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S. A. Eide (INEEL)
M. B. Calley (INEEL)
C. D. Gentillon (INEEL)
T. Wierman (INEEL)
D. Rasmuson (USNRC)
D. Marksberry (USNRC)

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WESTINGHOUSE REACTOR PROTECTION SYSTEM UNAVAILABILITY, 1984 – 1995

Steven Eide, Michael Calley, Cindy Gentillon, and Thomas Wierman
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625
Idaho Falls, ID 83415
(208) 526-3797

Dale Rasmuson and Don Marksberry

U.S. Nuclear Regulatory Commission
11545 Rockville Pike
Rockville, MD 20852
(301) 415-7571

ABSTRACT

An analysis was performed of the safety-related performance of the reactor protection system (RPS) at U.S. Westinghouse commercial reactors during the period 1984 through 1995. RPS operational data were collected from the Nuclear Plant Reliability Data System and Licensee Event Reports. A risk-based analysis was performed on the data to estimate the observed unavailability of the RPS, based on a fault tree model of the system. Results were compared with existing unavailability estimates from Individual Plant Examinations and other reports.

I. INTRODUCTION

Operational experience of the U.S. Westinghouse RPS from 1984 through 1995 was studied and documented in the report *Reliability Study: Westinghouse Reactor Protection System, 1984 - 1995.*[1] The analysis focused on the ability of the RPS to automatically shut down the reactor given a plant upset condition requiring a reactor trip while the plant is at full power. RPS spurious reactor trips or component failures not affecting the automatic shutdown function were not considered. Systems added as part of the anticipated transient without scram (ATWS) mitigation effort were not included in the analysis.

The Westinghouse RPS is a complex control system comprising numerous electronic components that combine to provide the ability to produce an automatic or manual rapid shutdown of the nuclear reactor, known as a reactor trip or scram. In spite of its complexity, the Westinghouse RPS can be roughly divided into four segments – instrumentation rack (channels), logic cabinet (trains), trip breakers, and rods – as shown in Figure 1. The rods segment includes the rod control cluster assemblies (RCCAs) and associated control rod drive mechanisms (CRDMs). Westinghouse RPSs typically have 40 to 60 RCCAs and associated CRDMs. The trip breaker segment includes the reactor trip breakers and associated undervoltage and shunt trip devices. For the logic cabinet (trains), approximately 70% of the RPSs have solid-state logic termed the Solid State Protection System (SSPS), while the remaining 30% have analog logic. Finally, for the instrumentation rack (channels) approximately 85% of the RPSs have analog systems to process the signals, while the remaining 15% have converted to the Eagle-21 solid state system.

RPS Segments			
Instrumentation Rack (Channels)	Logic Cabinet (Trains)	Trip Breakers	Rods
Generally, 3 channels for 3-loop plants, 4 channels for 2- and 4-loop plants; analog (Analog Series 7300 or earlier) or Eagle-21 signal processing	2 trains, SSPS or analog logic	2 reactor trip breakers (and 2 bypass breakers); DB-50 or DS-416 design; automated shunt trip and undervoltage devices	40 to 60 RCCAs and associated CRDMs

Figure 1. Segments of Westinghouse RPS.

The analysis of the Westinghouse RPS was based on a four-loop plant with either an Eagle-21 or Analog Series 7300 sensor processing system and an SSPS for the logic cabinet. This configuration is representative of many plant designs. The Westinghouse RPS includes many different types of trip signals. The trip signals include various neutron flux indications, pressurizer pressure and level, reactor coolant flow, steam generator level, and others. For most types of plant upset conditions, at least three different trip signals would be generated. For this study, only two of the trip signals were modeled: overpower ΔT and pressurizer high pressure.

There are two RPS trains in the logic cabinet, trains A and B. These trains receive trip signals from the channels, process the signals, and then open the reactor trip breakers given appropriate combinations of signals from the channels. For the RPS to fail, both of the trains (or their associated reactor trip breaker) must fail, a sufficient number of channel failures must occur, or a sufficient number of RCCAs must fail to insert. Since only two diverse trip signals were modeled, 3 of 4 channels for each of the two trip signals must fail. It was assumed that 10 or more of the 40 to 60 RCCAs must fail to fully insert (in a random pattern). A sensitivity study was conducted to determine the impact on RPS unavailability from this assumption.

Testing of the Westinghouse RPS can be summarized by RPS segment (Figure 1). Generally, the RPS channels are tested every three months, with the channel being placed in a bypass condition during the test. The trains and reactor trip breakers are tested on a staggered monthly basis. This means that each train (and associated breaker) is tested every two months. Finally, the RCCAs and associated CRDMs are tested every refueling or 18 months.

II. SYSTEM FAULT TREE

System fault trees were constructed for each of the two Westinghouse RPS designs analyzed: Analog Series 7300 and Eagle-21. The level of detail in the fault tree includes RCCA/CRDMs, reactor trip breakers and bypass trip breakers (broken down into mechanical/electrical, undervoltage device, and shunt trip device contributions), undervoltage driver and universal cards in the SSPS, selected relays, temperature and pressure sensor/transmitters, Eagle-21 and analog process logic modules, and bistables. As noted previously, two trip signals were included in the fault tree, even though at least three signals are typically generated for plant upset conditions. A sensitivity study was conducted to determine the impact on RPS unavailability if three trip signals had been modeled.

Common-cause failures (CCFs) across similar components were explicitly modeled in the RPS fault tree. In general, CCF events were defined to involve sufficient failures of the component type to fail the RPS. Lower-order CCF events, which must be combined with random component failures to cause an RPS failure, were not included in the fault tree. Results of the fault tree quantification were reviewed to ensure that the exclusion of lower-order CCF events did not significantly impact the results.

Test and maintenance outages and associated RPS configurations were modeled for the SSPS (and associated reactor trip breaker) and channel outages. For channel outages, the channel was assumed to be placed into a bypass condition, rather than a tripped mode. For SSPS train outages, only the other train is available to respond to plant upset conditions.

The Analog Series 7300 RPS fault tree model included approximately 120 basic events, of which approximately 40 were CCF events. Approximately 25,000 cut sets were generated when the fault tree model was solved using the SAPHIRE computer code.[2] The Eagle-21 fault tree model had a similar level of complexity.

III. DATA REVIEW AND ANALYSIS

U.S. Westinghouse RPS performance during the period 1984 through 1995 was assessed by reviewing Licensee Event Reports and the Nuclear Plant Reliability Data System reports. Fifty-three U.S. Westinghouse nuclear power plants were covered in the study. Approximately 15,000 reports were identified. Of these 15,000, approximately 1,000 involved actual component failures (independent or CCF) applicable to this study.

The data review process involved at least two independent reviews of each event report by knowledgeable engineers. Each event was characterized by safety function impact (fail-safe, non-fail-safe, or unknown) and degree of failure (complete failure, no failure, or unknown). This resulted in a three-by-three matrix, with nine different bins into which an event could be placed, as indicated in Figure 2. This classification scheme resulted in one bin with non-fail-safe, complete failures of components. Three other bins may also contain such events, but limited information from the event report did not allow the analysts to determine whether the events were non-fail-safe, complete failures.

	Safety Function Impact		
	Non-fail-safe, complete failure [a]	Unknown safety function impact, complete Failure [b]	Fail-safe, complete failure [c]
Failure Complete-ness	Non-fail-safe, unknown complete-ness [b]	Unknown safety function impact, unknown completeness [b]	Fail-safe, unknown complete-ness [c]
	Non-fail-safe, no failure [c]	Unknown safety function impact, no failure [c]	Fail-safe, no failure [c]

a. Events in this bin receive weights of 1.0.
b. Events in these bins receive weights of <1.0.
c. Events in these bins are not applicable.

Figure 2. Data classification scheme.

The data analysis considered events from these four bins (shaded bins in Figure 2), using a weighting scheme to account for the uncertainty in the unknown events.

Data analysis for the component failures involved several steps:

1. Demand count and exposure time estimation
2. Statistical analysis of data subgroups to identify differences
3. Component unavailability estimation
4. CCF event unavailability estimation
5. Trending with time evaluation.

The component demand counts were estimated from plant scram histories (for those components demanded by a scram), and testing intervals (generally staggered monthly, every three months, or every 18 months).

Statistical analysis of data subgroups was performed to identify differences in component performance resulting from plant mode (at power or shutdown), time period (1984 – 1989 versus 1990 – 1995), or type of demand (scram or test). The data from the selected data subgroup were then analyzed to determine component failure probabilities or rates.

Results of the data analysis to determine component failure probabilities or rates are presented in Figure 3. The numbers of component failures listed in Figure 3 are generally subsets of the total number of failures identified in the data review. For example, if the data subgroup analysis indicated a significant difference in component performance between 1984 – 1989 and 1990 – 1995, then only the 1990 – 1995 data were used. In general, the resultant component failure probabilities and rates are comparable with existing estimates.[3 through 6]

Quantification of the CCF events in the fault tree was performed using the alpha factor method outlined in the report *Common-Cause Failure Database and Analysis System: Event Definition and Classification*.[7] Only CCF events associated with the Westinghouse RPS during the period 1984 through 1995 were used in the quantification process. Several steps were required in the overall CCF evaluation:

1. Characterization of CCF data (component group size, impact vector, shared cause and timing factors, and failure completeness factor)
2. Characterization of CCF events modeled in the fault trees (component group size and required number of component failures)
3. Development of alpha factor equations for each of the CCF events modeled
4. Development of an appropriate prior for the alpha factors
5. Mapping up or down of CCF data to match the component group sizes modeled in the fault trees
6. Quantification of CCF event probabilities using component-specific CCF data and the prior.

Selected results of the CCF event quantification process are presented in Figure 4. In general, the CCF event probabilities reflect multipliers (from the alpha factor equations) of 0.002 to 0.08 on the component failure probabilities. These multipliers are influenced by the specific failure criterion (minimum number of component failures required and size of component group), strength of the component-specific CCF data, and the prior distribution for the alpha factors obtained from the Westinghouse CCF data. In general, there were very few complete CCF events (where all the components in the group fail due to a common cause). Also, there were no complete CCF events in the higher-order group sizes.

Trending analysis over time was performed for the component failure probabilities and the number of CCF events. Four of 14 component types exhibited decreasing trends over time with respect to failure probabilities. The remaining 10 component types did not exhibit any significant trends. Therefore, none of the component types exhibited increasing failure probabilities over time.

The number of CCF events reported each year dropped significantly over the period 1984 – 1995. This is the result of three component types exhibiting decreasing trends over time. The remaining 11 exhibited no trends. Therefore, none of the component types exhibited increasing numbers of CCF events over time. Most of the component trends (or lack of trends) were supported by a limited number of CCF events.

IV. RESULTS

The Westinghouse RPS fault trees were quantified using the basic event failure probabilities presented in Figures 3 and 4. The resultant RPS mean unavailability (failure probability upon demand) is 2.2E-5, assuming no credit for operator action. This result is for a four-loop plant with Analog Series 7300 channel processing and SSPS trains. If credit is taken for the operator to actuate the manual scram switch, then the mean unavailability drops to 5.4E-6. Dominant failures involve CCFs of the undervoltage driver cards, channel bistables, channel signal processing modules, SSPS universal cards, reactor trip breakers, and RCCA/CRDMs. Overall, CCF events contribute 95% to the RPS unavailability.

Quantification of the Eagle-21 fault tree resulted in an RPS mean unavailability of 2.0E-5. This drops to

Component Type	Number of Failures [a]	Number of Demands or Hours	Failure Probability or Rate [b]	Basic Event Description
Reactor trip breaker (mechanical/electrical)	0 (0.0)	13546	3.7E-5	Trip breaker failure to open (mechanical/ electrical failure that defeats both undervoltage and shunt trip devices)
Reactor trip breaker (shunt trip device)	8 (7.5)	13048	5.8E-4	Shunt trip failure to energize and open the reactor trip breaker
Reactor trip breaker (undervoltage coil device)	2 (2.0)	9856	2.5E-4	Undervoltage coil failure to de-energize and open the reactor trip breaker
Eagle-21 channel processor	11 (10.6)	972577 h	8.2E-6/h	Eagle-21 channel processor fails to process reactor trip signals and send appropriate outputs to channel
Channel bistable	44 (40.0)	56235	7.4E-4	Channel bistable fails to trip at its setpoint and actuate its train relays
Channel pressure processing module	14 (5.6)	38115	1.6E-4	Channel pressure processing module (Analog Series 7300) fails to process a reactor trip signal and send appropriate output to the channel bistable
Channel ΔT processing module	36 (15.1)	3157	4.8E-3	Channel ΔT processing module (Analog Series 7300) fails to process a reactor trip signal and send appropriate output the channel bistable
Channel pressure sensor/transmitter	3 (0.2)	5832	1.2E-4	Channel pressure sensor/transmitter fails to detect a high pressure and send appropriate output to the channel processing module
Channel temperature sensor/transmitter	11 (8.2)	14423	6.0E-4	Channel temperature sensor/transmitter fails to detect a high/low temperature and send appropriate output to the channel processing module
RCCA and CRDM (combined)	2 (1.0)	102088	1.5E-5	Failure of RCCA/CRDM, resulting in failure of RCCA to insert into the reactor core
SSPS universal card	24 (23.0)	58220	3.8E-5	SSPS universal card fails to recognize a reactor trip combination and send appropriate output to the train undervoltage driver card
Channel bistable relay; train undervoltage driver card relay	7 (6.2)	168686	3.9E-5	Relay associated with channel bistable fails to respond to bistable trip; undervoltage driver card shunt trip relay fails to respond
SSPS undervoltage driver card	2 (2.0)	7424	3.4E-4	SSPS undervoltage driver card fails to respond to a universal card reactor trip signal

a. Includes uncertain events and CCF events. The number in parentheses is the weighted average number of failures, resulting from the inclusion of uncertain events in Figure 2 (shaded bins).

b. The failure probability or rate calculation involves a complex simulation process to account for potential non-fail-safe, complete failure events (the three bins in Figure 2 with the "b" footnote). However, the probability can be approximated by the expression (n+0.5)/(D+1), where n is the weighted number of failures (in parentheses in column 2) and D is the number of demands. The failure rate can be approximated by the expression (n+0.5)/T, where T is the time in hours.

Figure 3. Westinghouse RPS component failure probabilities.

Component Type	Number of CCF Events	Component Failure Probability	CCF Event Probability	CCF Event Description
Reactor trip breaker (mechanical/electrical)	1	3.7E-5	1.6E-6	CCF of 2 of 2 trip breakers (mechanical/electrical failures)
Eagle-21 channel processor	2	6.5E-5 [a]	5.1E-7 [a]	CCF of 3 or more of 4 Eagle-21 channel modules
Channel bistable	43	7.4E-4	2.7E-6	CCF of 6 or more of 8 channel bistables
Channel pressure processing module	2	1.6E-4	4.5E-6	CCF of 3 or more of 4 pressurizer high pressure processing modules
Channel ΔT processing module	51	4.8E-3	5.6E-5	CCF of 3 or more of 4 overtemperature ΔT processing modules
Both types of processing modules	5	7.8E-4	1.8E-6	CCF of 3 or more of 4 pressurizer high pressure processing modules and 3 or more of 4 overtemperature ΔT processing modules
Channel pressure sensor/transmitter	29	1.2E-4	2.1E-6	CCF of 3 or more of 4 pressurizer pressure sensor/transmitters
Channel temperature sensor/transmitter	29	6.0E-4	3.7E-5	CCF of 1 or more of 2 reactor coolant temperature sensor/transmitters in 3 or more of 4 loops
RCCA/CRDM	2	1.5E-5	1.2E-6	CCF of 10 or more of 50 RCCA/CRDMs
SSPS universal card	6	3.8E-5	2.1E-6	CCF of 4 of 4 (pressurizer high pressure and ΔT) universal cards in both trains
Channel bistable relay	8	3.9E-5	8.1E-8	CCF of 3 or more of 4 relays for 4 of 4 trip signals
Undervoltage driver card relay	8	3.9E-5	2.0E-6	CCF of 2 of 2 shunt trip relays
SSPS undervoltage driver card	0 [b]	3.4E-4	1.0E-5	CCF of 2 of 2 undervoltage driver cards

a. The rates have been multiplied by a repair time of 8 hours to obtain an unavailability.
b. A 1989 CCF event involving both cards was not used in the quantification. Both card failures were caused by maintenance activities while the plant was shut down, and the failures were detected before the plant returned to power.

Figure 4. Selected Westinghouse RPS CCF event probabilities.

4.5E-6 if credit is taken for the operator to actuate the manual scram switch. Dominant failures for this design are similar to those listed for the Analog Series 7300 design. CCF events contribute 94% to the RPS unavailability.

The Westinghouse RPS unavailability results can be broken down into contributions by each of the four segments. These breakdowns are presented in Figure 5 for the Analog Series 7300 design. Train failures dominate, contributing 63.0% to the total. However, this drops to only 2.4% of the total if credit is taken for manual scram by the operator. This significant drop occurs because the manual scram signal bypasses the train undervoltage driver cards (CCF of these two cards dominates the train unavailability). The trip breaker failure contribution is only 7.6% (29.1% with credit for manual scram).

RPS segment contributions for the Eagle-21 design are presented in Figure 6. In general, the Eagle-21 results are similar to the results for the Analog Series 7300 design. However, the Eagle-21 results indicate more reliable channel signal processing.

Finally, uncertainty results for both RPS designs are presented in Figure 7. These uncertainty results incorporate only data uncertainties. They do not include any modeling uncertainties. Sensitivity studies were conducted to address certain modeling issues, such as the failure criterion for RCCA/CRDMs, use of two rather than three reactor trip signals in the fault tree, and others. In general, the sensitivity studies indicated that the data uncertainty results cover most of the modeling uncertainties. However, the choice of prior distribution for the alpha factors in the CCF calculations can significantly impact the RPS unavailability results.

The Westinghouse RPS unavailabilities obtained from the 1984 – 1995 data are compared with Individual Plant Examination (IPE) estimates in Figure 8. The IPE RPS estimates range from approximately 1.0E-6 to

	RPS Unavailability	
RPS Segment	No Credit for Manual Scram by Operator	Credit for Manual Scram by Operator
Train	1.3E-5 (63.0%)	1.3E-7 (2.4%)
Channel	5.1E-6 (23.8%)	2.6E-6 (46.9%)
Trip breaker	1.6E-6 (7.6%)	1.6E-6 (29.1%)
Rod	1.2E-6 (5.6%)	1.2E-6 (21.7%)
Total RPS	2.2E-5	5.4E-6

Figure 5. Westinghouse RPS unavailability by segment (Analog Series 7300).

	RPS Unavailability	
RPS Segment	No Credit for Manual Scram by Operator	Credit for Manual Scram by Operator
Train	1.3E-5 (69.3%)	1.3E-7 (2.9%)
Channel	3.1E-6 (16.1%)	1.6E-6 (34.8%)
Trip breaker	1.6E-6 (8.4%)	1.6E-6 (35.7%)
Rod	1.2E-6 (6.2%)	1.2E-6 (26.6%)
Total RPS	2.0E-5	4.5E-6

Figure 6. Westinghouse RPS unavailability by segment (Eagle-21 design).

	Unavailability			
RPS Design and Case	5th Percentile	Median	Mean	95th Percentile
Analog Series 7300 (no manual scram)	5.8E-6	1.5E-5	2.2E-5	5.7E-5
Analog Series 7300 (manual scram)	1.3E-6	3.8E-6	5.4E-6	1.4E-5
Eagle-21 (no manual scram)	4.5E-6	1.3E-5	2.0E-5	5.3E-5
Eagle-21 (manual scram)	8.8E-7	2.6E-6	4.5E-6	1.2E-5

Figure 7. Westinghouse RPS uncertainty results.

1.0E-4. Because of the lack of detailed information in the IPE submittals, it is not clear which estimates included credit for operator action. The uncertainty ranges obtained in this study cover most of the IPE range of RPS unavailabilities. However, most of these other sources estimated that the trip breaker CCF events would dominate the RPS unavailability. In this study, such events contribute less than 10% when no credit is taken for manual scram by the operator, and approximately 30% if credit is taken.

V. DISCUSSION AND INSIGHTS

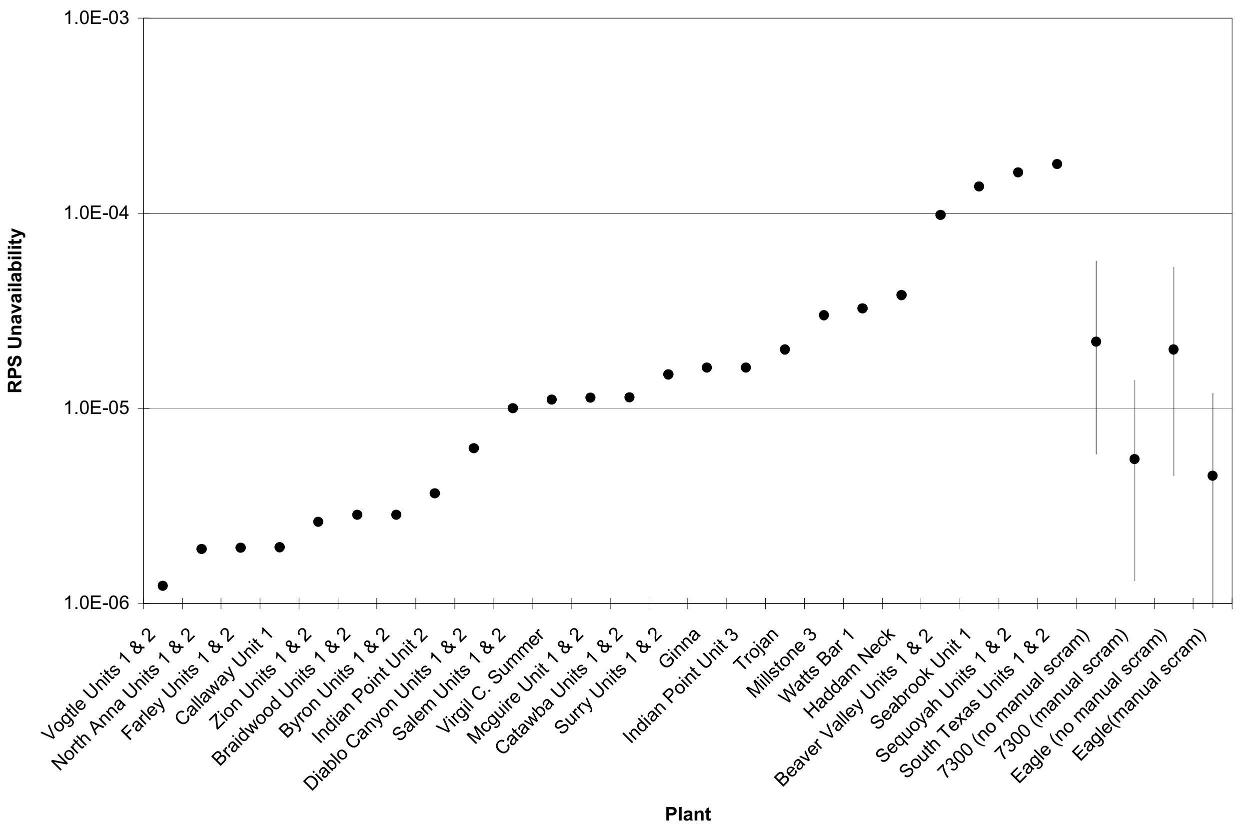
CCF events contribute approximately 95% to the RPS unavailabilities obtained in this study. Quantification of the CCF events in the RPS fault trees is a complex process. The channel and train portions of the RPS fault tree contain component group sizes ranging from two to 16, and the rod portion was assumed to have a representative group size of 50. A prior for the alpha factors was developed for the CCF quantification, based only on Westinghouse RPS component CCFs. The prior was then updated using CCF data specific to the component in question. In several cases the component-specific CCF data were sparse, resulting in a strong influence by the prior. However, this RPS CCF quantification is believed to be the most comprehensive and component-specific effort to date. The effort would not have been possible without the methodology outlined in the report *Common-Cause Failure Database and Analysis System: Event Definition and Classification*.

Several insights were obtained from this study:

1. Both the Analog Series 7300 and Eagle-21 RPS designs have a single undervoltage driver card in each of the two trains. Failure of both of these cards results in failure of RPS (unless manual scram is credited). This CCF event is the dominant contributor (almost 50%) to RPS unavailability. In 1989 a CCF event involving both driver cards occurred while the plant was shut down. The failures were caused by maintenance activities and were detected before the plant returned to power. Since then, the driver card design has been changed to minimize the chance of such maintenance activities causing such failures. Also, plant procedures for such maintenance have been improved. However, CCF of both of these cards is still predicted to be a dominant contributor to RPS unavailability.

2. Issues related to reactor trip breakers, arising during the early 1980s, are no longer dominant with respect to RPS unavailability. (This is true for both cases of RPS unavailabilities: without credit for manual scram and with credit for manual scram.) Automatic actuation of the shunt trip mechanism within the reactor trip breakers and improved maintenance procedures have resulted in improved performance of these components.

3. The design of the manual scram feature of the Westinghouse RPS is especially effective. If credit is taken for manual scram by the operator, the predicted unavailability is reduced by approximately 75%. This occurs because the manual scram signal bypasses the train undervoltage driver cards.



Note: The ranges shown for the 7300 (Analog Series 7300) and Eagle (Eagle-21) results from this study are the 5^{th} and 95^{th} percentiles. All other data points are mean values.

Figure 8. Westinghouse IPE RPS unavailabilities.

4. The Analog Series 7300 and Eagle-21 RPS designs have comparable unavailabilities. This occurs because the Eagle-21 design considered in this report involves only the channel-processing portion of the RPS. The dominant contributors to RPS unavailability result from other portions of the RPS.

5. Not many significant Westinghouse RPS CCF events were identified during the period 1984 – 1995. Therefore, current practices appear to be effective in preventing such events.

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