Auxiliary Feedwater System

1998–2010

1 INTRODUCTION

This report presents an unreliability evaluation over time of the auxiliary feedwater system (AFW) at 69 U.S. commercial nuclear power plants listed in Table 1. For each plant the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 1) was used in the yearly calculations. Demand, run hours, and failure data from fiscal year (FY) 1998 through FY 2010 for selected components in the AFW were obtained from the Equipment Performance and Information Exchange (EPIX) database. Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process (ROP) Safety System Unavailability (SSU) database (FY 1998–FY 2001) and the Mitigating Systems Performance Index (MSPI) database (FY 2002–FY 2010). Common-cause failure (CCF) data used in the models are from the 2005 update to the CCF database.

This report does not attempt to estimate basic event values for use in a probabilistic risk assessment (PRA). Suggested values for such use are presented in the report, *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*, NUREG/CR-6928 (Reference 1). Baseline AFW unreliability results using basic event values from that report are summarized in Section 3. Trend results for AFW (using system-specific data) are presented in Section 4. Similar to previous system study updates, Section 5 contains importance information (using the baseline results from Section 3), and Section 7 describes the AFW.

Table 1. AFW design class summary.

Class	Plant	Version
Class 2	Arkansas 1	3.31
Class 2	Braidwood 1	3.31
Class 2	Braidwood 2	3.31
Class 2	Byron 1	3.31
Class 2	Byron 2	3.31
Class 2	Crystal River 3	3.32
Class 2	Prairie Island 1	3.31
Class 2	Prairie Island 2	3.31
Class 2	Seabrook	3.21
Class 3	Arkansas 2	3.31
Class 3	Beaver Valley 2	3.31
Class 3	Callaway	3.31
Class 3	Catawba 1	3.32
Class 3	Catawba 2	3.32
Class 3	Comanche Peak 1	3.31
Class 3	Comanche Peak 2	3.31
Class 3	Cook 1	3.32
Class 3	Cook 2	3.32
Class 3	Diablo Canyon 1	3.31
Class 3	Diablo Canyon 2	3.31
Class 3	Farley 1	3.31
Class 3	Farley 2	3.31
Class 3	Fort Calhoun	3.31
Class 3	Harris	3.31

Class	Plant	Version
Class 3	Indian Point 2	3.31
Class 3	Indian Point 3	3.31
Class 3	Kewaunee	3.31
Class 3	McGuire 1	3.31
Class 3	McGuire 2	3.31
Class 3	Millstone 2	3.21
Class 3	Millstone 3	3.21
Class 3	North Anna 1	3.31
Class 3	North Anna 2	3.31
Class 3	Oconee 1	3.31
Class 3	Oconee 2	3.31
Class 3	Oconee 3	3.31
Class 3	Palisades	3.31
Class 3	Palo Verde 1	3.31
Class 3	Palo Verde 2	3.31
Class 3	Palo Verde 3	3.31
Class 3	Point Beach 1	3.31
Class 3	Point Beach 2	3.31
Class 3	Robinson 2	3.31
Class 3	Salem 1	3.22
Class 3	Salem 2	3.22
Class 3	San Onofre 2	3.21
Class 3	San Onofre 3	3.21
Class 3	Sequoyah 1	3.31

Class	Plant	Version
Class 3	Sequoyah 2	3.31
Class 3	St. Lucie 1	3.32
Class 3	St. Lucie 2	3.31
Class 3	Summer	3.32
Class 3	Three Mile Isl 1	3.31
Class 3	Turkey Point 3	3.31
Class 3	Turkey Point 4	3.31
Class 3	Vogtle 1	3.31
Class 3	Vogtle 2	3.31
Class 3	Waterford 3	3.31
Class 3	Watts Bar 1	3.21
Class 3	Wolf Creek	3.31
Class 4	Beaver Valley 1	3.31
Class 4	Calvert Cliffs 1	3.21
Class 4	Calvert Cliffs 2	3.21
Class 4	Davis-Besse	3.31
Class 4	Ginna	3.31
Class 4	South Texas 1	3.21
Class 4	South Texas 2	3.21
Class 4	Surry 1	3.31
Class 4	Surry 2	3.31

The AFW classes were categorized by number of pump trains (no specification on pump type) used in the SPAR models. Class 2 AFW includes configurations that effectively result in a success criterion of one of two pumps. Class 3 AFW includes configurations that effectively result in a success criterion of one of three pumps. AFW designs effectively resulting in a success criterion of one of four or more are included in Class 4. Table 1 summarizes the plants and their classes.

The AFW model is evaluated using the transient flag set in the SPAR model. The transient flag set assumes all support systems are available and that the AFW system is required to perform to mitigate the effects of the transient initiating event. All models include failures due to unavailability while in test or maintenance. Human error has not been included in the SPAR model logic. 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.

Two modes of the models for the AFW system are calculated. The AFW start-only model is the SPAR AFW model modified by setting all fail-to-run basic events to zero (False), setting all recovery events to False, setting all pump-ends events to False, and setting all cooling basic events to False. The 8-hour mission model includes all basic events in the SPAR AFW model.

2 SUMMARY OF FINDINGS

The results of this AFW system unreliability 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 AFW unreliability trend results. In addition, this update identified no statistically significant decreasing trends in the AFW results.

The industry-wide AFW start-only and 8-hour basic event group importances were evaluated and are shown in Figure 5. In both cases, the leading contributor to AFW system unreliability is the AFW motor-driven and turbine-driven pumps followed by the injection flow path. In the 8-hour mission case, recovery is also important.

3 INDUSTRY-WIDE UNRELIABILITY

The AFW fault trees from the SPAR models were evaluated for each of the 69 operating U.S. commercial pressurized water nuclear power plants with an AFW system.

The industry-wide unreliability of the AFW system has been estimated for two modes of operation. A start-only model and an 8-hour mission model were evaluated. The uncertainty distributions for AFW show both plant design variability and parameter uncertainty while using industry-wide component failure data (FY 1998–FY 2002)[2]. Table 2 shows the percentiles and mean of the aggregated sample data (Latin hypercube, 1000 samples for each model) collected from the uncertainty calculations of the AFW fault trees in the SPAR models. In Figure 1 and Figure 2, the 5th and 95th percentiles and mean point estimates are shown for each class and for the industry.

[1] Statistically significant is defined in terms of the 'p-value.' A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values of less than or equal to 0.05 indicate that we are 95% confident 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).

[2] By using industry-wide component failure data, individual plant performance is not included in the distribution of results.

Table 2. Industry-wide unreliability values.

Model	AFW Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	1.82E-08	1.27E-06	1.86E-05	5.89E-05
	Class 2	1.46E-07	2.89E-05	6.92E-05	2.37E-04
	Class 3	5.85E-08	1.32E-06	1.28E-05	2.28E-05
	Class 4	1.14E-09	1.74E-07	8.78E-07	4.34E-06
8-hour Mission	Industry	1.48E-07	3.57E-06	9.25E-05	5.05E-04
	Class 2	4.06E-07	1.24E-04	1.94E-04	6.73E-04
	Class 3	3.14E-07	4.07E-06	9.08E-05	5.08E-04
	Class 4	8.01E-09	5.52E-07	1.29E-06	5.03E-06

In Figure 1 and Figure 2, the width of the distribution for a class is affected by the differences in the plant modeling and the parameter uncertainty used in the models. Because the width is affected by the plant modeling, the width is also affected by the number of different plant models in a class. For those classes with very few plants that share a design, the width can be very small.

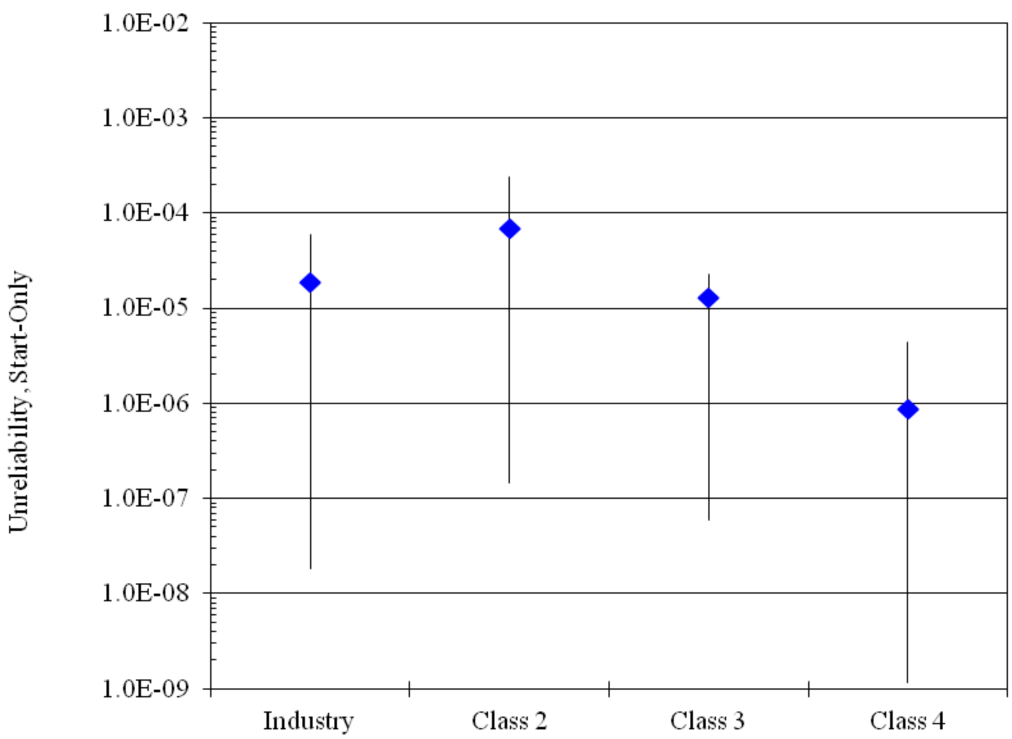

Figure 1. AFW start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

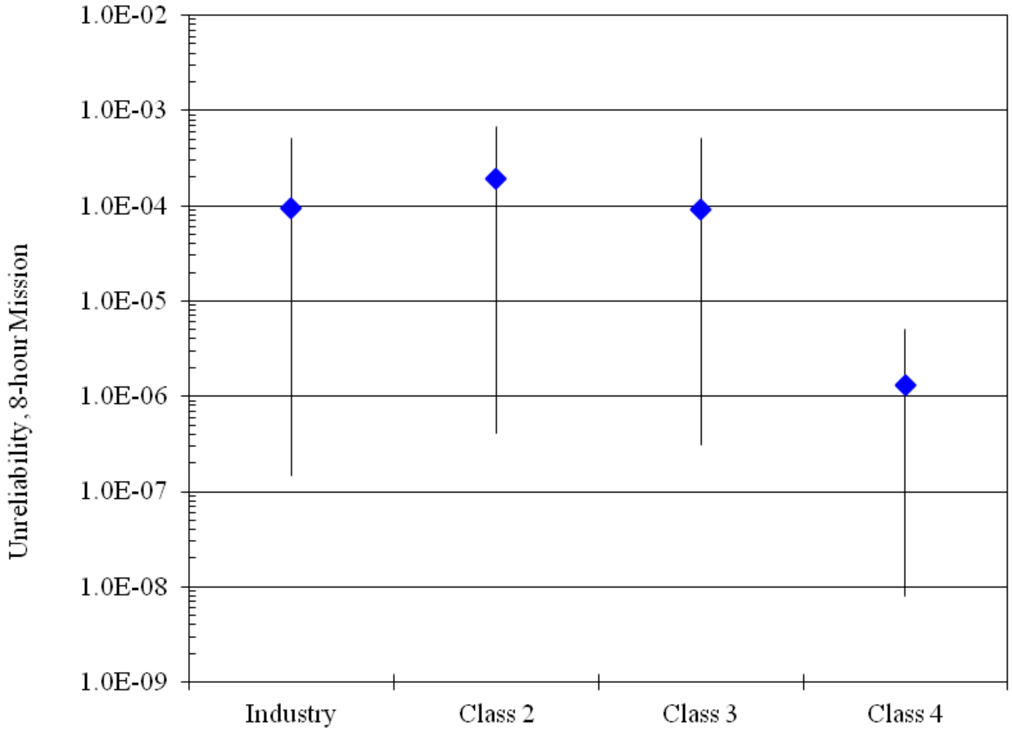

Figure 2. AFW 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4 INDUSTRY-WIDE TRENDS

The yearly (FY 1998–FY 2010) failure and demand or run time data were obtained from EPIX for the AFW system. AFW train maintenance unavailability data for trending are from the same time period, as reported in the ROP and EPIX. The component basic event uncertainty was calculated for the AFW system components using the trending methods described in Section 1 and 2 of the Overview and Reference document. Table 6 and Table 7 show the yearly data values for each AFW system specific component and failure mode combination that was varied in the model. These data were loaded into the AFW system fault tree in each SPAR model with an AFW system (see Table 1).

The trend charts show the results of varying component reliability data over time and updating generic, relatively flat prior distributions using data for each year. In addition, the calculated industry-wide system reliability from this update (SPAR/EPIX) is shown. Section 4 of the Overview and Reference link on the System Studies main web page provides more detailed discussion of the trending methods. In the lower left-hand corner of the trend figures, the regression method is reported.

The components that were varied in the AFW model are:

- AFW motor-driven pump start, run, and test and maintenance.
- AFW turbine-driven pump start, run, and test and maintenance.
- Injection valves fail-to-open.

Figure 3 shows the trend in the AFW start-only model unreliability. Table 4 shows the data points for Figure 3. No statistically significant trends within the industry-wide estimates of AFW system start-only mission on a per fiscal year basis were identified. Figure 4 shows the trend in the 8-hour mission unreliability. No statistically significant trend within the industry-wide estimates of AFW system unreliability (8-hour mission) on a per fiscal year basis was identified. Table 5 shows the data points for Figure 4.

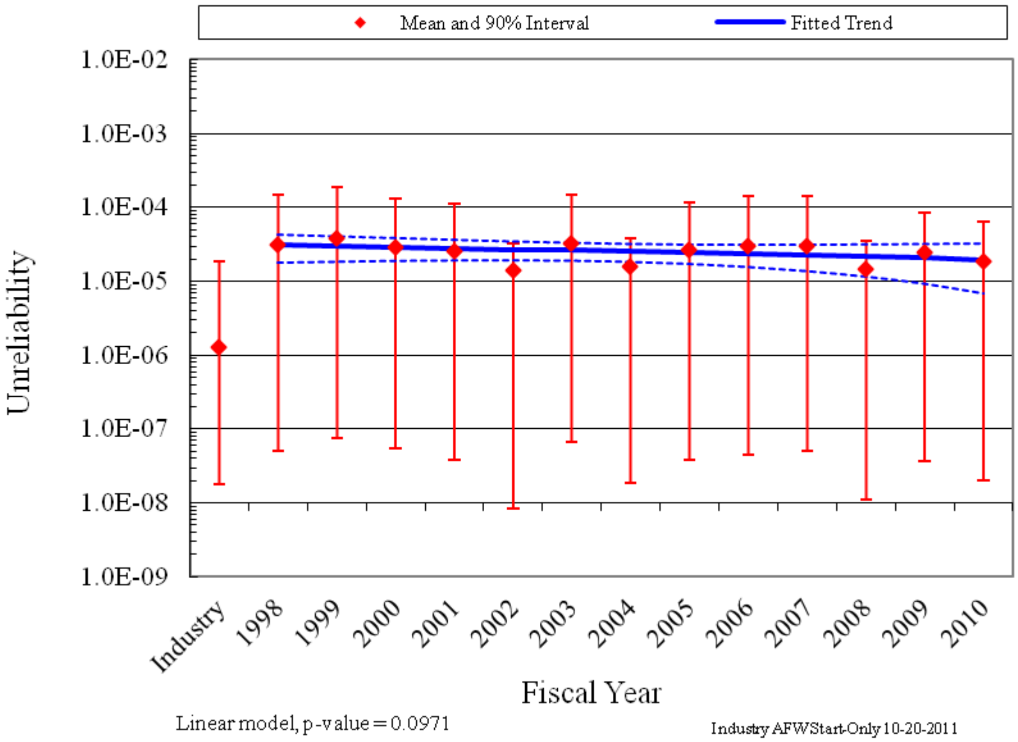

Figure 3. Trend of AFW system unreliability (start-only model), as a function of fiscal year.

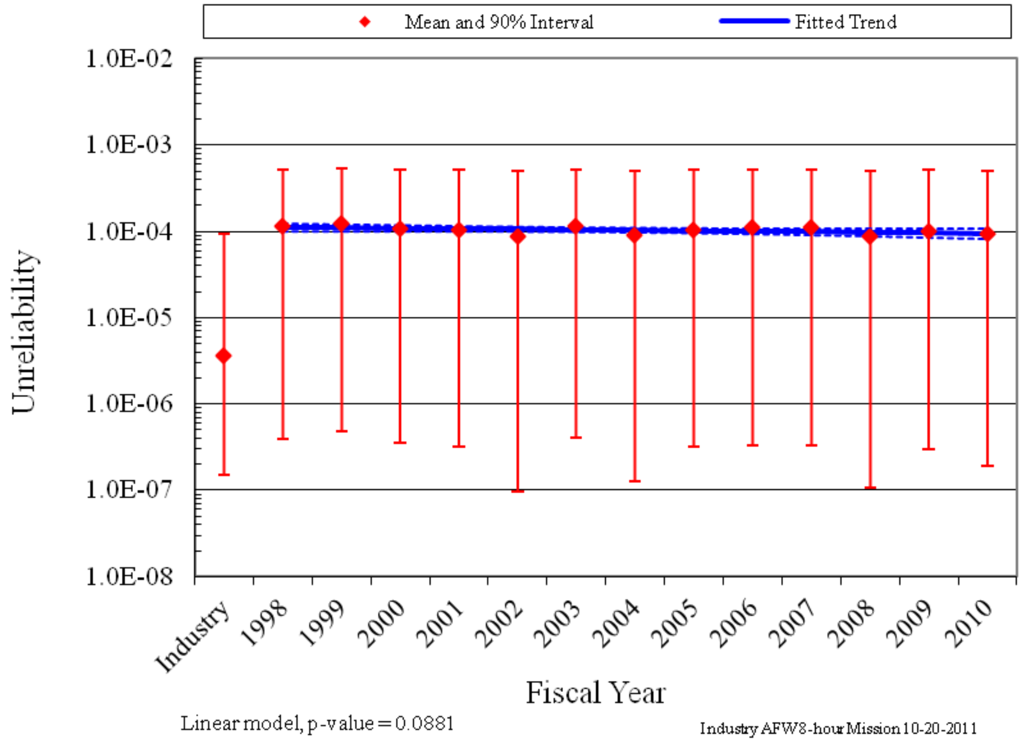

Figure 4. Trend of AFW system unreliability (8-hour model), as a function of fiscal year.

5 BASIC EVENT GROUP IMPORTANCES

The AFW basic event group Fussell-Vesely importances were calculated for the start-only and 8-hour modes for each plant using the industry-wide data (1998–2002). These basic event group importances were then averaged across all plants to represent an industry-wide basic event group importance. The industry-wide AFW start-only and 8-hour basic event group importances are shown in Figure 5. In both cases, the leading contributor to AFW system unreliability is the AFW motor-driven, and turbine-driven pumps followed by the injection flow path. In the 8-hour mission case, recovery is also important. For more discussion on the AFW motor/turbine-driven pumps, see the motor/turbine-driven pump component reliability studies at NRC Reactor Operational Experience Results and Databases. Table 3 shows the SPAR model AFW importance groups and their descriptions.

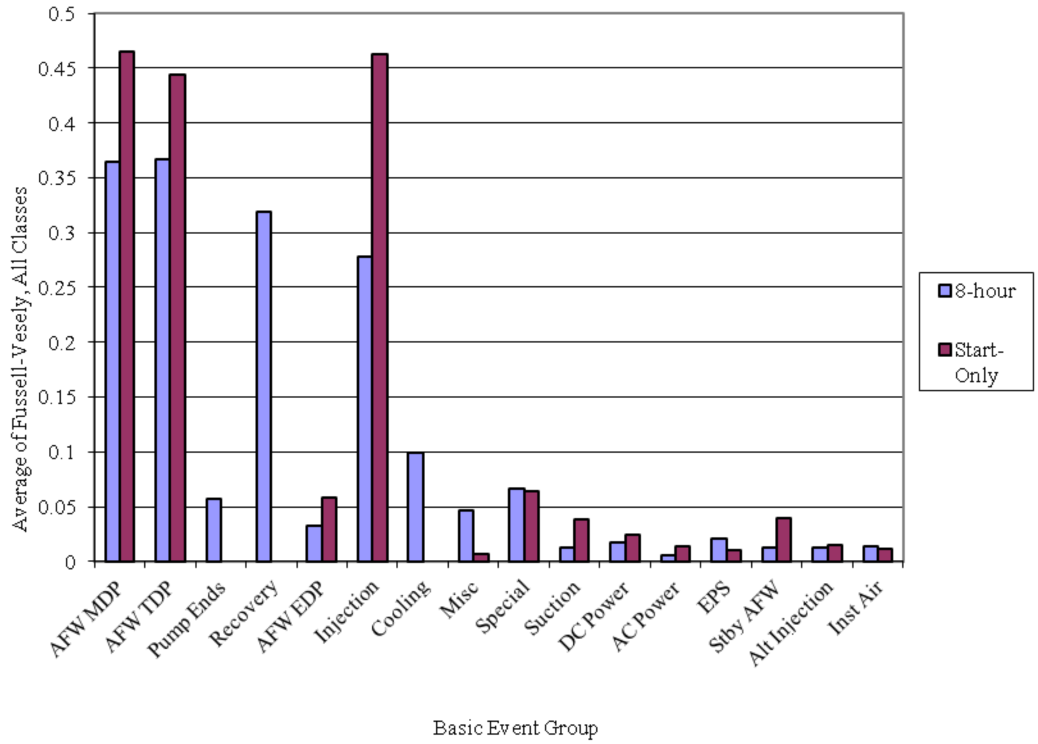

Figure 5. AFW industry-wide basic event group importances.

Table 3. AFW model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the AFW pumps.
AFW EDP	All basic events associated with the diesel engine-driven pumps. The start, run, common-cause, and test and maintenance are included in this group of basic events.
AFW MDP	All basic events associated with the motor-driven pumps. The start, run, common-cause, and test and maintenance are included in this group of basic events.
AFW TDP	All basic events associated with the turbine-driven pumps. The start, run, common-cause, and test and maintenance are included in this group of basic events.
Alternate Injection	Alternate injection sources such as firewater.
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the pumps. In addition, the pumps, valves, air-conditioning equipment that are modeled to provide room cooling to the AFW equipment
DC Power	The batteries and battery chargers that supply power to the pump control circuitry.
EPS	AFW dependency on the emergency power system.
Injection	The motor-operated valves and check valves in the injection path.
Inst Air	Instrument air support to the AFW model.
Misc	Other events that are not typically modeled or of very low importance.
Pump Ends	The common-cause failure of the pump ends. Used to model common-cause without the pump drivers.
Recovery	The operator recovery of the pump FTS, FTR, and other specialized modeled recovery events.
Special	Various events used in the models that are not directly associated with the AFW system.
Suction	The motor-operated valves and air-operated valves in the tank suction path. Includes the failure of the tank.
Stby AFW	Standby means of injecting water to the steam generators. Includes startup feedwater and cross-ties to adjacent units.

The basic event group importances were also averaged across plants of the same AFW class to represent class basic event group importances. The AFW class-specific start-only and 8-hour basic event group importances are shown in Figure 6 through Figure 8.

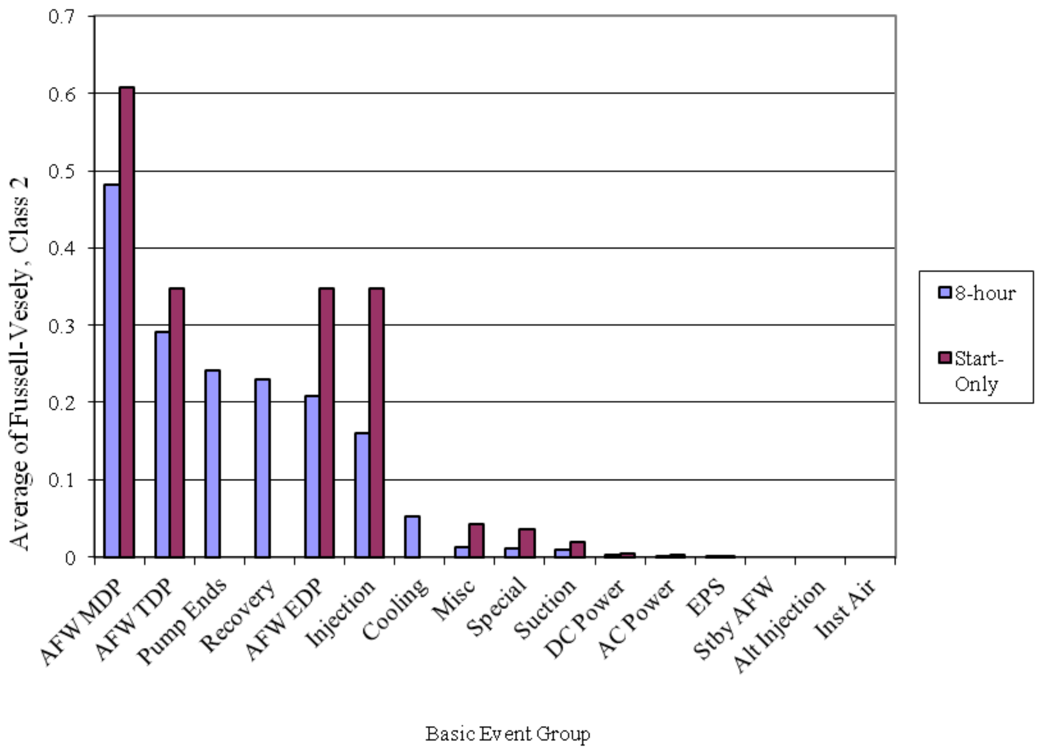

Figure 6. AFW Class 2 basic event group importances.

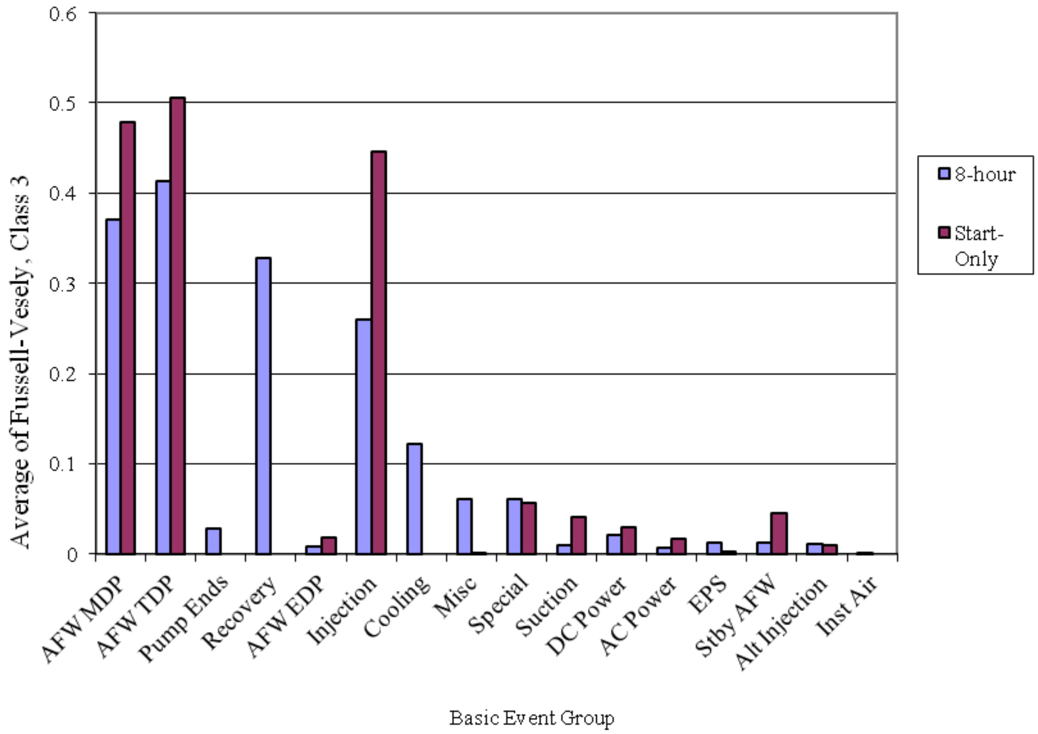

Figure 7. AFW Class 3 basic event group importances.

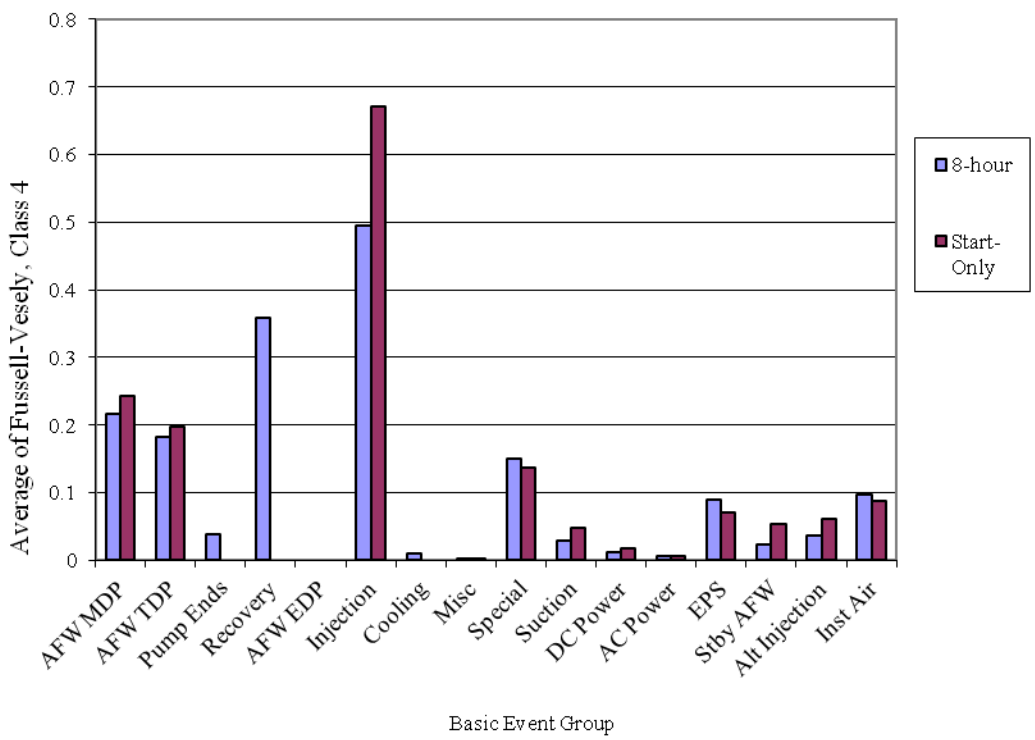

Figure 8. AFW Class 4 basic event group importances.

6 DATA TABLES

Table 4. Plot data for AFW start-only trend, Figure 3.

FY/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ EPIX				1.82E-08	1.86E-05	1.27E-06
1998	3.09E-05	1.79E-05	4.38E-05	4.98E-08	1.49E-04	3.13E-05
1999	2.99E-05	1.85E-05	4.14E-05	7.59E-08	1.89E-04	3.87E-05
2000	2.90E-05	1.90E-05	3.90E-05	5.53E-08	1.32E-04	2.90E-05
2001	2.81E-05	1.93E-05	3.68E-05	3.75E-08	1.14E-04	2.55E-05
2002	2.71E-05	1.94E-05	3.49E-05	8.31E-09	3.31E-05	1.41E-05
2003	2.62E-05	1.91E-05	3.33E-05	6.78E-08	1.50E-04	3.19E-05
2004	2.53E-05	1.84E-05	3.21E-05	1.88E-08	3.77E-05	1.55E-05
2005	2.43E-05	1.72E-05	3.14E-05	3.86E-08	1.17E-04	2.62E-05
2006	2.34E-05	1.56E-05	3.12E-05	4.47E-08	1.43E-04	2.96E-05
2007	2.25E-05	1.37E-05	3.12E-05	4.98E-08	1.40E-04	2.94E-05
2008	2.15E-05	1.15E-05	3.15E-05	1.09E-08	3.45E-05	1.48E-05
2009	2.06E-05	9.17E-06	3.20E-05	3.63E-08	8.48E-05	2.40E-05
2010	1.97E-05	6.72E-06	3.26E-05	2.05E-08	6.33E-05	1.85E-05

Table 5. Plot data for AFW 8-hour trend, Figure 4.

FY/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ EPIX				1.48E-07	9.25E-05	3.57E-06
1998	1.12E-04	9.87E-05	1.25E-04	3.87E-07	5.25E-04	1.13E-04
1999	1.10E-04	9.88E-05	1.22E-04	4.90E-07	5.41E-04	1.23E-04
2000	1.09E-04	9.87E-05	1.19E-04	3.49E-07	5.19E-04	1.09E-04
2001	1.07E-04	9.86E-05	1.16E-04	3.19E-07	5.14E-04	1.04E-04
2002	1.06E-04	9.81E-05	1.14E-04	9.73E-08	5.03E-04	8.59E-05
2003	1.04E-04	9.74E-05	1.12E-04	4.00E-07	5.24E-04	1.13E-04
2004	1.03E-04	9.62E-05	1.10E-04	1.29E-07	5.04E-04	8.90E-05
2005	1.02E-04	9.45E-05	1.09E-04	3.19E-07	5.15E-04	1.04E-04
2006	1.00E-04	9.24E-05	1.08E-04	3.34E-07	5.21E-04	1.10E-04
2007	9.87E-05	9.00E-05	1.08E-04	3.36E-07	5.19E-04	1.09E-04
2008	9.73E-05	8.73E-05	1.07E-04	1.07E-07	5.04E-04	8.71E-05
2009	9.59E-05	8.45E-05	1.07E-04	2.94E-07	5.13E-04	1.01E-04
2010	9.45E-05	8.15E-05	1.07E-04	1.90E-07	5.07E-04	9.29E-05

Table 6. Basic event reliability trending data.

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update Mean	Post A	Post B	Distribution
FTOC	AOV	1998	6	4936.6	1.21E-03	7.0	5762.9	Beta
FTOC	AOV	1999	2	5452.0	4.77E-04	3.0	6282.3	Beta
FTOC	AOV	2000	4	5119.8	8.40E-04	5.0	5948.2	Beta
FTOC	AOV	2001	6	5619.5	1.08E-03	7.0	6445.8	Beta
FTOC	AOV	2002	4	5636.9	7.73E-04	5.0	6465.2	Beta
FTOC	AOV	2003	2	5434.2	4.79E-04	3.0	6264.5	Beta
FTOC	AOV	2004	5	5421.9	9.59E-04	6.0	6249.2	Beta
FTOC	AOV	2005	5	5923.4	8.88E-04	6.0	6750.8	Beta
FTOC	AOV	2006	5	5050.2	1.02E-03	6.0	5877.6	Beta
FTOC	AOV	2007	1	5190.8	3.32E-04	2.0	6022.1	Beta
FTOC	AOV	2008	3	5054.4	6.79E-04	4.0	5883.8	Beta
FTOC	AOV	2009	1	4838.8	3.53E-04	2.0	5670.1	Beta
FTOC	AOV	2010	4	5005.4	8.56E-04	5.0	5833.8	Beta
FTOC	MOV	1998	5	5826.9	8.82E-04	6.2	7020.7	Beta
FTOC	MOV	1999	7	6108.3	1.12E-03	8.2	7300.1	Beta
FTOC	MOV	2000	8	6547.1	1.19E-03	9.2	7737.9	Beta
FTOC	MOV	2001	7	6306.1	1.09E-03	8.2	7497.9	Beta
FTOC	MOV	2002	7	6385.4	1.08E-03	8.2	7577.2	Beta
FTOC	MOV	2003	7	6275.9	1.10E-03	8.2	7467.7	Beta
FTOC	MOV	2004	3	6414.6	5.52E-04	4.2	7610.4	Beta
FTOC	MOV	2005	4	6760.5	6.53E-04	5.2	7955.3	Beta
FTOC	MOV	2006	2	6201.9	4.32E-04	3.2	7398.7	Beta
FTOC	MOV	2007	6	6284.1	9.62E-04	7.2	7476.9	Beta
FTOC	MOV	2008	2	6223.6	4.31E-04	3.2	7420.4	Beta
FTOC	MOV	2009	6	6083.3	9.89E-04	7.2	7276.1	Beta
FTOC	MOV	2010	6	6368.3	9.51E-04	7.2	7561.1	Beta
FTOP	AOV	1998	1	3179880	3.96E-07	1.3	3279880	Gamma
FTOP	AOV	1999	0	3179880	9.15E-08	0.3	3279880	Gamma
FTOP	AOV	2000	2	3249960	6.87E-07	2.3	3349960	Gamma
FTOP	AOV	2001	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2002	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2003	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2004	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2005	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2006	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2007	1	3171120	3.97E-07	1.3	3271120	Gamma
FTOP	AOV	2008	0	3171120	9.17E-08	0.3	3271120	Gamma
FTOP	AOV	2009	0	3153600	9.22E-08	0.3	3253600	Gamma
FTOP	AOV	2010	1	3153600	4.00E-07	1.3	3253600	Gamma
FTOP	MOV	1998	0	5107080	5.76E-08	0.3	5207080	Gamma
FTOP	MOV	1999	1	5072040	2.51E-07	1.3	5172040	Gamma
FTOP	MOV	2000	1	5072040	2.51E-07	1.3	5172040	Gamma
FTOP	MOV	2001	0	5072040	5.80E-08	0.3	5172040	Gamma
FTOP	MOV	2002	1	5072040	2.51E-07	1.3	5172040	Gamma
FTOP	MOV	2003	2	5072040	4.45E-07	2.3	5172040	Gamma
FTOP	MOV	2004	3	5072040	6.38E-07	3.3	5172040	Gamma
FTOP	MOV	2005	0	5072040	5.80E-08	0.3	5172040	Gamma
FTOP	MOV	2006	0	5072040	5.80E-08	0.3	5172040	Gamma
FTOP	MOV	2007	1	5072040	2.51E-07	1.3	5172040	Gamma
FTOP	MOV	2008	1	5115840	2.49E-07	1.3	5215840	Gamma
FTOP	MOV	2009	0	5168400	5.69E-08	0.3	5268400	Gamma

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	MOV	2010	1	5098320	2.50E-07	1.3	5198320	Gamma
FTR<1H	MDP	1998	1	1857.9	4.46E-04	2.5	5607.9	Gamma
FTR<1H	MDP	1999	2	1987.8	6.10E-04	3.5	5737.8	Gamma
FTR<1H	MDP	2000	1	2048.5	4.31E-04	2.5	5798.5	Gamma
FTR<1H	MDP	2001	0	2138.7	2.55E-04	1.5	5888.7	Gamma
FTR<1H	MDP	2002	2	2187.5	5.89E-04	3.5	5937.5	Gamma
FTR<1H	MDP	2003	0	2175.6	2.53E-04	1.5	5925.6	Gamma
FTR<1H	MDP	2004	1	2125.7	4.25E-04	2.5	5875.7	Gamma
FTR<1H	MDP	2005	2	2195.1	5.89E-04	3.5	5945.1	Gamma
FTR<1H	MDP	2006	0	1935.8	2.64E-04	1.5	5685.8	Gamma
FTR<1H	MDP	2007	1	2215.5	4.19E-04	2.5	5965.5	Gamma
FTR<1H	MDP	2008	0	1998.3	2.61E-04	1.5	5748.3	Gamma
FTR<1H	MDP	2009	0	1826.2	2.69E-04	1.5	5576.2	Gamma
FTR<1H	MDP	2010	1	2061.2	4.30E-04	2.5	5811.2	Gamma
FTR<1H	TDP	1998	1	1142.9	1.23E-03	1.8	1462.9	Gamma
FTR<1H	TDP	1999	4	1132.0	3.31E-03	4.8	1452.0	Gamma
FTR<1H	TDP	2000	2	1098.6	1.97E-03	2.8	1418.6	Gamma
FTR<1H	TDP	2001	4	1010.1	3.61E-03	4.8	1330.1	Gamma
FTR<1H	TDP	2002	2	1032.9	2.07E-03	2.8	1352.9	Gamma
FTR<1H	TDP	2003	7	1031.9	5.77E-03	7.8	1351.9	Gamma
FTR<1H	TDP	2004	3	987.6	2.91E-03	3.8	1307.6	Gamma
FTR<1H	TDP	2005	1	975.0	1.39E-03	1.8	1295.0	Gamma
FTR<1H	TDP	2006	1	972.5	1.39E-03	1.8	1292.5	Gamma
FTR<1H	TDP	2007	2	954.1	2.20E-03	2.8	1274.1	Gamma
FTR<1H	TDP	2008	3	936.3	3.02E-03	3.8	1256.3	Gamma
FTR<1H	TDP	2009	4	1086.1	3.41E-03	4.8	1406.1	Gamma
FTR<1H	TDP	2010	2	1131.8	1.93E-03	2.8	1451.8	Gamma
FTR>1H	MDP	1998	1	5796.2	1.68E-05	1.5	89129.6	Gamma
FTR>1H	MDP	1999	0	9162.2	5.41E-06	0.5	92495.5	Gamma
FTR>1H	MDP	2000	0	6532.9	5.56E-06	0.5	89866.2	Gamma
FTR>1H	MDP	2001	5	9673.1	5.91E-05	5.5	93006.4	Gamma
FTR>1H	MDP	2002	0	7855.7	5.48E-06	0.5	91189.0	Gamma
FTR>1H	MDP	2003	3	10640.6	3.72E-05	3.5	93973.9	Gamma
FTR>1H	MDP	2004	0	8976.5	5.42E-06	0.5	92309.8	Gamma
FTR>1H	MDP	2005	1	8065.0	1.64E-05	1.5	91398.4	Gamma
FTR>1H	MDP	2006	0	7855.2	5.48E-06	0.5	91188.6	Gamma
FTR>1H	MDP	2007	0	9251.9	5.40E-06	0.5	92585.2	Gamma
FTR>1H	MDP	2008	0	6864.6	5.54E-06	0.5	90197.9	Gamma
FTR>1H	MDP	2009	0	7444.1	5.51E-06	0.5	90777.5	Gamma
FTR>1H	MDP	2010	0	8983.1	5.42E-06	0.5	92316.4	Gamma
FTR>1H	TDP	1998	2	323.0	3.35E-04	2.5	7465.8	Gamma
FTR>1H	TDP	1999	0	2461.1	5.21E-05	0.5	9604.0	Gamma
FTR>1H	TDP	2000	0	518.8	6.53E-05	0.5	7661.7	Gamma
FTR>1H	TDP	2001	1	475.6	1.97E-04	1.5	7618.4	Gamma
FTR>1H	TDP	2002	0	1143.7	6.03E-05	0.5	8286.6	Gamma
FTR>1H	TDP	2003	0	415.9	6.61E-05	0.5	7558.8	Gamma
FTR>1H	TDP	2004	3	298.1	4.70E-04	3.5	7441.0	Gamma
FTR>1H	TDP	2005	1	214.9	2.04E-04	1.5	7357.7	Gamma
FTR>1H	TDP	2006	2	187.3	3.41E-04	2.5	7330.2	Gamma
FTR>1H	TDP	2007	0	207.9	6.80E-05	0.5	7350.8	Gamma
FTR>1H	TDP	2008	1	218.0	2.04E-04	1.5	7360.8	Gamma
FTR>1H	TDP	2009	0	206.1	6.80E-05	0.5	7349.0	Gamma
FTR>1H	TDP	2010	0	216.8	6.79E-05	0.5	7359.6	Gamma

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	MDP	1998	4	1857.9	1.99E-03	4.9	2453.0	Beta
FTS	MDP	1999	5	1987.8	2.28E-03	5.9	2581.9	Beta
FTS	MDP	2000	3	2048.5	1.47E-03	3.9	2644.6	Beta
FTS	MDP	2001	3	2138.7	1.42E-03	3.9	2734.8	Beta
FTS	MDP	2002	0	2187.5	3.23E-04	0.9	2786.6	Beta
FTS	MDP	2003	4	2175.6	1.77E-03	4.9	2770.7	Beta
FTS	MDP	2004	0	2125.7	3.30E-04	0.9	2724.8	Beta
FTS	MDP	2005	3	2195.1	1.40E-03	3.9	2791.2	Beta
FTS	MDP	2006	4	1935.8	1.93E-03	4.9	2530.9	Beta
FTS	MDP	2007	4	2215.5	1.74E-03	4.9	2810.6	Beta
FTS	MDP	2008	0	1998.3	3.46E-04	0.9	2597.4	Beta
FTS	MDP	2009	2	1826.2	1.20E-03	2.9	2423.3	Beta
FTS	MDP	2010	1	2061.2	7.14E-04	1.9	2659.3	Beta
FTS	TDP	1998	4	1142.9	3.67E-03	4.4	1195.6	Beta
FTS	TDP	1999	6	1132.0	5.38E-03	6.4	1182.7	Beta
FTS	TDP	2000	5	1098.6	4.67E-03	5.4	1150.3	Beta
FTS	TDP	2001	3	1010.1	3.19E-03	3.4	1063.8	Beta
FTS	TDP	2002	2	1032.9	2.20E-03	2.4	1087.6	Beta
FTS	TDP	2003	5	1031.9	4.96E-03	5.4	1083.6	Beta
FTS	TDP	2004	4	987.6	4.21E-03	4.4	1040.4	Beta
FTS	TDP	2005	4	975.0	4.26E-03	4.4	1027.8	Beta
FTS	TDP	2006	3	972.5	3.30E-03	3.4	1026.2	Beta
FTS	TDP	2007	4	954.1	4.35E-03	4.4	1006.9	Beta
FTS	TDP	2008	3	936.3	3.42E-03	3.4	990.1	Beta
FTS	TDP	2009	10	1086.1	9.10E-03	10.4	1132.8	Beta
FTS	TDP	2010	4	1131.8	3.70E-03	4.4	1184.5	Beta
SO	AOV	1998	0	3179880	6.41E-08	0.3	4679880	Gamma
SO	AOV	1999	0	3179880	6.41E-08	0.3	4679880	Gamma
SO	AOV	2000	0	3249960	6.32E-08	0.3	4749960	Gamma
SO	AOV	2001	2	3171120	4.92E-07	2.3	4671120	Gamma
SO	AOV	2002	0	3171120	6.42E-08	0.3	4671120	Gamma
SO	AOV	2003	1	3171120	2.78E-07	1.3	4671120	Gamma
SO	AOV	2004	1	3171120	2.78E-07	1.3	4671120	Gamma
SO	AOV	2005	2	3171120	4.92E-07	2.3	4671120	Gamma
SO	AOV	2006	0	3171120	6.42E-08	0.3	4671120	Gamma
SO	AOV	2007	1	3171120	2.78E-07	1.3	4671120	Gamma
SO	AOV	2008	1	3171120	2.78E-07	1.3	4671120	Gamma
SO	AOV	2009	1	3153600	2.79E-07	1.3	4653600	Gamma
SO	AOV	2010	1	3153600	2.79E-07	1.3	4653600	Gamma

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
AFW	UA	MDP	1998	2943.01	6.56E+05	0.0	0.3	54.63688
AFW	UA	MDP	1999	4996.45	9.34E+05	0.0	1.7	317.7448
AFW	UA	MDP	2000	5145.54	9.63E+05	0.0	1.1	205.4683
AFW	UA	MDP	2001	4224.2	9.62E+05	0.0	2.1	470.5145
AFW	UA	MDP	2002	3817.859	9.88E+05	0.0	1.5	397.3954
AFW	UA	MDP	2003	4328.783	9.66E+05	0.0	1.1	244.0141
AFW	UA	MDP	2004	3885.498	9.91E+05	0.0	1.4	351.7366
AFW	UA	MDP	2005	3850.743	9.81E+05	0.0	1.0	249.1449

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
AFW	UA	MDP	2006	3494.93	9.93E+05	0.0	1.0	285.8081
AFW	UA	MDP	2007	3414.86	9.92E+05	0.0	1.3	374.2099
AFW	UA	MDP	2008	3666.78	9.89E+05	0.0	0.9	233.691
AFW	UA	MDP	2009	2961.27	9.95E+05	0.0	1.0	336.9354
AFW	UA	MDP	2010	3171.52	9.77E+05	0.0	1.4	431.5998
AFW	UA	TDP	1998	2220.34	3.50E+05	0.0	1.1	164.015
AFW	UA	TDP	1999	2698.76	5.04E+05	0.0	1.4	259.9561
AFW	UA	TDP	2000	2766.07	5.16E+05	0.0	1.8	332.2657
AFW	UA	TDP	2001	3080.68	5.15E+05	0.0	1.2	192.8515
AFW	UA	TDP	2002	2423.043	5.18E+05	0.0	1.9	416.1565
AFW	UA	TDP	2003	3029.306	5.05E+05	0.0	1.4	236.4874
AFW	UA	TDP	2004	2993.303	5.22E+05	0.0	1.4	239.9749
AFW	UA	TDP	2005	2927.844	5.23E+05	0.0	2.7	474.2461
AFW	UA	TDP	2006	2831.503	5.25E+05	0.0	1.2	215.8341
AFW	UA	TDP	2007	2289.81	5.29E+05	0.0	1.0	239.0096
AFW	UA	TDP	2008	2413.31	5.26E+05	0.0	1.4	300.7099
AFW	UA	TDP	2009	2707.26	5.31E+05	0.0	1.0	192.9241
AFW	UA	TDP	2010	3220.6	5.08E+05	0.0	1.3	197.4844

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTLR	Fail to Load/Run
FTOC	Fail to Open/Close
FTOP	Fail to Operate (rate)
FTR	Fail to Run
FTR<1H	Fail to Run <1H
FTS	Fail to Start
SO	Spurious Operation
UA	Unavailability (Maintenance or State of another component)

7 AFW SYSTEM DESCRIPTION

The main purpose of the AFW system is to provide feedwater to the steam generators to maintain a heat sink in the event of (1) a loss of main feedwater, (2) a reactor trip and loss of offsite power, and (3) a small break loss of coolant accident. The system, at some plants, can also provide a source of feedwater to the steam generators during plant startup and shutdown. However, the system cannot supply sufficient feedwater flow during power operation. At most plants, the system can only supply adequate feedwater to the steam generators with steam loads less than 5% of rated flow.

The safety-related function of the AFW system is to maintain water inventory in the steam generators for reactor residual heat removal when the main feedwater system is unavailable. The system is designed to automatically start and supply sufficient feedwater to prevent the relief of primary coolant through the pressurizer safety valves. The AFW system, in conjunction with the steam generators and the main steam line atmospheric relief and/or safety valves, is used to cool the reactor coolant system to the residual heat removal cut-in temperature. At this temperature, the residual heat removal system is used to further cool the reactor coolant system. The AFW system may also be used to temporarily hold the plant in a hot standby condition while main feedwater flow is being restored, with the option of cooling the reactor coolant system to the residual heat removal system initiation temperature.

The AFW system typically consists of at least two independent divisions. The divisions consist of a number of different combinations of electric-motor-driven and/or turbine-driven pump trains or diesel-driven pump trains. Electrical power, control, and instrumentation associated with each division are independent from one another. Typically, the electric-motor-driven pump trains make up one division and the turbine-driven pump train the other. Some plants have a diesel-driven pump in place of the turbine-driven pump, or a second turbine-driven pump in place of the electric-motor-driven pumps.

The AFW system is typically started automatically by the engineered safety features actuation system (ESFAS) or equivalent, depending on plant design and terminology. The ESFAS system automatic start signals include a predetermined low water level condition in one or more steam generators, a loss of the operating main feedwater pumps, a loss of electrical power on safety-related buses, and a safety injection signal. There are additional start signals, but these four are the most common. There is significant variation among the plants in how the system responds given a start signal. However, in most cases, a low-level condition in one steam generator starts only the electric-motor-driven pumps, while a low-level condition in two or more steam generators starts both the electric and turbine-driven pumps. For the plants that have two divisions consisting of one train per division (i.e., an electric-motor and turbine-driven pump train), most start signals start both pumps.

Feedwater flow to each steam generator is normally controlled by a flow control valve that will modulate either open or closed to maintain steam generator level. The flow control valve can be controlled either automatically or manually. A flow recirculation line is provided downstream of each pump discharge. The recirculation line allows for continuous flow back to the suction source to provide minimum flow protection for the pump. In addition, a test return line is provided downstream of each pump discharge to allow for either full or partial testing of the pumps. To limit the flow, as steam generator pressure lowers during a cool down, the system utilizes several different methods depending on plant design. Some plants use a current limiter that acts to increase downstream pump pressure thereby reducing motor amps, others use flow restricting orifices or pipe design configurations, and others use the flow control valve that modulates closed when a flow reduction signal is received.

The turbine for each turbine-driven pump is classified as an atmospheric discharge, non-condensing turbine. Typically, driving steam is supplied from the main steam lines upstream of the main steam isolation valves from at least two steam generators. (Design class 11 turbine steam supply is from one steam generator.) Each steam supply line to the turbine contains a normally closed fail-open air operated steam isolation valve. Some plants have a dc-powered motor-operated valve. A bypass is provided around each of these isolation valves with a flow-restricting orifice and a normally closed fail-to-open air-operated bypass isolation valve. The bypass provides a small, controlled rate of steam flow to the AFW turbine for warming the steam lines and turbine. Steam drain traps are provided in the low points of the steam line to drain condensate from the lines as condensate present in the steam lines could have an adverse affect on turbine reliability during an unplanned demand.

Each turbine is supplied with a hydraulic governor control valve, and a trip and throttle valve with motor reset capability. The turbine is brought up to speed by governor control upon being supplied with steam by opening the steam supply isolation valve(s). The governor then controls the turbine speed at the pump rated speed by modulating the governor control valve. The governor controlled turbine speed can be adjusted from the control room, the remote shutdown panel, or manually at the governor.

The turbine is stopped by remotely closing the trip throttle valve from the control room or the remote shutdown panel. The trip and throttle valve is automatically (electrically) tripped on turbine overspeed at 115% of rated speed. The electric overspeed trip can be reset from either the control room or remote shutdown panel. A mechanical overspeed trip also provides automatic overspeed protection at 125% of rated speed. The mechanical overspeed trip can only be reset at the trip and throttle valve.

Feedwater is supplied to both divisions through either a single condensate storage tank with separate suction supply lines or two storage tanks with redundant supply lines. Each tank typically will have its level maintained above the minimum volume needed to provide a net positive suction head to the pumps and allow for 6 hours of system operation. For extended operation of the system or as a backup for the storage tanks, an ensured source of water is provided from a service water system. The switchover to the ensured source can be accomplished by either an automatic re-alignment of the suction valves based on a sensed, low-suction pressure condition or manually by operator action depending on the plant design (typical alignment at most plants is by manual capability).

The AFW systems analyzed can be grouped into three different design classes based on the effective redundancy of the pumps. Each system typically consists of at least two independent divisions. The divisions consist of a number of motor-, turbine-, and/or diesel-driven pumps. In addition, some SPAR models include other sources of emergency feed water such as the startup feedwater pump(s). The configurations are shown in Table 9.

Table 9. Listing of the AFW design classes.

Class	Plant	AFW EDP	AFW MDP	AFW TDP	Other
Class 2	Arkansas 1		1	1	
Class 2	Braidwood 1	1	1		
Class 2	Braidwood 2	1	1		
Class 2	Byron 1	1	1		
Class 2	Byron 2	1	1		
Class 2	Crystal River 3	1		1	
Class 2	Prairie Island 1		1	1	1[3]
Class 2	Prairie Island 2		1	1	1[3]
Class 2	Seabrook		1	1	1[4]
Class 3	Arkansas 2		1	1	1[4]
Class 3	Beaver Valley 2		2	1	
Class 3	Callaway		2	1	
Class 3	Catawba 1		2	1	
Class 3	Catawba 2		2	1	
Class 3	Comanche Peak 1		2	1	
Class 3	Comanche Peak 2		2	1	
Class 3	Cook 1		2	1	
Class 3	Cook 2		2	1	
Class 3	Diablo Canyon 1		2	1	
Class 3	Diablo Canyon 2		2	1	
Class 3	Farley 1		2	1	
Class 3	Farley 2		2	1	
Class 3	Fort Calhoun	1	1	1	
Class 3	Harris		2	1	
Class 3	Indian Point 2		2	1	
Class 3	Indian Point 3		2	1	
Class 3	Kewaunee		2	1	
Class 3	McGuire 1		2	1	
Class 3	McGuire 2		2	1	

[3] Shares AFW pump with other unit.

[4] Standby/Startup AFW pump.

Class	Plant	AFW EDP	AFW MDP	AFW TDP	Other
Class 3	Millstone 2		2	1	
Class 3	Millstone 3		2	1	
Class 3	North Anna 1		2	1	
Class 3	North Anna 2		2	1	
Class 3	Oconee 1		2	1	
Class 3	Oconee 2		2	1	
Class 3	Oconee 3		2	1	
Class 3	Palisades		2	1	
Class 3	Palo Verde 1		2	1	
Class 3	Palo Verde 2		2	1	
Class 3	Palo Verde 3		2	1	
Class 3	Point Beach 1		2	1	
Class 3	Point Beach 2		2	1	
Class 3	Robinson 2		2	1	
Class 3	Salem 1		2	1	
Class 3	Salem 2		2	1	
Class 3	San Onofre 2		2	1	
Class 3	San Onofre 3		2	1	
Class 3	Sequoyah 1		2	1	
Class 3	Sequoyah 2		2	1	

Class	Plant	AFW EDP	AFW MDP	AFW TDP	Other
Class 3	St. Lucie 1		2	1	
Class 3	St. Lucie 2		2	1	
Class 3	Summer		2	1	
Class 3	Three Mile Isl 1		2	1	
Class 3	Turkey Point 3			3	
Class 3	Turkey Point 4			3	
Class 3	Vogtle 1		2	1	
Class 3	Vogtle 2		2	1	
Class 3	Waterford 3		2	1	
Class 3	Watts Bar 1		2	1	
Class 3	Wolf Creek		2	1	
Class 4	Beaver Valley 1		2	1	1
Class 4	Calvert Cliffs 1		2	2	
Class 4	Calvert Cliffs 2		2	2	
Class 4	Davis-Besse		1	2	1
Class 4	Ginna		2	1	2
Class 4	South Texas 1		3	1	
Class 4	South Texas 2		3	1	
Class 4	Surry 1		2	1	3
Class 4	Surry 2		2	1	3

8 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.