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System Study: Auxiliary Feedwater 1998–2020

March 2022

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ABSTRACT

This report presents an unreliability evaluation of the auxiliary feedwater (AFW) system at 69 U.S. commercial nuclear reactors. Demand, run hour, and failure data from calendar year 1998–2020 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. Statistically significant decreasing trends were identified in the industry-wide estimates of AFW system start-only unreliability and AFW system 8-hour mission unreliability.

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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>1H	fail to run more than one hour (standby equipment)
FTR<1H	fail to run less than one hour (after start; standby equipment)
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 reactors listed in Table 1. For each reactor (or plant), the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 1) was used in the yearly calculations. Demand, run hour, and failure data from calendar year 1998–2020 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 (1998–2001) and the Mitigating Systems Performance Index (MSPI) database (2002–2020). 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 *2020 Component Reliability Update* documented in INL/EXT-21-65055 [1], which is the most recent 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), Section 6 presents the data used in the trending analysis, and Section 7 describes the AFW.

The AFW classes were categorized by the 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 AFW 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 *Overview and Reference* document [4] on the Nuclear Regulatory Commission (NRC) Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/).

Two variations of the AFW system model are implemented and calculated. The AFW start-only model is the AFW SPAR model modified by setting all fail-to-run basic events to zero (False), all human error and recovery events to False, all pump-ends events to False, and 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 (2018) AFW system study, this study used the *2010 Component Reliability Update*. The only variables subject to change in this analysis were the demand, run hour, failure, and unavailability data for selected components in the AFW system.

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 Island 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
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 any statistically significant[a] increasing trends. In this update, statistically significant **decreasing trends** were identified in the industry-wide estimates of **AFW system start-only unreliability** and the **AFW system 8-hour mission unreliability** for the most recent 10-year period.

The industry-wide AFW start-only and 8-hour basic event group importances were evaluated:

- In the **Start-Only** case—the leading contributors to AFW system unreliability are the **AFW motor-driven pump (MDP)**, Injection, Pump Ends, and AFW turbine-driven pump (TDP) groups of basic events
- In the **8-Hour Mission** case—the leading contributors to AFW system unreliability are the **AFW TDP**, AFW MDP, Pump Ends, and Injection group of basic events.

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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 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 variations. A start-only model and an 8-hour mission model were evaluated (see Table 2). 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 distribution width can be very small.

Table 2. Industry-wide unreliability values.

Model	AFW 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

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

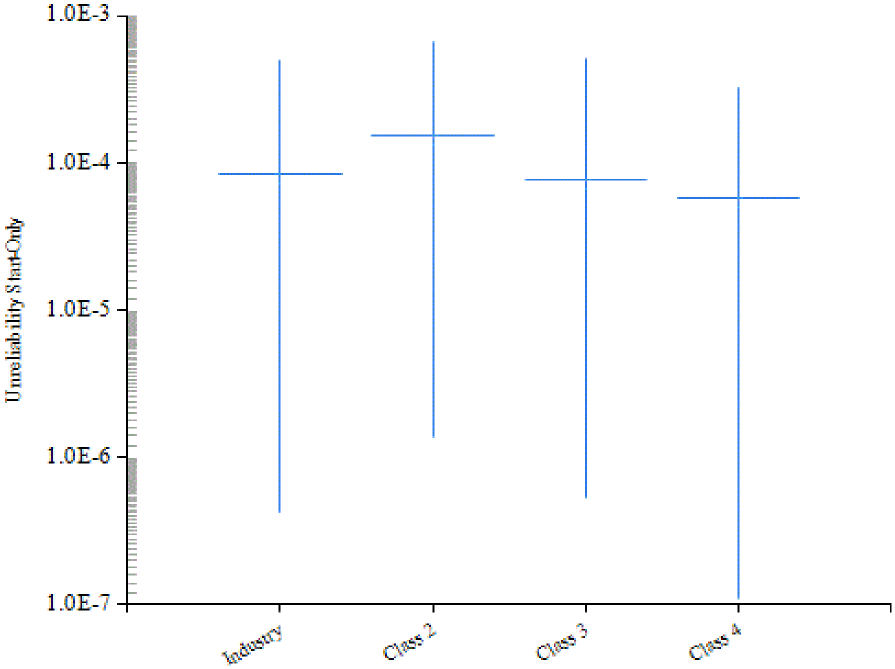


Figure 1. AFW start-only unreliability for Class 2, 3, and 4 and industry-wide groupings.

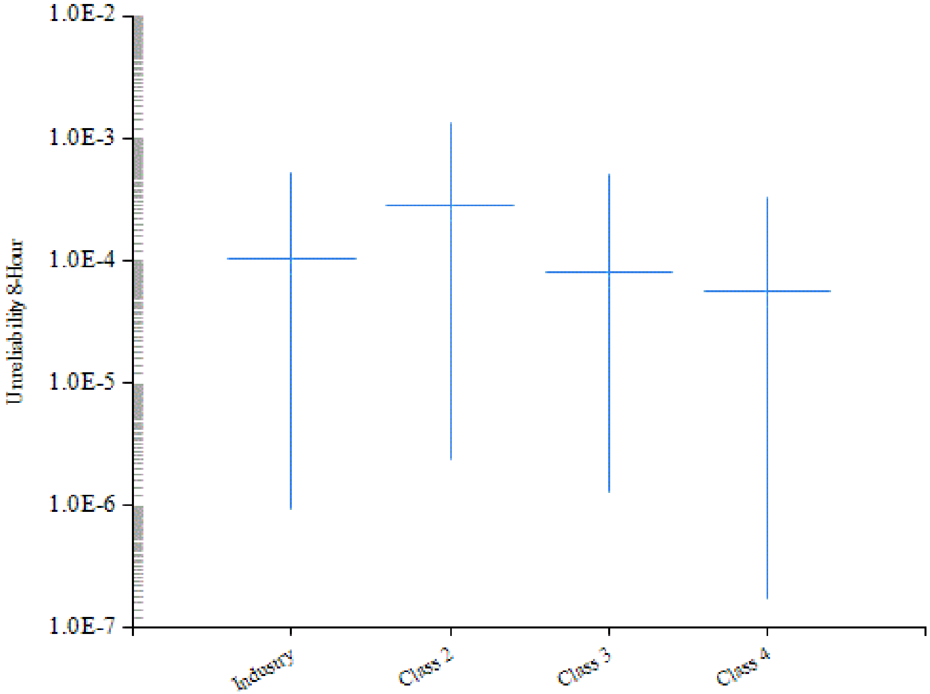


Figure 2. AFW 8-hour mission unreliability for Class 2, 3, and 4 and industry-wide groupings.

4. INDUSTRY-WIDE TRENDS

The yearly failure and demand or run time data from 1998–2020 were obtained from IRIS for the AFW system. AFW train maintenance unavailability data for trending are from the same time period, as reported in the ROP program and IRIS. The component basic event uncertainty was calculated for the AFW system components using the trending methods described in Sections 1 and 2 of Reference [4]. 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).

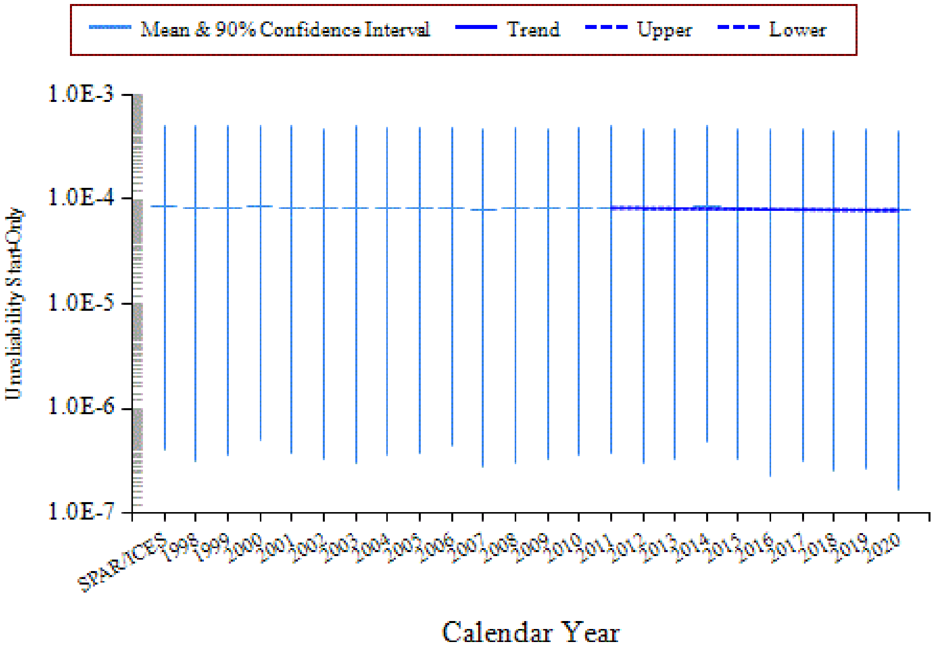
The trend charts show the results of varying component reliability data over time and updating generic, relatively flat prior distributions (or constrained noninformative distributions, refer to Section 2 of Reference [4]) using data for each year. In addition, the calculated industry-wide system reliability from this update (the "industry" values in Table 2) is shown as "SPAR/ICES" in the charts for comparison.. Section 2 of Reference [4] provides a more detailed discussion of the trending methods. The regression method is indicated in the lower left-hand corner of the trend figures.

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 unreliability. Table 4 shows the data points for Figure 3. A statistically significant **decreasing trend** was identified in the industry-wide estimates of **AFW system start-only unreliability** for the most recent 10-year period.

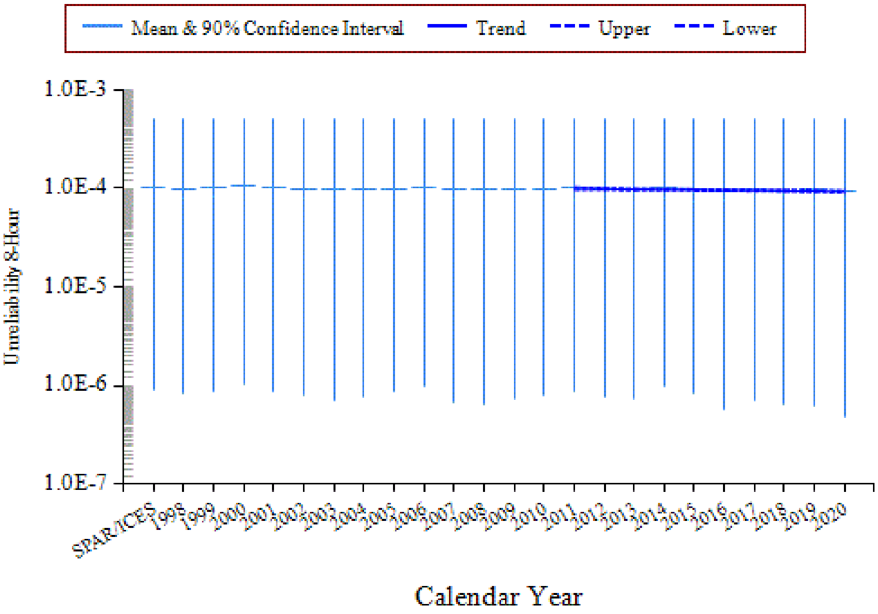
Figure 4 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 4. A statistically significant **decreasing trend** was identified in the industry-wide estimates of **AFW system 8-hour mission unreliability** for the most recent 10-year period.



LogisticTrend, p-value = 0.0221

AFW Industry Start-Only 3/14/2022

Figure 3. Trend of AFW system start-only unreliability.



LogisticTrend, p-value = 0.0403

AFW Industry 8-Hour 3/14/2022

Figure 4. Trend of AFW system 8-hour mission unreliability.

5. BASIC EVENT GROUP IMPORTANCES

The AFW basic event group Fussell-Vesely importances were calculated for the start-only and 8-hour mission models 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 mission 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**, Injection, Pump Ends, and AFW TDP groups of basic events
- In the **8-Hour Mission** case— the leading contributors to AFW system unreliability are the AFW TDP, AFW MDP, Pump Ends, and Injection group of basic events.

For more discussion on the AFW MDPs and TDPs, see the MDP and TDP component reliability studies at the NRC Reactor Operational Experience Results and Databases web page (https://nrcoe.inl.gov/). Table 3 shows the SPAR model AFW importance groups and their descriptions.

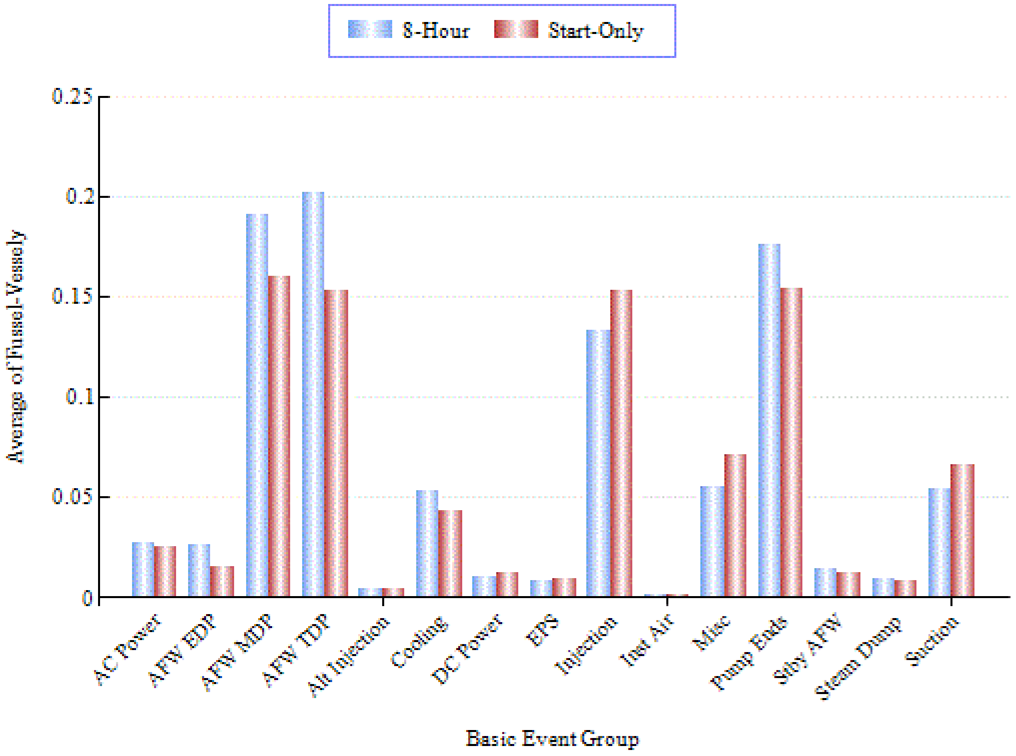


Figure 5. AFW industry-wide basic event group importances.

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, including the start, run, common-cause, and test and maintenance
Alternate Injection	Alternate injection sources such as firewater
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the pumps, as well as 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, which is 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, including startup feedwater and cross-ties to adjacent units
Suction	The motor-operated valves (MOVs) and air-operated valves (AOVs) in the tank suction path, including the tank failure

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

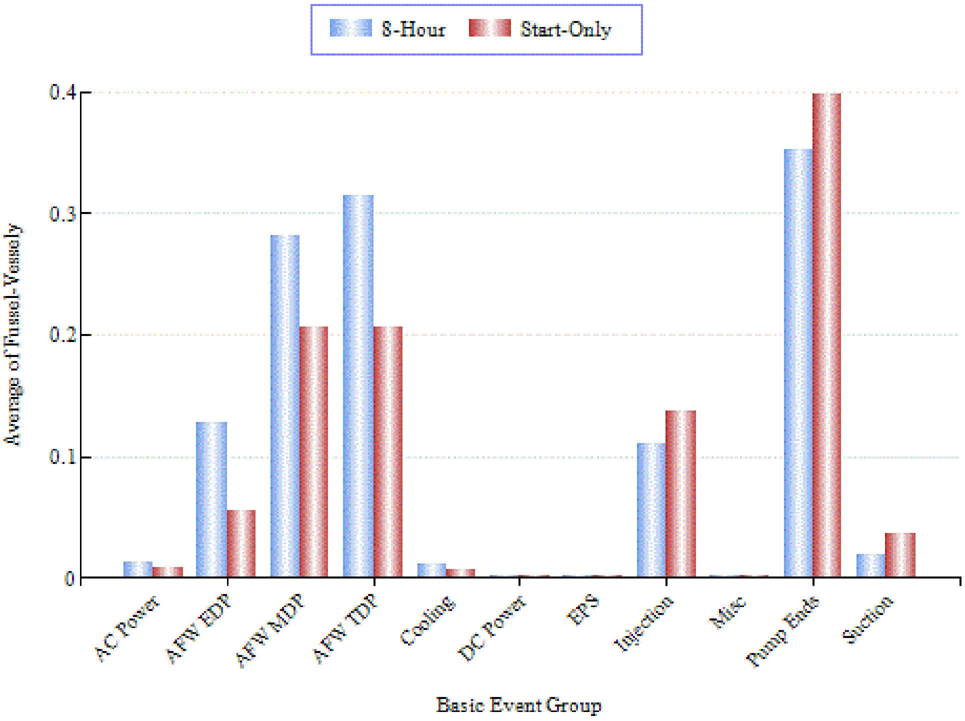


Figure 6. AFW Class 2 basic event group importances.

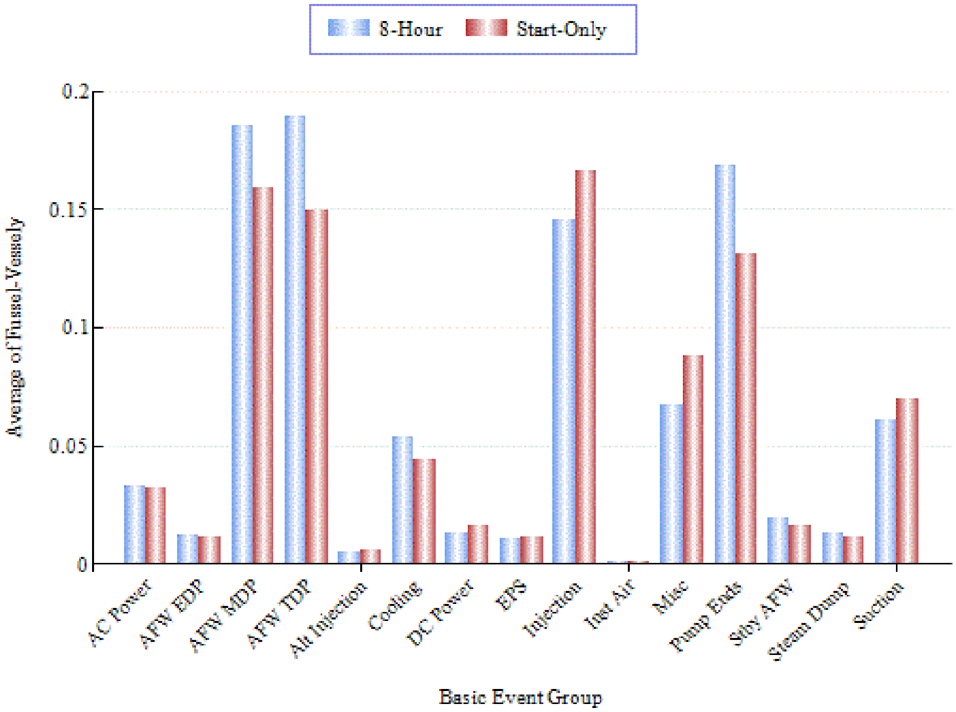


Figure 7. AFW Class 3 basic event group importances.

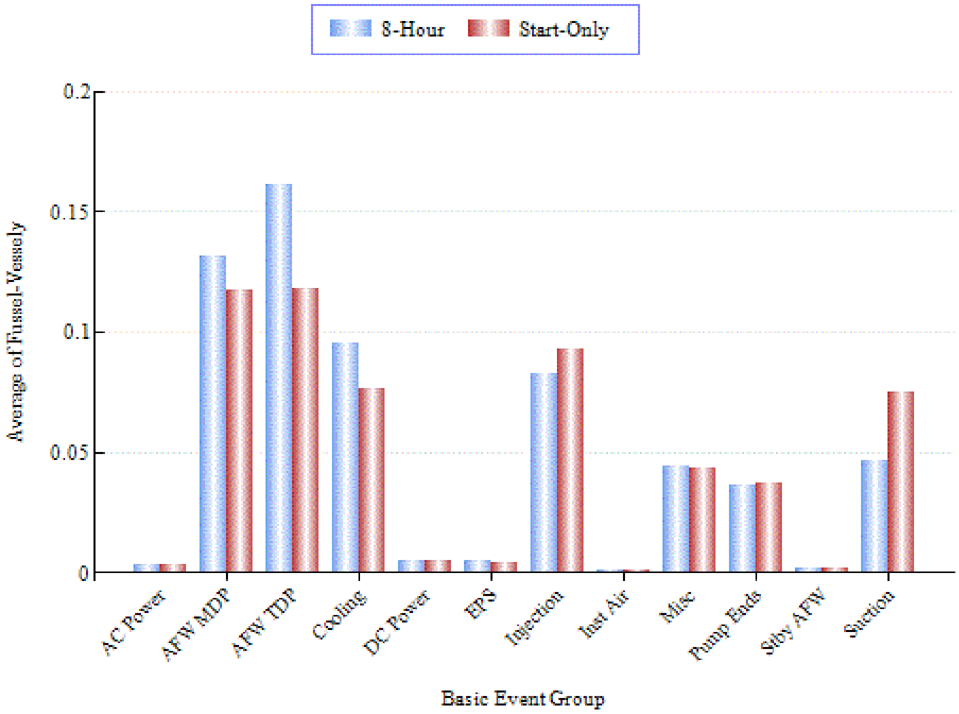


Figure 8. AFW Class 4 basic event group importances.

6. DATA TABLES

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

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	--	--	--	3.10E-07	8.35E-05	5.02E-04
1999	--	--	--	3.57E-07	8.35E-05	5.02E-04
2000	--	--	--	5.01E-07	8.56E-05	5.03E-04
2001	--	--	--	3.68E-07	8.27E-05	5.00E-04
2002	--	--	--	3.23E-07	8.17E-05	4.73E-04
2003	--	--	--	3.08E-07	8.17E-05	5.01E-04
2004	--	--	--	3.51E-07	8.17E-05	4.81E-04
2005	--	--	--	3.71E-07	8.21E-05	4.80E-04
2006	--	--	--	4.39E-07	8.30E-05	4.89E-04
2007	--	--	--	2.78E-07	8.06E-05	4.70E-04
2008	--	--	--	2.99E-07	8.12E-05	4.84E-04
2009	--	--	--	3.23E-07	8.15E-05	4.73E-04
2010	--	--	--	3.54E-07	8.20E-05	4.78E-04
2011	8.09E-05	8.29E-05	8.49E-05	3.67E-07	8.25E-05	5.00E-04
2012	8.08E-05	8.24E-05	8.41E-05	3.05E-07	8.09E-05	4.72E-04
2013	8.05E-05	8.19E-05	8.33E-05	3.22E-07	8.13E-05	4.71E-04
2014	8.03E-05	8.14E-05	8.26E-05	4.90E-07	8.49E-05	5.02E-04
2015	7.99E-05	8.10E-05	8.20E-05	3.31E-07	8.16E-05	4.68E-04
2016	7.95E-05	8.05E-05	8.15E-05	2.26E-07	7.91E-05	4.54E-04
2017	7.89E-05	8.00E-05	8.12E-05	3.09E-07	8.05E-05	4.60E-04
2018	7.82E-05	7.96E-05	8.09E-05	2.60E-07	7.99E-05	4.54E-04
2019	7.75E-05	7.91E-05	8.07E-05	2.66E-07	7.95E-05	4.55E-04
2020	7.68E-05	7.86E-05	8.05E-05	1.66E-07	7.74E-05	4.42E-04

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

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	--	--	--	8.42E-07	9.89E-05	5.11E-04
1999	--	--	--	8.59E-07	1.01E-04	5.13E-04
2000	--	--	--	1.04E-06	1.05E-04	5.15E-04
2001	--	--	--	8.60E-07	9.98E-05	5.09E-04
2002	--	--	--	7.94E-07	9.73E-05	5.08E-04
2003	--	--	--	6.91E-07	9.90E-05	5.10E-04
2004	--	--	--	7.53E-07	9.88E-05	5.08E-04
2005	--	--	--	8.73E-07	9.84E-05	5.09E-04
2006	--	--	--	9.96E-07	1.00E-04	5.10E-04
2007	--	--	--	6.72E-07	9.63E-05	5.08E-04
2008	--	--	--	6.48E-07	9.76E-05	5.08E-04
2009	--	--	--	7.18E-07	9.79E-05	5.07E-04
2010	--	--	--	7.81E-07	9.85E-05	5.08E-04
2011	9.62E-05	9.96E-05	1.03E-04	8.51E-07	9.95E-05	5.10E-04
2012	9.60E-05	9.88E-05	1.02E-04	7.72E-07	9.59E-05	5.08E-04
2013	9.57E-05	9.81E-05	1.01E-04	7.46E-07	9.71E-05	5.07E-04
2014	9.54E-05	9.74E-05	9.94E-05	9.90E-07	1.04E-04	5.13E-04
2015	9.49E-05	9.67E-05	9.85E-05	8.30E-07	9.66E-05	5.07E-04
2016	9.42E-05	9.60E-05	9.78E-05	5.65E-07	9.40E-05	5.06E-04
2017	9.33E-05	9.53E-05	9.73E-05	7.14E-07	9.56E-05	5.07E-04
2018	9.23E-05	9.46E-05	9.69E-05	6.33E-07	9.43E-05	5.06E-04
2019	9.11E-05	9.39E-05	9.66E-05	6.25E-07	9.54E-05	5.05E-04
2020	9.00E-05	9.32E-05	9.64E-05	4.79E-07	9.15E-05	5.04E-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	2,007	1.38E-03	4.83	3.49E+03	Beta
FTOC	AOV	1999	0	2,406	2.14E-04	0.83	3.90E+03	Beta
FTOC	AOV	2000	0	1,973	2.40E-04	0.83	3.46E+03	Beta
FTOC	AOV	2001	6	2,155	1.87E-03	6.83	3.64E+03	Beta
FTOC	AOV	2002	1	2,460	4.64E-04	1.83	3.95E+03	Beta
FTOC	AOV	2003	0	2,239	2.23E-04	0.83	3.73E+03	Beta
FTOC	AOV	2004	3	2,199	1.04E-03	3.83	3.69E+03	Beta
FTOC	AOV	2005	2	2,178	7.72E-04	2.83	3.67E+03	Beta
FTOC	AOV	2006	4	1,914	1.42E-03	4.83	3.40E+03	Beta
FTOC	AOV	2007	0	1,821	2.51E-04	0.83	3.31E+03	Beta
FTOC	AOV	2008	1	1,759	5.64E-04	1.83	3.25E+03	Beta
FTOC	AOV	2009	1	1,733	5.68E-04	1.83	3.22E+03	Beta
FTOC	AOV	2010	2	1,753	8.73E-04	2.83	3.24E+03	Beta
FTOC	AOV	2011	1	1,771	5.62E-04	1.83	3.26E+03	Beta
FTOC	AOV	2012	2	1,808	8.59E-04	2.83	3.30E+03	Beta
FTOC	AOV	2013	3	1,794	1.17E-03	3.83	3.28E+03	Beta
FTOC	AOV	2014	4	1,644	1.54E-03	4.83	3.13E+03	Beta
FTOC	AOV	2015	3	1,746	1.18E-03	3.83	3.23E+03	Beta
FTOC	AOV	2016	0	1,606	2.69E-04	0.83	3.10E+03	Beta
FTOC	AOV	2017	2	1,709	8.85E-04	2.83	3.20E+03	Beta
FTOC	AOV	2018	2	1,663	8.98E-04	2.83	3.15E+03	Beta
FTOC	AOV	2019	1	1,674	5.79E-04	1.83	3.16E+03	Beta
FTOC	AOV	2020	0	1,661	2.64E-04	0.83	3.15E+03	Beta
FTOP	AOV	1998	1	2,619,240	2.31E-07	2.26	9.79E+06	Gamma
FTOP	AOV	1999	0	2,619,240	1.29E-07	1.26	9.79E+06	Gamma
FTOP	AOV	2000	2	2,680,560	3.31E-07	3.26	9.85E+06	Gamma
FTOP	AOV	2001	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2002	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2003	2	2,610,480	3.33E-07	3.26	9.78E+06	Gamma
FTOP	AOV	2004	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2005	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2006	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2007	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2008	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2009	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2010	1	2,610,480	2.31E-07	2.26	9.78E+06	Gamma
FTOP	AOV	2011	1	2,715,600	2.29E-07	2.26	9.89E+06	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	AOV	2012	1	2,645,520	2.30E-07	2.26	9.82E+06	Gamma
FTOP	AOV	2013	4	2,645,520	5.36E-07	5.26	9.82E+06	Gamma
FTOP	AOV	2014	0	2,610,480	1.29E-07	1.26	9.78E+06	Gamma
FTOP	AOV	2015	3	2,715,600	4.31E-07	4.26	9.89E+06	Gamma
FTOP	AOV	2016	1	2,724,360	2.28E-07	2.26	9.89E+06	Gamma
FTOP	AOV	2017	0	2,733,120	1.27E-07	1.26	9.90E+06	Gamma
FTOP	AOV	2018	1	2,724,360	2.28E-07	2.26	9.89E+06	Gamma
FTOP	AOV	2019	1	2,724,360	2.28E-07	2.26	9.89E+06	Gamma
FTOP	AOV	2020	0	2,724,360	1.27E-07	1.26	9.89E+06	Gamma
SO	AOV	1998	0	2,619,240	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	1999	0	2,619,240	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	2000	0	2,680,560	4.94E-08	0.86	1.74E+07	Gamma
SO	AOV	2001	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2002	0	2,610,480	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	2003	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2004	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2005	0	2,610,480	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	2006	0	2,610,480	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	2007	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2008	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2009	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2010	1	2,610,480	1.07E-07	1.86	1.73E+07	Gamma
SO	AOV	2011	0	2,715,600	4.93E-08	0.86	1.74E+07	Gamma
SO	AOV	2012	0	2,645,520	4.95E-08	0.86	1.73E+07	Gamma
SO	AOV	2013	0	2,645,520	4.95E-08	0.86	1.73E+07	Gamma
SO	AOV	2014	0	2,610,480	4.96E-08	0.86	1.73E+07	Gamma
SO	AOV	2015	2	2,715,600	1.64E-07	2.86	1.74E+07	Gamma
SO	AOV	2016	0	2,724,360	4.93E-08	0.86	1.74E+07	Gamma
SO	AOV	2017	1	2,733,120	1.07E-07	1.86	1.74E+07	Gamma
SO	AOV	2018	0	2,724,360	4.93E-08	0.86	1.74E+07	Gamma
SO	AOV	2019	0	2,724,360	4.93E-08	0.86	1.74E+07	Gamma
SO	AOV	2020	0	2,724,360	4.93E-08	0.86	1.74E+07	Gamma
FTR>1H	MDP	1998	1	7,244	2.15E-05	1.51	7.01E+04	Gamma
FTR>1H	MDP	1999	0	8,182	7.19E-06	0.51	7.11E+04	Gamma
FTR>1H	MDP	2000	0	8,661	7.14E-06	0.51	7.16E+04	Gamma
FTR>1H	MDP	2001	4	7,862	6.37E-05	4.51	7.08E+04	Gamma
FTR>1H	MDP	2002	0	8,561	7.15E-06	0.51	7.15E+04	Gamma
FTR>1H	MDP	2003	2	9,671	3.46E-05	2.51	7.26E+04	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR>1H	MDP	2004	0	9,478	7.06E-06	0.51	7.24E+04	Gamma
FTR>1H	MDP	2005	0	7,941	7.21E-06	0.51	7.08E+04	Gamma
FTR>1H	MDP	2006	0	8,369	7.17E-06	0.51	7.13E+04	Gamma
FTR>1H	MDP	2007	0	8,133	7.19E-06	0.51	7.10E+04	Gamma
FTR>1H	MDP	2008	0	7,624	7.25E-06	0.51	7.05E+04	Gamma
FTR>1H	MDP	2009	0	8,346	7.17E-06	0.51	7.12E+04	Gamma
FTR>1H	MDP	2010	0	7,960	7.21E-06	0.51	7.09E+04	Gamma
FTR>1H	MDP	2011	0	9,875	7.02E-06	0.51	7.28E+04	Gamma
FTR>1H	MDP	2012	0	8,460	7.16E-06	0.51	7.14E+04	Gamma
FTR>1H	MDP	2013	3	7,924	4.96E-05	3.51	7.08E+04	Gamma
FTR>1H	MDP	2014	0	8,208	7.19E-06	0.51	7.11E+04	Gamma
FTR>1H	MDP	2015	2	8,752	3.50E-05	2.51	7.17E+04	Gamma
FTR>1H	MDP	2016	1	8,433	2.12E-05	1.51	7.13E+04	Gamma
FTR>1H	MDP	2017	0	10,798	6.93E-06	0.51	7.37E+04	Gamma
FTR>1H	MDP	2018	1	8,694	2.11E-05	1.51	7.16E+04	Gamma
FTR>1H	MDP	2019	0	8,019	7.21E-06	0.51	7.09E+04	Gamma
FTR>1H	MDP	2020	0	10,122	7.00E-06	0.51	7.30E+04	Gamma
FTR<1H	MDP	1998	1	1,996	1.89E-04	1.58	8.34E+03	Gamma
FTR<1H	MDP	1999	1	1,694	1.97E-04	1.58	8.03E+03	Gamma
FTR<1H	MDP	2000	1	1,833	1.93E-04	1.58	8.17E+03	Gamma
FTR<1H	MDP	2001	1	1,736	1.96E-04	1.58	8.08E+03	Gamma
FTR<1H	MDP	2002	0	2,014	6.93E-05	0.58	8.35E+03	Gamma
FTR<1H	MDP	2003	0	2,127	6.84E-05	0.58	8.47E+03	Gamma
FTR<1H	MDP	2004	1	2,038	1.88E-04	1.58	8.38E+03	Gamma
FTR<1H	MDP	2005	2	2,269	3.00E-04	2.58	8.61E+03	Gamma
FTR<1H	MDP	2006	1	2,134	1.86E-04	1.58	8.47E+03	Gamma
FTR<1H	MDP	2007	0	2,021	6.93E-05	0.58	8.36E+03	Gamma
FTR<1H	MDP	2008	0	2,101	6.86E-05	0.58	8.44E+03	Gamma
FTR<1H	MDP	2009	0	1,979	6.96E-05	0.58	8.32E+03	Gamma
FTR<1H	MDP	2010	1	1,825	1.93E-04	1.58	8.17E+03	Gamma
FTR<1H	MDP	2011	0	2,123	6.84E-05	0.58	8.46E+03	Gamma
FTR<1H	MDP	2012	0	1,996	6.95E-05	0.58	8.34E+03	Gamma
FTR<1H	MDP	2013	2	1,925	3.12E-04	2.58	8.26E+03	Gamma
FTR<1H	MDP	2014	0	1,951	6.98E-05	0.58	8.29E+03	Gamma
FTR<1H	MDP	2015	0	1,984	6.96E-05	0.58	8.32E+03	Gamma
FTR<1H	MDP	2016	0	1,832	7.08E-05	0.58	8.17E+03	Gamma
FTR<1H	MDP	2017	0	1,945	6.99E-05	0.58	8.29E+03	Gamma
FTR<1H	MDP	2018	0	1,869	7.05E-05	0.58	8.21E+03	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTR<1H	MDP	2019	0	1,782	7.13E-05	0.58	8.12E+03	Gamma
FTR<1H	MDP	2020	0	1,881	7.04E-05	0.58	8.22E+03	Gamma
FTS	MDP	1998	3	1,996	9.19E-04	5.07	5.51E+03	Beta
FTS	MDP	1999	4	1,694	1.16E-03	6.07	5.21E+03	Beta
FTS	MDP	2000	5	1,833	1.32E-03	7.07	5.35E+03	Beta
FTS	MDP	2001	1	1,736	5.84E-04	3.07	5.25E+03	Beta
FTS	MDP	2002	3	2,014	9.16E-04	5.07	5.53E+03	Beta
FTS	MDP	2003	1	2,127	5.43E-04	3.07	5.65E+03	Beta
FTS	MDP	2004	0	2,038	3.72E-04	2.07	5.56E+03	Beta
FTS	MDP	2005	4	2,269	1.05E-03	6.07	5.78E+03	Beta
FTS	MDP	2006	5	2,134	1.25E-03	7.07	5.65E+03	Beta
FTS	MDP	2007	2	2,021	7.34E-04	4.07	5.54E+03	Beta
FTS	MDP	2008	0	2,101	3.68E-04	2.07	5.62E+03	Beta
FTS	MDP	2009	1	1,979	5.58E-04	3.07	5.50E+03	Beta
FTS	MDP	2010	1	1,825	5.74E-04	3.07	5.34E+03	Beta
FTS	MDP	2011	3	2,123	8.98E-04	5.07	5.64E+03	Beta
FTS	MDP	2012	4	1,996	1.10E-03	6.07	5.51E+03	Beta
FTS	MDP	2013	1	1,925	5.64E-04	3.07	5.44E+03	Beta
FTS	MDP	2014	2	1,951	7.44E-04	4.07	5.47E+03	Beta
FTS	MDP	2015	4	1,984	1.10E-03	6.07	5.50E+03	Beta
FTS	MDP	2016	1	1,832	5.73E-04	3.07	5.35E+03	Beta
FTS	MDP	2017	2	1,945	7.44E-04	4.07	5.46E+03	Beta
FTS	MDP	2018	1	1,869	5.69E-04	3.07	5.39E+03	Beta
FTS	MDP	2019	1	1,782	5.79E-04	3.07	5.30E+03	Beta
FTS	MDP	2020	1	1,881	5.68E-04	3.07	5.40E+03	Beta
FTOC	MOV	1998	2	3,427	6.13E-04	4.43	7.23E+03	Beta
FTOC	MOV	1999	8	3,576	1.41E-03	10.43	7.37E+03	Beta
FTOC	MOV	2000	8	3,578	1.41E-03	10.43	7.37E+03	Beta
FTOC	MOV	2001	4	3,354	8.98E-04	6.43	7.15E+03	Beta
FTOC	MOV	2002	4	3,585	8.70E-04	6.43	7.38E+03	Beta
FTOC	MOV	2003	2	3,722	5.89E-04	4.43	7.52E+03	Beta
FTOC	MOV	2004	2	3,626	5.96E-04	4.43	7.42E+03	Beta
FTOC	MOV	2005	4	3,436	8.88E-04	6.43	7.23E+03	Beta
FTOC	MOV	2006	2	3,313	6.23E-04	4.43	7.11E+03	Beta
FTOC	MOV	2007	2	3,310	6.23E-04	4.43	7.11E+03	Beta
FTOC	MOV	2008	1	3,326	4.81E-04	3.43	7.12E+03	Beta
FTOC	MOV	2009	6	3,348	1.18E-03	8.43	7.14E+03	Beta
FTOC	MOV	2010	5	3,315	1.04E-03	7.43	7.11E+03	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOC	MOV	2011	5	3,351	1.04E-03	7.43	7.15E+03	Beta
FTOC	MOV	2012	0	3,318	3.41E-04	2.43	7.12E+03	Beta
FTOC	MOV	2013	4	3,337	9.01E-04	6.43	7.13E+03	Beta
FTOC	MOV	2014	4	3,404	8.92E-04	6.43	7.20E+03	Beta
FTOC	MOV	2015	5	3,379	1.03E-03	7.43	7.17E+03	Beta
FTOC	MOV	2016	3	3,495	7.44E-04	5.43	7.29E+03	Beta
FTOC	MOV	2017	0	3,498	3.33E-04	2.43	7.30E+03	Beta
FTOC	MOV	2018	1	3,520	4.68E-04	3.43	7.32E+03	Beta
FTOC	MOV	2019	2	3,502	6.06E-04	4.43	7.30E+03	Beta
FTOC	MOV	2020	0	3,445	3.35E-04	2.43	7.25E+03	Beta
FTOP	MOV	1998	0	4,502,640	2.90E-08	0.8	2.75E+07	Gamma
FTOP	MOV	1999	0	4,467,600	2.91E-08	0.8	2.75E+07	Gamma
FTOP	MOV	2000	1	4,467,600	6.55E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2001	0	4,476,360	2.90E-08	0.8	2.75E+07	Gamma
FTOP	MOV	2002	1	4,493,880	6.54E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2003	1	4,493,880	6.54E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2004	1	4,493,880	6.54E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2005	0	4,493,880	2.90E-08	0.8	2.75E+07	Gamma
FTOP	MOV	2006	1	4,511,400	6.54E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2007	0	4,493,880	2.90E-08	0.8	2.75E+07	Gamma
FTOP	MOV	2008	1	4,511,400	6.54E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2009	0	4,511,400	2.90E-08	0.8	2.75E+07	Gamma
FTOP	MOV	2010	2	4,511,400	1.02E-07	2.8	2.75E+07	Gamma
FTOP	MOV	2011	0	4,634,040	2.89E-08	0.8	2.76E+07	Gamma
FTOP	MOV	2012	1	4,537,680	6.53E-08	1.8	2.75E+07	Gamma
FTOP	MOV	2013	1	4,555,200	6.53E-08	1.8	2.76E+07	Gamma
FTOP	MOV	2014	0	4,590,240	2.89E-08	0.8	2.76E+07	Gamma
FTOP	MOV	2015	0	4,607,760	2.89E-08	0.8	2.76E+07	Gamma
FTOP	MOV	2016	0	4,686,600	2.88E-08	0.8	2.77E+07	Gamma
FTOP	MOV	2017	0	4,651,560	2.89E-08	0.8	2.77E+07	Gamma
FTOP	MOV	2018	1	4,651,560	6.50E-08	1.8	2.77E+07	Gamma
FTOP	MOV	2019	0	4,686,600	2.88E-08	0.8	2.77E+07	Gamma
FTOP	MOV	2020	0	4,616,520	2.89E-08	0.8	2.76E+07	Gamma
SO	MOV	1998	1	4,502,640	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	1999	0	4,467,600	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2000	1	4,467,600	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2001	1	4,476,360	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2002	0	4,493,880	2.54E-08	41.5	1.63E+09	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	MOV	2003	0	4,493,880	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2004	0	4,493,880	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2005	0	4,493,880	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2006	0	4,511,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2007	0	4,493,880	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2008	0	4,511,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2009	0	4,511,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2010	0	4,511,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2011	0	4,634,040	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2012	1	4,537,680	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2013	0	4,555,200	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2014	0	4,590,240	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2015	1	4,607,760	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2016	0	4,686,600	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2017	0	4,651,560	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2018	0	4,651,560	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2019	0	4,686,600	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2020	0	4,616,520	2.54E-08	41.5	1.63E+09	Gamma
FTR>1H	TDP	1998	0	2,026	2.10E-04	0.44	2.10E+03	Gamma
FTR>1H	TDP	1999	1	955	1.41E-03	1.44	1.02E+03	Gamma
FTR>1H	TDP	2000	1	420	2.94E-03	1.44	4.90E+02	Gamma
FTR>1H	TDP	2001	1	449	2.78E-03	1.44	5.18E+02	Gamma
FTR>1H	TDP	2002	0	1,093	3.79E-04	0.44	1.16E+03	Gamma
FTR>1H	TDP	2003	1	1,400	9.81E-04	1.44	1.47E+03	Gamma
FTR>1H	TDP	2004	3	299	9.34E-03	3.44	3.68E+02	Gamma
FTR>1H	TDP	2005	3	188	1.34E-02	3.44	2.57E+02	Gamma
FTR>1H	TDP	2006	0	186	1.73E-03	0.44	2.55E+02	Gamma
FTR>1H	TDP	2007	0	201	1.63E-03	0.44	2.70E+02	Gamma
FTR>1H	TDP	2008	1	223	4.93E-03	1.44	2.93E+02	Gamma
FTR>1H	TDP	2009	0	192	1.69E-03	0.44	2.62E+02	Gamma
FTR>1H	TDP	2010	0	195	1.67E-03	0.44	2.65E+02	Gamma
FTR>1H	TDP	2011	2	363	5.65E-03	2.44	4.32E+02	Gamma
FTR>1H	TDP	2012	3	183	1.36E-02	3.44	2.52E+02	Gamma
FTR>1H	TDP	2013	1	227	4.87E-03	1.44	2.96E+02	Gamma
FTR>1H	TDP	2014	2	248	7.70E-03	2.44	3.17E+02	Gamma
FTR>1H	TDP	2015	2	226	8.27E-03	2.44	2.95E+02	Gamma
FTR>1H	TDP	2016	0	292	1.22E-03	0.44	3.61E+02	Gamma
FTR>1H	TDP	2017	1	267	4.28E-03	1.44	3.37E+02	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	2018	2	155	1.09E-02	2.44	2.25E+02	Gamma
FTR>1H	TDP	2019	1	142	6.82E-03	1.44	2.11E+02	Gamma
FTR>1H	TDP	2020	0	198	1.65E-03	0.44	2.67E+02	Gamma
FTR<1H	TDP	1998	2	1,144	1.86E-03	2.44	1.32E+03	Gamma
FTR<1H	TDP	1999	2	1,032	2.03E-03	2.44	1.20E+03	Gamma
FTR<1H	TDP	2000	4	948	3.97E-03	4.44	1.12E+03	Gamma
FTR<1H	TDP	2001	3	921	3.15E-03	3.44	1.09E+03	Gamma
FTR<1H	TDP	2002	4	952	3.95E-03	4.44	1.13E+03	Gamma
FTR<1H	TDP	2003	6	984	5.57E-03	6.44	1.16E+03	Gamma
FTR<1H	TDP	2004	0	1,006	3.76E-04	0.44	1.18E+03	Gamma
FTR<1H	TDP	2005	1	996	1.23E-03	1.44	1.17E+03	Gamma
FTR<1H	TDP	2006	2	1,012	2.06E-03	2.44	1.19E+03	Gamma
FTR<1H	TDP	2007	2	954	2.17E-03	2.44	1.13E+03	Gamma
FTR<1H	TDP	2008	2	998	2.09E-03	2.44	1.17E+03	Gamma
FTR<1H	TDP	2009	4	1,092	3.51E-03	4.44	1.27E+03	Gamma
FTR<1H	TDP	2010	2	1,103	1.91E-03	2.44	1.28E+03	Gamma
FTR<1H	TDP	2011	2	1,104	1.91E-03	2.44	1.28E+03	Gamma
FTR<1H	TDP	2012	0	1,033	3.68E-04	0.44	1.21E+03	Gamma
FTR<1H	TDP	2013	0	1,076	3.56E-04	0.44	1.25E+03	Gamma
FTR<1H	TDP	2014	1	1,058	1.17E-03	1.44	1.23E+03	Gamma
FTR<1H	TDP	2015	3	1,099	2.71E-03	3.44	1.27E+03	Gamma
FTR<1H	TDP	2016	1	1,047	1.18E-03	1.44	1.22E+03	Gamma
FTR<1H	TDP	2017	0	1,067	3.58E-04	0.44	1.24E+03	Gamma
FTR<1H	TDP	2018	1	1,037	1.19E-03	1.44	1.21E+03	Gamma
FTR<1H	TDP	2019	0	1,000	3.78E-04	0.44	1.17E+03	Gamma
FTR<1H	TDP	2020	0	992	3.81E-04	0.44	1.16E+03	Gamma
FTS	TDP	1998	0	1,144	9.13E-04	1.26	1.38E+03	Beta
FTS	TDP	1999	2	1,032	2.57E-03	3.26	1.26E+03	Beta
FTS	TDP	2000	6	948	6.13E-03	7.26	1.18E+03	Beta
FTS	TDP	2001	2	921	2.82E-03	3.26	1.15E+03	Beta
FTS	TDP	2002	2	952	2.74E-03	3.26	1.19E+03	Beta
FTS	TDP	2003	4	984	4.31E-03	5.26	1.21E+03	Beta
FTS	TDP	2004	5	1,006	5.04E-03	6.26	1.24E+03	Beta
FTS	TDP	2005	3	996	3.46E-03	4.26	1.23E+03	Beta
FTS	TDP	2006	4	1,012	4.21E-03	5.26	1.24E+03	Beta
FTS	TDP	2007	3	954	3.58E-03	4.26	1.19E+03	Beta
FTS	TDP	2008	6	998	5.88E-03	7.26	1.23E+03	Beta
FTS	TDP	2009	6	1,092	5.46E-03	7.26	1.32E+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	2010	5	1,103	4.67E-03	6.26	1.33E+03	Beta
FTS	TDP	2011	4	1,104	3.93E-03	5.26	1.33E+03	Beta
FTS	TDP	2012	2	1,033	2.57E-03	3.26	1.27E+03	Beta
FTS	TDP	2013	4	1,076	4.01E-03	5.26	1.31E+03	Beta
FTS	TDP	2014	11	1,058	9.47E-03	12.26	1.28E+03	Beta
FTS	TDP	2015	2	1,099	2.44E-03	3.26	1.33E+03	Beta
FTS	TDP	2016	2	1,047	2.54E-03	3.26	1.28E+03	Beta
FTS	TDP	2017	4	1,067	4.04E-03	5.26	1.30E+03	Beta
FTS	TDP	2018	3	1,037	3.35E-03	4.26	1.27E+03	Beta
FTS	TDP	2019	4	1,000	4.25E-03	5.26	1.23E+03	Beta
FTS	TDP	2020	0	992	1.03E-03	1.26	1.23E+03	Beta

Table 7. Basic event unavailability (UA) trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	MDP	1998	4065.31	886,803	4.54E-03	1.26	2.76E+02	Beta
UA	MDP	1999	5123.83	935,811	5.13E-03	1.27	2.47E+02	Beta
UA	MDP	2000	4991.15	956,723	4.90E-03	2.24	4.55E+02	Beta
UA	MDP	2001	4092.12	971,171	4.29E-03	2.33	5.39E+02	Beta
UA	MDP	2002	3728.115	988,885	3.55E-03	2.1	5.89E+02	Beta
UA	MDP	2003	4326.49	961,833	4.03E-03	1.6	3.96E+02	Beta
UA	MDP	2004	3794.053	997,678	3.62E-03	3.11	8.57E+02	Beta
UA	MDP	2005	3583.168	983,670	3.30E-03	1.49	4.50E+02	Beta
UA	MDP	2006	3681.827	979,451	3.42E-03	1.52	4.42E+02	Beta
UA	MDP	2007	3567.86	1,005,597	3.32E-03	1.43	4.29E+02	Beta
UA	MDP	2008	3527.58	985,161	3.31E-03	1.14	3.42E+02	Beta
UA	MDP	2009	2895.27	978,472	2.65E-03	1.24	4.68E+02	Beta
UA	MDP	2010	3081.78	998,184	2.96E-03	1.74	5.87E+02	Beta
UA	MDP	2011	3607.99	957,227	3.65E-03	1.52	4.15E+02	Beta
UA	MDP	2012	3013.01	906,185	2.91E-03	1.14	3.91E+02	Beta
UA	MDP	2013	3118.16	914,122	3.05E-03	1.41	4.61E+02	Beta
UA	MDP	2014	3440.3	914,596	3.38E-03	0.79	2.34E+02	Beta
UA	MDP	2015	2649.07	911,694	2.70E-03	1.65	6.11E+02	Beta
UA	MDP	2016	2304.82	929,234	2.42E-03	1.1	4.53E+02	Beta
UA	MDP	2017	2519.7	916,344	2.52E-03	1.52	6.02E+02	Beta
UA	MDP	2018	2336.17	916,755	2.38E-03	1.84	7.69E+02	Beta
UA	MDP	2019	2089.43	917,422	2.13E-03	1.11	5.21E+02	Beta
UA	MDP	2020	1975.1	892,860	2.06E-03	1.16	5.63E+02	Beta
UA	TDP	1998	3008.72	475,481	6.17E-03	1.17	1.89E+02	Beta
UA	TDP	1999	2629.5	503,402	5.17E-03	1.62	3.11E+02	Beta
UA	TDP	2000	2781.15	512,807	5.91E-03	1.39	2.34E+02	Beta
UA	TDP	2001	2957.48	520,529	5.83E-03	1.2	2.05E+02	Beta
UA	TDP	2002	2440.879	514,211	4.80E-03	1.6	3.33E+02	Beta
UA	TDP	2003	3145.81	501,991	6.29E-03	1.35	2.14E+02	Beta
UA	TDP	2004	3079.15	529,086	6.06E-03	1.46	2.39E+02	Beta
UA	TDP	2005	2692.457	523,052	5.27E-03	1.29	2.44E+02	Beta
UA	TDP	2006	2649.003	519,333	5.11E-03	1.25	2.44E+02	Beta
UA	TDP	2007	2458.53	536,572	4.61E-03	0.85	1.84E+02	Beta
UA	TDP	2008	2537.98	524,396	4.85E-03	1.55	3.17E+02	Beta
UA	TDP	2009	2581.33	520,595	4.95E-03	0.87	1.75E+02	Beta
UA	TDP	2010	3151.31	519,882	6.07E-03	1.23	2.01E+02	Beta
UA	TDP	2011	3014.19	506,966	6.15E-03	0.71	1.14E+02	Beta

Table 7. (continued).

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
UA	TDP	2012	2105.74	489,026	4.02E-03	1.15	2.85E+02	Beta
UA	TDP	2013	2408.11	493,017	4.63E-03	0.88	1.88E+02	Beta
UA	TDP	2014	2691.14	495,480	5.57E-03	0.63	1.13E+02	Beta
UA	TDP	2015	2097.87	496,565	4.19E-03	0.87	2.07E+02	Beta
UA	TDP	2016	2208.15	502,560	4.26E-03	1.15	2.68E+02	Beta
UA	TDP	2017	2066.05	495,582	4.03E-03	1.44	3.56E+02	Beta
UA	TDP	2018	1769	495,532	3.58E-03	0.92	2.56E+02	Beta
UA	TDP	2019	1981.35	495,647	3.98E-03	1.17	2.93E+02	Beta
UA	TDP	2020	1529.84	484,321	3.17E-03	1.32	4.14E+02	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTOC	Fail to open/close
FTOP	Fail to operate
FTR>1H	Fail to run more than one hour (standby equipment)
FTR<1H	Fail to run less than one hour (after start; standby equipment)
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 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.

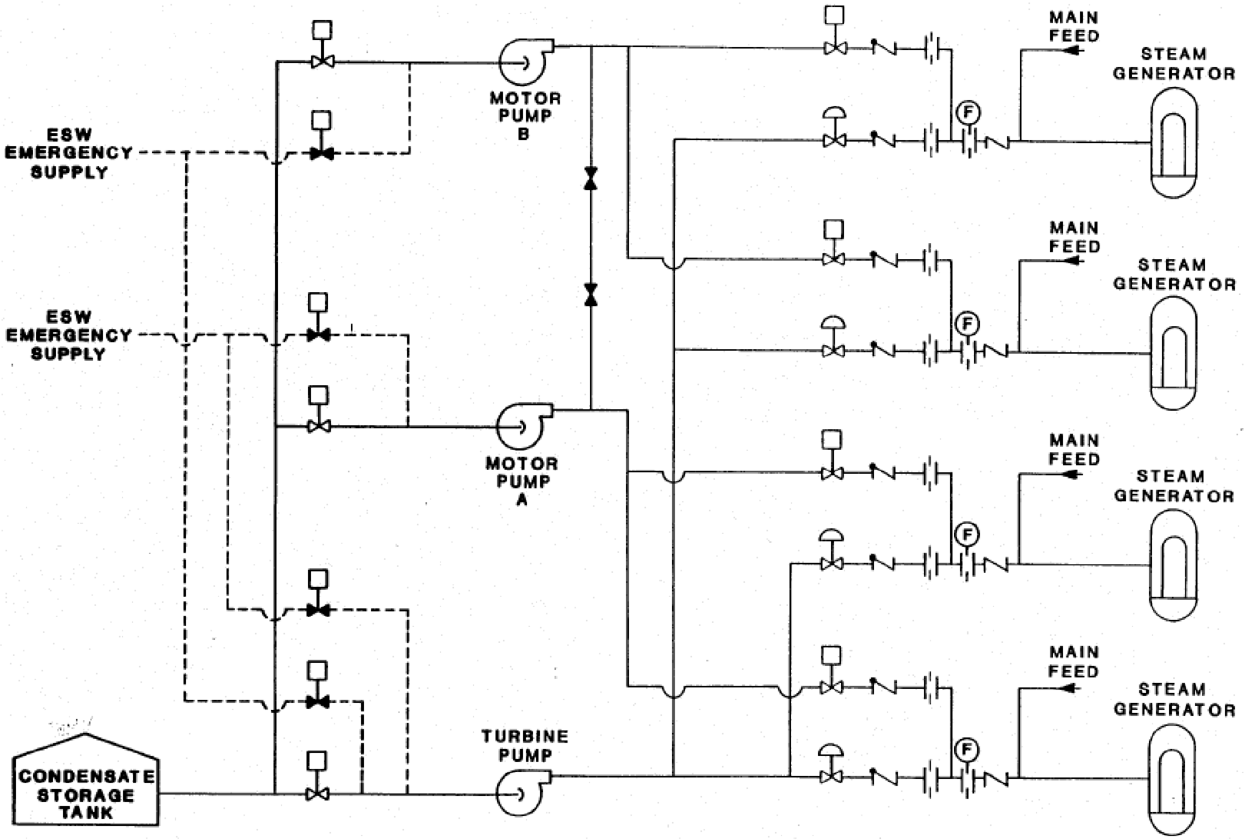


Figure 9. Simplified generic AFW system diagram.

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	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	Oconee 3		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] Z. Ma, T. E. Wierman, and K. J. Kvarfordt. 2021. “Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants: 2020 Update,” INL/EXT-21-65055, Idaho National Laboratory.

[2] S. A. Eide, T. E. Wierman, C. D. Gentillon, D. M. Rasmuson, and C. L. Atwood. 2007. “Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants,” NUREG/CR-6928, U.S. Nuclear Regulatory Commission.

[3] United States Nuclear Regulatory Commission. 2010. “Component Reliability Data Sheets Update 2010,” online. Available: https://nrcoe.inl.gov/resultsdb/publicdocs/AvgPerf/ComponentUR2010.pdf.

[4] C. D. Gentillion. 2016. “Overview and Reference Document for Operational Experience Results and Databases Trending,” online. Available: https://nrcoe.inl.gov/resultsdb/publicdocs/Overview-and-Reference.pdf.