

The Insight of PRA Sensitivity Analyses for AAC Designs

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The Station Blackout (SBO) is a dominant initiating event in the most of Probabilistic Risk Assessment (PRA), thus a lot of efforts have been made to mitigate SBO event. The utility and design companies are concerned which design concept of Alternate AC (AAC) power sources is effective to mitigate SBO since the AAC power source is an important SBO mitigation feature. It is expected that the PRA sensitivity analyses for various AAC design concepts can be helpful for the decision making of an AAC design in the nuclear power plant.

I. Introduction

The AAC power sources should have sufficient capacity to operate the systems necessary for coping with the SBO for the time required to bring and maintain the plant in safe shutdown according to U.S. NRC Regulatory Guide 1.155 (Ref. 1). It is also required that there should be a minimum potential for Common Cause Failure (CCF) with the preferred or the blacked-out unit's onsite emergency AC power sources.

In order to decide which AAC design concept is more effective to mitigate SBO in the view of PRA, sensitivity analyses using APR 1400 Level 1 internal PRA model at power are performed by changing numbers and types of AAC sources, and applying CCF with or without Emergency Diesel Generators (EDGs), etc. It is also expected that the following sensitivity methods estimated for Core Damage Frequency (CDF) using the Minimal Cutsets (MCS) reduce time for performing sensitive analyses since it takes a considerable time to perform several sensitive cases modified Event Trees (ETs), Fault Trees (FTs), and Database (DB).

II. The Description of Sensitivity Cases

The summary of sensitivity cases considered in these analyses are as follows:

TABLE 1. The Summary of Sensitivity Cases

Case No.	Description	Remark
Base Case	One (1) AAC DG ¹ + CCF with EDGs	<ul style="list-style-type: none">Two (2) EDGs and <u>one (1) AAC DG</u> are installed.There is <u>CCF</u> between EDGs and an AAC DG.
Case 1	One (1) AAC DG + CCF without EDGs	<ul style="list-style-type: none">Two (2) EDGs and <u>one (1) AAC DG</u> are installed.There is <u>no CCF</u> between EDGs and an AAC DG.
Case 2	Two (2) AAC DGs + CCF with EDGs	<ul style="list-style-type: none">Two (2) EDGs and <u>two (2) AAC DGs</u> are installed.There is <u>CCF</u> between EDGs and AAC DGs.

Case No.	Description	Remark
Case 3	Two (2) AAC DGs + CCF without EDGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC DGs. - Only <u>CCF</u> among EDGs and AAC DGs respectively.
Case 4	Two (2) AAC DGs + CCF with EDGs + no CCF among AAC DGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. There is <u>CCF</u> between EDGs and 1st AAC DG. There is <u>no CCF</u> between 1st AAC DG and 2nd AAC DG.
Case 5	Two (2) AAC DGs + CCF without EDGs + no CCF among AAC DGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC DGs. There is <u>no CCF</u> between 1st AAC DG and 2nd AAC DG.
Case 6	One (1) AAC GTG ²⁾ + CCF without EDGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>one (1) AAC GTG</u> are installed. There is <u>no CCF</u> between EDGs and an AAC GTG.
Case 7	Two (2) AAC GTGs + CCF without EDGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC GTGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC GTGs - Only <u>CCF</u> among EDGs and AAC GTGs respectively.
Case 8	Two (2) AAC GTGs + CCF without EDGs + no CCF among AAC GTGs	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC GTGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC GTGs. There is <u>no CCF</u> between 1st AAC GTG and 2nd AAC GTG.
Case 9	One (1) AAC DG + One (1) AAC GTG + CCF with EDGs	<ul style="list-style-type: none"> Two (2) EDGs, <u>one (1) AAC DG</u>, and <u>one (1) AAC GTG</u> are installed. There is <u>CCF</u> between EDGs and one (1) AAC DG. There is <u>no CCF</u> between one (1) AAC DG and one (1) AAC GTG.
Case 10	One (1) AAC DG + One (1) AAC GTG + CCF without EDGs	<ul style="list-style-type: none"> Two (2) EDGs, <u>one (1) AAC DG</u>, and <u>one (1) AAC GTG</u> are installed. There is <u>no CCF</u> between EDGs and one (1) AAC DG. There is <u>no CCF</u> between one (1) AAC DG and one (1) AAC GTG.

1) DG : Diesel Generators

2) GTG : Gas Turbine Generator

The detail of sensitivity analyses and how to develop each sensitivity case for AAC designs are described as follows.

II.A. Base Case : One (1) AAC DG + CCF with EDGs

Base Case describes that there are two (2) EDGs and one (1) AAC DG to supply power for the plant safety shutdown when loss of offsite power occurs. It is assumed that there is CCF between EDGs and an AAC DG . This case is the base case to confirm which AAC design concept is more useful to mitigate SBO.

In order to estimate the CDF for sensitivity cases, component reliability data and CCF parameter are based on the NUREG/CR-6928 (Ref. 2) and NUREG/CR-5497 (Ref. 3) respectively. Assumptions associated with development of sensitivity cases are as follows:

- The 2nd AAC source can be credited as a backup of the 1st AAC source if sensitivity cases consider two AAC sources.
- The operator action to align the 2nd AAC source is likely to be highly dependent on the operator action to align the 1st AAC source when 1st AAC source is failed, thus the operator action for 2nd AAC source is not considered.
- The CDF for all sensitivity cases are estimated using the cutsets derived from Base Case, thus detailed support systems for operating AAC source such as the fuel oil system and HVAC system, etc. are not considered.

II.B. Case 1 : One (1) AAC DG + CCF without EDGs

Case 1 represents that two (2) EDGs and one (1) AAC DG are installed and there is no CCF between EDGs and an AAC DG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDGs and AAC DG as shown in the Table below.

TABLE 2. CCF Data Change for Case 1

CCF Event			Base Case	Case 1	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG

II.C. Case 2 : Two (2) AAC DGs + CCF with EDGs

Case 2 represents that two (2) EDGs and two (2) AAC DGs are installed and there is CCF between EDGs and AAC DGs. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDGs and an AAC DG as shown in the Table below.

TABLE 3. CCF Data Change for Case 2

CCF Event			Base Case	Case 2	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	4.82E-05	• Data change from 3/3 CCF to 4/4 CCF between EDGs and AAC DGs
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	N/A	• Number of 3/4 CCF combination is 2 times higher than that of 2/4 CCF. It is applied 3/4 CCFs below
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	6.56E-05	• Data change from 2/3 CCF to 3/4 CCF between EDGs and AAC DGs * 2
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	6.56E-05	• Data change from 2/3 CCF to 3/4 CCF between EDGs and AAC DGs * 2
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	4.00E-05	• Data change from 3/3 CCF to 4/4 CCF between EDGs and AAC DGs
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	N/A	• Number of 3/4 CCF combination is 2 times higher than that of 2/4 CCF. It is applied 3/4 CCFs below
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	5.24E-05	• Data change from 2/3 CCF to 3/4 CCF between EDGs and AAC DGs * 2
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	5.24E-05	• Data change from 2/3 CCF to 3/4 CCF between EDGs and AAC DGs * 2

II.D. Case 3 : Two (2) AAC DGs + CCF without EDGs

Case 3 represents that two (2) EDGs and two (2) AAC DGs are installed and there is no CCF between EDGs and AAC DGs. Only CCF among EDGs or AAC DGs is considered respectively. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 4. CCF Data Change for Case 3

CCF Event			Base Case	Case 3	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs

CCF Event			Base Case	Case 3	Remark
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG

The failure data for an AAC DG in the cutsets are changed to considering 2/2 CCF of AAC DGs and 2nd AAC DG random failure as shown in the Table below.

TABLE 5. The Failure Data Change for Case 3

Basic Event		Base Case	Case 3	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	4.32E-03	• 2/2 CCF of AAC DGs FTS + DADGS-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	3.11E-03	• 2/2 CCF of AAC DGs FTR + DADGR-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	1.27E-03	• DADGM-S-AAC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)

II.E. Case 4 : Two (2) AAC DGs + CCF with EDGs + no CCF among AAC DGs

Case 4 represents that two (2) EDGs and two (2) AAC DGs are installed and there is CCF between EDGs and 1st AAC DG but no CCF between 1st AAC DG and 2nd AAC DG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed to considering 2nd AAC DG random failure as shown in the Table below.

TABLE 6. CCF Data Change for Case 4

CCF Event			Base Case	Case 4	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	1.02E-05	• DGDGWT3-DG01ABC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	1.03E-05	• No Change
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	9.43E-06	• DGDGWT2-DG01AC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	9.43E-06	• DGDGWT2-DG01BC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	7.89E-06	• DGDGKT3-DG01ABC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	1.01E-04	• No Change
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	7.68E-06	• DGDGKT2-DG01AC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	7.68E-06	• DGDGKT2-DG01BC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)

The failure data for an AAC DG in the cutsets are changed to considering 2nd AAC DG random failure as shown in the Table below.

TABLE 7. The Failure Data Change for Case 4

Basic Event		Base Case	Case 4	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	3.79E-03	• DADGS-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	2.70E-03	• DADGR-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)

Basic Event		Base Case	Case 4	Remark
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	1.27E-03	• DADGM-S-AAC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)

II.F. Case 5 : Two (2) AAC DGs + CCF without EDGs + no CCF among AAC DGs

Case 5 represents that two (2) EDGs and two (2) AAC DGs are installed and there is no CCF between EDGs and AAC DGs. In addition, there is no CCF between 1st AAC DG and 2nd AAC DG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 8. CCF Data Change for Case 5

CCF Event			Base Case	Case 5	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC DG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC DG

The failure data for an AAC DG in the cutsets are changed to considering 2nd AAC DG random failure as shown in the Table below.

TABLE 9. The Failure Data Change for Case 5

Basic Event		Base Case	Case 5	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	3.79E-03	• DADGS-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	2.70E-03	• DADGR-S-AACDG * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	1.27E-03	• DADGM-S-AAC * (2 nd AAC DG FTS + 2 nd AAC DG FTR + 2 nd AAC DG T&M)

II.G. Case 6 : One (1) AAC GTG + CCF without EDGs

Case 6 represents that two (2) EDGs and one (1) AAC Gas Turbine Generator (GTG) are installed and there is no CCF between EDGs and an AAC GTG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 10. CCF Data Change for Case 6

CCF Event			Base Case	Case 6	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

CCF Event			Base Case	Case 6	Remark
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

The failure data for an AAC DG in the cutsets are changed to considering AAC GTG random failure as shown in the Table below.

TABLE 11. The Failure Data Change for Case 6

Basic Event		Base Case	Case 6	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	1.56E-02	• NUREG/CR-6928 (Jan-2012), Combustion Turbine Generator FTS
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	1.78E-01	• NUREG/CR-6928 (Jan-2012), Combustion Turbine Generator FTR * mission time 24h
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	5.00E-02	• NUREG/CR-6928 (Jan-2012), Combustion Turbine Generator T&M

II.F. Case 7 : Two (2) AAC GTGs + CCF without EDGs

Case 7 represents that two (2) EDGs and two (2) AAC GTGs are installed and there is no CCF between EDGs and AAC GTGs. Only CCF among EDGs or AAC GTGs is considered respectively. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 12. CCF Data Change for Case 7

CCF Event			Base Case	Case 7	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG

CCF Event			Base Case	Case 7	Remark
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

The failure data for an AAC DG in the cutsets are changed to considering 2/2 CCF of AAC GTGs, 1st and 2nd AAC GTG random failure as shown in the Table below.

TABLE 13. The failure data change for Case 7

Basic Event		Base Case	Case 7	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	3.39E-03	• 2/2 CCF of AAC GTGs FTS + 1 st AAC GTG FTS * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	4.55E-02	• 2/2 CCF of AAC GTGs FTR + 1 st AAC GTG FTR * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	1.22E-02	• 1 st AAC GTG T&M * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)

II.G. Case 8 : Two (2) AAC GTGs + CCF without EDGs + no CCF among AAC GTGs

Case 8 represents that two (2) EDGs and two (2) AAC GTGs are installed and there is no CCF between EDGs and AAC GTGs. In addition, there is no CCF between 1st AAC GTG and 2nd AAC GTG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 14. CCF Data Change for Case 8

CCF Event			Base Case	Case 8	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

The failure data for an AAC DG in the cutsets are changed to considering 1st and 2nd AAC GTG random failure as shown in the Table below.

TABLE 15. The Failure Data Change for Case 8

Basic Event		Base Case	Case 8	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	3.79E-03	• 1 st AAC GTG FTS * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	4.32E-02	• 1 st AAC GTG FTR * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	1.22E-02	• 1 st AAC GTG T&M * (2 nd AAC GTG FTS + 2 nd AAC GTG FTR + 2 nd AAC GTG T&M)

II.H. Case 9 : One (1) AAC DG + One (1) AAC GTG + CCF with EDGs

Case 9 represents that two (2) EDGs, one (1) AAC DG, and one (1) AAC GTG are installed and there is CCF between EDGs and one (1) AAC DG but no CCF between one (1) AAC DG and one (1) AAC GTG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed to considering one (1) AAC GTG random failure as shown in the Table below.

TABLE 16. CCF Data Change for Case 9

CCF Event			Base Case	Case 9	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	2.82E-05	• DGDGWT3-DG01ABC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	1.03E-05	• No Change
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	2.60E-05	• DGDGWT2-DG01AC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	2.60E-05	• DGDGWT2-DG01BC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	2.18E-05	• DGDGKT3-DG01ABC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	1.01E-04	• No Change
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	2.12E-05	• DGDGKT2-DG01AC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	2.12E-05	• DGDGKT2-DG01BC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)

The failure data for an AAC DG in the cutsets are changed to considering one (1) AAC GTG random failure as shown in the Table below.

TABLE 17. The Failure Data Change for Case 9

Basic Event		Base Case	Case 9	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	1.05E-02	• DADGS-S-AACDG * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	7.46E-03	• DADGR-S-AACDG * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	3.50E-03	• DADGM-S-AAC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)

II.I. Case 10 : One (1) AAC DG + One (1) AAC GTG + CCF without EDGs

Case 10 represents that two (2) EDGs, one (1) AAC DG, and one (1) AAC GTG are installed and there is no CCF between EDGs and one (1) AAC DG. In addition, there is no CCF between one (1) AAC DG and one (1) AAC GTG. The CDF for this case is estimated using the cutsets derived from Base Case by changing the CCF failure data associated with the EDG and AAC DG and random failure data (fails to start, fails to run, and unavailable due to test and maintenance) associated with the AAC DG.

The CCF data related to the EDGs and an AAC DG are changed as shown in the Table below.

TABLE 18. CCF Data Change for Case 10

CCF Event			Base Case	Case 10	Remark
Fail to Start (FTS)	DGDGWT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	1.16E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.03E-05	3.55E-05	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGWT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
	DGDGWT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	1.07E-04	N/A	• No CCF between EDGs and an AAC GTG
Fail to Run (FTR)	DGDGKT3-DG01ABC	3/3 CCF between EDGs and an AAC DG	8.96E-05	N/A	• No CCF between EDGs and an AAC GTG
	DGDGKT2-DG01AB	2/3 CCF between EDG-A and EDG-B	1.01E-04	3.26E-04	• Data change from 2/3 CCF to 2/2 CCF among EDGs
	DGDGKT2-DG01AC	2/3 CCF between EDG-A and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

CCF Event			Base Case	Case 10	Remark
	DGDGKT2-DG01BC	2/3 CCF between EDG-B and an AAC DG	8.72E-05	N/A	• No CCF between EDGs and an AAC GTG

The failure data for an AAC DG in the cutsets are changed to considering one (1) AAC GTG random failure as shown in the Table below.

TABLE 19. The Failure Data Change for Case 10

Basic Event		Base Case	Case 10	Remark
DADGS-S-AACDG	The AAC DG fails to start (FTS)	4.30E-02	1.05E-02	• DADGS-S-AACDG * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
DADGR-S-AACDG	The AAC DG fails to run (FTR)	3.07E-02	7.46E-03	• DADGR-S-AACDG * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)
DADGM-S-AAC	The AAC DG unavailable due to test and Maintenance (T&M)	1.44E-02	3.50E-03	• DADGM-S-AAC * (AAC GTG FTS + AAC GTG FTR + AAC GTG T&M)

III. The Result of Sensitivity Analyses

The result of sensitivity analyses for AAC designs are as follows:

TABLE 20. The Result of Sensitivity Analyses for AAC Designs

Case No.	Description	ΔCDF	Remark
Base Case	One (1) AAC DG + CCF with EDGs	-	• Two (2) EDGs and <u>one (1) AAC DG</u> are installed. • There is <u>CCF</u> between EDGs and an AAC DG.
Case 1	One (1) AAC DG + CCF without EDGs	-6.9%	• Two (2) EDGs and <u>one (1) AAC DG</u> are installed. • There is <u>no CCF</u> between EDGs and an AAC DG.
Case 2	Two (2) AAC DGs + CCF with EDGs	-5.0%	• Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. • There is <u>CCF</u> between EDGs and AAC DGs.
Case 3	Two (2) AAC DGs + CCF without EDGs	-20.5%	• Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. • There is <u>no CCF</u> between EDGs and AAC DGs. - Only <u>CCF</u> among EDGs and AAC DGs respectively.
Case 4	Two (2) AAC DGs + CCF with EDGs + no CCF among AAC DGs	-20.6%	• Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. • There is <u>CCF</u> between EDGs and 1 st AAC DG. • There is <u>no CCF</u> between 1 st AAC DG and 2 nd AAC DG.

Case No.	Description	ΔCDF	Remark
Case 5	Two (2) AAC DGs + CCF without EDGs + no CCF among AAC DGs	-20.7%	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC DGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC DGs. There is <u>no CCF</u> between 1st AAC DG and 2nd AAC DG.
Case 6	One (1) AAC GTG + CCF without EDGs	18.4%	<ul style="list-style-type: none"> Two (2) EDGs and <u>one (1) AAC GTG</u> are installed. There is <u>no CCF</u> between EDGs and an AAC GTG.
Case 7	Two (2) AAC GTGs + CCF without EDGs	-11.5%	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC GTGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC GTGs - Only <u>CCF</u> among EDGs and AAC GTGs respectively.
Case 8	Two (2) AAC GTGs + CCF without EDGs + no CCF among AAC GTGs	-11.9%	<ul style="list-style-type: none"> Two (2) EDGs and <u>two (2) AAC GTGs</u> are installed. There is <u>no CCF</u> between EDGs and AAC GTGs. There is <u>no CCF</u> between 1st AAC GTG and 2nd AAC GTG.
Case 9	One (1) AAC DG + One (1) AAC GTG + CCF with EDGs	-17.2%	<ul style="list-style-type: none"> Two (2) EDGs, <u>one (1) AAC DG</u>, and <u>one (1) AAC GTG</u> are installed. There is <u>CCF</u> between EDGs and one (1) AAC DG. There is <u>no CCF</u> between one (1) AAC DG and one (1) AAC GTG.
Case 10	One (1) AAC DG + One (1) AAC GTG + CCF without EDGs	-18.5%	<ul style="list-style-type: none"> Two (2) EDGs, <u>one (1) AAC DG</u>, and <u>one (1) AAC GTG</u> are installed. There is <u>no CCF</u> between EDGs and one (1) AAC DG. There is <u>no CCF</u> between one (1) AAC DG and one (1) AAC GTG.

The sensitivity studies show that adding one more AAC DG (Case 3, 4, and 5) reduces the CDF much if there is no CCF among four (4) SBO mitigation features (i.e, two (2) EDGs and two (2) AAC DGs).

Changing an AAC DG to AAC GTG (Case 6) increase the CDF because unavailability of AAC GTG is higher than that of AAC DG based on the reliability data in NUREG/CR-6928, however two (2) AAC GTGs (Case 7 and 8) can reduce the CDF.

Adding one more AAC GTG (Case 9 and 10) reduces the CDF much but it seems that two (2) AAC DGs (Case 3, 4, and 5) are better design than these cases due to high unavailability of AAC GTG.

It is expected that CDF for sensitivity cases of considering additional AAC source will not increase significantly and the insight of results will not change even if the detailed support systems are considered. Therefore, the detailed support systems for the additional AAC source such as the fuel oil system and HVAC system, etc. are not considered in these sensitivity studies.

IV. CONCLUSIONS

A lot of efforts have been made to mitigate SBO event which is a dominant initiating event of the PRA. The AAC power source is an important SBO mitigation feature, thus various sensitivity analyses are performed to decide which design concept of AAC power sources is efficient. The result of sensitivity analyses show that CDF can be reduced by installing an additional AAC source and minimizing CCF between EDGs and AAC DGs. It is also expected that these sensitive methods using the Minimal Cutsets (MCS) can be helpful to save time for performing sensitive analyses.

REFERENCES

1. U.S. NRC, Regulatory Guide 1.155, “Station Blackout” (1988).
2. U.S. NRC, NUREG/CR-6928, “Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants,” (2012).
3. U.S. NRC, NUREG/CR-5497, “CCF Parameter Estimations, 2010 Update” (2012).