60E+02
2013	27,197	101.6	2.65E+02	2.61E+02	2.69E+02	2.65E+02	2.70E+02	2.68E+02
2014	26,955	100.0	2.68E+02	2.64E+02	2.71E+02	2.67E+02	2.72E+02	2.70E+02
2015	26,884	99.0	2.71E+02	2.68E+02	2.74E+02	2.69E+02	2.74E+02	2.72E+02
2016	26,922	99.2	2.74E+02	2.71E+02	2.77E+02	2.69E+02	2.74E+02	2.71E+02
2017	27,204	99.0	2.77E+02	2.75E+02	2.79E+02	2.72E+02	2.78E+02	2.75E+02
2018	27,283	98.7	2.80E+02	2.78E+02	2.83E+02	2.74E+02	2.79E+02	2.76E+02
2019	27,271	97.0	2.83E+02	2.81E+02	2.86E+02	2.78E+02	2.84E+02	2.81E+02
2020	27,227	95.3	2.87E+02	2.83E+02	2.90E+02	2.83E+02	2.89E+02	2.86E+02
2021	27,184	93.3	2.90E+02	2.86E+02	2.94E+02	2.88E+02	2.94E+02	2.91E+02
2022	27,564	92.4	2.93E+02	2.89E+02	2.98E+02	2.95E+02	3.01E+02	2.98E+02
Total	686,718	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	16	103.0	--	--	--	9.36E-02	2.23E-01	1.48E-01
1999	9	103.0	--	--	--	4.54E-02	1.47E-01	8.52E-02
2000	11	103.3	--	--	--	5.86E-02	1.68E-01	1.03E-01
2001	11	103.0	--	--	--	5.87E-02	1.69E-01	1.03E-01
2002	5	103.0	--	--	--	2.05E-02	1.00E-01	4.93E-02
2003	14	103.0	--	--	--	7.94E-02	2.02E-01	1.30E-01
2004	10	103.3	--	--	--	5.19E-02	1.57E-01	9.39E-02
2005	6	103.0	--	--	--	2.64E-02	1.12E-01	5.83E-02
2006	14	103.0	--	--	--	7.94E-02	2.02E-01	1.30E-01
2007	8	103.6	--	--	--	3.87E-02	1.34E-01	7.58E-02
2008	5	104.3	--	--	--	2.03E-02	9.91E-02	4.88E-02
2009	8	104.0	--	--	--	3.85E-02	1.34E-01	7.56E-02
2010	13	104.0	--	--	--	7.18E-02	1.89E-01	1.20E-01
2011	16	104.0	--	--	--	9.28E-02	2.21E-01	1.47E-01
2012	4	104.3	--	--	--	1.47E-02	8.72E-02	3.99E-02
2013	14	101.6	1.28E-01	8.18E-02	2.01E-01	8.05E-02	2.04E-01	1.32E-01
2014	11	100.0	1.01E-01	6.97E-02	1.47E-01	6.03E-02	1.74E-01	1.06E-01
2015	7	99.0	7.98E-02	5.80E-02	1.10E-01	3.38E-02	1.28E-01	6.98E-02
2016	6	99.2	6.30E-02	4.67E-02	8.50E-02	2.74E-02	1.16E-01	6.04E-02
2017	3	99.0	4.97E-02	3.60E-02	6.85E-02	1.01E-02	7.87E-02	3.26E-02
2018	5	98.7	3.92E-02	2.69E-02	5.71E-02	2.13E-02	1.04E-01	5.13E-02
2019	4	97.0	3.09E-02	1.97E-02	4.86E-02	1.58E-02	9.33E-02	4.27E-02
2020	5	95.3	2.44E-02	1.42E-02	4.20E-02	2.20E-02	1.08E-01	5.30E-02
2021	2	93.3	1.92E-02	1.02E-02	3.65E-02	5.63E-03	6.91E-02	2.46E-02
2022	0	92.4	1.52E-02	7.24E-03	3.18E-02	1.95E-05	3.87E-02	4.96E-03
Total	207	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	10	103.0	--	--	--	4.31E-02	1.31E-01	7.81E-02
1999	5	103.0	--	--	--	1.70E-02	8.31E-02	4.09E-02
2000	5	103.3	--	--	--	1.70E-02	8.30E-02	4.08E-02
2001	2	103.0	--	--	--	4.26E-03	5.23E-02	1.86E-02
2002	5	103.0	--	--	--	1.70E-02	8.31E-02	4.09E-02
2003	1	103.0	--	--	--	1.31E-03	4.12E-02	1.12E-02
2004	3	103.3	--	--	--	8.04E-03	6.28E-02	2.60E-02
2005	4	103.0	--	--	--	1.24E-02	7.32E-02	3.35E-02
2006	2	103.0	--	--	--	4.26E-03	5.23E-02	1.86E-02
2007	0	103.6	--	--	--	1.46E-05	2.89E-02	3.70E-03
2008	8	104.3	--	--	--	3.19E-02	1.11E-01	6.26E-02
2009	1	104.0	--	--	--	1.30E-03	4.09E-02	1.11E-02
2010	3	104.0	--	--	--	8.00E-03	6.24E-02	2.58E-02
2011	1	104.0	--	--	--	1.30E-03	4.09E-02	1.11E-02
2012	1	104.3	--	--	--	1.30E-03	4.08E-02	1.10E-02
2013	2	101.6	2.10E-02	7.40E-03	5.97E-02	4.31E-03	5.29E-02	1.88E-02
2014	4	100.0	1.85E-02	7.66E-03	4.47E-02	1.26E-02	7.48E-02	3.42E-02
2015	2	99.0	1.63E-02	7.75E-03	3.43E-02	4.39E-03	5.39E-02	1.92E-02
2016	0	99.2	1.44E-02	7.53E-03	2.73E-02	1.50E-05	2.99E-02	3.83E-03
2017	1	99.0	1.26E-02	6.90E-03	2.31E-02	1.35E-03	4.24E-02	1.15E-02
2018	2	98.7	1.11E-02	5.89E-03	2.10E-02	4.40E-03	5.40E-02	1.92E-02
2019	3	97.0	9.80E-03	4.72E-03	2.03E-02	8.44E-03	6.59E-02	2.72E-02
2020	0	95.3	8.63E-03	3.64E-03	2.05E-02	1.55E-05	3.08E-02	3.95E-03
2021	0	93.3	7.60E-03	2.73E-03	2.12E-02	1.58E-05	3.13E-02	4.01E-03
2022	1	92.4	6.69E-03	2.01E-03	2.22E-02	1.42E-03	4.47E-02	1.21E-02
Total	66	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	2	103.0	--	--	--	4.52E-03	5.55E-02	1.97E-02
1999	4	103.0	--	--	--	1.31E-02	7.76E-02	3.55E-02
2000	5	103.3	--	--	--	1.80E-02	8.80E-02	4.33E-02
2001	2	103.0	--	--	--	4.52E-03	5.55E-02	1.97E-02
2002	2	103.0	--	--	--	4.52E-03	5.55E-02	1.97E-02
2003	4	103.0	--	--	--	1.31E-02	7.76E-02	3.55E-02
2004	0	103.3	--	--	--	1.55E-05	3.07E-02	3.93E-03
2005	2	103.0	--	--	--	4.52E-03	5.55E-02	1.97E-02
2006	0	103.0	--	--	--	1.55E-05	3.08E-02	3.94E-03
2007	1	103.6	--	--	--	1.38E-03	4.34E-02	1.18E-02
2008	2	104.3	--	--	--	4.47E-03	5.49E-02	1.95E-02
2009	3	104.0	--	--	--	8.48E-03	6.62E-02	2.74E-02
2010	2	104.0	--	--	--	4.48E-03	5.50E-02	1.96E-02
2011	4	104.0	--	--	--	1.30E-02	7.70E-02	3.52E-02
2012	5	104.3	--	--	--	1.79E-02	8.73E-02	4.29E-02
2013	4	101.6	4.19E-02	2.79E-02	6.29E-02	1.33E-02	7.85E-02	3.59E-02
2014	4	100.0	3.41E-02	2.42E-02	4.80E-02	1.34E-02	7.95E-02	3.64E-02
2015	5	99.0	2.77E-02	2.07E-02	3.70E-02	1.86E-02	9.11E-02	4.48E-02
2016	2	99.2	2.25E-02	1.74E-02	2.92E-02	4.66E-03	5.72E-02	2.03E-02
2017	1	99.0	1.83E-02	1.42E-02	2.37E-02	1.43E-03	4.51E-02	1.22E-02
2018	1	98.7	1.49E-02	1.12E-02	1.98E-02	1.44E-03	4.52E-02	1.22E-02
2019	1	97.0	1.21E-02	8.68E-03	1.69E-02	1.46E-03	4.58E-02	1.24E-02
2020	1	95.3	9.85E-03	6.62E-03	1.47E-02	1.48E-03	4.65E-02	1.26E-02
2021	1	93.3	8.01E-03	5.01E-03	1.28E-02	1.50E-03	4.73E-02	1.28E-02
2022	0	92.4	6.52E-03	3.77E-03	1.12E-02	1.69E-05	3.36E-02	4.30E-03
Total	58	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	1	103.0	--	--	--	9.88E-04	3.11E-02	8.43E-03
1999	3	103.0	--	--	--	6.09E-03	4.75E-02	1.97E-02
2000	6	103.3	--	--	--	1.65E-02	7.01E-02	3.65E-02
2001	0	103.0	--	--	--	1.10E-05	2.19E-02	2.81E-03
2002	0	103.0	--	--	--	1.10E-05	2.19E-02	2.81E-03
2003	2	103.0	--	--	--	3.22E-03	3.95E-02	1.40E-02
2004	3	103.3	--	--	--	6.08E-03	4.74E-02	1.96E-02
2005	3	103.0	--	--	--	6.09E-03	4.75E-02	1.97E-02
2006	0	103.0	--	--	--	1.10E-05	2.19E-02	2.81E-03
2007	3	103.6	--	--	--	6.07E-03	4.74E-02	1.96E-02
2008	2	104.3	--	--	--	3.19E-03	3.92E-02	1.39E-02
2009	1	104.0	--	--	--	9.83E-04	3.09E-02	8.38E-03
2010	1	104.0	--	--	--	9.83E-04	3.09E-02	8.38E-03
2011	0	104.0	--	--	--	1.10E-05	2.18E-02	2.79E-03
2012	0	104.3	--	--	--	1.10E-05	2.18E-02	2.79E-03
2013	2	101.6	6.80E-03	2.58E-03	1.79E-02	3.24E-03	3.98E-02	1.42E-02
2014	0	100.0	6.43E-03	2.82E-03	1.47E-02	1.12E-05	2.23E-02	2.86E-03
2015	1	99.0	6.08E-03	3.04E-03	1.22E-02	1.01E-03	3.18E-02	8.62E-03
2016	1	99.2	5.75E-03	3.19E-03	1.04E-02	1.01E-03	3.18E-02	8.61E-03
2017	0	99.0	5.44E-03	3.20E-03	9.26E-03	1.13E-05	2.25E-02	2.87E-03
2018	0	98.7	5.15E-03	3.02E-03	8.76E-03	1.13E-05	2.25E-02	2.88E-03
2019	1	97.0	4.87E-03	2.69E-03	8.79E-03	1.02E-03	3.22E-02	8.72E-03
2020	0	95.3	4.60E-03	2.30E-03	9.22E-03	1.15E-05	2.29E-02	2.94E-03
2021	0	93.3	4.35E-03	1.91E-03	9.94E-03	1.17E-05	2.32E-02	2.97E-03
2022	1	92.4	4.12E-03	1.56E-03	1.09E-02	1.05E-03	3.31E-02	8.96E-03
Total	31	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	2	103.0	--	--	--	3.22E-03	3.95E-02	1.40E-02
1999	7	103.0	--	--	--	2.04E-02	7.75E-02	4.21E-02
2000	4	103.3	--	--	--	9.32E-03	5.52E-02	2.52E-02
2001	3	103.0	--	--	--	6.09E-03	4.75E-02	1.97E-02
2002	7	103.0	--	--	--	2.04E-02	7.75E-02	4.21E-02
2003	2	103.0	--	--	--	3.22E-03	3.95E-02	1.40E-02
2004	1	103.3	--	--	--	9.87E-04	3.10E-02	8.41E-03
2005	1	103.0	--	--	--	9.88E-04	3.11E-02	8.43E-03
2006	2	103.0	--	--	--	3.22E-03	3.95E-02	1.40E-02
2007	1	103.6	--	--	--	9.85E-04	3.10E-02	8.40E-03
2008	4	104.3	--	--	--	9.27E-03	5.49E-02	2.51E-02
2009	2	104.0	--	--	--	3.20E-03	3.93E-02	1.40E-02
2010	2	104.0	--	--	--	3.20E-03	3.93E-02	1.40E-02
2011	2	104.0	--	--	--	3.20E-03	3.93E-02	1.40E-02
2012	4	104.3	--	--	--	9.27E-03	5.49E-02	2.51E-02
2013	0	101.6	4.69E-03	1.53E-03	1.43E-02	1.11E-05	2.21E-02	2.83E-03
2014	0	100.0	4.75E-03	1.84E-03	1.23E-02	1.12E-05	2.23E-02	2.86E-03
2015	2	99.0	4.81E-03	2.17E-03	1.07E-02	3.29E-03	4.04E-02	1.44E-02
2016	0	99.2	4.88E-03	2.48E-03	9.62E-03	1.13E-05	2.24E-02	2.87E-03
2017	2	99.0	4.95E-03	2.69E-03	9.11E-03	3.29E-03	4.04E-02	1.44E-02
2018	1	98.7	5.01E-03	2.72E-03	9.23E-03	1.01E-03	3.19E-02	8.63E-03
2019	0	97.0	5.08E-03	2.58E-03	1.00E-02	1.14E-05	2.27E-02	2.91E-03
2020	0	95.3	5.15E-03	2.32E-03	1.14E-02	1.15E-05	2.29E-02	2.94E-03
2021	0	93.3	5.22E-03	2.02E-03	1.35E-02	1.17E-05	2.32E-02	2.97E-03
2022	1	92.4	5.29E-03	1.73E-03	1.62E-02	1.05E-03	3.31E-02	8.96E-03
Total	50	2,527.3	--	--	--	--	--	--

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

			Regression Curve Data Points			Yearly Estimate Data Points		
Year	Failures	Reactor Years	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	0	103.0	--	--	--	6.60E-06	1.31E-02	1.68E-03
1999	2	103.0	--	--	--	1.92E-03	2.36E-02	8.39E-03
2000	0	103.3	--	--	--	6.59E-06	1.31E-02	1.68E-03
2001	2	103.0	--	--	--	1.92E-03	2.36E-02	8.39E-03
2002	1	103.0	--	--	--	5.90E-04	1.86E-02	5.03E-03
2003	0	103.0	--	--	--	6.60E-06	1.31E-02	1.68E-03
2004	1	103.3	--	--	--	5.90E-04	1.86E-02	5.03E-03
2005	0	103.0	--	--	--	6.60E-06	1.31E-02	1.68E-03
2006	0	103.0	--	--	--	6.60E-06	1.31E-02	1.68E-03
2007	0	103.6	--	--	--	6.58E-06	1.31E-02	1.67E-03
2008	0	104.3	--	--	--	6.57E-06	1.31E-02	1.67E-03
2009	1	104.0	--	--	--	5.88E-04	1.85E-02	5.01E-03
2010	1	104.0	--	--	--	5.88E-04	1.85E-02	5.01E-03
2011	0	104.0	--	--	--	6.57E-06	1.31E-02	1.67E-03
2012	2	104.3	--	--	--	1.91E-03	2.35E-02	8.35E-03
2013	1	101.6	2.97E-03	1.61E-03	5.49E-03	5.93E-04	1.87E-02	5.06E-03
2014	0	100.0	2.76E-03	1.63E-03	4.66E-03	6.66E-06	1.32E-02	1.69E-03
2015	0	99.0	2.56E-03	1.65E-03	3.98E-03	6.68E-06	1.33E-02	1.70E-03
2016	1	99.2	2.38E-03	1.64E-03	3.46E-03	5.98E-04	1.88E-02	5.10E-03
2017	0	99.0	2.21E-03	1.59E-03	3.07E-03	6.68E-06	1.33E-02	1.70E-03
2018	0	98.7	2.05E-03	1.49E-03	2.82E-03	6.69E-06	1.33E-02	1.70E-03
2019	0	97.0	1.91E-03	1.35E-03	2.69E-03	6.73E-06	1.34E-02	1.71E-03
2020	0	95.3	1.77E-03	1.19E-03	2.64E-03	6.77E-06	1.35E-02	1.72E-03
2021	0	93.3	1.64E-03	1.02E-03	2.64E-03	6.82E-06	1.35E-02	1.73E-03
2022	0	92.4	1.53E-03	8.71E-04	2.68E-03	6.84E-06	1.36E-02	1.74E-03
Total	12	2,527.3	--	--	--	--	--	--

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