High Pressure Coolant Injection System Reliability Study

1 HPCI DESCRIPTION

When the high pressure coolant injection (HPCI) system receives an automatic start signal as a result of an actual low reactor pressure vessel (RPV) water level condition, high drywell pressure, or a manual start, the system functions successfully if the turbine starts and obtains rated speed and pressure, the injection valve opens, and coolant flow is delivered to the RPV until the flow is no longer needed. In addition, the suction needs to transfer on a low level in the condensate storage tank. Failure may occur at any point in this process. For the purposes of this study, the following failure modes were observed in the operating data:

- Maintenance-out-of-service (MOOS) occurs if, because of maintenance activities the HPCI system is prevented from starting during an unplanned demand.

- Failure-to-start injection valve (FTSI) occurs if the system is in service but fails to automatically or manually start, obtain rated speed in the turbine, or develop sufficient injection pressure and flow to the reactor pressure vessel. This failure mode does not include the injection valve.

- Injection valve failure-to-open (FTSV) occurs on the start demand if the valve fails to respond to the automatic signal to open.

- Failure to run (FTRI) occurs if, at any time after the system is delivering sufficient coolant flow, the HPCI system fails to maintain this flow to the RPV while it is needed.

- Injection valve failure-to-reopen (FRO) occurs during the later part of the demand if the valve fails to respond to a manual signal to open. This event is coupled with the probability that multiple injections may be required.

- Failure to transfer suction (FTRT) from the condensate storage tank (CST) to the suppression pool when the level in the CST reaches a low-level setpoint.

Recovery of failures is important and was considered when estimating system unreliability. To recover from a failure, operators have to recognize that the system is in a failed state, restart it without performing maintenance (for example, without replacing components), and restore coolant flow to the RPV. An example of such a recovery would be an operator (a) noticing that the injection motor operated valve (MOV) had not opened during an automatic start of the system, and (b) manually operating the control switch for this valve, thereby causing the MOV to open fully and allow coolant flow to the RPV. Recovery for the other failure modes is defined in a similar manner. Each failure was evaluated to determine whether recovery by an operator occurred.

2 HPCI SYSTEM FAULT TREES

Estimates of HPCI system unreliability are calculated using a simple PRA model (fault tree). Basic event failure probabilities based on operational data were used to quantify the model.

The demands represent opportunities for HPCI system success. Each failure observed in a HPCI operational phase that was not recovered takes away an opportunity from a following phase. With this in mind, the demands are based on the following logic:

1. For the HPCI system to have the opportunity to start, the system could not be inoperable due to maintenance at the time of the demand. If so, then there is no opportunity for HPCI to start. The opportunities to start consist of the number of initial demands minus any MOOS failures observed. The failure to start the HPCI system was partitioned into failure to start other than injection valve (FTSI) and FTSV to gain additional insights into the reliability for this operational phase and to use as much of the cyclic test data as possible.

2. The next operating event in a HPCI system response deals with FTSV. Therefore, any FTSI failure eliminates an opportunity for FTSV. The FTSV unplanned demand counts differ from the FTSI demands, since the injection valve receives a permissive signal to open only if adequate pump discharge pressure is present and the low RPV water level signal is locked in. Since the injection valve is not tested under the conditions experienced during an unplanned demand, cyclic test data were not used for FTSV.

3. Once the pump has started and the injection valve has opened, the pump is required to run until stopped. This is referred to as the failure to run injection valve (FTRI).

4. For the unplanned demands, the failures observed during the run phase have the opportunity to be recovered. Failures observed during the run phase of a cyclic test generally result in the test being terminated, and no effort to recover the failure is attempted. Therefore, no fail to recover entries for the test-related events would be tabulated even if failures had occurred.

5. The FRO failure data refers to the failure to re-open the injection valve. This is required only for some of the longer events. Therefore, the probability of multiple injections (PMI) was calculated and this was combined with the failure to recover the FRO.

6. The remaining operational phase of the HPCI involves the failure to transfer the suction source (FTRT). Recovery of the FTRT is also modeled.

2.1 HPCI Unreliability for an Eight Hour Mission

The unreliability of the HPCI system was calculated using the simple fault tree model shown in Figure 1. The model was constructed to reflect the logical combination of the failure modes developed using the operational data.

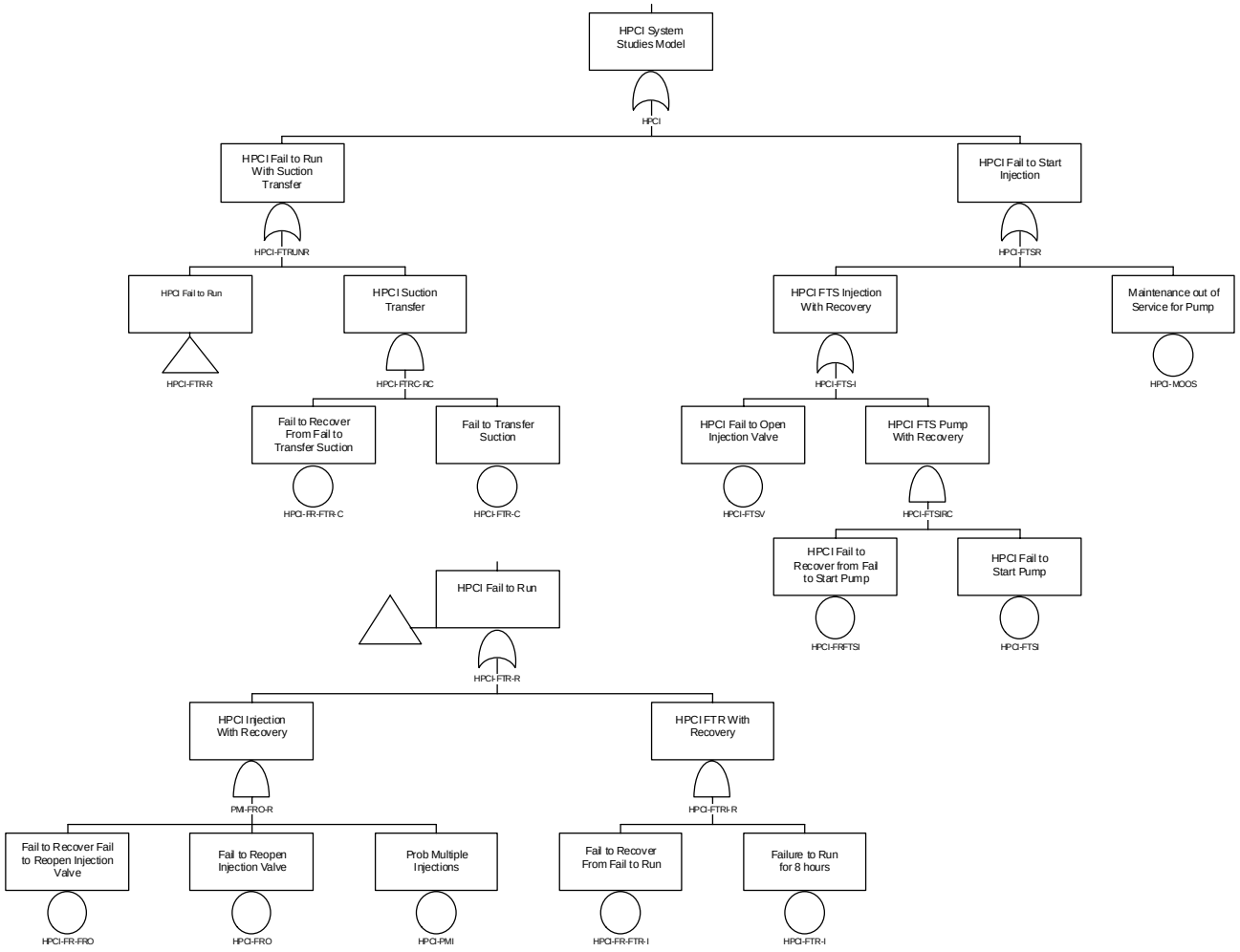

Figure 1. Unreliability model of HPCI operation for an 8-hour mission.

2.2 HPCI Unavailability for a Start Only Mission

The unavailability of the HPCI system for conditions requiring start only operation of HPCI was calculated using the system fault tree model shown in Figure 2. For these transients, HPCI is started and runs for a short period before it is stopped, either automatically or manually. Based on the operating data, the time of HPCI operation for these types of missions is generally in the 5 to 10 minute range and is less than 15 minutes. These types of demands are referred to as *start only*.

Estimates of HPCI unreliability for start only operations were calculated from the operating experience data. The following failure modes were used in estimating HPCI system unreliability for the start only mission:

- Maintenance-out-of-service (MOOS) occurs if, because of maintenance activities the HPCI system is prevented from starting during an unplanned demand.

- Failure to start (FTSI) occurs if the system is in service but fails to automatically or manually start, obtain rated speed in the turbine, or develop sufficient injection pressure and flow to the reactor pressure vessel. This failure mode does not include the injection valve.

- Injection valve failure-to-open (FTSV) occurs on the start demand if the valve fails to respond to the automatic signal to open.

Recovery of failures is important and was considered when estimating system unavailability. To recover from a failure, operators have to recognize that the system is in a failed state, restart it without performing maintenance (for example, without replacing components). The unavailability model only models the recovery of the injection valve.

For the purposes of quantifying the fault tree, the following conditions were assumed:

- A demand to inject coolant to the RPV is received by the HPCI system.
- HPCI is required to restore RPV water level.
- Feedwater and/or other high-pressure makeup systems are also available to restore and maintain RPV water level.
- HPCI operation is required only for the short term (i.e., less than 15 minutes).

The demands represent opportunities for HPCI system success. Each failure observed in a HPCI operational phase that was not recovered takes away an opportunity from a following phase. With this in mind, the demands are based on the following logic:

1. For the HPCI system to have the opportunity to start, the system could not be inoperable due to maintenance at the time of the demand. If so, then there is no opportunity for HPCI to start. The opportunities to start consist of the number of initial demands minus any MOOS failures observed. The failure to start the HPCI system was partitioned into failure to start other than injection valve (FTSI) and FTSV to gain additional insights into the reliability for this operational phase and to use as much of the cyclic test data as possible.

2. The next operating event in a HPCI system response deals with FTSV. Therefore, any FTSI failure eliminates an opportunity for FTSV. The FTSV unplanned demand counts differ from the FTSI demands, since the injection valve receives a permissive signal to open only if adequate pump discharge pressure is present and the low RPV water level signal is locked in. Since the injection

valve is not tested under the conditions experienced during an unplanned demand, cyclic test data were not used for FTSV.

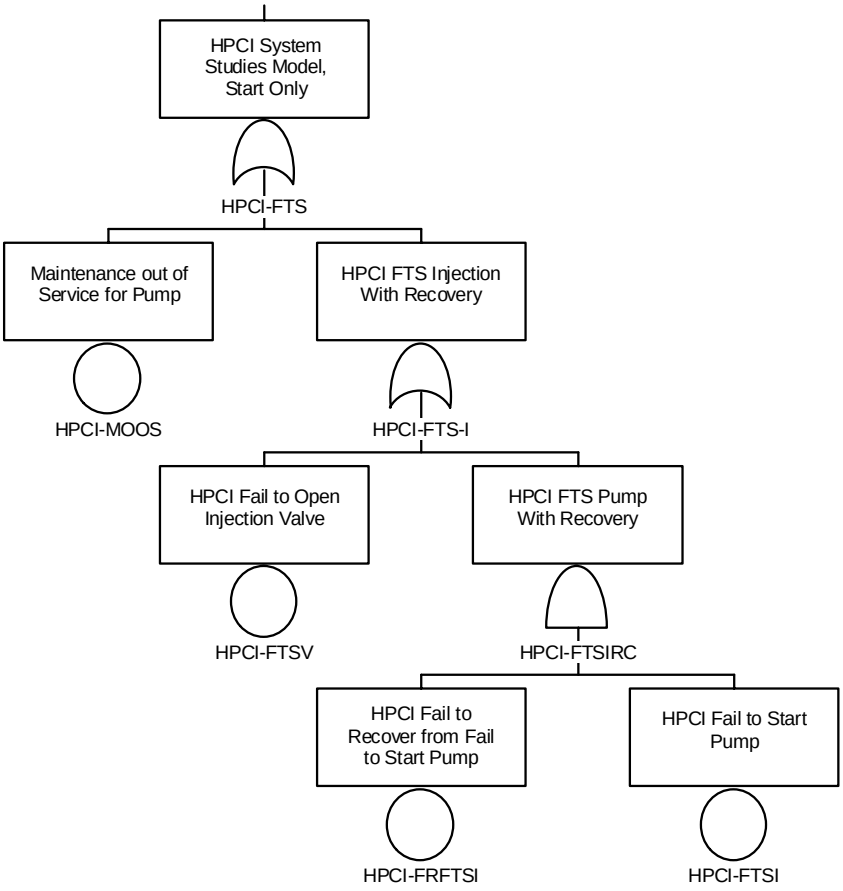

Figure 2. Unavailability model of HPCI system for a start only mission.

3 ACRONYMS

FR	failure to recover
FTR	failure to run
FTRI	failure to run injection valve
FTRT	failure to transfer suction source
FRO	failure to re-open injection valve
FTS	failure to start
FTSI	failure to start other than injection valve
FTSV	failure to start injection valve
MOOS	maintenance-out-of-service
PMI	probability of multiple injection
HPCI	high pressure coolant injection

4 TERMINOLOGY

Demand—An event requiring the HPCI system to inject coolant to the reactor pressure vessel (RPV). This event may be the result of a scheduled (i.e., surveillance test) or an unscheduled (i.e., unplanned) demand. An unplanned demand is either a manual or automatic start because of an actual low RPV water level condition. Engineered safety feature (ESF) actuations of portions of the system (e.g., steam supply isolation valve closures for containment isolation) were not considered as demands.

Failure—An inoperability in which the injection function was lost. For estimating the operational unreliability, a subset of the failures was used. (That is, only those that occurred on unplanned actuations or cyclic surveillance tests were used.)

Failure to run (FTR)—Any failure to complete the mission after a successful start. This includes obvious cases of failure to continue running and cases when the system started and injected, tripped off for a valid reason, and then could not be restarted. Excluded from the failure to run events were failures to restart and failures to transfer during recirculation to injection.

Failure to start—Failure of the system to start and inject coolant into the RPV on a valid demand signal.

Fault—An inoperability in which the injection function of the system was *not* lost. This includes administrative technical specifications violations such as late performance of a surveillance test.

Inoperability—An event affecting the HPCI system such that it did not meet the operability requirements of plant technical specifications and therefore was required to be reported in a LER.

Maintenance-out-of-service (MOOS)—HPCI system failure attributed to the system being out of service for either preventive or corrective maintenance at the time of the unplanned demand.

Maintenance unavailability—Probability that the system is out of service for maintenance at any moment in time.

Mission time—The elapsed clock time from the first demand for the system until plant conditions are such that the system is no longer required. PRAs typically assume that HPCI is needed for injection throughout the entire mission time. In the plant operating experience, this period includes not only injection but also recirculation through the test return line or system shut down and restart.

Operating conditions—Conditions in which technical specifications require HPCI operability, typically with the reactor vessel pressurized.

Operating data—A term used to represent the industry operating experience as reported in LERs. It is also referred to as operating experience or industry experience.

PRA/IPE—A term used to represent the data sources (PRAs, IPEs and NUREGs) that describe plant-specific system modeling and risk assessment, rather than a simple focus on operating data.

P-value—The probability that the data would be as extreme as it is, assuming the model or hypothesis is correct. It is the significance level (0.05 for this study) at which the assumed model or hypothesis is statistically rejected.

Recovery—An act that enables the HPCI system to be recovered from a failure without maintenance intervention. Generally, recovery of the HPCI system was only considered in the unplanned demand events. Each failure reported during an unplanned demand was evaluated to determine whether recovery of the system by operator actions had occurred. Typically, a failure was recovered if the operator was able to reposition a switch, open a valve or reset the governor to restore injection to the RPV. Events that required replacing components were not considered as recoveries. In addition, recovery was not considered during the performance of a surveillance test.

Unreliability—Probability that the HPCI system will not perform its required mission. This happens if the system is out of service for maintenance, or if the HPCI system fails to start, run, restart, or transfer suction during operation.