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System Study: Isolation Condenser 1998–2014

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ABSTRACT

This report presents an unreliability evaluation of the isolation condenser (ISO) system at four U.S. boiling water reactors. Demand, run hours, and failure data from fiscal year 1998 through 2014 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 increasing trends were identified. A statistically significant decreasing trend was identified for ISO unreliability. The magnitude of the trend indicated a 1.5 percent decrease in system unreliability over the last 10 years.

CONTENTS

FIGURES

TABLES

ACRONYMS

CCF	common-cause failure
EPIX	Equipment Performance and Information Exchange
FTOC	fail to open/close
FTOP	fail to operate
FY	fiscal year
ICES	INPO Consolidated Events Database
INPO	Institute of Nuclear Power Operations
ISO	isolation condenser
MSPI	Mitigating Systems Performance Index
PRA	probabilistic risk assessment
SO	spurious operation
SPAR	standardized plant analysis risk
SSU	safety system unavailability

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1. INTRODUCTION

This report presents an unreliability evaluation of the isolation condenser (ISO) system at 4 U.S. commercial boiling water reactors 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. Demand, run hours, and failure data from fiscal year (FY)-98 through FY-14 for selected components in the ISO 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 (FY-98 through FY-01) and the Mitigating Systems Performance Index (MSPI) database (FY-02 through FY-14). 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 1), which is an update to Reference 2 (NUREG/CR-6928). Baseline ISO unreliability results using basic event values from that report are summarized in Section 3. Trend results for ISO (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 ISO.

The ISO model is evaluated using the station blackout flag set in the SPAR model. The station blackout flag set assumes no support systems or normal sources of makeup water are available and that the ISO system is required to perform to mitigate the effects of the station blackout 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.

One mode of the models for the ISO system is calculated. The fail to operate (FTOP) model includes the initial opening of the condensate return valve and make-up capabilities to continue to operate for 8 hours.

Table 1. BWR plants with an ISO system selected for the study.

Plant	Version
Dresden 2	8.18
Dresden 3	8.18
Nine Mile Pt. 1	8.21
Oyster Creek	8.22

2. SUMMARY OF FINDINGS

The results of this ISO system unreliability study are summarized in this section. Of particular interest is the existence of any statistically significant[a] increasing trends. In this update, no statistically significant increasing trends were identified in the ISO unreliability trend results. A statistically significant decreasing trend was identified for ISO system unreliability. The magnitude of the trend indicates a 1.5 percent decrease in system unreliability over the most recent 10 years in the data set.

The industry-wide ISO 8-hour basic event group importance was evaluated and is shown in Figure 2. The leading contributor to ISO system unreliability is failure of the alternate source (only source of makeup water during a station blackout), followed by recovery, the condenser, a dependency on the EPS, and the ISO valves.

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 ISO fault trees from the SPAR models were evaluated for each of the 4 operating U.S. commercial boiling water nuclear power plants with an ISO system.

The industry-wide unreliability of the ISO system has been estimated for one mode of operation, fail-to-operate-and-makeup. The uncertainty distributions for ISO 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 ISO 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%)
Operate and makeup	2.43E−05	6.65E−03	3.30E−02	1.18E−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 (FY-98 through FY-14) failure and demand or run time data were obtained from ICES for the ISO system. The component basic event uncertainty was calculated for the ISO system components using the trending methods described in Section 1 and 2 of the Overview and Reference document. Table 5 shows the yearly data values for each ISO system specific component and failure mode combination that was varied in the model. These data were loaded into the ISO system fault tree in each SPAR model with an ISO 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 (current SPAR/ICES) 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.

Figure 1 shows the trend in the system unreliability (operate and makeup). The trend is a statistically significant decreasing trend within the industry-wide estimates of ISO system unreliability (operate and makeup) on a per fiscal year basis. The observed trend represents a 1.5 percent decrease in system unreliability. Table 4 shows the data points for Figure 1.

The components that were varied in the ISO model are the ISO condensate MOV or AOV fail-to-open.

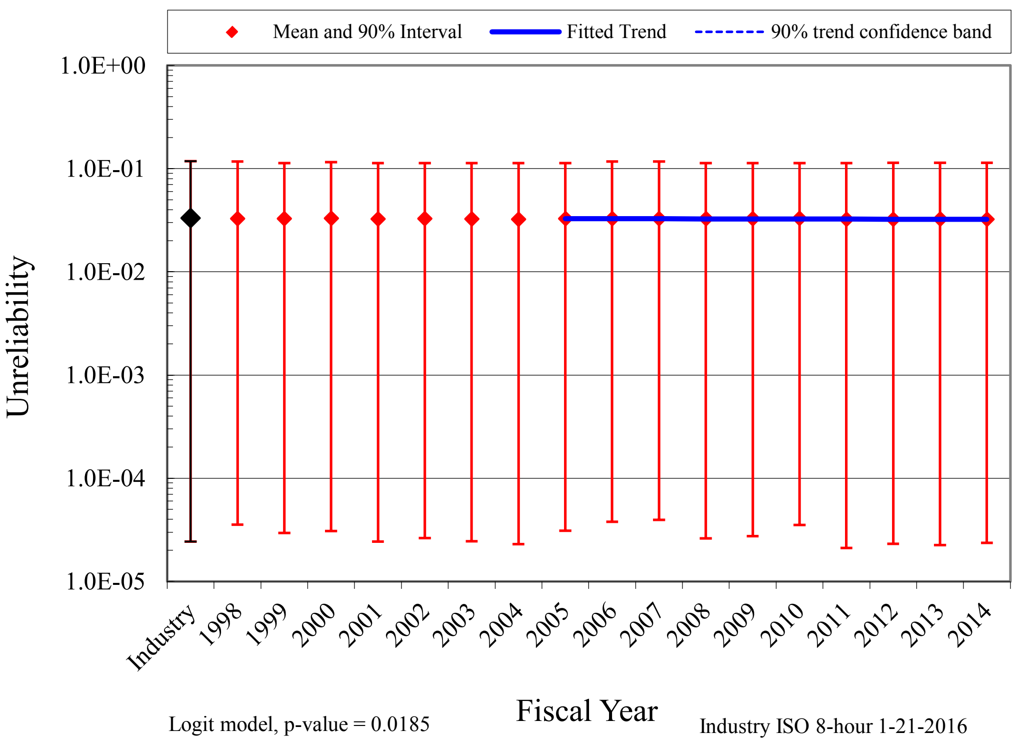

Figure 1. Trend of ISO system unreliability (operate and makeup), as a function of fiscal year.

5. BASIC EVENT GROUP IMPORTANCES

The ISO basic event group Fussell-Vesely importances were calculated for the operate and makeup mode 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 ISO operate and makeup basic event group importances are shown in Figure 2. The leading contributors to ISO system unreliability are the isolation condenser heat exchanger, recovery and the ISO valves. For more discussion on the ISO valves, see the motor-operated and air-operated valve component reliability studies at NRC Reactor Operational Experience Results and Databases. Table 3 shows the SPAR model ISO importance groups and their descriptions.

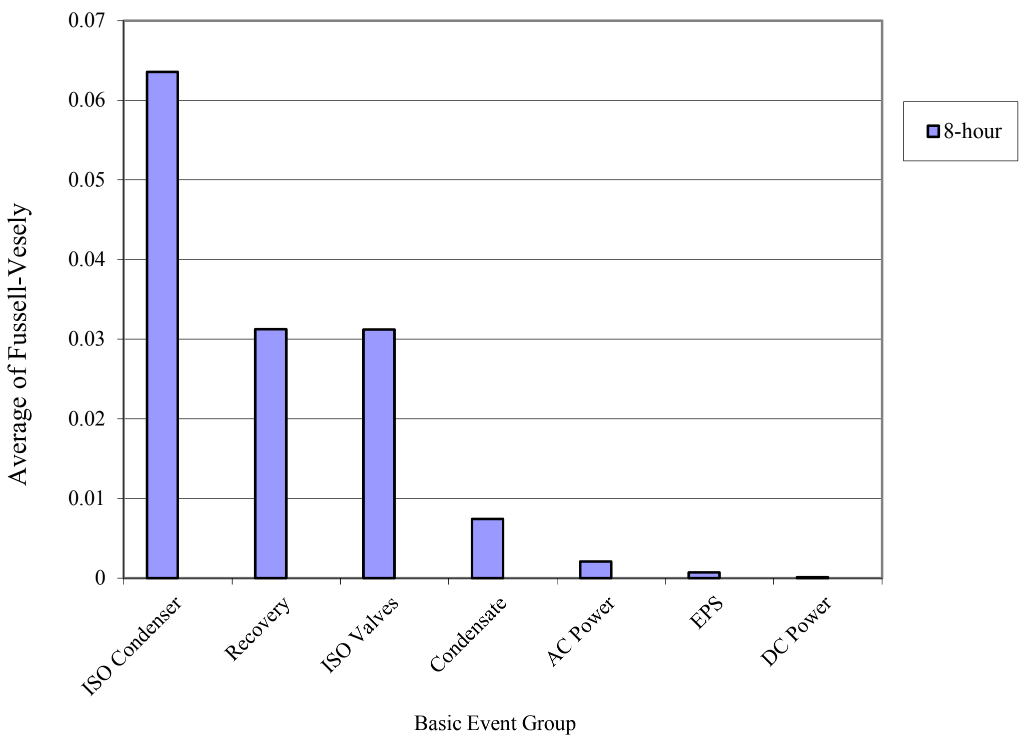

Figure 2. ISO basic event group importances.

Table 3. ISO model basic event importance group descriptions.

Group	Description
AC Power	The ac buses and circuit breakers that supply power to the makeup water source pumps and motor-operated valves if used.
Condensate	Normal source of cooling water to the isolation condenser includes pumps and valves.
DC Power	The batteries and battery chargers that supply power to the ISO circuitry and valves.
EPS	Emergency power system dependency.
ISO Condenser	The isolation condenser heat exchanger.
ISO Valves	Air or motor-operated valves required for the isolation condenser function.
Recovery	Recovery from failure to actuate.

6. DATA TABLES

Table 4. Plot data for ISO operate and makeup trend, Figure 1.

FY/Source	Regression Curve Data Points			Annual Estimate Data Points		
	Mean	Lower (5%)	Upper (95%)	Lower (5%)	Upper (95%)	Mean
SPAR/ICES				2.43E−05	1.18E−01	3.30E−02
1998				3.54E-05	1.17E-01	3.25E-02
1999				2.94E-05	1.13E-01	3.27E-02
2000				3.07E-05	1.16E-01	3.28E-02
2001				2.43E-05	1.14E-01	3.23E-02
2002				2.62E-05	1.13E-01	3.26E-02
2003				2.45E-05	1.14E-01	3.23E-02
2004				2.30E-05	1.13E-01	3.22E-02
2005	3.28E-02	3.25E-02	3.31E-02	3.11E-05	1.13E-01	3.27E-02
2006	3.27E-02	3.25E-02	3.30E-02	3.78E-05	1.17E-01	3.26E-02
2007	3.27E-02	3.25E-02	3.29E-02	3.96E-05	1.17E-01	3.26E-02
2008	3.26E-02	3.24E-02	3.28E-02	2.62E-05	1.13E-01	3.27E-02
2009	3.26E-02	3.24E-02	3.27E-02	2.74E-05	1.13E-01	3.27E-02
2010	3.25E-02	3.24E-02	3.26E-02	3.52E-05	1.13E-01	3.28E-02
2011	3.24E-02	3.23E-02	3.26E-02	2.11E-05	1.14E-01	3.22E-02
2012	3.24E-02	3.22E-02	3.26E-02	2.32E-05	1.14E-01	3.22E-02
2013	3.23E-02	3.21E-02	3.26E-02	2.24E-05	1.14E-01	3.24E-02
2014	3.23E-02	3.20E-02	3.26E-02	2.36E-05	1.14E-01	3.22E-02

Table 5. 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	39.56	9.20E-04	1.112	1207.56	Beta
FTOC	AOV	1999	0	40.06	9.20E-04	1.112	1208.06	Beta
FTOC	AOV	2000	0	42.06	9.18E-04	1.112	1210.06	Beta
FTOC	AOV	2001	0	42.06	9.18E-04	1.112	1210.06	Beta
FTOC	AOV	2002	0	40.02	9.20E-04	1.112	1208.02	Beta
FTOC	AOV	2003	0	66.87	9.00E-04	1.112	1234.87	Beta
FTOC	AOV	2004	0	50.82	9.12E-04	1.112	1218.82	Beta
FTOC	AOV	2005	0	60.3	9.04E-04	1.112	1228.3	Beta
FTOC	AOV	2006	0	40.6	9.19E-04	1.112	1208.6	Beta
FTOC	AOV	2007	0	50.64	9.12E-04	1.112	1218.64	Beta
FTOC	AOV	2008	0	49.64	9.12E-04	1.112	1217.64	Beta
FTOC	AOV	2009	0	66.64	9.00E-04	1.112	1234.64	Beta
FTOC	AOV	2010	0	49.64	9.12E-04	1.112	1217.64	Beta
FTOC	AOV	2011	0	52.64	9.10E-04	1.112	1220.64	Beta
FTOC	AOV	2012	0	45.64	9.15E-04	1.112	1213.64	Beta
FTOC	AOV	2013	0	65.64	9.01E-04	1.112	1233.64	Beta
FTOC	AOV	2014	0	41.64	9.18E-04	1.112	1209.64	Beta
FTOP	AOV	1998	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	1999	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2000	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2001	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2002	1	52560	4.19E-07	2.421	5771560	Gamma
FTOP	AOV	2003	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2004	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2005	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2006	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2007	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2008	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2009	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2010	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2011	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2012	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2013	0	52560	2.46E-07	1.421	5771560	Gamma
FTOP	AOV	2014	0	52560	2.46E-07	1.421	5771560	Gamma
SO	AOV	1998	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	1999	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2000	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2001	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2002	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2003	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2004	0	52560	1.29E-07	0.6801	5263560	Gamma

Table 5. (continued).

Failure Mode	Component	Year	Number of Failures	Demands/ Run Hours	Bayesian Update			
					Mean	Post A	Post B	Distribution
SO	AOV	2005	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2006	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2007	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2008	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2009	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2010	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2011	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2012	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2013	0	52560	1.29E-07	0.6801	5263560	Gamma
SO	AOV	2014	0	52560	1.29E-07	0.6801	5263560	Gamma

Table 6. Failure mode acronyms.

Failure Mode	Failure Mode Description
FTOC	Fail to open/close
FTOP	Fail to operate
SO	Spurious operation

7. SYSTEM DESCRIPTION

This analysis focused on the ability of the ISO system to start and provide design-rated core cooling for its required mission time.

The models used in this report are limited to the models that represent the set of plants listed in Table 1. This analysis focused only on the isolation condenser's emergency core cooling system function to reduce reactor pressure and remove fission product decay heat. The containment isolation function of the system was not evaluated in this study.

Table 7. BWR plants with a dedicated ISO system.

Plant Name	Docket	Trains	Total Number of ISO Condensers	Number of Condensers per Train	Condenser Design	Time Before Make-up is Required (min)
Dresden 2	237	1	1	1	Dual-pass	20
Dresden 3	249	1	1	1	Dual-pass	20
Millstone 1[a]	245	1	1	1	Dual-pass	30
Nine Mile Pt. 1	220	2	4	2	Single-pass	90
Oyster Creek	219	2	2	1	Dual-pass	45

a. Decommissioned.

The ISO system is a standby high-pressure system that removes residual and decay heat from the reactor vessel in the event of a scram in which the reactor becomes isolated from the main condenser, or if any other high pressure condition exists. Also, at most plants, the ISO system aids in reactor vessel depressurization in the event that either (depending on plant design) the feedwater coolant injection or high-pressure coolant injection system fails. Because of its role in emergency core cooling, the ISO system is designated as an emergency core cooling system. The ISO system is a single-train system in three plants and dual-train system in the other two plants.

Figure 3 provides a simplified single train ISO system diagram. This configuration is typical of the single train plants and is effectively doubled for the dual-train plants. Four plants have a single dual-pass isolation condenser per train, while one plant (Nine Mile Pt. 1) has two single-pass isolation condensers per train.

The ISO system transfers residual and decay heat from the reactor coolant to the water in the shell side of the heat exchanger resulting in steam generation. The steam generated in the shell side of the heat exchanger is then vented to the outside atmosphere. The system employs natural circulation as the driving head from the reactor steam side, through the isolation condenser tubes, and back to the reactor.

A typical ISO system is designed to handle three percent reactor power, which means that five minutes after a scram and initiation of the ISO system, the heat removal capacity of the system equals the decay heat production rate of the shutdown reactor. Therefore, reactor water inventory will only be lost through the relief valves for five minutes following a scram and isolation. This represents a minor loss relative to the vessel inventory.

The ISO system is typically required to be operable when there is fuel in the reactor vessel and steam is being produced. During normal operation the isolation condensers are in standby, and are placed in service automatically when needed to provide heat transfer to the environment. In the stand-by condition, the steam isolation valves are open so that the condenser tube bundles are at reactor pressure. Condensate builds up in the condenser and condensate return piping; the condensate is prevented from returning to the reactor by having one of the condensate return valves for that train closed. The steam lines contain vent valves, which are open to vent air and noncondensibles to the main steam system. Collection of air or noncondensible gases in the ISO system could prevent natural circulation flow. The initiation signal places the ISO system into operation by opening the condensate return isolation valve. This valve can also be remotely operated from the control room.

The ISO system operates in a closed loop mode. Steam rises from the reactor vessel to the condenser where it is condensed by boiling the water in the condenser shell. As the reactor steam condenses, it returns by gravity flow through the condensate return valve to the suction of a reactor recirculation pump and thus to the reactor vessel. The water inventory on the shell side of the condenser will provide heat removal for between 20 and 90 minutes depending on the plant design, at which time makeup water must be provided to prevent uncovering the condenser tubes. The sources of makeup water are a combination of condensate water, demineralized water, or the fire water system depending on individual plant design. One plant (Nine Mile Pt. 1) has gravity fed makeup water tanks, which can supply enough water for eight hours of operation before additional makeup is required.

The ISO system instrumentation and control consists of initiation and containment isolation circuitry. These circuits provide different functions, both of which are important to system reliability. The initiation circuitry provides for automatic and manual start of the system. The purpose of the containment isolation circuitry is to initiate closure of appropriate primary containment isolation valves to limit fission product release should a steam line rupture occur.

The ISO system is automatically initiated if a high reactor pressure condition is sustained for 15 seconds. The time delay prevents unnecessary system initiation during turbine trips. Also at most plants, the ISO system automatically initiates on a low vessel water level to aid in reducing reactor pressure for small line breaks. The isolation condenser system can be operated manually by opening the condensate return valve. The ISO system is designed to provide core cooling regardless of whether electrical power is available.

The ISO system is automatically isolated if high ISO steam flow or condensate return flow is sensed indicating a line break (Group V isolation). This isolation shuts all the steam and condensate isolation valves and the steam line vent valves, rendering the ISO system inoperable. The steam line vent valves will also automatically shut on a low vessel water level condition (Group I isolation). Isolation of the vent valves for a prolonged period could render the heat exchanger inoperable due to the buildup of non-condensable gases. However, failure of this circuit to close the vent valves would not preclude operation of the system.

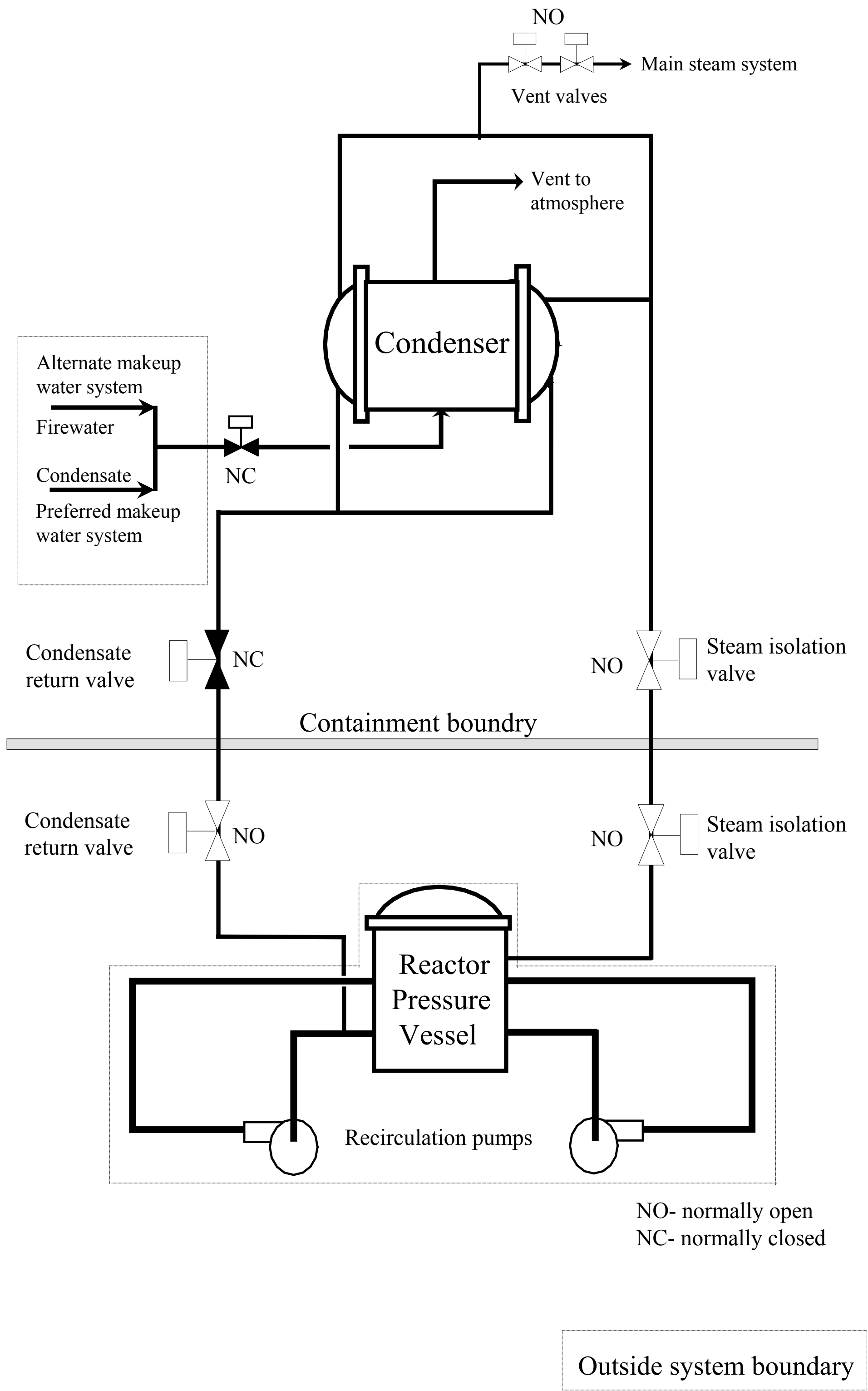

Figure 3. Simplified single train isolation condenser system schematic.

8. REFERENCES

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