System Study: Auxiliary Feedwater 1998–2018

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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 calendar year 1998 through 2018 for selected components were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the 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
EDP	engine-driven pump
ESFAS	engineered safety features actuation system
FTOC	fail to open/close
FTOP	fail to operate
FTR	fail to run
FTR>1H	fail to run more than one hour (standby)
FTR<1H	fail to run less than one hour (after start)
FTS	fail to start
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
IRIS	Industry Reporting and Information System
MDP	motor-driven pump
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
ROP	Reactor Oversight Process
SO	spurious operation
SPAR	standardized plant analysis risk
SSU	safety system unavailability
TDP	turbine-driven pump
UA	unavailability (maintenance or state of another component)

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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 calendar year 1998 through 2018 for selected components in the AFW were obtained from the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS), formerly the INPO Consolidated Events Database (ICES) and the Equipment Performance and Information Exchange Database (EPIX). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process (ROP) Safety System Unavailability (SSU) database (1998 through 2001) and the Mitigating Systems Performance Index (MSPI) database (2002 through 2018). 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 2015 Component Reliability Update [1], which is an update to NUREG/CR-6928 [2] and the 2010 Component Reliability Update [3]. Baseline AFW unreliability results using basic event values from the 2010 Component Reliability Update[a] 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 1 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 and recovery events in the models are set to False in the study for the results to represent the mechanical part of the system. An overview of the trending methods, glossary of terms, and abbreviations can be found in the paper Overview and Reference [4] on the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/resultsdb/).

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

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[a] For comparison purposes, in order to keep the SPAR models and basic event data the same as those used in the previous (2016) AFW system study, the 2010 Component Reliability Update data is used here. The only variables subject to change in this analysis were the demand, run hours, failure, and unavailability data for selected components in the AFW system.

1

Table 1. AFW design class and SPAR model version 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 or decreasing trends were identified** in the AFW unreliability trend 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 contributors to AFW system unreliability are the **AFW MDP (motor-driven pump),** AFW TDP (turbine-driven pump), Pump Ends, and Injection groups of basic events.

- In the *8-Hour* case— the leading contributor to AFW system unreliability is the **AFW TDP** group of basic events followed by the AFW MDP, Recovery, Pump Ends, and Injection groups.

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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

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 (1998–2010).[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 unique 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	4.19E-07	7.50E-06	8.38E-05	5.01E-04
	Class 2	1.39E-06	5.24E-05	1.54E-04	6.53E-04
	Class 3	5.38E-07	5.94E-06	7.78E-05	5.04E-04
	Class 4	1.09E-07	1.02E-05	5.69E-05	3.23E-04
8-hour Mission	Industry	9.34E-07	1.10E-05	1.02E-04	5.10E-04
	Class 2	2.40E-06	6.55E-05	2.80E-04	1.31E-03
	Class 3	1.30E-06	9.58E-06	8.12E-05	5.06E-04
	Class 4	1.73E-07	1.04E-05	5.71E-05	3.21E-04

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

4
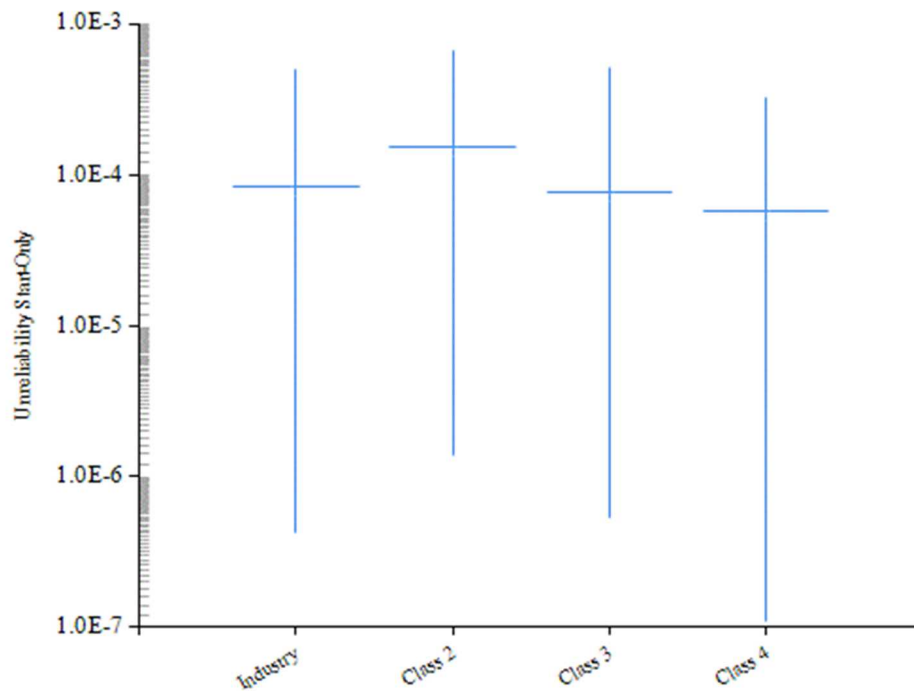
Figure 1. AFW start-only mission unreliability for Class 2, 3, and 4 and industry-wide groupings.
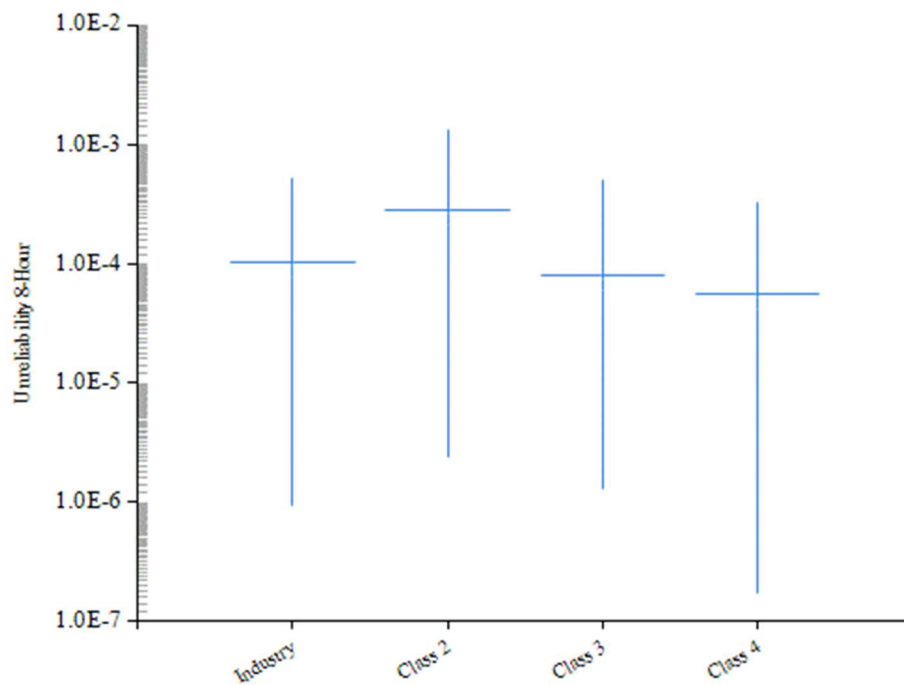
Figure 2. AFW 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly (1998 through 2018) 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 program 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 [4]. 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 (or constrained noninformative distributions, refer to Section 2 of the Overview and Reference document) 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 document 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 MDP start, run, and test and maintenance.

- AFW TDP 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 trend was identified** within the industry-wide estimates of AFW system start-only mission on a per fiscal year basis.

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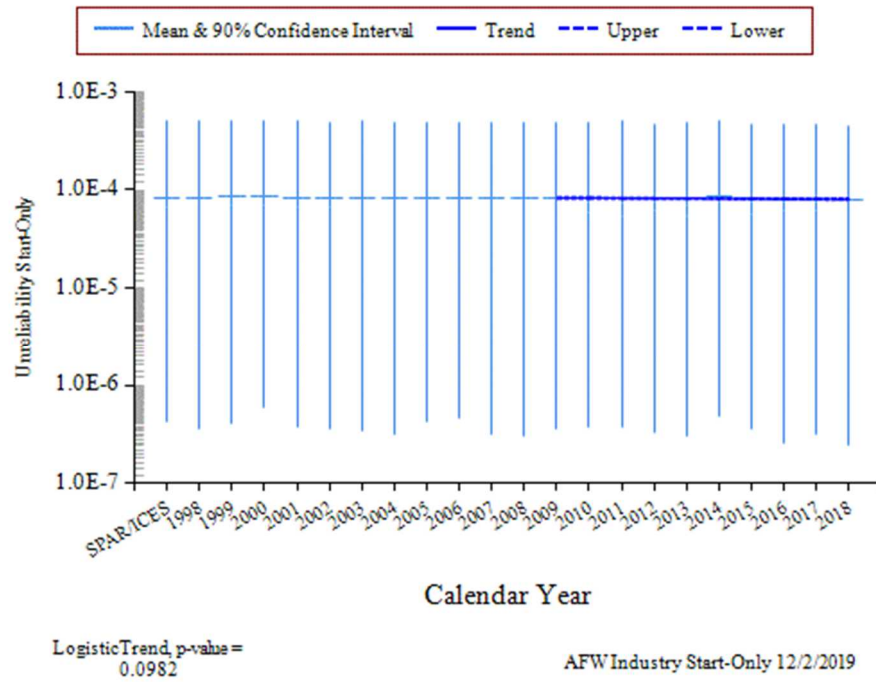
Figure 3. Trend of AFW system unreliability (start-only model).
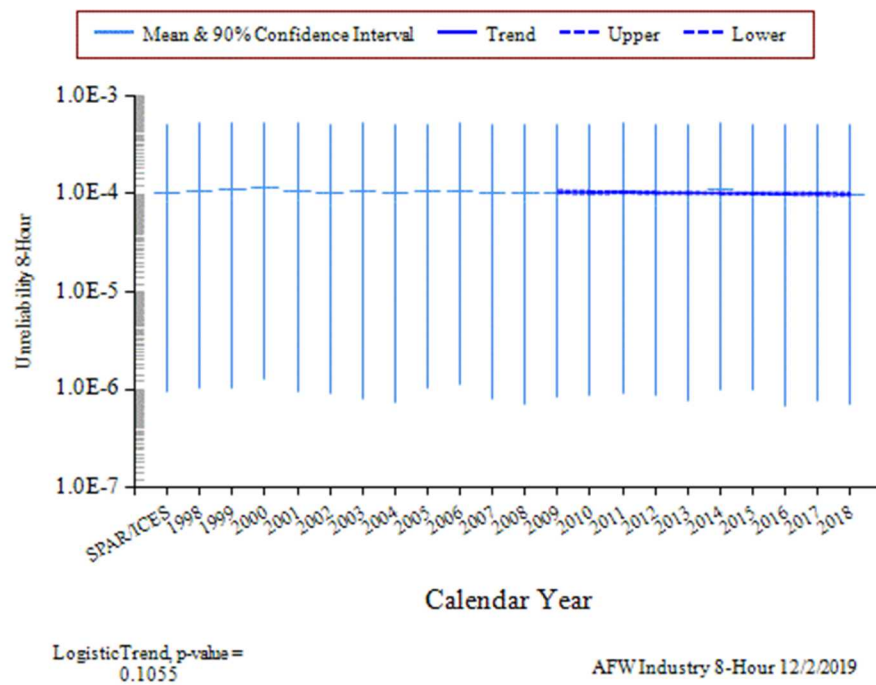
Figure 4. Trend of AFW system unreliability (8-hour model).

7

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 contributors to AFW system unreliability are the **AFW MDP,** AFW TDP, Pump Ends, and Injection groups of basic events.

- In the ***8-Hour*** case— the leading contributor to AFW system unreliability is the **AFW TDP** group of basic events followed by the AFW MDP, Pump Ends, and Injection groups.

For more discussion on the AFW motor/turbine-driven pumps, see the motor/turbine-driven pump component reliability studies at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/resultsdb/). Table 3 shows the SPAR model AFW importance groups and their descriptions.
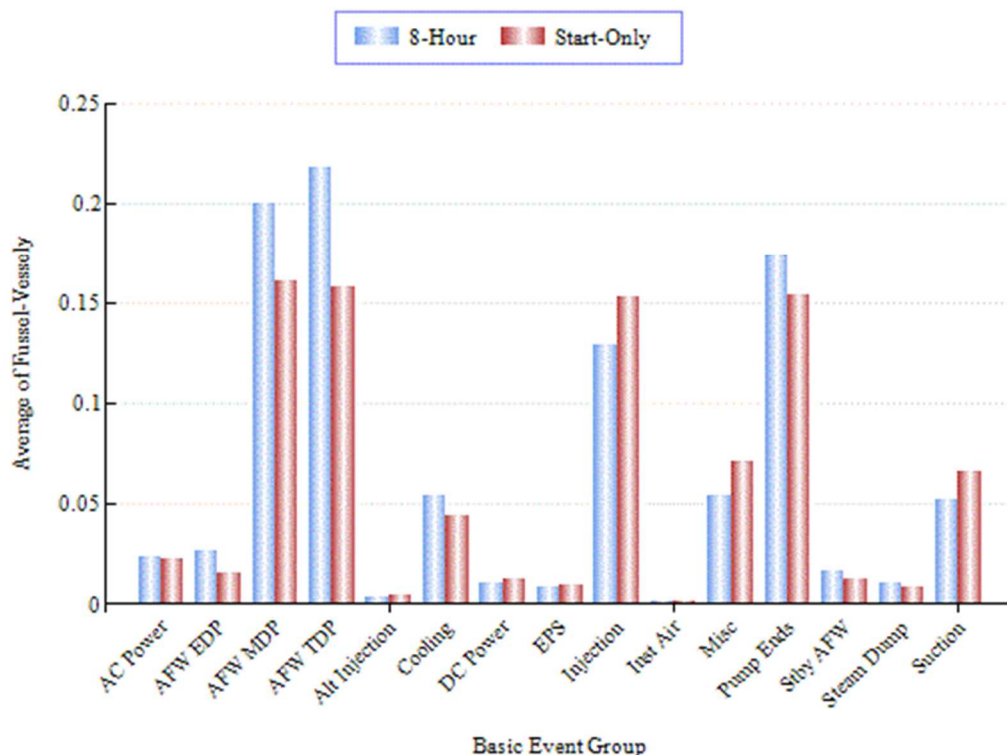
Figure 5. AFW industry-wide basic event group importances.

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 (EDPs). 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.
Miscellaneous	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.
Steam Dump	All basic events associated with the steam dump.
Stby AFW	Standby means of injecting water to the steam generators. Includes startup feedwater and cross-ties to adjacent units.
Suction	The motor-operated valves and air-operated valves in the tank suction path. Includes the failure of the tank.

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.
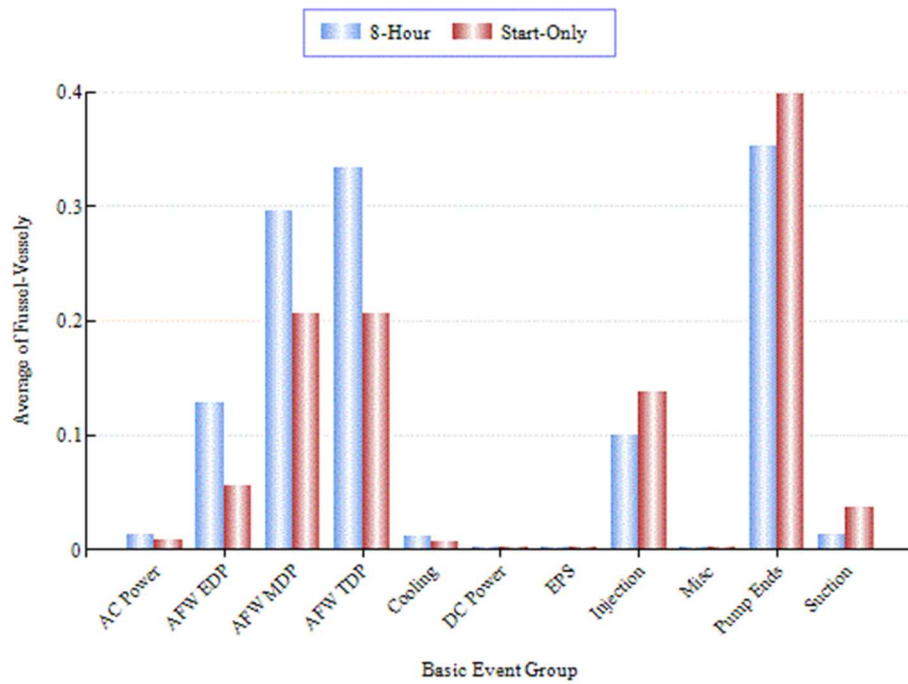
Figure 6. AFW Class 2 basic event group importances.
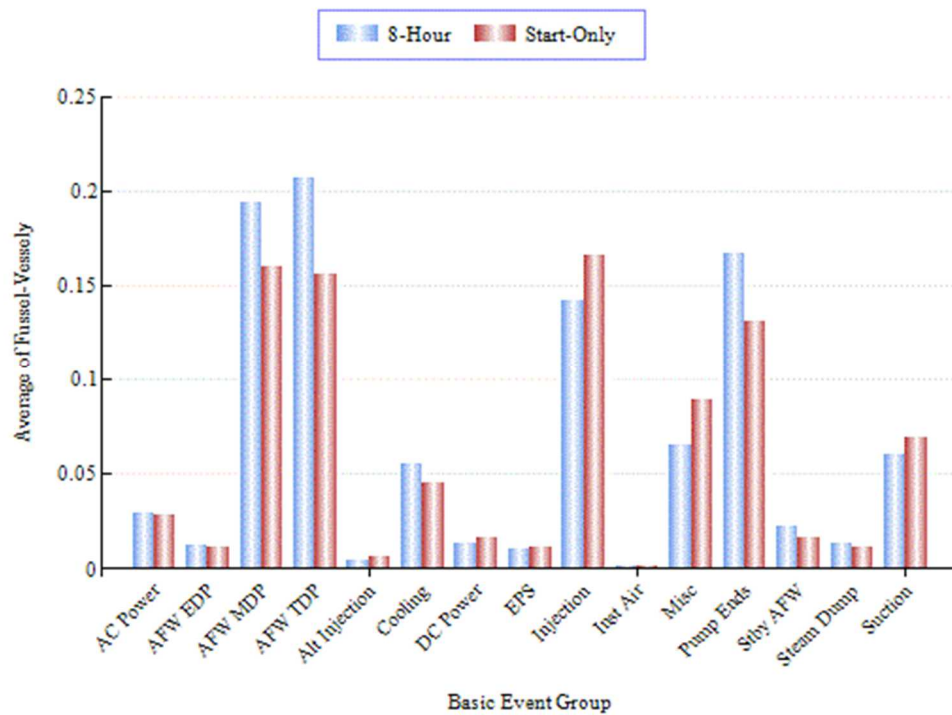
Figure 7. AFW Class 3 basic event group importances.

10
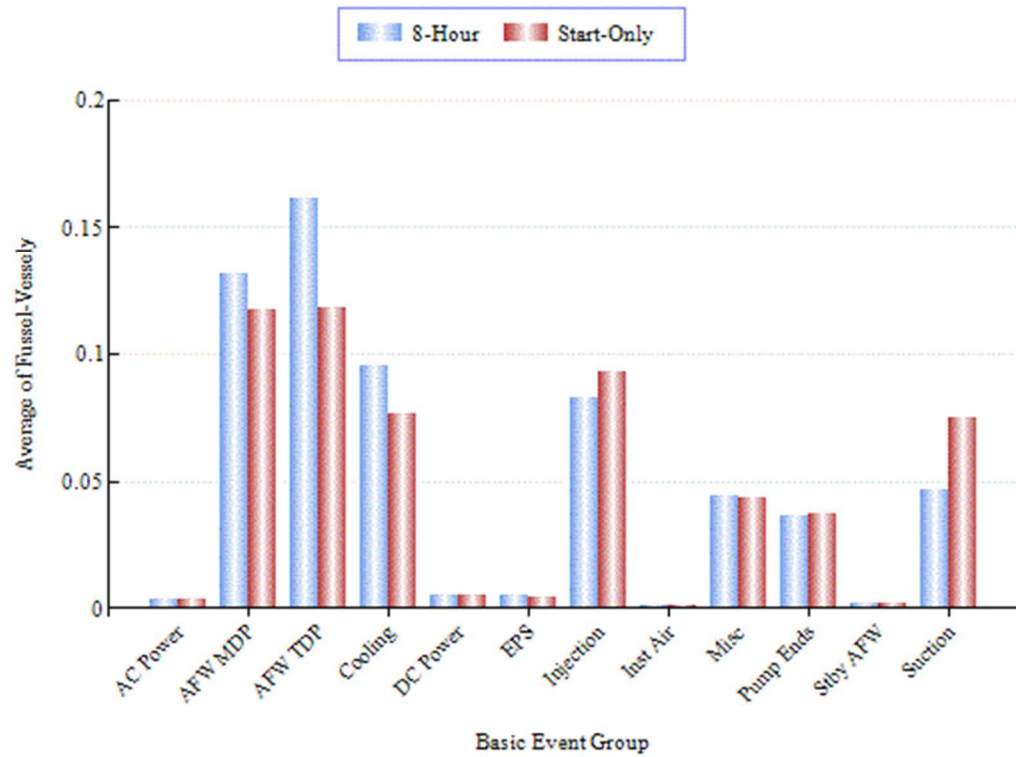
Figure 8. AFW Class 4 basic event group importances.

6. DATA TABLES

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

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	4.19E-07	8.38E-05	5.01E-04
1998	--	--	--	3.54E-07	8.32E-05	5.01E-04
1999	--	--	--	4.12E-07	8.48E-05	5.03E-04
2000	--	--	--	5.86E-07	8.73E-05	5.04E-04
2001	--	--	--	3.74E-07	8.29E-05	5.00E-04
2002	--	--	--	3.50E-07	8.16E-05	4.79E-04
2003	--	--	--	3.41E-07	8.20E-05	5.00E-04
2004	--	--	--	3.21E-07	8.16E-05	4.92E-04
2005	--	--	--	4.15E-07	8.28E-05	4.87E-04
2006	--	--	--	4.67E-07	8.36E-05	4.94E-04
2007	--	--	--	3.17E-07	8.15E-05	4.78E-04
2008	--	--	--	3.07E-07	8.16E-05	4.88E-04
2009	8.13E-05	8.32E-05	8.51E-05	3.62E-07	8.22E-05	4.78E-04
2010	8.13E-05	8.29E-05	8.45E-05	3.75E-07	8.27E-05	4.81E-04
2011	8.12E-05	8.26E-05	8.39E-05	3.79E-07	8.31E-05	5.01E-04
2012	8.11E-05	8.23E-05	8.34E-05	3.28E-07	8.15E-05	4.73E-04
2013	8.10E-05	8.20E-05	8.30E-05	3.00E-07	8.15E-05	4.76E-04
2014	8.07E-05	8.17E-05	8.27E-05	4.72E-07	8.50E-05	5.02E-04
2015	8.02E-05	8.14E-05	8.25E-05	3.59E-07	8.24E-05	4.70E-04
2016	7.98E-05	8.11E-05	8.24E-05	2.52E-07	7.95E-05	4.61E-04
2017	7.92E-05	8.08E-05	8.23E-05	3.15E-07	8.05E-05	4.64E-04
2018	7.87E-05	8.05E-05	8.23E-05	2.43E-07	7.98E-05	4.54E-04

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

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Lower (5%)	Mean		Lower (5%)	Mean	
SPAR/ICES	--	--	--	9.34E-07	1.02E-04	5.10E-04
1998	--	--	--	1.01E-06	1.06E-04	5.19E-04
1999	--	--	--	1.02E-06	1.09E-04	5.26E-04
2000	--	--	--	1.26E-06	1.13E-04	5.30E-04
2001	--	--	--	9.38E-07	1.05E-04	5.16E-04
2002	--	--	--	8.96E-07	1.03E-04	5.14E-04
2003	--	--	--	7.94E-07	1.04E-04	5.16E-04
2004	--	--	--	7.42E-07	1.03E-04	5.13E-04
2005	--	--	--	1.02E-06	1.04E-04	5.15E-04
2006	--	--	--	1.11E-06	1.06E-04	5.17E-04
2007	--	--	--	7.96E-07	1.02E-04	5.14E-04
2008	--	--	--	6.93E-07	1.02E-04	5.14E-04
2009	1.01E-04	1.05E-04	1.09E-04	8.38E-07	1.02E-04	5.12E-04
2010	1.01E-04	1.04E-04	1.07E-04	8.74E-07	1.03E-04	5.13E-04
2011	1.01E-04	1.03E-04	1.06E-04	9.15E-07	1.05E-04	5.16E-04
2012	1.01E-04	1.03E-04	1.05E-04	8.75E-07	1.01E-04	5.13E-04
2013	1.00E-04	1.02E-04	1.04E-04	7.48E-07	1.01E-04	5.12E-04
2014	9.96E-05	1.02E-04	1.04E-04	9.98E-07	1.09E-04	5.21E-04
2015	9.88E-05	1.01E-04	1.03E-04	9.64E-07	1.02E-04	5.12E-04
2016	9.79E-05	1.00E-04	1.03E-04	6.61E-07	9.82E-05	5.10E-04
2017	9.68E-05	9.99E-05	1.03E-04	7.60E-07	9.99E-05	5.11E-04
2018	9.57E-05	9.93E-05	1.03E-04	6.97E-07	9.73E-05	5.09E-04

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	4	1,883	1.67E-03	5.11	3.05E+03	Beta
FTOC	AOV	1999	0	2,263	3.24E-04	1.11	3.43E+03	Beta
FTOC	AOV	2000	0	1,845	3.69E-04	1.11	3.01E+03	Beta
FTOC	AOV	2001	3	2,031	1.28E-03	4.11	3.20E+03	Beta
FTOC	AOV	2002	1	2,307	6.08E-04	2.11	3.47E+03	Beta
FTOC	AOV	2003	0	2,114	3.39E-04	1.11	3.28E+03	Beta
FTOC	AOV	2004	0	2,081	3.42E-04	1.11	3.25E+03	Beta
FTOC	AOV	2005	2	2,095	9.53E-04	3.11	3.26E+03	Beta
FTOC	AOV	2006	2	1,831	1.04E-03	3.11	3.00E+03	Beta
FTOC	AOV	2007	0	1,738	3.83E-04	1.11	2.91E+03	Beta
FTOC	AOV	2008	0	1,676	3.91E-04	1.11	2.84E+03	Beta
FTOC	AOV	2009	1	1,650	7.49E-04	2.11	2.82E+03	Beta
FTOC	AOV	2010	1	1,670	7.44E-04	2.11	2.84E+03	Beta
FTOC	AOV	2011	0	1,688	3.89E-04	1.11	2.86E+03	Beta
FTOC	AOV	2012	1	1,725	7.30E-04	2.11	2.89E+03	Beta
FTOC	AOV	2013	0	1,712	3.86E-04	1.11	2.88E+03	Beta
FTOC	AOV	2014	0	1,561	4.07E-04	1.11	2.73E+03	Beta
FTOC	AOV	2015	2	1,667	1.10E-03	3.11	2.83E+03	Beta
FTOC	AOV	2016	0	1,500	4.17E-04	1.11	2.67E+03	Beta
FTOC	AOV	2017	0	1,538	4.11E-04	1.11	2.71E+03	Beta
FTOC	AOV	2018	2	1,504	1.16E-03	3.11	2.67E+03	Beta
FTOP	AOV	1998	0	1,568,040	1.95E-07	1.42	7.29E+06	Gamma
FTOP	AOV	1999	0	1,568,040	1.95E-07	1.42	7.29E+06	Gamma
FTOP	AOV	2000	1	1,603,080	3.31E-07	2.42	7.32E+06	Gamma
FTOP	AOV	2001	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2002	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2003	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2004	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2005	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2006	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2007	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2008	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2009	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2010	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2011	0	1,708,200	1.91E-07	1.42	7.43E+06	Gamma
FTOP	AOV	2012	0	1,638,120	1.93E-07	1.42	7.36E+06	Gamma
FTOP	AOV	2013	3	1,638,120	6.01E-07	4.42	7.36E+06	Gamma
FTOP	AOV	2014	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2015	0	1,603,080	1.94E-07	1.42	7.32E+06	Gamma
FTOP	AOV	2016	1	1,568,040	3.32E-07	2.42	7.29E+06	Gamma

System
 Study
Auxiliary Feedwater

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update Mean	Post A	Post B	Distribution
FTOP	AOV	2017	0	1,568,040	1.95E-07	1.42	7.29E+06	Gamma
FTOP	AOV	2018	0	1,559,280	1.95E-07	1.42	7.28E+06	Gamma
SO	AOV	1998	0	1,568,040	1.00E-07	0.68	6.78E+06	Gamma
SO	AOV	1999	0	1,568,040	1.00E-07	0.68	6.78E+06	Gamma
SO	AOV	2000	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2001	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2002	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2003	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2004	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2005	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2006	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2007	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2008	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2009	1	1,603,080	2.47E-07	1.68	6.81E+06	Gamma
SO	AOV	2010	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2011	0	1,708,200	9.83E-08	0.68	6.92E+06	Gamma
SO	AOV	2012	0	1,638,120	9.93E-08	0.68	6.85E+06	Gamma
SO	AOV	2013	0	1,638,120	9.93E-08	0.68	6.85E+06	Gamma
SO	AOV	2014	0	1,603,080	9.98E-08	0.68	6.81E+06	Gamma
SO	AOV	2015	2	1,603,080	3.93E-07	2.68	6.81E+06	Gamma
SO	AOV	2016	0	1,568,040	1.00E-07	0.68	6.78E+06	Gamma
SO	AOV	2017	1	1,568,040	2.48E-07	1.68	6.78E+06	Gamma
SO	AOV	2018	0	1,559,280	1.00E-07	0.68	6.77E+06	Gamma
FTR>1H	MDP	1998	1	7,198	2.17E-05	1.78	8.22E+04	Gamma
FTR>1H	MDP	1999	0	8,158	9.39E-06	0.78	8.32E+04	Gamma
FTR>1H	MDP	2000	0	8,660	9.33E-06	0.78	8.37E+04	Gamma
FTR>1H	MDP	2001	4	7,862	5.77E-05	4.78	8.29E+04	Gamma
FTR>1H	MDP	2002	0	8,539	9.35E-06	0.78	8.35E+04	Gamma
FTR>1H	MDP	2003	2	9,660	3.28E-05	2.78	8.47E+04	Gamma
FTR>1H	MDP	2004	0	9,013	9.30E-06	0.78	8.40E+04	Gamma
FTR>1H	MDP	2005	0	7,940	9.42E-06	0.78	8.30E+04	Gamma
FTR>1H	MDP	2006	0	8,309	9.37E-06	0.78	8.33E+04	Gamma
FTR>1H	MDP	2007	0	8,050	9.40E-06	0.78	8.31E+04	Gamma
FTR>1H	MDP	2008	0	7,586	9.46E-06	0.78	8.26E+04	Gamma
FTR>1H	MDP	2009	0	8,332	9.37E-06	0.78	8.33E+04	Gamma
FTR>1H	MDP	2010	0	7,946	9.41E-06	0.78	8.30E+04	Gamma
FTR>1H	MDP	2011	0	9,863	9.20E-06	0.78	8.49E+04	Gamma
FTR>1H	MDP	2012	0	8,445	9.36E-06	0.78	8.35E+04	Gamma
FTR>1H	MDP	2013	3	7,909	4.56E-05	3.78	8.29E+04	Gamma
FTR>1H	MDP	2014	0	8,194	9.39E-06	0.78	8.32E+04	Gamma
FTR>1H	MDP	2015	2	8,739	3.32E-05	2.78	8.37E+04	Gamma

15

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR>1H	MDP	2016	1	8,419	2.13E-05	1.78	8.34E+04	Gamma
FTR>1H	MDP	2017	0	7,177	9.50E-06	0.78	8.22E+04	Gamma
FTR>1H	MDP	2018	0	7,697	9.44E-06	0.78	8.27E+04	Gamma
FTR<1H	MDP	1998	1	1,755	1.70E-04	2.82	1.65E+04	Gamma
FTR<1H	MDP	1999	1	1,655	1.71E-04	2.82	1.64E+04	Gamma
FTR<1H	MDP	2000	1	1,828	1.70E-04	2.82	1.66E+04	Gamma
FTR<1H	MDP	2001	1	1,732	1.71E-04	2.82	1.65E+04	Gamma
FTR<1H	MDP	2002	0	1,991	1.08E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2003	0	2,102	1.08E-04	1.82	1.69E+04	Gamma
FTR<1H	MDP	2004	1	1,986	1.68E-04	2.82	1.68E+04	Gamma
FTR<1H	MDP	2005	2	2,219	2.25E-04	3.82	1.70E+04	Gamma
FTR<1H	MDP	2006	1	2,081	1.67E-04	2.82	1.69E+04	Gamma
FTR<1H	MDP	2007	0	1,969	1.09E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2008	0	2,090	1.08E-04	1.82	1.69E+04	Gamma
FTR<1H	MDP	2009	0	1,997	1.08E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2010	1	1,879	1.69E-04	2.82	1.67E+04	Gamma
FTR<1H	MDP	2011	0	2,189	1.07E-04	1.82	1.70E+04	Gamma
FTR<1H	MDP	2012	0	2,013	1.08E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2013	2	1,942	2.28E-04	3.82	1.67E+04	Gamma
FTR<1H	MDP	2014	0	1,965	1.09E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2015	0	2,000	1.08E-04	1.82	1.68E+04	Gamma
FTR<1H	MDP	2016	0	1,841	1.09E-04	1.82	1.66E+04	Gamma
FTR<1H	MDP	2017	0	1,903	1.09E-04	1.82	1.67E+04	Gamma
FTR<1H	MDP	2018	0	1,847	1.09E-04	1.82	1.66E+04	Gamma
FTS	MDP	1998	3	1,755	1.30E-03	4.95	3.81E+03	Beta
FTS	MDP	1999	4	1,655	1.60E-03	5.95	3.71E+03	Beta
FTS	MDP	2000	5	1,828	1.79E-03	6.95	3.88E+03	Beta
FTS	MDP	2001	1	1,732	7.78E-04	2.95	3.78E+03	Beta
FTS	MDP	2002	3	1,991	1.22E-03	4.95	4.04E+03	Beta
FTS	MDP	2003	1	2,102	7.09E-04	2.95	4.16E+03	Beta
FTS	MDP	2004	0	1,986	4.82E-04	1.95	4.04E+03	Beta
FTS	MDP	2005	4	2,219	1.39E-03	5.95	4.27E+03	Beta
FTS	MDP	2006	5	2,081	1.68E-03	6.95	4.13E+03	Beta
FTS	MDP	2007	2	1,969	9.81E-04	3.95	4.02E+03	Beta
FTS	MDP	2008	0	2,090	4.70E-04	1.95	4.14E+03	Beta
FTS	MDP	2009	1	1,997	7.27E-04	2.95	4.05E+03	Beta
FTS	MDP	2010	1	1,879	7.49E-04	2.95	3.93E+03	Beta
FTS	MDP	2011	3	2,189	1.17E-03	4.95	4.24E+03	Beta
FTS	MDP	2012	4	2,013	1.46E-03	5.95	4.06E+03	Beta
FTS	MDP	2013	1	1,942	7.37E-04	2.95	3.99E+03	Beta
FTS	MDP	2014	2	1,965	9.82E-04	3.95	4.02E+03	Beta

16

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	MDP	2015	4	2,000	1.47E-03	5.95	4.05E+03	Beta
FTS	MDP	2016	1	1,841	7.56E-04	2.95	3.89E+03	Beta
FTS	MDP	2017	2	1,903	9.97E-04	3.95	3.95E+03	Beta
FTS	MDP	2018	1	1,847	7.55E-04	2.95	3.90E+03	Beta
FTOC	MOV	1998	2	3,366	7.37E-04	4.05	5.49E+03	Beta
FTOC	MOV	1999	7	3,502	1.61E-03	9.05	5.62E+03	Beta
FTOC	MOV	2000	7	3,525	1.60E-03	9.05	5.64E+03	Beta
FTOC	MOV	2001	4	3,302	1.11E-03	6.05	5.42E+03	Beta
FTOC	MOV	2002	1	3,524	5.39E-04	3.05	5.65E+03	Beta
FTOC	MOV	2003	1	3,721	5.21E-04	3.05	5.84E+03	Beta
FTOC	MOV	2004	1	3,666	5.26E-04	3.05	5.79E+03	Beta
FTOC	MOV	2005	2	3,470	7.23E-04	4.05	5.59E+03	Beta
FTOC	MOV	2006	1	3,362	5.55E-04	3.05	5.48E+03	Beta
FTOC	MOV	2007	2	3,333	7.41E-04	4.05	5.45E+03	Beta
FTOC	MOV	2008	1	3,389	5.52E-04	3.05	5.51E+03	Beta
FTOC	MOV	2009	5	3,376	1.28E-03	7.05	5.49E+03	Beta
FTOC	MOV	2010	5	3,350	1.29E-03	7.05	5.47E+03	Beta
FTOC	MOV	2011	4	3,386	1.10E-03	6.05	5.50E+03	Beta
FTOC	MOV	2012	0	3,331	3.75E-04	2.05	5.45E+03	Beta
FTOC	MOV	2013	3	3,339	9.23E-04	5.05	5.46E+03	Beta
FTOC	MOV	2014	4	3,411	1.09E-03	6.05	5.53E+03	Beta
FTOC	MOV	2015	4	3,334	1.11E-03	6.05	5.45E+03	Beta
FTOC	MOV	2016	2	3,300	7.46E-04	4.05	5.42E+03	Beta
FTOC	MOV	2017	0	3,260	3.80E-04	2.05	5.38E+03	Beta
FTOC	MOV	2018	1	3,269	5.65E-04	3.05	5.39E+03	Beta
FTOP	MOV	1998	0	3,731,760	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	1999	0	3,696,720	5.66E-08	1.46	2.57E+07	Gamma
FTOP	MOV	2000	1	3,696,720	9.55E-08	2.46	2.57E+07	Gamma
FTOP	MOV	2001	0	3,705,480	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2002	1	3,714,240	9.54E-08	2.46	2.58E+07	Gamma
FTOP	MOV	2003	1	3,714,240	9.54E-08	2.46	2.58E+07	Gamma
FTOP	MOV	2004	0	3,714,240	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2005	0	3,714,240	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2006	0	3,731,760	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2007	0	3,714,240	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2008	1	3,731,760	9.53E-08	2.46	2.58E+07	Gamma
FTOP	MOV	2009	0	3,731,760	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2010	1	3,731,760	9.53E-08	2.46	2.58E+07	Gamma
FTOP	MOV	2011	0	3,854,400	5.63E-08	1.46	2.59E+07	Gamma
FTOP	MOV	2012	1	3,758,040	9.52E-08	2.46	2.58E+07	Gamma
FTOP	MOV	2013	1	3,740,520	9.53E-08	2.46	2.58E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update Mean	Bayesian Update Post A	Bayesian Update Post B	Distribution
FTOP	MOV	2014	0	3,766,800	5.65E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2015	0	3,714,240	5.66E-08	1.46	2.58E+07	Gamma
FTOP	MOV	2016	0	3,679,200	5.67E-08	1.46	2.57E+07	Gamma
FTOP	MOV	2017	0	3,644,160	5.67E-08	1.46	2.57E+07	Gamma
FTOP	MOV	2018	1	3,644,160	9.57E-08	2.46	2.57E+07	Gamma
SO	MOV	1998	1	3,731,760	7.63E-08	1.57	2.06E+07	Gamma
SO	MOV	1999	0	3,696,720	2.78E-08	0.57	2.05E+07	Gamma
SO	MOV	2000	1	3,696,720	7.65E-08	1.57	2.05E+07	Gamma
SO	MOV	2001	1	3,705,480	7.64E-08	1.57	2.05E+07	Gamma
SO	MOV	2002	0	3,714,240	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2003	0	3,714,240	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2004	0	3,714,240	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2005	0	3,714,240	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2006	0	3,731,760	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2007	0	3,714,240	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2008	0	3,731,760	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2009	0	3,731,760	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2010	0	3,731,760	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2011	0	3,854,400	2.76E-08	0.57	2.07E+07	Gamma
SO	MOV	2012	0	3,758,040	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2013	0	3,740,520	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2014	0	3,766,800	2.77E-08	0.57	2.06E+07	Gamma
SO	MOV	2015	1	3,714,240	7.64E-08	1.57	2.06E+07	Gamma
SO	MOV	2016	0	3,679,200	2.78E-08	0.57	2.05E+07	Gamma
SO	MOV	2017	0	3,644,160	2.78E-08	0.57	2.05E+07	Gamma
SO	MOV	2018	0	3,644,160	2.78E-08	0.57	2.05E+07	Gamma
FTR>1H	TDP	1998	0	2,018	1.24E-03	12.5	1.00E+04	Gamma
FTR>1H	TDP	1999	1	951	1.50E-03	13.5	8.98E+03	Gamma
FTR>1H	TDP	2000	1	418	1.60E-03	13.5	8.45E+03	Gamma
FTR>1H	TDP	2001	1	448	1.59E-03	13.5	8.48E+03	Gamma
FTR>1H	TDP	2002	0	1,073	1.37E-03	12.5	9.10E+03	Gamma
FTR>1H	TDP	2003	1	1,398	1.43E-03	13.5	9.43E+03	Gamma
FTR>1H	TDP	2004	3	301	1.86E-03	15.5	8.33E+03	Gamma
FTR>1H	TDP	2005	3	190	1.89E-03	15.5	8.22E+03	Gamma
FTR>1H	TDP	2006	0	188	1.52E-03	12.5	8.22E+03	Gamma
FTR>1H	TDP	2007	0	203	1.52E-03	12.5	8.23E+03	Gamma
FTR>1H	TDP	2008	1	226	1.64E-03	13.5	8.25E+03	Gamma
FTR>1H	TDP	2009	0	195	1.52E-03	12.5	8.22E+03	Gamma
FTR>1H	TDP	2010	0	198	1.52E-03	12.5	8.23E+03	Gamma
FTR>1H	TDP	2011	2	365	1.73E-03	14.5	8.39E+03	Gamma
FTR>1H	TDP	2012	3	185	1.89E-03	15.5	8.21E+03	Gamma

18

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR>1H	TDP	2013	1	229	1.64E-03	13.5	8.26E+03	Gamma
FTR>1H	TDP	2014	2	250	1.75E-03	14.5	8.28E+03	Gamma
FTR>1H	TDP	2015	2	228	1.76E-03	14.5	8.26E+03	Gamma
FTR>1H	TDP	2016	0	294	1.50E-03	12.5	8.32E+03	Gamma
FTR>1H	TDP	2017	1	267	1.63E-03	13.5	8.29E+03	Gamma
FTR>1H	TDP	2018	2	157	1.77E-03	14.5	8.19E+03	Gamma
FTR<1H	TDP	1998	2	1,049	2.34E-03	2.96	1.27E+03	Gamma
FTR<1H	TDP	1999	2	1,013	2.41E-03	2.96	1.23E+03	Gamma
FTR<1H	TDP	2000	4	937	4.30E-03	4.96	1.15E+03	Gamma
FTR<1H	TDP	2001	3	915	3.50E-03	3.96	1.13E+03	Gamma
FTR<1H	TDP	2002	4	934	4.31E-03	4.96	1.15E+03	Gamma
FTR<1H	TDP	2003	6	963	5.90E-03	6.96	1.18E+03	Gamma
FTR<1H	TDP	2004	0	970	8.11E-04	0.96	1.19E+03	Gamma
FTR<1H	TDP	2005	1	960	1.67E-03	1.96	1.18E+03	Gamma
FTR<1H	TDP	2006	2	974	2.49E-03	2.96	1.19E+03	Gamma
FTR<1H	TDP	2007	2	917	2.61E-03	2.96	1.13E+03	Gamma
FTR<1H	TDP	2008	2	977	2.48E-03	2.96	1.19E+03	Gamma
FTR<1H	TDP	2009	4	1,089	3.80E-03	4.96	1.30E+03	Gamma
FTR<1H	TDP	2010	2	1,100	2.25E-03	2.96	1.32E+03	Gamma
FTR<1H	TDP	2011	2	1,100	2.25E-03	2.96	1.32E+03	Gamma
FTR<1H	TDP	2012	0	1,015	7.81E-04	0.96	1.23E+03	Gamma
FTR<1H	TDP	2013	0	1,057	7.55E-04	0.96	1.27E+03	Gamma
FTR<1H	TDP	2014	1	1,039	1.56E-03	1.96	1.26E+03	Gamma
FTR<1H	TDP	2015	3	1,081	3.05E-03	3.96	1.30E+03	Gamma
FTR<1H	TDP	2016	1	1,024	1.58E-03	1.96	1.24E+03	Gamma
FTR<1H	TDP	2017	0	1,013	7.82E-04	0.96	1.23E+03	Gamma
FTR<1H	TDP	2018	1	987	1.63E-03	1.96	1.20E+03	Gamma
FTS	TDP	1998	0	1,049	7.89E-04	0.94	1.19E+03	Beta
FTS	TDP	1999	2	1,013	2.54E-03	2.94	1.15E+03	Beta
FTS	TDP	2000	6	937	6.41E-03	6.94	1.08E+03	Beta
FTS	TDP	2001	2	915	2.78E-03	2.94	1.06E+03	Beta
FTS	TDP	2002	2	934	2.73E-03	2.94	1.08E+03	Beta
FTS	TDP	2003	4	963	4.46E-03	4.94	1.10E+03	Beta
FTS	TDP	2004	5	970	5.33E-03	5.94	1.11E+03	Beta
FTS	TDP	2005	3	960	3.57E-03	3.94	1.10E+03	Beta
FTS	TDP	2006	4	974	4.42E-03	4.94	1.11E+03	Beta
FTS	TDP	2007	3	917	3.71E-03	3.94	1.06E+03	Beta
FTS	TDP	2008	6	977	6.19E-03	6.94	1.12E+03	Beta
FTS	TDP	2009	6	1,089	5.63E-03	6.94	1.23E+03	Beta
FTS	TDP	2010	5	1,100	4.77E-03	5.94	1.24E+03	Beta
FTS	TDP	2011	4	1,100	3.97E-03	4.94	1.24E+03	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	TDP	2012	2	1,015	2.54E-03	2.94	1.16E+03	Beta
FTS	TDP	2013	4	1,057	4.11E-03	4.94	1.20E+03	Beta
FTS	TDP	2014	11	1,039	1.01E-02	11.94	1.17E+03	Beta
FTS	TDP	2015	2	1,081	2.40E-03	2.94	1.22E+03	Beta
FTS	TDP	2016	2	1,024	2.52E-03	2.94	1.17E+03	Beta
FTS	TDP	2017	4	1,013	4.27E-03	4.94	1.15E+03	Beta
FTS	TDP	2018	1	987	1.72E-03	1.94	1.13E+03	Beta

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	4,065	886,803	4.54E-03	1.26	275.95	Beta
UA	MDP	1999	5,124	935,811	5.13E-03	1.27	247.3	Beta
UA	MDP	2000	4,991	956,723	4.90E-03	2.24	454.8	Beta
UA	MDP	2001	4,092	971,171	4.29E-03	2.33	539.44	Beta
UA	MDP	2002	3,728	988,885	3.55E-03	2.1	589.16	Beta
UA	MDP	2003	4,326	961,833	4.03E-03	1.6	396.27	Beta
UA	MDP	2004	3,794	997,678	3.62E-03	3.11	856.53	Beta
UA	MDP	2005	3,583	983,670	3.30E-03	1.49	450.1	Beta
UA	MDP	2006	3,682	979,451	3.42E-03	1.52	442	Beta
UA	MDP	2007	3,568	1,005,597	3.32E-03	1.43	429.34	Beta
UA	MDP	2008	3,528	985,161	3.31E-03	1.14	342.05	Beta
UA	MDP	2009	2,895	978,472	2.65E-03	1.24	467.54	Beta
UA	MDP	2010	3,082	998,184	2.96E-03	1.74	586.67	Beta
UA	MDP	2011	3,608	957,227	3.65E-03	1.52	414.77	Beta
UA	MDP	2012	3,013	906,185	2.91E-03	1.14	391.25	Beta
UA	MDP	2013	3,118	914,122	3.05E-03	1.41	460.6	Beta
UA	MDP	2014	3,440	914,596	3.38E-03	0.79	233.81	Beta
UA	MDP	2015	2,649	911,694	2.70E-03	1.65	610.92	Beta
UA	MDP	2016	2,305	929,234	2.42E-03	1.1	452.74	Beta
UA	MDP	2017	2,520	916,344	2.52E-03	1.52	602.31	Beta
UA	MDP	2018	2,345	916,755	2.39E-03	1.87	781.02	Beta
UA	TDP	1998	3,009	475,481	6.17E-03	1.17	189.18	Beta
UA	TDP	1999	2,630	503,402	5.17E-03	1.62	311.22	Beta
UA	TDP	2000	2,781	512,807	5.91E-03	1.39	234.36	Beta
UA	TDP	2001	2,957	520,529	5.83E-03	1.2	204.6	Beta
UA	TDP	2002	2,441	514,211	4.80E-03	1.6	332.67	Beta
UA	TDP	2003	3,146	501,991	6.29E-03	1.35	213.9	Beta
UA	TDP	2004	3,079	529,086	6.06E-03	1.46	238.86	Beta
UA	TDP	2005	2,692	523,052	5.27E-03	1.29	243.62	Beta
UA	TDP	2006	2,649	519,333	5.11E-03	1.25	243.98	Beta
UA	TDP	2007	2,459	536,572	4.61E-03	0.85	184.1	Beta
UA	TDP	2008	2,538	524,396	4.85E-03	1.55	317.36	Beta
UA	TDP	2009	2,581	520,595	4.95E-03	0.87	175.42	Beta
UA	TDP	2010	3,151	519,882	6.07E-03	1.23	201.17	Beta
UA	TDP	2011	3,014	506,966	6.15E-03	0.71	114.46	Beta
UA	TDP	2012	2,106	489,026	4.02E-03	1.15	285.29	Beta
UA	TDP	2013	2,408	493,017	4.63E-03	0.88	188.45	Beta
UA	TDP	2014	2,691	495,480	5.57E-03	0.63	113	Beta
UA	TDP	2015	2,098	496,565	4.19E-03	0.87	206.74	Beta

Table 7. (continued).

Failure	Component	Year	UA	Critical		Bayesian Update		
UA	TDP	2016	2,208	502,560	4.26E-03	1.15	268.45	Beta
UA	TDP	2017	2,066	495,582	4.03E-03	1.44	356.25	Beta
UA	TDP	2018	1,760	495,532	3.56E-03	0.9	253.3	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTOC	Fail to open/close
FTOP	Fail to operate
FTR	Fail to run
FTR>1H	Fail to run more than one hour (standby)
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 and pressure. At this temperature and pressure, 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. Figure 9 shows a simplified generic AFW system diagram.

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

23

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.
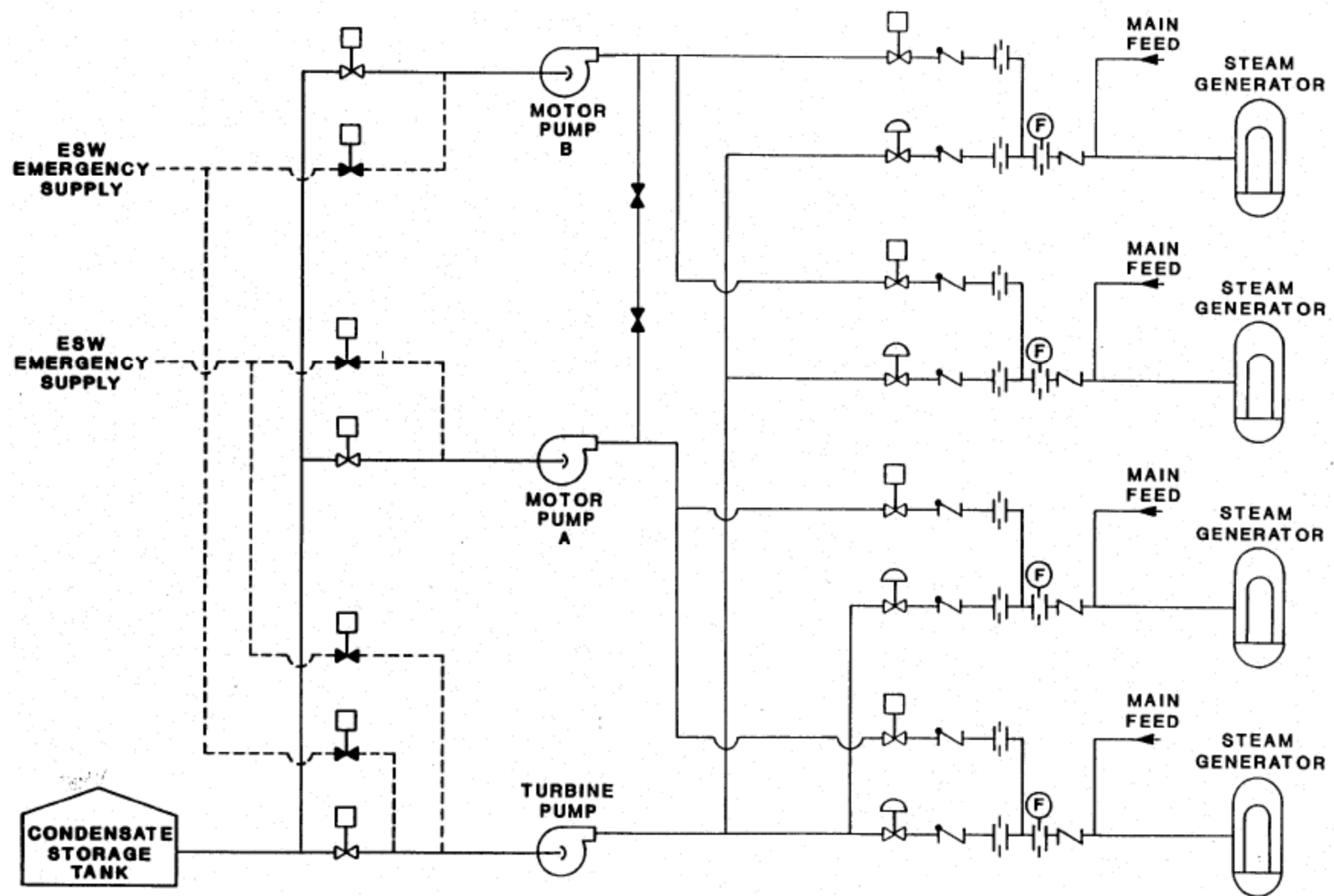
Figure 9. Simplified generic AFW system diagram.

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

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