A Level 1 Fire PRA on PGSFR

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Abstract: Prototype Generation IV Sodium Fast Reactor (PGSFR) is under design with defense in depth concept with active, passive, and inherent safety features. A level 1 fire PSA on PGSFR was done. The typical difference between PGSFR and the commercial Nuclear Power Plant (NPP) are; 1) PGSFR is very simple plant and 2) PGSFR has sodium which can be an ignition source. These differences are reflected in the PGSFR fire PSA, and the characteristics of the level 1 fire PSA on PGSFR are described in this paper.

Keywords: PRA, Sodium, Fast Reactor

1. INTRODUCTION

A Prototype Generation IV Sodium Fast Reactor (PGSFR) is under design with defence in depth concept with active, passive, and inherent safety features.

A level 1 fire PSA on PGSFR was done. The typical difference between PGSFR and the commercial Nuclear Power Plant (NPP) are; 1) PGSFR is very simple plant and 2) PGSFR has sodium which can be an ignition source. These differences are reflected in the PGSFR fire PSA, and the characteristics of the level 1 fire PSA on PGSFR are described in this paper.

197 fire areas are determined, and among them, 36 fire areas including 7 sodium leak areas are quantitatively in detail analysed.

2. METHODS

2.1 Ignition Frequency of PGSFR Fire PSA

The first step of fire PSA is to find ignition sources and the possible damage items caused by fires of the ignition sources. The difference between normal nuclear power plants and sodium fast reactors is that there would be a fire caused by sodium leak. Therefore, sodium flow path would be additional ignition source.

The ignition frequencies of the fire areas are calculated by the methodology and data of NUREG-2169[1]. Generally, there are two ignition sources: 1) <u>fixed source</u> due to the fire of equipment such as pumps, electric cabinets, etc., 2) <u>transient source</u> due to the maintenance work, welding, etc. However, in PGSFR, additionally, there is another ignition source, i.e., sodium fire which is separately mentioned in the section 2.2.

An example of ignition frequencies based on the fixed and transient sources is shown in the Table 1. However, the ignition frequencies of Table 1 are based on the large commercial nuclear power plants (NPPs) where there are many components. Since the number of components of PGSFR is much fewer than those of commercial NPPs, it was assumed that the generic fire ignition frequency of PGSFR is proportionally smaller than the large commercial NPPs. The equipment number of PGSFR vs commercial NPPs is 592 vs 1177. Thus, it was assumed that the ignition frequency of PGSFR is smaller by the (592/1177) factor.

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2.2 Increased Fire Frequency By Sodium Leak

When there is a leak from sodium piping, a weak fire occurs. Even though there are catch pans and sodium liners to prevent such sodium fires, we assumed conservatively that there is a sodium fire if there is a leak from sodium piping.

Currently, the sodium fire frequency in the PGSFR fire PSA was based on the history data of BN-600. In BN-600, it is known that sodium fire occurred 6 times when sodium leaked 13 times from intermediate cooling pipe during 30 years(1980~2010) [2]. Thus, about 0.2/yr is used for the sodium fire ignition frequency due to sodium leak. Thus, the ignition frequency due to the sodium leak in each fire area, can be derived by checking the length of the sodium piping passing the fire area, and the results are shown in Table 2. In Table 2, for example, the sodium piping line of IHX, ADHRS, and PDHRS are passing the fire area F-C304. And the total length of the sodium piping lines passing the F-C304, is 155.7 m, which is 23 % of the total sodium piping lines of PGSFR. Thus, the sodium fire frequency at fire area F-C304 is 0.046/yr which is 23% of 0.2/yr, in Table 2.

Table 1: Example of Ignition Frequencies of PGSFR

Fire Area	Fire Area Name	Fixed	Transient	Total
F-C101	REACTOR CAVITY	1.37E-03	1.26E-06	1.37.E-03
F-C206	CONTAINMENT ANNULUS AREA	4.75E-04	5.63E-05	5.31.E-04
F-C303	CONTAINMENT ANNULUS AREA	2.98E-04	5.63E-05	3.54.E-04
F-C311	SP SODIUM SURGE TANK RM	0	1.26E-05	1.26.E-05
F-C312	SP EM PUMP RM	0	1.26E-05	1.26.E-05
F-C313	SP VACCUM PUMP RM	5.44E-04	1.26E-05	5.57.E-04
F-A106A	ESSENTIAL CHILLED WATER PUMP RM	1.09E-03	4.44E-05	1.13.E-03
F-A106B	ESSENTIAL CHILLED WATER PUMP RM	1.09E-03	4.44E-05	1.13.E-03
F-A108A	ESSENTIAL CHILLED WATER PUMP RM	5.44E-04	4.44E-05	5.88.E-04
F-A108B	ESSENTIAL CHILLED WATER PUMP RM	5.44E-04	4.44E-05	5.88.E-04

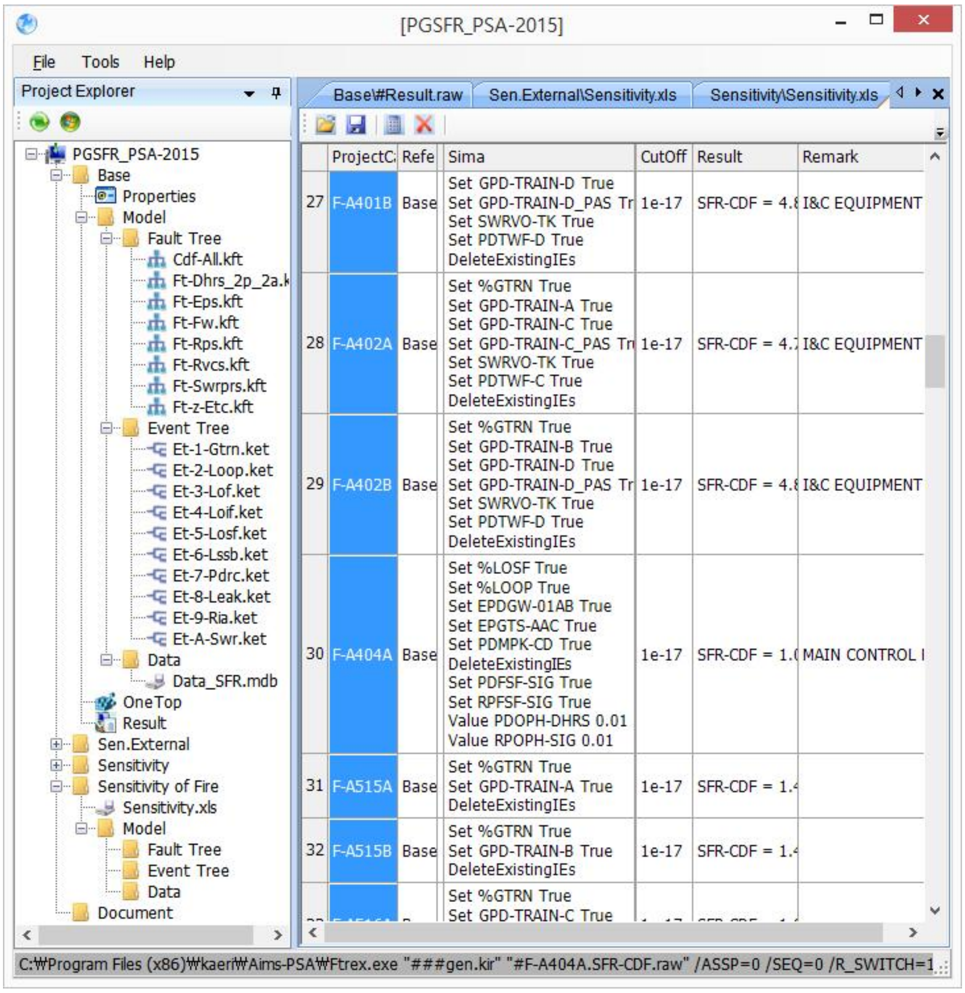
Table 2: Ignition Frequencies of PGSFR Due To Sodium Leak Fire

Fire Area		Piping length (%)	Ignition freq. (/y)
F-C304	HEAD ACCESS AREA	0.228	0.046
F-C303	CONTAINMENT ANNULUS AREA	0.1	0.02
F-A122A	Steam Generator room	0.102	0.02
F-A122B	Steam Generator room	0.102	0.02
F-A316A	PIPE CHASE	0.055	0.011
F-A316B	PIPE CHASE	0.055	0.011
F-A123A	SWRPR SODIUM DUMP TANK RM	0.09	0.018
F-A123B	SWRPR SODIUM DUMP TANK RM	0.09	0.018
F-A518A	AHX RM	0.038	0.008
F-A518B	AHX RM	0.038	0.008
F-A519A	FHX RM	0.051	0.01
F-A519B	FHX RM	0.051	0.01
	SUM	1	0.2

2.3 Fire PSA Modeling of PGSFR

Fire PSA model of PGSFR is based on the internal PSA. The illustrative example is shown in the Fig. 1. In Fig. 1, conditional core damage probability (CCDP) of each fire areas is derived by the AIMS-PSA code. The Core Damage Frequency (CDF) induced by a fire is derived by calculating the CCDP of each fire area. It is also assumed that if there is a fire in a fire area, all equipment and cables are lost in the fire area (whole room burn up model).

Figure 1: An Example Screen of PGSFR PSA Model



2.4 CDF By MCR Fire of PGSFR

<u>Ignition frequency of MCR</u>

Main control room (MCR) of PGSFR was not yet in detail designed. However, in this study, it is assumed that only two electric cabinets are used as MCR since PGSFR is a small reactor; 1) one cabinet is for DHRS (Decay Heat Removal System), 2) another one is for EPS (Electric Power System).

Since the console of PGSFR has only two electric cabinets, we are not using generic MCR ignition frequency. Instead, since there are 187 electric cabinets in PGSFR, if the generic ignition frequency (= 3E-2/yr) is used for the electric cabinets, the fire ignition frequency for the console is;

(2/187)*(3E-2) = 3.21E-4/yr

If we are using the small reactor factor mentioned in section 2.1, the ignition frequency of MCR (Console) is;

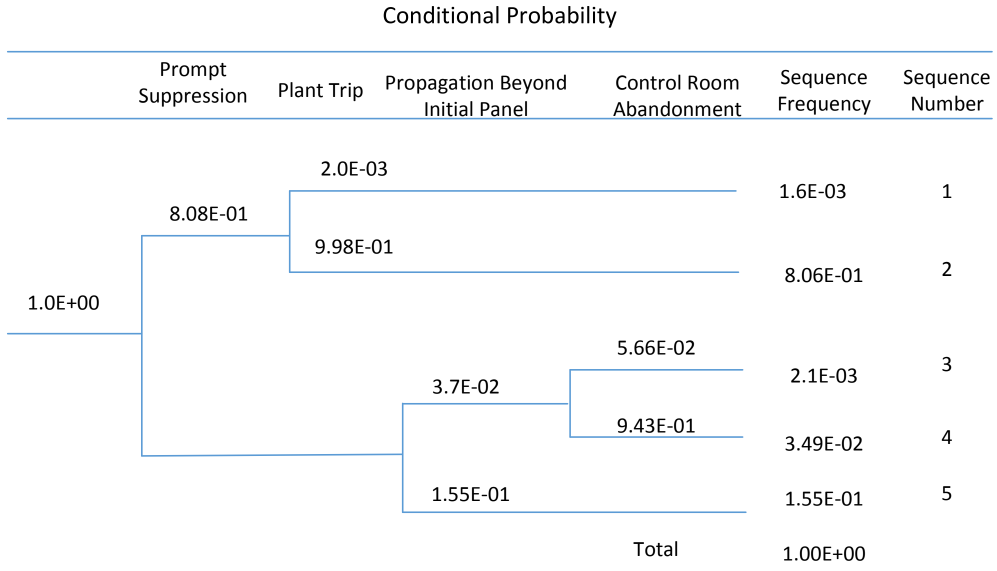
(592/1177)*(3.21E-4/yr) = 1.61E-4/yr

<u>MCR abandonment</u>

For MCR fire modeling, FDS [3] is used and the result of the FDS analysis shows that MCR abandonment occurs after 18.7 min. due to the optical density of the smoke is less than 0.3 m^{-1}.

As a similar method suggested in Ref. [4], an evaluation logic for MCR panel fire was set up as shown in Fig. 2.

Figure 2: Evaluation Logic for MCR Panel Fires



In Fig. 2, since sequence 3 is the only MCR abandonment case;

$CDF_{(abandon)}$ = (Ignition Freq. in Console) * (Prob. of Sequence 3) * (Operator's Failure to Use Remote Shutdown Panel) * (Failure of Manually Open of PDRC Damper) (1)

where, ignition Freq. in Console = 1.61E-4/yr,
probability of "Failure of Manually Open of PDRC Damper" is increased by 10 times than that of internal PSA.

In Eq. (1), even though operators fail to give a reactor control right to the remote shutdown panel when they escape MCR, it is assumed that PGSFR core is safe if PDRC damper could be manually opened.

In Fig. 2, since Sequence 4, 5 are the MCR non-abandonment case;

$CDF_{(No\ abandon)}$ = (Ignition Freq. in Console) * (1/2) * (Prob. of Sequence 5) * [CCDP(DHRS) + CCDP(EPS)] + (Ignition Freq. in Console) *

$$(\text{Prob. of Sequence 4}) * [CCDP(EPS + DHRS)] \quad (2)$$

3. RESULTS

3.1. Core Damage Frequency (CDF)

The 3rd column (ignition frequency) of Table 3 is derived by multiplying the small reactor factor (592/1177) to the result of Table 1. The 4th column of Table 3 is the ignition frequency caused by the sodium piping leak. The 5th column is the CDF portion of each fire area. The head access area (F-C304) is the most important area (CDF portion is 16.55%) since the sodium fire could occur frequently because many sodium piping lines pass through this area.

The other important fire areas are MCR (F-A433B). The CDF portion caused by MCR(Console) fire is 13% which is the sum of Eq.(1) and Eq.(2).

Table 3: CDF portion of each fire area

Fire Area		Ignition Freq.	Sodium Fire Freq.	CDF %
F-C304	HEAD ACCESS AREA	1.26E-05	4.56E-02	16.55%
F-C303	CONTAINMENT ANNULUS AREA	3.54E-04	2.01E-02	7.36%
F-A122A	Steam Generator room	1.15E-05	2.05E-02	5.12%
F-A122B	Steam Generator room	1.15E-05	2.05E-02	5.12%
F-A316A	PIPE CHASE	7.58E-06	1.09E-02	0.27%
F-A316B	PIPE CHASE	7.58E-06	1.09E-02	0.27%
F-A123A	SWRPR SODIUM DUMP TANK RM	7.58E-06	1.79E-02	0.45%
F-A123B	SWRPR SODIUM DUMP TANK RM	7.58E-06	1.79E-02	0.45%
F-A202A	480V CLASS 1E LOAD CENTER & MCC RM	9.50E-04		5.95%
F-A202B	480V CLASS 1E LOAD CENTER & MCC RM	9.50E-04		5.95%
F-A205A	CLASS 1E BATTERY RM	6.45E-04		0.01%
F-A205B	CLASS 1E BATTERY RM	4.85E-05		0.00%
F-A207A	DC & IP EQUIPMENT RM	8.00E-04		0.01%
F-A207B	DC & IP EQUIPMENT RM	8.00E-04		0.01%
F-A209A	4.16kV CLASS 1E SWGR RM	1.99E-03		1.25%
F-A209B	4.16kV CLASS 1E SWGR RM	1.99E-03		1.25%
F-A518A	AHX RM	1.98E-04	7.68E-03	0.12%
F-A518B	AHX RM	4.52E-04	7.68E-03	9.77%
F-A519A	FHX RM	4.45E-04	1.02E-02	9.76%
F-A519B	FHX RM	4.45E-04	1.02E-02	12.88%
F-D201A	DIESEL GENERATOR ROOM	3.33E-03		0.31%
F-D201B	DIESEL GENERATOR ROOM	3.32E-03		0.04%
F-T000	TURBINE BUILDING GENERAL AREA	4.01E-02		0.55%
F-D202	SWITCHGEAR ROOM	2.83E-03		1.36%
F-Y001	MAIN TRANSFORMER	3.00E-03		0.04%
F-Y003	UNIT AUX TRANSFORMER	1.88E-03		0.03%
F-Y004	STANDBY AUX TRANSFORMER	1.88E-03		0.02%
...	....	....		
F-A433B	MCR			13%
				100%

3.2. Sensitivity Analysis

However, we can think the other approach for the sodium fire ignition frequency. That is, we can use the sodium piping leakage rate (3.0E-9/ft/h)[5], to estimate the sodium fire ignition frequency for each compartment. Actually, this method was used for estimating the initiating event frequency of ‘Loss of a PDRC train. Anyway, this approach is 3.4 times more optimistic than the previous history data approach.

As the result of the first sensitivity analysis, if we are using the optimistic ignition frequency of sodium leak, the CDF can be reduced by 51%.

Also, if we do not consider the small reactor factor even though PGSFR is a very small reactor, the CDF can be increased by 27%.

If the probabilities that ‘Operator’s Failure to use Remote Shutdown Panel’ and ‘Failure of Manually Open of PDRC Damper’ in Eq. (1) are increased to double, respectively, the CDF increases by 13%.

4. DISCUSSIONS

Since the PGSFR is not in detailed design phase, many things are simplified as follows;

The ignition frequencies of all of the non-sodium fire sources are scaled down by a ratio between the total number of components in PGSFR to that in the light water commercial NPP. This is oversimplified. The scaling factor should be dependent on the equipment type (i.e., ignition source bins). Especially, for the calculation of the MCR console fire frequency, it could be too optimistic to scale down the ignition frequency of electrical cabinets by the same ratio of as that for the total number of plant components. However, as discussed in the section 3.2, the small reactor factor was not that serious factor (27% impact factor).

The total sodium fire frequency is apportioned to the various fire areas only by the pipe length. Although the size/diameter of the pipe can impact on this frequency apportionment, it is not considered.

It is also not decided whether the type of cables inside the MCR console is fiber optic cables.

Also, it is further checked that a fire might be a way to lead to a reactivity accident.

5. CONCLUSIONS

We have completed the level 1 fire PSA on PGSFR. PGSFR is very safe reactor since the CDF result of level 1 fire PSA is several order lower than those of commercial NPPs. The characteristics of PGSFR are described in this paper; 1) sodium fire ignition, 2) small reactor factor, 3) a console type MCR and MCR abandonment logic. The fire area having the highest CDF portion is where a lot of sodium piping lines are passing through. And the next higher CDF portion fire area is MCR. Also, it is verified through the sensitivity analysis that the result of level 1 fire PSA on PGSFR can be feasible.

Acknowledgements

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea Grant funded by the Korean government Ministry of Science and ICT.

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