PSNN-2018-0480

Toshiba Project Document No.	Rev. No.
FC51-3809-1000	2

■Safety-Related
□Non-Safety-Related
□ASME CODE
□Others(   )

NRW-FPGA-Based I&C System Qualification Project

Calculation

Title: Availability/Reliability Analysis Report for Safety-Related Oscillation Power Range Monitor (OPRM)

Customer Name	None
Project Name	NRW-FPGA-Based I&C System Qualification Project
Item Name	OPRM Equipment
Item Number	C51
Job Number	9P04482
Applicable Plant	None

TOSHIBA ESS, NICSD verified this Document;

Method : Design Review
Verification Report No. : DVR-JHS-000876 Rev.0
Verification Results : Acceptable
Verified by Z. Sato
Group Name NICSD IV&V Team
Date Jun. 5, 2018

TOSHIBA

2	Jun.5.2018	See DECN-FC51-3809-1000-02	K. Wakita Jun. 5. 2018	K. Wakita Jun 5. 2018	H. Ito Jun. 5. 2018
Rev.No	Issue Date	Description	Approved by	Reviewed by	Prepared by

Initial Issue Date	Issued by	Approved by	Reviewed by	Prepared by	Document filing No.
April 5, 2013	Nuclear Instrumentation Systems Development & Designing Group	T. Furusawa April 5, 2013	T. Furusawa April 4, 2013	T. Tamura April 2, 2013	5B8K0097

Record of Revisions

Rev No.	Date	Description	Approved by	Reviewed by	Prepared by
0	See Cover Page	Initial Issue	See Cover Page	See Cover Page	See Cover Page
1	May.18, 2018	See DECN-FC51-3809-1000-01	K. Wakita May.18, 2018	K. Wakita May.18, 2018	H. Ito May.18, 2018
2	See Cover Page	See DECN-FC51-3809-1000-02	See Cover Page	See Cover Page	See Cover Page

Table of Contents

APPENDIXES

TABLES

FIGURES

1. Purpose

The purpose of this report is to document the result of the availability and reliability analysis for the Oscillation Power Range Monitor (OPRM) of the NRW-FPGA-Based I&C System Qualification Project. The availability and reliability analysis was performed to meet the requirements in Section 4.2.3 of the EPRI TR-107330 (Reference (1)) using the analysis methods described in ANSI/IEEE Std 352-1987 (Reference (2)).

2. Scope

The scope of equipment subject to availability and reliability analysis is one OPRM unit and two Power Factor Correction modules (PFCs). The scope of analysis is enclosed by the bold and dotted line in Figure 2-1 which is a copy of Figure 4-1 of the Equipment Design Specification (EDS) (Reference (4)).

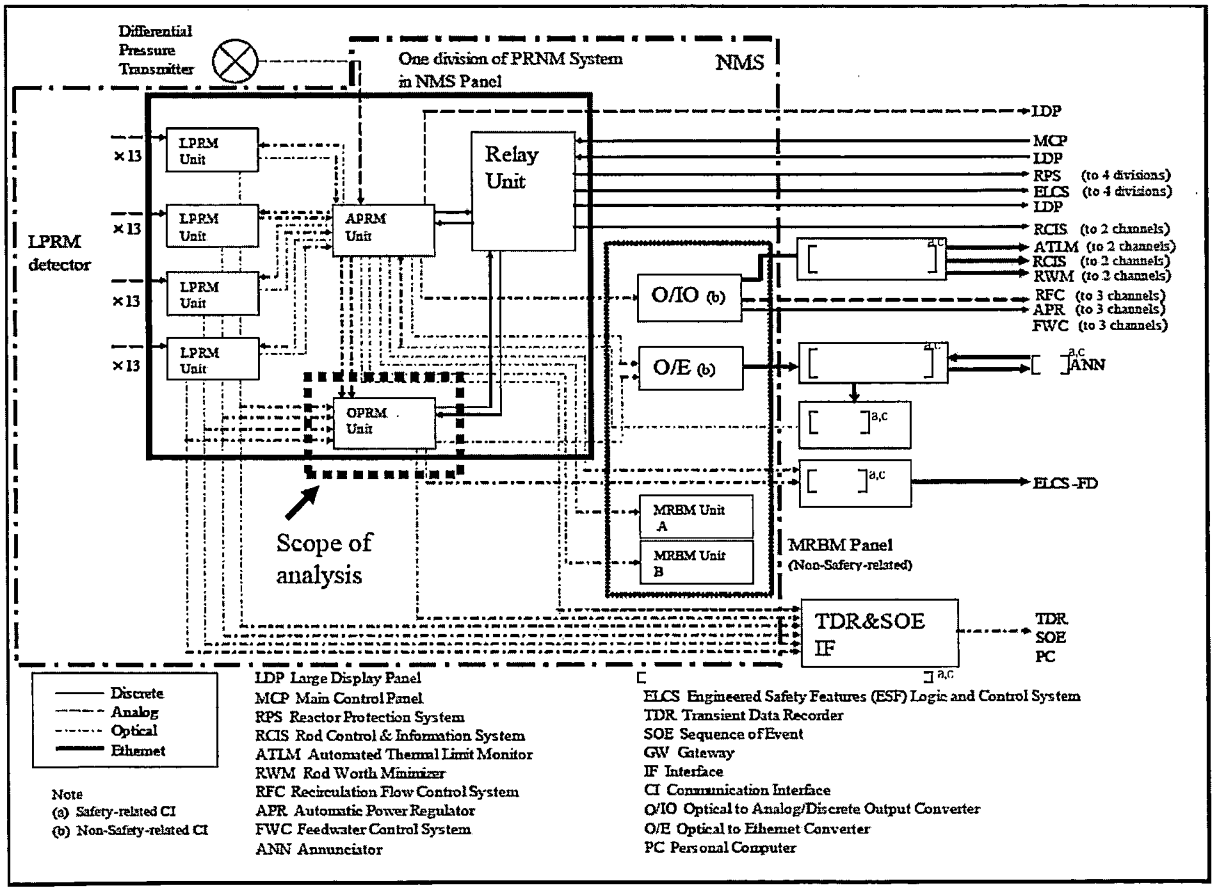


Figure 2-1 Scope of Analysis

3. Applicable Documents

(1) EPRI TR-107330 "Generic Requirements Specification for Qualifying a Commercially Available PLC for Safety-Related Applications in Nuclear Power Plants, December 1996"
(2) ANSI/IEEE Std 352-1987, "IEEE Guidelines for General Principles of Reliability Analysis of Nuclear Power Generating Station Safety Systems"
(3) MIL-HDBK-217F, "Military Handbook Reliability Prediction of Electronic Equipment"
(4) FC51-3002-1000 Rev.6, "Equipment Design Specification for Power Range Neutron Monitor"

4. Abbreviations

EDS	Equipment Design Specification
FIT	Failure In Time
FPGA	Field Programmable Gate Array
I&C	Instrumentation and Control
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NMS	Neutron Monitoring System
NRW	Non-Rewritable
OPRM	Oscillation Power Range Monitor
PC	Personnel Computer
PFC	Power Factor Correction module
PRNM	Power Range Neutron Monitor
SDD	System Design Description
SOE	Sequence of Event
TDR	Transient Data Recorder

5. Analysis

5.1 Approaches

The availability and reliability requirements for the Power Range Neutron Monitor (PRNM) system determined based on Section 4.2.3 of EPRI TR-107330 (Reference (1)) are described in Section 5.1.9 of the EDS (Reference (4)) as follows.

1. The PRNM system shall be designed to support the overall required plant availability more than 95% to System Design Description (SDD) for Neutron Monitoring System (NMS).
2. The availability of the PRNM system is calculated for the combination of four PRNM divisions, which are shown in Figure 4-1 of the EDS.
3. Each unit of PRNM system shall have an availability goal of 99% on the condition that Mean Time To Repair (MTTR) is 24 hours.
4. Availability is calculated by MTTR and Mean Time Between Failures (MTBF). MTTR is assumed as 24 hours. Reliability is calculated by MTBF.
5. The MTBF of each subcomponent (electronic component) is calculated using the reference given in MIL-HDBK 217F (Reference (3))

In this analysis, analysis for the PRNM system was not performed because the scope of this project is limited to the qualification of the OPRM equipment. Thus, the availability and reliability analysis was performed for one OPRM unit and two PFCs under the conditions specified in the items 3, 4 and 5 of Section 5.1.9 of the EDS stated above.

Module failure rates shown in APPENDIX 1 of this document calculated in accordance with MIL-HDBK-217F were used. Each of those module failure rates is the rate of the worst case condition, which is calculated by summing up the failure rates of respective components that make up each module. The OPRM unit adopts modular design, which supports module replacement and 24 hours for the MTTR using spare and replacement parts stored at the plant site. Failures of non-safety-related functions, which do not affect safety-related functions and plant availability, are excluded from the analysis. The analysis was performed in the following sequences using the analysis methods described in ANSI/IEEE Std 352-1987 (Reference (2)).

(1) Define an analysis model of the OPRM equipment using reliability block diagram of series configuration and parallel configuration.

(2) Calculate the MTBF of the OPRM equipment using module failure rates which were calculated in accordance with MIL-HDBK-217F and Section 7.5 of ANSI/IEEE Std 352-1987 (Reference (2)).

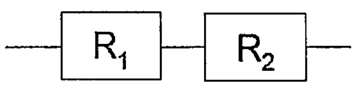
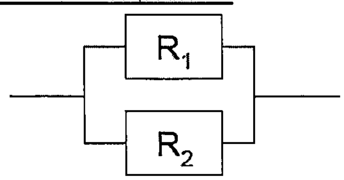
(3) Calculate the failure rate of the OPRM equipment using the MTBF of the OPRM equipment.

(4) Calculate the availability of the OPRM equipment using the MTBF of the OPRM equipment and 24 hours MTTR.

5.1.1 Reliability Block Diagram

A reliability block diagram is used to represent the logic of a system to be analyzed. The reliability block diagram is developed through analysis of the functional relationship among components in the system using the blocks which represent components in the system to be analyzed. Table 5-1 shows the ways of connecting blocks in the reliability block diagram.

Table 5-1 Configuration of Blocks

Series configuration 	In the serial configuration, a failure of either component, (i.e. R_1 or R_2) causes system failure.
Parallel configuration 	In the parallel configuration, failures of both components (i.e. R_1 and R_2) cause system failure.

5.1.2 Reliability

The reliability of any continuously operating item for a mission time t_m is calculated by the following equation.

$$R(t_m) = \exp\left[-\int_0^{t_m} \lambda(t)dt\right] \qquad (5.1)$$

where

$R(t_m)$ = reliability

$\lambda(t)$ = failure rate
t_m= mission duration

For many types of equipment, a "bathtub-shaped" function is thought to be appropriate. Early in life, the failure rate may be large, but it usually decreases as early failures occur. This is followed by a period in which the failure is relatively constant, followed by a period of increasing failure rate as "wear out" occurs. If the mission occurs over a period of time in which the failure rate can be taken as a constant, reliability $R(t_m)$ reduces to the following equation.

$$R(t_m) = \exp(-\lambda t_m) \qquad (5.2)$$

where λ is the constant value of $\lambda(t)$ over the mission's duration.

The cumulative distribution function F(t) and probability density function f(t) are defined by the following equations.

$$F(t) = 1 - R(t) \qquad (5.3)$$

$$\frac{dF(t)}{dt} = f(t) = -\frac{dR(t)}{dt} \qquad (5.4)$$

The MTBF is defined by the following equation.

$$MTBF = \int_0^\infty tf(t)dt \qquad (5.5)$$

From equation (5.4), the MTBF is calculated using a partial integral by the following equation.

$$MTBF = \int_0^\infty tf(t)dt = -\int_0^\infty t\frac{dR(t)}{dt}dt = \int_0^\infty R(t)dt \qquad (5.6)$$

From equation (5.6), the MTBF of exponential distribution is calculated by the following equation.

$$
\begin{aligned}
MTBF &= \int_0^\infty R(t_m)dt_m \\
&= \int_0^\infty \exp(-\lambda t_m)dt_m \\
&= \frac{1}{\lambda} \qquad (5.7)
\end{aligned}
$$

5.1.3 Failure Rate of Series Configuration

The reliability of series configuration shown in Section 5.1.1 is calculated by the following equation.

$$
\begin{aligned}
R(t) &= R_1(t) \times R_2(t) \ldots\ldots\ldots \times R_n(t) \\
&= \exp(-\lambda_1 t) \times \exp(-\lambda_2 t) \ldots\ldots\ldots \times \exp(-\lambda_n t) \\
&= \exp(-(\lambda_1 + \lambda_2 \ldots\ldots\ldots + \lambda_n) t)
\end{aligned}
$$

Therefore, the failure rate of series configuration is calculated by the following equation.

$$\lambda_{Series} = \lambda_1 + \lambda_2 \ldots\ldots\ldots + \lambda_n \qquad (5.8)$$

From equation (5.7), the relation between the MTBF and the failure rate is shown by the following equation.

$$
\begin{aligned}
MTBF_{Series} &= \frac{1}{\lambda_{Series}} \\
&= \frac{1}{\lambda_1 + \lambda_2 \ldots + \lambda_n} \qquad (5.9)
\end{aligned}
$$

5.1.4 Failure Rate of Parallel Configuration

The reliability of parallel configuration shown in Section 5.1.1 that consists of two repairable components is defined by the following equation.

$$R(t) = \frac{1}{S_1 - S_2}\left(S_1 e^{S_2 t} - S_2 e^{S_1 t}\right) \qquad (5.10)$$

where

$$S_1 = \frac{1}{2}\left\{-(3\lambda+\mu)+\sqrt{\lambda^2+6\lambda\mu+\mu^2}\right\}$$
$$S_2 = \frac{1}{2}\left\{-(3\lambda+\mu)-\sqrt{\lambda^2+6\lambda\mu+\mu^2}\right\}$$
$$S_1 < 0, \quad S_2 < 0$$

μ = repair rate
=1/MTTR
=1/24

From equation (5.6), the relation between the MTBF, the failure rate and the repair rate is shown by the following equation.

$$\begin{aligned} MTBF_{Parallel} &= \int_0^\infty R(t)dt \\ &= \int_0^\infty \frac{1}{S_1 - S_2}\left(S_1 e^{S_2 t} - S_2 e^{S_1 t}\right)dt \\ &= \frac{3}{2\lambda} + \frac{\mu}{2\lambda^2} \end{aligned}$$

When the failure rate is much smaller than the repair rate (i.e. $\lambda \ll \mu$), S_1 comes close to zero. Thus, the reliability of parallel configuration that consists of two repairable components can be considered as exponential distribution.

Therefore, failure rate of parallel configuration that consists of two repairable components can be calculated by the following equation.

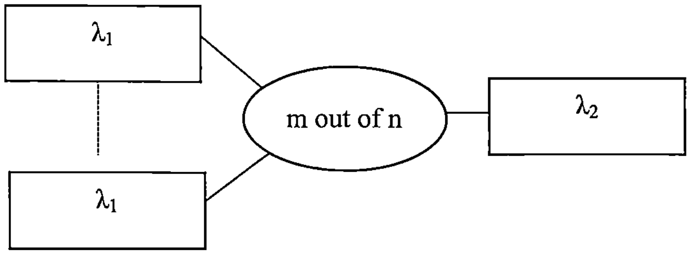
$$\begin{aligned} \lambda_{Parallel} &= \frac{1}{MTBF_{Parallel}} \\ &= \frac{2\lambda^2}{3\lambda+\mu} \end{aligned}$$

When repair is not possible, by setting μ =0 the above equation becomes:

$\lambda_{Parallel} = 2\lambda/3$

However, using $\lambda_{Parallel}$ derived in this manner for the evaluation of MTBF of a unit combining failure rate in series as discussed in section 5.1.3 generally generates errors.

Consider a unit that have the following configuration.



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

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

$$= \int_0^{\infty} \{R_2 \sum_{i=0}^{(n-m)} [{}_nC_{(n-i)} \quad R_1{}^{(21-i)} \sum_{k=0}^{i} {}_iC_k \quad (-R_1)^k]\} dt \qquad (5.11)$$

Where $R_1 = \mathrm{e}^{-\lambda_1 t}$, $R_2 = \mathrm{e}^{-\lambda_2 t}$, λ_1 and $\lambda 2$ are 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. When a redundant part is connected in series to other parts as shown in Figure 5-1, Equation (5.11) can be simplified to the form below by setting m=1 and n=2

$$MTBF = (3\lambda_1 + \lambda_2) / ((\lambda_1 + \lambda_2)(2\lambda_1 + \lambda_2)) \qquad (5.12)$$

λ_1 is the failure rate of the module which configures a redundant part.

λ_2 is the summation of the failure rate of the modules that are connected in series to a redundant part.

The evaluation of the MTBF of one OPRM unit is conservatively performed assuming that the repair of unit is not possible, even though one division of the OPRM systems can be bypassed and repaired since the OPRM systems have four divisions. So the MTBF of the OPRM unit is evaluated based on Equation (5.12).

5.1.5 Availability

Availability is defined by the following equation as described in Section 5.1.2 of ANSI/IEEE Std 352-1987 (Reference (2)).

$$Availability = \frac{MTBF}{(MTBF + \ MTTR)} \qquad (5.13)$$

5.2 Configuration of OPRM Equipment

The identification, description, and quantity of the OPRM equipment are shown in Table 5-2.

Table 5-2 Configuration of OPRM Equipment

OPRM Equipment	Description	Model Number	Manufacturer	Quantity	Note
OPRM unit	CELL Module	HNS0400B00000	Toshiba	1	
	AGRD Module	HNS0420B00000	Toshiba	1	
	PBD Module	HNS0430B00000	Toshiba	1	
	DAT/ST Module	HNS0410B00000	Toshiba	1	
	LVPS Module	HNS0500B00000	Toshiba	2	For redundant power supply
	DIO Module	HNS0520B00000	Toshiba	1	
	TRN Module	HNS0531B00001	Toshiba	2	One TRN module for non-safety-related function is excluded from the analysis model.
	RCV Module	HNS0541B00001	Toshiba	2	
	OPRM Chassis	[ ]a,c		1	
PFC	PFC			2	For redundant power supply

5.3 Availability Analysis Model of OPRM Equipment

Figure 5-1 shows an availability analysis model of the OPRM equipment. In this availability analysis model, the LVPS modules and PFCs for redundant power supply are analyzed as a parallel configuration. One TRN module is used to transmit the OPRM Record Data which is non-safety-related optical signals to PC via Transient Data Recorder (TDR) and Sequence of Event (SOE) interface, and failure of this TRN module does not affect plant availability. Thus, the TRN module for non-safety-related function is excluded from the availability analysis.

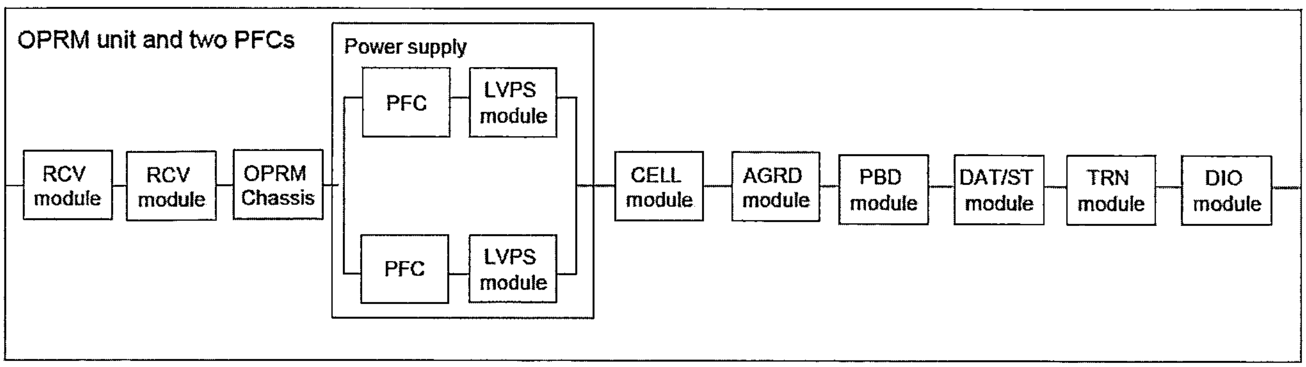


Figure 5-1 Availability Analysis Model of OPRM Equipment

5.4 Availability Analysis of OPRM Equipment

In this section, the failure rate, MTBF, and availability of the OPRM equipment were calculated. Table 5-3 shows the module failure rates which were calculated in accordance with MIL-HDBK-217F (Reference (3)).

Table 5-3 Failure Rate of OPRM Equipment

OPRM Equipment	Description	Model Number	Module Failure Rate ($1/10^9$ Hour)		
OPRM unit	CELL Module	HNS0400B00000	λ_{CELL}	[ ]a,c	
	AGRD Module	HNS0420B00000	λ_{AGRD}		
	PBD Module	HNS0430B00000	λ_{PBD}		
	DAT/ST Module	HNS0410B00000	$\lambda_{DAT/ST}$		
	TRN Module	HNS0531B00001	λ_{TRN}		
	RCV Module	HNS0541B00001	λ_{RCV}		
	DIO Module	HNS0520B00000	λ_{DIO}		
	LVPS Module	HNS0500B00000	λ_{LVPS}		
	OPRM Chassis	[ ]a,c	$\lambda_{OPRM\_Chassis}$		
PFC	PFC		λ_{PFC}		

Note: 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 A.

The availability of the OPRM equipment was calculated as follows.

(1) Failure rate of power supply

As shown in Figure 5-1, the OPRM unit has the redundantly configured power supply which consists of PCF and LVPS module. Since a PCF and a LVPS module are connected in series, failure rate of a channel of the power supply is provided by as follows:

$$\lambda_{Power} = \lambda_{PCF} + \lambda_{LVPS}$$

(2) MTBF of OPRM equipment

As explained in Section 5.1.4, the reliability of power supply can be approximated to exponential distribution. Therefore the MTBF of the OPRM equipment which is series configuration shown in Figure 5-1 is calculated by the following equation.

$$MTBF_{OPRM} = (3\lambda_1 + \lambda_2) / ((\lambda_1 + \lambda_2)(2\lambda_1 + \lambda_2)) \quad (5.14)$$

$$\lambda_1 = \lambda_{Power}$$

$$\lambda_2 = 2\lambda_{RCV} + \lambda_{OPRM\_Chassis} + \lambda_{CELL} + \lambda_{AGRD} + \lambda_{PBD} + \lambda_{DAT} + \lambda_{TRN} + \lambda_{DIO}$$

Thus, $MTBF_{OPRM}$=[ ]a,c(Hour) =[ ]a,c(Year)

For the calculations above, failure rates 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 rates at 50 degrees Celsius used for the first two weeks and failure rates at 25 degrees Celsius are used after the first two weeks. This evaluation is done by calculating equation Eq. (5.11) 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. (5.15). The results show that the reduction of MTBF is negligibly small in the order of 10^{-5} year.

$$MTBF_{OPRM} = \int_0^T \left\{ R_2 \sum_{i=0}^{(n-m)} {}_nC_{(n-i)} {R_1}^{(n-i)} (1-R_1)^i \right\} dt + \int_T^\infty \left\{ R_2 \sum_{i=0}^{(n-m)} {}_nC_{(n-i)} {R_1}^{(n-i)} (1-R_1)^i \right\} dt \qquad (5.15)$$

where T= Two weeks, $R_1 = e^{-\lambda_1 t}$, $R_2 = e^{-\lambda_2 t}$, m=1, n=2. Failure rates λ_1 and λ_2 in the first integral are calculated using the failure rates at 50 degrees Celsius.

(3) Failure rate of OPRM equipment

$\lambda_{OPRM} == 10^9 / MTBF_{OPRM}$

= [ ]a,c fit

(4) Availability of OPRM equipment

$Availability_{OPRM} = MTBF_{OPRM} / (MTBF_{OPRM} + MTTR_{OPRM})$

= [ ]a,c / ([ ]a,c +24)

= [ ]a,c >0.99

In case that once a year surveillance period with 24 hour work duration is taken into account, the availability is evaluated as follows:

$Availability_{OPRM} = (MTBF_{OPRM} - DT_{surveillance}) / (MTBF_{OPRM} + MTTR)$

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

$DT_{surveillance} = 24 \times (MTBF_{OPRM} / 24/365)$

Thus, $Availability_{OPRM}$ is calculated as follows

$Availability_{OPRM}$ = [ ]a,c -24×[ ]a,c /365/24)/([ ]a,c +24)

= [ ]a,c > 0.99

6. Conclusion

The availability and reliability analysis was performed meeting the requirements in Section 4.2.3 of the EPRI TR-107330 (Reference (1)) using the analysis methods described in ANSI/IEEE Std 352-1987 (Reference (2)).
It was concluded that the OPRM equipment has adequate availability more than 99% as required in the EDS (Reference (4)).

APPENDIX 1. Failure Rate 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."

● CELL Module

Item		Unit	Evaluation Temperature		
Name	Doc. No.		(0°C)	(25°C)	(50°C)
CELL-M	5J8H3082G1	(FIT)			
CELL-S1	5J8H3083G1	(FIT)			
CELL-S2	5J8H3084G1	(FIT)			
FP-CELL	5J8H3085G1	(FIT)			
FRAME_PARTS	2Y8HF040G1	(FIT)			
CELL MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

● AGRD Module

Item		Unit	Evaluation Temperature		
Name	Doc. No.		(0°C)	(25°C)	(50°C)
AGRD-M	5J8H3072G1	(FIT)			
AGRD-S	5J8H3073G1	(FIT)			
FP-APRM	5J8H2922G5	(FIT)			
FRAME_PARTS	2Y8HF042G1	(FIT)			
AGRD MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

●PBD Module

Item		Unit	Evaluation Temperature		
Name	Doc. No.		(0°C)	(25°C)	(50°C)
AGRD-M	5J8H3072G2	(FIT)			
AGRD-S	5J8H3073G2	(FIT)			
FP-APRM	5J8H2922G6	(FIT)			
FRAME_PARTS	2Y8HF043G1	(FIT)			
PBD MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

●DAT/ST Module

Item		Unit	Evaluation Temperature		
Name	Doc. No.		(0°C)	(25°C)	(50°C)
DATST-M	5J8H3074G1	(FIT)			
FP-STS	5J8H2924G5	(FIT)			
FRAME_PARTS	2Y8HF041G1	(FIT)			
DAT/ST MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

●TRN Module

Item		Unit	Evaluation Temperature		
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

●RCV Module

Item		Unit	Evaluation Temperature		
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

●DIO Module

Item		Unit	Evaluation Temperature		
Name	Doc. No.		(0°C)	(25°C)	(50°C)
RM-MAIN	5J8H2934G2	(FIT)			
FRAME_PARTS	2Y8HF052G1	(FIT)			
DIO MODULE		(FIT)			
		(Hour)			
		(Year)			

a,c

●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.

●OPRM Chassis

Item	Unit	Evaluation Temperature		
		(0°C)	(25°C)	(50°C)
OPRM Chassis	(FIT)			
	(Hour)			
	(Year)			

[a,c]

●PFC

Item	Unit	Evaluation Temperature		
		(0°C)	(25°C)	(50°C)
PFC	(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.