

# **System Study: Reactor Core Isolation Cooling 1998–2016**

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Reactor Core Isolation Cooling  
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## **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 hours, and failure data from calendar years 1998 through 2016 for selected components were obtained from the Institute of Nuclear Power Operations (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 trends were identified in the RCIC results.



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## ACRONYMS

BWR	boiling water reactor
CCF	common-cause failure
CST	condensate storage tank
CY	calendar year
EPIX	Equipment Performance and Information Exchange
FY	fiscal year
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
MSPI	Mitigating Systems Performance Index
PRA	probabilistic risk assessment
RCIC	reactor core isolation cooling
SPAR	standardized plant analysis risk
SSU	safety system unavailability



# System Study: Reactor Core Isolation Cooling 1998–2016

## 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 plant, the corresponding Standardized Plant Analysis Risk (SPAR) model (version model indicated in Table 1) was used in the yearly calculations. Different from previous year's updates, this year's results are based on calendar year (CY) instead of fiscal year (FY). Demand, run hours, and failure data from 1998 through 2016 for selected components in the RCIC system were obtained from the Institute of Nuclear Power Operations (INPO) Consolidated Events Database (ICES). Train unavailability data (outages from test or maintenance) were obtained from the Reactor Oversight Process Safety System Unavailability (SSU) database (1998 through 2001) and the Mitigating Systems Performance Index (MSPI) database (2002 through 2016). 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 2010 Component Reliability Update (Reference i), which is an update to Reference ii (NUREG/CR-6928). Baseline RCIC unreliability results using basic event values from that report are summarized in Section 3.<sup>a</sup> Trend results for HPCI (using system-specific data) are presented in Section 4. Similar to previous system study updates, Section 5 contains importance information (using the baseline results from Section 3), 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 has not been included in the SPAR model logic. An overview of the trending methods, glossary of terms, and abbreviations can be found in the [Overview and Reference document](#) on the Reactor Operational Experience Results and Databases web page.

Two modes of the models for the RCIC system are calculated. The RCIC start-only model is the SPAR RCIC model modified by setting all fail-to-run basic events to zero (False), setting all recovery events to False, setting the suction transfer to the suppression pool to False, and setting all cooling basic events to False. The 8-hour mission model includes all basic events in the SPAR RCIC model.

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<sup>a</sup> Note that the 2015 Component Reliability Update (Reference iii) is now available to report more current estimated basic event values for use in a PRA. Estimates from the 2015 Update will be used in the next system study.

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

<b>Plant</b>	<b>Version</b>
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 the existence of any statistically significant<sup>a</sup> increasing trends. In this update, no statistically significant trends were identified in the RCIC unreliability trend results.

The industry-wide RCIC start-only and 8-hour basic event group importances were evaluated and are shown in Figure 3. In both cases, the leading contributor to RCIC system unreliability is the RCIC turbine-driven pump group of basic events. Recovery, restart, and the suppression pool are important to the 8-hour mission model.

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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 of 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 modes of operation. A failure to start (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).<sup>a</sup>

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.*

<b>Model</b>	<b>Lower (5%)</b>	<b>Median</b>	<b>Mean</b>	<b>Upper (95%)</b>
Start	1.09E-02	2.36E-02	2.94E-02	6.62E-02
8-hour	2.59E-02	5.11E-02	5.72E-02	1.08E-01

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 (1998 through 2016) failure and demand or run time data were obtained from EPIX for the RCIC system. RCIC train maintenance unavailability data for trending are from the same time period, as reported in the ROP and EPIX. The component basic event uncertainty was calculated for the RCIC system components using the trending methods described in Section 1 and 2 of the Overview and Reference document. Tables 6 and 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 using data for each year. In addition, for comparison, the calculated industry-wide system reliability from this update (SPAR/EPIX) is shown. Section 4 of the Overview and Reference link on the System Studies main web page provides more detailed discussion of the trending methods. In the lower left hand corner of the trend figures, the regression method is reported.

The components and failure modes that were varied in the RCIC model are

- RCIC turbine-driven pump start, run, and test and maintenance.
- RCIC injection MOV fail-to-open.

Figure 1 shows the trend in the start-only model unreliability. Table 4 shows the data points for Figure 1. No statistically significant trend within the industry-wide estimates of RCIC system unreliability (start-only) was identified.

Figure 2 shows the trend in the 8-hour mission unreliability. No statistically significant trend within the industry-wide estimates of RCIC system unreliability (8-hour mission) was identified. Table 5 shows the data points for Figure 2.

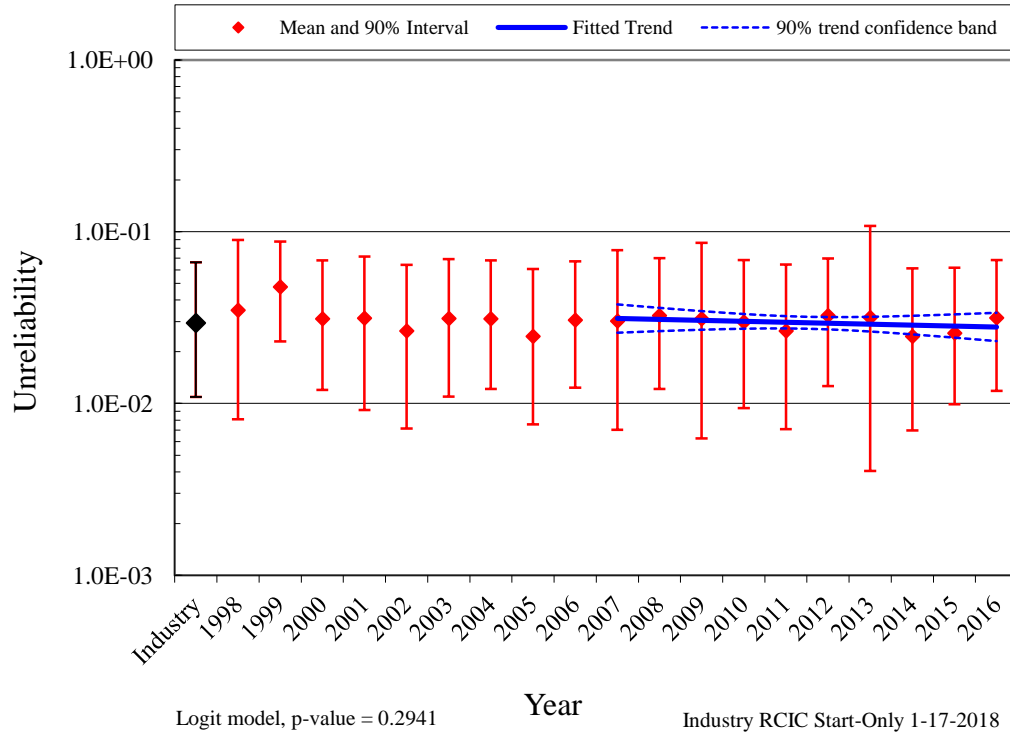


Figure 1. Trend of RCIC system unreliability (start-only model).

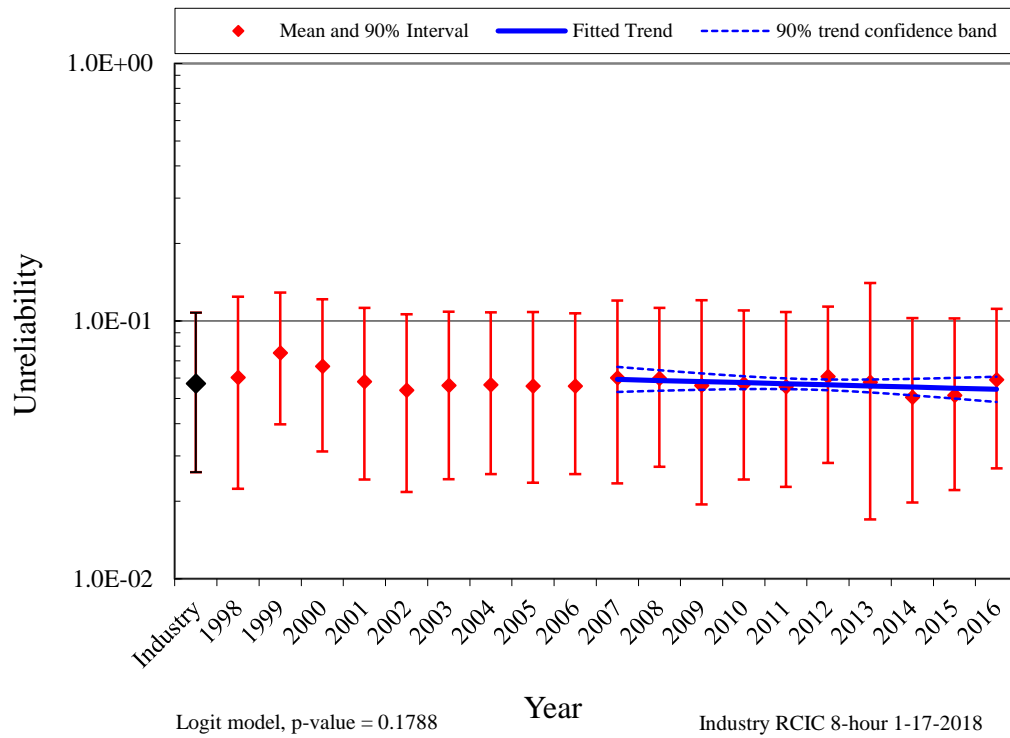


Figure 2. Trend of RCIC system unreliability (8-hour model).

## 5. BASIC EVENT GROUP IMPORTANCES

The RCIC basic event group Fussell-Vesely importances were calculated for the start-only and 8-hour modes 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 basic event group importances are shown in Figure 3.

In both cases, the leading contributor to RCIC system unreliability is the RCIC turbine-driven pump group of basic events. Recovery, restart, and the suppression pool are important to the 8-hour mission model. For more discussion on the RCIC turbine-driven pumps, see the turbine-driven pump component reliability study at NRC Reactor Operational Experience Results and Databases web site. Table 3 shows the SPAR model RCIC importance groups and their descriptions.

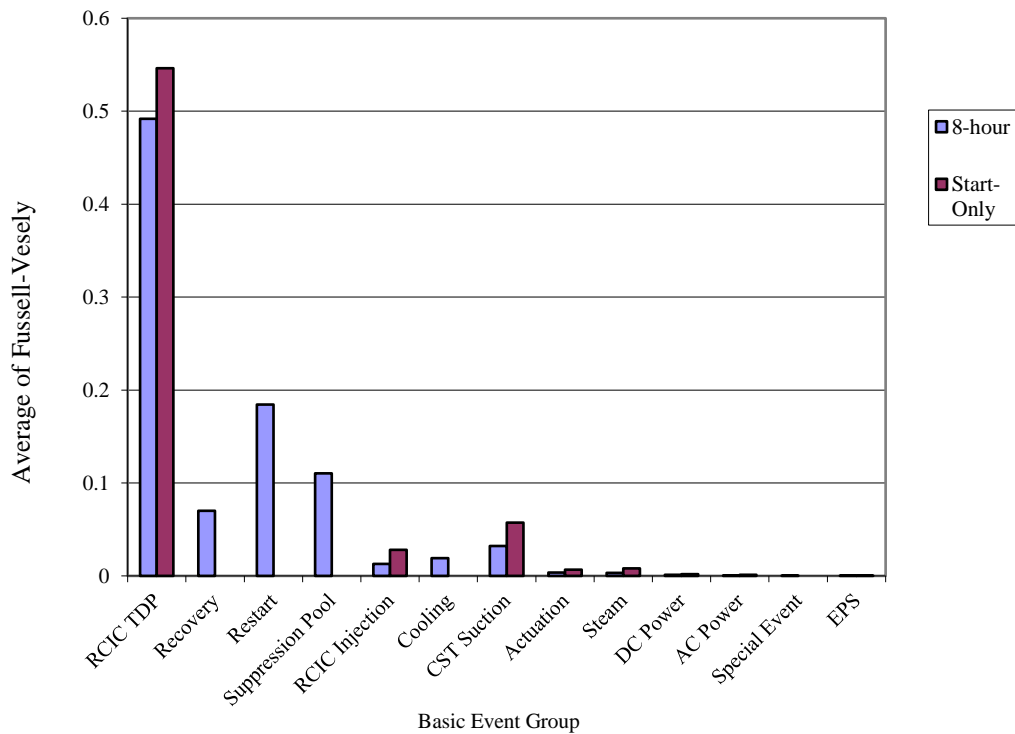


Figure 3. RCIC basic event group importances.

*Table 3. RCIC model basic event importance group descriptions.*

<b>Group</b>	<b>Description</b>
AC Power	The ac buses and circuit breakers that supply power to the service water pumps and motor-operated valves.
Actuation	ESF actuation circuitry.
Cooling	The pumps, valves, and heat exchangers that provide heat removal to the RCIC turbine-driven pump and the RCIC room.
CST Suction	The motor-operated valves and air-operated valves in the condensate storage tank suction path. Includes the failure of the condensate storage tank.
DC Power	The batteries and battery chargers that supply power to the RCIC turbine-driven pump control circuitry.
EPS	RCIC dependency on the emergency power system.
RCIC Injection	The motor-operated valves and check valves in the RCIC injection path.
RCIC TDP	All basic events associated with the turbine-driven pumps. The start, run, common-cause, and test and maintenance are included in this group of basic events.
Recovery	The operator recovery of the TDP FTS, FTR, and other specialized modeled recovery events.
Restart	The required restart of the RCIC turbine-driven pump. Includes the probability that restart is required and the probability that the turbine-driven pump 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 motor-operated valves, check valves, and strainers required when a need to transfer to the suppression pool (torus) occurs.

## 6. DATA TABLES

*Table 4. Plot data for RCIC start-only trend, Figure 1.*

Year/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ICES				1.09E-02	6.62E-02	2.94E-02
1998				8.08E-03	8.93E-02	3.50E-02
1999				2.30E-02	8.76E-02	4.78E-02
2000				1.20E-02	6.80E-02	3.11E-02
2001				9.15E-03	7.16E-02	3.14E-02
2002				7.14E-03	6.40E-02	2.65E-02
2003				1.10E-02	6.94E-02	3.13E-02
2004				1.22E-02	6.80E-02	3.11E-02
2005				7.54E-03	6.07E-02	2.46E-02
2006				1.24E-02	6.72E-02	3.07E-02
2007	3.12E-02	2.58E-02	3.77E-02	7.03E-03	7.80E-02	3.03E-02
2008	3.08E-02	2.64E-02	3.60E-02	1.21E-02	7.03E-02	3.24E-02
2009	3.04E-02	2.69E-02	3.45E-02	6.25E-03	8.60E-02	3.12E-02
2010	3.01E-02	2.72E-02	3.32E-02	9.40E-03	6.82E-02	2.99E-02
2011	2.97E-02	2.73E-02	3.22E-02	7.07E-03	6.44E-02	2.65E-02
2012	2.93E-02	2.70E-02	3.18E-02	1.26E-02	6.97E-02	3.25E-02
2013	2.89E-02	2.62E-02	3.19E-02	4.05E-03	1.08E-01	3.17E-02
2014	2.86E-02	2.52E-02	3.24E-02	6.97E-03	6.11E-02	2.47E-02
2015	2.82E-02	2.41E-02	3.30E-02	9.87E-03	6.16E-02	2.56E-02
2016	2.79E-02	2.30E-02	3.37E-02	1.18E-02	6.85E-02	3.15E-02

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

Year/Source	Regression Curve Data Points			Plot Trend Error Bar Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ICES				2.59E-02	1.08E-01	5.72E-02
1998				2.24E-02	1.24E-01	6.05E-02
1999				3.97E-02	1.29E-01	7.52E-02
2000				3.12E-02	1.21E-01	6.67E-02
2001				2.42E-02	1.12E-01	5.83E-02
2002				2.17E-02	1.06E-01	5.39E-02
2003				2.44E-02	1.09E-01	5.63E-02
2004				2.55E-02	1.08E-01	5.66E-02
2005				2.36E-02	1.08E-01	5.59E-02
2006				2.55E-02	1.07E-01	5.60E-02
2007	5.94E-02	5.30E-02	6.64E-02	2.34E-02	1.20E-01	6.02E-02
2008	5.88E-02	5.36E-02	6.45E-02	2.72E-02	1.13E-01	6.00E-02
2009	5.82E-02	5.41E-02	6.27E-02	1.94E-02	1.20E-01	5.63E-02
2010	5.77E-02	5.44E-02	6.11E-02	2.43E-02	1.10E-01	5.71E-02
2011	5.71E-02	5.44E-02	6.00E-02	2.27E-02	1.08E-01	5.55E-02
2012	5.65E-02	5.38E-02	5.94E-02	2.81E-02	1.14E-01	6.09E-02
2013	5.60E-02	5.28E-02	5.94E-02	1.70E-02	1.41E-01	5.79E-02
2014	5.55E-02	5.15E-02	5.97E-02	1.98E-02	1.03E-01	5.06E-02
2015	5.49E-02	5.00E-02	6.02E-02	2.21E-02	1.02E-01	5.15E-02
2016	5.44E-02	4.85E-02	6.09E-02	2.68E-02	1.12E-01	5.92E-02

Table 6. Basic event reliability trending data.

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTOC	AOV	1998	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	1999	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2000	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2001	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2002	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2003	0	66	9.00E-04	1.112	1234	Beta
FTOC	AOV	2004	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2005	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2006	0	66.24	9.00E-04	1.112	1234.24	Beta
FTOC	AOV	2007	1	67.24	1.71E-03	2.112	1234.24	Beta
FTOC	AOV	2008	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2009	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2010	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2011	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2012	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2013	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2014	0	71.75999	8.96E-04	1.112	1239.76	Beta
FTOC	AOV	2015	0	54.72	9.09E-04	1.112	1222.72	Beta
FTOC	AOV	2016	0	54.72	9.09E-04	1.112	1222.72	Beta
FTOC	MOV	1998	2	2371.95	9.00E-04	4.046	4492.95	Beta
FTOC	MOV	1999	5	2555.49	1.51E-03	7.046	4673.49	Beta
FTOC	MOV	2000	3	2516.51	1.09E-03	5.046	4636.51	Beta
FTOC	MOV	2001	2	2755.73	8.29E-04	4.046	4876.73	Beta
FTOC	MOV	2002	3	2946.8	9.95E-04	5.046	5066.8	Beta
FTOC	MOV	2003	2	3097.81	7.75E-04	4.046	5218.81	Beta
FTOC	MOV	2004	3	2597.74	1.07E-03	5.046	4717.74	Beta
FTOC	MOV	2005	3	2619.76	1.06E-03	5.046	4739.76	Beta
FTOC	MOV	2006	2	2609.58	8.55E-04	4.046	4730.58	Beta
FTOC	MOV	2007	2	2703.55	8.38E-04	4.046	4824.55	Beta
FTOC	MOV	2008	4	2646.01	1.27E-03	6.046	4765.01	Beta
FTOC	MOV	2009	0	2509.79	4.41E-04	2.046	4632.79	Beta
FTOC	MOV	2010	2	2574.13	8.61E-04	4.046	4695.13	Beta
FTOC	MOV	2011	1	2484.67	6.61E-04	3.046	4606.67	Beta
FTOC	MOV	2012	6	2632.3	1.69E-03	8.046	4749.3	Beta
FTOC	MOV	2013	3	2740.14	1.04E-03	5.046	4860.14	Beta
FTOC	MOV	2014	0	2517.57	4.41E-04	2.046	4640.57	Beta
FTOC	MOV	2015	3	2457.98	1.10E-03	5.046	4577.98	Beta
FTOC	MOV	2016	0	2454.38	4.47E-04	2.046	4577.38	Beta
FTOP	AOV	1998	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	1999	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2000	0	43800	2.47E-07	1.421	5762800	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTOP	AOV	2001	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2002	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2003	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2004	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2005	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2006	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2007	0	43800	2.47E-07	1.421	5762800	Gamma
FTOP	AOV	2008	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2009	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2010	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2011	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2012	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2013	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2014	0	43800	2.47E-07	1.421	5.76E+06	Gamma
FTOP	AOV	2015	0	35040	2.47E-07	1.421	5.75E+06	Gamma
FTOP	AOV	2016	0	35040	2.47E-07	1.421	5.75E+06	Gamma
FTOP	MOV	1998	1	2514120	1.00E-07	2.458	2.46E+07	Gamma
FTOP	MOV	1999	1	2531640	1.00E-07	2.458	2.46E+07	Gamma
FTOP	MOV	2000	0	2557920	5.92E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2001	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2002	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2003	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2004	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2005	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2006	0	2549160	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2007	0	2549160	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2008	0	2549160	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2009	0	2549160	5.93E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2010	0	2663040	5.90E-08	1.458	2.47E+07	Gamma
FTOP	MOV	2011	0	2584200	5.92E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2012	0	2575440	5.92E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2013	0	2575440	5.92E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2014	0	2575440	5.92E-08	1.458	2.46E+07	Gamma
FTOP	MOV	2015	1	2584200	9.98E-08	2.458	2.46E+07	Gamma
FTOP	MOV	2016	0	2531640	5.93E-08	1.458	2.46E+07	Gamma
FTR<1H	TDP	1998	0	219.57	2.21E-03	0.9618	435.97	Gamma
FTR<1H	TDP	1999	1	246.15	4.24E-03	1.9618	462.55	Gamma
FTR<1H	TDP	2000	5	273.99	1.22E-02	5.9618	490.39	Gamma
FTR<1H	TDP	2001	1	304.17	3.77E-03	1.9618	520.57	Gamma
FTR<1H	TDP	2002	1	277.5	3.97E-03	1.9618	493.9	Gamma
FTR<1H	TDP	2003	0	363.02	1.66E-03	0.9618	579.42	Gamma



Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTR<1H	TDP	2004	0	289.2	1.90E-03	0.9618	505.6	Gamma
FTR<1H	TDP	2005	3	272.15	8.11E-03	3.9618	488.55	Gamma
FTR<1H	TDP	2006	0	283.45	1.92E-03	0.9618	499.85	Gamma
FTR<1H	TDP	2007	2	266.95	6.13E-03	2.9618	483.35	Gamma
FTR<1H	TDP	2008	1	272.64	4.01E-03	1.9618	489.04	Gamma
FTR<1H	TDP	2009	0	256.65	2.03E-03	0.9618	473.05	Gamma
FTR<1H	TDP	2010	1	279.78	3.95E-03	1.9618	496.18	Gamma
FTR<1H	TDP	2011	2	275.68	6.02E-03	2.9618	492.08	Gamma
FTR<1H	TDP	2012	1	295.7	3.83E-03	1.9618	512.1	Gamma
FTR<1H	TDP	2013	0	294.24	1.88E-03	0.9618	510.64	Gamma
FTR<1H	TDP	2014	0	273.77	1.96E-03	0.9618	490.17	Gamma
FTR<1H	TDP	2015	0	250.92	2.06E-03	0.9618	467.32	Gamma
FTR<1H	TDP	2016	1	267.92	4.05E-03	1.9618	484.32	Gamma
FTR>1H	TDP	1998	0	40.42	1.55E-03	12.5	8068.16	Gamma
FTR>1H	TDP	1999	0	68.8	1.54E-03	12.5	8096.54	Gamma
FTR>1H	TDP	2000	1	32.95	1.67E-03	13.5	8060.69	Gamma
FTR>1H	TDP	2001	0	146.11	1.53E-03	12.5	8173.85	Gamma
FTR>1H	TDP	2002	0	55.62	1.55E-03	12.5	8083.36	Gamma
FTR>1H	TDP	2003	0	77.15	1.54E-03	12.5	8104.89	Gamma
FTR>1H	TDP	2004	0	35.48	1.55E-03	12.5	8063.22	Gamma
FTR>1H	TDP	2005	0	27.54	1.55E-03	12.5	8055.28	Gamma
FTR>1H	TDP	2006	0	36.02	1.55E-03	12.5	8063.76	Gamma
FTR>1H	TDP	2007	1	34.71	1.67E-03	13.5	8062.45	Gamma
FTR>1H	TDP	2008	0	33.6	1.55E-03	12.5	8061.34	Gamma
FTR>1H	TDP	2009	0	21.11	1.55E-03	12.5	8048.85	Gamma
FTR>1H	TDP	2010	0	65.93	1.54E-03	12.5	8093.67	Gamma
FTR>1H	TDP	2011	0	24.85	1.55E-03	12.5	8052.59	Gamma
FTR>1H	TDP	2012	1	96.34	1.66E-03	13.5	8124.08	Gamma
FTR>1H	TDP	2013	1	69.29	1.67E-03	13.5	8097.03	Gamma
FTR>1H	TDP	2014	1	47.53	1.67E-03	13.5	8075.27	Gamma
FTR>1H	TDP	2015	0	35.13	1.55E-03	12.5	8062.87	Gamma
FTR>1H	TDP	2016	1	43.67	1.67E-03	13.5	8071.41	Gamma
FTS	TDP	1998	2	219.57	8.07E-03	2.9421	361.67	Beta
FTS	TDP	1999	7	246.15	2.03E-02	7.9421	383.25	Beta
FTS	TDP	2000	3	273.99	9.41E-03	3.9421	415.09	Beta
FTS	TDP	2001	2	304.17	6.55E-03	2.9421	446.27	Beta
FTS	TDP	2002	0	277.5	2.23E-03	0.9421	421.6	Beta
FTS	TDP	2003	3	363.02	7.76E-03	3.9421	504.12	Beta
FTS	TDP	2004	4	289.2	1.14E-02	4.9421	429.3	Beta
FTS	TDP	2005	1	272.15	4.66E-03	1.9421	415.25	Beta
FTS	TDP	2006	3	283.45	9.20E-03	3.9421	424.55	Beta

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
FTS	TDP	2007	2	266.95	7.14E-03	2.9421	409.05	Beta
FTS	TDP	2008	4	272.64	1.18E-02	4.9421	412.74	Beta
FTS	TDP	2009	2	256.65	7.32E-03	2.9421	398.75	Beta
FTS	TDP	2010	2	279.78	6.93E-03	2.9421	421.88	Beta
FTS	TDP	2011	1	275.68	4.62E-03	1.9421	418.78	Beta
FTS	TDP	2012	3	295.7	8.94E-03	3.9421	4.37E+02	Beta
FTS	TDP	2013	1	294.24	4.42E-03	1.9421	4.37E+02	Beta
FTS	TDP	2014	1	273.77	4.64E-03	1.9421	4.17E+02	Beta
FTS	TDP	2015	1	250.92	4.90E-03	1.9421	3.94E+02	Beta
FTS	TDP	2016	3	267.92	9.55E-03	3.9421	4.09E+02	Beta
SO	AOV	1998	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	1999	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2000	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2001	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2002	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2003	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2004	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2005	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2006	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2007	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2008	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2009	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2010	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2011	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2012	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2013	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2014	0	43800	1.29E-07	0.6801	5.25E+06	Gamma
SO	AOV	2015	0	35040	1.30E-07	0.6801	5.25E+06	Gamma
SO	AOV	2016	0	35040	1.30E-07	0.6801	5.25E+06	Gamma
SO	MOV	1998	0	2514120	2.95E-08	0.5703	1.94E+07	Gamma
SO	MOV	1999	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2000	2	2557920	1.33E-07	2.5703	1.94E+07	Gamma
SO	MOV	2001	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2002	1	2531640	8.11E-08	1.5703	1.94E+07	Gamma
SO	MOV	2003	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2004	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2005	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2006	0	2549160	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2007	0	2549160	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2008	1	2549160	8.10E-08	1.5703	1.94E+07	Gamma
SO	MOV	2009	1	2549160	8.10E-08	1.5703	1.94E+07	Gamma

Table 6. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/Run Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
SO	MOV	2010	0	2663040	2.92E-08	0.5703	1.95E+07	Gamma
SO	MOV	2011	0	2584200	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2012	2	2575440	1.32E-07	2.5703	1.94E+07	Gamma
SO	MOV	2013	1	2575440	8.09E-08	1.5703	1.94E+07	Gamma
SO	MOV	2014	0	2575440	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2015	0	2584200	2.94E-08	0.5703	1.94E+07	Gamma
SO	MOV	2016	0	2531640	2.94E-08	0.5703	1.94E+07	Gamma

Table 7. Basic event UA trending data.

Failure Mode	Component	Year	UA Hours	Critical Hours	Bayesian Update			Distribution
					Mean	Post A	Post B	
UA	TDP	1998	2876.65	208350	1.50E-02	0.531558	34.79267	Beta
UA	TDP	1999	3475.171	234392.5	0.015224	1.925426	124.5509	Beta
UA	TDP	2000	2343.673	244857.4	9.58E-03	2.154063	222.7879	Beta
UA	TDP	2001	3202.477	244285.6	1.33E-02	1.320083	98.23778	Beta
UA	TDP	2002	3026.113	248545.1	1.22E-02	2.024415	164.1129	Beta
UA	TDP	2003	2847.03	242932.3	1.19E-02	1.860213	154.0376	Beta
UA	TDP	2004	1913.641	247149.2	7.68E-03	1.648808	213.0301	Beta
UA	TDP	2005	1832.18	243870.4	7.59E-03	2.026415	265.0939	Beta
UA	TDP	2006	2361.344	248054.5	9.45E-03	3.095679	324.3879	Beta
UA	TDP	2007	2620.95	243836.9	1.12E-02	0.489163	43.15568	Beta
UA	TDP	2008	2075.75	247817.2	8.30E-03	1.065584	127.2474	Beta
UA	TDP	2009	2909.55	240793.2	1.25E-02	0.375741	29.75247	Beta
UA	TDP	2010	2751.94	247361.8	1.11E-02	1.47122	131.088	Beta
UA	TDP	2011	2344.64	238173.5	1.04E-02	1.511844	144.2565	Beta
UA	TDP	2012	2614.27	240165	1.07E-02	1.943447	180.1524	Beta
UA	TDP	2013	3828.38	240850.6	1.53E-02	0.191261	12.28148	Beta
UA	TDP	2014	2161.38	246590	8.74E-03	2.011458	228.1119	Beta
UA	TDP	2015	2042.96	238049.6	8.61E-03	6.239323	718.4968	Beta
UA	TDP	2016	2521.96	237938.6	1.08E-02	2.376403	216.7545	Beta

Table 8. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTLR	Fail to load/run
FTOC	Fail to open/close
FTOP	Fail to operate
FTR	Fail to run
FTR<1H	Fail to run less than one hour
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. 19H19H 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 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

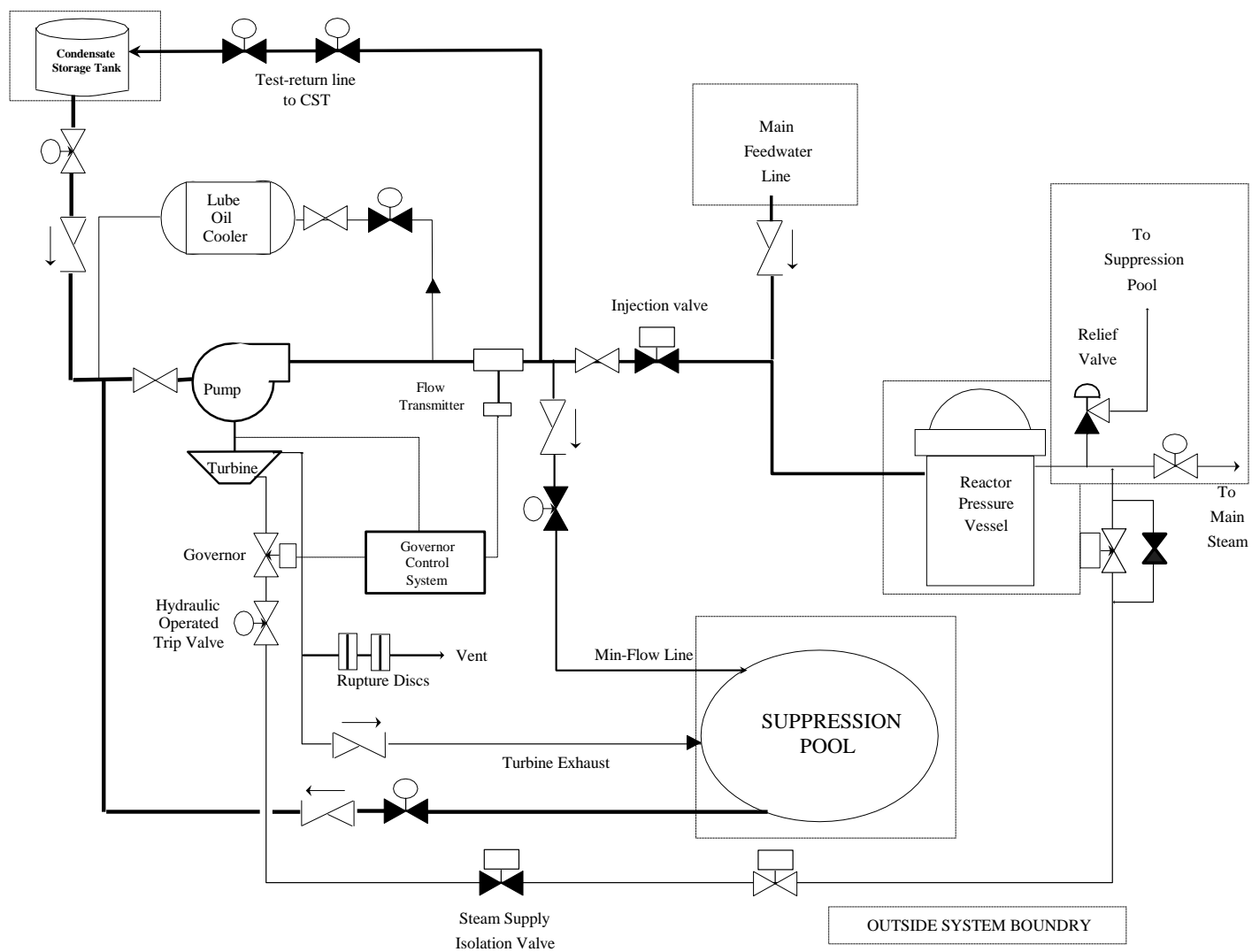
provided, which uses a shaft-driven lubrication oil pump. The shaft-driven pump provides lubrication oil to the turbine bearings and governor assembly as soon as the turbine begins to roll, enhancing both turbine lubrication and governor response.

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 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.



**BWR Reactor Core Isolation Cooling**

*Figure 4. Simplified RCIC system schematic.*





## 8. REFERENCES

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