REVIEW AND UPDATE OF I&C COMPONENT RELIABILITY

Steven A. Eide[1]

[1] *Curtiss-Wright/Scientech: 160 2nd Street East, #105, Ketchum, ID, 83340, seide@curtisswright.com*

Reliability estimates for Westinghouse RPS/ESF digital I&C components were generated based on historical experience of US commercial nuclear power plants. The US NRC software package NROD was used to identify failure events within the INPO ICES database covering 1998 - 2015. Using other sources to determine the numbers of plants with Eagle-21 and SSPS assemblies, numbers of DI&C piece parts per plant, and test intervals, failure rate and demand probability contributions to unreliability were determined. The event review also looked for common-cause failure events

I. INTRODUCTION

This paper describes a review of United States (US) commercial nuclear power plant reliability data for selected digital instrumentation and control (DI&C) assemblies. The focus is on Westinghouse Eagle-21 and Solid State Protection System (SSPS) assemblies within the Reactor Protection System (RPS) and Engineered Safety Features (ESF) actuation system. Data were obtained from the US Nuclear Regulatory Commission (NRC) Reactor Operating Experience Data (NROD)[1] software and database and US licensee event reports (LERs).[2] The period covered is 1998 through 2015. Event descriptions were reviewed to identify non-fail-safe failures (NFS) for these assemblies. Combined with estimates of assembly counts, operating hours, and test demands, failure rates were estimated. Also, CCF events were identified and discussed, but not quantified.

II. BACKGROUND

Nuclear power plant RPS and ESF designs were originally analog based. However, newer plant designs have included some DI&C assemblies, some existing plant analog-based functions have been converted to DI&C, and many of the advanced reactor designs include extensive use of DI&C. In the US, the NRC has been struggling with how to effectively modernize its DI&C regulatory infrastructure. Recently a draft integrated action plan has been developed by NRC to accomplish this goal.[3] Also, NRC is funding various research programs related to DI&C.[4] In addition to dedicated digital devices and I&C, the plan also addresses the use of embedded digital devices (EDDs) within safety-related systems.[5] A major concern with DI&C is the potential for CCF, especially in the software embedded in the DI&C. The US industry has also been working to support this goal through the Nuclear Energy Institute (NEI) and the Electric Power Research Institute (EPRI), as well as individual vendor activities. Selected reports of interest have been generated.[6-8]

There are limited data collection and analyses related to the in-plant reliability of DI&C assemblies in US RPS/ESFs. Those are described below.

The Westinghouse RPS for US commercial nuclear power plants was analyzed for reliability in the report *Reliability Study: Westinghouse Reactor Protection System, 1984 – 1995*.[9] At that time, there were approximately 50 Westinghouse plants in operation. The RPS was subdivided into the following segments: instrumentation rack (channels), logic cabinet (trains), trip breakers, and rods. Failure data were obtained from a review of events contained in the Nuclear Plant Reliability Data System (NPRDS, a predecessor to NROD) and LERs. That study estimated failure rates and CCF probabilities for both the Eagle-21 assemblies and SSPS universal logic cards (ULCs). However, no updates to this report have been produced.

A similar study covering RPSs for US Combustion Engineering plants is the report *Reliability Study: Combustion Engineering Reactor Protection System, 1984 – 1998*.[10] That study covered the 15 Combustion Engineer plants in the US at that time. Seven of the plants had a digital Core Protection Calculator System (CPCS), while others had an analog system.

That study estimated failure rates and CCF probabilities for the digital CPCS (four per plant, each monitoring one-fourth of the reactor core). Failure data were obtained from a review of NPRDS and LERs.

A more recent study analyzing Combustion Engineer RPS DI&C component reliability is the paper "Risk implications of digital reactor protection system operating experience."[11] US LERs covering 1984 through 2001 were reviewed for RPS performance. The DI&C assemblies included the CPCS and Core Element Assembly Calculators (CEACs, two per plant). Failures of the CPCS involved both individual and CCF events grouped at a piece part level (computer board, memory board, multiplexer board, watch dog timer, and others). CEAC failures were similarly grouped.

The report *Risk-Informed Assessment of the RPS and ESFAS Surveillance Test Intervals and Reactor Trip Breaker Test and Completion Times* provided an analysis of the impact on risk if RPS/ESFAS surveillance test intervals were extended.[12] Failure data for RPS components were obtained from both Ref. 9 and a limited collection of plant-specific experience from before 2000. However, the plant-specific data are considered proprietary and are not included in the report.

Limited RPS/ESFAS data for selected DI&C components covering 2007 through 2011 are presented in the paper "Insights from the Estimation of RPS/ESFAS Component Demand Failure Probabilities based on Performance Monitoring Data after a Risk Informed Surveillance Test Interval Extension."[13]

Recently the Oconee nuclear power station upgraded its RPS/ESF to the fully digital AREVA TELEPERM® XS platform.[14] That system has been installed in over 60 plants worldwide over the past 20 years. Siemans Power Corporation collects performance data on modules within that system, such as computer processing, input/output (I/O), and signal conditioning. However, that system is used only for the Oconee plants in the US.

III. WESTINGHOUSE EAGLE-21 AND SSPS DESCRIPTIONS

III.A. Eagle-21

The Westinghouse Eagle-21 Process Protection System replacement platforms perform the following:

1. Reactor trip protection (channel trip to voting logic)
2. ESF actuations
3. Isolated outputs to control systems, control panels, and plant computers
4. Isolated outputs to information displays for post-accident monitoring (PAM) indication
5. Automatic surveillance testing to verify channel performance.[15]

The basic subsystems of the Eagle-21 platform are the loop processor, input/output (I/O), and tester. The loop processor subsystem receives process signals, performs algorithms, and generates RPS trip signals and ESF actuation signals. The I/O subsystem interfaces with field signals and outputs loop processor signals. The tester subsystem provides the interface for adjusting setpoints and constants, testing, and maintenance. For purposes of data collection and classification, the following piece parts were identified:

1. Processor subsystem
    a. Digital filter processor (DFP)
    b. Loop calculation processor (LCP)
    c. Communication controller (CC)
    d. Digital I/O module (DI/OM)
    e. Digital to analog converter (D/AC)
2. I/O subsystem
    a. Analog/contact input module (A/CIM)
    b. Analog/contact output module (A/COM)
    c. Partial trip module (EPT).
3. Tester subsystem (included in process and I/O subsystem impacts if applicable).

III.B. SSPS

The Westinghouse SSPS trains receive channel inputs from monitored plant parameters, process them, and generate output signals (trip for RPS and various types for ESF).[16] Each protection cabinet (A and B) has an input section, logic section, and output section. The input and output sections are analog (relay) based, but the logic section is solid state. For purposes of data collection and classification, the following SSPS piece parts were identified:

1. Input section (analog, not included)
2. Logic section
    a. Universal logic card (ULC)
    b. Safeguards driver card (SDC)
    c. Under-voltage driver card (UVDC)
    d. Semi-automatic tester card (SATC)
    e. Clock counter card (CCC)
    f. Decoder card (DC)
    g. Isolation card (IC)
    h. Memory card (MC)
3. Output section (analog, not included).

The SATC, CCC, DC, IC, and MC piece parts were not addressed in the reliability analysis.

IV. FAILURE DATA SEARCH PROTOCOL

The main source of data for Eagle-21 and SSPS failures in US commercial nuclear power plants is the Institute of Nuclear Power Operations (INPO) Consolidated Events System, or ICES (previously termed Equipment Performance and Information Exchange, or EPIX). For those assemblies failure events are reported. However, presently there is no standard subdivision of these assemblies into piece parts (such as modules or cards), so failure events must be assigned to the piece parts described in Section III. The NROD software was used to search failure record texts in ICES for the mention of "Eagle-21" or "SSPS" (and variations of these). Failure events identified from these searches were then reviewed to determine if they were applicable. Because ICES includes failures starting in late 1997, the period covered by the searches was chosen to start with 1998 and include through 2015.

Similar to what was done in the RPS studies described in Section II, failure records were reviewed to determine whether the event was a complete failure (rather than a degraded or incipient condition). Also, failures could be either fail-safe (FS) or NFS with respect to the safety function of the RPS or ESF actuation. Examples of FS failures include an Eagle-21 channel generating a trip signal when there was no valid reason for the trip or an SSPS train generating a trip signal for the RPS when trip conditions did not exist. These FS failures have plant operability impacts but generally do not indicate that the RPS or ESF actuation functions were compromised. The NFS failures are those that indicated the component did not perform its safety-related function when demanded. Because of limited information in some of the failure records, there can be uncertainty in whether the event was a complete failure and/or whether the event was FS or NFS. The failure event classification scheme is presented in Figure 1, showing nine possible classifications.

NFS/CF (safety function impact, complete failure)	UKN/CF (unknown safety function impact, complete failure; potential NFS/CF)	FS/CF (no safety function impact, complete failure)
NFS/UC (safety function impact, unknown completeness; potential NFS/CF)	UKN/UC (unknown safety function impact, unknown completeness; potential NFS/CF)	FS/UC (no safety function impact, unknown completeness)
NFS/NF (safety function impact, no failure)	UKN/NF (unknown safety function impact, no failure)	FS/NF (no safety function impact, no failure)

Fig. 1. Event classification scheme (reproduced from Fig. 5 in Ref. 9).

The focus of this report is on NFS, complete failures of Eagle-21 and SSPS DI&C piece parts identified in Section III. Therefore, four of the nine classifications are of interest, those noted as NFS/CF or potential NFS/CF. NFS/CF events were assigned weights of 1.0, UKN/CF and NFS/UC events were given weights of 0.5, and UKN/UC events were assigned weights of 0.25 for reliability evaluations.

An additional important consideration for the failure events is how the failure was detected. The failures that are noticed immediately (or within an operator shift duration) typically have a short period in which the DI&C element cannot perform its function, based on a repair or replacement duration (and possibly a short detection time). Those failures are treated as time-related, annunciated failures. Other failures are detected when demands (unplanned or test related) occur. Those failures have much longer periods in which the element cannot perform its function, typically based on one-half of the test interval. Because of limited information in some event reports, there may be uncertainty in whether the failure should be modeled as time related and annunciated or demand (test) related. For events with this uncertainty, the event was given a 0.5 probability and assigned to both categories.

To supplement the NROD data searches, US LERs (1998 – 2015) were also reviewed for potential Eagle-21 and SSPS DI&C failures. The LER reporting requirements include such events as plant trips, violation of technical specifications, degradation of safety barriers, actuation of safety systems, significant CCFs, and others. However, generally individual component failures are not reportable through LERs. Similar to the NROD searches, the LERs were searched for mentions of "Eagle-21" or "SSPS" (and variations of these). Applicable events were processed similar to those from the NROD searches. A summary of Eagle-21 and SSPS piece part NFS failures is presented in Table I.

TABLE I. Eagle 21 and SSPS Piece Part NFS DI&C Failures

System	Subsystem	Piece Part	Identifier	NFS DI&C Failures for Eagle 21 and SSPS			
				RPS Annunciated	RPS Test	ESF Annunciated	ESF Test
Eagle 21	Processor	Digital filter processor	DFP				
		Loop calculation processor	LCP	1.5	1	0.75	0.25
		Communication controller	CC				
		Digital I/O module	DI/OM				
		Digital to analog converter	D/AC				
	I/O	Analog/contact input module	A/CIM				
		Analog/contact output module	A/COM	0.5		0.5	
		Partial trip module	EPT				1.5
SSPS	Input	Not included					
	Logic	Universal logic card	ULC	2	4.5	1	4
		Safeguards driver card	SDC			1	2
		Under-voltage driver card	UVDC	0	1		
	Output	Not included					

a. Weights of 0.5 used if uncertainty concerning fail-safe or non-fail-safe and concerning whether detected by annunciation or test.

V. ESTIMATION OF EXPOSURE TIME AND DEMANDS

There were 12 plants with Eagle-21 platforms during 1998 – 2015. The total reactor calendar years (rcy's) for 1998 – 2015 is 12 plants*18 calendar years = 216 rcy's. During that same period, those plants experienced 195.8 reactor critical years (rcry's) of operation. The corresponding total calendar hours are 1.89E+6 h and total critical operation hours are 1.72E+6 h.

There were approximately 45 plants with SSPSs during 1998 – 2015. The total calendar year exposure for SSPS plants is 810 rcy's. The corresponding approximate critical operation years total is 737 rcry's. The corresponding calendar hours are 7.10E+6 h and approximate critical operation hours are 6.46E+6 h.

Estimates for the number of Eagle-21 and SSPS piece parts per plant (see Section III.A) are presented in Table II. This information was obtained from various sources[9, 13, 15 and 16] or was estimated.

TABLE II. Eagle 21 and SSPS Piece Part Counts

System	Subsystem	Piece Part	Identifier	Count/plant
Eagle 21 (a)	Processor	Digital filter processor	DFP	4 or 3
		Loop calculation processor	LCP	4 or 3
		Communication controller	CC	4 or 3
		Digital I/O module	DI/OM	4 or 3
		Digital to analog converter	D/AC	4 or 3
	I/O	Analog/contact input module	A/CIM	4 or 3
		Analog/contact output module	A/COM	4 or 3
		Partial trip module	EPT	4 or 3
SSPS (b)	Input	Not included (analog)		NA
	Logic	Universal logic card	ULC	32
		Safeguards driver card	SDC	6
		Under-voltage driver card	UVDC	2
	Output	Not included (analog)		NA

a. 1 Eagle 21 assembly per plant reactor coolant loop (10 plants with 4 loops, 2 plants with 3 loops).
b. 2 SSPS trains per plant (45 plants)

The Eagle-21 piece parts were assumed to be tested quarterly for the first half of the data collection period and every six months for the second half of the data collection period. The SSPS piece parts were tested every two months for the first half and every six months for the second half. These are on a calendar year basis.

VI. EAGLE-21 AND SSPS DI&C PIECE PART RELIABILITY ESTIMATES

Given the failure event information in Section IV and total exposure time and demands determined from the piece part counts and plant counts in Section V, Table III summarizes the Eagle-21 piece part reliability results for RPS. Table IV summarizes the results for the ESF actuation piece parts. Because of the limited numbers of failure events, the mean rates and mean probabilities were generated using a Bayesian update of the Jeffreys non-informative prior. The mean rate is then

$$\text{Mean Rate} = (\text{Events} + 0.5)/\text{Time} \qquad (1)$$

and the mean probability is

$$\text{Mean Probability} = (\text{Events} + 0.5)/(\text{Demands} + 1) \qquad (2).$$

Because of the limited numbers of piece part failures, difficulty in interpreting some event reports, and some variation in plant piece part counts, large uncertainties should be assigned to the rates and probabilities in Tables III and IV. The rate distributions are recommended to be gamma with the alpha parameter = 0.3. The demand probability distributions are recommended to be beta with the alpha parameter = 0.3.

The unreliability of a piece part includes both the failure rate and the failure probability in the following equation:

$$\text{Unreliability} = \text{Rate} * T_{\text{detect and repair}} + \text{Probability} * 1_{\text{demand}} \qquad (3).$$

TABLE III. Eagle 21 and SSPS DI&C Piece Part RPS Reliability Estimates

System	Subsystem	Piece Part	Identifier	Count/ plant	RPS NFS Annunciated Failures			RPS NFS Test Failures		
					Events	Time (h)	Mean Rate (1/h)	Events	Demands	Mean Probability
Eagle 21	Processor	Digital filter processor	DFP	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Loop calculation processor	LCP	4 or 3	1.5	7.25E+06	2.76E-07	1	2482	6.04E-04
		Communication controller	CC	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Digital I/O module	DI/OM	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Digital to analog converter	D/AC	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
	I/O	Analog and contact input module	A/CIM	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Analog and contact output module	A/COM	4 or 3	0.5	7.25E+06	1.38E-07	0	2482	2.01E-04
		Partial trip module	EPT	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
SSPS	Logic	Universal logic card	ULC	32	2	2.27E+08	1.10E-08	4.5	103680	4.82E-05
		Under-voltage driver card	UVDC	2	0	1.42E+07	3.52E-08	1	6480	2.31E-04

TABLE IV. Eagle 21 and SSPS DI&C Piece Part ESF Reliability Estimates

System	Subsystem	Piece Part	Identifier	Count/ plant	ESF NFS Annunciated Failures			ESF NFS Test Failures		
					Events	Time (h)	Mean Rate (1/h)	Events	Demands	Mean Probability
Eagle 21	Processor	Digital filter processor	DFP	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Loop calculation processor	LCP	4 or 3	0.75	7.25E+06	1.72E-07	0.25	2482	3.02E-04
		Communication controller	CC	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Digital I/O module	DI/OM	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Digital to analog converter	D/AC	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
	I/O	Analog and contact input module	A/CIM	4 or 3	0	7.25E+06	6.89E-08	0	2482	2.01E-04
		Analog and contact output module	A/COM	4 or 3	0.5	7.25E+06	1.38E-07	0	2482	2.01E-04
		Partial trip module	EPT	4 or 3	0	7.25E+06	6.89E-08	1.5	2482	8.06E-04
SSPS	Logic	Universal logic card	ULC	32	1	2.27E+08	6.60E-09	4	103680	4.34E-05
		Safeguards driver card	SDC	6	1	4.26E+07	3.52E-08	2	19440	1.29E-04

A complete failure model would also include unavailability due to testing and maintenance, which must be determined separately based on the test interval and duration and whether the piece part is unable to perform its safety function while in test. Planned maintenance outages would also need to be considered, if applicable. In addition, potential CCF events would need to be modeled.

The piece part failure rates and probabilities presented in Tables III and IV reflect US operational practices related to the Eagle-21 and SSPS assemblies. In some cases when a DI&C card failed and was replaced, other similar cards were also replaced as a precautionary step. So in some cases the piece parts are not allowed to run to failure. Also, there have been some replacements with newer design cards, and in a few cases the newer design cards have had problems and were then replaced with older designs, at least until the newer designs had been modified to eliminate those problems.

Some failure rates and probabilities in Table III can be compared with results from the older RPS study, which covered data over 1984 – 1995.[9] For the Eagle-21 LCP, the older RPS Study data treated all failures as time-related and then generated a failure rate of 8.1E-6/h. Assuming a detection and repair duration of 12 h, the LCP failure probability per demand is then (8.1E-6/h)*(12 h) = 9.7E-5. In comparison, the present results based on data over 1998 – 2015 indicate a failure probability upon demand of (2.76E-7/h)*(12 h) + (6.04E-4)*(1) = 6.1E-4. For the SSPS ULC, the older study failure probability upon demand is 3.8E-4 (all failures were considered to be test or demand related), while the present study result is (1.10E-8/h)*(12 h) + (4.82E-5)*(1) = 4.8E-5. The present results indicate a large improvement in SSPS ULC performance but degradation in Eagle 21 LCP performance. However, the degradation might be misleading given that the older RPS Study did not split failures into annunciated and demand related categories.

Ref. 13 provides failure probabilities for the SSPS ULC (4.09E-4), SDC (7.70E-4), and UVDC (3.40E-4) based on a subset of Westinghouse plants (not specified) and experience over mid-2007 through mid-2011. The failure events do not appear to have been separated into annunciated and test related. These compare with the results generated in this paper – 9.2E-5, 1.3E-4, and 2.3E-4 respectively (combining annunciated and test related for both RPS and ESF). In all three cases, the present results are lower than those in Ref. 13. However, Ref. 13 used a much smaller data set and performed Bayesian updates of generic priors, so the approaches differ significantly.

VII. EAGLE-21 AND SSPS DI&C PIECE PART CCF EVENTS

The LER and NROD data for Eagle-21 DI&C piece parts over 1998 – 2015 indicated no actual CCF events. However, two might have developed into actual CCF events. The first involved the use of the wrong instrument for calibrating the channel setpoints for pressurizer high water level. The first channel setpoint was (incorrectly) determined to be out of calibration and was reset. The channel was then returned to service. When the second channel setpoint was also (incorrectly) determined to be out of calibration, the plant personnel decided to check the calibration instrument and determined it was not the correct one to be used. If the personnel had not become suspicious, all three channel setpoints could have been incorrectly set and returned to service in a NFS status. However, the actual event resulted in channel 1 being in a NFS status for 30 h, channel 2 being tripped for 16 of those same 30 h (while being calibrated), and channel 3 being functional.

The second event involved high humidity causing multiple false indications and alarms. However, there were no actual FS or NFS failures involved. If not annunciated, the high humidity might have led to an actual CCF.

For the SSPS, there was one CCF NFS event with a very short duration. A test error resulted in both LTOP trains being unable to perform their functions. This condition was noticed immediately and the functions were restored. Several potential CCF FS events involved development of “whiskers” (metallic growth) that grew sufficiently to cause an electrical short in one of the boards but not sufficient growth of the “whiskers” to short out other cards. Another potential CCF FS event involved signal noise causing a ULC and a UVDC to spuriously cause a reactor trip and SI signal.

With no actual Eagle-21 DI&C CCF events and only one SSPS DI&C CCF of short duration, CCF alpha parameters specific to these piece parts have not been generated. The older RPS Study presented CCF probabilities for the Eagle-21 module and for the SSPS ULC. Given the independent failure probabilities presented in that report, one could back out the effective CCF multipliers for the various combinations of failures. Because of the limited CCF experience, one could also use the generic CCF alpha parameters from the US NRC website.

VIII. CONCLUSIONS

This study was performed to determine whether there may be sufficient failure event information in the US NRC NROD/EPIX and LER databases for RPS/ESF DI&C components. The search for such events covered 1998 – 2015. Failure events were identified (mostly from NROD/EPIX but a few from LERs) and classified by piece part and whether FS or NFS. Combined with estimates of piece parts per plant and plants containing Eagle-21 and SSPS assemblies, unreliability estimates were generated. The individual piece part failure rates and probabilities are judged to contain significant uncertainty (alpha parameter = 0.3 for the beta and gamma distributions).

The data review indicated no actual Eagle-21 DI&C piece part CCFs over 1998 – 2015. Also, only one SSPS CCF was identified, but the duration of that condition was extremely short. So the CCF review indicated no significant CCF events.

The review of Eagle-21 and SSPS data also identified non-DI&C piece part failures that could be analyzed to obtain failure rates and probabilities for select analog equipment. Also, the DI&C events also included FS failures, which can lead to plant operability issues. Those could also be reviewed to generate FS rates and probabilities.

ACKNOWLEDGMENTS

The author thanks the US NRC and INPO for allowing the use of the NROD software and database package. However, the contents of this paper should not be interpreted as having those organizations' concurrence.

REFERENCES

1. "NRC Reactor Operating Experience Data (NROD)," US Nuclear Regulatory Commission, Version 2.1.0.0, https://nrod.inl.gov.
2. *Event Report Guidelines 10 CFR 50.72 and 50.73*, US Nuclear Regulatory Commission, NUREG-1022, Rev. 3, January 2013.
3. "Integrated Strategy to Modernize the Nuclear Regulatory Commission's Digital Instrumentation and Control Regulatory Infrastructure," US Nuclear Regulatory Commission, SECY-16-0070, May 31, 2016.
4. M. Li and K. Coyne, "NRC Research on Digital System Modeling for Use in PRA," *PSA 2015*, Sun Valley, Idaho, April 26-30, 2015, American Nuclear Society, (2015).
5. "Embedded Digital Devices in Safety-Related Systems," US Nuclear Regulatory Commission, RIS-2016-05, April 29, 2016.
6. *Guidelines for 10 CFR 50.59 Evaluations, Appendix D*, Nuclear Energy Institute, NEI 96-07.
7. *Guideline on Evaluation and Acceptance of Commercial-Grade Digital Equipment for Nuclear Safety Applications*, Electric Power Research Institute, EPRI TR-106439.
8. *Generic Requirements Specification for Qualifying a Commercially Available PLC for Safety0Related Applications in Nuclear Power Plants*, Electric Power Research Institute, EPRI TR-107330.
9. S. A. Eide et al., *Reliability Study: Westinghouse Reactor Protection System, 1984 – 1995*, US Nuclear Regulatory Commission, NUREG/CR-5500, Vol. 2, December 1998.
10. T. E. Wierman et al., *Reliability Study: Combustion Engineering Reactor Protection System, 1984 – 1998*, US Nuclear Regulatory Commission, NUREG/CR-5500, Vol. 10, November 2001.
11. J. H. Bickel, "Risk implications of digital reactor protection system operating experience," *Reliability Engineering & System Safety*, **93**, 107-124 (2008).
12. D. V. Lockridge et al., *Risk-Informed Assessment of the RPS and ESFAS Surveillance Test Intervals and Reactor Trip Breaker Test and Completion Times*, Westinghouse Electric Company, WCAP-15377, Rev. 0, October 2000.
13. Y. G. Jo, "Insights from the Estimation of RPS/ESFAS Component Demand Failure Probabilities based on Performance Monitoring Data a Risk Informed Surveillance Test Interval Extension," *PSA 2015*, Sun Valley, Idaho, April 26-30, 2015, American Nuclear Society, (2015).
14. J. S. Allen and R. S. Enzinna, "Oconee Digital Protection System PSA Model," *PSA 2015*, Sun Valley, Idaho, April 26-30, 2015, American Nuclear Society (2015).
15. L. E. Erin, *Topical Report Eagle-21 Microprocessor-Based Process Protection System*, Westinghouse Electric Company, WCAP-12375, Rev. 1, December 1991.
16. "Westinghouse Technology Systems Manual, Section 12.1, Reactor Protection System," US Nuclear Regulatory Commission, Rev. 0109, www.nrc.gov/docs/ML1122/ML11223A300.pdf.