INL/RPT-22-66589

System Study: Reactor Core Isolation Cooling 1998–2020

March 2022

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Prepared for the
Division of Risk Assessment
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
NRC Agreement Number 31310019N0006
Task Order Number 31310019F0022

ABSTRACT

This report presents an unreliability evaluation of the reactor core isolation cooling (RCIC) system at 31 U.S. commercial boiling water reactors. Demand, run hour, and failure data from calendar years 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. No statistically significant increasing or decreasing trends were identified in the RCIC results.

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ACRONYMS

AOV	air-operated valve
BWR	boiling water reactor
CCF	common-cause failure
CST	condensate storage tank
EPIX	Equipment Performance and Information Exchange
FTOC	fail to open/close
FTOP	fail to operate
FTR	fail to run (normally running equipment)
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
MOV	motor-operated valve
MSPI	Mitigating Systems Performance Index
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling
ROP	Reactor Oversight Process
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 reactor core isolation cooling (RCIC) systems at the 31 U.S. commercial boiling water reactors (BWRs) (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 RCIC system 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 RCIC unreliability results using basic event values from the *2010 Component Reliability Update*[a] are summarized in Section 1. Trend results for HPCI (using system-specific data) are presented in Section 1. Similar to previous system study updates, Section 1 contains importance information (using the baseline results from Section 1), Section 6 presents the data used in the trending analysis, and Section 7 describes the RCIC.

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

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

Plant	Version
Duane Arnold	8.22
Browns Ferry 1	8.22
Browns Ferry 2	8.22
Browns Ferry 3	8.18
Brunswick 1	8.20
Brunswick 2	8.20
Clinton 1	8.17
Columbia 2	8.16
Cooper	8.22
Fermi 2	8.20
FitzPatrick	8.17
Grand Gulf	8.22
Hatch 1	8.20
Hatch 2	8.20
Hope Creek	8.18
Limerick 1	8.20
Limerick 2	8.19
La Salle 1	8.21
La Salle 2	8.21
Monticello	8.20
Nine Mile Pt. 2	8.17
Peach Bottom 2	8.25
Peach Bottom 3	8.21
Perry	8.19
Pilgrim	8.21
Quad Cities 1	8.18
Quad Cities 2	8.18
River Bend	8.20
Susquehanna 1	8.23
Susquehanna 2	8.21
Vermont Yankee	8.19

2. SUMMARY OF FINDINGS

The results of this RCIC system unreliability study are summarized in this section. Of particular interest is any statistically significant[a] increasing trends. In this update, **no statistically significant increasing or decreasing trends** were identified in the **RCIC unreliability** trend results.

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

- In the **Start-Only** case—the leading contributor to RCIC system unreliability is the **RCIC turbine-driven pump (TDP)** group of basic events followed by the Restart, CST (condensate storage tank) Suction, and Suppression Pool groups.
- In the **8-Hour Mission** case—the leading contributor to RCIC system unreliability is also the **RCIC TDP** group of basic events followed by the Restart, CST Suction, and Suppression Pool groups.

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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 RCIC fault trees from the SPAR models were evaluated for each of the 31 operating U.S. commercial boiling water nuclear power plants with a RCIC system.

The industry-wide unreliability of the RCIC system has been estimated for two variations. A start-only model and an 8-hour mission model were evaluated. The uncertainty distributions for RCIC show both plant design variability and parameter uncertainty from the 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 RCIC fault trees in the SPAR models. The lower and upper bounds are based directly on the samples (Latin hypercube) from the uncertainty calculations in the SPAR models. For the industry-level results, the SPAR samples were combined into one large sample in order to determine the industry-level bounds, mean, and median.

Table 2. Industry-wide unreliability values.

Model	Lower (5%)	Median	Mean	Upper (95%)
Start-only	1.27E-02	2.48E-02	2.89E-02	5.58E-02
8-hour Mission	2.00E-02	3.84E-02	4.31E-02	8.02E-02

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

4. INDUSTRY-WIDE TRENDS

The yearly failure and demand or run time data from 1998–2020 were obtained from IRIS for the RCIC system. RCIC 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 RCIC system components using the trending methods described in Sections 1 and 2 of Reference [4]. Tables Table 6 and Table 7 show the yearly data values for each RCIC system specific component and failure mode combination that was varied in the model. These data were loaded into the RCIC system fault tree in each SPAR model with a RCIC 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 in Table 2 is shown as “SPAR/ICES” in the charts for comparison. Section 1 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 and failure modes that were varied in the RCIC model are:

- RCIC TDP start, run, and test and maintenance
- RCIC injection motor-operated valve (MOV) fail-to-open.

Figure 1 shows the trend in the start-only unreliability. Table 4 shows the data points for Figure 1. **No statistically significant trend** was identified within the industry-wide estimates of **RCIC system start-only unreliability** on a per fiscal year basis.

Figure 2 shows the trend in the 8-hour mission unreliability. Table 5 shows the data points for Figure 2. **No statistically significant trend** was identified within the industry-wide estimates of **RCIC system 8-hour mission unreliability** on a per fiscal year basis.

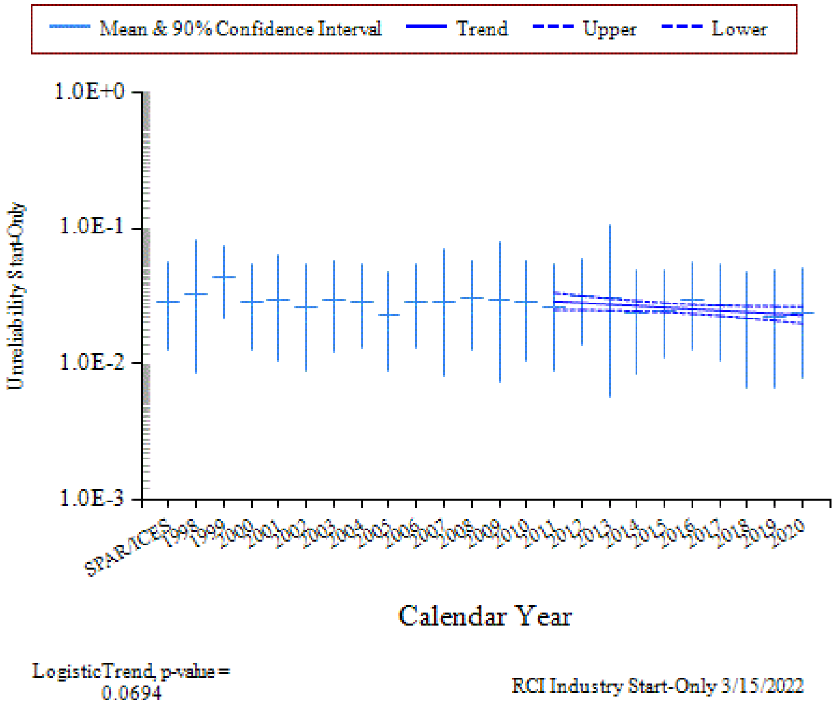

Figure 1. Trend of RCIC system start-only unreliability.

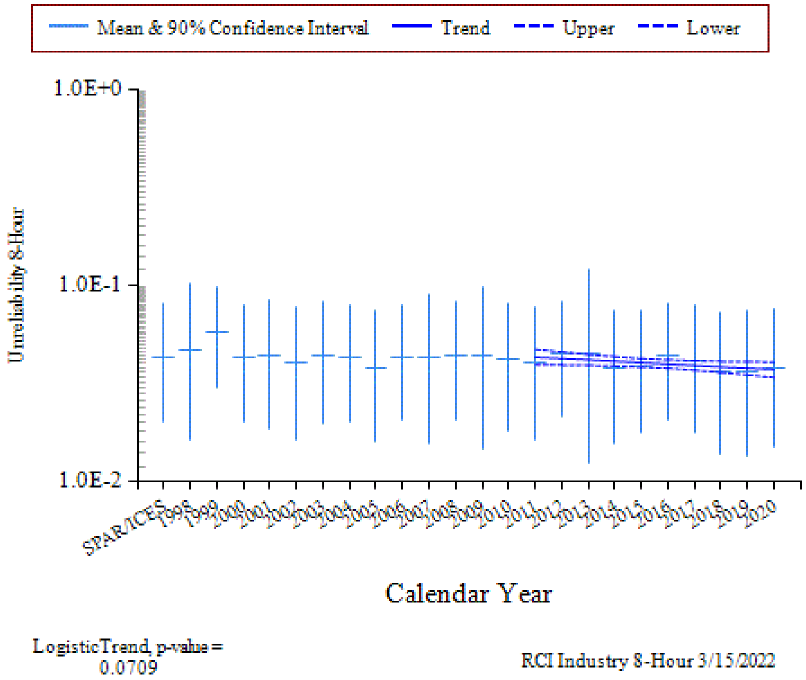

Figure 2. Trend of RCIC system 8-hour mission unreliability.

5. BASIC EVENT GROUP IMPORTANCES

The RCIC 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 RCIC start-only and 8-hour mission basic event group importances are shown in Figure 3.

- In the **Start-Only** case—the leading contributor to RCIC system unreliability is the **RCIC TDP** group of basic events followed by the Restart, CST Suction, and Suppression Pool groups.
- In the **8-Hour Mission** case—the leading contributor to RCIC system unreliability is also the **RCIC TDP** group of basic events followed by the Restart, CST Suction, and Suppression Pool groups.

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

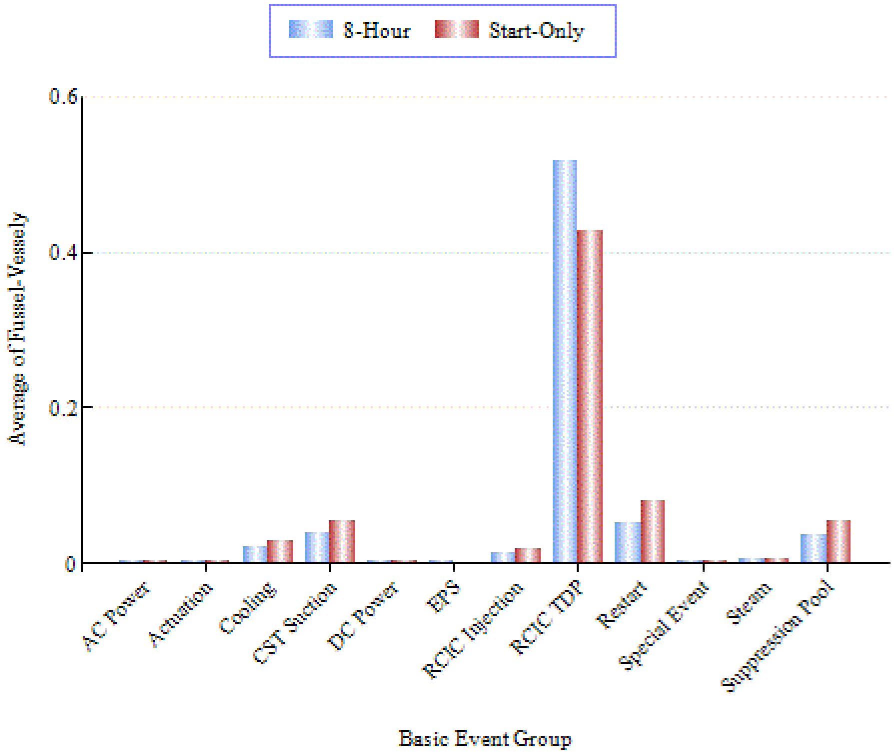

Figure 3. RCIC basic event group importances.

Table 3. RCIC model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the MOVs
Actuation	ESF actuation circuitry
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the RCIC TDP and the RCIC room
CST Suction	The MOVs and air-operated valves (AOVs) in the condensate storage tank suction path, including the condensate storage tank failure
DC Power	The batteries and battery chargers that supply power to the RCIC TDP control circuitry
EPS	RCIC dependency on the emergency power system
RCIC Injection	The MOVs and check valves in the RCIC injection path
RCIC TDP	All basic events associated with the RCIC TDP, including the start, run, common-cause, and test and maintenance
Restart	The required restart of the RCIC TDP, including the probability that restart is required and the probability that the TDP will restart
Special Event	Various events used in the models that are not directly associated with the RCIC system
Steam	The turbine steam supply valves
Suppression Pool	The suppression pool MOVs, check valves, and strainers required when a need to transfer to the suppression pool (torus) occurs

6. DATA TABLES

Table 4. Plot data for Figure 1, RCIC 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	--	--	--	1.27E-02	2.89E-02	5.58E-02
1998	--	--	--	8.73E-03	3.23E-02	8.18E-02
1999	--	--	--	2.18E-02	4.33E-02	7.49E-02
2000	--	--	--	1.27E-02	2.89E-02	5.49E-02
2001	--	--	--	1.05E-02	3.01E-02	6.27E-02
2002	--	--	--	8.92E-03	2.59E-02	5.38E-02
2003	--	--	--	1.21E-02	2.99E-02	5.80E-02
2004	--	--	--	1.29E-02	2.89E-02	5.48E-02
2005	--	--	--	8.88E-03	2.34E-02	4.84E-02
2006	--	--	--	1.32E-02	2.86E-02	5.37E-02
2007	--	--	--	8.12E-03	2.86E-02	7.03E-02
2008	--	--	--	1.28E-02	3.02E-02	5.85E-02
2009	--	--	--	7.38E-03	2.94E-02	7.89E-02
2010	--	--	--	1.06E-02	2.84E-02	5.74E-02
2011	2.52E-02	2.90E-02	3.33E-02	8.94E-03	2.58E-02	5.39E-02
2012	2.51E-02	2.82E-02	3.18E-02	1.38E-02	3.11E-02	5.86E-02
2013	2.49E-02	2.75E-02	3.04E-02	5.65E-03	3.08E-02	1.05E-01
2014	2.46E-02	2.68E-02	2.92E-02	8.50E-03	2.36E-02	4.90E-02
2015	2.42E-02	2.61E-02	2.82E-02	1.13E-02	2.46E-02	4.89E-02
2016	2.36E-02	2.55E-02	2.75E-02	1.27E-02	2.95E-02	5.60E-02
2017	2.28E-02	2.48E-02	2.71E-02	1.03E-02	2.69E-02	5.42E-02
2018	2.19E-02	2.42E-02	2.68E-02	6.74E-03	2.20E-02	4.84E-02
2019	2.09E-02	2.36E-02	2.66E-02	6.68E-03	2.20E-02	4.90E-02
2020	1.99E-02	2.30E-02	2.65E-02	7.91E-03	2.38E-02	5.10E-02

Table 5. Plot data for Figure 2, RCIC 8-hour mission unreliability trend.

Year/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Lower (5%)	Mean	Upper (95%)	Lower (5%)	Mean	Upper (95%)
SPAR/ICES	--	--	--	2.00E-02	4.31E-02	8.02E-02
1998	--	--	--	1.65E-02	4.64E-02	1.01E-01
1999	--	--	--	3.04E-02	5.72E-02	9.76E-02
2000	--	--	--	2.02E-02	4.31E-02	8.00E-02
2001	--	--	--	1.83E-02	4.42E-02	8.51E-02
2002	--	--	--	1.63E-02	4.01E-02	7.79E-02
2003	--	--	--	1.99E-02	4.40E-02	8.21E-02
2004	--	--	--	2.03E-02	4.31E-02	7.99E-02
2005	--	--	--	1.58E-02	3.76E-02	7.43E-02
2006	--	--	--	2.05E-02	4.28E-02	7.91E-02
2007	--	--	--	1.55E-02	4.28E-02	9.08E-02
2008	--	--	--	2.04E-02	4.43E-02	8.24E-02
2009	--	--	--	1.47E-02	4.36E-02	9.85E-02
2010	--	--	--	1.82E-02	4.26E-02	8.11E-02
2011	3.95E-02	4.32E-02	4.72E-02	1.63E-02	4.00E-02	7.79E-02
2012	3.94E-02	4.25E-02	4.58E-02	2.15E-02	4.53E-02	8.28E-02
2013	3.92E-02	4.18E-02	4.46E-02	1.24E-02	4.49E-02	1.21E-01
2014	3.89E-02	4.11E-02	4.34E-02	1.55E-02	3.78E-02	7.45E-02
2015	3.85E-02	4.04E-02	4.25E-02	1.79E-02	3.88E-02	7.47E-02
2016	3.79E-02	3.98E-02	4.18E-02	2.04E-02	4.37E-02	8.06E-02
2017	3.71E-02	3.91E-02	4.13E-02	1.78E-02	4.11E-02	7.85E-02
2018	3.61E-02	3.85E-02	4.11E-02	1.37E-02	3.62E-02	7.32E-02
2019	3.51E-02	3.79E-02	4.09E-02	1.36E-02	3.63E-02	7.37E-02
2020	3.40E-02	3.73E-02	4.08E-02	1.50E-02	3.81E-02	7.55E-02

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	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	1999	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2000	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2001	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2002	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2003	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2004	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2005	0	75	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2006	0	72	5.32E-04	0.83	1.56E+03	Beta
FTOC	AOV	2007	1	72	1.17E-03	1.83	1.56E+03	Beta
FTOC	AOV	2008	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2009	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2010	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2011	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2012	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2013	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2014	0	76	5.31E-04	0.83	1.57E+03	Beta
FTOC	AOV	2015	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOC	AOV	2016	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOC	AOV	2017	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOC	AOV	2018	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOC	AOV	2019	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOC	AOV	2020	0	59	5.37E-04	0.83	1.55E+03	Beta
FTOP	AOV	1998	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	1999	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2000	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2001	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2002	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2003	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2004	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2005	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2006	0	78,840	1.74E-07	1.26	7.25E+06	Gamma
FTOP	AOV	2007	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2008	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2009	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2010	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2011	0	70,080	1.74E-07	1.26	7.24E+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	70,080	3.12E-07	2.26	7.24E+06	Gamma
FTOP	AOV	2013	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2014	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2015	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2016	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2017	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2018	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2019	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
FTOP	AOV	2020	0	70,080	1.74E-07	1.26	7.24E+06	Gamma
SO	AOV	1998	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	1999	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2000	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2001	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2002	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2003	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2004	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2005	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2006	0	78,840	5.81E-08	0.86	1.48E+07	Gamma
SO	AOV	2007	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2008	1	70,080	1.26E-07	1.86	1.48E+07	Gamma
SO	AOV	2009	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2010	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2011	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2012	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2013	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2014	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2015	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2016	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2017	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2018	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2019	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
SO	AOV	2020	0	70,080	5.82E-08	0.86	1.48E+07	Gamma
FTOC	MOV	1998	2	2,409	7.13E-04	4.43	6.21E+03	Beta
FTOC	MOV	1999	5	2,564	1.17E-03	7.43	6.36E+03	Beta
FTOC	MOV	2000	3	2,513	8.60E-04	5.43	6.31E+03	Beta
FTOC	MOV	2001	2	2,747	6.76E-04	4.43	6.54E+03	Beta
FTOC	MOV	2002	3	2,918	8.08E-04	5.43	6.71E+03	Beta
FTOC	MOV	2003	2	3,076	6.44E-04	4.43	6.87E+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	2004	3	2,595	8.49E-04	5.43	6.39E+03	Beta
FTOC	MOV	2005	3	2,598	8.48E-04	5.43	6.40E+03	Beta
FTOC	MOV	2006	2	2,577	6.94E-04	4.43	6.38E+03	Beta
FTOC	MOV	2007	2	2,675	6.84E-04	4.43	6.47E+03	Beta
FTOC	MOV	2008	4	2,576	1.01E-03	6.43	6.37E+03	Beta
FTOC	MOV	2009	0	2,465	3.88E-04	2.43	6.26E+03	Beta
FTOC	MOV	2010	2	2,536	6.99E-04	4.43	6.33E+03	Beta
FTOC	MOV	2011	2	2,458	7.08E-04	4.43	6.26E+03	Beta
FTOC	MOV	2012	7	2,601	1.47E-03	9.43	6.39E+03	Beta
FTOC	MOV	2013	3	2,704	8.35E-04	5.43	6.50E+03	Beta
FTOC	MOV	2014	0	2,483	3.87E-04	2.43	6.28E+03	Beta
FTOC	MOV	2015	3	2,417	8.73E-04	5.43	6.21E+03	Beta
FTOC	MOV	2016	0	2,446	3.89E-04	2.43	6.25E+03	Beta
FTOC	MOV	2017	2	2,420	7.12E-04	4.43	6.22E+03	Beta
FTOC	MOV	2018	1	2,520	5.43E-04	3.43	6.32E+03	Beta
FTOC	MOV	2019	3	2,459	8.67E-04	5.43	6.26E+03	Beta
FTOC	MOV	2020	1	2,353	5.57E-04	3.43	6.15E+03	Beta
FTOP	MOV	1998	1	2,531,640	7.04E-08	1.8	2.55E+07	Gamma
FTOP	MOV	1999	1	2,540,400	7.04E-08	1.8	2.55E+07	Gamma
FTOP	MOV	2000	0	2,566,680	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2001	0	2,540,400	3.12E-08	0.8	2.55E+07	Gamma
FTOP	MOV	2002	0	2,540,400	3.12E-08	0.8	2.55E+07	Gamma
FTOP	MOV	2003	0	2,540,400	3.12E-08	0.8	2.55E+07	Gamma
FTOP	MOV	2004	0	2,540,400	3.12E-08	0.8	2.55E+07	Gamma
FTOP	MOV	2005	0	2,540,400	3.12E-08	0.8	2.55E+07	Gamma
FTOP	MOV	2006	0	2,557,920	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2007	0	2,557,920	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2008	0	2,557,920	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2009	0	2,557,920	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2010	0	2,680,560	3.11E-08	0.8	2.57E+07	Gamma
FTOP	MOV	2011	0	2,601,720	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2012	0	2,592,960	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2013	0	2,592,960	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2014	0	2,592,960	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2015	1	2,601,720	7.02E-08	1.8	2.56E+07	Gamma
FTOP	MOV	2016	0	2,575,440	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2017	0	2,575,440	3.12E-08	0.8	2.56E+07	Gamma
FTOP	MOV	2018	0	2,671,800	3.11E-08	0.8	2.57E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTOP	MOV	2019	1	2,584,200	7.03E-08	1.8	2.56E+07	Gamma
FTOP	MOV	2020	0	2,531,640	3.13E-08	0.8	2.55E+07	Gamma
SO	MOV	1998	0	2,531,640	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	1999	0	2,540,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2000	2	2,566,680	2.66E-08	43.5	1.63E+09	Gamma
SO	MOV	2001	0	2,540,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2002	1	2,540,400	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2003	0	2,540,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2004	0	2,540,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2005	0	2,540,400	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2006	0	2,557,920	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2007	0	2,557,920	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2008	1	2,557,920	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2009	1	2,557,920	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2010	2	2,680,560	2.66E-08	43.5	1.63E+09	Gamma
SO	MOV	2011	0	2,601,720	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2012	3	2,592,960	2.73E-08	44.5	1.63E+09	Gamma
SO	MOV	2013	1	2,592,960	2.60E-08	42.5	1.63E+09	Gamma
SO	MOV	2014	0	2,592,960	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2015	0	2,601,720	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2016	0	2,575,440	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2017	0	2,575,440	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2018	0	2,671,800	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2019	0	2,584,200	2.54E-08	41.5	1.63E+09	Gamma
SO	MOV	2020	0	2,531,640	2.54E-08	41.5	1.63E+09	Gamma
FTR>1H	TDP	1998	0	66	3.26E-03	0.44	1.35E+02	Gamma
FTR>1H	TDP	1999	0	93	2.71E-03	0.44	1.63E+02	Gamma
FTR>1H	TDP	2000	1	58	1.13E-02	1.44	1.27E+02	Gamma
FTR>1H	TDP	2001	0	175	1.80E-03	0.44	2.44E+02	Gamma
FTR>1H	TDP	2002	0	59	3.44E-03	0.44	1.28E+02	Gamma
FTR>1H	TDP	2003	0	77	3.01E-03	0.44	1.47E+02	Gamma
FTR>1H	TDP	2004	0	35	4.20E-03	0.44	1.05E+02	Gamma
FTR>1H	TDP	2005	0	28	4.54E-03	0.44	9.70E+01	Gamma
FTR>1H	TDP	2006	0	36	4.18E-03	0.44	1.06E+02	Gamma
FTR>1H	TDP	2007	1	35	1.38E-02	1.44	1.04E+02	Gamma
FTR>1H	TDP	2008	0	34	4.28E-03	0.44	1.03E+02	Gamma
FTR>1H	TDP	2009	0	21	4.87E-03	0.44	9.06E+01	Gamma
FTR>1H	TDP	2010	0	66	3.26E-03	0.44	1.35E+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	2011	0	25	4.67E-03	0.44	9.44E+01	Gamma
FTR>1H	TDP	2012	1	96	8.69E-03	1.44	1.66E+02	Gamma
FTR>1H	TDP	2013	1	69	1.04E-02	1.44	1.39E+02	Gamma
FTR>1H	TDP	2014	1	48	1.23E-02	1.44	1.17E+02	Gamma
FTR>1H	TDP	2015	0	35	4.21E-03	0.44	1.05E+02	Gamma
FTR>1H	TDP	2016	1	44	1.27E-02	1.44	1.13E+02	Gamma
FTR>1H	TDP	2017	1	42	1.29E-02	1.44	1.11E+02	Gamma
FTR>1H	TDP	2018	0	46	3.81E-03	0.44	1.16E+02	Gamma
FTR>1H	TDP	2019	0	53	3.59E-03	0.44	1.23E+02	Gamma
FTR>1H	TDP	2020	0	49	3.71E-03	0.44	1.19E+02	Gamma
FTR<1H	TDP	1998	0	241	1.07E-03	0.44	4.14E+02	Gamma
FTR<1H	TDP	1999	1	264	3.31E-03	1.44	4.37E+02	Gamma
FTR<1H	TDP	2000	5	292	1.17E-02	5.44	4.65E+02	Gamma
FTR<1H	TDP	2001	1	314	2.97E-03	1.44	4.87E+02	Gamma
FTR<1H	TDP	2002	1	275	3.22E-03	1.44	4.48E+02	Gamma
FTR<1H	TDP	2003	0	363	8.29E-04	0.44	5.36E+02	Gamma
FTR<1H	TDP	2004	0	289	9.61E-04	0.44	4.62E+02	Gamma
FTR<1H	TDP	2005	3	272	7.74E-03	3.44	4.45E+02	Gamma
FTR<1H	TDP	2006	0	283	9.73E-04	0.44	4.56E+02	Gamma
FTR<1H	TDP	2007	2	268	5.54E-03	2.44	4.41E+02	Gamma
FTR<1H	TDP	2008	1	273	3.24E-03	1.44	4.46E+02	Gamma
FTR<1H	TDP	2009	0	257	1.03E-03	0.44	4.30E+02	Gamma
FTR<1H	TDP	2010	1	280	3.19E-03	1.44	4.53E+02	Gamma
FTR<1H	TDP	2011	2	276	5.45E-03	2.44	4.49E+02	Gamma
FTR<1H	TDP	2012	1	296	3.08E-03	1.44	4.69E+02	Gamma
FTR<1H	TDP	2013	0	294	9.50E-04	0.44	4.67E+02	Gamma
FTR<1H	TDP	2014	0	274	9.94E-04	0.44	4.47E+02	Gamma
FTR<1H	TDP	2015	0	251	1.05E-03	0.44	4.24E+02	Gamma
FTR<1H	TDP	2016	1	268	3.27E-03	1.44	4.41E+02	Gamma
FTR<1H	TDP	2017	0	253	1.04E-03	0.44	4.26E+02	Gamma
FTR<1H	TDP	2018	2	261	5.64E-03	2.44	4.34E+02	Gamma
FTR<1H	TDP	2019	0	250	1.05E-03	0.44	4.23E+02	Gamma
FTR<1H	TDP	2020	1	242	3.48E-03	1.44	4.15E+02	Gamma
FTS	TDP	1998	2	241	6.84E-03	3.26	4.74E+02	Beta
FTS	TDP	1999	7	264	1.65E-02	8.26	4.92E+02	Beta
FTS	TDP	2000	3	292	8.07E-03	4.26	5.24E+02	Beta
FTS	TDP	2001	2	314	5.93E-03	3.26	5.47E+02	Beta
FTS	TDP	2002	0	275	2.46E-03	1.26	5.10E+02	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
FTS	TDP	2003	3	363	7.11E-03	4.26	5.95E+02	Beta
FTS	TDP	2004	4	289	1.00E-02	5.26	5.20E+02	Beta
FTS	TDP	2005	1	272	4.45E-03	2.26	5.06E+02	Beta
FTS	TDP	2006	3	283	8.20E-03	4.26	5.15E+02	Beta
FTS	TDP	2007	2	268	6.46E-03	3.26	5.01E+02	Beta
FTS	TDP	2008	4	273	1.03E-02	5.26	5.04E+02	Beta
FTS	TDP	2009	2	257	6.61E-03	3.26	4.90E+02	Beta
FTS	TDP	2010	2	280	6.32E-03	3.26	5.13E+02	Beta
FTS	TDP	2011	1	276	4.41E-03	2.26	5.10E+02	Beta
FTS	TDP	2012	3	296	8.01E-03	4.26	5.28E+02	Beta
FTS	TDP	2013	1	294	4.26E-03	2.26	5.28E+02	Beta
FTS	TDP	2014	1	274	4.43E-03	2.26	5.08E+02	Beta
FTS	TDP	2015	1	251	4.64E-03	2.26	4.85E+02	Beta
FTS	TDP	2016	3	268	8.45E-03	4.26	5.00E+02	Beta
FTS	TDP	2017	2	253	6.66E-03	3.26	4.86E+02	Beta
FTS	TDP	2018	0	261	2.54E-03	1.26	4.96E+02	Beta
FTS	TDP	2019	0	250	2.59E-03	1.26	4.85E+02	Beta
FTS	TDP	2020	1	242	4.72E-03	2.26	4.76E+02	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	TDP	1998	2876.65	208,350	1.45E-02	0.5	3.42E+01	Beta
UA	TDP	1999	3475.171	234,393	1.52E-02	1.93	1.25E+02	Beta
UA	TDP	2000	2343.673	244,857	9.58E-03	2.15	2.23E+02	Beta
UA	TDP	2001	3202.477	244,286	1.33E-02	1.32	9.82E+01	Beta
UA	TDP	2002	3026.113	248,545	1.22E-02	2.02	1.64E+02	Beta
UA	TDP	2003	2847.03	242,932	1.19E-02	1.86	1.54E+02	Beta
UA	TDP	2004	1913.641	247,149	7.68E-03	1.65	2.13E+02	Beta
UA	TDP	2005	1832.18	243,870	7.59E-03	2.03	2.65E+02	Beta
UA	TDP	2006	2361.344	248,055	9.45E-03	3.1	3.24E+02	Beta
UA	TDP	2007	2620.95	243,860	1.12E-02	0.49	4.32E+01	Beta
UA	TDP	2008	2075.75	247,817	8.30E-03	1.07	1.27E+02	Beta
UA	TDP	2009	2909.55	240,793	1.25E-02	0.38	2.98E+01	Beta
UA	TDP	2010	2751.94	247,362	1.11E-02	1.47	1.31E+02	Beta
UA	TDP	2011	2344.64	238,174	1.04E-02	1.51	1.44E+02	Beta
UA	TDP	2012	2614.27	240,165	1.07E-02	1.94	1.80E+02	Beta
UA	TDP	2013	3828.38	240,851	1.53E-02	0.19	1.23E+01	Beta
UA	TDP	2014	2161.38	246,590	8.74E-03	2.01	2.28E+02	Beta
UA	TDP	2015	2032.57	238,050	8.56E-03	6.13	7.10E+02	Beta
UA	TDP	2016	2506.86	237,939	1.08E-02	2.29	2.10E+02	Beta
UA	TDP	2017	2184.12	238,614	9.24E-03	1.5	1.60E+02	Beta
UA	TDP	2018	2035.88	235,917	8.67E-03	1.53	1.75E+02	Beta
UA	TDP	2019	1827.85	234,433	8.00E-03	1.21	1.51E+02	Beta
UA	TDP	2020	1846.1	227,278	8.38E-03	1.26	1.49E+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

This is a generic description of the RCIC system. The models in SPAR incorporate plant-specific features that may not be described here.

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 and does not have a loss-of-coolant accident 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 one of the following occurs:

- 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 shutdown cooling system can be placed into operation
- The reactor pressure vessel is isolated in conjunction with a loss of coolant flow from the feedwater system
- A station blackout event occurs.

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 system can be placed into operation.

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 reactor pressure vessel 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 4 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 1,040 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 2,000 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 reactor pressure vessel. 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.

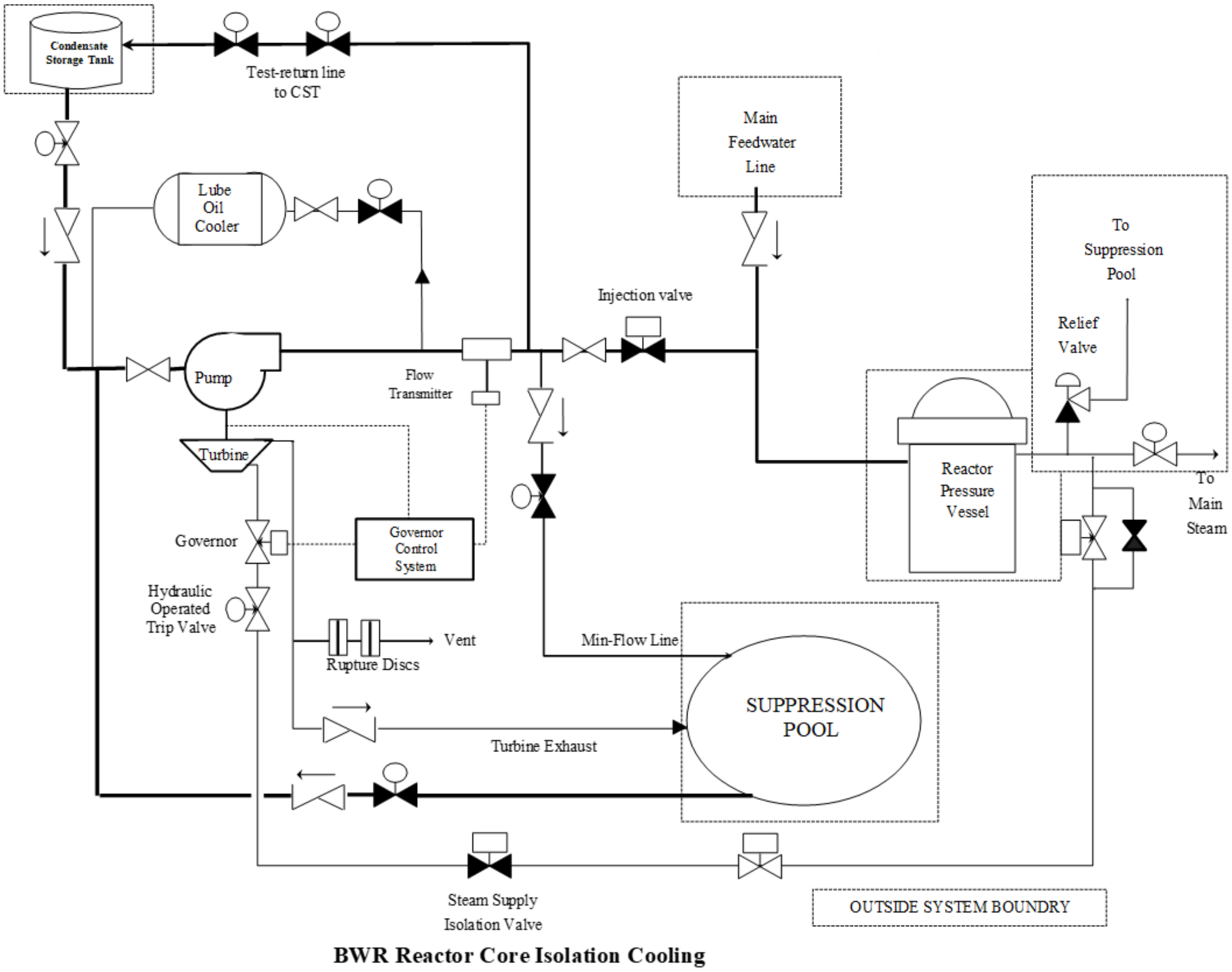

Figure 4. Simplified RCIC system schematic.

8. REFERENCES

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