INL/EXT-15-34439

System Study: Auxiliary Feedwater 1998–2013

John A. Schroeder

February 2015

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

NOTICE

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed herein, or represents that its use by such third party would not infringe privately owned rights. The views expressed herein are not necessarily those of the U.S. Nuclear Regulatory Commission.

INL/EXT-15-34439

System Study:
Auxiliary Feedwater
1998–2013

John A. Schroeder

Update Completed December 2014

Idaho National Laboratory
Risk Assessment and Management Services Department
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC Agreement Number NRC-HQ-14-D-0018

ABSTRACT

This report presents an unreliability evaluation of the auxiliary feedwater (AFW) system at 69 U.S. commercial nuclear power plants. Demand, run hours, and failure data from fiscal year 1998 through 2013 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). The unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period. No statistically significant increasing or decreasing trends were identified in the AFW results.

CONTENTS

FIGURES

TABLES

ACRONYMS

AFW	auxiliary feedwater
AOV	air-operated valve
CCF	common-cause failure
EPIX	Equipment Performance and Information Exchange
ESFAS	engineered safety features actuation system
FTLR	fail to load/run
FTOC	fail to open/close
FTOP	fail to operate
FTR	fail to run
FTR<1H	fail to run less than one hour (after start)
FTS	fail to start
FY	fiscal year
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
PRA	probabilistic risk assessment
SO	spurious operation
SPAR	standardized plant analysis risk
SSU	safety system unavailability
TDP	turbine-driven pump
UA	unavailability (maintenance or state of another component)

System Study: Auxiliary Feedwater

1998–2013

1. INTRODUCTION

This report presents an unreliability evaluation of the auxiliary feedwater (AFW) system 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)-98 through FY-13 for selected components in the AFW were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process Safety System Unavailability (SSU) database (FY-98 through FY-01) and the Mitigating Systems Performance Index (MSPI) database (FY-02 through FY-13). Common-cause failure (CCF) data used in the models are from the 2010 update to the CCF database. The system unreliability results are trended for the most recent 10-year period while yearly estimates for system unreliability are provided for the entire active period.

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 2010 Component Reliability Update (Reference 1), which is an update to Reference 2 (NUREG/CR-6928). 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.

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.

Table 1. AFW design class summary.

Class	Plant	Version
Class 2	Arkansas 1	8.19
Class 2	Braidwood 1	8.21
Class 2	Braidwood 2	8.21
Class 2	Byron 1	8.21
Class 2	Byron 2	8.21
Class 2	Crystal River 3	8.16
Class 2	Prairie Island 1	8.19
Class 2	Prairie Island 2	8.19
Class 2	Seabrook	8.20
Class 3	Arkansas 2	8.21
Class 3	Beaver Valley 2	8.23
Class 3	Callaway	8.21
Class 3	Catawba 1	8.20
Class 3	Catawba 2	8.20
Class 3	Comanche Peak 1	8.21
Class 3	Comanche Peak 2	8.21
Class 3	Cook 1	8.20
Class 3	Cook 2	8.20
Class 3	Diablo Canyon 1	8.19
Class 3	Diablo Canyon 2	8.19
Class 3	Farley 1	8.18
Class 3	Farley 2	8.18
Class 3	Fort Calhoun	8.20
Class 3	Harris	8.23
Class 3	Indian Point 2	8.19
Class 3	Indian Point 3	8.20
Class 3	Kewaunee	8.20
Class 3	McGuire 1	8.20
Class 3	McGuire 2	8.20
Class 3	Millstone 2	8.17
Class 3	Millstone 3	8.20
Class 3	North Anna 1	8.20
Class 3	North Anna 2	8.20
Class 3	Oconee 1	8.19
Class 3	Oconee 2	8.19
Class 3	Oconee 3	8.19
Class 3	Palisades	8.20
Class 3	Palo Verde 1	8.20
Class 3	Palo Verde 2	8.20
Class 3	Palo Verde 3	8.20
Class 3	Point Beach 1	8.20
Class 3	Point Beach 2	8.20
Class 3	Robinson 2	8.17
Class 3	Salem 1	8.20
Class 3	Salem 2	8.20
Class 3	San Onofre 2	8.22
Class 3	San Onofre 3	8.22
Class 3	Sequoyah 1	8.16
Class 3	Sequoyah 2	8.16
Class 3	St. Lucie 1	8.19
Class 3	St. Lucie 2	8.19
Class 3	Summer	8.23
Class 3	Three Mile Isl 1	8.20
Class 3	Turkey Point 3	8.20
Class 3	Turkey Point 4	8.20
Class 3	Vogtle 1	8.21
Class 3	Vogtle 2	8.21
Class 3	Waterford 3	8.16
Class 3	Watts Bar 1	8.16
Class 3	Wolf Creek	8.20
Class 4	Beaver Valley 1	8.22
Class 4	Calvert Cliffs 1	8.22
Class 4	Calvert Cliffs 2	8.21
Class 4	Davis-Besse	8.19
Class 4	Ginna	8.23
Class 4	South Texas 1	8.17
Class 4	South Texas 2	8.17
Class 4	Surry 1	8.19
Class 4	Surry 2	8.15

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[a] 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 the ***Start-Only*** case—the leading contributor is the injection flow path followed by the TDP and MDP components (only the fail-to-start failure mode).
- In the ***8-Hour*** case—the leading contributor to AFW system unreliability is the AFW motor-driven and turbine-driven pumps followed by recovery and the pump ends.

---

[a] Statistically significant is defined in terms of the ‘p-value.’ A p-value is a probability indicating whether to accept or reject the null hypothesis that there is no trend in the data. P-values of less than or equal to 0.05 indicate that we are 95% confident 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. 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 2010).[a] 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.

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.

Table 2. Industry-wide unreliability values.

Model	EPS Grouping	Lower (5%)	Median	Mean	Upper (95%)
Start-only	Industry	2.13E−08	1.47E−06	1.27E−05	3.08E−05
	Class 2	3.66E−07	9.10E−06	2.60E−05	1.07E−04
	Class 3	4.91E−08	1.34E−06	1.21E−05	1.62E−05
	Class 4	7.06E−09	5.22E−07	2.46E−06	1.08E−05
8-hour Mission	Industry	3.86E−07	7.39E−06	6.97E−05	5.02E−04
	Class 2	1.13E−06	4.48E−05	1.96E−04	9.49E−04
	Class 3	8.47E−07	7.35E−06	5.70E−05	5.03E−04
	Class 4	1.94E−08	1.59E−06	1.23E−05	5.24E−05

---

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

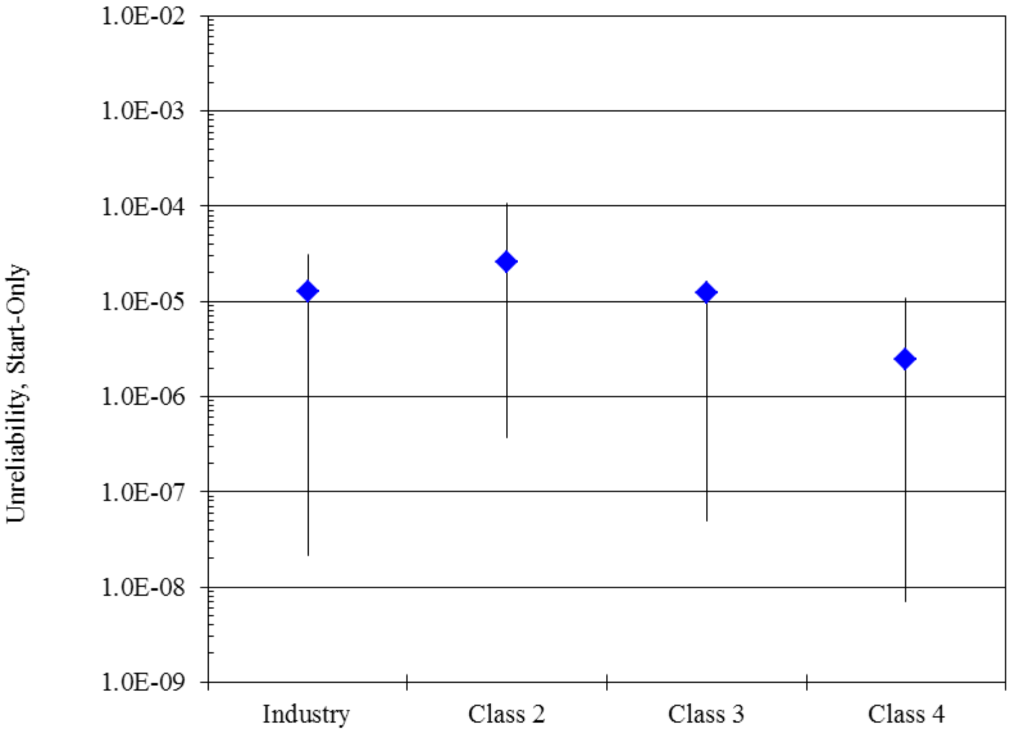

Figure 1. AFW start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

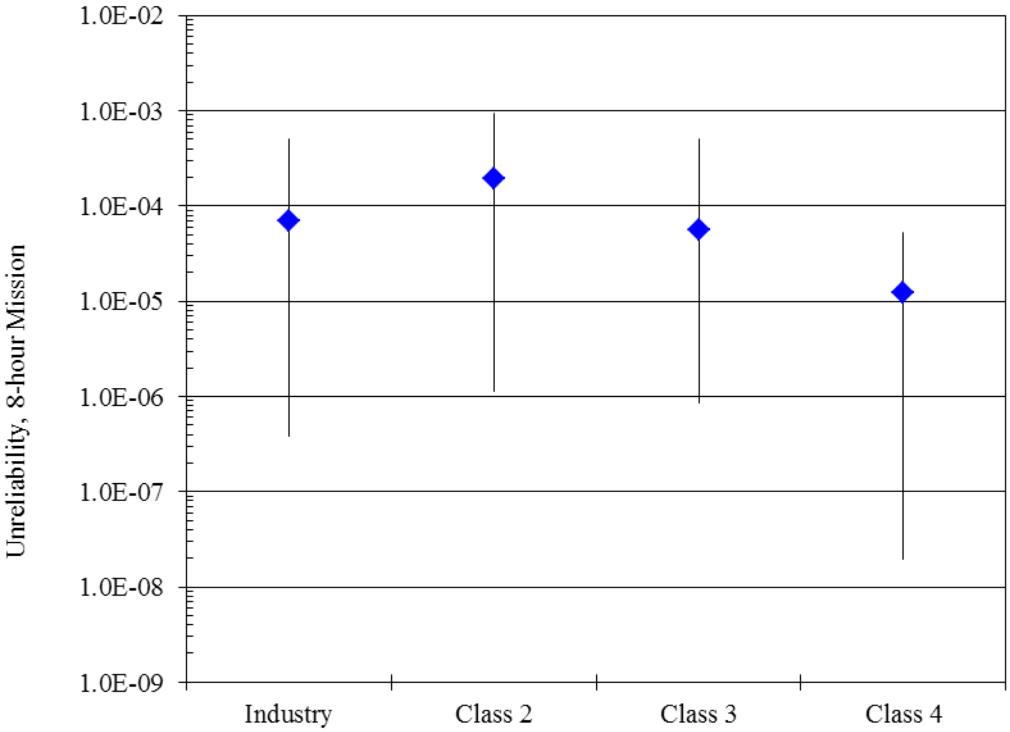

Figure 2. AFW 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (FY-98 through FY-13) failure and demand or run time data were obtained from ICES for the AFW system. AFW train maintenance unavailability data for trending are from the same time period, as reported in the ROP and ICES. 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. Tables 6 and 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/ICES) 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.

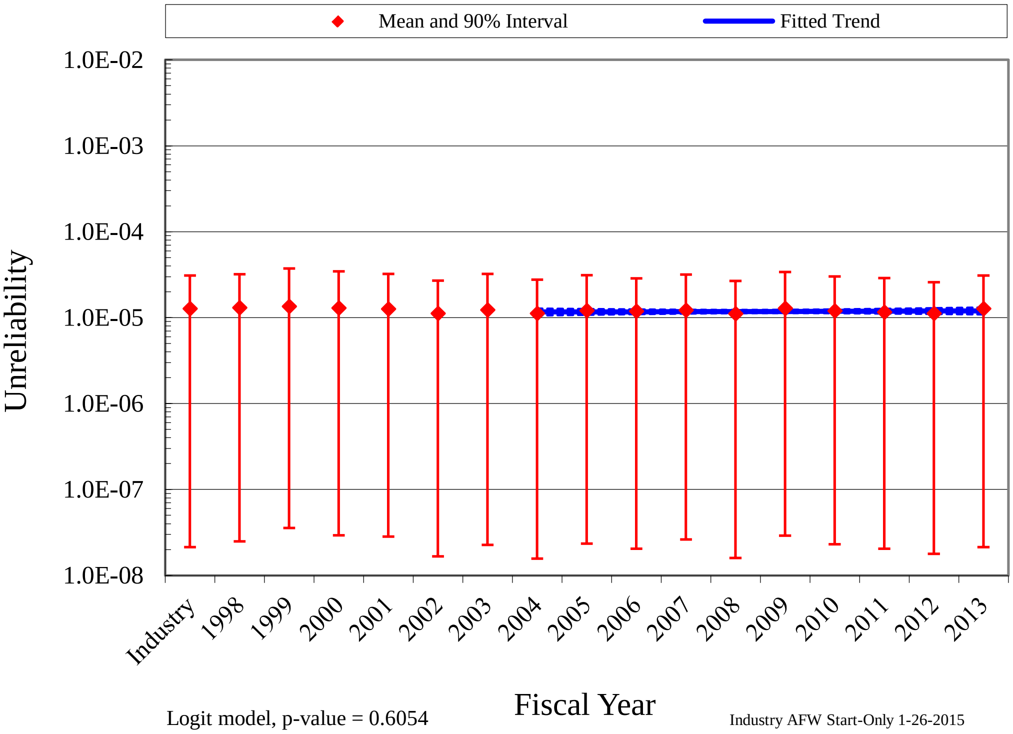

Figure 3. Trend of AFW system unreliability (start-only model), as a function of fiscal year.

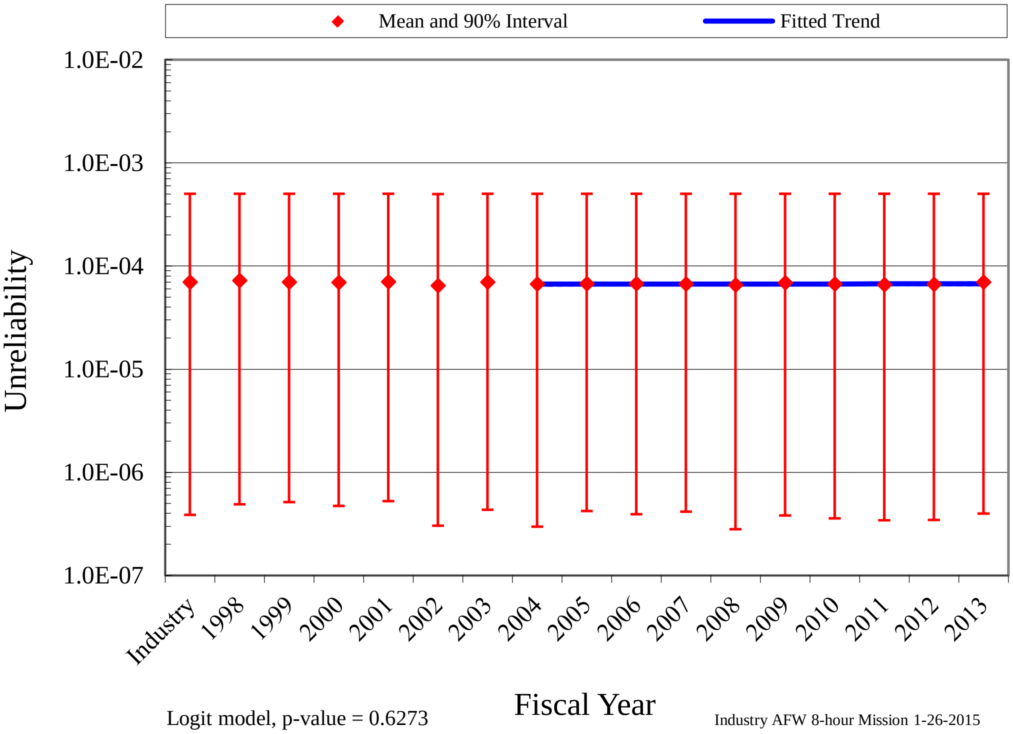

Figure 4. Trend of AFW system unreliability (8-hour model), as a function of fiscal year.

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 (1998–2010). 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 the **Start-Only** case—the leading contributor is the injection flow path followed by the TDP and MDP components (only the fail-to-start failure mode).
- In the **8-Hour** case—the leading contributor to AFW system unreliability is the AFW motor-driven and turbine-driven pumps followed by recovery and the pump ends.

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.

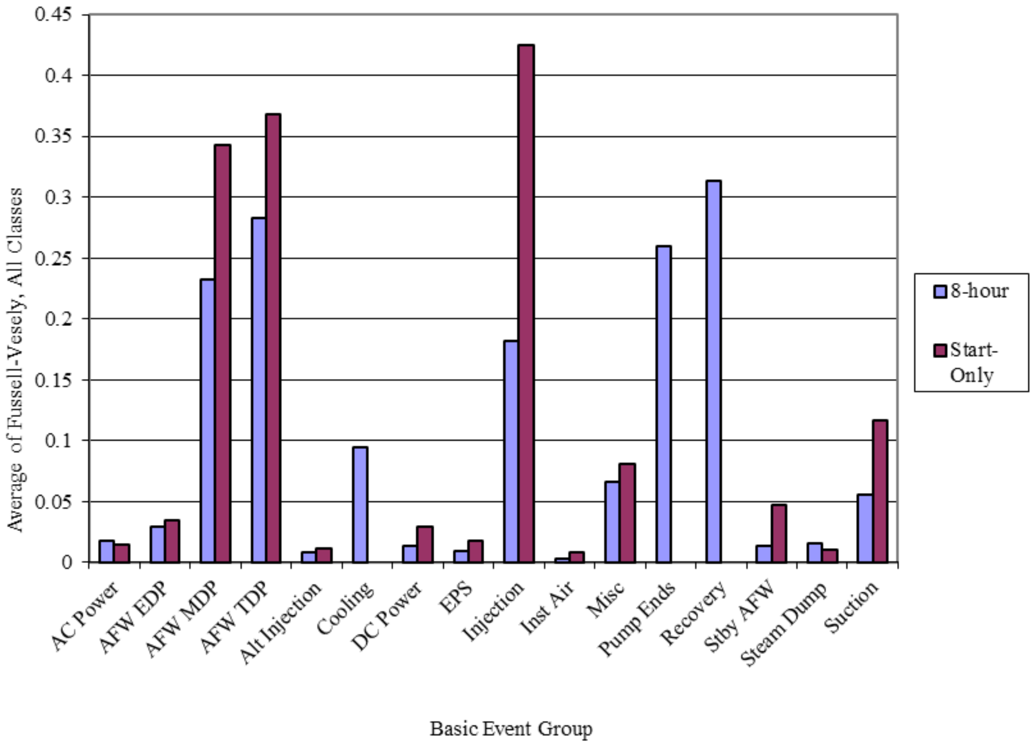

Figure 5. AFW industry-wide basic event group importances.

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.

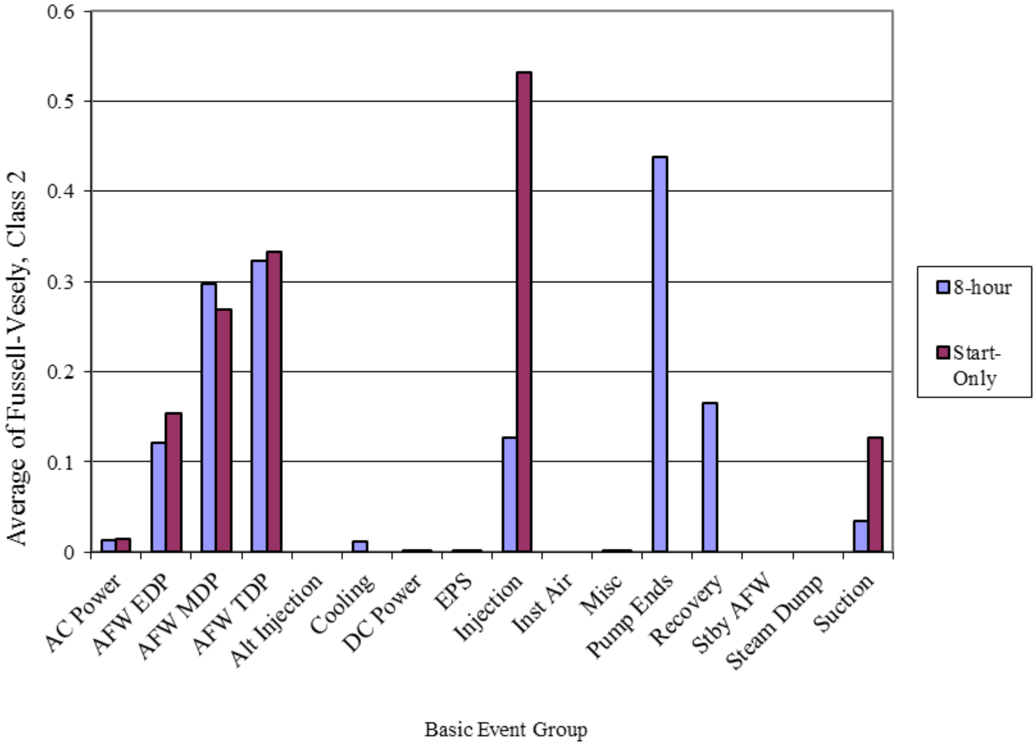

Figure 6. AFW Class 2 basic event group importances.

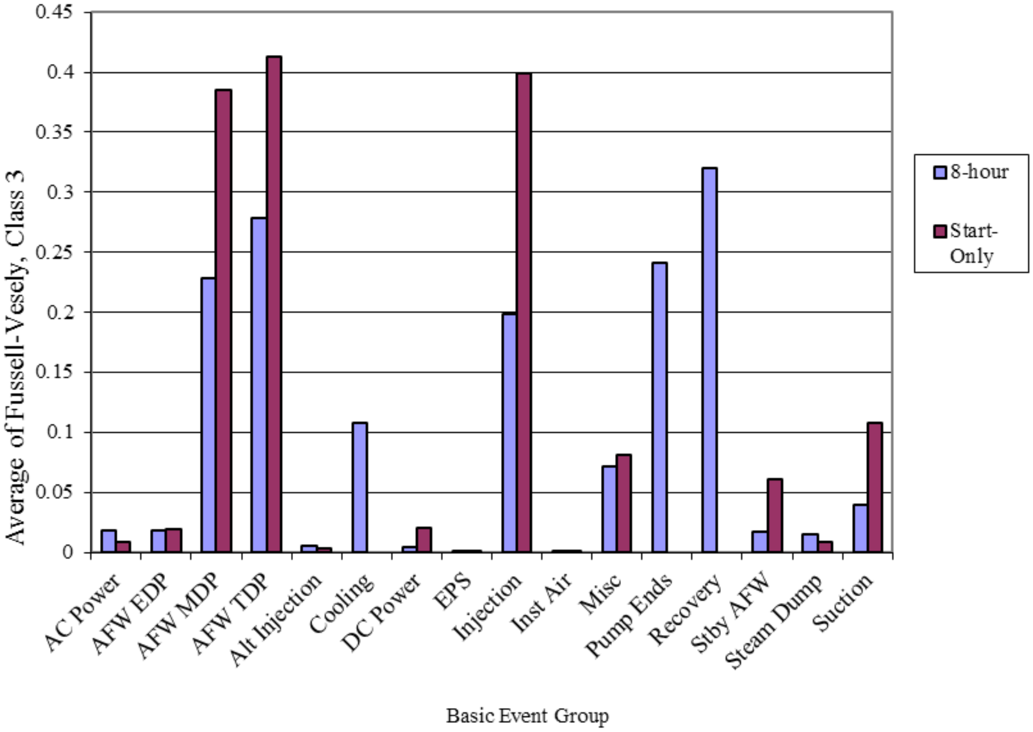

Figure 7. AFW Class 3 basic event group importances.

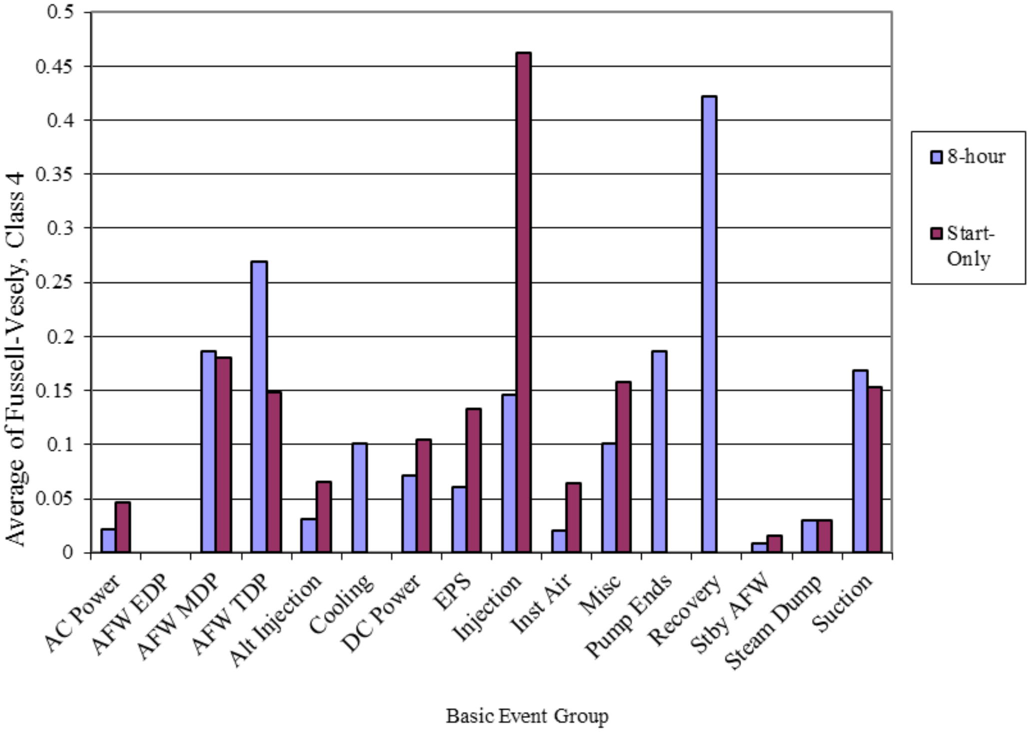

Figure 8. AFW Class 4 basic event group importances.

6. DATA TABLES

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

	Regression Curve Data Points			Plot Trend Error Bar Points		
FY/Source	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
SPAR/ICES				2.13E−08	3.08E−05	1.27E−05
1998				2.49E-08	3.20E-05	1.29E-05
1999				3.58E-08	3.72E-05	1.34E-05
2000				2.93E-08	3.45E-05	1.29E-05
2001				2.83E-08	3.22E-05	1.25E-05
2002				1.67E-08	2.69E-05	1.12E-05
2003				2.26E-08	3.22E-05	1.23E-05
2004	1.16E-05	1.06E-05	1.27E-05	1.57E-08	2.77E-05	1.12E-05
2005	1.17E-05	1.08E-05	1.26E-05	2.34E-08	3.11E-05	1.20E-05
2006	1.17E-05	1.10E-05	1.24E-05	2.04E-08	2.88E-05	1.18E-05
2007	1.17E-05	1.12E-05	1.23E-05	2.63E-08	3.18E-05	1.21E-05
2008	1.18E-05	1.13E-05	1.23E-05	1.60E-08	2.67E-05	1.10E-05
2009	1.18E-05	1.13E-05	1.23E-05	2.90E-08	3.39E-05	1.28E-05
2010	1.19E-05	1.13E-05	1.24E-05	2.30E-08	3.03E-05	1.19E-05
2011	1.19E-05	1.12E-05	1.26E-05	2.05E-08	2.89E-05	1.15E-05
2012	1.19E-05	1.11E-05	1.28E-05	1.79E-08	2.58E-05	1.11E-05
2013	1.20E-05	1.09E-05	1.31E-05	2.13E-08	3.11E-05	1.26E-05

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

	Regression Curve Data Points			Plot Trend Error Bar Points		
FY/Source	**Mean**	**Lower (5%)**	**Upper (95%)**	**Lower (5%)**	**Upper (95%)**	**Mean**
SPAR/ICES				3.86E−07	5.02E−04	6.97E−05
1998				4.90E-07	5.03E-04	7.18E-05
1999				5.13E-07	5.03E-04	6.93E-05
2000				4.73E-07	5.02E-04	6.89E-05
2001				5.24E-07	5.03E-04	7.02E-05
2002				3.02E-07	5.01E-04	6.45E-05
2003				4.34E-07	5.03E-04	6.97E-05
2004	6.66E-05	6.48E-05	6.85E-05	2.98E-07	5.01E-04	6.68E-05
2005	6.67E-05	6.52E-05	6.83E-05	4.20E-07	5.02E-04	6.72E-05
2006	6.68E-05	6.55E-05	6.80E-05	3.92E-07	5.02E-04	6.70E-05
2007	6.68E-05	6.58E-05	6.79E-05	4.15E-07	5.02E-04	6.68E-05
2008	6.69E-05	6.61E-05	6.78E-05	2.80E-07	5.01E-04	6.53E-05
2009	6.70E-05	6.61E-05	6.79E-05	3.80E-07	5.02E-04	6.87E-05
2010	6.71E-05	6.61E-05	6.81E-05	3.58E-07	5.01E-04	6.66E-05
2011	6.71E-05	6.59E-05	6.84E-05	3.42E-07	5.01E-04	6.58E-05
2012	6.72E-05	6.57E-05	6.88E-05	3.44E-07	5.01E-04	6.61E-05
2013	6.73E-05	6.54E-05	6.92E-05	3.97E-07	5.02E-04	6.94E-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	5	1855	2.02E-03	6.112	3017.9	Beta
FTOC	AOV	1999	1	1864	6.96E-04	2.112	3031.2	Beta
FTOC	AOV	2000	3	1848	1.36E-03	4.112	3012.7	Beta
FTOC	AOV	2001	3	2021	1.29E-03	4.112	3186.5	Beta
FTOC	AOV	2002	3	2137	1.24E-03	4.112	3301.6	Beta
FTOC	AOV	2003	0	2035	3.47E-04	1.112	3202.8	Beta
FTOC	AOV	2004	0	2175	3.33E-04	1.112	3343.1	Beta
FTOC	AOV	2005	2	2365	8.81E-04	3.112	3531.2	Beta
FTOC	AOV	2006	2	1886	1.02E-03	3.112	3052.0	Beta
FTOC	AOV	2007	1	1866	6.96E-04	2.112	3033.3	Beta
FTOC	AOV	2008	1	1748	7.24E-04	2.112	2915.1	Beta
FTOC	AOV	2009	1	1717	7.32E-04	2.112	2884.4	Beta
FTOC	AOV	2010	3	1749	1.41E-03	4.112	2914.0	Beta
FTOC	AOV	2011	0	1732	3.83E-04	1.112	2900.1	Beta
FTOC	AOV	2012	0	1706	3.87E-04	1.112	2874.0	Beta
FTOC	AOV	2013	1	1729	7.29E-04	2.112	2896.0	Beta
FTOC	MOV	1998	3	3613	8.79E-04	5.046	5733.1	Beta
FTOC	MOV	1999	5	3705	1.21E-03	7.046	5823.1	Beta
FTOC	MOV	2000	4	3962	9.93E-04	6.046	6080.7	Beta
FTOC	MOV	2001	6	3728	1.37E-03	8.046	5845.1	Beta
FTOC	MOV	2002	3	3990	8.25E-04	5.046	6109.8	Beta
FTOC	MOV	2003	0	3901	3.40E-04	2.046	6023.7	Beta
FTOC	MOV	2004	0	4027	3.33E-04	2.046	6150.1	Beta
FTOC	MOV	2005	3	4144	8.05E-04	5.046	6264.1	Beta
FTOC	MOV	2006	1	3753	5.18E-04	3.046	5875.1	Beta
FTOC	MOV	2007	6	3786	1.36E-03	8.046	5903.1	Beta
FTOC	MOV	2008	2	3752	6.88E-04	4.046	5873.3	Beta
FTOC	MOV	2009	5	3748	1.20E-03	7.046	5866.3	Beta
FTOC	MOV	2010	5	3749	1.20E-03	7.046	5866.8	Beta
FTOC	MOV	2011	3	3623	8.78E-04	5.046	5743.3	Beta
FTOC	MOV	2012	2	3464	7.24E-04	4.046	5584.7	Beta
FTOC	MOV	2013	0	3473	3.65E-04	2.046	5596.5	Beta
FTOP	AOV	1998	0	1673160	1.92E-07	1.421	7392160.0	Gamma
FTOP	AOV	1999	0	1673160	1.92E-07	1.421	7392160.0	Gamma
FTOP	AOV	2000	1	1708200	3.26E-07	2.421	7427200.0	Gamma
FTOP	AOV	2001	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2002	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2003	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2004	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2005	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2006	0	1708200	1.91E-07	1.421	7427200.0	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	AOV	2007	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2008	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2009	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2010	1	1708200	3.26E-07	2.421	7427200.0	Gamma
FTOP	AOV	2011	0	1778280	1.90E-07	1.421	7497280.0	Gamma
FTOP	AOV	2012	0	1708200	1.91E-07	1.421	7427200.0	Gamma
FTOP	AOV	2013	2	1708200	4.61E-07	3.421	7427200.0	Gamma
FTOP	MOV	1998	0	3950760	5.61E-08	1.458	26000760.0	Gamma
FTOP	MOV	1999	0	3915720	5.62E-08	1.458	25965720.0	Gamma
FTOP	MOV	2000	1	3915720	9.47E-08	2.458	25965720.0	Gamma
FTOP	MOV	2001	0	3915720	5.62E-08	1.458	25965720.0	Gamma
FTOP	MOV	2002	1	3915720	9.47E-08	2.458	25965720.0	Gamma
FTOP	MOV	2003	1	3915720	9.47E-08	2.458	25965720.0	Gamma
FTOP	MOV	2004	2	3915720	1.33E-07	3.458	25965720.0	Gamma
FTOP	MOV	2005	0	3915720	5.62E-08	1.458	25965720.0	Gamma
FTOP	MOV	2006	0	3915720	5.62E-08	1.458	25965720.0	Gamma
FTOP	MOV	2007	0	3915720	5.62E-08	1.458	25965720.0	Gamma
FTOP	MOV	2008	1	3924480	9.46E-08	2.458	25974480.0	Gamma
FTOP	MOV	2009	0	3994560	5.60E-08	1.458	26044560.0	Gamma
FTOP	MOV	2010	1	3924480	9.46E-08	2.458	25974480.0	Gamma
FTOP	MOV	2011	0	4047120	5.59E-08	1.458	26097120.0	Gamma
FTOP	MOV	2012	1	3793080	9.51E-08	2.458	25843080.0	Gamma
FTOP	MOV	2013	1	3819360	9.50E-08	2.458	25869360.0	Gamma
FTR<1H	MDP	1998	1	1687	1.71E-04	2.820	16477.2	Gamma
FTR<1H	MDP	1999	2	1639	2.33E-04	3.820	16428.9	Gamma
FTR<1H	MDP	2000	1	1727	1.71E-04	2.820	16517.3	Gamma
FTR<1H	MDP	2001	0	1805	1.10E-04	1.820	16595.3	Gamma
FTR<1H	MDP	2002	2	1890	2.29E-04	3.820	16680.3	Gamma
FTR<1H	MDP	2003	0	2033	1.08E-04	1.820	16823.5	Gamma
FTR<1H	MDP	2004	1	2126	1.67E-04	2.820	16916.0	Gamma
FTR<1H	MDP	2005	2	2203	2.25E-04	3.820	16993.2	Gamma
FTR<1H	MDP	2006	0	1944	1.09E-04	1.820	16734.3	Gamma
FTR<1H	MDP	2007	1	2234	1.66E-04	2.820	17023.8	Gamma
FTR<1H	MDP	2008	0	1999	1.08E-04	1.820	16789.0	Gamma
FTR<1H	MDP	2009	0	1841	1.09E-04	1.820	16630.9	Gamma
FTR<1H	MDP	2010	1	2070	1.67E-04	2.820	16859.6	Gamma
FTR<1H	MDP	2011	0	2054	1.08E-04	1.820	16844.0	Gamma
FTR<1H	MDP	2012	0	1854	1.09E-04	1.820	16643.7	Gamma
FTR<1H	MDP	2013	2	2065	2.27E-04	3.820	16855.1	Gamma
FTR<1H	TDP	1998	2	1067	2.31E-03	2.962	1283.4	Gamma
FTR<1H	TDP	1999	3	975	3.32E-03	3.962	1191.6	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR<1H	TDP	2000	2	980	2.48E-03	2.962	1196.0	Gamma
FTR<1H	TDP	2001	4	913	4.39E-03	4.962	1129.2	Gamma
FTR<1H	TDP	2002	2	904	2.64E-03	2.962	1120.6	Gamma
FTR<1H	TDP	2003	7	975	6.68E-03	7.962	1191.4	Gamma
FTR<1H	TDP	2004	3	992	3.28E-03	3.962	1208.4	Gamma
FTR<1H	TDP	2005	1	981	1.64E-03	1.962	1197.0	Gamma
FTR<1H	TDP	2006	1	985	1.63E-03	1.962	1201.7	Gamma
FTR<1H	TDP	2007	2	961	2.51E-03	2.962	1177.7	Gamma
FTR<1H	TDP	2008	3	979	3.31E-03	3.962	1195.8	Gamma
FTR<1H	TDP	2009	4	1094	3.79E-03	4.962	1310.5	Gamma
FTR<1H	TDP	2010	2	1135	2.19E-03	2.962	1351.7	Gamma
FTR<1H	TDP	2011	1	1112	1.48E-03	1.962	1328.7	Gamma
FTR<1H	TDP	2012	2	1056	2.33E-03	2.962	1272.1	Gamma
FTR<1H	TDP	2013	0	1135	7.12E-04	0.962	1351.7	Gamma
FTR>1H	MDP	1998	1	5834	2.20E-05	1.781	80844.5	Gamma
FTR>1H	MDP	1999	0	9198	9.27E-06	0.781	84208.1	Gamma
FTR>1H	MDP	2000	0	6577	9.57E-06	0.781	81586.5	Gamma
FTR>1H	MDP	2001	5	9592	6.83E-05	5.781	84601.5	Gamma
FTR>1H	MDP	2002	0	7902	9.42E-06	0.781	82912.5	Gamma
FTR>1H	MDP	2003	2	10606	3.25E-05	2.781	85615.7	Gamma
FTR>1H	MDP	2004	0	9024	9.29E-06	0.781	84033.6	Gamma
FTR>1H	MDP	2005	1	7718	2.15E-05	1.781	82728.1	Gamma
FTR>1H	MDP	2006	0	7892	9.42E-06	0.781	82901.9	Gamma
FTR>1H	MDP	2007	0	9245	9.27E-06	0.781	84255.0	Gamma
FTR>1H	MDP	2008	0	6860	9.54E-06	0.781	81869.9	Gamma
FTR>1H	MDP	2009	0	7409	9.48E-06	0.781	82419.0	Gamma
FTR>1H	MDP	2010	0	8951	9.30E-06	0.781	83961.1	Gamma
FTR>1H	MDP	2011	0	8880	9.31E-06	0.781	83889.6	Gamma
FTR>1H	MDP	2012	0	8170	9.39E-06	0.781	83179.6	Gamma
FTR>1H	MDP	2013	1	8828	2.12E-05	1.781	83838.5	Gamma
FTR>1H	TDP	1998	2	328	1.74E-03	14.500	8355.3	Gamma
FTR>1H	TDP	1999	0	2472	1.19E-03	12.500	10499.7	Gamma
FTR>1H	TDP	2000	0	525	1.46E-03	12.500	8552.5	Gamma
FTR>1H	TDP	2001	1	480	1.59E-03	13.500	8508.0	Gamma
FTR>1H	TDP	2002	0	1162	1.36E-03	12.500	9189.9	Gamma
FTR>1H	TDP	2003	0	1394	1.33E-03	12.500	9422.1	Gamma
FTR>1H	TDP	2004	3	301	1.86E-03	15.500	8328.6	Gamma
FTR>1H	TDP	2005	1	214	1.64E-03	13.500	8242.0	Gamma
FTR>1H	TDP	2006	2	190	1.76E-03	14.500	8217.5	Gamma
FTR>1H	TDP	2007	0	211	1.52E-03	12.500	8238.4	Gamma
FTR>1H	TDP	2008	1	217	1.64E-03	13.500	8244.7	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR>1H	TDP	2009	0	203	1.52E-03	12.500	8230.3	Gamma
FTR>1H	TDP	2010	0	215	1.52E-03	12.500	8242.4	Gamma
FTR>1H	TDP	2011	2	354	1.73E-03	14.500	8381.3	Gamma
FTR>1H	TDP	2012	3	196	1.88E-03	15.500	8223.5	Gamma
FTR>1H	TDP	2013	1	233	1.63E-03	13.500	8260.6	Gamma
FTS	MDP	1998	4	1687	1.59E-03	5.948	3737.2	Beta
FTS	MDP	1999	5	1639	1.88E-03	6.948	3687.9	Beta
FTS	MDP	2000	3	1727	1.31E-03	4.948	3778.3	Beta
FTS	MDP	2001	3	1805	1.28E-03	4.948	3856.3	Beta
FTS	MDP	2002	0	1890	4.94E-04	1.948	3944.3	Beta
FTS	MDP	2003	4	2033	1.45E-03	5.948	4083.5	Beta
FTS	MDP	2004	0	2126	4.66E-04	1.948	4180.0	Beta
FTS	MDP	2005	3	2203	1.16E-03	4.948	4254.2	Beta
FTS	MDP	2006	4	1944	1.49E-03	5.948	3994.3	Beta
FTS	MDP	2007	4	2234	1.39E-03	5.948	4283.8	Beta
FTS	MDP	2008	0	1999	4.80E-04	1.948	4053.0	Beta
FTS	MDP	2009	1	1841	7.57E-04	2.948	3893.9	Beta
FTS	MDP	2010	1	2070	7.15E-04	2.948	4122.6	Beta
FTS	MDP	2011	2	2054	9.61E-04	3.948	4106.0	Beta
FTS	MDP	2012	3	1854	1.27E-03	4.948	3904.7	Beta
FTS	MDP	2013	4	2065	1.44E-03	5.948	4115.1	Beta
FTS	TDP	1998	1	1067	1.60E-03	1.942	1210.1	Beta
FTS	TDP	1999	6	975	6.20E-03	6.942	1113.3	Beta
FTS	TDP	2000	5	980	5.28E-03	5.942	1118.7	Beta
FTS	TDP	2001	3	913	3.73E-03	3.942	1053.9	Beta
FTS	TDP	2002	2	904	2.80E-03	2.942	1046.3	Beta
FTS	TDP	2003	5	975	5.31E-03	5.942	1114.1	Beta
FTS	TDP	2004	4	992	4.35E-03	4.942	1132.1	Beta
FTS	TDP	2005	4	981	4.39E-03	4.942	1120.7	Beta
FTS	TDP	2006	3	985	3.49E-03	3.942	1126.4	Beta
FTS	TDP	2007	4	961	4.47E-03	4.942	1101.4	Beta
FTS	TDP	2008	3	979	3.51E-03	3.942	1120.5	Beta
FTS	TDP	2009	10	1094	8.83E-03	10.942	1228.2	Beta
FTS	TDP	2010	4	1135	3.86E-03	4.942	1275.4	Beta
FTS	TDP	2011	4	1112	3.93E-03	4.942	1252.4	Beta
FTS	TDP	2012	2	1056	2.45E-03	2.942	1197.8	Beta
FTS	TDP	2013	1	1135	1.52E-03	1.942	1278.4	Beta
SO	AOV	1998	0	1673160	9.88E-08	0.680	6884160.0	Gamma
SO	AOV	1999	0	1673160	9.88E-08	0.680	6884160.0	Gamma
SO	AOV	2000	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	AOV	2001	1	1708200	2.43E-07	1.680	6919200.0	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	AOV	2002	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	AOV	2003	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2004	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2005	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2006	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	AOV	2007	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2008	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2009	1	1708200	2.43E-07	1.680	6919200.0	Gamma
SO	AOV	2010	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	AOV	2011	1	1778280	2.40E-07	1.680	6989280.0	Gamma
SO	AOV	2012	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	AOV	2013	0	1708200	9.83E-08	0.680	6919200.0	Gamma
SO	MOV	1998	1	3950760	7.55E-08	1.570	20790760.0	Gamma
SO	MOV	1999	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2000	1	3915720	7.57E-08	1.570	20755720.0	Gamma
SO	MOV	2001	1	3915720	7.57E-08	1.570	20755720.0	Gamma
SO	MOV	2002	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2003	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2004	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2005	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2006	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2007	0	3915720	2.75E-08	0.570	20755720.0	Gamma
SO	MOV	2008	0	3924480	2.75E-08	0.570	20764480.0	Gamma
SO	MOV	2009	0	3994560	2.74E-08	0.570	20834560.0	Gamma
SO	MOV	2010	0	3924480	2.75E-08	0.570	20764480.0	Gamma
SO	MOV	2011	0	4047120	2.73E-08	0.570	20887120.0	Gamma
SO	MOV	2012	0	3793080	2.76E-08	0.570	20633080.0	Gamma
SO	MOV	2013	0	3819360	2.76E-08	0.570	20659360.0	Gamma

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	MDP	1998	4180	655697	7.24E-03	0.594	81.5	Beta
UA	MDP	1999	4996	934480	5.15E-03	1.883	363.5	Beta
UA	MDP	2000	5146	963225	4.87E-03	1.315	268.4	Beta
UA	MDP	2001	4224	962348	4.39E-03	2.442	553.8	Beta
UA	MDP	2002	3818	988118	3.71E-03	2.621	703.7	Beta
UA	MDP	2003	4329	966360	4.03E-03	1.501	370.7	Beta
UA	MDP	2004	3885	990896	3.64E-03	2.315	633.9	Beta
UA	MDP	2005	3851	981394	3.68E-03	1.925	521.6	Beta
UA	MDP	2006	3495	993315	3.11E-03	1.287	412.6	Beta
UA	MDP	2007	3415	991570	3.31E-03	1.992	599.1	Beta
UA	MDP	2008	3667	988561	3.32E-03	1.218	365.9	Beta
UA	MDP	2009	2898	994989	2.61E-03	1.511	576.3	Beta
UA	MDP	2010	3144	976748	3.09E-03	1.782	574.3	Beta
UA	MDP	2011	3428	966489	3.43E-03	1.541	447.9	Beta
UA	MDP	2012	3376	926068	3.28E-03	0.939	285.2	Beta
UA	MDP	2013	3165	906883	3.20E-03	1.110	345.6	Beta
UA	TDP	1998	3025	350430	8.72E-03	0.941	107.0	Beta
UA	TDP	1999	2699	503558	5.42E-03	1.366	250.7	Beta
UA	TDP	2000	2766	516118	5.33E-03	1.743	325.0	Beta
UA	TDP	2001	3081	514966	6.14E-03	1.153	186.6	Beta
UA	TDP	2002	2423	517926	4.70E-03	2.019	427.8	Beta
UA	TDP	2003	3029	505485	6.01E-03	1.434	237.1	Beta
UA	TDP	2004	2993	521680	5.95E-03	1.486	248.2	Beta
UA	TDP	2005	2928	523076	5.68E-03	2.968	519.4	Beta
UA	TDP	2006	2832	525399	5.35E-03	1.226	228.0	Beta
UA	TDP	2007	2290	529216	4.35E-03	1.041	238.5	Beta
UA	TDP	2008	2413	526129	4.59E-03	1.402	304.1	Beta
UA	TDP	2009	2704	530917	5.09E-03	0.990	193.5	Beta
UA	TDP	2010	3222	508310	6.48E-03	1.291	198.0	Beta
UA	TDP	2011	2790	512711	5.52E-03	0.839	151.2	Beta
UA	TDP	2012	2340	495453	4.71E-03	0.894	189.0	Beta
UA	TDP	2013	2242	489741	4.60E-03	1.243	269.2	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTLR	Fail to load/run
FTOC	Fail to open/close
FTOP	Fail to operate
FTR	Fail to run
FTR<1H	Fail to run less than one hour (after start)
FTS	Fail to start
SO	Spurious operation
UA	Unavailability (maintenance or state of another component)

7. 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 effect 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[a]
Class 2	Prairie Island 2		1	1	1[a]
Class 2	Seabrook		1	1	1[b]
Class 3	Arkansas 2		1	1	1[b]
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	
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 3	St. Lucie 1		2	1	
Class 3	St. Lucie 2		2	1	
Class 3	Summer		2	1	
Class 3	Three Mile Island 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

a. Shares AFW pump with other unit.
b. Standby/Startup AFW pump.

8. REFERENCES

1. Nuclear Regulatory Commission, *Component Reliability Data Sheets Update 2010*, January 2012, http://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentReliabilityDataSheets2010.pdf

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