Enhanced Component Performance Study

Air-Operated Valves

1998–2010

1 INTRODUCTION

This report presents an enhanced performance evaluation of air-operated valves (AOVs) at U.S. commercial nuclear power plants. This report does not estimate values for use in probabilistic risk assessments (PRAs), but does evaluate component performance over time. Reference 1 (NUREG/CR-6928) reports AOV unreliability estimates using Equipment Performance and Information Exchange (EPIX) data from 1998–2002 for use in PRAs.

The trend evaluations in this study are based on the operating experience failure reports from fiscal year (FY) 1998 through FY 2010 for the component reliability as reported in EPIX. The AOV failure modes considered are failure-to-open/close (FTOC), (failure to operate or control) (FTOP), and spurious operation (SO).

Previously, the study relied on operating experience obtained from licensee event reports, Nuclear Plant Reliability Data System (NPRDS), and EPIX. The EPIX database (which includes as a subset the Mitigating Systems Performance Index (MSPI) designated devices) has matured to the point where component availability and reliability can be estimated with a higher degree of assurance of accuracy. In addition, the population of data is much larger than the population used in the previous study.

The objective of the effort for the updated component performance studies is to obtain annual performance trends of failure rates and probabilities. An overview of the trending methods, glossary of terms, and abbreviations can be found in the Overview and Reference document on the Reactor Operational Experience Results and Databases web page.

The objective of the enhanced component performance study is to present an analysis of factors that could influence the system and component trends in addition to annual performance trends of failure rates and probabilities. Engineering analyses were performed with respect to time period and failure mode (Section 4.1). The factors analyzed are: sub-component, failure cause, detection method, recovery.

2 SUMMARY OF FINDINGS

The results of this study are summarized in this section. Of particular interest is the existence of any statistically significant[1] increasing trends. In this update, no statistically significant increasing trends were identified in the AOV results.

Statistically significant decreasing trends were identified in the AOV results for the following:

- All systems, industry-wide AOV FTOC trend AOVs with ≤ 20 demands per year. (see Figure 1)
- All systems, industry-wide AOV FTOC trend AOVs with > 20 demands per year. (see Figure 2)
- Frequency (failures per reactor year) of AOV FTOC events > 20 demands per year. (see Figure 10)

Highly statistically significant decreasing trends were identified in the AOV results for the following:

- Frequency (failures per reactor year) of AOV FTOC events ≤ 20 demands per year. (see Figure 9)

Extremely statistically significant decreasing trends were identified in the AOV results for the following:

- Frequency (demands per reactor year) of AOV operation demands, ≤ 20 demands per year. (see Figure 7)

Considering the low-demand AOVs; Table 3 shows that 87% of the AOV FTOC failures occurred in seven systems. Table 4 shows that 87% of the AOV FTOP failures occurred in five systems. Similarly, Table 5 shows that 82% of the AOV SO failures occurred in five systems. And considering the high-demand AOVs; Table 6 shows that 95% of the AOV FTOC failures occurred in six systems. Table 7 shows that 93% of the AOV FTOP failures occurred in three systems. Similarly, Table 8 shows that 100% of the AOV SO failures occurred in six systems.

3 FAILURE PROBABILITIES AND FAILURE RATES

3.1 Overview

Trends of industry-wide failure probabilities and failure rates of AOVs have been calculated from the operating experience for the FTOC, FTOP, and SO failure modes. The AOV data set obtained from EPIX was segregated to AOVs with ≤ 20 demands/year (d/yr) and AOVs with > 20 d/yr and includes AOVs in the systems listed in Table 1. NUREG/CR-6928 lists the industry failure data for AOVs with ≤ 20 d/yr. Table 2 shows industry-wide failure probability and failure rate results for the AOV with ≤ 20

[1] 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).

d/yr from Reference 1. No results are shown for >20d/yr AOVs because Reference 1 does not present results for >20 d/yr.

The AOVs are assumed to operate both when the reactor is critical and during shutdown periods. The number of valves in operation is assumed to be constant throughout the study period. All demand types are considered—testing, non-testing, and, as applicable, emergency safeguard feature (ESF) demands.

Table 1. AOV systems.

		AOV Component Count		
System	Description	Total	≤20 d/yr	>20 d/yr
AFW	Auxiliary feedwater	361	206	155
CCW	Component cooling water	435	302	133
CDS	Condensate system	29	19	10
CRD	Control rod drive	115	81	34
CSR	Containment spray recirculation	30	28	2
CVC	Chemical and volume control	488	349	139
EPS	Emergency power supply	48	25	23
HCI	High pressure coolant injection	14	8	6
HPI	High pressure injection	93	72	21
ISO	Isolation condenser	10	6	4
LCS	Low pressure core spray	12	12	
MFW	Main feedwater	324	174	150
MSS	Main steam	118	103	15
RCI	Reactor core isolation	7	6	1
RCS	Reactor coolant	110	56	54
RHR	Residual heat removal	259	162	97
SWN	Emergency service water (Standby)	511	315	196
SWS	Standby service water	55	22	33
	Total	3019	1946	1073

Table 2. Industry-wide distributions of p (failure probability) and λ (hourly rate) for AOVs (≤ 20 d/yr).

Failure Mode	5%	Median	Mean	95%	Distribution		
					Type	α	β
FTOC	6.0E-05	8.0E-04	1.2E-03	4.0E-03	Beta	1.00	8.33E+02
SO	2.0E-11	5.0E-08	2.0E-07	9.0E-07	Gamma	0.30	1.50E+06
FTOP	3.0E-10	7.0E-07	3.0E-06	1.5E-05	Gamma	0.30	1.00E+05

3.2 AOV Failure Probability and Failure Rate Trends

Trends in failure probabilities and failure rates are shown in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6. The data for the trend plots are contained in Table 10, Table 11, Table 12, Table 13, Table 14, and Table 15, respectively.

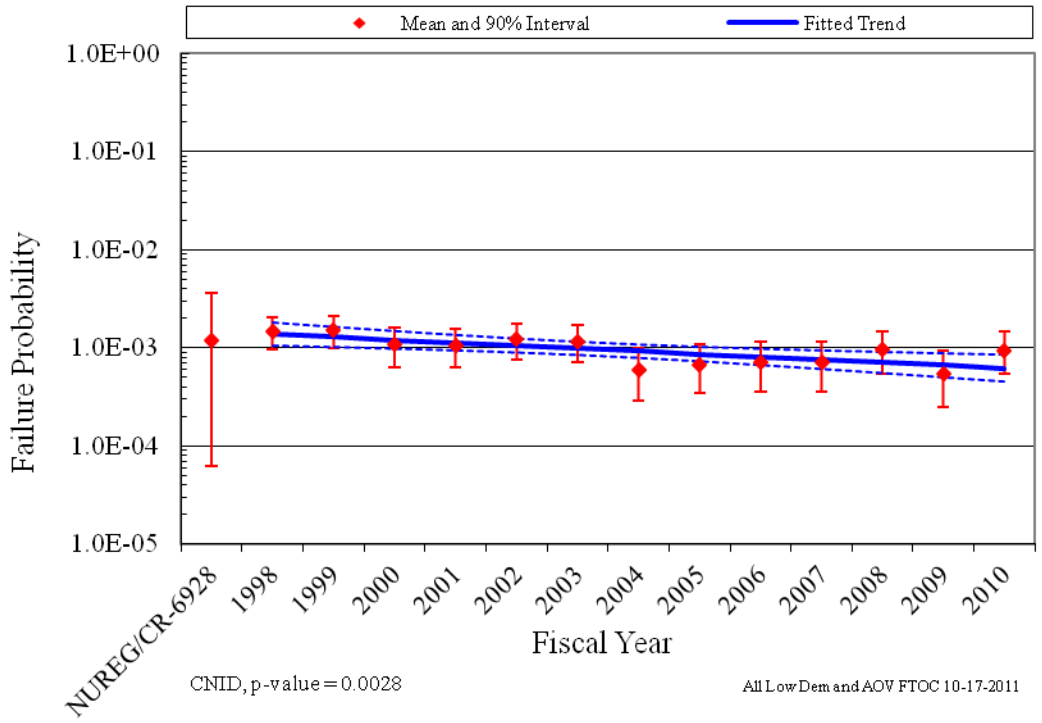

Figure 1. All systems, industry-wide AOV FTOC trend AOVs with ≤ 20 demands per year.

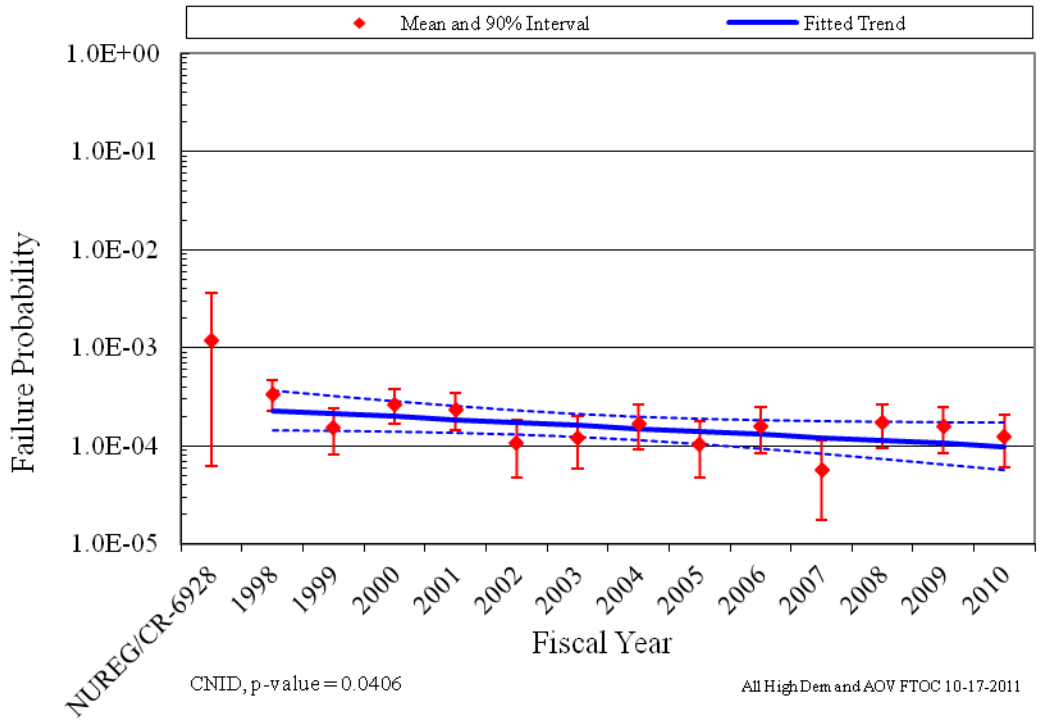

Figure 2. All systems, industry-wide AOV FTOC trend AOVs with > 20 demands per year.

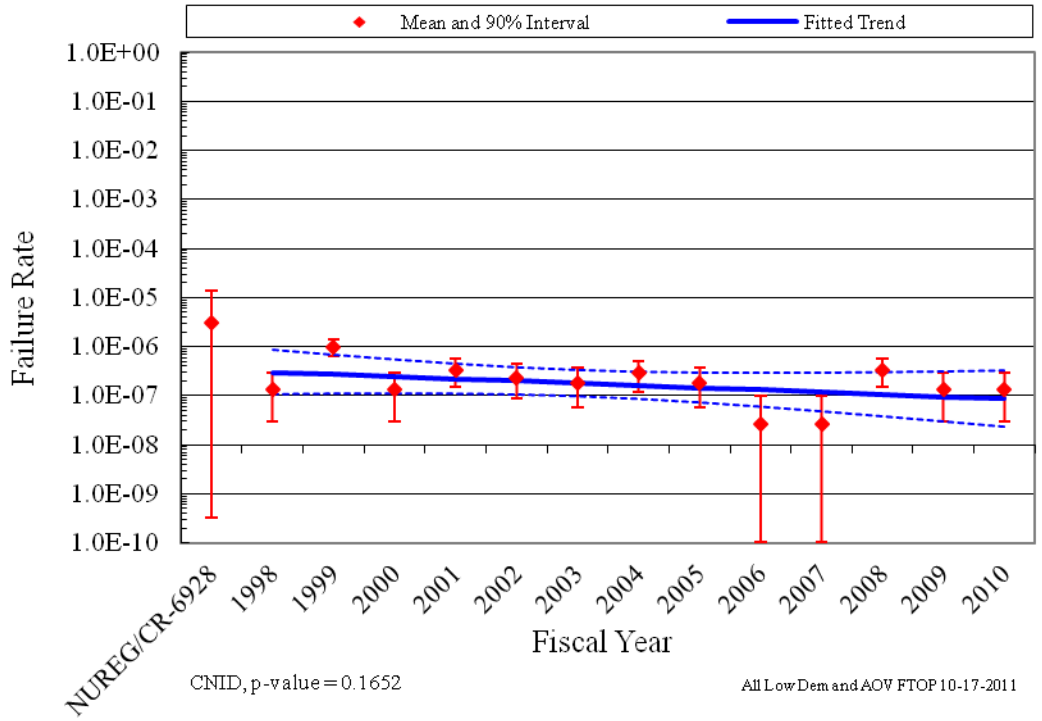

Figure 3. All systems, industry-wide AOV FTOP trend AOVs with ≤ 20 demands per year.

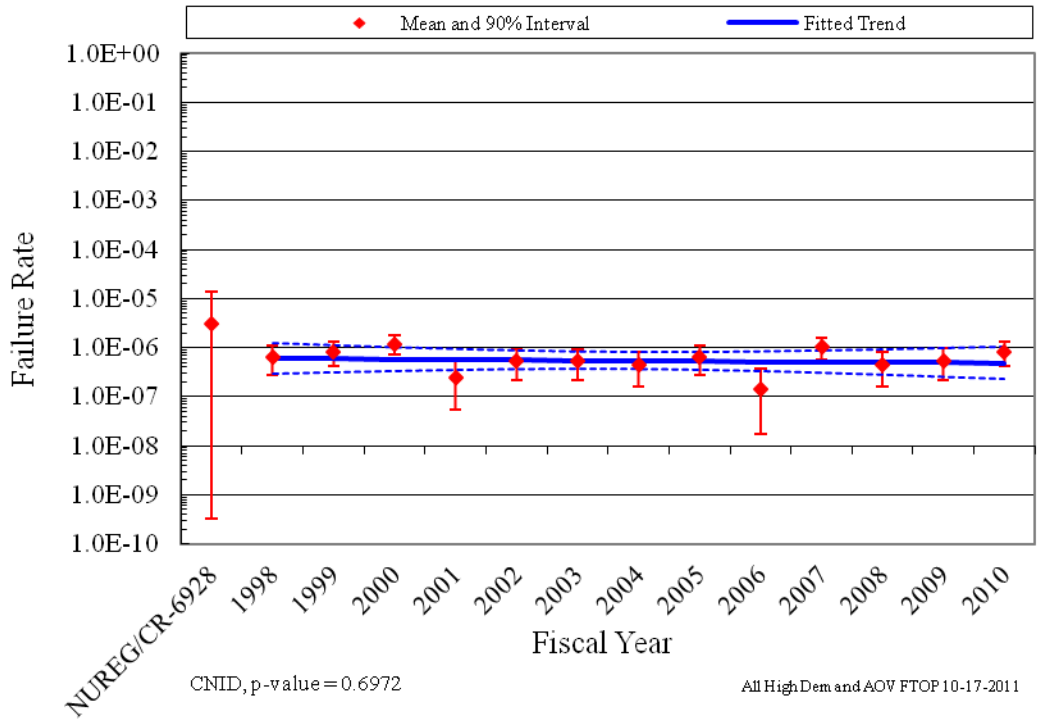

Figure 4. All systems, industry-wide AOV FTOP trend AOVs with > 20 demands per year.

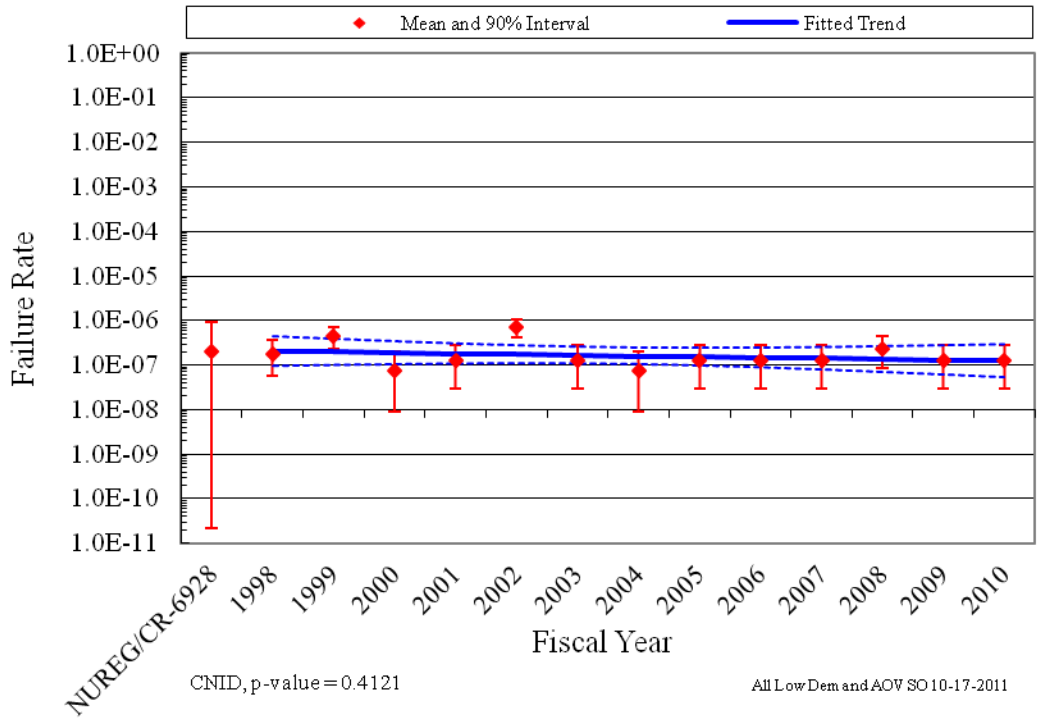

Figure 5. All systems, industry-wide AOV SO trend with ≤ 20 demands per year.

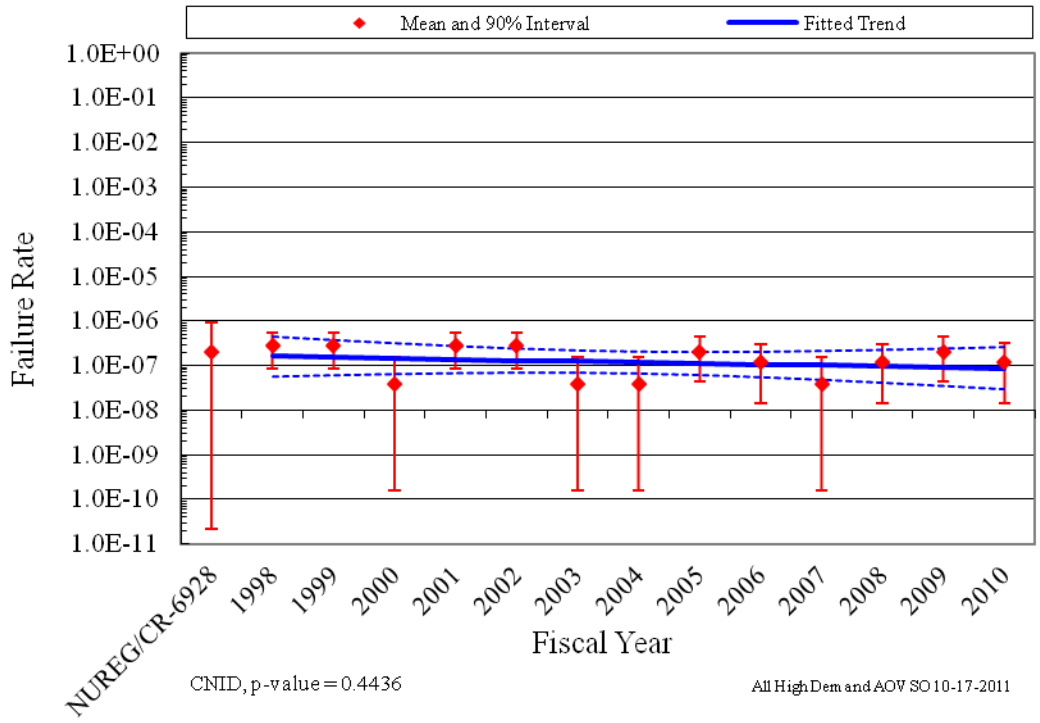

Figure 6. All systems, industry-wide AOV SO trend with > 20 demands per year.

In the plots, the means of the posterior distributions from the Bayesian update process were trended across the years. The posterior distributions were also used for the vertical bounds for each year. The 5th and 95th percentiles of these distributions give an indication of the relative variation from year to year in the data. When there are no failures, the interval is larger than the interval for years when there are one or more failures. The larger interval reflects the uncertainty that comes from having little information in that year's data. Such uncertainty intervals are determined by the prior distribution. In each plot, a relatively "flat" constrained noninformative prior distribution (CNID) is used, which has large bounds.

The horizontal curves plotted around the regression lines in the graphs form 90 percent simultaneous confidence bands for the fitted lines. The bounds are larger than ordinary confidence intervals for the trended values because they form a band that has a 90% probability of containing 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 on whether the slope of the regression line might be zero. Low p-values indicate that the slopes are not likely to be zero, and that trends exist. Further information on the trending methods is provided in Section 2 of the Overview and Reference document. A final feature of the trend graphs is that the baseline industry values from Table 2 are shown for comparison.

4 ENGINEERING TRENDS

This section presents frequency trends for AOV failures and demands. The data are normalized by reactor year for plants that have the equipment being trended. Figure 7 shows the trend for AOV demands. Figure 9 shows the trend in failure events for FTOC mode, and Figure 13 shows the trend for the SO failure events. Table 3 and Table 6 summarize the failures by system, year, and the FTOC failure mode. The top five contributing systems for the FTOC failure mode are AFW, CCW, CVC, MFW, and SWN. Table 4 and Table 7 summarize the failures by system, year, and the FTOP failure mode. The top five contributing systems for the FTOC failure mode are CCW, CRD, HPI, ISO, and MSS. Table 5 and

Table 8 summarize the failures by system, year, and the SO failure mode. The top five contributing systems for the SO failure mode are AFW, CCW, CRD, CVC, and MFW. Table 16, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22, and Table 23 provide the frequency (per reactor year) of AOV demands, FTOC events, FTOP events, and SO events, respectively. The systems from Table 2 are trended together for each figure. The rate methods described in Section 2 of the Overview and Reference document are used.

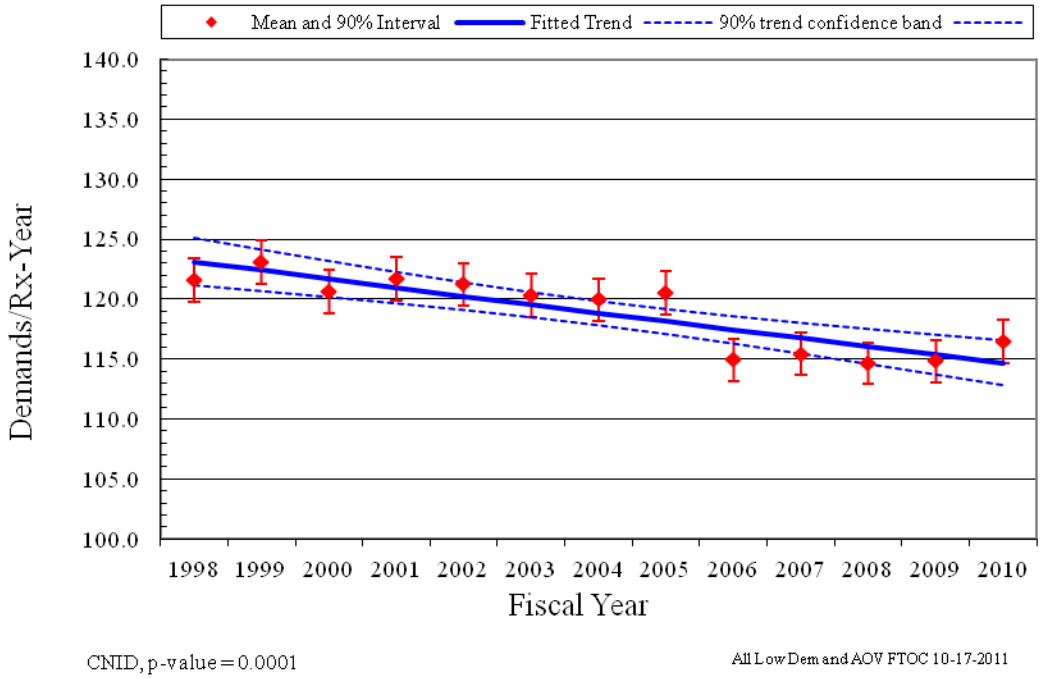

Figure 7. Frequency (demands per reactor year) of AOV operation demands, ≤ 20 demands per year.

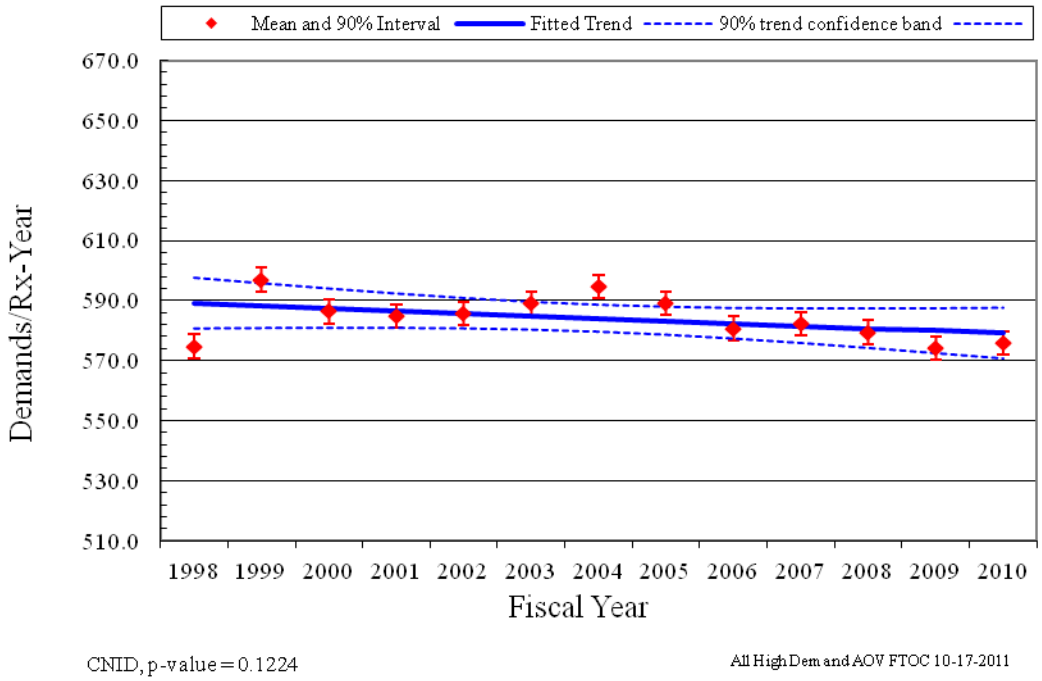

Figure 8. Frequency (demands per reactor year) of AOV operation demands, > 20 demands per year.

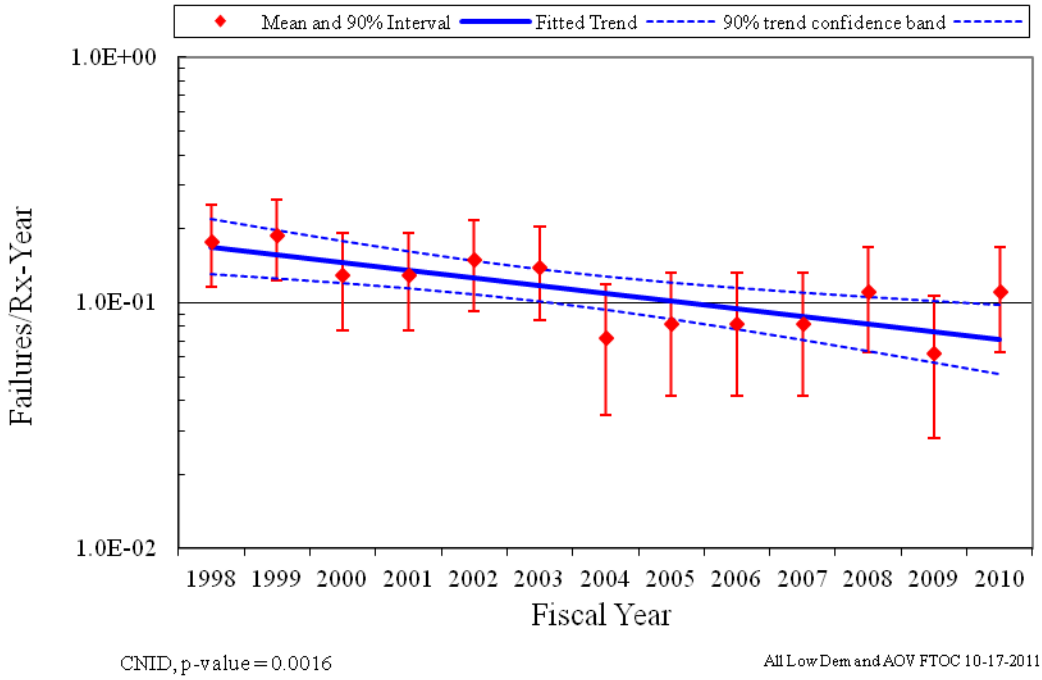

Figure 9. Frequency (failures per reactor year) of AOV FTOC events ≤ 20 demands per year.

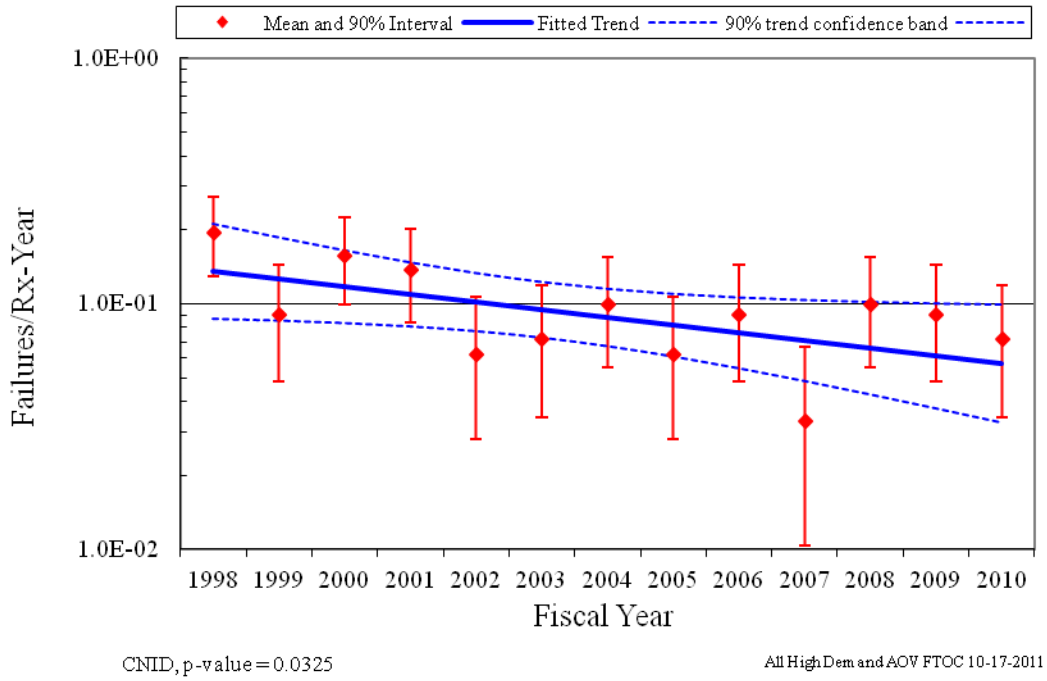

Figure 10. Frequency (failures per reactor year) of AOV FTOC events > 20 demands per year.

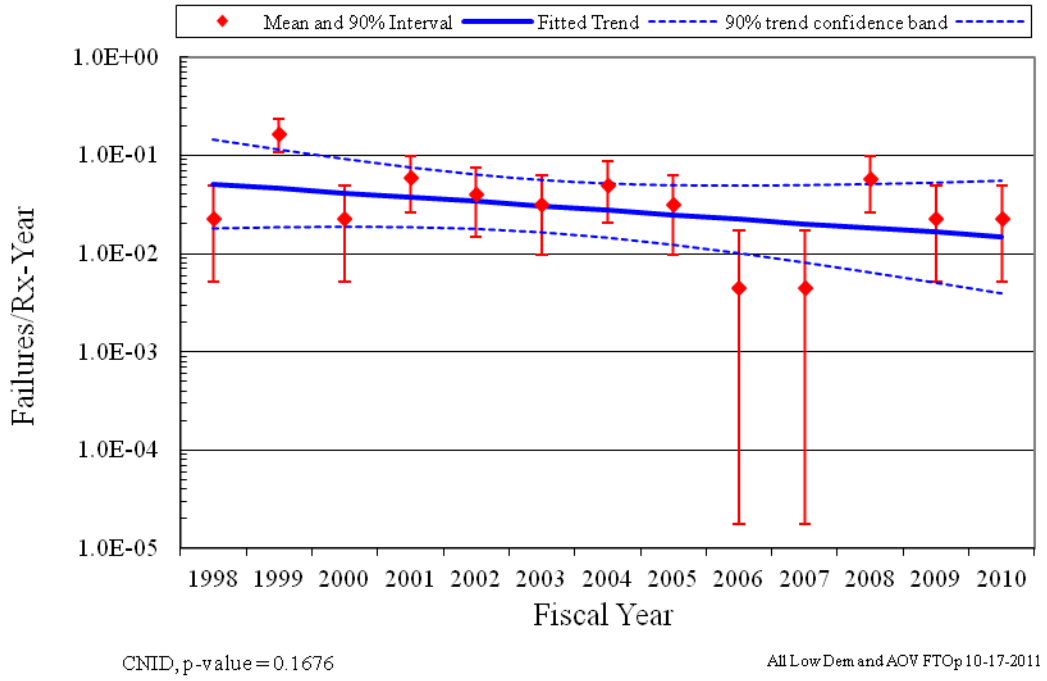

Figure 11. Frequency (failures per reactor year) of AOV FTOP events ≤ 20 demands per year.

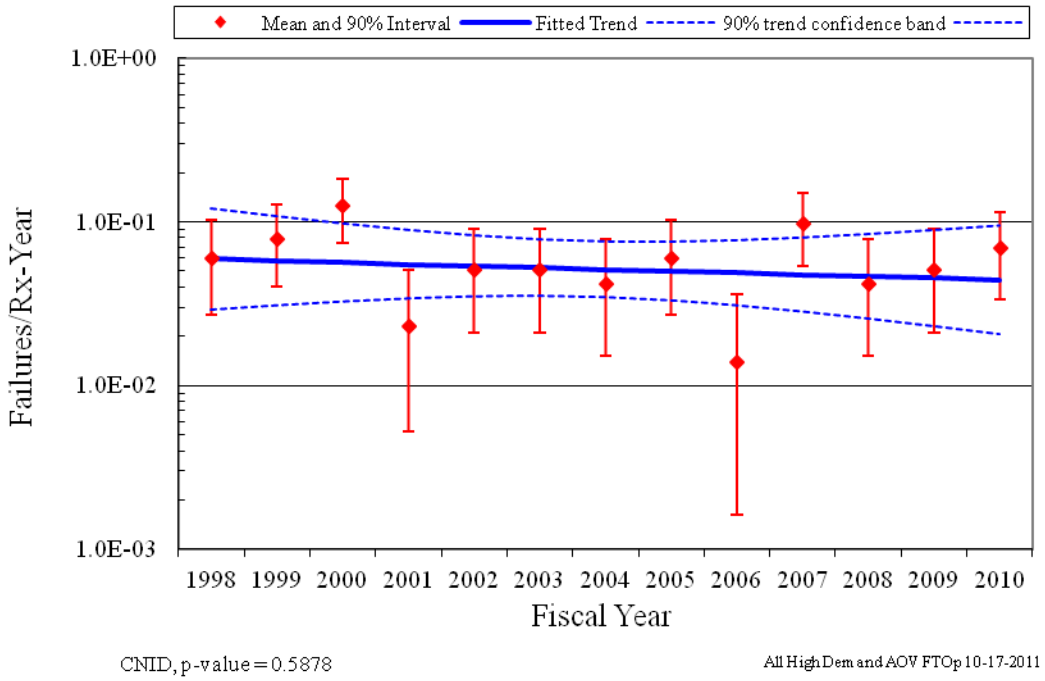

Figure 12. Frequency (failures per reactor year) of AOV FTOP events > 20 demands per year.

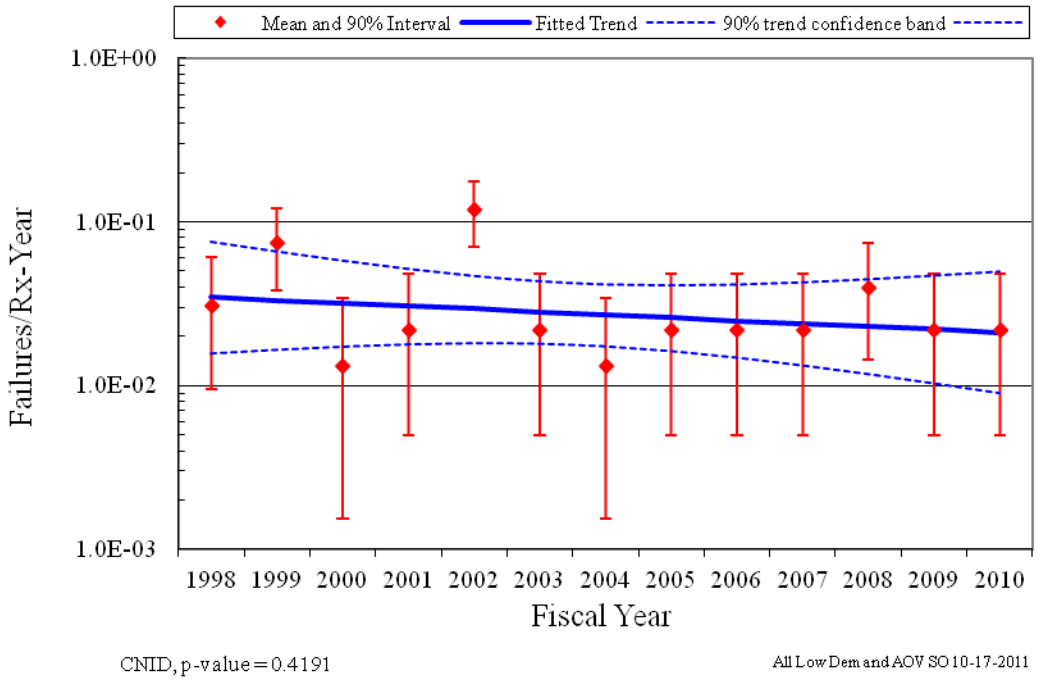

Figure 13. Frequency (failures per reactor year) of AOV SO events ≤ 20 demands per year.

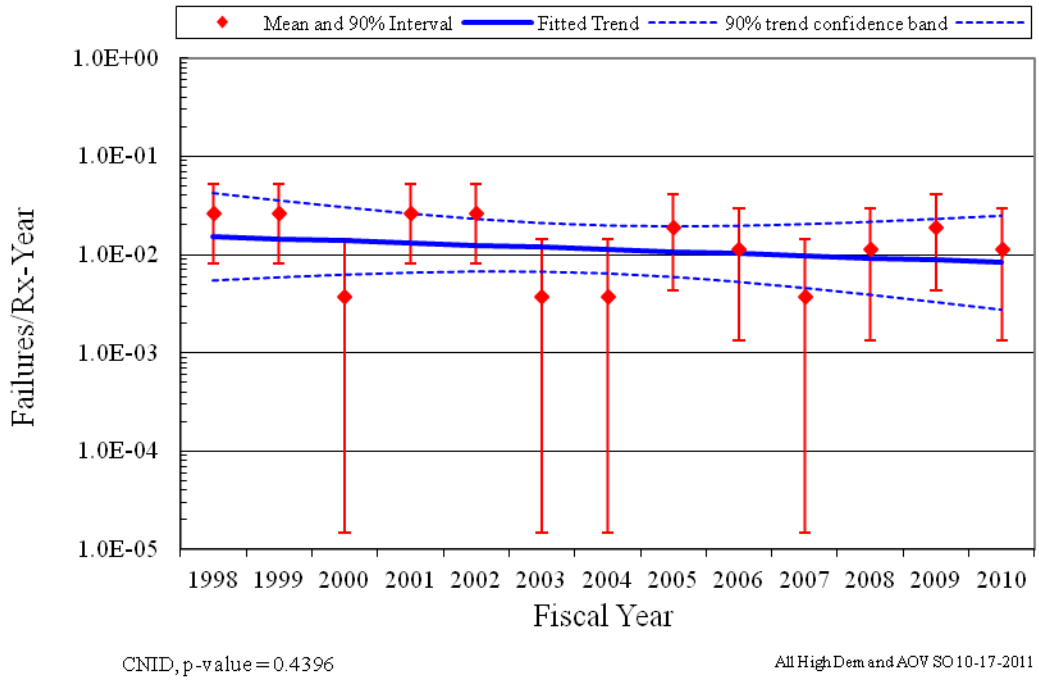

Figure 14. Frequency (failures per reactor year) of AOV SO events > 20 demands per year.

Table 3. Summary of AOV failure counts for the FTOC failure mode over time by system ≤ 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	***Percent of Failures***
AFW	205	10.9%	5		3	3	4			2	1	1		1	3	23	15.2%
CCW	302	16.0%	1			2	3	1	1	1	2	2	7		1	21	13.9%
CRD	81	4.3%		1												1	0.7%
CSR	28	1.5%	1							1		1				3	2.0%
CVC	349	18.5%	2	2	1	2	4	2			1	1		1	1	17	11.3%
HPI	72	3.8%						2			1		1			4	2.6%
LCS	12	0.6%		1												1	0.7%
MFW	174	9.2%	2	5	3	3	1	1	1	3		1			2	22	14.6%
MSS	103	5.5%	1		4		2	1								8	5.3%
RCI	6	0.3%											1			1	0.7%
RCS	56	3.0%		1				1	1					1	1	5	3.3%
RHR	162	8.6%	1	5			1	1			2	1		1	2	14	9.3%
SWN	315	16.7%	5	4	2	3		1	4	1	1	1	2	2	1	27	17.9%
SWS	22	1.2%						4								4	2.6%
Total	1887	100.0%	18	19	13	13	15	14	7	8	8	8	11	6	11	151	100.0%

Table 4. Summary of AOV failure counts for the FTOP failure mode over time by system ≤ 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	***Percent of Failures***
AFW	205	11.6%			1										1	2	3.8%
CCW	302	17.1%		1		1	1			1			2	1		7	13.2%
CRD	349	19.8%		2		1	1		1							5	9.4%
CSR	72	4.1%				1										1	1.9%
CVC	6	0.3%					1									1	1.9%
HPI	174	9.9%	1	10	1	2		2	4	1			2	1		24	45.3%
ISO	103	5.8%		2			1						1			4	7.5%
LCS	56	3.2%													1	1	1.9%
MFW	162	9.2%	1													1	1.9%
MSS	315	17.8%		2		1		1		1			1			6	11.3%
RCI	22	1.2%		1												1	1.9%
Total	1766	100.0%	2	18	2	6	4	3	5	3	0	0	6	2	2	53	100.0%

Table 5. Summary of AOV failure counts for the SO failure mode over time by system ≤ 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	***Percent of Failures***
AFW	205	11.1%				2		1	1			1	1	1		7	15.9%
CCW	302	16.4%		1	1		7					1			1	11	25.0%
CRD	81	4.4%		4												4	9.1%
CVC	349	19.0%					5			1				1		7	15.9%
HPI	72	3.9%						1								1	2.3%
MFW	174	9.5%	1							1	2		2		1	7	15.9%
MSS	103	5.6%		2												2	4.5%
RCS	56	3.0%		1			1									2	4.5%
RHR	162	8.8%	1										1			2	4.5%
SWN	315	17.1%	1													1	2.3%
SWS	22	1.2%														0	0.0%
Total	1841	100.0%	3	8	1	2	13	2	1	2	2	2	4		2	44	100.0%

Table 6. Summary of AOV failure counts for the FTOC failure mode over time by system > 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	***Percent of Failures***
AFW	155	15.4%	1	2	1	3		2	5	3	4		3		1	25	21.4%
CCW	133	13.2%	2		4						1				1	8	6.8%
CRD	34	3.4%	2		1											3	2.6%
CVC	139	13.8%	1	1			1					1				4	3.4%
MFW	150	14.9%	5	1	5	3	1	1	2					3	1	22	18.8%
MSS	15	1.5%			2						1		1			4	3.4%
RCS	54	5.4%				4		2	2	1		1	1		1	12	10.3%
RHR	97	9.6%	2	3	1		1	1			1	1	1	2	1	14	12.0%
SWN	196	19.5%	3	2	2	4	3	1	1	2	2		4	4	2	30	25.6%
SWS	33	3.3%	4													4	3.4%
Total	1006	100.0%	20	9	16	14	6	7	10	6	9	3	10		7	117	100.0%

Table 7. Summary of AOV failure counts for the FTOP failure mode over time by system > 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	*Percent of Failures*
AFW	155	16.5%	1		1							1				3	4.2%
CCW	133	14.2%	1													1	1.4%
CVC	139	14.8%		1			1					1	1			4	5.6%
MFW	150	16.0%	4	5	6		2	2	2	2	1	6	1	3	3	37	52.1%
MSS	15	1.6%			1											1	1.4%
RCS	54	5.8%										1			1	2	2.8%
RHR	97	10.3%		1			1						1			3	4.2%
SWN	196	20.9%		1	5	2	1	3	2	4		1	1	2	3	25	35.2%
Total	939	100.0%	6	8	13	2	5	5	4	6	1	10	4		7	71	100.0%

Table 8. Summary of AOV failure counts for the SO failure mode over time by system > 20 demands per year.

System Code	*Valve Count*	*Valve Percent*	*FY 98*	*FY 99*	*FY 00*	*FY 01*	*FY 02*	*FY 03*	*FY 04*	*FY 05*	*FY 06*	*FY 07*	*FY 08*	*FY 09*	*FY 10*	*Total*	*Percent of Failures*
AFW	155	23.0%								1					1	2	10.5%
CCW	133	19.7%		1												1	5.3%
CVC	139	20.6%	1													1	5.3%
MFW	150	22.3%	2			1	2			1						6	31.6%
RHR	97	14.4%											1			1	5.3%
SWN	196	29.1%		2		2	1				1			2		8	42.1%
Total	674	100.0%	3	3	0	3	3	0	0	2	1	0	1	2	1	19	100.0%

4.1 AOV Engineering Analysis by Failure Modes

The engineering analysis of AOV failure sub-components, causes, detection methods, and recovery are presented in this section. Each analysis divides the events into two periods: before July 2003 and after July 2003 (the start of the data begins in FY 1998 and the last date is FY 2010). This breakdown was chosen for two reasons: first, July 2003 represents a point in which the MSPI data collection attains a "higher level" of scrutiny; second, this date represents a point about half way through the full data period.

The second division of the events is by the failure mode determined after EPIX data review by the staff. See Section 5 for more description of failure modes.

AOV sub-component contributions to the three failure modes are presented in Figure 15. The sub-component contributions 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. In the FTOP failure mode, the valve was shown to have no contribution to the failure rates/probabilities.

AOV 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 most likely cause for all three failure modes is grouped as Internal. Internal means that the cause was related to something within the AOV component such as a worn out part or the normal internal environment. Of particular interest is the Human cause group under the FTOC and FTOP failure modes. The human cause group is primarily influenced by maintenance and operating procedures and practices.

AOV detection methods to the three failure modes are presented in Figure 17. The most likely detection method for FTOC is a testing demand. The most likely detection method for FTOP and SO is an actual demand.

AOV recovery to the three failure modes are presented in Figure 18. The overall non-recovery to recovery ratio is approximately 3:1.

Table 9. Component failure cause groups.

Group	Specific Cause	Description
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	Design error or inadequacy	Used when a design error is made.
Design	Manufacturing error or inadequacy	Used when a manufacturing error is made during component manufacture.
External	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 no fuel in the fuel storage tanks.
External	Ambient environmental stress	Used when the cause of a failure is the result of an environmental condition from the location of the component.
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	Human action procedure	Used when the procedure is not followed or the procedure is incorrect. For example: when a missed step or incorrect step in a surveillance procedure results in a component failure.
Human	Inadequate maintenance	Used when a human error (during the performance of maintenance) results in an unintentional or undesired action.

Group	Specific Cause	Description
Internal	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.
Internal	Internal environment	The internal environment led to the failure. Debris/Foreign material as well as an operating medium chemistry issue.
Internal	Setpoint drift	Used when the cause of a failure is the result of setpoint drift or adjustment.
Internal	Age/Wear	Used when the cause of the failure is a non-specific aging or wear issue.
Other	Unknown	Used when the cause of the failure is not known.
Other	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.
Procedure	Inadequate procedure	Used when the cause of a failure is the result of an inadequate procedure operating or maintenance.

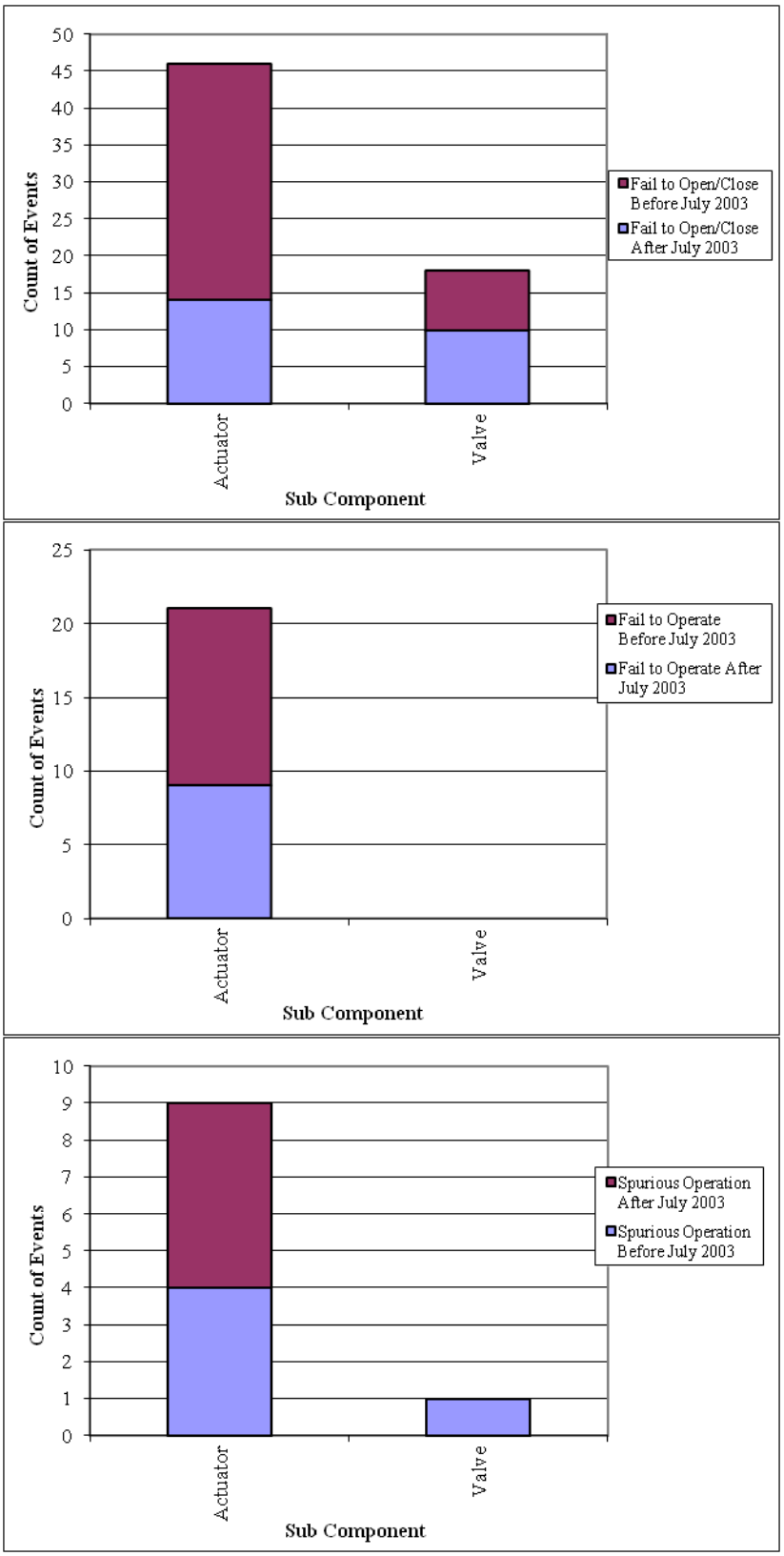

Figure 15. AOV failure breakdown by period, sub component, and failure mode.

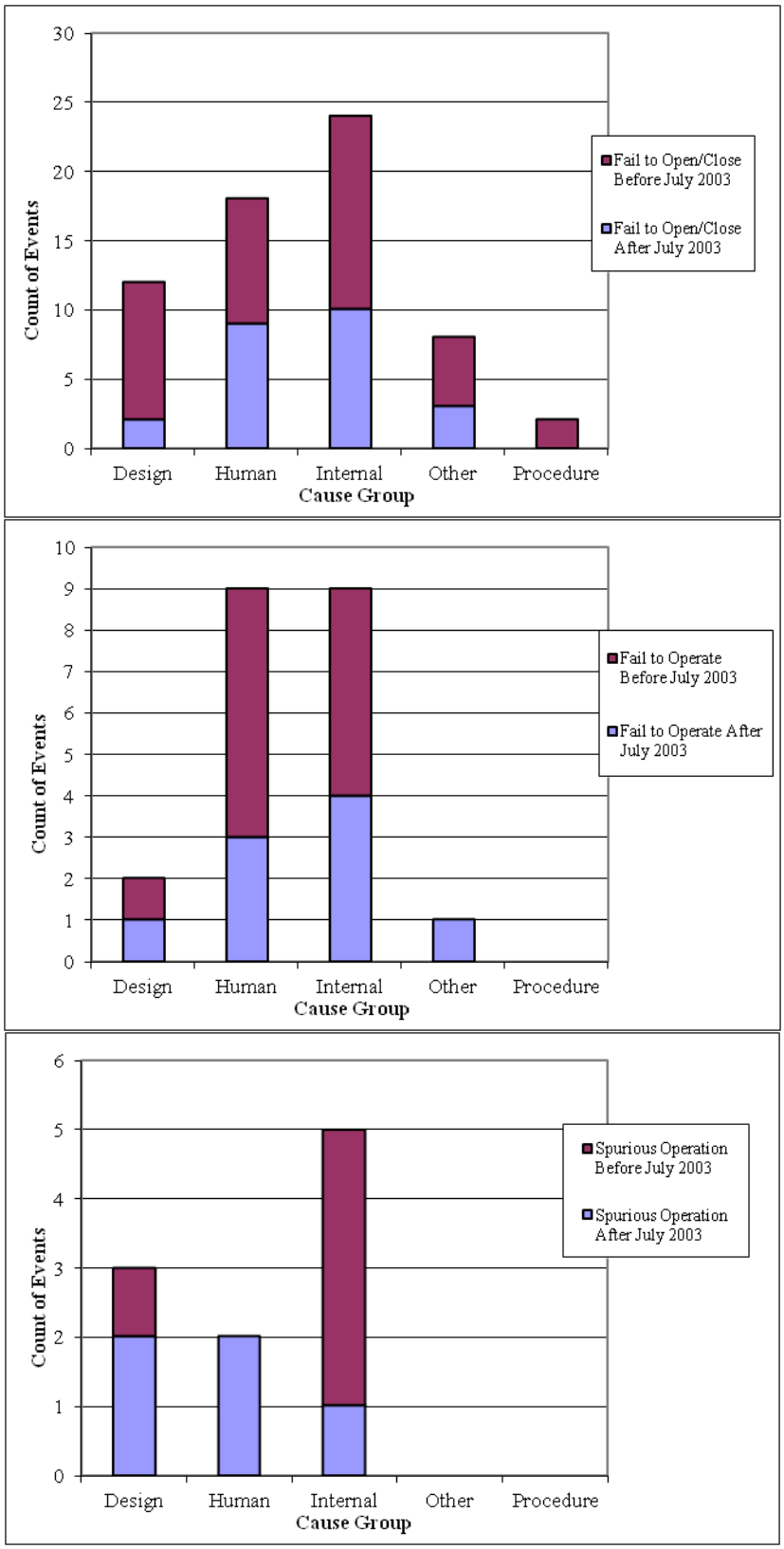

Figure 16. AOV breakdown by time period, cause group, and failure mode.

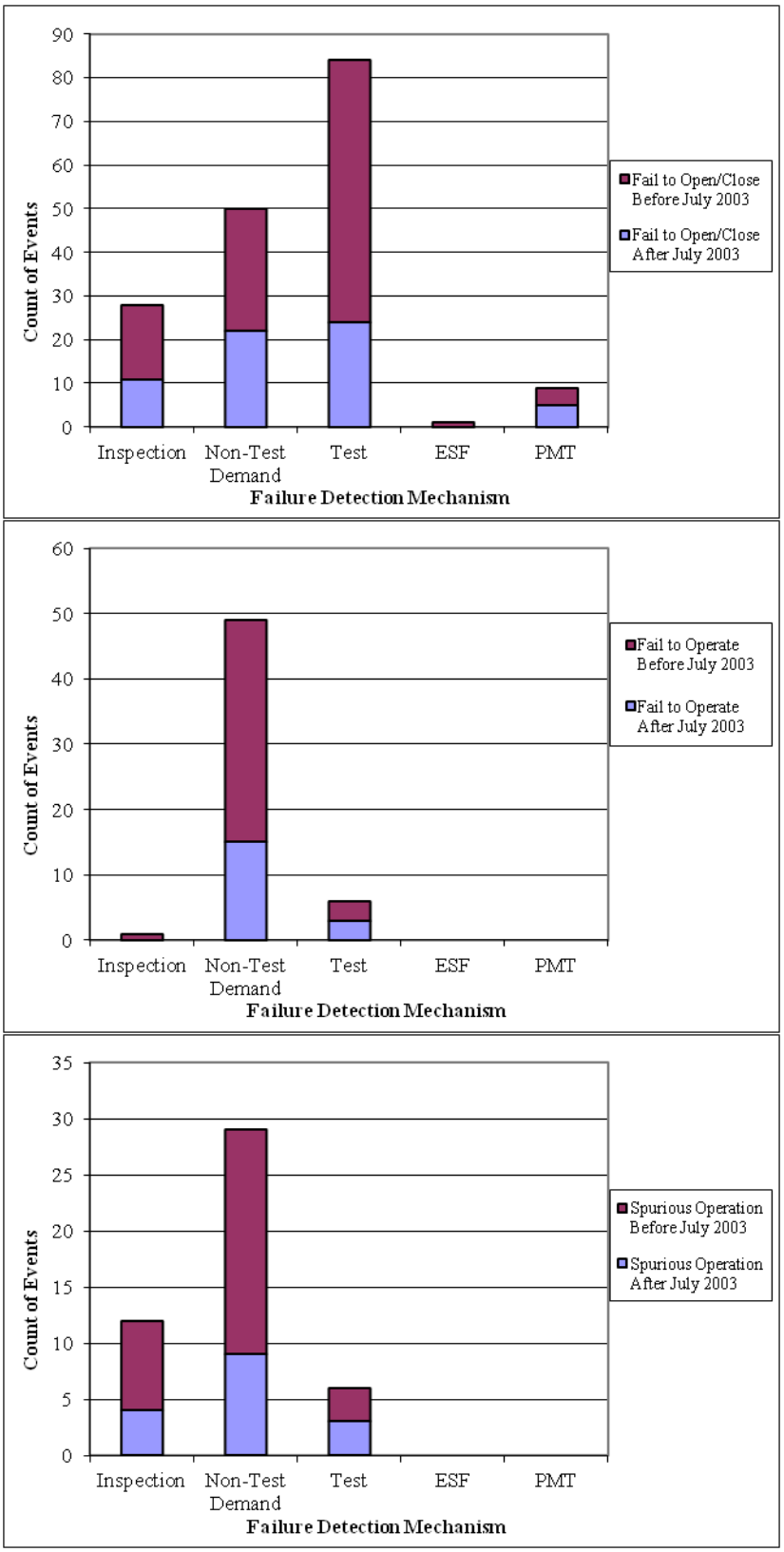

Figure 17. AOV component failure distribution by period, failure mode, and method of detection.

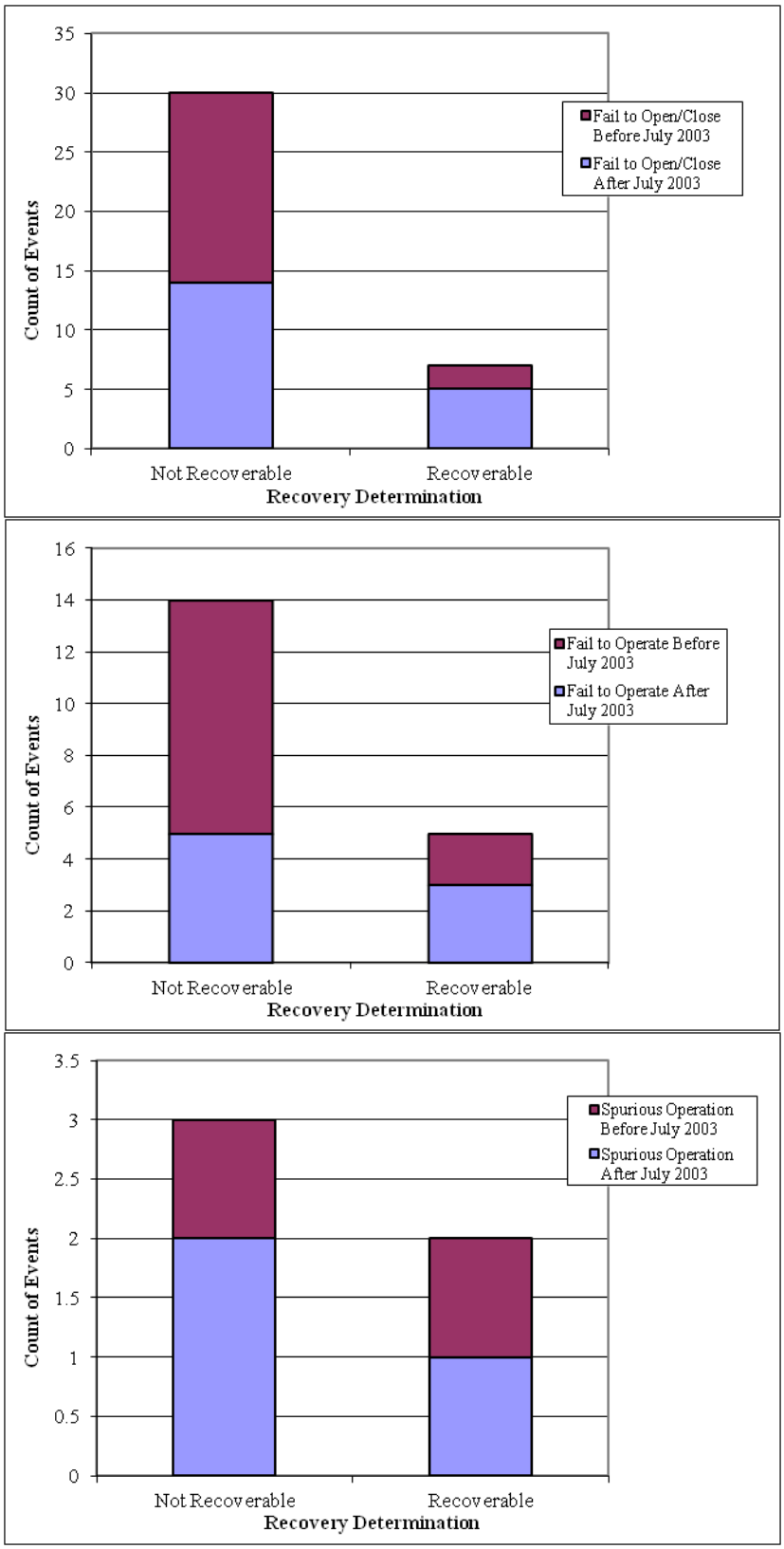

Figure 18. AOV component failure distribution by period, failure mode, and recovery.

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, airline, 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 Fail to Open/Close, which combines the Fail to Open and Fail to Close (FTOC) failure modes into a single category; Fail to Operate (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 not including spurious operation; and Spurious Operation (SO), which includes Spurious Opening and Spurious Closing.

6 DATA TABLES

Table 10. Plot data for industry-wide AOV FTOC trend with ≤ 20 demands per year. Figure 1

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						6.16E-05	3.59E-03	1.20E-03
1998	18	12162	1.37E-03	1.06E-03	1.79E-03	9.49E-04	2.06E-03	1.46E-03
1999	19	12311	1.29E-03	1.02E-03	1.62E-03	1.00E-03	2.12E-03	1.52E-03
2000	13	12094	1.20E-03	9.83E-04	1.47E-03	6.40E-04	1.59E-03	1.07E-03
2001	13	12172	1.13E-03	9.42E-04	1.34E-03	6.36E-04	1.58E-03	1.06E-03
2002	15	12121	1.05E-03	8.97E-04	1.24E-03	7.62E-04	1.78E-03	1.23E-03
2003	14	12031	9.85E-04	8.45E-04	1.15E-03	7.05E-04	1.69E-03	1.16E-03
2004	7	12026	9.22E-04	7.87E-04	1.08E-03	2.89E-04	9.96E-04	5.98E-04
2005	8	12049	8.62E-04	7.26E-04	1.02E-03	3.45E-04	1.10E-03	6.77E-04
2006	8	11494	8.07E-04	6.65E-04	9.80E-04	3.61E-04	1.15E-03	7.08E-04
2007	8	11540	7.55E-04	6.05E-04	9.43E-04	3.60E-04	1.14E-03	7.05E-04
2008	11	11495	7.06E-04	5.48E-04	9.10E-04	5.45E-04	1.46E-03	9.58E-04
2009	6	11483	6.61E-04	4.95E-04	8.81E-04	2.45E-04	9.32E-04	5.42E-04
2010	11	11645	6.18E-04	4.47E-04	8.55E-04	5.38E-04	1.45E-03	9.46E-04

Table 11. Plot data for industry-wide AOV FTOC trend with > 20 demands per year. Figure 2

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						6.16E-05	3.59E-03	1.20E-03
1998	20	57474	2.29E-04	1.44E-04	3.62E-04	2.26E-04	4.71E-04	3.39E-04
1999	9	59689	2.13E-04	1.43E-04	3.19E-04	8.07E-05	2.40E-04	1.52E-04
2000	16	58797	1.99E-04	1.40E-04	2.83E-04	1.69E-04	3.83E-04	2.67E-04
2001	14	58482	1.86E-04	1.36E-04	2.53E-04	1.44E-04	3.46E-04	2.36E-04
2002	6	58562	1.73E-04	1.31E-04	2.29E-04	4.78E-05	1.82E-04	1.06E-04
2003	7	58894	1.61E-04	1.24E-04	2.11E-04	5.86E-05	2.02E-04	1.21E-04
2004	10	59620	1.51E-04	1.15E-04	1.97E-04	9.25E-05	2.61E-04	1.68E-04
2005	6	58905	1.40E-04	1.05E-04	1.88E-04	4.76E-05	1.81E-04	1.05E-04
2006	9	58073	1.31E-04	9.39E-05	1.83E-04	8.28E-05	2.47E-04	1.56E-04
2007	3	58226	1.22E-04	8.35E-05	1.79E-04	1.77E-05	1.15E-04	5.72E-05
2008	10	58097	1.14E-04	7.38E-05	1.76E-04	9.48E-05	2.67E-04	1.72E-04
2009	9	57416	1.06E-04	6.49E-05	1.74E-04	8.37E-05	2.49E-04	1.57E-04
2010	7	57580	9.90E-05	5.69E-05	1.73E-04	5.99E-05	2.06E-04	1.24E-04

Table 12. Plot data for industry-wide AOV FTOP trend with ≤ 20 demands per year. Figure 3

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						3.21E-10	1.37E-05	3.00E-06
1998	2	16915560	3.02E-07	1.07E-07	8.55E-07	3.02E-08	2.92E-07	1.32E-07
1999	18	16889280	2.72E-07	1.09E-07	6.77E-07	6.35E-07	1.38E-06	9.76E-07
2000	2	16976880	2.45E-07	1.11E-07	5.44E-07	3.01E-08	2.91E-07	1.31E-07
2001	6	16976880	2.21E-07	1.10E-07	4.46E-07	1.55E-07	5.87E-07	3.41E-07
2002	4	16976880	1.99E-07	1.05E-07	3.78E-07	8.73E-08	4.44E-07	2.36E-07
2003	3	16994400	1.80E-07	9.69E-08	3.33E-07	5.69E-08	3.69E-07	1.84E-07
2004	5	17038200	1.62E-07	8.55E-08	3.07E-07	1.20E-07	5.15E-07	2.88E-07
2005	3	17038200	1.46E-07	7.24E-08	2.94E-07	5.67E-08	3.68E-07	1.83E-07
2006	0	17099520	1.31E-07	5.94E-08	2.91E-07	1.03E-10	1.00E-07	2.61E-08
2007	0	17046960	1.18E-07	4.78E-08	2.94E-07	1.03E-10	1.00E-07	2.62E-08
2008	6	17064480	1.07E-07	3.78E-08	3.01E-07	1.54E-07	5.84E-07	3.40E-07
2009	2	17038200	9.62E-08	2.97E-08	3.12E-07	3.00E-08	2.90E-07	1.31E-07
2010	2	17038200	8.67E-08	2.31E-08	3.25E-07	3.00E-08	2.90E-07	1.31E-07

Table 13. Plot data for industry-wide AOV FTOP trend with > 20 demands per year. Figure 4

FY/ Source	Failures	Demands	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						3.21E-10	1.37E-05	3.00E-06
1998	6	9513360	6.22E-07	3.03E-07	1.27E-06	2.85E-07	1.08E-06	6.30E-07
1999	8	9539640	6.07E-07	3.23E-07	1.14E-06	4.19E-07	1.33E-06	8.21E-07
2000	13	9530880	5.93E-07	3.41E-07	1.03E-06	7.81E-07	1.94E-06	1.31E-06
2001	2	9495840	5.79E-07	3.56E-07	9.40E-07	5.56E-08	5.37E-07	2.43E-07
2002	5	9583440	5.65E-07	3.67E-07	8.70E-07	2.20E-07	9.47E-07	5.29E-07
2003	5	9548400	5.51E-07	3.70E-07	8.22E-07	2.21E-07	9.50E-07	5.31E-07
2004	4	9513360	5.38E-07	3.63E-07	7.98E-07	1.61E-07	8.20E-07	4.36E-07
2005	6	9522120	5.26E-07	3.47E-07	7.96E-07	2.85E-07	1.08E-06	6.29E-07
2006	1	9487080	5.13E-07	3.24E-07	8.13E-07	1.71E-08	3.80E-07	1.46E-07
2007	10	9495840	5.01E-07	2.97E-07	8.45E-07	5.62E-07	1.59E-06	1.02E-06
2008	4	9522120	4.89E-07	2.69E-07	8.89E-07	1.61E-07	8.19E-07	4.36E-07
2009	5	9495840	4.77E-07	2.42E-07	9.42E-07	2.22E-07	9.55E-07	5.34E-07
2010	7	9399480	4.66E-07	2.16E-07	1.00E-06	3.56E-07	1.22E-06	7.35E-07

Table 14. Plot data for industry-wide AOV SO trend with ≤ 20 demands per year. Figure 5

FY/ Source	Failures	Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						2.14E-11	9.15E-07	2.00E-07
1998	3	16915560	2.04E-07	9.33E-08	4.46E-07	5.59E-08	3.63E-07	1.80E-07
1999	8	16889280	1.96E-07	9.83E-08	3.90E-07	2.24E-07	7.12E-07	4.39E-07
2000	1	16976880	1.88E-07	1.03E-07	3.43E-07	9.04E-09	2.01E-07	7.71E-08
2001	2	16976880	1.80E-07	1.06E-07	3.06E-07	2.94E-08	2.84E-07	1.28E-07
2002	13	16976880	1.73E-07	1.08E-07	2.77E-07	4.15E-07	1.03E-06	6.94E-07
2003	2	16994400	1.66E-07	1.07E-07	2.57E-07	2.94E-08	2.84E-07	1.28E-07
2004	1	17038200	1.59E-07	1.03E-07	2.46E-07	9.01E-09	2.00E-07	7.68E-08
2005	2	17038200	1.53E-07	9.61E-08	2.43E-07	2.93E-08	2.84E-07	1.28E-07
2006	2	17099520	1.47E-07	8.76E-08	2.45E-07	2.92E-08	2.83E-07	1.28E-07
2007	2	17046960	1.41E-07	7.83E-08	2.53E-07	2.93E-08	2.83E-07	1.28E-07
2008	4	17064480	1.35E-07	6.91E-08	2.63E-07	8.50E-08	4.33E-07	2.30E-07
2009	2	17038200	1.29E-07	6.04E-08	2.77E-07	2.93E-08	2.84E-07	1.28E-07
2010	2	17038200	1.24E-07	5.26E-08	2.93E-07	2.93E-08	2.84E-07	1.28E-07

Table 15. Plot data for industry-wide AOV SO trend, >20 demands per year. Figure 6

FY/ Source	Failures	Hours	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
NUREG/ CR-6928						2.14E-11	9.15E-07	2.00E-07
1998	3	9513360	1.60E-07	5.71E-08	4.50E-07	8.54E-08	5.55E-07	2.76E-07
1999	3	9539640	1.52E-07	6.13E-08	3.78E-07	8.53E-08	5.53E-07	2.75E-07
2000	0	9530880	1.45E-07	6.53E-08	3.21E-07	1.55E-10	1.51E-07	3.94E-08
2001	3	9495840	1.38E-07	6.85E-08	2.77E-07	8.56E-08	5.55E-07	2.76E-07
2002	3	9583440	1.31E-07	7.04E-08	2.44E-07	8.50E-08	5.51E-07	2.74E-07
2003	0	9548400	1.25E-07	7.01E-08	2.22E-07	1.55E-10	1.51E-07	3.93E-08
2004	0	9513360	1.19E-07	6.73E-08	2.09E-07	1.55E-10	1.51E-07	3.94E-08
2005	2	9522120	1.13E-07	6.21E-08	2.05E-07	4.51E-08	4.36E-07	1.97E-07
2006	1	9487080	1.07E-07	5.54E-08	2.08E-07	1.39E-08	3.09E-07	1.19E-07
2007	0	9495840	1.02E-07	4.82E-08	2.16E-07	1.55E-10	1.52E-07	3.95E-08
2008	1	9522120	9.70E-08	4.12E-08	2.29E-07	1.39E-08	3.08E-07	1.18E-07
2009	2	9495840	9.23E-08	3.48E-08	2.45E-07	4.52E-08	4.37E-07	1.97E-07
2010	1	9399480	8.78E-08	2.92E-08	2.64E-07	1.40E-08	3.11E-07	1.19E-07

Table 16. Plot data for frequency (events per reactor year) of AOV operation demands with ≤ 20 demands per year. Figure 7

FY	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	12162	100.0	1.23E+02	1.21E+02	1.25E+02	1.20E+02	1.23E+02	1.22E+02
1999	12311	100.0	1.22E+02	1.21E+02	1.24E+02	1.21E+02	1.25E+02	1.23E+02
2000	12094	100.3	1.22E+02	1.20E+02	1.23E+02	1.19E+02	1.22E+02	1.21E+02
2001	12172	100.0	1.21E+02	1.20E+02	1.22E+02	1.20E+02	1.24E+02	1.22E+02
2002	12121	100.0	1.20E+02	1.19E+02	1.21E+02	1.19E+02	1.23E+02	1.21E+02
2003	12031	100.0	1.20E+02	1.18E+02	1.21E+02	1.19E+02	1.22E+02	1.20E+02
2004	12026	100.3	1.19E+02	1.18E+02	1.20E+02	1.18E+02	1.22E+02	1.20E+02
2005	12049	100.0	1.18E+02	1.17E+02	1.19E+02	1.19E+02	1.22E+02	1.20E+02
2006	11494	100.0	1.17E+02	1.16E+02	1.19E+02	1.13E+02	1.17E+02	1.15E+02
2007	11540	100.0	1.17E+02	1.15E+02	1.18E+02	1.14E+02	1.17E+02	1.15E+02
2008	11495	100.3	1.16E+02	1.15E+02	1.18E+02	1.13E+02	1.16E+02	1.15E+02
2009	11483	100.0	1.15E+02	1.14E+02	1.17E+02	1.13E+02	1.17E+02	1.15E+02
2010	11645	100.0	1.15E+02	1.13E+02	1.17E+02	1.15E+02	1.18E+02	1.16E+02

Table 17. Plot data for frequency (events per reactor year) of AOV operation demands with > 20 demands per year. Figure 8

FY	Demands	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	57474	100.0	5.89E+02	5.81E+02	5.98E+02	5.71E+02	5.79E+02	5.75E+02
1999	59689	100.0	5.88E+02	5.81E+02	5.96E+02	5.93E+02	6.01E+02	5.97E+02
2000	58797	100.3	5.87E+02	5.81E+02	5.94E+02	5.82E+02	5.90E+02	5.86E+02
2001	58482	100.0	5.87E+02	5.81E+02	5.92E+02	5.81E+02	5.89E+02	5.85E+02
2002	58562	100.0	5.86E+02	5.81E+02	5.91E+02	5.82E+02	5.90E+02	5.86E+02
2003	58894	100.0	5.85E+02	5.80E+02	5.90E+02	5.85E+02	5.93E+02	5.89E+02
2004	59620	100.3	5.84E+02	5.80E+02	5.89E+02	5.91E+02	5.99E+02	5.95E+02
2005	58905	100.0	5.83E+02	5.79E+02	5.88E+02	5.85E+02	5.93E+02	5.89E+02
2006	58073	100.0	5.82E+02	5.77E+02	5.87E+02	5.77E+02	5.85E+02	5.81E+02
2007	58226	100.0	5.82E+02	5.76E+02	5.87E+02	5.78E+02	5.86E+02	5.82E+02
2008	58097	100.3	5.81E+02	5.74E+02	5.87E+02	5.75E+02	5.83E+02	5.79E+02
2009	57416	100.0	5.80E+02	5.73E+02	5.87E+02	5.70E+02	5.78E+02	5.74E+02
2010	57580	100.0	5.79E+02	5.71E+02	5.88E+02	5.72E+02	5.80E+02	5.76E+02

Table 18. Plot data for frequency (events per reactor year) of AOV FTOC events with ≤ 20 demands per year. Figure 9

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	18	100.0	1.69E-01	1.30E-01	2.20E-01	1.15E-01	2.50E-01	1.77E-01
1999	19	100.0	1.57E-01	1.25E-01	1.98E-01	1.23E-01	2.62E-01	1.87E-01
2000	13	100.3	1.46E-01	1.20E-01	1.79E-01	7.72E-02	1.92E-01	1.29E-01
2001	13	100.0	1.36E-01	1.14E-01	1.62E-01	7.74E-02	1.92E-01	1.29E-01
2002	15	100.0	1.27E-01	1.08E-01	1.49E-01	9.24E-02	2.16E-01	1.49E-01
2003	14	100.0	1.18E-01	1.01E-01	1.37E-01	8.49E-02	2.04E-01	1.39E-01
2004	7	100.3	1.09E-01	9.35E-02	1.28E-01	3.47E-02	1.20E-01	7.17E-02
2005	8	100.0	1.02E-01	8.57E-02	1.21E-01	4.16E-02	1.32E-01	8.15E-02
2006	8	100.0	9.47E-02	7.79E-02	1.15E-01	4.16E-02	1.32E-01	8.15E-02
2007	8	100.0	8.81E-02	7.04E-02	1.10E-01	4.16E-02	1.32E-01	8.15E-02
2008	11	100.3	8.19E-02	6.34E-02	1.06E-01	6.26E-02	1.68E-01	1.10E-01
2009	6	100.0	7.62E-02	5.70E-02	1.02E-01	2.82E-02	1.07E-01	6.23E-02
2010	11	100.0	7.08E-02	5.11E-02	9.82E-02	6.28E-02	1.69E-01	1.10E-01

Table 19. Plot data for frequency (events per reactor year) of AOV FTOC events with > 20 demands per year. Figure 10

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	20	100.0	1.36E-01	8.71E-02	2.12E-01	1.30E-01	2.71E-01	1.95E-01
1999	9	100.0	1.26E-01	8.56E-02	1.87E-01	4.81E-02	1.43E-01	9.04E-02
2000	16	100.3	1.18E-01	8.36E-02	1.65E-01	9.90E-02	2.25E-01	1.57E-01
2001	14	100.0	1.09E-01	8.10E-02	1.48E-01	8.42E-02	2.02E-01	1.38E-01
2002	6	100.0	1.02E-01	7.75E-02	1.34E-01	2.80E-02	1.06E-01	6.18E-02
2003	7	100.0	9.46E-02	7.29E-02	1.23E-01	3.45E-02	1.19E-01	7.13E-02
2004	10	100.3	8.80E-02	6.73E-02	1.15E-01	5.50E-02	1.55E-01	9.96E-02
2005	6	100.0	8.19E-02	6.11E-02	1.10E-01	2.80E-02	1.06E-01	6.18E-02
2006	9	100.0	7.62E-02	5.47E-02	1.06E-01	4.81E-02	1.43E-01	9.04E-02
2007	3	100.0	7.09E-02	4.85E-02	1.04E-01	1.03E-02	6.69E-02	3.33E-02
2008	10	100.3	6.59E-02	4.27E-02	1.02E-01	5.50E-02	1.55E-01	9.96E-02
2009	9	100.0	6.13E-02	3.75E-02	1.00E-01	4.81E-02	1.43E-01	9.04E-02
2010	7	100.0	5.70E-02	3.28E-02	9.91E-02	3.45E-02	1.19E-01	7.13E-02

Table 20. Plot data for frequency (events per reactor year) of AOV FTOP events with ≤ 20 demands per year. Figure 9

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	2	100.0	5.11E-02	1.81E-02	1.45E-01	5.11E-03	4.94E-02	2.23E-02
1999	18	100.0	4.61E-02	1.86E-02	1.15E-01	1.07E-01	2.33E-01	1.65E-01
2000	2	100.3	4.16E-02	1.88E-02	9.21E-02	5.09E-03	4.92E-02	2.22E-02
2001	6	100.0	3.75E-02	1.86E-02	7.57E-02	2.63E-02	9.97E-02	5.80E-02
2002	4	100.0	3.38E-02	1.79E-02	6.41E-02	1.48E-02	7.54E-02	4.01E-02
2003	3	100.0	3.05E-02	1.65E-02	5.65E-02	9.66E-03	6.27E-02	3.12E-02
2004	5	100.3	2.75E-02	1.45E-02	5.21E-02	2.03E-02	8.75E-02	4.89E-02
2005	3	100.0	2.48E-02	1.23E-02	5.00E-02	9.66E-03	6.27E-02	3.12E-02
2006	0	100.0	2.24E-02	1.01E-02	4.95E-02	1.75E-05	1.71E-02	4.46E-03
2007	0	100.0	2.02E-02	8.15E-03	5.01E-02	1.75E-05	1.71E-02	4.46E-03
2008	6	100.3	1.82E-02	6.46E-03	5.14E-02	2.62E-02	9.94E-02	5.78E-02
2009	2	100.0	1.64E-02	5.08E-03	5.32E-02	5.11E-03	4.94E-02	2.23E-02
2010	2	100.0	1.48E-02	3.96E-03	5.55E-02	5.11E-03	4.94E-02	2.23E-02

Table 21. Plot data for frequency (events per reactor year) of AOV FTOP events with > 20 demands per year. Figure 10

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	6	100.0	5.93E-02	2.89E-02	1.22E-01	2.72E-02	1.03E-01	5.99E-02
1999	8	100.0	5.79E-02	3.07E-02	1.09E-01	4.00E-02	1.27E-01	7.83E-02
2000	13	100.3	5.65E-02	3.24E-02	9.82E-02	7.42E-02	1.84E-01	1.24E-01
2001	2	100.0	5.51E-02	3.39E-02	8.95E-02	5.28E-03	5.10E-02	2.30E-02
2002	5	100.0	5.37E-02	3.49E-02	8.28E-02	2.11E-02	9.07E-02	5.07E-02
2003	5	100.0	5.24E-02	3.52E-02	7.82E-02	2.11E-02	9.07E-02	5.07E-02
2004	4	100.3	5.12E-02	3.45E-02	7.59E-02	1.53E-02	7.78E-02	4.14E-02
2005	6	100.0	4.99E-02	3.30E-02	7.56E-02	2.72E-02	1.03E-01	5.99E-02
2006	1	100.0	4.87E-02	3.08E-02	7.72E-02	1.62E-03	3.60E-02	1.38E-02
2007	10	100.0	4.75E-02	2.82E-02	8.02E-02	5.34E-02	1.51E-01	9.68E-02
2008	4	100.3	4.64E-02	2.55E-02	8.43E-02	1.53E-02	7.78E-02	4.14E-02
2009	5	100.0	4.53E-02	2.29E-02	8.93E-02	2.11E-02	9.07E-02	5.07E-02
2010	7	100.0	4.42E-02	2.05E-02	9.52E-02	3.35E-02	1.15E-01	6.91E-02

Table 22. Plot data for frequency (events per reactor year) of AOV SO events ≤ 20 demands per year. Figure 13

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	3	100.0	3.46E-02	1.58E-02	7.55E-02	9.45E-03	6.14E-02	3.05E-02
1999	8	100.0	3.32E-02	1.67E-02	6.60E-02	3.78E-02	1.20E-01	7.42E-02
2000	1	100.3	3.18E-02	1.74E-02	5.82E-02	1.53E-03	3.40E-02	1.31E-02
2001	2	100.0	3.06E-02	1.80E-02	5.19E-02	5.00E-03	4.83E-02	2.18E-02
2002	13	100.0	2.94E-02	1.83E-02	4.71E-02	7.05E-02	1.75E-01	1.18E-01
2003	2	100.0	2.82E-02	1.82E-02	4.37E-02	5.00E-03	4.83E-02	2.18E-02
2004	1	100.3	2.71E-02	1.75E-02	4.18E-02	1.53E-03	3.40E-02	1.31E-02
2005	2	100.0	2.60E-02	1.64E-02	4.13E-02	5.00E-03	4.83E-02	2.18E-02
2006	2	100.0	2.49E-02	1.49E-02	4.17E-02	5.00E-03	4.83E-02	2.18E-02
2007	2	100.0	2.39E-02	1.33E-02	4.30E-02	5.00E-03	4.83E-02	2.18E-02
2008	4	100.3	2.30E-02	1.18E-02	4.49E-02	1.45E-02	7.36E-02	3.92E-02
2009	2	100.0	2.21E-02	1.03E-02	4.73E-02	5.00E-03	4.83E-02	2.18E-02
2010	2	100.0	2.12E-02	8.97E-03	5.00E-02	5.00E-03	4.83E-02	2.18E-02

Table 23. Plot data for frequency (events per reactor year) of AOV SO events > 20 demands per year. Figure 14

FY	Failures	Reactor Years	Regression Curve Data Points			Plot Trend Error Bar Points		
			Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
1998	3	100.0	1.53E-02	5.44E-03	4.28E-02	8.13E-03	5.27E-02	2.62E-02
1999	3	100.0	1.45E-02	5.84E-03	3.60E-02	8.13E-03	5.27E-02	2.62E-02
2000	0	100.3	1.38E-02	6.22E-03	3.06E-02	1.47E-05	1.44E-02	3.74E-03
2001	3	100.0	1.31E-02	6.52E-03	2.64E-02	8.13E-03	5.27E-02	2.62E-02
2002	3	100.0	1.25E-02	6.69E-03	2.32E-02	8.13E-03	5.27E-02	2.62E-02
2003	0	100.0	1.19E-02	6.67E-03	2.11E-02	1.47E-05	1.44E-02	3.75E-03
2004	0	100.3	1.13E-02	6.39E-03	1.99E-02	1.47E-05	1.44E-02	3.74E-03
2005	2	100.0	1.07E-02	5.90E-03	1.95E-02	4.29E-03	4.15E-02	1.87E-02
2006	1	100.0	1.02E-02	5.26E-03	1.97E-02	1.32E-03	2.93E-02	1.12E-02
2007	0	100.0	9.68E-03	4.57E-03	2.05E-02	1.47E-05	1.44E-02	3.75E-03
2008	1	100.3	9.21E-03	3.91E-03	2.17E-02	1.32E-03	2.92E-02	1.12E-02
2009	2	100.0	8.75E-03	3.30E-03	2.32E-02	4.29E-03	4.15E-02	1.87E-02
2010	1	100.0	8.32E-03	2.76E-03	2.50E-02	1.32E-03	2.93E-02	1.12E-02

7 REFERENCE

1. S.A. Eide, et al, *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*, U.S. Nuclear Regulatory Commission, NUREG/CR-6928, February 2007.