Auxiliary Feedwater Reliability Study

1 AFW SYSTEM OPERATION AND DESCRIPTION

1.1 System Purpose

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 reliefs and/or safety valves, is used to cool the reactor coolant system to the residual heat removal cut-in temperature. At this temperature, the residual heat removal system is used to further cool the reactor coolant system. The AFW system may also be used to temporarily hold the plant in a hot standby condition while main feedwater flow is being restored, with the option of cooling the reactor coolant system to the residual heat removal system initiation temperature.

1.2 System Description

The AFW systems analyzed can be grouped into 11 different design classes as shown in Table 1. Figure 1 provides a block diagram of each of the design classes. Each 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. 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. Because of the diversity in system design, operation, and response to a plant transient, a detailed discussion of the different systems for each plant is not practical. A general description is provided of a two-division system for a four-steam generator plant consisting of two electric-motor-driven pumps in one division and a turbine-driven pump in the other. Differences between the other types of system design classes are also discussed.

Table 1. Listing of the AFW design classes, PWRs associated with each design class, the number and type of AFW trains, the number of steam generators, and the success criterion (as stated in the IPEs).

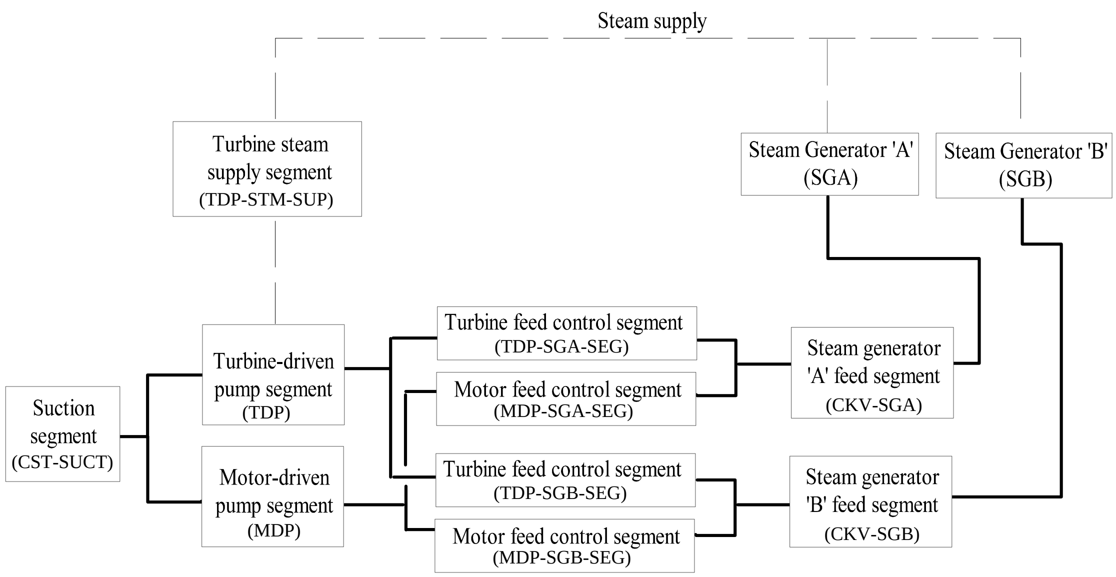
AFW Design Class	Plant Name	Motor Trains	Turbine Trains	Diesel Trains	Total Pump Trains	Steam Generators	Success Criterion Reported in the IPE
1	Arkansas Nuclear One 2	1	1		2	2	1 of 2 trains to 1 of 2 SGs
1	Crystal River 3	1	1	1*	2	2	1 of 2 trains to 1 of 2 SGs. Crystal River 3, in 2002, added a diesel driven emergency feedwater pump to the system, functionally replacing the motor driven pump. The system now has 3 pumps - 1 TD, 1 DD, and 1 MD. The TDP and the DDP start automatically, whereas, now, the MDP is a manual start.
1	Fort Calhoun	1	1	1*	3	2	1 of 2 trains or FW-54 (diesel-driven) to 1 of 2 SGs; since diesel is non-safety and manual start—model as 1 of 2 trains with diesel as recovery train
1	Palo Verde 1, 2, & 3	2*	1		3	2	1 of 3 pumps to one (1 of 2) SGs; one motor train (MD-N) is nonessential; so net is 1 of 2 trains
1	Prairie Island 1 & 2	1	1		2	2	1 of 2 trains to 1 of 2 SGs
2	Calvert Cliffs 1 & 2	1	2		3	2	300 gpm to 1 (or 2) SGs -- IPE models pumps as 1 of 4 (3 plus xtie) available
3	Davis-Besse	1*	2		3	2	1 of 3 trains to at least 1 SG (1 of 2 SGs); the MDFP serves as the MDP train and as BU to turbines, needs to be manually started; treat the MD train as recovery if the auto turbines fail. Success is 1 of 2 safety trains to 1 of 2 SGs
4	Arkansas Nuclear One 1	1	1		2	2	1 of 2 trains to 1 of 2 SGs
4	Ginna	2	1		3	2	1 of 3 pumps to 1 of 2 SGs
4	Kewaunee	2	1		3	2	200 gpm to 1 of 2 SGs from 1 of 3 AFW pumps
4	Millstone 2	2	1		3	2	1 of 2 MDP or the steam-driven pump delivers flow to 1 of 2 SGs
4	Oconee 1, 2, & 3	2	1		3	2	1 of 3 trains to 1 of 2 SGs
4	Palisades	2	1		3	2	1 of 3 pumps to 1 of 2 SGs
4	Point Beach 1 & 2	2	1		3	2	The units have only one MDP but supplies a SG at each unit net effect is 2 MD trains; 1 of 3 trains to 1 of 2 SGs
4	San Onofre 1, 2 & 3	2	1		3	2	1 of 3 AFW pumps to 1 of 2 SGs
4	St. Lucie 1 & 2	2	1		3	2	1 of 3 AFW pumps to 1 of 2 SGs
4	Three Mile Island 1	2	1		3	2	1 of 3 pumps to 1 of 2 SGs
4	Waterford 3	2	1		3	2	Any pump (1 of 3 AFW) to 1 of 2 SGs
5	Beaver Valley 1 & 2	2	1		3	3	1 of 3 trains to 1 of 3 SGs
5	Farley 1 & 2	2	1		3	3	1 of 3 trains to 2 of 3 SGs
5	Harris 1	2	1		3	3	1 of 3 trains to 1 of 3 SGs
5	Maine Yankee [1]	2	1		3	3	1 of 3 trains to 1 of 3 SGs (2 of 2 pumps with flow diversion)
5	North Anna 1 & 2	2	1		3	3	1 of 3 trains to 1 of 3 SGs

[1] Decommissioned August 1997.

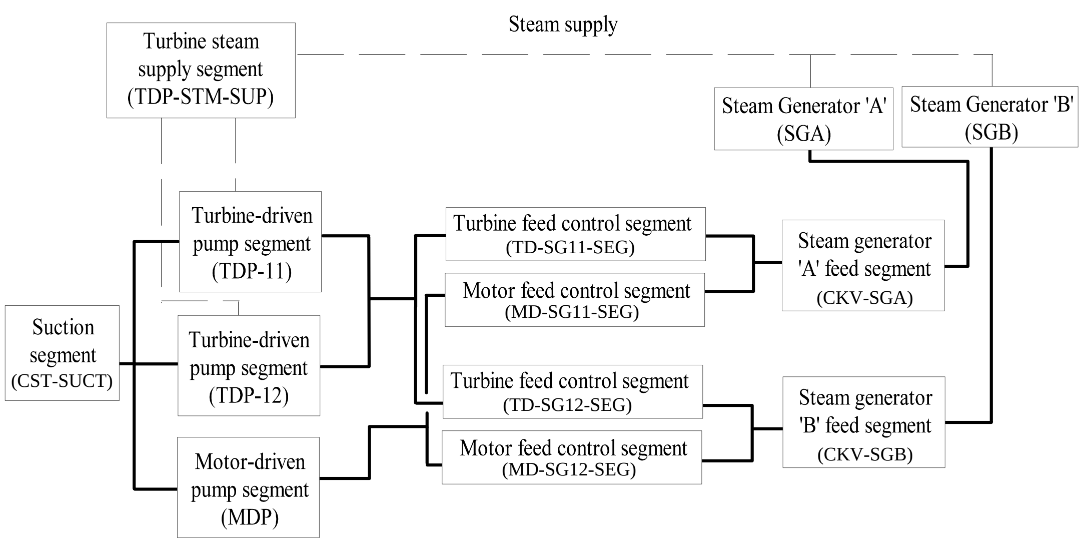
AFW Design Class	Plant Name	Motor Trains	Turbine Trains	Diesel Trains	Total Pump Trains	Steam Generators	Success Criterion Reported in the IPE
5	Robinson	2	1		3	3	1 of 3 pumps to 1 of 3 SGs
5	Summer 1	2	1		3	3	1 of 2 MDPs OR 1 TDP to 1 of 3 SGs
5	Surry 1 & 2	2	1		3	3	1 of 3 pumps to any one SG
6	Turkey Point 3 & 4		3		3	3	1 of 3 pumps to at least 1 of 3 SGs (375 gpm)
7	Braidwood 1 & 2	1		1	2	4	1 of 2 trains to 1 of 4 SGs
7	Byron 1 & 2	1		1	2	4	1 of 2 trains to 1 of 4 SGs
8	Seabrook	1	1		2	4	PRA states 1 of 2 pumps to 2 of 4 SGs
9	Haddam Neck [2]		2		2	4	(1 of 2 AFW pumps to 3 of 4 SGs) OR (2 of 2 pumps to 2 of 4 SGs)
10	Callaway	2	1		3	4	1 of 3 trains delivering flow to at least 2 SGs
10	Catawba 1 & 2	2	1		3	4	1 of 3 trains to 2 SGs
10	Comanche Peak 1 & 2	2	1		3	4	At least 300 gpm (1 of 3 trains) to 1 of 4 SGs; also have a 860 gpm (2 of MDP to 1 of 4 SGs or 1 TDP flow to 2 SGs); full flow--3 of 3 pumps with MDPs to 1 SG and TDP to 2 SGs
10	Cook 1 & 2	2	1		3	4	450 gpm AFW flow (1 of 3 trains) to 2 of 4 SGs
10	Diablo Canyon 1 & 2	2	1		3	4	1 of 3 trains to 1 of 4 SGs
10	Indian Point 2	2	1		3	4	1 of 3 AFW pumps to 1 SG
10	Indian Point 3	2	1		3	4	1 of 3 trains injecting to 1 of 4 SGs
10	McGuire 1 & 2	2	1		3	4	1 of 3 trains to 2 of 4 SGs
10	Millstone 3	2	1		3	4	1 of 3 pumps to any 2 of 4 SGs
10	Salem 1 & 2	2	1		3	4	426 gpm flow (1 of 3 pumps) to 2 SGs (MDP 440 gpm; TDP 880 gpm)
10	Sequoyah 1 & 2	2	1		3	4	at least one pump (1 of 3) feeding 2 SGs
10	Vogtle 1 & 2	2	1		3	4	Flow to 2 of 4 SGs from 1 of 2 MDPs or 1 TDP
10	Watts Bar	2	1		3	4	1 of 3 trains to 2 of 4 SGs
10	Wolf Creek	2	1		3	4	1 of 3 trains to 2 of 4 SGs
10	Zion 1 & 2 [3]	2	1		3	4	1 of 3 pumps to 4 of 4 SGs or 1 of 4 SGs w/o all power. Page 4-48 states 1 MDP supplying 2/4 SGs is enough to safely cool down plant to RHR temp.
11	South Texas 1 & 2	3	1		4	4	1 of 4 AFW trains to 1 of 4 SGs (pump flow to its respective SG) no xtie to other SGs modeled in PRA

[2] Decommissioned August 1997.

[3] Decommissioned February 2000.

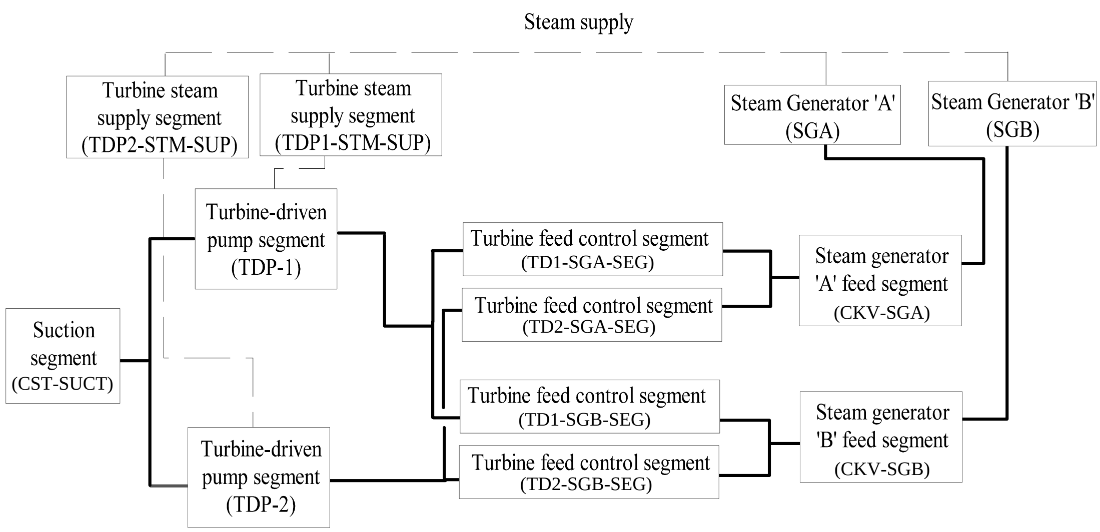


Crystal River 3 (Design Class 1)

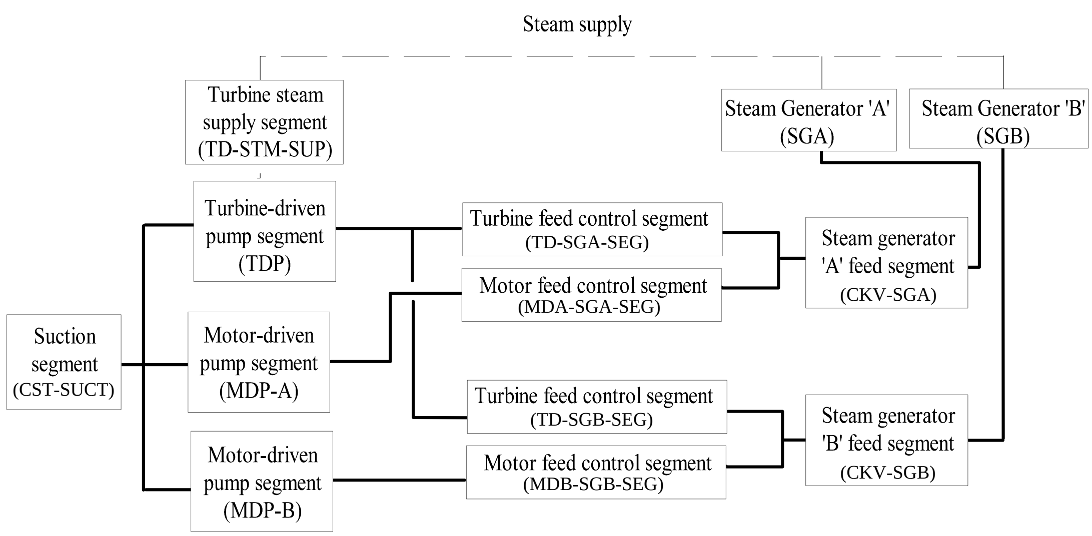


Calvert Cliffs 1 (Design Class 2)

Figure 1. Simplified block diagrams of AFW systems for each of the 11 design classes.

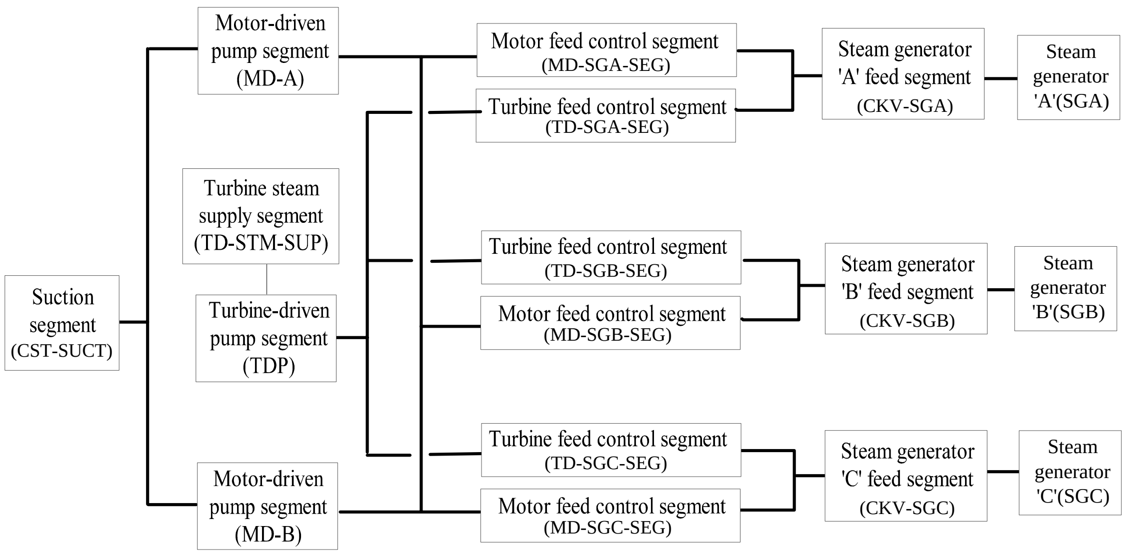


Davis-Besse (Design Class 3)

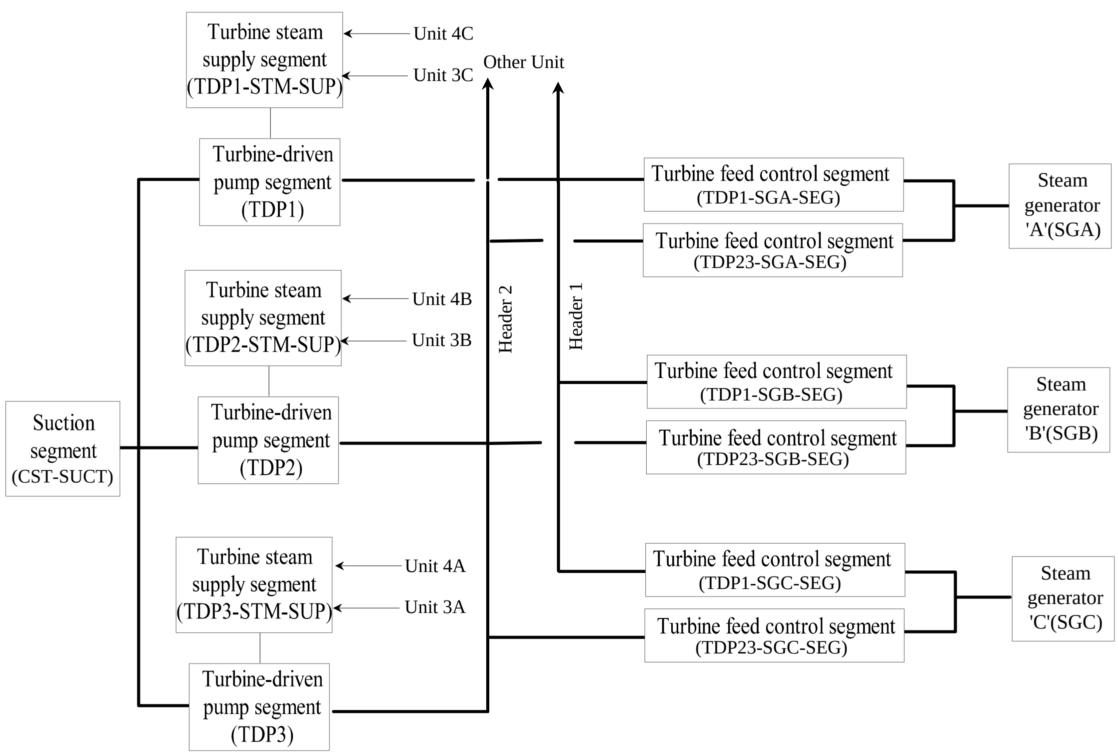


St. Lucie 1 (Design Class 4)

Figure 1. (continued).

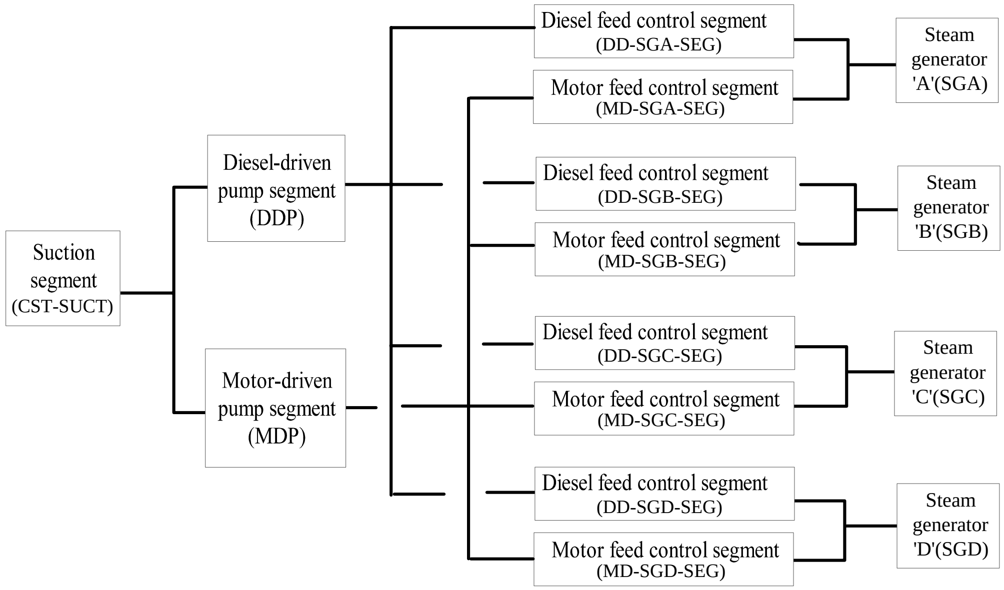


Farley 1 (Design Class 5)

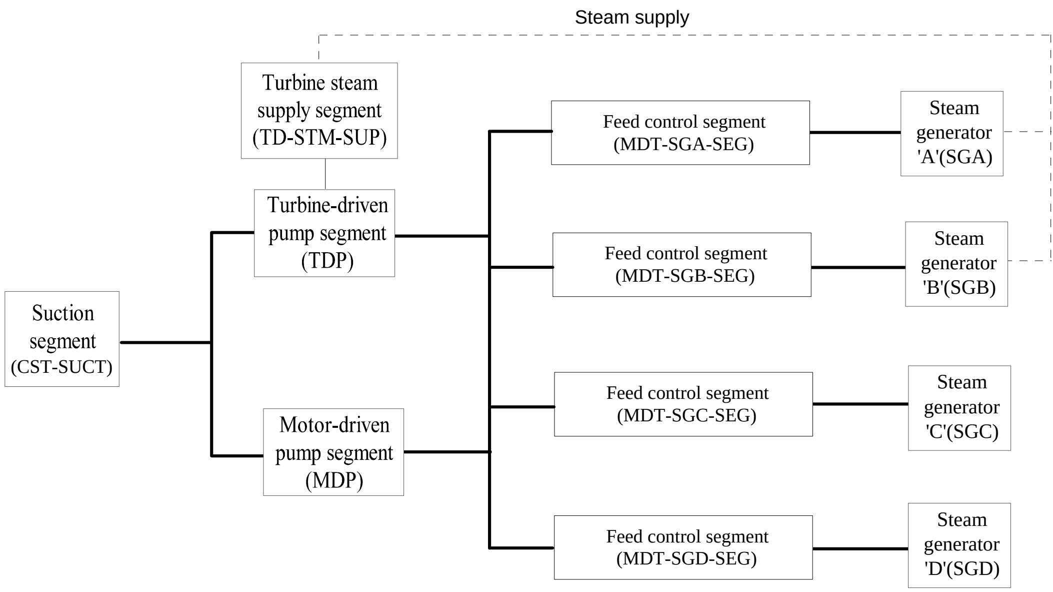


Turkey Point 3 (Design Class 6)

Figure 1. (continued).

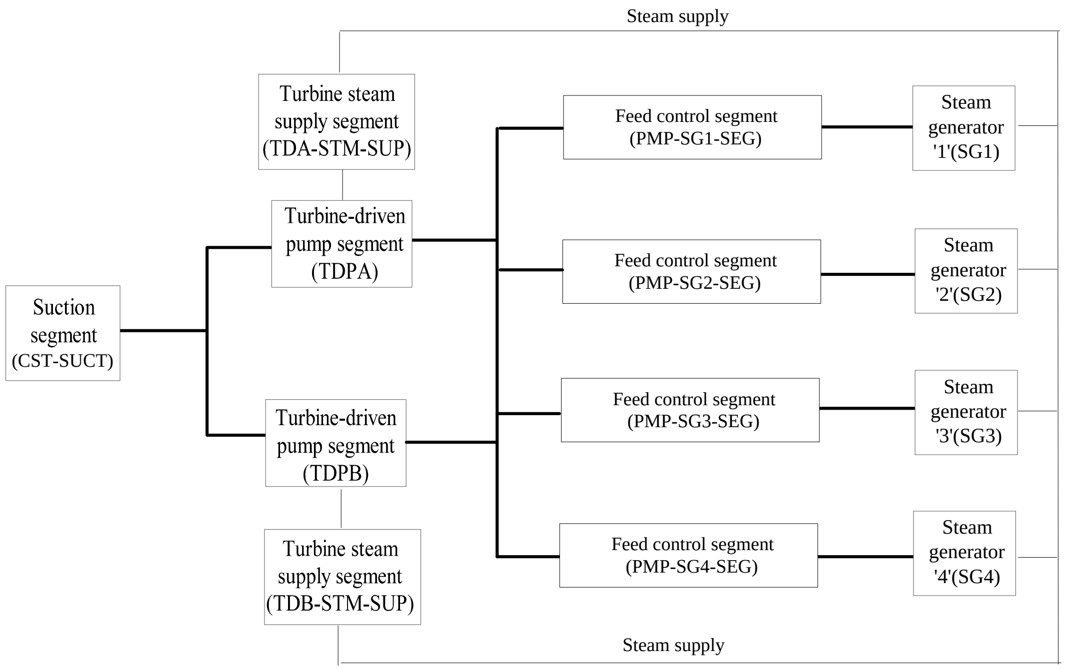


Braidwood (Design Class 7)

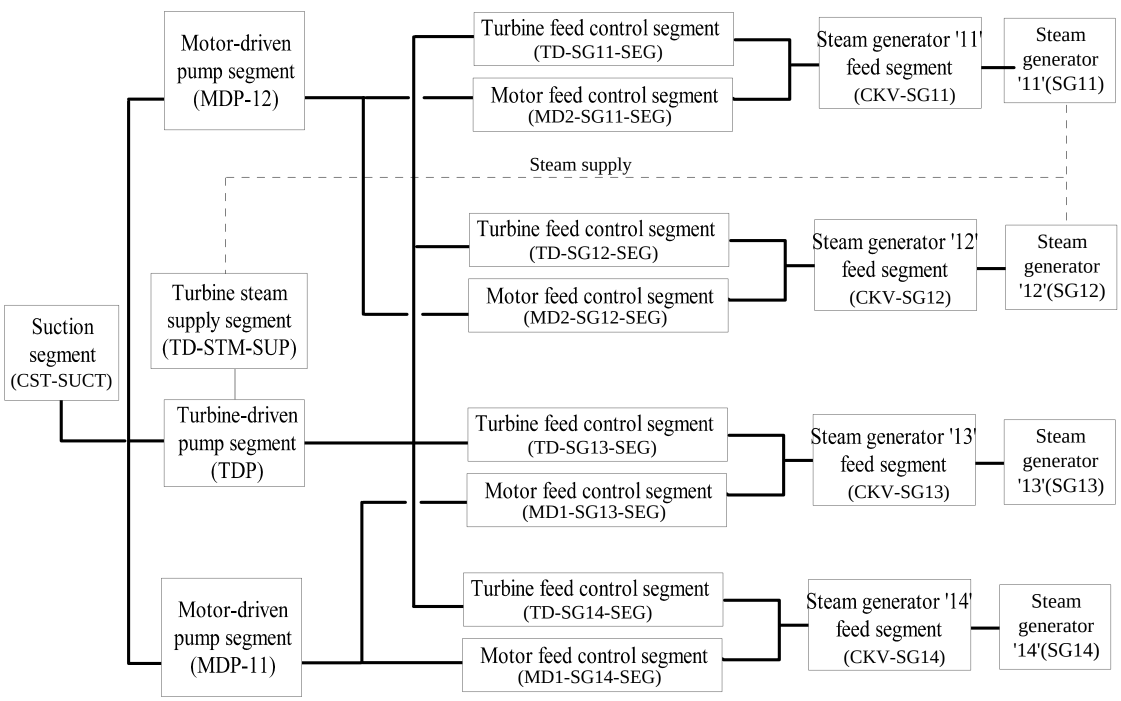


Seabrook (Design Class 8)

Figure 1. (continued).

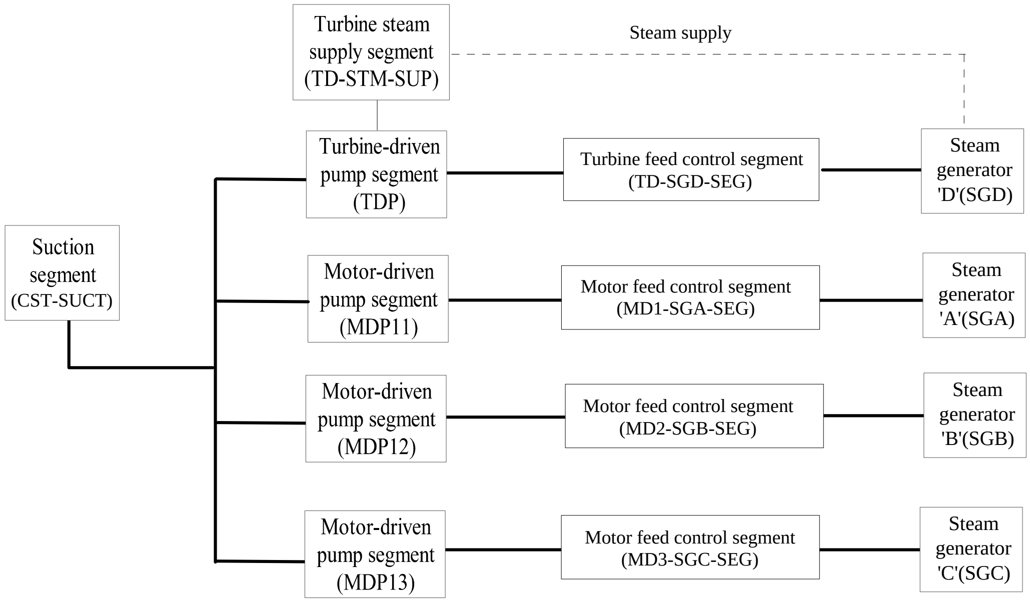


Haddam Neck (Design Class 9)



Salem 1 (Design Class 10)

Figure 1. (continued).



South Texas 1 (Design Class 11)

Figure 1. (continued).

The reader is cautioned against making comparisons or assumptions across the industry or between plants (including dual unit sites) concerning the operation and design features of the AFW system. Even if the system configuration is the same between similar plants, the system may have different initiation parameters, and the response during a steam generator level transient may also be different. For example, given a low water level condition in a steam generator at some plants, all pumps start, while at others, only the electric-motor-driven pumps start. In addition, once the pumps start, at some plants, the system may not provide flow to the steam generators until level reaches a second lower level setpoint or until a time delay relay times out. Along with these differences, control of feedwater flow also differs considerably. Some plants have automatic flow control, while others control flow manually upon system initiation. In addition, some flow control valves are normally open and modulate closed to control flow, while others are normally closed and must open to provide flow.

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.

A typical AFW system is configured with two separate mechanical divisions. Each division has independent initiation and control functions, and is designed to feed all the steam generators at full capacity. One division may consist of two electric-motor-driven pumps, while the other division may have only one turbine-driven pump. Typically, in a four-steam generator plant, each electric-motor-driven pump train has the capacity to supply two steam generators, while the turbine-driven pump train can supply all four steam generators. In the two-division two-train plants, both pumps are aligned and rated to supply all the steam generators.

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-open air-operated bypass isolation valve. The bypass provides a small, controlled rate of steam flow to the AFW turbine for warming the steam lines and turbine. Steam drain traps are provided in the low points of the steam line to drain condensate from the lines as condensate present in the steam lines could have an adverse affect on turbine reliability during an unplanned demand.

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

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

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

1.3 System Boundaries

For the purposes of this analysis, the AFW system was partitioned into several different segments. These segments are (1) suction, (2) turbine-driven pump, (3) turbine steam supply, (4) turbine-driven pump feed control, (5) electric-motor-driven pump, (6) electric-motor-driven pump feed control, (7) diesel-driven pump, (8) diesel-driven pump feed control, (9) common feed control, and (10) steam generator feed. These segments are described in more detail below:

1. The suction segment includes all piping and valves (including valve operators) from the condensate storage tank (or equivalent based on plant terminology) to the pump suction isolation.

2. The turbine-driven pump segment includes the turbine, trip and throttle valve, governor assembly with the associated controls, the turbine steam supply isolation just upstream of the trip throttle valve, and the valve operators. Also included with this segment is the pump and associated piping from and including the suction isolation up to and including the discharge isolation valve, and associated valve operators. The minimum flow and test recirculation line is included if the associated tap off is prior to the discharge isolation valve.

3. The turbine steam supply segment includes the associated piping, valves, and valve operators from the main steam line penetrations (but not including) to the turbine steam supply isolation valve. The instrument air supply and dc power to the solenoid-operated valves were excluded.

4. The turbine-driven pump feed control segment includes the piping and valves from the pump discharge isolation up to the steam generator for plants with only one AFW injection header per steam generator or plants where AFW has no connection with the main feedwater system. For plants with more than one injection header per steam generator or AFW connects with the main feedwater system, the turbine-driven pump feed control segment includes the pump discharge isolation valve and upstream piping up to the connection point for the alternate injection path or main feedwater system. Included with the segment are the associated valves and valve operators, the flow control valve and the control logic, and the test recirculation line where applicable.

5. The electric-motor driven pump segment includes the motor and associated breaker at the power board (excluding the power board itself). Also included with this segment is the pump and associated piping from and including the suction isolation up to and including the discharge isolation valve, and associated valve operators. The minimum flow and test recirculation line is included if the associated tap off is prior to the discharge isolation valve.

6. The electric motor driven pump feed control segment includes the piping and valves from the pump discharge isolation up the steam generator for plants with only one AFW injection header per steam generator or plants where AFW has no connection with the main feedwater system. For plants with more than one injection header per steam generator or AFW connects with the main feedwater system, the electric-motor driven pump feed control segment includes the pump discharge isolation valve and upstream piping up to the connection point for the alternate injection path or main feedwater system. Included with the segment are the associated valves and valve operators, the flow control valve and the control logic, and the test recirculation line where applicable

7. The diesel-driven pump segment includes the diesel engine, the associated fuel oil including the day tank, diesel cooling water back to the supply isolation and the governor, and the engine starting system. Also included with this segment is the pump and associated piping from and including the suction isolation up to and including the discharge isolation valve, and associated valve operators. The minimum flow and test recirculation line is included if the associated tap off is prior to the discharge isolation valve.

8. The diesel-driven pump feed control segment includes the piping and valves from the pump discharge isolation up to the steam generator for plants with only one AFW injection header per steam generator or plants where AFW has no connection with the main feedwater system. For plants with more than one injection header per steam generator or AFW connects with the main feedwater system, the diesel-driven pump feed control segment includes the pump discharge isolation valve and upstream piping up to the connection point for the alternate injection path or main feedwater system. Included with the segment are the associated valves and valve operators, the flow control valve and the control logic, and the test recirculation line where applicable.

9. The common feed control segment applies to plants where the turbine/diesel and electric-motor-driven pumps discharge to a shared header with flow to the steam generator being regulated in the common header. This segment includes the piping and valves from (but not including) the pump discharge isolation up to the steam generator for plants with only one AFW injection header per steam generator or plants where AFW has no connections with the main feedwater system. For plants with more than one injection header per steam generator or AFW connects with the main feedwater system, the feed control segment includes the pump discharge isolation valve and upstream piping up to the connection point for the alternate injection path or main feedwater system. Included with this segment are the associated valves and valve operators, the flow control valve and the control logic, and the test recirculation line where applicable.

10. The steam generator feed segment includes the check valve(s) and associated piping downstream of the common or turbine/motor feed segments. This segment generally includes the last check valves in the feedwater system piping that prevent short cycling of AFW flow to the main feedwater system.

The Instrumentation and Control subsystem includes the circuits for the system initiation, operation, and the containment isolation function of the AFW turbine steam lines. However, each of the component failures in these circuits were screened to ensure that the failed component identified in the circuit was dedicated to the AFW system. Instrumentation and Control failures are implicit in the segment boundaries. That is, the segment affected by this type of failure would be recorded as a segment failure caused by instrumentation and control.

Additional components that were considered part of the AFW system are the circuit breakers at the motor control centers (MCCs) (but not the MCCs themselves). Heating, ventilating, and air conditioning systems and room cooling associated with the AFW system were also included. Losses of a specific AFW room cooler are included, but not failures within the service water system.

AFW system failures caused by support system failures were captured in this AFW study. Support system failures were defined as failures of systems that affect the operation of the AFW system. These systems included, but were not limited to, 4160 vac vital power, 125 vdc power, service water, engineered safety feature actuation system (ESFAS), and solid state protection system (SSPS). However, because the support system failure contribution to the overall AFW system failure probabilities would be modeled separately in the PRAs, support system failures were not included in the unreliability estimates.