High Pressure Safety Injection Reliability Study

1 HPI SYSTEM OPERATION AND DESCRIPTION

1.1 System Purpose

The HPI system is part of the Emergency Core Cooling System (ECCS) that performs emergency coolant injection and recirculation functions to maintain reactor core coolant inventory and adequate decay heat removal following a loss-of-coolant accident (LOCA). The coolant injection function is performed during a relatively short-term period after LOCA initiation, followed by realignment to a recirculation mode of operation to maintain long-term, post-LOCA core cooling. In addition to the above, reactors which are equipped with pressurizer (PZR) power operated relief valves (PORVs) could use the PORVs and HPI to remove decay heat from the reactor in the event of the loss of the Main Feedwater (MFW) and Auxiliary Feedwater (AFW) systems.

The HPI system actuates automatically on low PZR pressure, high containment pressure, or when steam line pressure or flow anomalies are detected. Therefore, in addition to a LOCA, other events will lead to HPI actuation. Some examples of such events are Steam Generator Tube Ruptures (SGTRs), RCS overcooling events resulting from steam line breaks (e.g. Stuck open main steam safety valves), or RCS depressurization events (e.g. stuck open PZR spray valves).

1.2 System Description

The HPI systems analyzed have been grouped into six different design classes as shown in Table 1. The criteria used to determine this grouping are: the number of steam generators, and the number of intermediate- and high-head safety injection trains available for automatic actuation. The number of steam generators rather than the number of cold legs was used as the criterion since that reduced the number of possible groupings of HPI design. Other groupings are possible, but this grouping utilizes two dominant design characteristics, which have the potential to dominate system reliabilities. Figure 1 is a block diagram of each of the design classes. These block diagrams show how the major system segments (e.g. RWST, pump trains, injection headers and cold legs) are connected to accomplish the HPI function. Even though a single block diagram represents all plants in a given design class, the design and operational differences within a design class (e.g. crossties, normally operating versus standby HPI pumps) were accommodated in modeling individual fault trees. Each system typically consists of at least two independent divisions. The divisions consist of a number of different combinations of motor-driven pump trains. Because of the diversity in system design, operation, and response to plant transients, a detailed discussion of the each plant-specific system is not practical. A general description is provided for the two major designs utilizing high head or intermediate head functional schemes. Differences between the other types of system design classes are also discussed.

Table 1. Listing of the HPI design classes, Units associated with each design class, the number and type of HPI trains, the number of cold-legs, and the success criterion for a small LOCA (as stated in the IPEs).

HPI Class	Plant	Centrifugal Charging Pumps (CCP)	Intermediate Head Safety Injection Pumps (IHSI)	Total High-Pressure Motor Trains	IHSI and CCP for ES Auto or Immediate Manual Start	Cold Leg Injection Paths	Steam Generators	Small LOCA success for HPI (injection phase)
1	Arkansas Nuclear One 2	—	3 (1 swing pump never operates unless one of the two is in maintenance)	3	2	4	2	1/3 pumps; 2/4 injection paths
1	Calvert Cliffs 1 & 2	—	3 (backup pump requires operator)	3	2	4	2	1/2 pumps to 2/4injection paths;
1	Davis-Besse	—	2	2	2	4	2	1/2 HPI pumps and flow to associated R/X nozzle
1	Kewaunee	—	2	2	2	2	2	1/2 HPIs to 1/2 cold legs, also allow for manual start of comp that didn't auto start
1	Millstone 2	—	3 (one pump is a swing pump that requires operator)	3	2	8; 4per sys	2	1/3 HPIs to 3 of 3 unfaulted loops OR 2/3 HPI supplying 2/3 unfaulted loops
1	Palisades	—	2	2	2	4	2	1/2 HPIs to 1/3 intact headers; assume SBLOCA fails fourth header
1	Palo Verde 1, 2, & 3	—	2	2	2	4	2	1/2 HPIs to 3/6 injection headers that feed the 3 RCS SI cold legs; SBLOCA assumed to fault one cold leg path
1	Point Beach 1 & 2	—	2	2	2	2	2	1/2 HPIs to the unfaulted loop initially takes suction from BAST then auto switch to RWST
1	Prairie Island 1 & 2	—	2	2	2	2	2	1/2 HPIs to 1/2 cold legs
1	San Onofre 1 [1], 2, & 3	—	3 (one requires operator to manual realign)	3	2	4	2	1/3 HPIs to 2/4 cold legs

[1] Decommissioned November 1992.

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1	St. Lucie 1 & 2	—	2	2	2	4	2	1/2 HPIs to 1/4 cold legs
1	Waterford 3	—	3 (one needs operator; installed spare)	3	2	4	2	1/2 HPIs to 2 intact cold leg injection paths
2	Arkansas Nuclear One 1	3 (1 pump running; 1 swing pump never operates unless one of the two is in maintenance)	—	3	2	4	2	1/3 pumps; 2/4 injection paths; the swing pump has to be manually aligned to EDG and SW
2	Crystal River 3	3 (1 pump running)	—	3	3	4	2	1/3 MUPs to 1/4 injection paths
2	Fort Calhoun	—	3	3	3	4	2	1/3 HPI to 2/4 legs
2	Ginna	—	3	3	3	2	2	1/3 HPI to 1/2 legs
2	Oconee 1, 2, & 3	3 (1 pump running)	—	3	3	4	2	1/3 HPIs to 1/4 RCS injection nozzles
2	Three Mile Island 1	3 (1 pump running)	—	3	3	4	2	1/3 HPIs through 1/4 injection paths
3	Beaver Valley 1 & 2	3 (1 pump spare)	—	3	2	3	3	1/3 Charging/HHSI pumps to 3/3 cold legs; model as 1/2CCPs to 3/3 cold legs since spare pump is unpowered
3	Farley 1 & 2	3 (serves as HPI; one requires operator)	—	3	2	3	3	1/2 HPI pumps to 2/3 cold legs for 4 hours; 1 normally operating, 1 in standby, 1 as backup to be aligned if one of the others is not available
3	H.B. Robinson	—	3 (1 pump breaker is racked out)	2	2	3	3	1/2 HPIs; 1 HPI pump is at time of IPE undergoing major overhaul hence disabled.

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3	Maine Yankee [2]	3 (1 pump run, 1 pump standby, 1 pump spare)	—	3	2	3	3	1/2 HPSI trains to 1/2 intact cold water loops from RWST; no credit for spare
3	North Anna 1 & 2	3 (1 pump running; 1 needs operator)	—	3	2	3	3	1/3 HHIs; model as 1/2 HHIs since third pump needs manual alignment
3	Shearon Harris 1	3 (1 pump running; 1 pump spare)	—	3	2	3	3	1/2 HPIs *(one normally operating; have a spare pump that can be available in 8 hours)
3	Summer 1	3 (1 pump running; 1 pump breaker is racked out)	—	3	2	3	3	1/2 HPSIs to 2/3 cold legs
3	Surry 1 & 2	3 (1 pump is in "pull-to –lock")	—	3	2	3	3	1/3 HHSIs to 1/3 cold legs; HHSI limited to simultaneous operation of 2 of 3 HHSI pumps
4	Turkey Point 3 & 4	—	4 (2 per unit)	4 (2 per unit)	2	3	3	2/4 HHSI trains to 1/3 cold legs; taking credit for other units pumps
5	Indian Point 2	—	3	3	3	4	4	1/3 HPIs to 1/4 cold legs
5	Indian Point 3	—	3	3	3	8	4	1/3 HPIs to 1/4 cold legs
5	South Texas 1 & 2	—	3	3	3	3	4	1/3 HPSIs to 1/3 cold legs
6	Braidwood 1&2	2	2	4	4	8; 4per sys	4	1/4 CC or SI pumps to 2/4 injection paths
6	Byron 1 & 2	2	2	4	4	8; 4per sys	4	1/4 CC or SI pumps to 2/4 injection paths
6	Callaway	2	2	4	4	8; 4per sys	4	1/4 CC or SI pumps to 2/4 injection paths
6	Catawba 1 & 2	2 (1 pump running)	2	4	4	8; 4per sys	4	1/4 NI or NV pumps to 2/4 injection paths
6	Comanche Peak 1 & 2	2	2	4	4	8; 4per sys	4	1/4 pumps to 2/4 injection paths

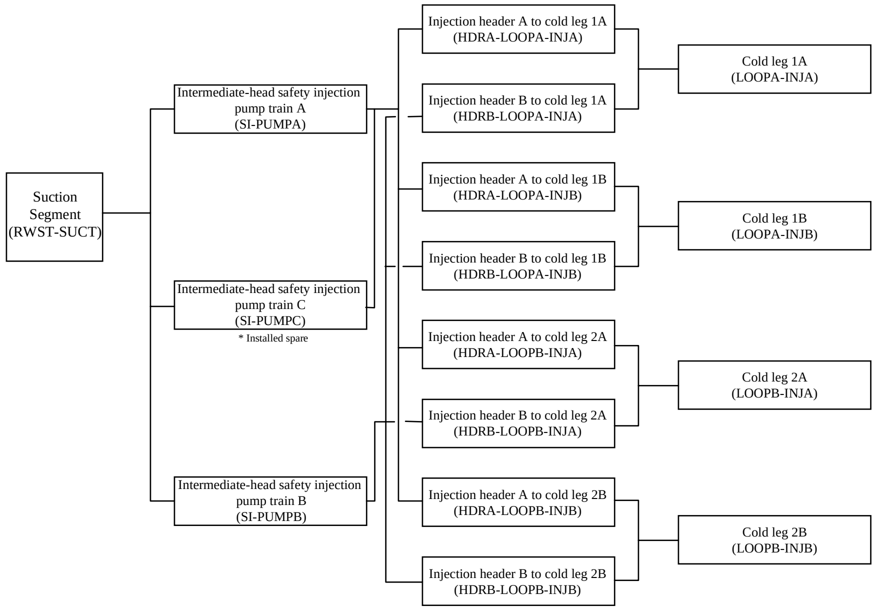
[2] Decommissioned August 1997.

HPI Class	Plant	Centrifugal Charging Pumps (CCP)	Intermediate Head Safety Injection Pumps (IHSI)	Total High-Pressure Motor Trains	IHSI and CCP for ES Auto or Immediate Manual Start	Cold Leg Injection Paths	Steam Generators	Small LOCA success for HPI (injection phase)
6	Cook 1 & 2	2	2	4	4	8; 4per sys	4	1/2 CCPs AND 1/2 SI pumps to 1/3 intact loops
6	Diablo Canyon 1 & 2	2	2	4	4	8; 4per sys	4	1/4 CCPs or SI pumps to 1/4 RCS cold legs
6	Haddam Neck [3]	2	2	4	4	5	4	(1/2 HPIs to 3 of 3 unfaulted legs OR 2/2 HPIs to 2 of 3 unfaulted legs) AND 1/2 CCPs to # 2 cold leg
6	McGuire 1 & 2	2 (1 pump running)	2	4	4	8; 4per sys	4	1/4 CC or SI pumps to 2/4 injection paths
6	Millstone 3	3 (1 pump running, 1 needs operator)	2	5	4	8; 4per sys	4	1/4 HPIs to 3/3 unfaulted RCS cold legs
6	Salem 1 & 2	2	2	4	4	8; 4per sys	4	1/4 centrifugal charging or SJS pumps
6	Seabrook	2	2	4	4	8; 4per sys	4	1/4 HPI trains (SI or CVCS) to 2/4 cold legs
6	Sequoyah 1 & 2	2	2	4	4	8; 4per sys	4	1/4 HPI trains (SI or CVCS) to 2/4 cold legs
6	Vogtle 1 & 2	2 (1 pump running)	2	4	4	8; 4per sys	4	1/2 CCPs through 3/4 cold legs for 3 hrs. OR 1/2 SIs through 3/4 cold legs for 6 hours
6	Watts Bar	2	2	4	4	8; 4per sys	4	1/4 HPS is to 3/4 cold legs
6	Wolf Creek	2	2	4	4	8; 4per sys	4	1/4 HPS is to 3/4 cold legs
6	Zion 1[4] & 2 [5]	2 (1 pump running)	2	4	4	8; 4per sys	4	1 CCP (high-pressure) or 1 SIP (medium pressure)

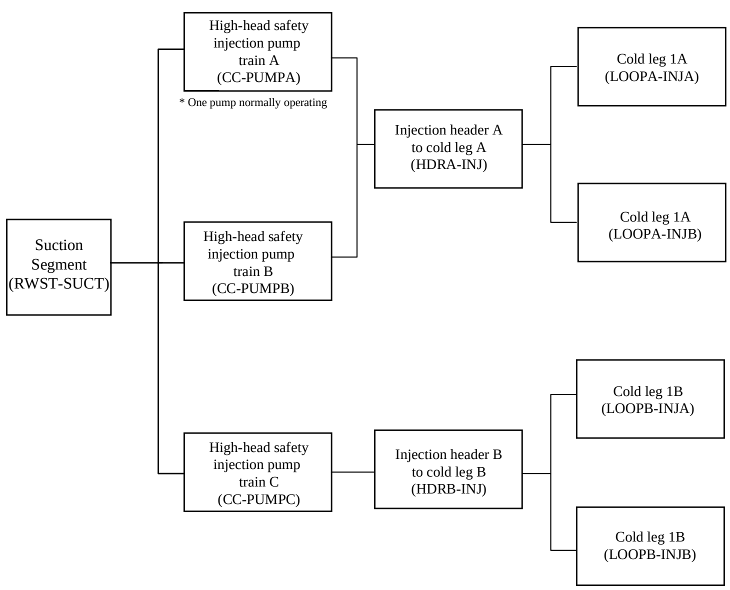
[3] Decommissioned August 1997.

[4] Decommissioned December 1997.

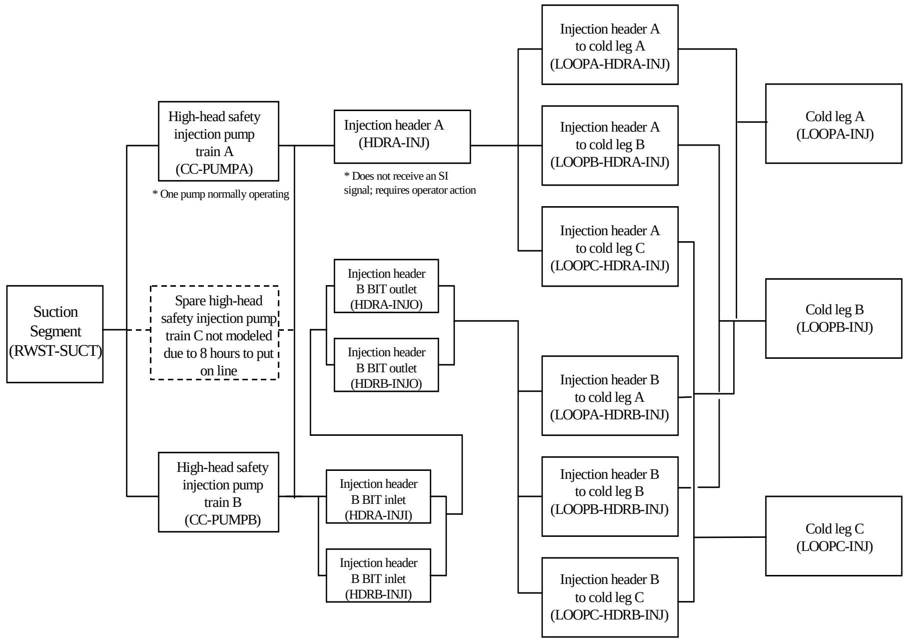
[5] Decommissioned December 1997.



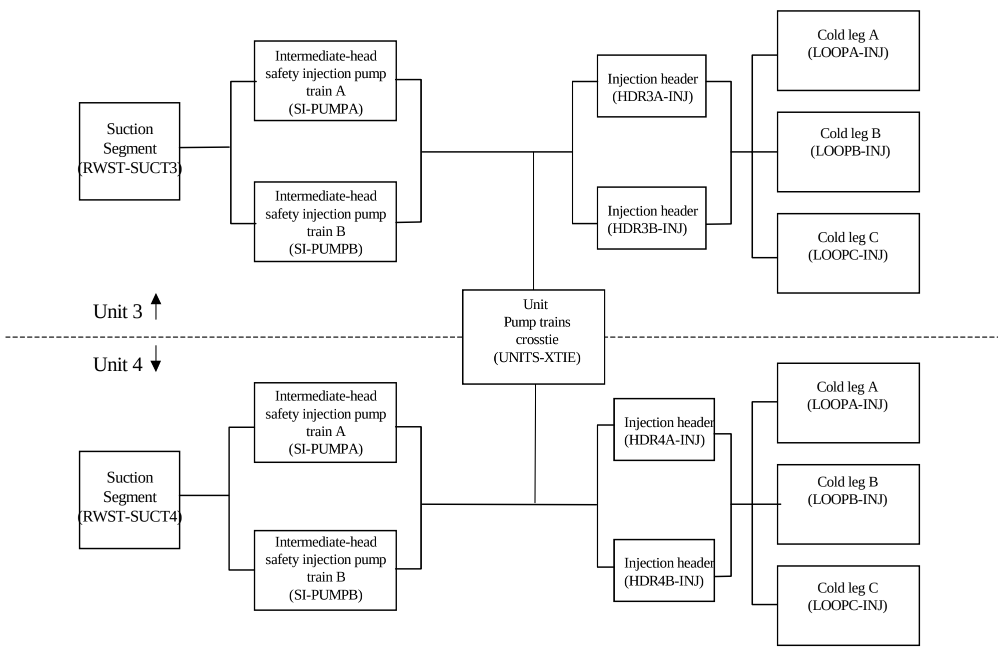
Waterford 3 (Design Class 1)



Oconee 1,2, & 3 (Design Class 2)

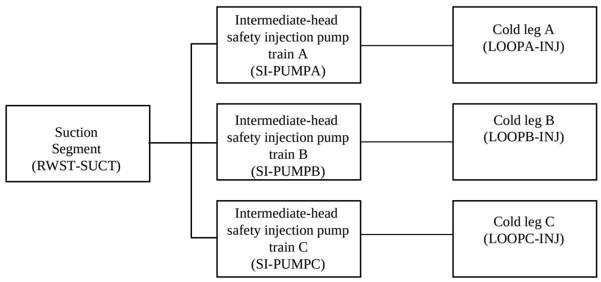


Harris (Design Class 3)

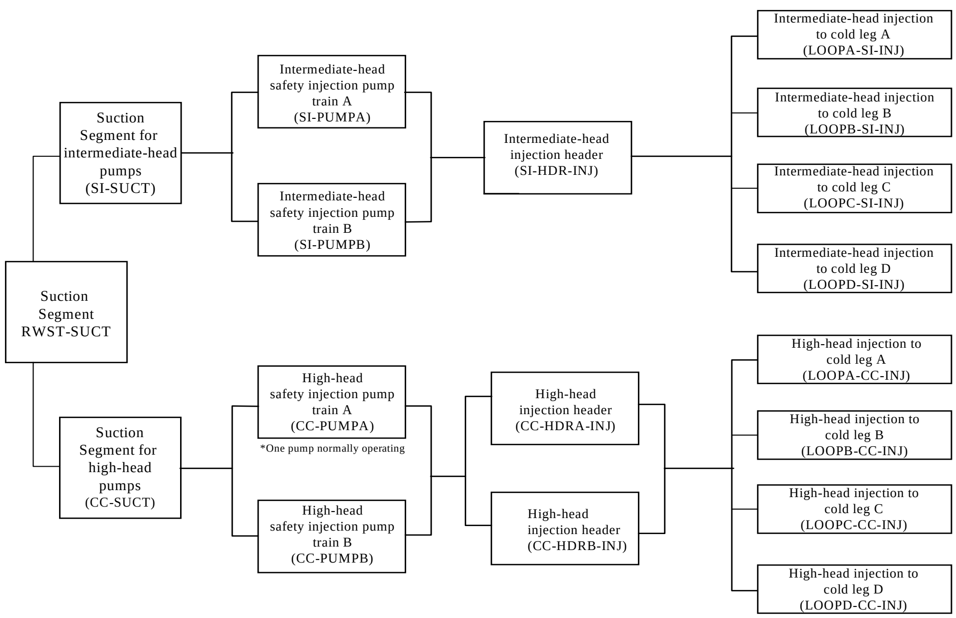


* All 4 pumps start on ES signal; only affected unit valves operate

Turkey Point 3 & 4 (Design Class 4)



South Texas (Design Class 5)



Braidwood 1 and 2 (Design Class 6)

The HPI system is typically not in service during normal plant operations. It is considered part of the Emergency Core Cooling System (ECCS) and is used to restore primary coolant volume during LOCAs, depressurization events, and overcooling events. However, the HPI systems have wide variation from vendor to vendor and from plant to plant. In some plants, B&W in particular and in some Westinghouse designs, the normal make-up pumps are also the HPI pumps, and therefore a portion of the HPI system is in service during normal modes of plant operation. The Combustion Engineering and other Westinghouse designs commonly use a charging system for normal make-up that is separate from the safety injection pumps, which are used only during emergency or abnormal situations. However, even in these designs the make-up and safety injection systems are inter-related because they share common valves, water sources, piping runs, and other equipment. Consequently, the safety injection systems can be either intermediate-head capacity (approximately 1400 psi), or high-head capacity (approximately 2200 psi) depending on whether they are used for normal charging (high-head) or not (intermediate-head). These differences in system pressure determine how it is used during emergencies.

The HPI system is typically started automatically by the engineered safety features actuation system (ESFAS) or equivalent, depending on plant design and terminology. Generally, the ESFAS automatic start signal setpoints include a low reactor coolant system pressure or a high reactor building (i.e., containment) pressure signal. There are additional start signals, but these two are typical.

As mentioned before, in some PWRs (includes Arkansas Nuclear One–Unit 1 and all Design Class 2 and 3 plants except Fort Calhoun, Ginna, and H.B. Robinson), the normally running charging pumps are used to perform the HPI function. In these plants, during normal operations, the charging-pump/make-up pump takes suction from the volume control tank (VCT)/make-up tank (MUT). The level in this tank is maintained from letdown received from the purification loop of the reactor coolant system (RCS), reactor coolant pump (RCP) seal return, charging/make-up pump recirculation, and other minor sources. Borated water is added to the VCT/MUT occasionally depending on losses in the system, such as RCS leakage or operational requirements to borate or deborate. During emergency operation, the suction of the charging/make-up pumps is changed. Several valves reposition automatically upon receipt of a safety injection signal. This allows a large reserve tank to supply borated water to the suction of the charging/safety injection pumps. This large tank is commonly called the refueling water storage tank (RWST) or borated water storage tank (BWST). The water in this tank has a high boron concentration, generally 2400 ppm boron. The tank volume varies from about 245,000 to as high as 450,000 gallons but is often in the 338,000 to 425,000 gallon range. Once the valves have repositioned, the head from the RWST/BWST seats the VCT/MUT outlet check valve, and thereby the highly borated water is supplied to the SI pumps.

During emergency situations, when the water in the RWST/BWST is depleted, water is available to the HPI pumps from the reactor building or containment building sump. This water may be directly available to the SI pumps via piping and valves or it may require a low-pressure stage pump to provide sufficient net positive suction head (NPSH) to the SI and charging/make-up pumps. This source of water becomes extremely important during emergencies that require a prolonged time for injection before being terminated and possibly exhausting the RWST/BWST water capacity. In this case, the HPI system is used in the “recirculation mode.”

The above discussion mainly applies to designs where the charging/make-up pumps used in normal operation are also the HPI pumps during emergencies. These pumps require the low-pressure pumps to provide NPSH from the reactor building or containment building sump, for example Oconee 1, 2, and 3 utilize this design. The following applies to those designs that incorporate separate SI pumps and charging/make-up pumps. For these designs, the charging/make-up pumps operate the same as mentioned above. That is, during normal operation the charging pumps take suction from the VCT/MUT. However, upon receipt of a safety injection signal, the pumps take suction from the RWST and the valves between the VCT/MUT and the charging pump suction close (typically, there are two valves). However, the dedicated SI pumps can only take water from the RWST/BWST and not the VCT/MUT like the charging/make-up pumps. These SI pumps are intermediate head. The intermediate-head SI pumps will require the charging/make-up pumps to be in operation until the RCS press decreases to the pressure where the intermediate-head pumps can inject water. At this point, the charging/make-up pumps can be turned off or left on to help inject a greater volume of water. Braidwood 1 and 2 is an example of this design. The final plant design contains only intermediate-head SI pumps that are used for HPI. These pumps take suction from the RWST/BWST for injection and are aligned to take suction directly from the reactor building or containment build sump during "recirculation mode." Waterford is an example of this design.

In the plants equipped with charging/make-up pumps and dedicated SI pumps (Design Class 6 plants), typically, during normal operation, the charging/make-up pumps supply make-up or cooling water to plant equipment. One is the RCP seal supply. This normally requires 8 to 10 gpm per reactor coolant pump. Another function is pressurizer level control. This system senses pressurizer level and opens or closes the pressurizer level control valve allowing more or less make-up to maintain the selected pressurizer level setpoint. Most of the flow from the charging/make-up pumps is returned to the VCT/MUT via recirculation piping and valves during normal system operation. Once an ECCS signal is received or the operator manually repositions valves to their emergency position, the discharge of the charging/make-up pumps is redirected. There are generally three or four injection nozzles to the RCS for HPI. These nozzles, located in the cold legs of the RCS have instrumented piping connected to them from the charging/make-up pumps and SI pumps depending on the design. Some of the devices and instrumentation on the discharge piping include, but is not limited to injection/isolation valves, flow-balancing orifices, flow crossover piping, and nozzle and total flow indicators. The flow from the SI and the charging/make-up pumps to the RCP seals is reduced. The charging/make-up pump recirculation back to the VCT/MUT is also automatically terminated in order to maximize SI flow into the RCS.

1.2.1 System Boundaries

For the purposes of this analysis, the HPI system is partitioned into several different segments. These segments are (1) suction, (2) pump train, (3) pump injection header, (4) shared injection header, (5) cold leg injection, and (6) Instrumentation and Control subsystem. These segments are described in more detail below:

1. The suction segment includes all piping and valves (including valve operators) from the RWST/BWST to the pump suction header. Also included in this segment are the components and equipment used for VCT isolation and the transfer of pump suction to the RWST.

2. The pump train segment includes the motor and associated breaker, but excludes the electrical power bus itself. Also included with this segment is the pump and associated piping from (and including) the pump-suction header up to and including the discharge header valves, and associated valve operators. The minimum flow and test recirculation line is included if the associated tap off connects prior to the discharge isolation valve.

3. The pump injection header segment includes the piping and valves from the pump discharge isolation valve up to the cold-leg or cold-leg injection segment depending on whether multiple injection segments feed a common cold-leg injection header. This segment begins downstream from the pump discharge isolation valve (or discharge header) and terminates at the point connecting to alternate injection paths (or cold-leg for plants that do not have a shared injection header since these plants have dedicated injection paths from the pumps to the cold legs). Included with the segment are the associated valves and valve operators, the injection valve and control logic, and the test recirculation line where applicable.

4. The common injection control segment applies to plants where the pump discharges to a shared header with flow to the cold-leg being regulated in this common line. This segment includes the piping and valves from (but not including) the pump discharge isolation up to the cold-leg for plants with only one injection header per cold-leg. For plants with more than one injection header per cold-leg or where the injection path connects with another injection systems, the injection control segment includes piping up to the connection point for the alternate injection path. Included with this segment are the associated valves and valve operators, the injection/isolation valve and the control logic, and the test recirculation line where applicable.

5. The cold-leg (loop) injection segment includes the check valve(s) and associated piping downstream of the common injection header segments. This segment generally includes the last check valves in the injection system piping immediately upstream of the RCS cold leg.

6. The Instrumentation and Control subsystem includes the circuits for initiation of the HPI system. It includes sensors, transmitters, instrument channels, and analog or solid state components used for HPI train actuation.

Additional components that were considered part of the HPI system are the circuit breakers at the motor control centers (MCCs) (but not the MCCs themselves) that are specifically dedicated to the HPI system. Heating, ventilating, and air conditioning systems and room cooling dedicated with the HPI system were also included. Losses of a specific HPI room cooler are included if the losses cause failure of the HPI system or train to perform its intended function. However, failures within the service water system are not included in the quantification.

Failures associated with the HPI system caused by support system failures are captured in this study in order to derive engineering insights and to perform sensitivity analysis of these failures on the HPI system unreliability. Support system failures were defined as failures of systems (or components) that affect the operation of the HPI system. These support systems included, but were not limited to, 4160 and 480 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 HPI system failure probabilities would be modeled separately in the PRAs, support system failures were not included in the unreliability estimates.