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

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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 2018 as reported in the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). The AOV failure modes considered are failure-to-open/close (FTOC), failure 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.

One extremely statistically significant increasing trend was identified for the frequency of FTOC demands per reactor year for high-demand (> 20 demands per year) valves. One highly statistically significant increasing trend was identified for the frequency of FTOC demands per reactor year for low-demand (≤ 20 demands per year) valves.

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TABLES

ACRONYMS

AFW	auxiliary feed water
AOV	air-operated valve
CCW	component cooling water
CNID	constrained non-informative prior distribution
CRD	control rod drive
CSR	containment spray recirculation
CY	calendar year
EDG	emergency diesel generator
EPIX	Equipment Performance and Information Exchange
FTOC	failure-to-open/close
FTOP	failure to operate or control
FY	fiscal year
HPCI	high pressure cooling injection
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
NPRDS	Nuclear Plant Reliability Data System
OLS	ordinary least squares
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
SO	spurious operation
SWN	normally operating service water
SWS	standby service water
TDP	turbine-driven pump
UA	unavailability

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

1. INTRODUCTION

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

The enhanced component performance studies are conducted for the following component types: 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/LTD-17-44119, *Enhanced Component Performance Study: Air-Operated Valves 1998-2016* [2]. The Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page provides the links to the historical and current results of component performance studies (http://nrcoe.inl.gov/resultsdb/CompPerf). An overview of the trending methods, glossary of terms, and abbreviations is documented in the paper Overview and Reference [3] that can also be found on that web page.

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

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 failure-to-open/close (FTOC), failure to operate or control (FTOP), and spurious operation (SO). Annual failure probabilities (failures per demand) are provided for FTOC events and annual failure rates (failures per valve hour) are provided for FTOP and SO events. The estimates are trended for the most recent 10-year period while yearly estimates are provided for the entire study period.

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

comparisons. Those estimates are labelled “2015 Update” (or “Update 2015”) in the associated tables and figures.

Section 2 of this report presents the summary of findings from the study, with particular interest in the existence of any statistically significant increasing or decreasing trends in component performances. Section 3 provides annual estimates of failure probabilities and rates related to AOVs as well as the trending of the estimates. Section 4 presents engineering analyses performed for AOV 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: sub-component, 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 for the **frequency of FTOC demands** (demands per reactor year) for **high-demand AOVs** with a p-value of 0.0005 (see Figure 8). This is a new trend that was not observed in the 2016 AOV update study [2].

2.1.2 Highly Statistically Significant

- Highly statistically significant **increasing trend** was identified for the **frequency of FTOC demands** (demands per reactor year) for **low-demand AOVs** with a p-value of 0.0015 (see Figure 7). The same trend was observed in the 2016 AOV update study.

2.1.3 Statistically Significant

- None.

2.2 Decreasing Trends

2.2.1 Extremely Statistically Significant

- None

2.2.2 Highly Statistically Significant

- None

2.2.3 Statistically Significant

- None.

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

3. FAILURE PROBABILITIES AND FAILURE RATES

3.1 Overview

Trends of industry-wide failure probabilities and failure rates for AOVs have been calculated from the operating experience for the FTOC, FTOP, and SO failure modes. The AOV data set obtained from ICES 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 Reference [6], or the 2015 Update. No 2015 Update results are shown for high-demand AOVs because Reference [6] does not provide them. The 2015 Update results are provided for comparison purposes and are important because they are intended for use in PRA. The results in this section demonstrate the extent to which the 2015 Update results remain suitable estimates for use in PRA.

The 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 some time during the study period. So new devices put in service during the period are included, as are devices that were in service at one time but have since been removed from service. All demand types are considered—testing, non-testing, and, as applicable, engineered safety feature demands.

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

System	Description	AOV Count		
		Total	Low Demand	High Demand
AFW	Auxiliary feedwater	389	195	194
CCW	Component cooling water	469	307	162
CRD	Control rod drive	122	67	55
CSR	Containment spray recirculation	38	31	7
HPCI	High pressure coolant injection	15	6	9
HPSI	High pressure safety injection	104	74	30
ISO	Isolation condenser	10	6	4
LPCS	Low pressure core spray	12	8	4
RCIC	Reactor core isolation	5	5	0
RCS	Reactor coolant	117	47	70
RHR	Residual Heat Removal (LPCI in BWRs; LPSI in PWRs)	293	135	158
SWN	Normally operating service water	550	293	257
SWS	Standby service water	63	17	46
	Total	2187	1191	996

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

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTOC	3.89E-5	5.25E-4	7.56E-4	2.27E-3	Beta	1.00	1.32E+03
FTOP	2.39E-8	1.76E-7	2.27E-7	6.03E-7	Gamma	1.41	6.22E+06
SO	5.76E-9	7.18E-8	1.02E-7	3.01E-7	Gamma	1.04	1.02E+07

3.2 AOV Failure Probability and Failure Rate Trends

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

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

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

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

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

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

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

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

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

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

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 suggest a trend does exist. P-values of less than or equal to 0.05 indicate that we are 95% confident that there is a trend in the data (reject the null hypothesis of no trend.) By convention, this study uses the "Michelin Guide" scale: p-value < 0.05 (statistically significant), p-value < 0.01 (highly statistically significant); p-value < 0.001 (extremely statistically significant).

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

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

Figure 1 to Figure 6 provide the plots for all systems, industry-wide failure probabilities/rates of 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 probability estimate trends for AOV FTOP events for low-demand and high-demand AOVs, respectively.
- Figure 5 and Figure 6 show the failure probability estimate trends for AOV SO events for low-demand and high-demand AOVs, respectively.

No trends were identified for AOV failure probabilities/rates for FTOC, FTOP, and SO events in the most recent 10-year period.

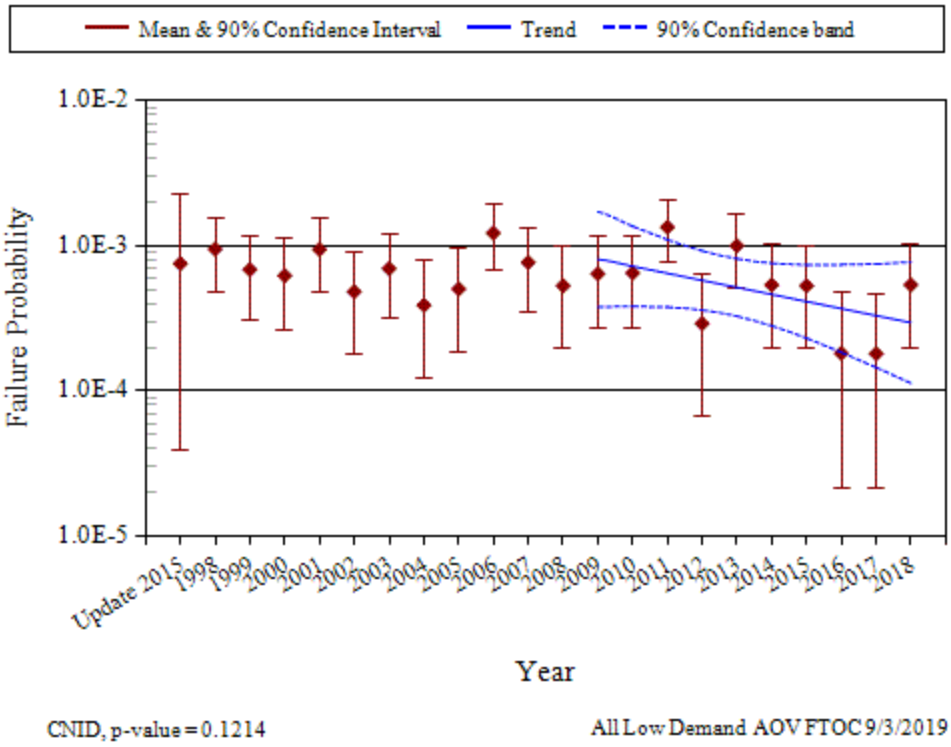

Figure 1. Failure probability estimate trend for low-demand AOV FTOC.

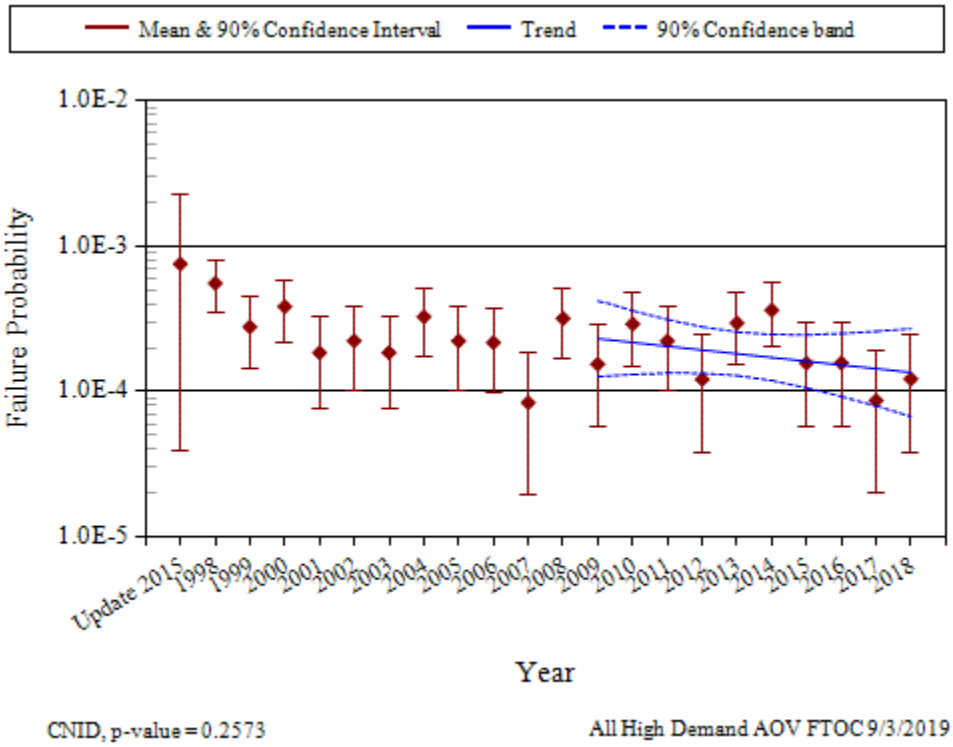

Figure 2. Failure probability estimate trend for high-demand AOV FTOC.

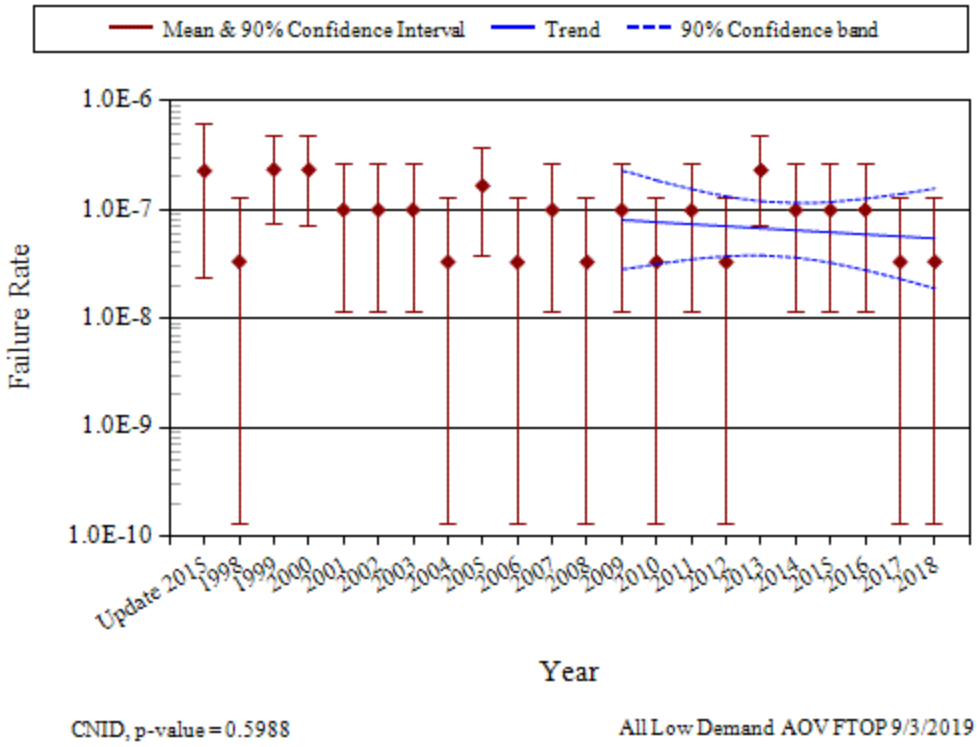

Figure 3. Failure rate estimate trend for low-demand AOV FTOP.

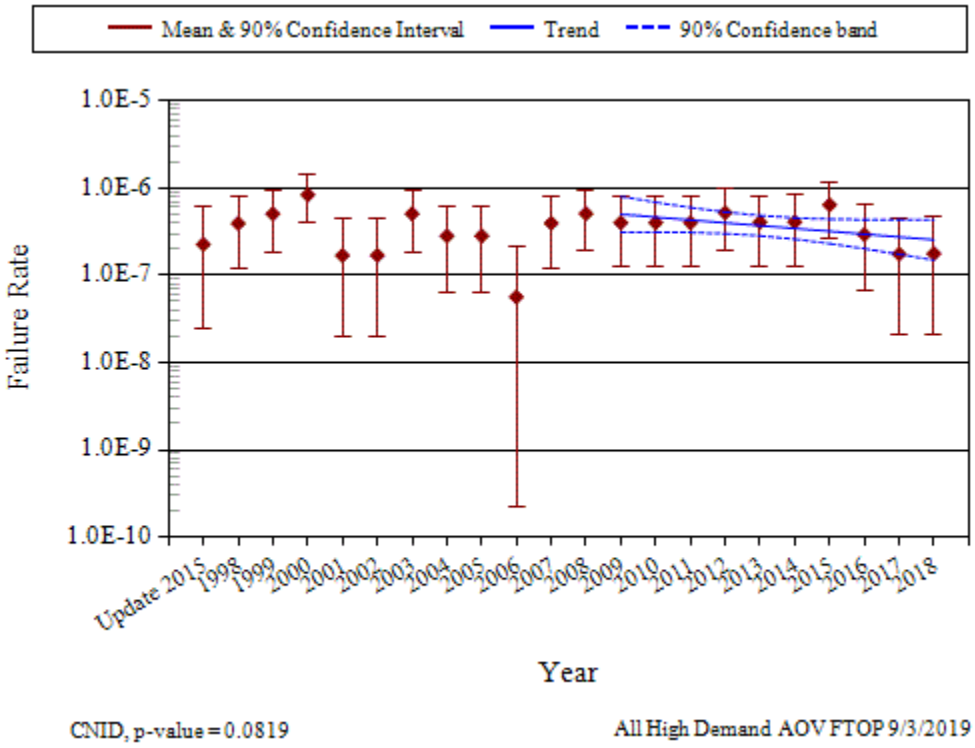

Figure 4. Failure rate estimate trend for high-demand AOV FTOP.

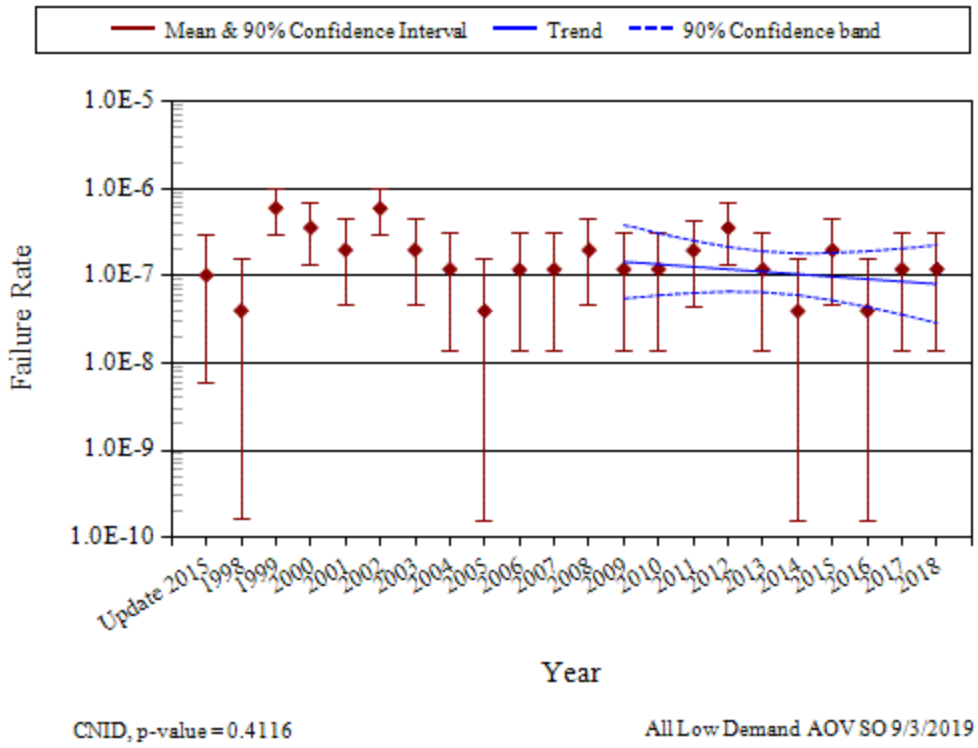

Figure 5. Failure rate estimate trend for low-demand AOV SO.

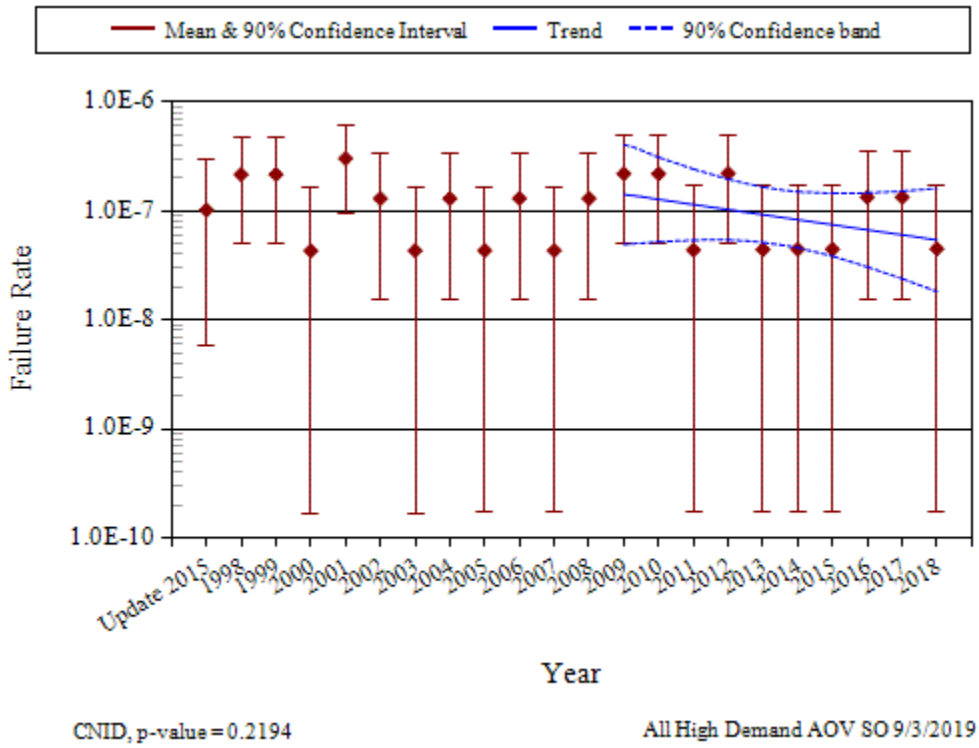

Figure 6. Failure rate estimate trend for high-demand AOV SO.

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 events, FTOP events, and SO events.

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

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

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

- Table 3 presents the FTOC failure counts by system and year for low-demand 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 the most recent 10-year period:

- Extremely statistically significant **increasing trend** for the **frequency of FTOC demands** (demands per reactor year) for **high-demand AOVs**, with a p-value of 0.0005 (see Figure 8). This is a new trend that was not observed in the 2016 AOV update study [2]
- Highly statistically significant **increasing trend** for the **frequency of FTOC demands** (demands per reactor year) for **low-demand AOVs**, with a p-value of 0.0015 (see Figure 7). The same trend was observed in the 2016 AOV update study.

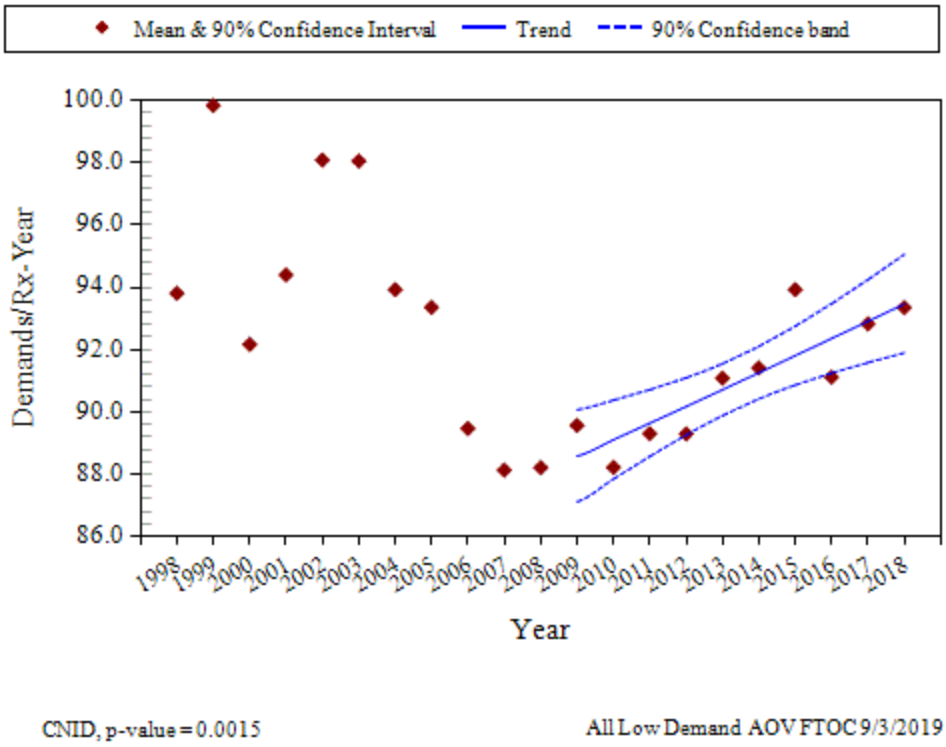

Figure 7. Frequency of FTOC demands (demands per reactor year) for low-demand AOVs.

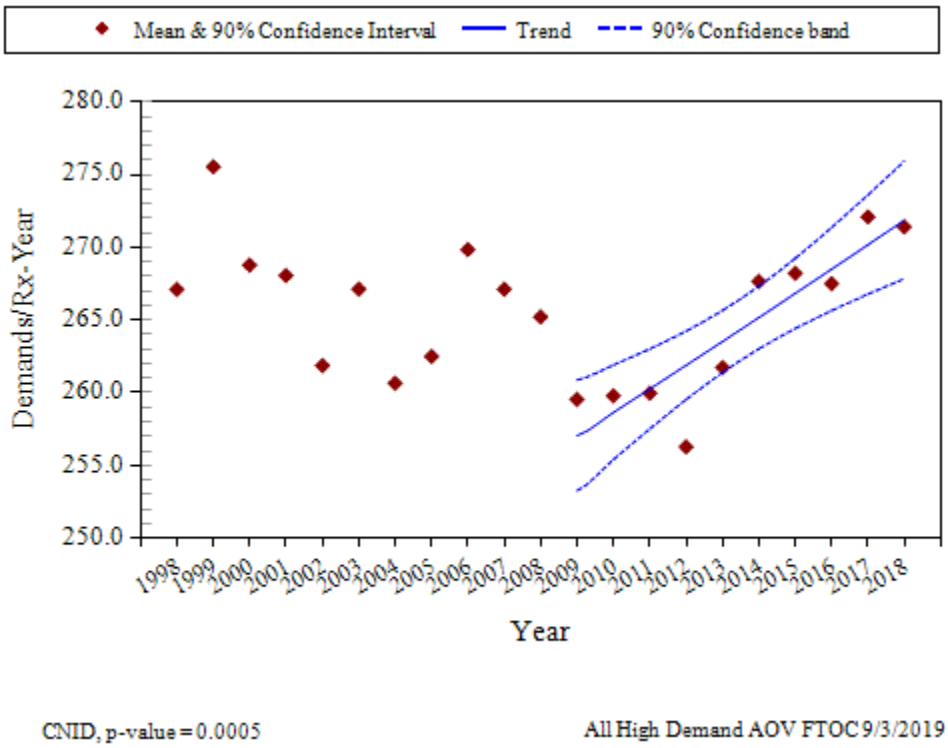

Figure 8. Frequency of FTOC demands (demands per reactor year) for high-demand AOVs.

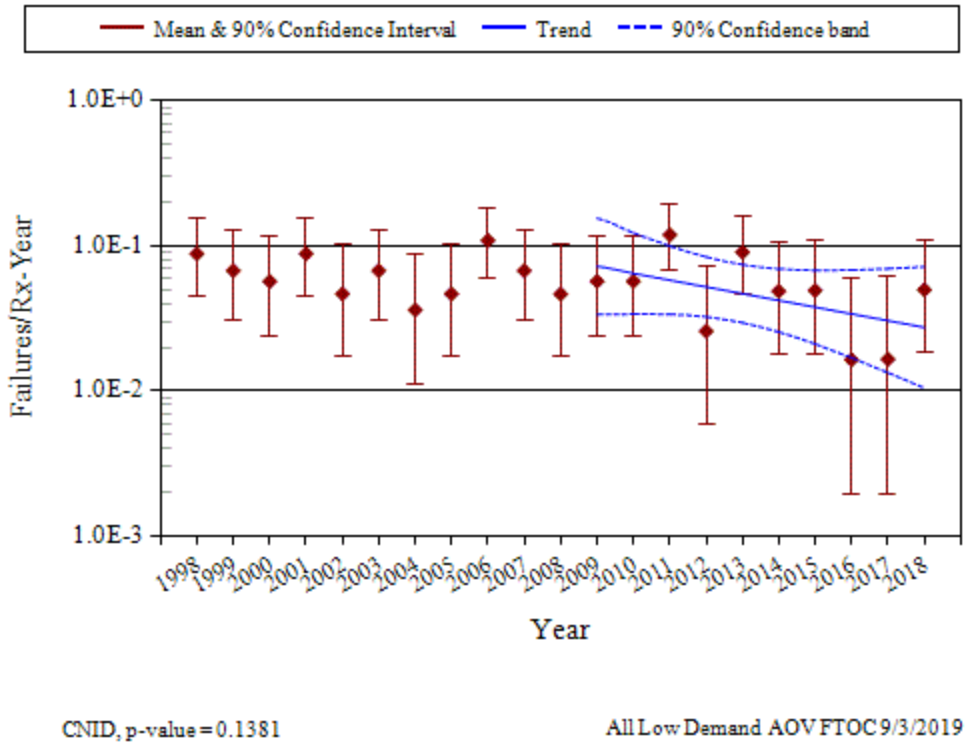

Figure 9. Frequency of FTOC events (failures per reactor year) for low-demand AOVs.

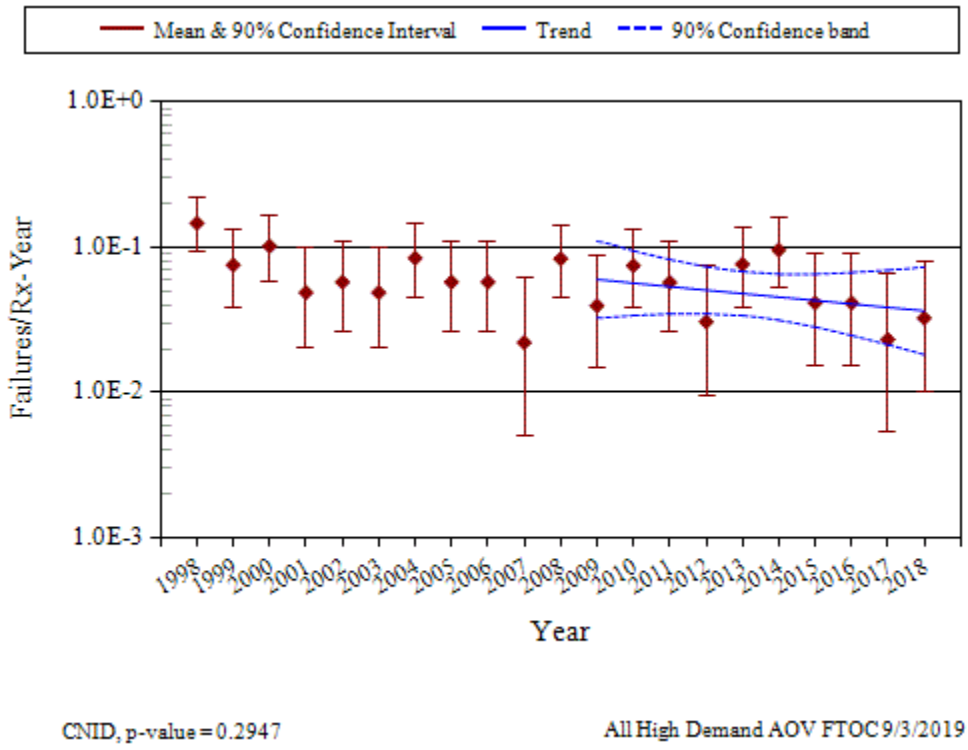

Figure 10. Frequency of FTOC events (failures per reactor year) for high-demand AOVs.

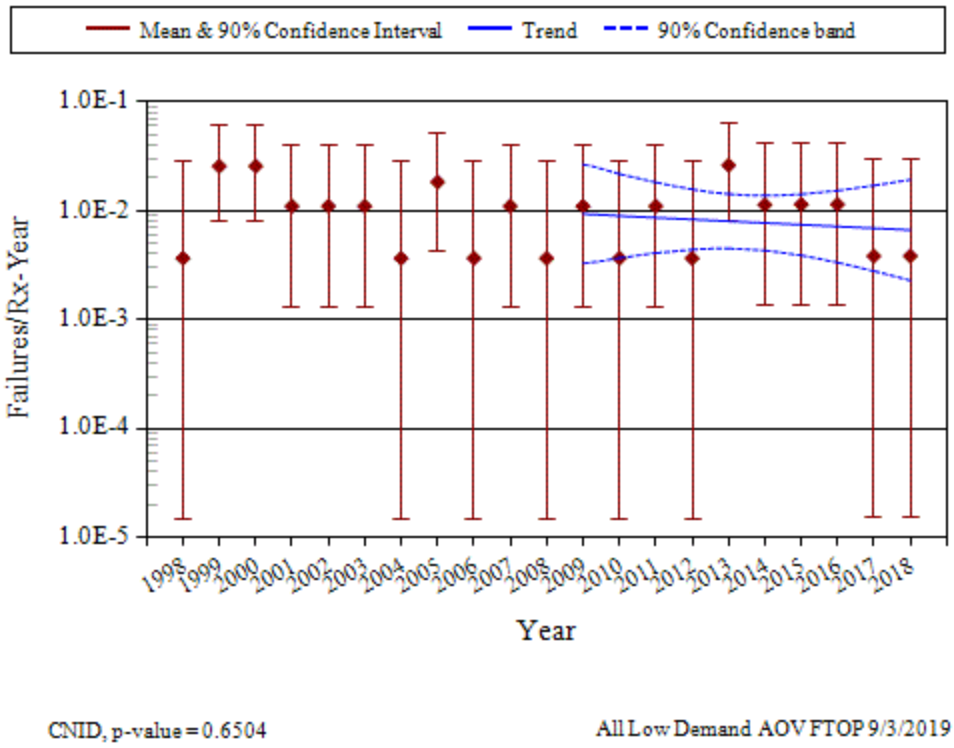

Figure 11. Frequency of FTOP events (failures per reactor year) for low-demand AOVs.

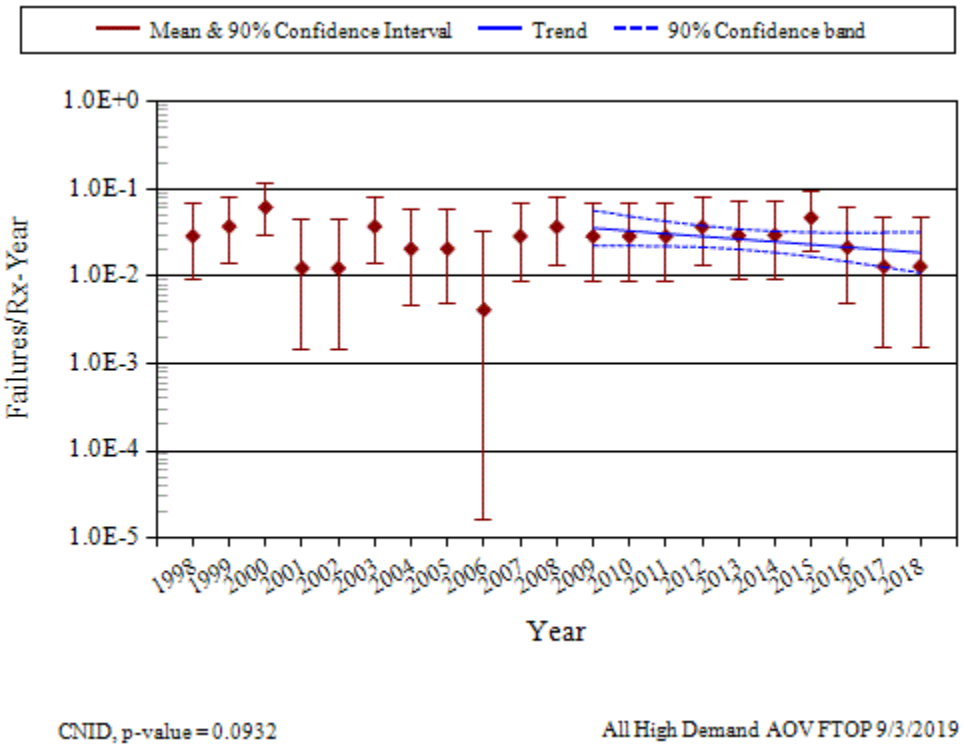

Figure 12. Frequency of FTOP events (failures per reactor year) for high-demand AOVs.

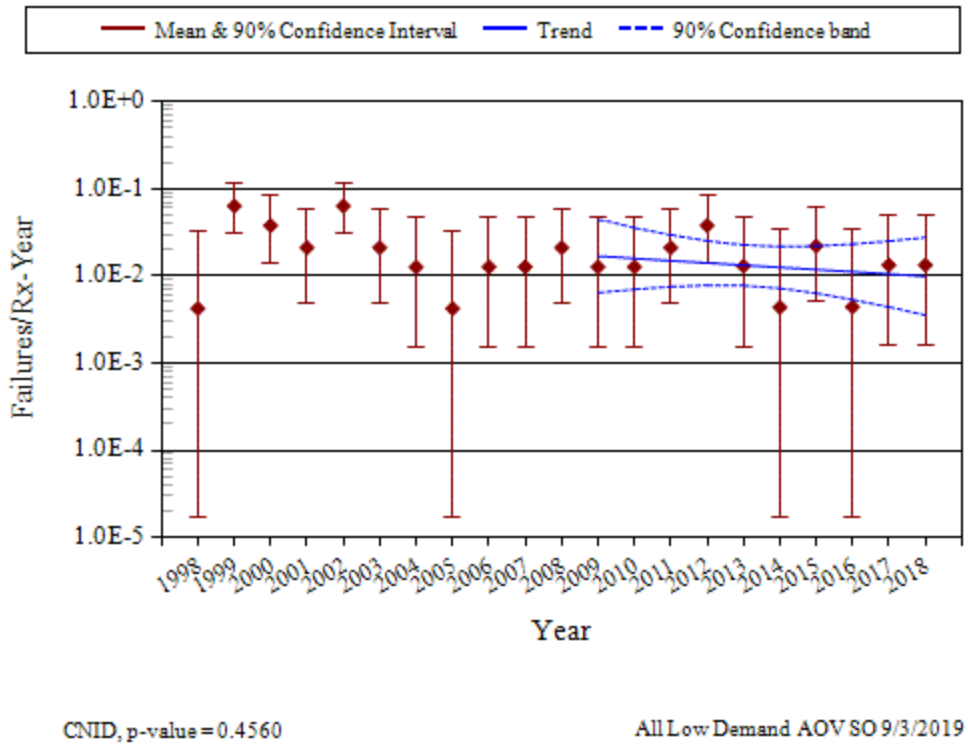

Figure 13. Frequency of SO events (failures per reactor year) for low-demand AOVs.

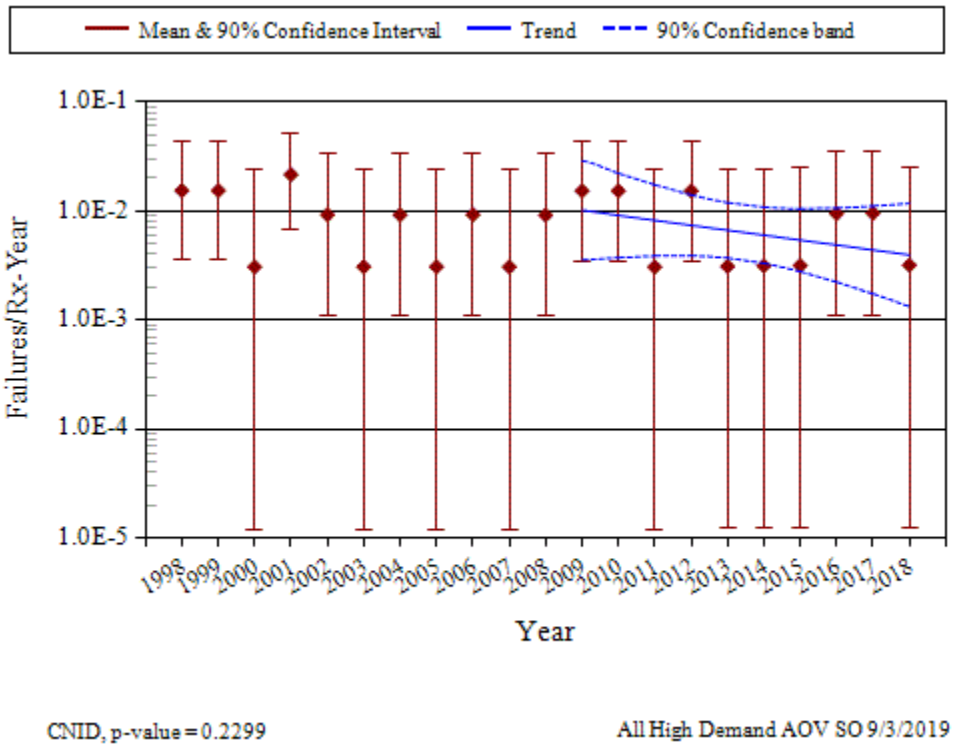

Figure 14. Frequency of SO events (failures per reactor year) for high-demand AOVs.

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

System	Valve Count	Valve Percent	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	195	16.4 %	1	1		1			2			2	7	15.6 %
CCW	307	25.8 %		2	3		6	3	2				16	35.6 %
CRD	67	5.6 %											0	0.0 %
CSR	31	2.6 %											0	0.0 %
HPCI	6	0.5 %											0	0.0 %
HPSI	74	6.2 %			3			1					4	8.9 %
ISO	6	0.5 %											0	0.0 %
LPCS	8	0.7 %											0	0.0 %
RCIC	5	0.4 %											0	0.0 %
RCS	47	3.9 %	1		1								2	4.4 %
RHR	135	11.3 %	1									1	2	4.4 %
SWN	293	24.6 %	2	2	3	1	2			1	1	1	13	28.9 %
SWS	17	1.4 %			1								1	2.2 %
Total	1191	100.0%	5	5	11	2	8	4	4	1	1	4	45	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	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	195	16.4 %					3			1			4	50.0 %
CCW	307	25.8 %	1						1				2	25.0 %
CRD	67	5.6 %											0	0.0 %
CSR	31	2.6 %											0	0.0 %
HPCI	6	0.5 %											0	0.0 %
HPSI	74	6.2 %											0	0.0 %
ISO	6	0.5 %											0	0.0 %
LPCS	8	0.7 %											0	0.0 %
RCIC	5	0.4 %											0	0.0 %
RCS	47	3.9 %											0	0.0 %
RHR	135	11.3 %											0	0.0 %
SWN	293	24.6 %						1					1	12.5 %
SWS	17	1.4 %			1								1	12.5 %
Total	1191	100.0%	1	0	1	0	3	1	1	1	0	0	8	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	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	195	16.4 %	1						2		1		4	30.8 %
CCW	307	25.8 %		1	1	3							5	38.5 %
CRD	67	5.6 %											0	0.0 %
CSR	31	2.6 %											0	0.0 %
HPCI	6	0.5 %											0	0.0 %
HPSI	74	6.2 %											0	0.0 %
ISO	6	0.5 %											0	0.0 %
LPCS	8	0.7 %											0	0.0 %
RCIC	5	0.4 %											0	0.0 %
RCS	47	3.9 %											0	0.0 %
RHR	135	11.3 %				1							1	7.7 %
SWN	293	24.6 %					1					1	2	15.4 %
SWS	17	1.4 %			1								1	7.7 %
Total	1191	100.0%	1	1	2	4	1	0	2	0	1	1	13	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	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	194	19.5 %		2	1	1	3	5	1		1	1	15	26.8 %
CCW	162	16.3 %		1		1	1						3	5.4 %
CRD	55	5.5 %				1	1						2	3.6 %
CSR	7	0.7 %											0	0.0 %
HPCI	9	0.9 %											0	0.0 %
HPSI	30	3.0 %											0	0.0 %
ISO	4	0.4 %											0	0.0 %
LPCS	4	0.4 %											0	0.0 %
RCS	70	7.0 %		3						1			4	7.1 %
RHR	158	15.9 %	3	1	2		1	1	1	1		1	11	19.6 %
SWN	257	25.8 %	1	2	3		2	4	2	3	1	1	19	33.9 %
SWS	46	4.6 %		2									2	3.6 %
Total	996	100.0%	4	11	6	3	8	10	4	5	2	3	56	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	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	194	19.5 %		1	1	1	2		4			1	10	35.7 %
CCW	162	16.3 %					1			1			2	7.1 %
CRD	55	5.5 %				1							1	3.6 %
CSR	7	0.7 %											0	0.0 %
HPCI	9	0.9 %											0	0.0 %
HPSI	30	3.0 %											0	0.0 %
ISO	4	0.4 %											0	0.0 %
LPCS	4	0.4 %											0	0.0 %
RCS	70	7.0 %								1	1		2	7.1 %
RHR	158	15.9 %				2		1	1				4	14.3 %
SWN	257	25.8 %	3	2	2			2					9	32.1 %
SWS	46	4.6 %											0	0.0 %
Total	996	100.0%	3	3	3	4	3	3	5	2	1	1	28	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	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Total	Percent of Failures
AFW	194	19.5 %		2		1					1		4	50.0 %
CCW	162	16.3 %				1				1			2	25.0 %
CRD	55	5.5 %											0	0.0 %
CSR	7	0.7 %											0	0.0 %
HPCI	9	0.9 %											0	0.0 %
HPSI	30	3.0 %											0	0.0 %
ISO	4	0.4 %											0	0.0 %
LPCS	4	0.4 %											0	0.0 %
RCS	70	7.0 %											0	0.0 %
RHR	158	15.9 %											0	0.0 %
SWN	257	25.8 %	2										2	25.0 %
SWS	46	4.6 %											0	0.0 %
Total	996	100.0%	2	2	0	2	0	0	0	1	1	0	8	100.0%

4.2 AOV Engineering Analysis by Failure Modes

This section presents the engineering analysis of AOV failure sub-components, causes, detection methods, and recoverability. Each analysis first 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). The second division of the events is by the failure mode determined after ICES data review by the staff. See Section 5 for more description of failure modes.

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

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

- The Component cause group is the most likely cause for FTOP, and the second most likely cause for FTOC and 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 previous studies [2].
- 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 and 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.

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

- Overall, the most likely detection method for FTOC is testing demand. The most likely detection method for FTOP is non-test demand. The most likely detection method for SO is inspection.
- For low-demand AOVs, the most likely detection method for FTOC is testing demand. The most likely detection method for FTOP and SO is non-test demand.
- For high-demand AOVs, the most likely detection method for FTOC and FTOP is non-test demand followed by testing demand. The most likely detection method for SO is inspection followed by testing demand.

Figure 18 shows the AOV failure recoverability determination for three failure modes. The overall non-recovery to recovery ratio is approximately 7:1, meaning that 7 of every 8 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 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 re-arranged in order to align with those currently used in the CCF database.

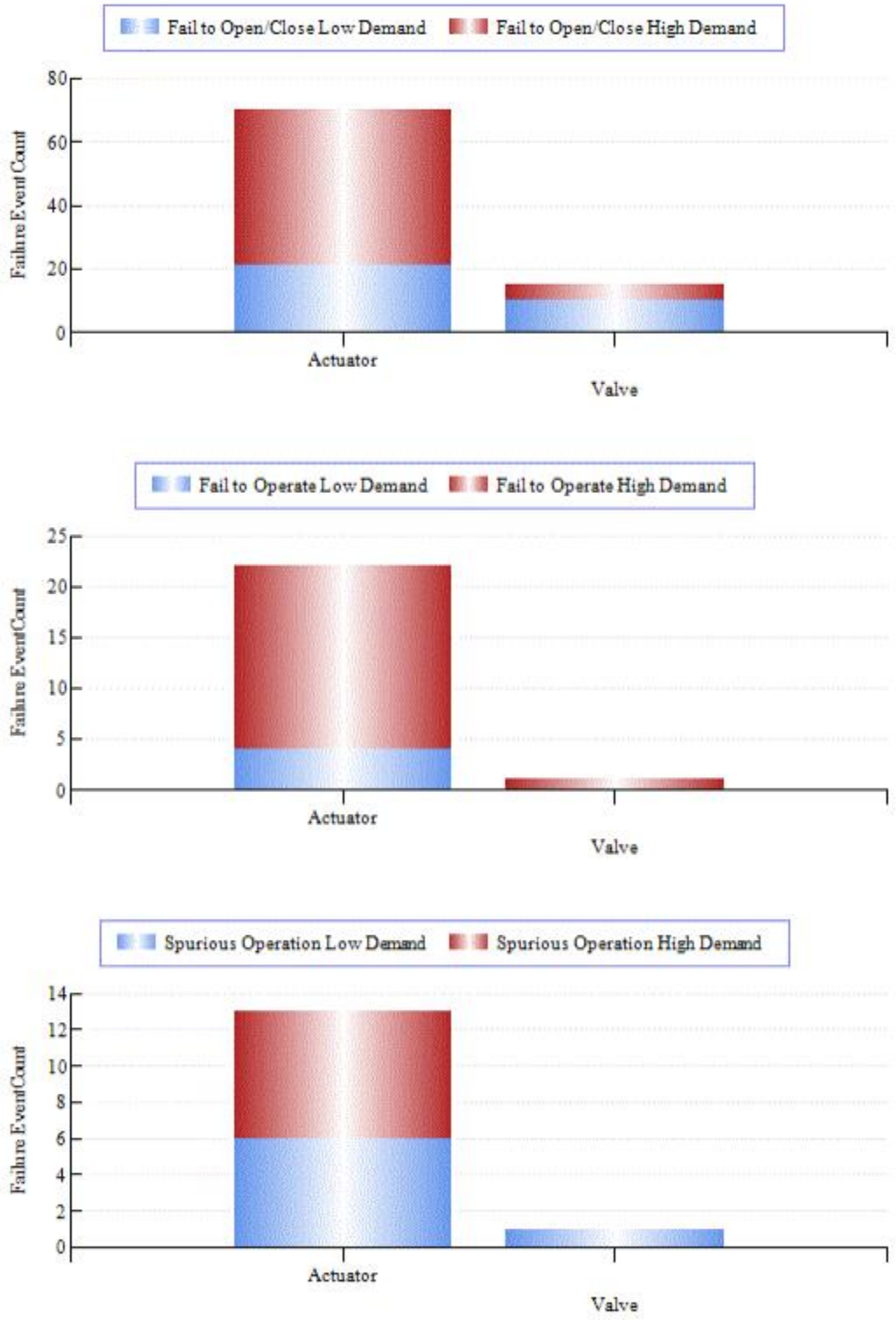

Figure 15. AOV failure event breakdown by subcomponent, failure mode, and demand rate

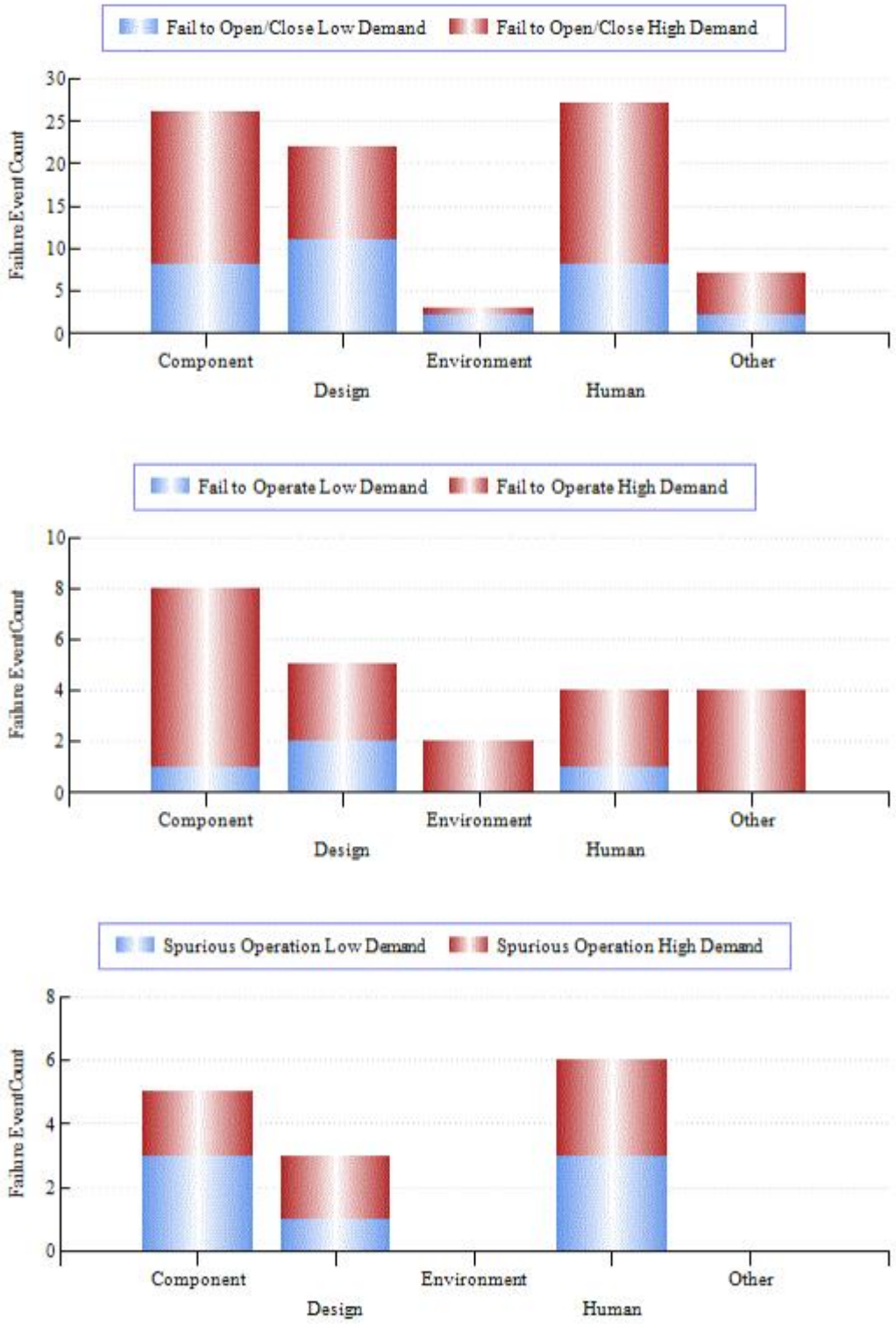

Figure 16. AOV failure event breakdown by cause group, failure mode, and demand rate

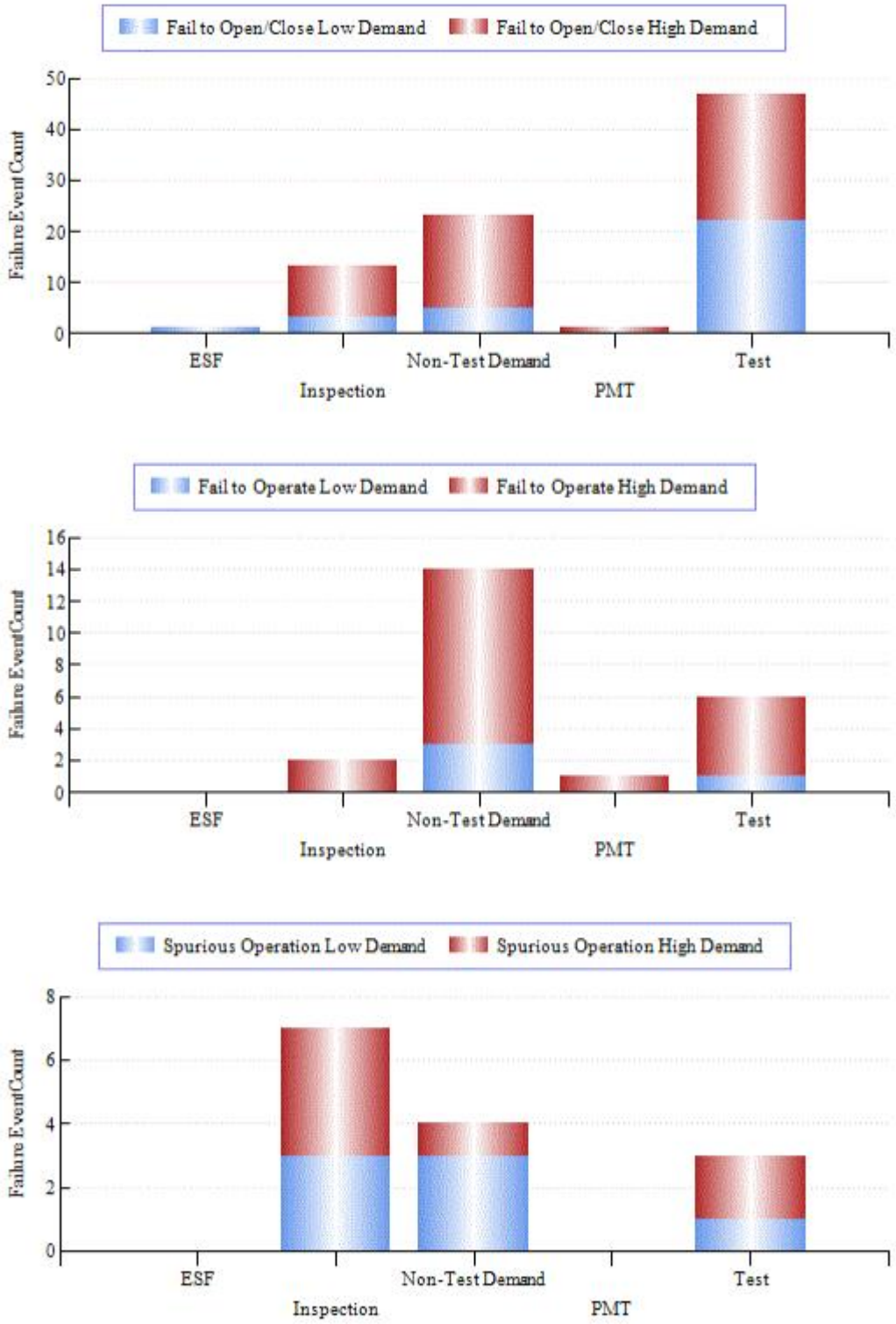

Figure 17. AOV failure event breakdown by method of detection, failure mode, and demand rate

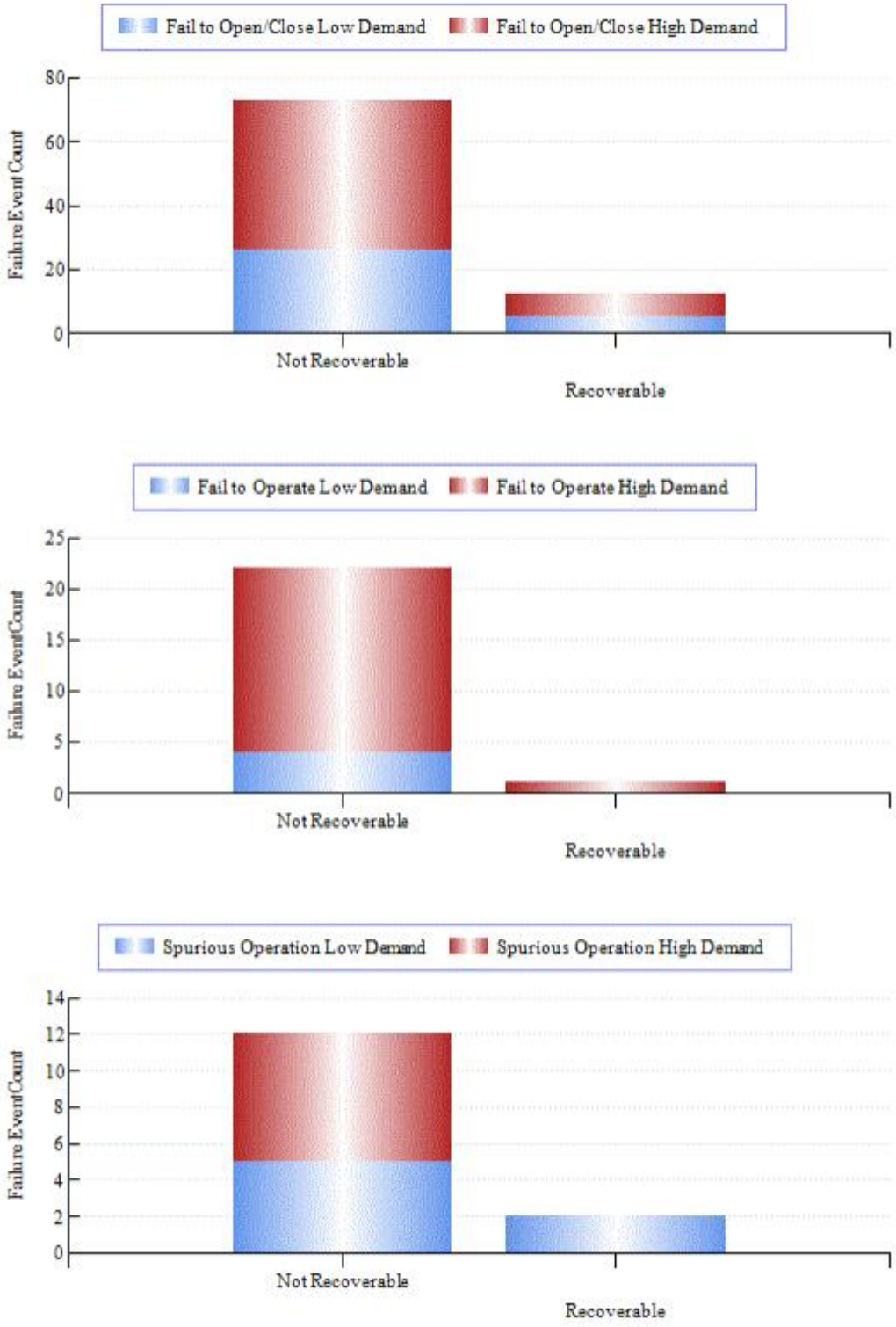

Figure 18. AOV failure event breakdown by recoverability, failure mode, and demand rate

5. AOV ASSEMBLY DESCRIPTION

An AOV assembly consists of a valve body and pneumatic operator sub-components. 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, and
- SO, which includes spurious opening and spurious closing.

6. DATA TABLES

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

Figure	Table	Analysis
Figure 1	Table 10	Failure probability estimate trend for low-demand 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
2015 Update						3.89E-05	2.27E-03	7.56E-04
1998	8	8,162	--	--	--	4.82E-04	1.67E-03	9.44E-04
1999	6	8,687	--	--	--	3.09E-04	1.31E-03	6.82E-04
2000	5	8,040	--	--	--	2.58E-04	1.26E-03	6.19E-04
2001	8	8,213	--	--	--	4.79E-04	1.66E-03	9.39E-04
2002	4	8,534	--	--	--	1.77E-04	1.05E-03	4.80E-04
2003	6	8,531	--	--	--	3.14E-04	1.33E-03	6.93E-04
2004	3	8,194	--	--	--	1.20E-04	9.36E-04	3.87E-04
2005	4	8,122	--	--	--	1.85E-04	1.10E-03	5.02E-04
2006	10	7,783	--	--	--	6.72E-04	2.04E-03	1.22E-03
2007	6	7,667	--	--	--	3.46E-04	1.47E-03	7.64E-04
2008	4	7,695	--	--	--	1.95E-04	1.15E-03	5.27E-04
2009	5	7,792	8.10E-04	3.81E-04	1.72E-03	2.65E-04	1.29E-03	6.37E-04
2010	5	7,675	7.24E-04	3.84E-04	1.37E-03	2.69E-04	1.31E-03	6.46E-04
2011	11	7,769	6.48E-04	3.80E-04	1.11E-03	7.60E-04	2.19E-03	1.34E-03
2012	2	7,790	5.79E-04	3.62E-04	9.27E-04	6.64E-05	8.15E-04	2.90E-04
2013	8	7,703	5.18E-04	3.28E-04	8.17E-04	5.08E-04	1.76E-03	9.95E-04
2014	4	7,587	4.63E-04	2.82E-04	7.61E-04	1.97E-04	1.17E-03	5.34E-04
2015	4	7,702	4.14E-04	2.32E-04	7.41E-04	1.95E-04	1.15E-03	5.27E-04
2016	1	7,469	3.70E-04	1.85E-04	7.41E-04	2.12E-05	6.66E-04	1.80E-04
2017	1	7,519	3.31E-04	1.46E-04	7.53E-04	2.10E-05	6.62E-04	1.79E-04
2018	4	7,561	2.96E-04	1.13E-04	7.73E-04	1.98E-04	1.17E-03	5.36E-04
Total	109	166,198						

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
2015 Update						3.89E-05	2.27E-03	7.56E-04
1998	16	27,512	--	--	--	3.47E-04	8.28E-04	5.49E-04
1999	8	28,380	--	--	--	1.40E-04	4.87E-04	2.75E-04
2000	11	27,759	--	--	--	2.16E-04	6.21E-04	3.79E-04
2001	5	27,610	--	--	--	7.59E-05	3.71E-04	1.82E-04
2002	6	26,972	--	--	--	9.98E-05	4.23E-04	2.20E-04
2003	5	27,513	--	--	--	7.61E-05	3.72E-04	1.83E-04
2004	9	26,920	--	--	--	1.72E-04	5.54E-04	3.22E-04
2005	6	27,036	--	--	--	9.96E-05	4.22E-04	2.20E-04
2006	6	27,794	--	--	--	9.71E-05	4.12E-04	2.14E-04
2007	2	27,675	--	--	--	1.90E-05	2.33E-04	8.27E-05
2008	9	27,657	--	--	--	1.67E-04	5.41E-04	3.15E-04
2009	4	26,991	2.31E-04	1.27E-04	4.20E-04	5.63E-05	3.33E-04	1.52E-04
2010	8	27,018	2.18E-04	1.32E-04	3.60E-04	1.47E-04	5.10E-04	2.88E-04
2011	6	27,035	2.05E-04	1.34E-04	3.14E-04	9.96E-05	4.22E-04	2.20E-04
2012	3	26,727	1.93E-04	1.34E-04	2.79E-04	3.70E-05	2.89E-04	1.20E-04
2013	8	26,583	1.82E-04	1.29E-04	2.58E-04	1.49E-04	5.17E-04	2.92E-04
2014	10	26,765	1.72E-04	1.19E-04	2.48E-04	1.98E-04	6.00E-04	3.58E-04
2015	4	26,553	1.62E-04	1.06E-04	2.47E-04	5.71E-05	3.38E-04	1.55E-04
2016	4	26,487	1.53E-04	9.27E-05	2.51E-04	5.73E-05	3.39E-04	1.55E-04
2017	2	26,665	1.44E-04	7.96E-05	2.60E-04	1.96E-05	2.41E-04	8.56E-05
2018	3	26,528	1.36E-04	6.77E-05	2.72E-04	3.73E-05	2.91E-04	1.20E-04
Total	135	570,180						

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

Year	Failures	Hours	Regression Curve Data Points			Yearly Estimate Data Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						2.39E-08	6.03E-07	2.27E-07
1998	0	9,890,040	--	--	--	1.25E-10	2.48E-07	3.17E-08
1999	3	9,855,000	--	--	--	6.88E-08	5.37E-07	2.22E-07
2000	3	9,960,120	--	--	--	6.84E-08	5.34E-07	2.21E-07
2001	1	9,960,120	--	--	--	1.11E-08	3.49E-07	9.46E-08
2002	1	9,960,120	--	--	--	1.11E-08	3.49E-07	9.46E-08
2003	1	9,977,640	--	--	--	1.11E-08	3.49E-07	9.45E-08
2004	0	9,977,640	--	--	--	1.24E-10	2.46E-07	3.15E-08
2005	2	9,977,640	--	--	--	3.61E-08	4.43E-07	1.58E-07
2006	0	10,091,520	--	--	--	1.23E-10	2.44E-07	3.13E-08
2007	1	9,995,160	--	--	--	1.11E-08	3.48E-07	9.44E-08
2008	0	10,003,920	--	--	--	1.24E-10	2.46E-07	3.15E-08
2009	1	9,986,400	8.02E-08	2.83E-08	2.27E-07	1.11E-08	3.49E-07	9.45E-08
2010	0	9,986,400	7.68E-08	3.18E-08	1.86E-07	1.24E-10	2.46E-07	3.15E-08
2011	1	10,144,080	7.36E-08	3.50E-08	1.55E-07	1.10E-08	3.45E-07	9.35E-08
2012	0	10,047,720	7.05E-08	3.74E-08	1.33E-07	1.23E-10	2.45E-07	3.14E-08
2013	3	10,065,240	6.75E-08	3.81E-08	1.20E-07	6.79E-08	5.30E-07	2.19E-07
2014	1	10,047,720	6.47E-08	3.64E-08	1.15E-07	1.10E-08	3.47E-07	9.41E-08
2015	1	10,038,960	6.19E-08	3.26E-08	1.18E-07	1.10E-08	3.47E-07	9.42E-08
2016	1	9,968,880	5.93E-08	2.79E-08	1.26E-07	1.11E-08	3.49E-07	9.46E-08
2017	0	9,968,880	5.68E-08	2.31E-08	1.39E-07	1.24E-10	2.46E-07	3.15E-08
2018	0	9,925,080	5.44E-08	1.89E-08	1.57E-07	1.24E-10	2.47E-07	3.16E-08
Total	20	209,828,280						

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
2015 Update						2.39E-08	6.03E-07	2.27E-07
1998	3	7,594,920	--	--	--	1.22E-07	9.53E-07	3.94E-07
1999	4	7,568,640	--	--	--	1.88E-07	1.11E-06	5.09E-07
2000	7	7,621,200	--	--	--	4.08E-07	1.55E-06	8.43E-07
2001	1	7,559,880	--	--	--	1.99E-08	6.26E-07	1.70E-07
2002	1	7,542,360	--	--	--	1.99E-08	6.28E-07	1.70E-07
2003	4	7,559,880	--	--	--	1.88E-07	1.11E-06	5.09E-07
2004	2	7,542,360	--	--	--	6.49E-08	7.97E-07	2.83E-07
2005	2	7,533,600	--	--	--	6.50E-08	7.98E-07	2.84E-07
2006	0	7,524,840	--	--	--	2.23E-10	4.44E-07	5.68E-08
2007	3	7,516,080	--	--	--	1.23E-07	9.62E-07	3.98E-07
2008	4	7,524,840	--	--	--	1.89E-07	1.12E-06	5.11E-07
2009	3	7,402,200	5.01E-07	3.15E-07	7.98E-07	1.25E-07	9.75E-07	4.03E-07
2010	3	7,402,200	4.65E-07	3.14E-07	6.88E-07	1.25E-07	9.75E-07	4.03E-07
2011	3	7,419,720	4.32E-07	3.10E-07	6.00E-07	1.25E-07	9.73E-07	4.02E-07
2012	4	7,305,840	4.00E-07	3.01E-07	5.33E-07	1.94E-07	1.15E-06	5.24E-07
2013	3	7,288,320	3.72E-07	2.84E-07	4.86E-07	1.27E-07	9.87E-07	4.09E-07
2014	3	7,227,000	3.45E-07	2.60E-07	4.57E-07	1.27E-07	9.95E-07	4.12E-07
2015	5	7,227,000	3.20E-07	2.32E-07	4.42E-07	2.69E-07	1.31E-06	6.47E-07
2016	2	7,227,000	2.97E-07	2.02E-07	4.36E-07	6.73E-08	8.27E-07	2.94E-07
2017	1	7,227,000	2.76E-07	1.75E-07	4.35E-07	2.07E-08	6.51E-07	1.76E-07
2018	1	7,139,400	2.56E-07	1.50E-07	4.37E-07	2.09E-08	6.58E-07	1.78E-07
Total	59	155,954,280						

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

Year	Failures	Hours	Regression Curve Data Points			Yearly Estimate Data Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
2015 Update						5.76E-09	3.01E-07	1.02E-07
1998	0	9,890,040	--	--	--	1.45E-10	2.87E-07	3.68E-08
1999	7	9,855,000	--	--	--	2.68E-07	1.02E-06	5.53E-07
2000	4	9,960,120	--	--	--	1.22E-07	7.20E-07	3.29E-07
2001	2	9,960,120	--	--	--	4.19E-08	5.14E-07	1.83E-07
2002	7	9,960,120	--	--	--	2.66E-07	1.01E-06	5.49E-07
2003	2	9,977,640	--	--	--	4.18E-08	5.14E-07	1.83E-07
2004	1	9,977,640	--	--	--	1.29E-08	4.04E-07	1.10E-07
2005	0	9,977,640	--	--	--	1.44E-10	2.85E-07	3.65E-08
2006	1	10,091,520	--	--	--	1.27E-08	4.01E-07	1.09E-07
2007	1	9,995,160	--	--	--	1.28E-08	4.04E-07	1.09E-07
2008	2	10,003,920	--	--	--	4.18E-08	5.13E-07	1.82E-07
2009	1	9,986,400	1.45E-07	5.52E-08	3.82E-07	1.28E-08	4.04E-07	1.10E-07
2010	1	9,986,400	1.36E-07	6.01E-08	3.09E-07	1.28E-08	4.04E-07	1.10E-07
2011	2	10,144,080	1.28E-07	6.41E-08	2.54E-07	4.13E-08	5.08E-07	1.80E-07
2012	4	10,047,720	1.20E-07	6.63E-08	2.16E-07	1.21E-07	7.15E-07	3.27E-07
2013	1	10,065,240	1.12E-07	6.53E-08	1.92E-07	1.28E-08	4.02E-07	1.09E-07
2014	0	10,047,720	1.05E-07	6.04E-08	1.83E-07	1.43E-10	2.84E-07	3.63E-08
2015	2	10,038,960	9.84E-08	5.27E-08	1.84E-07	4.17E-08	5.12E-07	1.82E-07
2016	0	9,968,880	9.22E-08	4.41E-08	1.93E-07	1.44E-10	2.86E-07	3.66E-08
2017	1	9,968,880	8.64E-08	3.60E-08	2.08E-07	1.29E-08	4.05E-07	1.10E-07
2018	1	9,925,080	8.10E-08	2.89E-08	2.27E-07	1.29E-08	4.06E-07	1.10E-07
Total	40	209,828,280						

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
2015 Update						5.76E-09	3.01E-07	1.02E-07
1998	2	7,594,920	--	--	--	4.82E-08	5.92E-07	2.10E-07
1999	2	7,568,640	--	--	--	4.83E-08	5.93E-07	2.11E-07
2000	0	7,621,200	--	--	--	1.65E-10	3.28E-07	4.20E-08
2001	3	7,559,880	--	--	--	9.15E-08	7.14E-07	2.95E-07
2002	1	7,542,360	--	--	--	1.49E-08	4.68E-07	1.27E-07
2003	0	7,559,880	--	--	--	1.66E-10	3.30E-07	4.22E-08
2004	1	7,542,360	--	--	--	1.49E-08	4.68E-07	1.27E-07
2005	0	7,533,600	--	--	--	1.66E-10	3.31E-07	4.23E-08
2006	1	7,524,840	--	--	--	1.49E-08	4.69E-07	1.27E-07
2007	0	7,516,080	--	--	--	1.67E-10	3.31E-07	4.24E-08
2008	1	7,524,840	--	--	--	1.49E-08	4.69E-07	1.27E-07
2009	2	7,402,200	1.42E-07	4.95E-08	4.06E-07	4.90E-08	6.02E-07	2.14E-07
2010	2	7,402,200	1.27E-07	5.22E-08	3.11E-07	4.90E-08	6.02E-07	2.14E-07
2011	0	7,419,720	1.14E-07	5.40E-08	2.43E-07	1.68E-10	3.34E-07	4.27E-08
2012	2	7,305,840	1.03E-07	5.41E-08	1.96E-07	4.94E-08	6.07E-07	2.16E-07
2013	0	7,288,320	9.25E-08	5.15E-08	1.66E-07	1.70E-10	3.38E-07	4.32E-08
2014	0	7,227,000	8.31E-08	4.60E-08	1.50E-07	1.71E-10	3.39E-07	4.34E-08
2015	0	7,227,000	7.47E-08	3.85E-08	1.45E-07	1.71E-10	3.39E-07	4.34E-08
2016	1	7,227,000	6.71E-08	3.08E-08	1.46E-07	1.53E-08	4.81E-07	1.30E-07
2017	1	7,227,000	6.03E-08	2.39E-08	1.52E-07	1.53E-08	4.81E-07	1.30E-07
2018	0	7,139,400	5.42E-08	1.82E-08	1.61E-07	1.72E-10	3.42E-07	4.38E-08
Total	19	155,954,280						

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	8,162	87.0	--	--	--	9.21E+01	9.55E+01	9.38E+01
1999	8,687	87.0	--	--	--	9.81E+01	1.02E+02	9.99E+01
2000	8,040	87.2	--	--	--	9.05E+01	9.39E+01	9.22E+01
2001	8,213	87.0	--	--	--	9.27E+01	9.61E+01	9.44E+01
2002	8,534	87.0	--	--	--	9.64E+01	9.99E+01	9.81E+01
2003	8,531	87.0	--	--	--	9.63E+01	9.98E+01	9.81E+01
2004	8,194	87.2	--	--	--	9.22E+01	9.57E+01	9.39E+01
2005	8,122	87.0	--	--	--	9.17E+01	9.51E+01	9.34E+01
2006	7,783	87.0	--	--	--	8.78E+01	9.12E+01	8.95E+01
2007	7,667	87.0	--	--	--	8.65E+01	8.98E+01	8.81E+01
2008	7,695	87.2	--	--	--	8.66E+01	8.99E+01	8.82E+01
2009	7,792	87.0	8.86E+01	8.71E+01	9.01E+01	8.79E+01	9.13E+01	8.96E+01
2010	7,675	87.0	8.91E+01	8.78E+01	9.04E+01	8.66E+01	8.99E+01	8.82E+01
2011	7,769	87.0	8.96E+01	8.86E+01	9.07E+01	8.76E+01	9.10E+01	8.93E+01
2012	7,790	87.2	9.02E+01	8.93E+01	9.11E+01	8.76E+01	9.10E+01	8.93E+01
2013	7,703	84.6	9.07E+01	8.99E+01	9.16E+01	8.94E+01	9.28E+01	9.11E+01
2014	7,587	83.0	9.13E+01	9.04E+01	9.21E+01	8.97E+01	9.32E+01	9.14E+01
2015	7,702	82.0	9.18E+01	9.09E+01	9.28E+01	9.22E+01	9.57E+01	9.39E+01
2016	7,469	82.0	9.24E+01	9.12E+01	9.35E+01	8.94E+01	9.29E+01	9.11E+01
2017	7,519	81.0	9.29E+01	9.16E+01	9.43E+01	9.11E+01	9.46E+01	9.28E+01
2018	7,561	81.0	9.35E+01	9.19E+01	9.51E+01	9.16E+01	9.51E+01	9.34E+01
Total	166,198	1,799.5						

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	27,512	103.0	--	--	--	2.64E+02	2.70E+02	2.67E+02
1999	28,380	103.0	--	--	--	2.73E+02	2.78E+02	2.76E+02
2000	27,759	103.3	--	--	--	2.66E+02	2.71E+02	2.69E+02
2001	27,610	103.0	--	--	--	2.65E+02	2.71E+02	2.68E+02
2002	26,972	103.0	--	--	--	2.59E+02	2.64E+02	2.62E+02
2003	27,513	103.0	--	--	--	2.64E+02	2.70E+02	2.67E+02
2004	26,920	103.3	--	--	--	2.58E+02	2.63E+02	2.61E+02
2005	27,036	103.0	--	--	--	2.60E+02	2.65E+02	2.62E+02
2006	27,794	103.0	--	--	--	2.67E+02	2.73E+02	2.70E+02
2007	27,675	103.6	--	--	--	2.64E+02	2.70E+02	2.67E+02
2008	27,657	104.3	--	--	--	2.63E+02	2.68E+02	2.65E+02
2009	26,991	104.0	2.57E+02	2.53E+02	2.61E+02	2.57E+02	2.62E+02	2.60E+02
2010	27,018	104.0	2.59E+02	2.55E+02	2.62E+02	2.57E+02	2.62E+02	2.60E+02
2011	27,035	104.0	2.60E+02	2.58E+02	2.63E+02	2.57E+02	2.63E+02	2.60E+02
2012	26,727	104.3	2.62E+02	2.60E+02	2.64E+02	2.54E+02	2.59E+02	2.56E+02
2013	26,583	101.6	2.64E+02	2.61E+02	2.66E+02	2.59E+02	2.64E+02	2.62E+02
2014	26,765	100.0	2.65E+02	2.63E+02	2.67E+02	2.65E+02	2.70E+02	2.68E+02
2015	26,553	99.0	2.67E+02	2.64E+02	2.69E+02	2.66E+02	2.71E+02	2.68E+02
2016	26,487	99.0	2.68E+02	2.66E+02	2.71E+02	2.65E+02	2.70E+02	2.67E+02
2017	26,665	98.0	2.70E+02	2.67E+02	2.74E+02	2.69E+02	2.75E+02	2.72E+02
2018	26,528	97.7	2.72E+02	2.68E+02	2.76E+02	2.69E+02	2.74E+02	2.71E+02
Total	570,180	2,147.1						

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	8	87.0	--	--	--	4.50E-02	1.57E-01	8.83E-02
1999	6	87.0	--	--	--	3.06E-02	1.30E-01	6.75E-02
2000	5	87.2	--	--	--	2.37E-02	1.16E-01	5.70E-02
2001	8	87.0	--	--	--	4.50E-02	1.57E-01	8.83E-02
2002	4	87.0	--	--	--	1.73E-02	1.02E-01	4.68E-02
2003	6	87.0	--	--	--	3.06E-02	1.30E-01	6.75E-02
2004	3	87.2	--	--	--	1.12E-02	8.77E-02	3.63E-02
2005	4	87.0	--	--	--	1.73E-02	1.02E-01	4.68E-02
2006	10	87.0	--	--	--	6.02E-02	1.83E-01	1.09E-01
2007	6	87.0	--	--	--	3.06E-02	1.30E-01	6.75E-02
2008	4	87.2	--	--	--	1.72E-02	1.02E-01	4.66E-02
2009	5	87.0	7.20E-02	3.35E-02	1.55E-01	2.38E-02	1.16E-01	5.71E-02
2010	5	87.0	6.47E-02	3.41E-02	1.23E-01	2.38E-02	1.16E-01	5.71E-02
2011	11	87.0	5.81E-02	3.39E-02	9.98E-02	6.80E-02	1.96E-01	1.19E-01
2012	2	87.2	5.22E-02	3.25E-02	8.40E-02	5.94E-03	7.29E-02	2.59E-02
2013	8	84.6	4.69E-02	2.96E-02	7.43E-02	4.62E-02	1.61E-01	9.06E-02
2014	4	83.0	4.22E-02	2.56E-02	6.95E-02	1.80E-02	1.07E-01	4.88E-02
2015	4	82.0	3.79E-02	2.11E-02	6.79E-02	1.82E-02	1.08E-01	4.93E-02
2016	1	82.0	3.40E-02	1.70E-02	6.83E-02	1.93E-03	6.07E-02	1.64E-02
2017	1	81.0	3.06E-02	1.34E-02	6.98E-02	1.95E-03	6.13E-02	1.66E-02
2018	4	81.0	2.75E-02	1.05E-02	7.20E-02	1.84E-02	1.09E-01	4.99E-02
Total	109	1,799.5						

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	16	103.0	--	--	--	9.26E-02	2.21E-01	1.46E-01
1999	8	103.0	--	--	--	3.85E-02	1.34E-01	7.55E-02
2000	11	103.3	--	--	--	5.80E-02	1.67E-01	1.02E-01
2001	5	103.0	--	--	--	2.03E-02	9.93E-02	4.88E-02
2002	6	103.0	--	--	--	2.62E-02	1.11E-01	5.77E-02
2003	5	103.0	--	--	--	2.03E-02	9.93E-02	4.88E-02
2004	9	103.3	--	--	--	4.48E-02	1.45E-01	8.41E-02
2005	6	103.0	--	--	--	2.62E-02	1.11E-01	5.77E-02
2006	6	103.0	--	--	--	2.62E-02	1.11E-01	5.77E-02
2007	2	103.6	--	--	--	5.06E-03	6.21E-02	2.21E-02
2008	9	104.3	--	--	--	4.44E-02	1.43E-01	8.34E-02
2009	4	104.0	5.98E-02	3.26E-02	1.10E-01	1.46E-02	8.66E-02	3.96E-02
2010	8	104.0	5.66E-02	3.39E-02	9.44E-02	3.82E-02	1.33E-01	7.48E-02
2011	6	104.0	5.36E-02	3.49E-02	8.24E-02	2.59E-02	1.10E-01	5.72E-02
2012	3	104.3	5.07E-02	3.50E-02	7.36E-02	9.51E-03	7.43E-02	3.07E-02
2013	8	101.6	4.80E-02	3.39E-02	6.80E-02	3.90E-02	1.36E-01	7.64E-02
2014	10	100.0	4.55E-02	3.16E-02	6.55E-02	5.29E-02	1.60E-01	9.58E-02
2015	4	99.0	4.31E-02	2.83E-02	6.55E-02	1.53E-02	9.06E-02	4.14E-02
2016	4	99.0	4.08E-02	2.48E-02	6.70E-02	1.53E-02	9.05E-02	4.14E-02
2017	2	98.0	3.86E-02	2.14E-02	6.97E-02	5.32E-03	6.53E-02	2.32E-02
2018	3	97.7	3.65E-02	1.83E-02	7.30E-02	1.01E-02	7.88E-02	3.26E-02
Total	135	2,147.1						

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	0	87.0	--	--	--	1.44E-05	2.86E-02	3.66E-03
1999	3	87.0	--	--	--	7.94E-03	6.20E-02	2.56E-02
2000	3	87.2	--	--	--	7.92E-03	6.19E-02	2.56E-02
2001	1	87.0	--	--	--	1.29E-03	4.05E-02	1.10E-02
2002	1	87.0	--	--	--	1.29E-03	4.05E-02	1.10E-02
2003	1	87.0	--	--	--	1.29E-03	4.05E-02	1.10E-02
2004	0	87.2	--	--	--	1.44E-05	2.86E-02	3.66E-03
2005	2	87.0	--	--	--	4.20E-03	5.15E-02	1.83E-02
2006	0	87.0	--	--	--	1.44E-05	2.86E-02	3.66E-03
2007	1	87.0	--	--	--	1.29E-03	4.05E-02	1.10E-02
2008	0	87.2	--	--	--	1.44E-05	2.86E-02	3.66E-03
2009	1	87.0	9.30E-03	3.26E-03	2.65E-02	1.29E-03	4.05E-02	1.10E-02
2010	0	87.0	8.95E-03	3.69E-03	2.18E-02	1.44E-05	2.86E-02	3.66E-03
2011	1	87.0	8.63E-03	4.09E-03	1.82E-02	1.29E-03	4.05E-02	1.10E-02
2012	0	87.2	8.31E-03	4.40E-03	1.57E-02	1.44E-05	2.86E-02	3.66E-03
2013	3	84.6	8.01E-03	4.50E-03	1.42E-02	8.08E-03	6.31E-02	2.61E-02
2014	1	83.0	7.71E-03	4.32E-03	1.38E-02	1.33E-03	4.18E-02	1.13E-02
2015	1	82.0	7.43E-03	3.89E-03	1.42E-02	1.34E-03	4.21E-02	1.14E-02
2016	1	82.0	7.16E-03	3.35E-03	1.53E-02	1.34E-03	4.21E-02	1.14E-02
2017	0	81.0	6.90E-03	2.79E-03	1.70E-02	1.51E-05	2.99E-02	3.83E-03
2018	0	81.0	6.64E-03	2.29E-03	1.93E-02	1.51E-05	2.99E-02	3.83E-03
Total	20	1,799.5						

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	3	103.0	--	--	--	8.97E-03	7.01E-02	2.90E-02
1999	4	103.0	--	--	--	1.38E-02	8.15E-02	3.73E-02
2000	7	103.3	--	--	--	3.00E-02	1.14E-01	6.20E-02
2001	1	103.0	--	--	--	1.46E-03	4.58E-02	1.24E-02
2002	1	103.0	--	--	--	1.46E-03	4.58E-02	1.24E-02
2003	4	103.0	--	--	--	1.38E-02	8.15E-02	3.73E-02
2004	2	103.3	--	--	--	4.73E-03	5.81E-02	2.07E-02
2005	2	103.0	--	--	--	4.74E-03	5.82E-02	2.07E-02
2006	0	103.0	--	--	--	1.63E-05	3.24E-02	4.14E-03
2007	3	103.6	--	--	--	8.93E-03	6.97E-02	2.88E-02
2008	4	104.3	--	--	--	1.36E-02	8.06E-02	3.69E-02
2009	3	104.0	3.55E-02	2.24E-02	5.64E-02	8.90E-03	6.95E-02	2.87E-02
2010	3	104.0	3.31E-02	2.24E-02	4.89E-02	8.90E-03	6.95E-02	2.87E-02
2011	3	104.0	3.08E-02	2.22E-02	4.28E-02	8.90E-03	6.95E-02	2.87E-02
2012	4	104.3	2.87E-02	2.16E-02	3.81E-02	1.36E-02	8.06E-02	3.69E-02
2013	3	101.6	2.67E-02	2.05E-02	3.49E-02	9.08E-03	7.09E-02	2.93E-02
2014	3	100.0	2.49E-02	1.88E-02	3.30E-02	9.20E-03	7.18E-02	2.97E-02
2015	5	99.0	2.32E-02	1.68E-02	3.20E-02	1.96E-02	9.58E-02	4.71E-02
2016	2	99.0	2.16E-02	1.47E-02	3.16E-02	4.91E-03	6.02E-02	2.14E-02
2017	1	98.0	2.01E-02	1.28E-02	3.17E-02	1.52E-03	4.78E-02	1.30E-02
2018	1	97.7	1.87E-02	1.10E-02	3.19E-02	1.52E-03	4.79E-02	1.30E-02
Total	59	2,147.1						

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	0	87.0	--	--	--	1.66E-05	3.31E-02	4.23E-03
1999	7	87.0	--	--	--	3.07E-02	1.17E-01	6.35E-02
2000	4	87.2	--	--	--	1.40E-02	8.31E-02	3.80E-02
2001	2	87.0	--	--	--	4.85E-03	5.95E-02	2.12E-02
2002	7	87.0	--	--	--	3.07E-02	1.17E-01	6.35E-02
2003	2	87.0	--	--	--	4.85E-03	5.95E-02	2.12E-02
2004	1	87.2	--	--	--	1.49E-03	4.67E-02	1.27E-02
2005	0	87.0	--	--	--	1.66E-05	3.31E-02	4.23E-03
2006	1	87.0	--	--	--	1.49E-03	4.68E-02	1.27E-02
2007	1	87.0	--	--	--	1.49E-03	4.68E-02	1.27E-02
2008	2	87.2	--	--	--	4.84E-03	5.94E-02	2.11E-02
2009	1	87.0	1.68E-02	6.43E-03	4.39E-02	1.49E-03	4.68E-02	1.27E-02
2010	1	87.0	1.59E-02	7.03E-03	3.58E-02	1.49E-03	4.68E-02	1.27E-02
2011	2	87.0	1.50E-02	7.55E-03	2.96E-02	4.85E-03	5.95E-02	2.12E-02
2012	4	87.2	1.41E-02	7.85E-03	2.54E-02	1.40E-02	8.31E-02	3.80E-02
2013	1	84.6	1.33E-02	7.77E-03	2.28E-02	1.52E-03	4.78E-02	1.30E-02
2014	0	83.0	1.26E-02	7.24E-03	2.18E-02	1.72E-05	3.42E-02	4.38E-03
2015	2	82.0	1.18E-02	6.36E-03	2.21E-02	5.06E-03	6.21E-02	2.21E-02
2016	0	82.0	1.12E-02	5.36E-03	2.33E-02	1.74E-05	3.45E-02	4.42E-03
2017	1	81.0	1.05E-02	4.40E-03	2.52E-02	1.57E-03	4.93E-02	1.34E-02
2018	1	81.0	9.94E-03	3.56E-03	2.77E-02	1.57E-03	4.93E-02	1.34E-02
Total	40	1,799.5						

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	2	103.0	--	--	--	3.52E-03	4.33E-02	1.54E-02
1999	2	103.0	--	--	--	3.52E-03	4.33E-02	1.54E-02
2000	0	103.3	--	--	--	1.21E-05	2.40E-02	3.07E-03
2001	3	103.0	--	--	--	6.67E-03	5.21E-02	2.15E-02
2002	1	103.0	--	--	--	1.08E-03	3.41E-02	9.23E-03
2003	0	103.0	--	--	--	1.21E-05	2.40E-02	3.08E-03
2004	1	103.3	--	--	--	1.08E-03	3.40E-02	9.21E-03
2005	0	103.0	--	--	--	1.21E-05	2.40E-02	3.08E-03
2006	1	103.0	--	--	--	1.08E-03	3.41E-02	9.23E-03
2007	0	103.6	--	--	--	1.21E-05	2.40E-02	3.07E-03
2008	1	104.3	--	--	--	1.07E-03	3.38E-02	9.16E-03
2009	2	104.0	1.01E-02	3.53E-03	2.89E-02	3.50E-03	4.30E-02	1.53E-02
2010	2	104.0	9.09E-03	3.73E-03	2.22E-02	3.50E-03	4.30E-02	1.53E-02
2011	0	104.0	8.20E-03	3.87E-03	1.74E-02	1.20E-05	2.39E-02	3.06E-03
2012	2	104.3	7.39E-03	3.89E-03	1.40E-02	3.50E-03	4.29E-02	1.53E-02
2013	0	101.6	6.66E-03	3.71E-03	1.19E-02	1.22E-05	2.43E-02	3.10E-03
2014	0	100.0	6.00E-03	3.32E-03	1.08E-02	1.23E-05	2.45E-02	3.13E-03
2015	0	99.0	5.40E-03	2.79E-03	1.05E-02	1.24E-05	2.47E-02	3.15E-03
2016	1	99.0	4.87E-03	2.23E-03	1.06E-02	1.11E-03	3.49E-02	9.46E-03
2017	1	98.0	4.39E-03	1.74E-03	1.11E-02	1.12E-03	3.51E-02	9.52E-03
2018	0	97.7	3.95E-03	1.33E-03	1.17E-02	1.25E-05	2.48E-02	3.18E-03
Total	19	2,147.1						

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