Reactor Core Isolation Cooling Reliability Study

This study documents an analysis of the operating experience of the 30 BWRs listed in Table 1, all of which have a RCIC system. The analysis focused on the ability of the RCIC system to start and provide adequate core cooling flow for its required mission time. The containment isolation function associated with the RCIC system is not within the scope of this study. The system description and boundaries, data collection, failure categorization, and limitations of the study are briefly described in this section.

Table 1. BWR plants with a RCIC system selected for the study.

Plant Name	Docket	Plant Name	Docket
Browns Ferry 2	260	LaSalle 2	374
Browns Ferry 3	296	Limerick 1	352
Brunswick 1	325	Limerick 2	353
Brunswick 2	324	Monticello	263
Clinton	461	Nine Mile Pt. 2	410
Columbia Nuclear 2	397	Peach Bottom 2	277
Cooper	298	Peach Bottom 3	278
Duane Arnold	331	Perry	440
Fermi 2	341	Pilgrim	293
Fitzpatrick	333	Quad Cities 1	254
Grand Gulf	416	Quad Cities 2	265
Hatch 1	321	River Bend	458
Hatch 2	366	Susquehanna 1	387
Hope Creek	354	Susquehanna 2	388
LaSalle 1	373	Vermont Yankee	271

1 SYSTEM OPERATION AND DESCRIPTION

The RCIC system is a single train standby system required by plant technical specifications for safe shut down of the plant. The system is not considered part of the emergency core cooling system (ECCS), and does not have a loss of coolant accident (LOCA) function. The RCIC system is designed to ensure that sufficient reactor water inventory is maintained in the vessel to permit adequate core cooling. This prevents the reactor fuel from overheating in the event that:

1. A complete plant shut down occurs under conditions of a loss of the feedwater system before the reactor is depressurized to a point where the shut down cooling system can be placed into operation.

2. The reactor pressure vessel (RPV) is isolated in conjunction with a loss of coolant flow from the feedwater system.

Following a normal reactor shut down, core fission product decay heat causes steam generation to continue, albeit at a reduced rate. During this time, the turbine bypass system diverts the steam to the main condenser, and the RCIC system supplies the makeup water required to maintain reactor vessel inventory. (Note that the RCIC system is just one of a number of systems capable of performing this function.) The turbine-driven pump supplies makeup water from the condensate storage tank (CST) to the reactor vessel. An alternate source of water is available from the suppression pool. The turbine is driven by a portion of the steam generated by the decay heat and exhausts to the suppression pool. This operation continues until the vessel pressure and temperature is reduced to the point that the residual heat removal (RHR) system can be placed into operation.

1.1 System Operation

Based on the operating data reviewed for this study, the RCIC system was found to have two operational missions. We categorized these two missions as either short-term or long-term, depending on the plant conditions associated with the need for RCIC to provide coolant flow to the RPV. The distinction between the two operational missions is based on the time the system was operated for the particular event. The short-term missions were defined as those missions where the use of RCIC for coolant injection was required for less than 15 minutes. These short-term missions were typically only a few minutes in duration. The long-term missions were defined as those missions where the need for RCIC operation was required beyond 15 minutes. Long-term missions may have required RCIC operation for several hours.

The short-term missions observed in the operating data were of two types: either they required the RCIC system to start automatically on a low RPV water level signal, or they required operators to manually start the system to mitigate a RPV water level transient. For both of these cases, the need for RCIC was observed following a reactor scram from high power operations and may have involved either a RPV level control problem or a closure of the turbine stop valves. In these events the RCIC system quickly restored the RPV water level. In a few cases, the system was restarted a second time to restore RPV water level. Overall, the use of the system was required for only a few minutes. In these short-term missions, feedwater was available or was restored within a few minutes to provide normal RPV water level control.

In some of the short-term missions, the plant experienced a reactor scram during power operations without a loss of normal feedwater or a closure of the turbine stop valves. In these cases, the void collapse associated with the scram caused a demand for RCIC injection; the high-pressure core spray (HPCS) or high-pressure coolant injection (HPCI) systems (depending on plant design) also automatically initiated to supply makeup water to the reactor vessel. In these cases, the systems were shut down after RPV water level was restored to the normal operating band.

The long-term missions observed in the operating data were events where the plant would experience a reactor scram during power operations either as a result of a loss of normal feedwater or an isolation of the reactor vessel. In either case, RCIC would operate to provide adequate RPV water level for periods up to several hours. For these long-term missions, either the control room operator would manually initiate the RCIC system, or the system would automatically start at the predetermined low reactor water level setpoint. At this point, the system would inject until the system was shut down by the operator or the high level trip setpoint was reached, at which time the RCIC turbine steam supply and coolant injection valves were closed. With the continued steam generated by decay heat and corresponding lowering of vessel level (as a result of safety relief valve or turbine bypass valve operation), the system would be re-started during the event and the cycle repeated one or more times.

As an alternative to having the system either manually or automatically cycled on and off between high and low vessel level setpoints, the system can be used to raise level to the normal operating level band, and then the control room operator can open the test-return-line motor-operated valve (MOV) and divert RCIC flow back to the CST. This practice, similar to the pressure control mode of operation of the HPCI system, would minimize repeated restarts of the system. The RCIC system would operate continuously throughout the event by providing flow to the vessel when needed and by recirculating flow back to the CST through the test-return-line when not needed. In these events, the injection and test-return-line MOVs are cycled for the duration of the event, which could last several hours. If the RCIC system were to fail during the event, the HPCS/HPCI system could provide adequate vessel coolant inventory.

For some BWR designs, there is another option available for removing decay heat during a planned isolation event when the main condenser is not available. With this option, the RCIC system would operate in conjunction with the RHR system in the steam-condensing mode. In this mode, condensed steam is delivered from the RHR heat exchangers through an interconnection to the RCIC pump suction for return to the RPV. Thus, closed loop cooling is provided by this mode. This mode of operation was not observed in the operating data reviewed in this study.

1.2 System Description

The RCIC system is a single train standby system that contains a single 100% capacity steam turbine-driven pump. The RCIC system is capable of delivering reactor grade water from the CST to the RPV using reactor-decay-heat-generated steam as a source of energy to drive the turbine-driven pump. In the event that CST water is not available, an alternate source of water is available from the suppression pool. Figure 1 provides a simplified diagram of a typical RCIC system.

The RCIC system steam turbines (at all plants) are Dresser-Rand Terry-Turbodyne (Terry) turbines designed for constant capacity over varying ranges of inlet steam pressure, typically 1040 psig to 50 psig. These turbines have horsepower ratings that vary from 460 to 875 with associated pump flow rates from 400 to 800 gpm, depending on plant design. All Terry turbines that drive RCIC pumps use Woodward governors (type EG-M with EGR actuators) for speed control, including prevention of overspeed during “cold quick-starts.” The ratings for the RCIC system varies by plant design class, with the older Design Class II plants having the smaller capacity systems and the newer Design Class VI plants having the higher capacity systems. However, because of the overall similarities of the system in the various design classes (same equipment manufacturer), no distinction was made in this report between the different design classes.

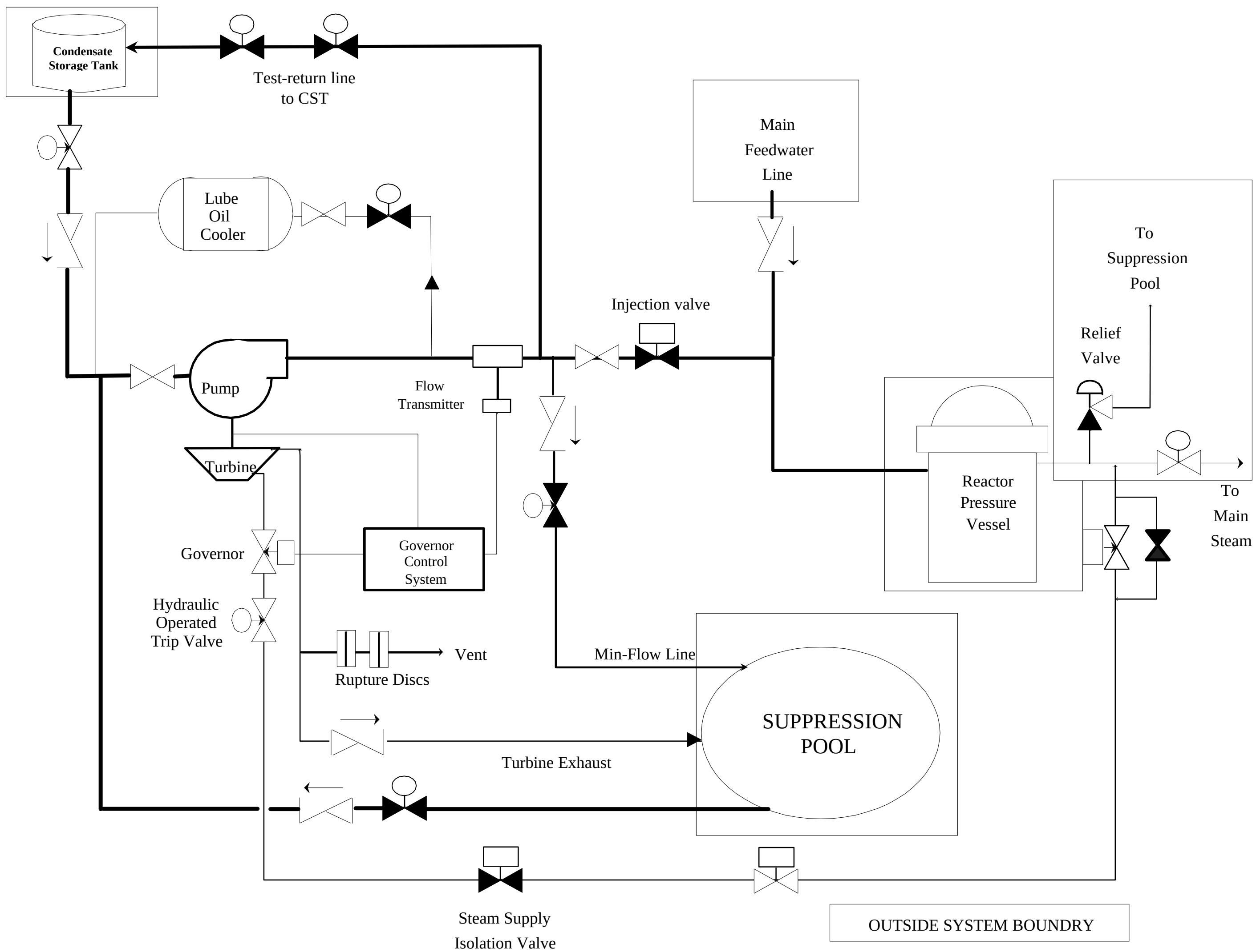
Turbine “cold quick-starts” are required to meet pump starting time limits in Safety Analysis Reports, and other requirements specified to meet the reactor safety analyses of the nuclear steam supply system vendor. A cold start is considered a start that occurs when a turbine has not been operated for at least 72 hours. Turbine “quick-starts” occur when the turbine is required to reach rated speed and pump flow in 30 to 120 seconds. Since standby turbines are idle for extended periods, lubricating oil drains from the turbine bearings, leaving the bearings vulnerable to excessive wear. Standby turbines supplied by Terry typically also use turbine lubricating oil as the hydraulic operating fluid for the governors and actuators. To provide bearing lubrication and governor oil on quick starts, a pressurized lubrication oil system is provided, which uses a shaft-driven lubrication oil pump. The shaft-driven pump provides lubrication oil to the turbine bearings and governor assembly as soon as the turbine begins to roll, enhancing both turbine lubrication and governor response.

To control turbine speed, a governor valve is provided for the turbine; the valve is typically supplied by Terry. The governor valve is fully open at the beginning of a quick-start and is designed to assume speed control during the startup when the turbine speed reaches the governor’s minimum speed setting (approximately 2000 rpm). During a quick start the turbine steam admission valve opens fully and the turbine accelerates rapidly to the governor’s minimum speed setting. At the minimum speed setting the governor starts to control turbine speed by throttling closed the governor valve. This limits the acceleration of the turbine to prevent an overspeed trip of the turbine. The closing of the governor valve slows the turbine to a speed less than the minimum speed. At this point the governor in conjunction with the ramp-generator increases turbine speed in a controlled manner to rated speed by slowly opening the governor valve. The ramp-generator controls and limits the time for the turbine to reach rated speed to approximately 30 seconds after the governor gains control. If inlet steam flow is excessive during a quick start, the governor valve cannot close sufficiently to limit speed before the turbine overspeeds.

The RCIC system instrumentation and control consists of system initiation and containment isolation circuitry. These two circuits provide different functions, both of which can contribute to system unreliability. The purpose of the initiation circuitry is to initiate actions (that is, start up the RCIC system) to ensure adequate core cooling when the reactor vessel is isolated from its primary heat sink and normal coolant makeup flow from the feedwater system is insufficient or unavailable. The purpose of the containment isolation circuitry is to initiate closure of appropriate containment isolation valves to limit fission product release should a RCIC steam line rupture occur.

The RCIC system initiation circuit allows for manual and automatic initiation of the system. Automatic initiation occurs for conditions of low reactor water level. The low reactor water level parameter is monitored by four transmitters that are connected to relays whose contacts are arranged in a one-out-of-two taken twice logic arrangement. Once initiated, the RCIC logic seals in and can be reset by the operator only when the reactor vessel level signals have cleared. Upon system initiation, the turbine steam supply valve opens to supply steam to the turbine, and the injection valve and the suction valve from the CST open to supply coolant flow to the RPV. In addition, the test-return line isolation valve is closed to allow full system flow and maintain primary containment isolation. Failure of any one of these valves to function during an initiation results in a failure of the system.

The RCIC system containment isolation circuitry typically provides automatic closure of the RCIC turbine steam supply isolation valves and turbine exhaust valve in the event of a steam line failure (high energy line break). The parameters monitored typically include high steam flow, low steam line pressure, high room delta-temperature, and high area temperature. Isolation of these valves disables the RCIC injection function: however, failure of this circuit to close these valves would not preclude operation of the system. During system standby a spurious isolation of the steam supply line caused by this circuit contributes to system unavailability, and during system operation the spurious isolation can contribute to system unreliability.



BWR Reactor Core Isolation Cooling

Figure 1. Simplified RCIC system schematic.

1.3 System Boundaries

The RCIC system for this study was partitioned into three subsystems for analysis purposes. These subsystems are: (1) the Turbine and Turbine Control Valves, (2) Coolant Piping and Valves, and (3) Instrumentation and Control. These three subsystems are composed of the following:

- The Turbine and Control Valves subsystem includes the turbine and governor assembly and associated controls. Also included with this subsystem are all steam piping from the main steam line penetration to the turbine, the turbine exhaust piping to the suppression pool with associated valves, and the turbine control and steam line isolation valves and valve operators.
- The Coolant Piping and Valves subsystem includes the turbine-driven pump assembly and associated fluid piping, including the normal (from the CST) and alternate (from the suppression pool) pump suction sources and the pump discharge to the reactor pressure vessel penetration or main feedwater line, depending on plant design. Included with this subsystem are the associated valves and valve operators. The suppression pool and the CST are not included in the system boundaries.
- The Instrumentation and Control subsystem includes the circuits for system initiation, operation, and containment isolation of the RCIC steam lines. However, each failure of these circuits was screened to ensure that the component identified in the circuit was dedicated to the RCIC system before it was included in this report.

Additional components that were considered part of the RCIC system were the circuit breakers at the motor control centers (MCCs) (but not the MCCs themselves), the dedicated DC power system that supplies RCIC system power, and the associated inverters. Heating, ventilating, and air conditioning (HVAC) systems and room cooling associated with the RCIC system were included, with the exception of the service water system that supplies cooling to the room coolers. Only a specific loss of service water to individual RCIC room coolers was included, and not the entire service water system.

Support system failures were considered for possible inclusion in this RCIC study. However, support systems were treated as outside the scope of this study since they are separately modeled in PRAs.