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NRW-FPGA-Based PRM System Qualification Project

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1 Purpose

The purpose of this document is to document the Availability/Reliability Analysis of the Non-Rewritable Field Programmable Gate Array (NRW-FPGA) based PRM system to be qualified by Toshiba during the NRW-FPGA-Based PRM System Qualification Project. The availability/reliability study was performed to meet the requirements of EPRI TR-107330 (Reference (1)), Section 4.2.3.

2 Reference Documents

(1) EPRI Report TR-107330, "Generic Requirements Specification for Qualifying a Commercially Available PLC for Safety-Related Applications in Nuclear Power Plants," December 1996.

(2) MIL-HDBK-217F, "Military Handbook, Reliability Prediction of Electronic Equipment," 2 December 1991.

(3) FPG-RQS-C51-0001, "Equipment Requirement Specification of FPGA based Units," Rev.8.

(4) Toshiba Fuchu procedure FP-SS-10832.

3 Results

The NRW-FPGA-Based PRM system Test Specimen was analyzed for reliability and availability using MIL-HDBK-217F (Reference (2)). The reliability values are calculated by summing failure rates of whole devices.

The system analyzed contained LPRM, LPRM/APRM, and FLOW units configured in the arrangement shown in ERS (Reference (3)) for the PRM Test Specimen to be qualified in Toshiba's NRW-FPGA-Based PRM System Qualification Project. Results of this analysis are as follows:

3.1 Test Specimen

MTBF of test specimen is calculated based on MIL-HDBK-217F and Toshiba Fuchu procedure FP-SS-10832 (Reference (4)). The results are listed in Table-3.1. Figure A-1 shows a representation of the test specimen.

Table-3.1 Availability Reliability Analysis Results (Test Specimen)

	MTBF	MTTR	Availability
Test Specimen Figure A-1	[ ]a,c year ([ ]a,c H)	24H	[ ]a,c *> 0.99
	using MIL-HDBK-217F	using TR-107330 Section 4.2.3.3 C.	using TR-107330 Section 4.2.3.3 C.

Note *): It is recommended to perform once a year surveillance work for linearity check which need 24 hours at most. Taking this surveillance work into account, the availability is [ ]a,c which is also greater than 0.99. As EPRI TR-107330 requires, the evaluation is

also performed for the case where the failure rate at 50 degrees Celsius used for the first two weeks and failure rate at 25 degrees Celsius are used after the first two weeks. The evaluation provides the negligible small MTBF reduction in the order of [ ]a,c year.

3.2 Full PRM System

MTBF of the PRM system is calculated based on MIL-HDBK-217F and Toshiba Fuchu procedure FP-SS-10832. The results are listed in Table-3.2. Figure A-2 shows a representation of the system configuration of the PRM system. MTBF evaluation are made for the following two cases.

Case 1 At least two of the three PRM channels shall be functional in both of the two trip channels. One PRM channel out of the three PRM channels in each trip channels can be bypassed and repaired as long as the other two channels in the trip channel are functional. This is the typical manner to operate and maintain the PRM system in BWR-5. This case is considered as two out of three twice system with repair.

Case 2 Although Case1 provides the MTBF for the typical use of the PRM, the MTBF is expected to pretty long since the repair of a failed channel is possible. To understand the PRM system reliability in a prudential manner, the system condition to maintain minimum trip functionality without any repair is considered. That is, at least one PRM channel out of three PRM channels shall be functional in both trip channels. This case is considered as one out of three twice system without repair.

Table-3.2 Availability Reliability Analysis Results (PRM Full System)

		MTBF	MTTR	Availability
PRM System Figure A-2	Case 1	[ ]a,c year ([ ]a,c H)	24H	[ ]a,c > 0.99
	Case 2	[ ]a,c year ([ ]a,c H)	24H	[ ]a,c *> 0.99
Case 1: (2 out of 3) twice with repair Case 2: (1 out of 3) twice without repair		Using MIL-STD-217F	using TR-107330 Section4.2.3.3 C.	using TR-107330 Section4.2.3.3 C.

Note *): When once a year surveillance work with duration of 24 hours is taken into account, the availability is [ ]a,c which is also greater than 0.99.

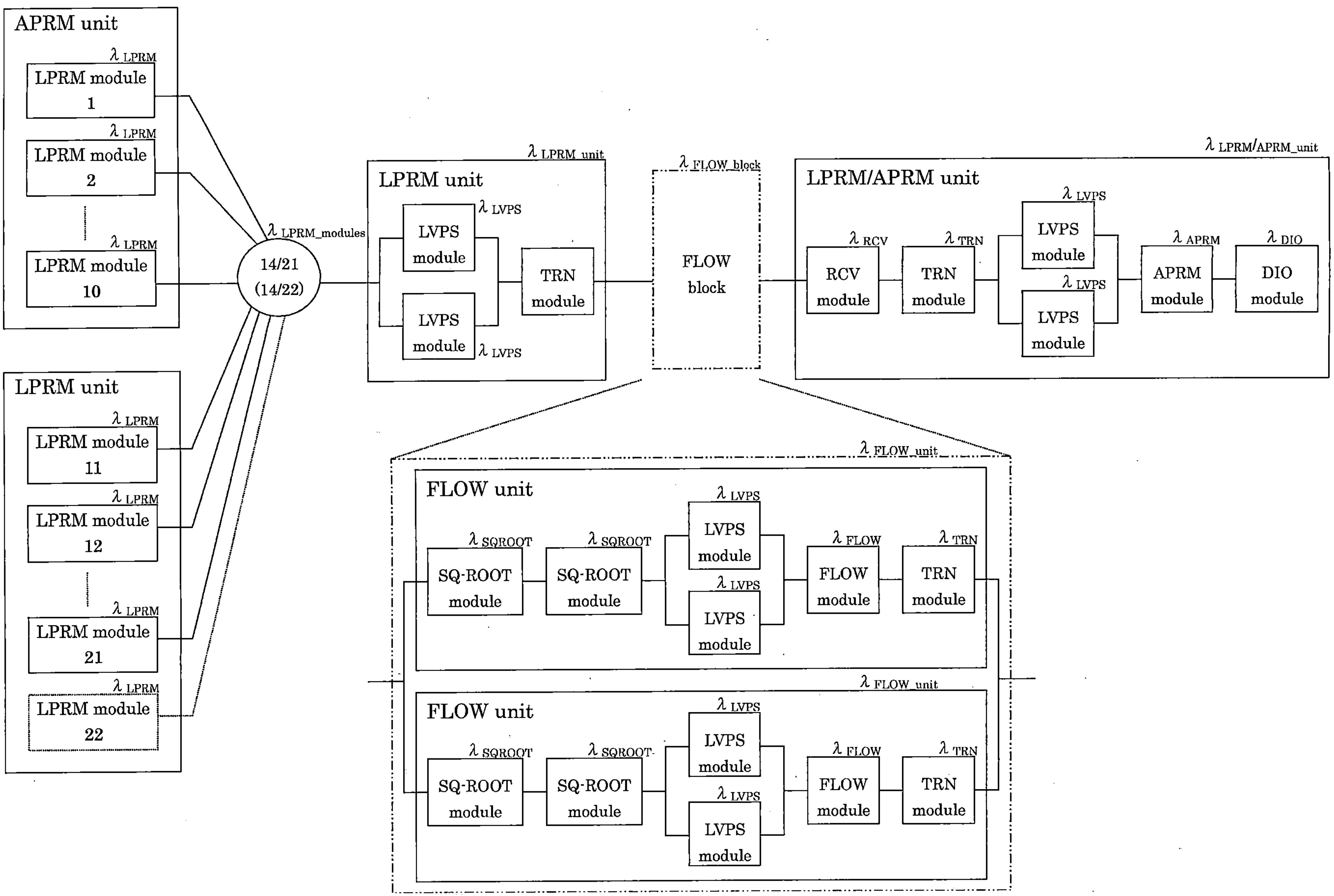
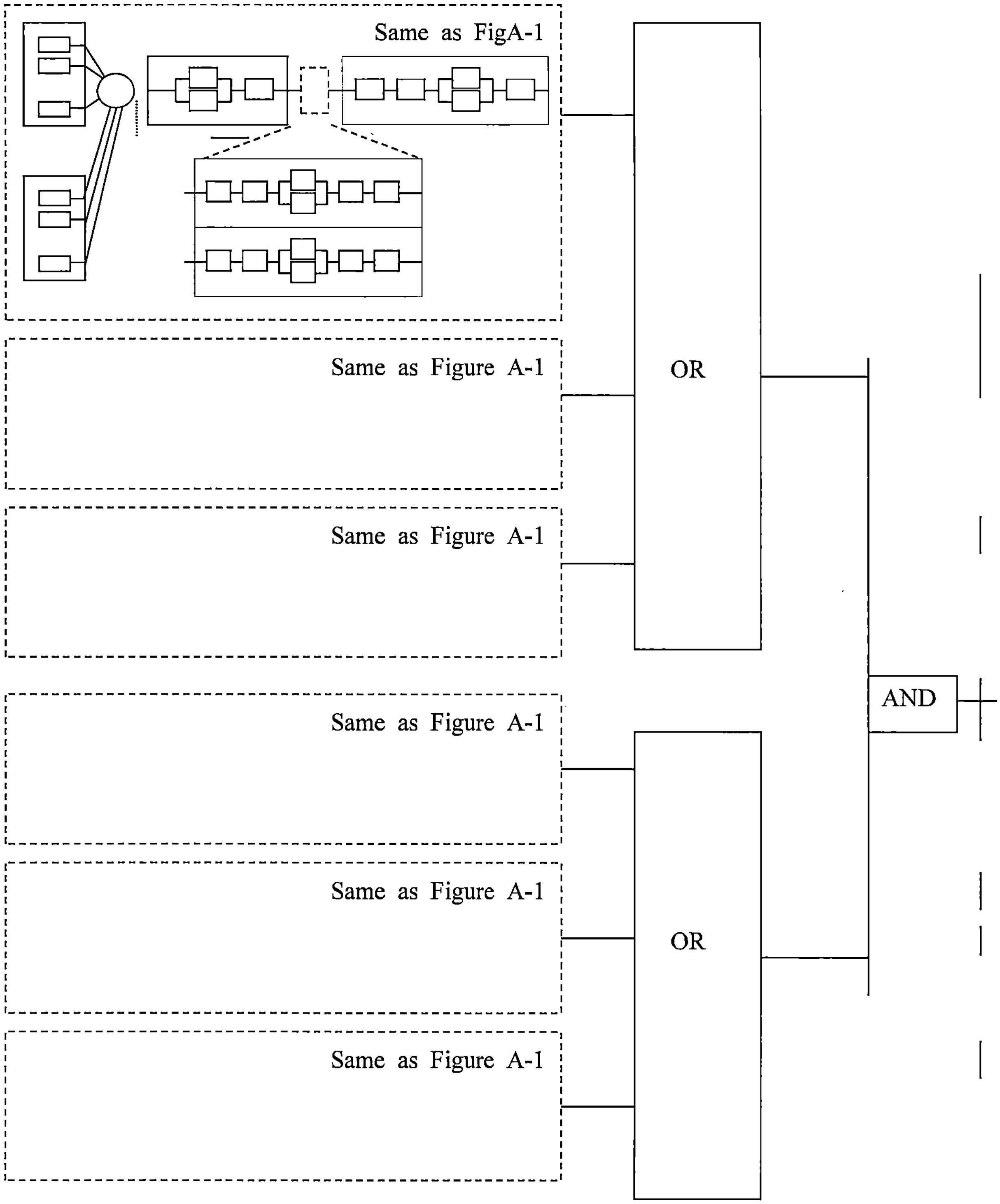


Figure A-1 PRM Trip Function Block Diagram in one channel PRM



* One channel of the three can be bypassed.

Figure A-2 PRM Trip Function Block Diagram in Full PRM System

3.3 Detailed MTBF Calculation for PRM

The PRM trip function to be evaluated is defined by the diagram in Figure A-1. The table below shows the failure rate of each module.

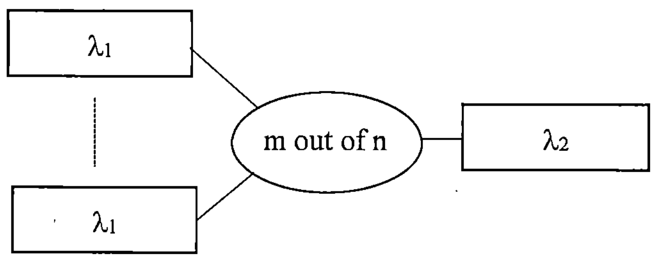
PRM FAILURE RATE			
	MODULE NAME	MODULE FAILURE RATE (fit) (1/10^{9}H)	
1	APRM MODULE	λ_{APRM}	[a,c]
2	LPRM MODULE	λ_{LPRM}	
3	STS MODULE	λ_{STS}	
4	AO MODULE	λ_{AO}	
5	DIO MODULE	λ_{DIO}	
6	TRN MODULE	λ_{TRN}	
7	RCV MODULE	λ_{RCV}	
8	FLOW MODULE	λ_{FLOW}	
9	SQ-ROOT MODULE	λ_{SQROOT}	
10	LVPS MODULE	λ_{LVPS}	
11	LPRM/APRM Unit Chassis	$\lambda_{\text{LPRM/APRM Unit Chassis}}$	
12	LPRM Unit Chassis	$\lambda_{\text{LPRM Unit Chassis}}$	
13	FLOW Unit Chassis	$\lambda_{\text{FLOW Unit Chassis}}$	

*: Each failure rate is calculated by the reliability of components given in MIL-STD-217F when applicable. Reliability data for FPGA are provided by Microsemi Corporation. Module failure rates were calculated on the condition that temperature is 25 degrees Celsius. Failure rates of the modules at 50 degrees Celsius and 0 degrees Celsius are also evaluated as shown in Appendix 1.

Repair rate μ is defined as 1/MTTR. MTTR is assumed 24 h in compliance with EPRI TR-107330 Section4.2.3.3 C.

(1) FAILURE RATE for more than or equal to eight (8) LPRM modules out of twenty one (21) or twenty two (22) LPRM modules fails.

Fourteen (14) LPRM modules out of twenty-one (21) or twenty-two (22) LPRM modules in a PRM channel shall be operational. If the number of operational LPRM modules decreases less than fourteen (14), the PRM channel becomes inoperable. This logic is interpreted as m out of n logic where m=14, and n= 21 or 22. It is assumed that the LPRM module cannot be repaired to simplify the equation even though the repair is possible in the actual system. The evaluation for the failure rate with the repair for this many m out of n logic is too complicated to handle. The evaluation with the condition without repair provides much more conservative results.



MTBF of the system that has n out m voting logic as shown above is calculated by the following equation

$$\int_0^\infty \{R_2 \sum_{i=0}^{(n-m)} {}_nC_{(n-i)} \; R_1^{\,(n-i)} \; (1-R_1)^i\}dt$$

$$= \int_0^\infty \{R_2 \sum_{i=0}^{(n-m)} [{}_nC_{(n-i)} \; R_1^{\,(21-i)} \sum_{k=0}^{i} {}_iC_k \; (-R_1)^k]\}dt \qquad \text{Eq. (1)}$$

where $R_1 = e^{-\lambda_1 t}$, $R_2 = e^{-\lambda_2 t}$, λ_1 and λ_2 are the failure rate of each element in the figure.

The above equation is used to calculate MTBF values for the blocks that have redundant

elements in the following subsections.

(2) FAILURE RATE for LPRM unit

a) FAILURE RATE for LVPS modules

LVPS modules have redundant and parallel configuration. As long as one of the two LVPS modules is operational then the power is supplied successfully. The failure rate of this configuration is given by the following equations

$$\lambda_{LVPS\_block} = 2\lambda_{LVPS}^2 / (3\lambda_{LVPS} + \mu) \quad \text{when repair is possible}$$
$$= [\quad]^{a,c} \text{fit.}$$

When repair is not possible λ_{LVPS_block} is evaluated by setting 0 to μ in the equation above. So the λ_{LVPS_block} can be evaluated as follows

$$\lambda_{LVPS\_block} = 2\lambda_{LVPS} / 3.$$

However, using λ_{LVPS_block} derived in this manner for the evaluation of MTBF of units generally generates error in case that the repair is not considered. So the general form Eq. (1) is used for in the following calculation of MTBF values of units by setting n=2 and m=1.

b) FAILURE RATE for LPRM unit

$$MTBF_{LPRM\_unit} = (3\lambda_1 + \lambda_2) / ((\lambda_1 + \lambda_2)(2\lambda_1 + \lambda_2))$$
$$\lambda_1 = \lambda_{\text{LVPS module}}$$
$$\lambda_2 = \lambda_{TRN} + \lambda_{\text{LPRM unit Chassis}}$$
$$= [\quad]^{a,c} \text{hours}$$
$$\lambda_{LPRM\_unit} = 1 / MTBF_{LPRM\_unit}$$
$$= [\quad]^{a,c} \text{fit}$$

(3) FAILURE RATE for FLOW unit

$$MTBF_{FLOW\_unit} = (3\lambda_1 + \lambda_2) / ((\lambda_1 + \lambda_2)(2\lambda_1 + \lambda_2))$$
$$\lambda_1 = \lambda_{\text{LVPS module}}$$
$$\lambda_2 = \lambda_{SQROOT} + \lambda_{SQROOT} + \lambda_{FLOW} + \lambda_{TRN} + \lambda_{\text{FLOW Unit Chassis}}$$
$$= [\quad]^{a,c} \text{hours}$$
$$\lambda_{FLOW\_unit} = 1 / MTBF_{FLOW\_unit}$$

=[ ]a,c fit

(4) FAILURE RATE for FLOW block

Since there are two FLOW units providing the flow signal to all three PRM channels in a trip channel, and they are reparable, the failure rate of the FLOW block shown in Figure A-1 is given by the following equation

$$\lambda_{FLOW\_block} = 2\lambda_{FLOW\ Unit}^2 / (3\lambda_{FLOW\ Unit} + \mu)$$

=[ ]a,c fit.

(5) FAILURE RATE for LPRM/APRM unit

$$MTBF_{LPRM/APRM\_unit} = (3\lambda_1 + \lambda_2) / ((\lambda_1 + \lambda_2)(2\lambda_1 + \lambda_2))$$

$$\lambda_1 = \lambda_{LVPS\ module}$$

$$\lambda_2 = \lambda_{RCV} + \lambda_{TRN} + \lambda_{APRM} + \lambda_{DIO} + \lambda_{LPRM/APRM\ unit\ Chassis}$$

=[ ]a,c hours

$$\lambda_{LPRM/APRM\_unit} = 1/ MTBF_{LPRM/APRM\_unit}$$

=[ ]a,c fit

(6) MTBF for PRM (per One Channel)

$MTBF_{PRM\ ch}$ is calculated by Eq. (1). Setting m=14 and N=21, Eq. (1) becomes

$$MTBF_{PRM\ ch} =$$

$$116280/(14\lambda_1+\lambda_2) - 759696/(15\lambda_1+\lambda_2) + 2136645/(16\lambda_1+\lambda_2)$$

$$- 3351600/(17\lambda_1+\lambda_2) + 3165400/(18\lambda_1+\lambda_2) - 1799280/(19\lambda_1+\lambda_2)$$

$$+ 569772/(20\lambda_1+\lambda_2) - 77520/(21\lambda_1+\lambda_2)$$

where $\lambda_1 = \lambda_{LPRM\_modules}$, $\lambda_2 = \lambda_{LPRM\_unit} + \lambda_{FLOW\_block} + \lambda_{LPRM/APRM\_unit}$.

Thus, $MTBF_{PRM\ ch}$ =[ ]a,c hours =[ ]a,c years

For the calculations above, failure rate of the modules at 25 degrees Celsius are used. As EPRI TR-107330 requires, the evaluation is also performed for the case where the failure rate at 50 degrees Celsius is used for the first two weeks and the failure rate at 25 degrees Celsius is used after the first two weeks. This evaluation is done by calculating equation Eq. (1) in two separate time durations, one is from zero to two weeks and the other is

from two weeks to infinite time, as shown in Eq. (2). The results show that the reduction of MTBF is negligibly small in the order of[ ]a,c year.

$$MTBF = \int_0^T \left\{ R_2 \sum_{i=0}^{(n-m)} {}_nC_{(n-i)} R_1{}^{(n-i)} (1-R_1)^i \right\} dt + \int_T^\infty \left\{ R_2 \sum_{i=0}^{(n-m)} {}_nC_{(n-i)} R_1{}^{(n-i)} (1-R_1)^i \right\} dt \quad \text{Eq. (2)}$$

where T= Two weeks, $R_1 = e^{-\lambda_1 t}$, $R_2 = e^{-\lambda_2 t}$, m=14, n=21. Failure rates λ_1 and λ_2 in the first integral are those at 50 degrees Celsius.

(7) FAILURE RATE for PRM (per One Channel)

$\lambda_{PRM\ ch}$ = 1/ $MTBF_{PRM\ ch}$=[ ]a,c fit

(8) Availability for PRM (per One Channel)

Availability $_{PRM\ ch}$ = MTBF $_{PRM\ ch}$ / (MTBF $_{PRM\ ch}$ + MTTR)
= [ ]a,c + 24)
=[ ]a,c (> 0.99)

However, it is recommended to perform surveillance work once a year for linearity check of the system which is completed within 24 hours. When this surveillance test period and time are considered, the availability of the PRM is evaluated by as follows

Availability $_{PRM\ ch}$ = (MTBF $_{PRM\ ch}$ -$DT_{surveillance}$) / (MTBF $_{PRM\ ch}$ + MTTR).

$DT_{surveillance}$ is the total down time required for the surveillance tests during the PRM MTBF, which is calculated as follows

$DT_{surveillance}$=24×(MTBF $_{PRM\ ch}$ /24/365).

Thus, Availability $_{PRM\ ch}$ is calculated as follows

Availability $_{PRM\ ch}$ =[ ]a,c -24×[ ]a,c /365/24)/([ ]a,c +24)
[ ]a,c

(9) FAILURE RATE for PRM (Full System)

The full system of the PRM is shown in Figure A-2. The PRM system availability evaluations are performed for the following two cases.

Case 1 At least two of the three PRM channels shall be functional in both of the two trip channels. One PRM channel out of the three PRM channels in each trip channels can be bypassed and repaired as long as the other two channel in the trip channel is functional. This is the typical manner to operate and maintain the PRM system in BWR-5. This case is considered as two out of three twice system with repair.

Case 2 Although Case1 provides the MTBF for the typical use of the PRM, the MTBF is expected to pretty long since the repair of a failed channel is possible. To understand the PRM system reliability in a prudential manner, the system condition to maintain minimum trip functionality without any repair is considered. That is, at least one PRM channel out of three PRM channels shall be functional in both trip channels. This case is considered as one out of three twice system without repair.

a) Case 1: Two out of three twice with repair configuration

The failure rate of the two out of three system with the allowance of one channel repair is given as follows

$$\lambda_{2\ \mathrm{out\ of}\ 3} = 6\lambda_{\mathrm{PRM\ ch}}{}^{2} / (5\lambda_{\mathrm{PRM\ ch}} + \mu)$$
$$= [\quad]^{a,c}\ \mathrm{fit.}$$

Since both trip channels shall be operational at the same time, the failure rate of the PRM system is calculated as follows

$$\lambda_{2\ \mathrm{out\ of}\ 3\ \mathrm{system}} = 2\lambda_{2\ \mathrm{out\ of}\ 3}$$
$$= [\quad]^{a,c}\ \mathrm{fit.}$$

b) Case 2: One out of three twice without repair configuration

The failure rate of the one out of three systems without repair is given as follows

$$\lambda_{1\ \mathrm{out\ of}\ 3} = 1/[1 / \lambda_{\mathrm{PRM\ ch}} + 1 / (2\lambda_{\mathrm{PRM\ ch}}) + 1 / (3\lambda_{\mathrm{PRM\ ch}})] = [\quad]^{a,c}\ \mathrm{fit}$$

$$\lambda_{1\ \mathrm{out\ of}\ 3\ \mathrm{system}} = 2\lambda_{1\ \mathrm{out\ of}\ 3}$$
$$= [\quad]^{a,c}\ \mathrm{fit.}$$

(10) MTBF for PRM (Full System)

a) Case 1: Two out of three twice with repair configuration

$$MTBF_{2\ out\ of\ 3\ system} = 10^9 / \lambda_{2\ out\ of\ 3system}$$
$$= 10^9 / [\quad]^{a,c}$$
$$= [\quad]^{a,c} (hour)$$
$$= [\quad]^{a,c} (year)$$

b) Case 2: One out of three twice without repair configuration

$$MTBF_{1\ out\ of\ 3\ system} = 10^9 / \lambda_{1\ out\ of\ 3\ system}$$
$$= 10^9 / [\quad]^{a,c}$$
$$= [\quad]^{a,c} (hour)$$
$$= [\quad]^{a,c} (year)$$

(11) Availability for PRM (Full System)

a) Case 1: Two out of three twice with repair configuration

$$Availability_{2\ out\ of\ 3\ system} = MTBF_{2\ out\ of\ 3\ system} / (MTBF_{2\ out\ of\ 3\ system} + MTTR)$$
$$= [\quad]^{a,c} / ([\quad]^{a,c} + 24)$$
$$= [\quad]^{a,c} (> 0.99)$$

Note that one of the three PRM channel can be bypassed, surveillance tests of PRM channels are possible without losing the functionality of the PRM system.

b) Case 2: One out of three twice without repair configuration

$$Availability_{1\ out\ of\ 3\ system} = MTBF_{1\ out\ of\ 3\ system} / (MTBF_{1\ out\ of\ 3\ system} + MTTR)$$
$$= [\quad]^{a,c} / ([\quad]^{a,c} + 24)$$
$$= [\quad]^{a,c} (> 0.99)$$

It is highly expected that once a year surveillance test is possible by bypassing one PRM channel before the PRM system loses the functionality because the $MTBF_{PRM\ Ch}$ is much longer than the surveillance work period.

However, the PRM system availability for this case is evaluated for once a year surveillance work with the duration of 24 hours.

$$Availability_{1\ out\ of\ 3\ system} = (MTBF_{1\ out\ of\ 3\ system} - DT_{surveillance}) /$$

$(MTBF_{1\ out\ of\ 3\ system} + MTTR)$

$DT_{surveillance}$ is the total down time required for the surveillance tests during the $MTBF_{1\ out\ of\ 3\ system}$, which is calculated as follows

$$DT_{surveillance} = 24 \times (MTBF_{1\ out\ of\ 3\ system} / 24/365).$$

Thus, $Availability_{1\ out\ of\ 3\ system}$ is calculated as follows

$Availability_{1\ out\ of\ 3\ system}$ =([ ][a,c] × [ ][a,c] /365/24)/([ ][a,c] +24)

[ ][a,c]

APPENDIX 1. Failure Rates for Each Component

This appendix provides the failure rates and the MTBF for each module and chassis. The unit of the failure rates is indicated as "FIT." The units of the MTBF are indicated as "Hour" and "Year."

1 APRM Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
APRM-M	5J8H2919G1	(FIT)			a,c
APRM-S	5J8H2920G1	(FIT)			
FP-APRM	5J8H2922G1	(FIT)			
FRAME_PARTS	2Y8HF002G1	(FIT)			
APRM MODULE		(FIT)			
		(Hour)			
		(Year)			

2 LPRM Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
LPRM	5J8H3015G1	(FIT)			a,c
FP-LPRM	5J8H2918G1	(FIT)			
FRAME_PARTS	2Y8HF001G3	(FIT)			
LPRM MODULE		(FIT)			
		(Hour)			
		(Year)			

3 STS Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
STS	5J8H2923G1	(FIT)			
FP-STS	5J8H2924G1	(FIT)			
FRAME_PARTS	2Y8HF009G1	(FIT)			
STS MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

4 AO Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
AO-M	5J8H3013G1	(FIT)			
AO-S	5J8H3014G1	(FIT)			
FRAME_PARTS	2Y8HF051G1	(FIT)			
AO MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

5 DIO Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
RM-MAIN	5J8H2934G1	(FIT)			
FRAME_PARTS	2Y8HF052G1	(FIT)			
DIO MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

6 TRN Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
TRN-M	5J8H2909G1	(FIT)			
TRN-S	5J8H2910G1	(FIT)			
FRAME_PARTS	2Y8HF053G1	(FIT)			
TRN MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

7 RCV Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
RCV-M	5J8H2911G1	(FIT)			
RCV-S	5J8H2912G1	(FIT)			
FRAME_PARTS	2Y8HF054G1	(FIT)			
RCV MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

8 FLOW Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
FLOW	5J8H2914G1	(FIT)			
FP-FLOW	5J8H2915G1	(FIT)			
FRAME_PARTS	2Y8HF004G1	(FIT)			
FLOW MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

9 SQ-ROOT Module

Item		Unit			
Name	Doc. No.		(0°C)	(25°C)	(50°C)
SQ-ROOT	5J8H2913G1	(FIT)			
FP-ROOT	5J8H2916G1	(FIT)			
FRAME_PARTS	2Y8HF003G1	(FIT)			
SQ-ROOT MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

10 LVPS Module

Item	Unit	Evaluation Temperature		
		(0°C)	(25°C)	(50°C)
LVPS MODULE	(FIT)			
	(Hour)			
	(Year)			

a,c

Note: The failure rate and the MTBF at the evaluation temperature 0 degrees Celsius were conservatively evaluated as the same values as those at 25 degrees Celsius. The failure rate assumed at the evaluation temperatures 50 degrees Celsius was conservatively evaluated based on the failure rate at 25 degrees Celsius. It was evaluated that the assumed failure rate doubles the failure rate at 25 degrees Celsius every 10-degree increase starting at 25 degrees Celsius. The MTBF at the evaluation temperatures 50 degrees Celsius was calculated using those assumed failure rates.

11 LPRM/APRM Unit Chassis

Item	Unit			
		(0°C)	(25°C)	(50°C)
LPRM/APRM Chassis	(FIT)			
	(Hour)			
	(Year)			

a,c

12 LPRM Unit Chassis

Item	Unit			
		(0°C)	(25°C)	(50°C)
LPRM Chassis	(FIT)			
	(Hour)			
	(Year)			

a,c

13 FLOW Unit Chassis

Item	Unit			
		(0°C)	(25°C)	(50°C)
FLOW Chassis	(FIT)			
	(Hour)			
	(Year)			

a,c