

# Development of Risk Assessment Method for Fires Caused by Earthquake (VI)

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**Abstract:** A concept and calculation formula is presented for the conditional occurrence probability of fire in case of earthquake. The median values of precursory phenomenon capacity for important components of nuclear power plants are calculated by the proposed formula and results are listed up. A method to quantify risk due to earthquake-induced fire is presented. The procedure of risk assessment for fires caused by Earthquake is explained with a flow chart. An analysis framework for the earthquake-induced fire PSA, which is now being developed, is explained.

**Keywords:** PSA, Nuclear Power Plant, Fire PSA, Seismic PSA.

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## 1. INTRODUCTION

We have been long pointing out the necessity to assess the risks of fires caused by earthquake in nuclear power plants[1,2]. “The Niigataken Chuetsu-oki earthquake” has occurred on 16th July 2007. The epicenter of earthquake was about 16 km north of the site of the Kashiwazaki-Kariwa nuclear power plant. Just after the earthquake, a fire incident has occurred in the unit 3. It is the first case of earthquake-induced fire at nuclear power plant in the world.

In the present paper, a concept of precursory phenomenon is considered, which leads to fires in case of earthquake. Then, calculation formula are presented for the conditional occurrence probability of fire in case of earthquake. The values of parameters used in this formula are discussed and estimated based on the data obtained in the Niigataken Chuetsu-oki earthquake. Median values of precursory phenomenon capacities are estimated for many important components, based on this calculation formula.

For a given earthquake, there is a possibility of core damage even if no fire incidents happen. This task is to evaluate risks increased by earthquake-induced fire. The risk of fires caused by earthquake must be separated from the total risks produced by the same earthquake. The procedure of risk assessment for fires caused by Earthquake is explained with a flow chart.

The authors are discussing and developing an analysis framework for the earthquake induced fire PSA. It handles different kinds of software and inter-relates input output data, and also relates information concerning plant, components, earthquake, fire events, and so on. Main parts of this analysis framework are explained. This analysis framework will be expected to be applicable to the assessment of nuclear power plants generally.

## 2. OCCURRENCE PROBABILITY OF EARTHQUAKE-INDUCED FIRE

### 2.1. Fire Occurrence Probability

The fire may occur in the following process in case of earthquake. At first, some precursory phenomenon happens to a component by earthquake, with a probability  $P_p$ . Then, fire is set off by catching ignition energy with a probability  $\gamma$ (ignition probability). Then, fire occurrence probability ( $P_f$ ) due to earthquake becomes

$$P_f = P_p \times \gamma \quad (1).$$

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## 2.2. Probability of Precursory Phenomenon for Earthquake-Induced Fire

We introduce the concept of precursory phenomenon capacity of a component, and its distribution is assumed as a log-normal distribution like that of seismic capacity. The probabilities  $P_p$  is derived by the following equation,

$$P_p = \Pr(A_p < M_i) = \int_0^{M_i} f_p(A_p) dA_p = \int_0^{M_i} \frac{1}{\sqrt{2\pi\sigma_p^2}x} \exp\left(-\frac{(\ln x - \ln A_{pm})^2}{2\sigma_p^2}\right) dx \quad (2)$$

where  $A_p$  is precursory phenomenon capacity for earthquake induced fire,  $A_{pm}$  is a median value of  $A_p$ ,  $M_i$  is the magnitude of acceleration act on a component. Logarithmic standard deviation  $\beta_p$ , which expresses uncertainty, has the following relations to  $A_{pm}$  and  $\sigma_p$ .

$$\beta_p = \sqrt{\exp(2\ln A_{pm} + \sigma_p^2)\{\exp(\sigma_p^2) - 1\}} \quad (3)$$

$$\sigma_p^2 = \ln \left\{ \frac{A_{pm} + \sqrt{A_{pm}^2 + 4\beta_p^2}}{2A_{pm}} \right\} \quad (4)$$

Basically,  $A_{pm}$  is evaluated from occurrence mechanism of precursory phenomena, for example, failure of oil tank, fracture of fuel pipe, or damage of electrical wire coating. It can be deduced by analyzing the response of component to an acted load (acceleration by an earthquake). This is the same procedure for the evaluation of seismic capacity.

The probabilities  $P_p$  can be directly estimated from the incidents happened at the Kashiwazaki-Kariwa nuclear power plant in 2007 earthquake. The values of  $P_p$  have been estimated as 0.125 and 0.0204 at the 659 gal of the building floor motion for electrical transformer and oil tank, respectively[3]. The data of seismic capacity for important components of nuclear power plants give us the values of standard deviations  $\beta$ . These values ( $\beta=0.269, 0.26$ ) are used as the standard deviations  $\beta_p$  for electrical transformer and oil tank. Then, it can be calculated the values of  $A_{pm}$  from Eqs. (2)-(4). The values of  $A_{pm}$  for electrical transformer and oil tank are evaluated as 0.887G, 1.08G, respectively.

## 2.3. Ignition Probability

For the calculation of fire occurrence probability ( $P_f$ ), the value of  $\gamma$  must be known. There was no experience of earthquake induced fire in NPPs, except for Kashiwazaki-Kariwa NPP. So the ignition probability ( $\gamma$ ) must be deduced from some fire related data. The following relation between the ignition probability ( $\gamma$ ) and fire occurrence frequency( $f_f$ ) in NPPs is assumed.

$$\gamma = \gamma_m \cdot \{1 - \exp(-\alpha \cdot f_f)\} \quad (5)$$

Above equation is similar to logistic curve, and it satisfies the boundary conditions ( $\gamma=0$  with  $f_f=0$ ) and ( $\gamma=\gamma_m$  with  $f_f=\infty$ ). By engineering judgment,  $\gamma_m=0.5$  is assumed. Electrical transformer has the value of  $6.0 \times 10^{-5}/y$ [4] for fire occurrence frequency. And,  $\gamma=0.2$  approximately for electrical transformer in the Kashiwazaki-Kariwa NPP at 2007 earthquake [3]. With these values, equation (5) becomes as follows,

$$\gamma = 0.5 \cdot \{1 - \exp(-8514 \cdot f_f)\} \quad (6)$$

Fire event data base[5] has no record of oil tank fire, so 0.5 times fire incident is assumed and  $f_f$  is estimated at  $2.86 \times 10^{-5}/y$ . This value is substituted into the equation (6) and  $\gamma=0.108$  is obtained for ignition probability of lubricating oil tank. This value is used in the section 2.4.

## 2.4. Estimation of Median Value of Precursory Phenomenon Capacity ( $A_{Pm}$ )

Median values of seismic capacity ( $A_m$ ) are estimated for many important components [6], and electrical transformer and oil tank have the values of 0.66G, 3.4G with the uncertainties ( $\beta=0.269, 0.26$ ), respectively. Then, ratios of  $A_m$  and  $A_{Pm}$  are 1.34 and 0.32.

In case of no information about the occurrence probability of precursory phenomenon ( $P_p$ ), the  $A_{Pm}$  for specific component must be estimated directly. The value of the ratio of  $A_{Pm}$  and  $A_m$  for electrical transformer is used as  $A_{Pm} = 1.34A_m$  for other components. The uncertainty of precursory phenomenon capacity is calculated as the square root of the sum of squares of  $\beta$  (for seismic capacity) and  $\beta_\gamma$  (for general fire occurrence frequency).

Table 1 shows the median value of precursory phenomenon capacity, which are calculated by the procedure above mentioned.

**Table 1: Median values of precursory phenomenon capacity for important components**

Component	Median value of seismic capacity: $A_m$	Fire occurrence frequency: $f_f$	Ignition probability: $\gamma$	Median value of $A_p : A_{Pm}$	Uncertainty: $\beta_p$
Transformers	0.66G	$1.45 \times 10^{-3}/y$	0.2	<b>1.02G</b>	<b>0.27</b>
Lubricant tanks	3.4G	$4.1 \times 10^{-6}/y$	0.00072	<b>3.82G</b>	<b>0.26</b>
Main control board	6.5G	$4.1 \times 10^{-4}/y$	0.49	<b>8.7G</b>	<b>0.21</b>
Cable duct and inside cables	7.0G	$5.0 \times 10^{-5}/y$	0.17	<b>9.38G</b>	<b>0.32</b>
Pipes connecting to a tank	3.4G	$2.0 \times 10^{-3}/y$	0.5	<b>4.6G</b>	<b>0.115</b>
Hydrogen pipes	3.4G	$4.2 \times 10^{-3}/y$	0.5	<b>4.6G</b>	<b>0.115</b>
Diesel generators	2.2G	$2.9 \times 10^{-4}/y$	0.46	<b>2.9G</b>	<b>0.12</b>
Air conditioner	2.6G	$8.1 \times 10^{-6}/y$	0.033	<b>3.5G</b>	<b>0.046</b>
Turbines	2.7G	$5.5 \times 10^{-4}/y$	0.5	<b>3.6G</b>	<b>0.49</b>

## 3. RISKS INCREASED BY EARTHQUAKE-INDUCED FIRE

Core damage frequency of earthquake-induced fire is calculated by the following equation.

$$CDF_{EF} = \sum_{i=1}^{n2} F(E_i) \left\{ \sum_{j=1}^{j_m} P\left(\frac{IG_j}{E_i}\right) \left\{ \sum_{k=1}^{n4} P\left(\frac{IE_k}{E_i, IG_j}\right) \left\{ \sum_{l=1}^{S_n} P\left(\frac{S_{f,l}}{E_i, IG_j, IE_k}\right) \right\} \right\} \right\} \quad (7),$$

where,  $F(E_i)$  is occurrence frequency of  $i$ -th level of earthquake,  $P(IG_j/E_i)$  is the occurrence probability of ignition group  $j$  ( $IG_j$ ), when earthquake  $E_i$  happens. Here all possible combinations of ignition locations should be considered,

$$j_m = \sum_{k=1}^{n1'} n1' C_k \quad (8),$$

$n1'$  is the total number of possible ignition locations. In the evaluation of equation (7), the value  $P(IG_m/E_i)$  must be subtracted from  $P(IG_s/E_i)$ , if  $IG_s$  is an ignition group with single location and  $IG_m$  is with multiple location, and single location ( $IG_s$ ) is included in the multiple locations ( $IG_m$ ),

$P(IE_k/E_i, IG_j)$  is the occurrence probability of initiating event  $IE_k$ , under the condition of earthquake level  $E_i$  and ignition location  $IG_j$ . Initiating events are categorized into 10 groups. These are Interface

system LOCA, Large LOCA, Medium LOCA, Small LOCA, Steam generator tube rupture, Secondary system failure, Loss of CCWS, Loss of offsite power, Automatic scram without PCS, and Automatic scram with PCS.

$P(S_{f,l}/E_i, IG_j, IE_k)$  is the occurrence probability of sequence  $S_{f,l}$ , in which core damage occurs, with the condition of damaged components produced by fire, earthquake, and random failure.

For a given earthquake, there is a possibility of core damage even if no fire incidents happen. This task is to evaluate risks increased by earthquake-induced fire. The risk of fires caused by earthquake must be separated from the total risks produced by the same earthquake.

$$CDF_{Ew/oF} = \sum_{i=1}^{n2} F(E_i) \left\{ \left( \sum_{j=1}^{j_m} P(IG_j/E_i) \right) \cdot \left( \sum_{k=1}^{n4} P(IE_k/E_i) \right) \left\{ \sum_{l=1}^{S_n} P(S_{e,l}/E_i, IE_k) \right\} \right\} \quad (9)$$

Equation (9) gives the contribution to  $CDF_{EF}$  from core damage frequency produced by earthquake without any fire incidents. Summation of  $P(IG_j/E_i)$  is the total probability of events in which some fire incident occur.  $P(IE_k/E_i)$  is the occurrence probability of initiating event  $IE_k$ , under the condition of earthquake level  $E_i$ .  $P(S_{e,l}/E_i, IE_k)$  is the occurrence probability of sequence  $S_{e,l}$ , in which core damage occurs with the condition of damaged components produced by earthquake and random failure.

Core damage frequency by fires occurred at earthquake is expressed in the following equation.

$$CDF_{EF} - CDF_{Ew/oF} \quad (10)$$

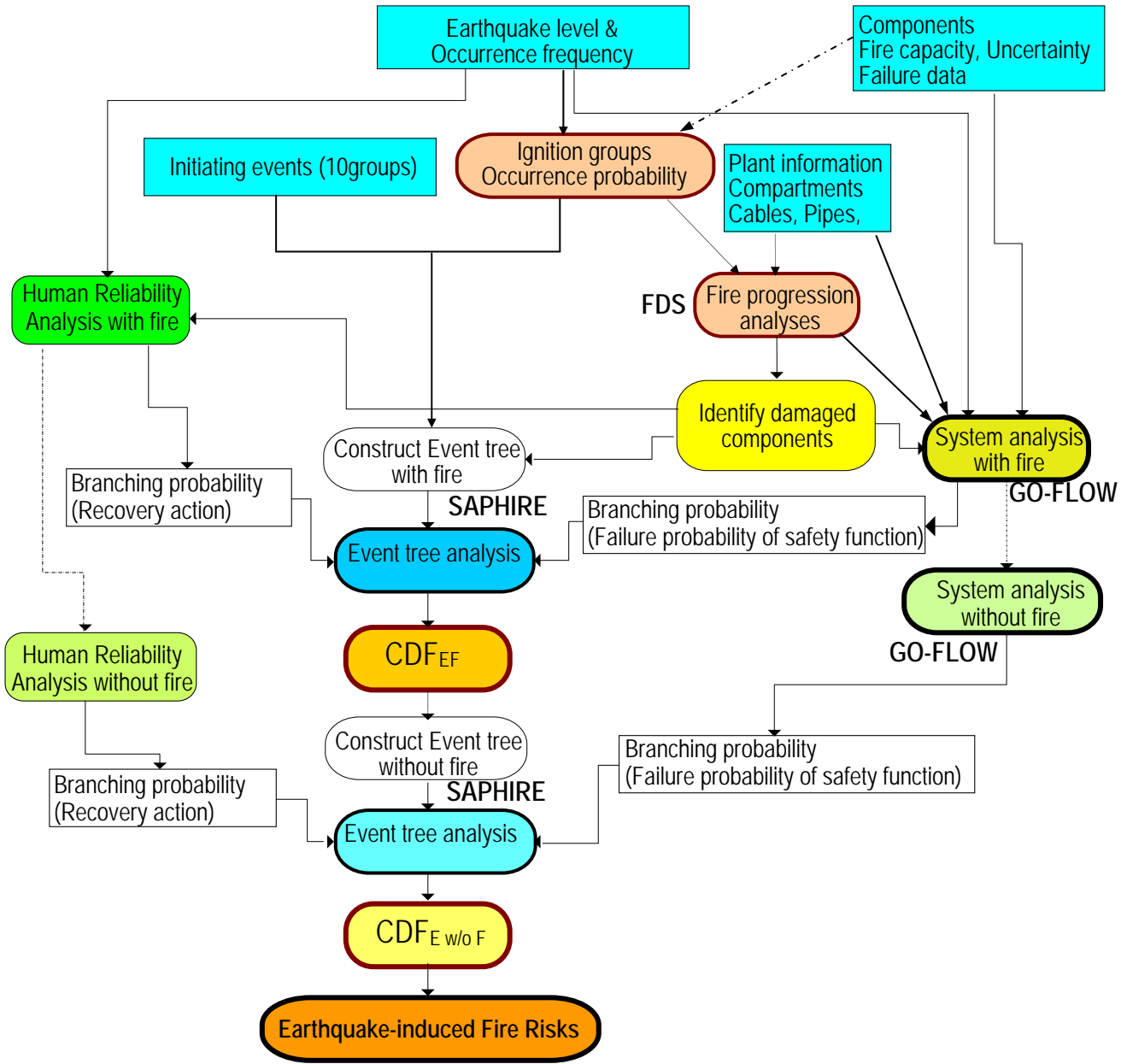
#### 4. PROCEDURE OF RISK ASSESSMENT FOR EARTHQUAKE-INDEUCED FIRES

The equations (7)-(10) suggest us the calculation procedure is more or less tedious. Many different acceleration levels have to be considered, and possible ignition sources and all the possible combinations of these sources for each acceleration level have to be identified.

It is necessary to estimate the occurrence probabilities of fire ignition for all the combinations of ignition sources. Also it is necessary to make fire progression analysis and to determine the damaged components by fire. Fire progression analyses are done by the simulation code "Fire Dynamic Simulation (FDS)[7]" provided by NIST, USA.

For a specific acceleration level and combination of ignition sources, accident sequences (ET: event trees) which begin with a specific initiating event, are developed. Then, these ETs with the boundary condition of damaged components by fires, earthquake itself and random failures, are quantified. Summing up all the core damage frequencies (CDFs) over all the combinations of ignition sources, acceleration levels and initiating events, then  $CDF_{EF}$  is evaluated.

Almost the same procedure has to be done for the conditions without fire ignition, and  $CDF_{Ew/oF}$  is evaluated. Finally, subtract the second contribution( $CDF_{Ew/oF}$ ) from the first one( $CDF_{EF}$ ). These step by step procedures are expressed in figure 1 in the next page.



**Figure 1. Procedures of risk assessment for earthquake-induced fire.**

## 5. FRAMEWORK OF EARTHQUAKE-INDUCED FIRE PSA

A framework to assess the earthquake-induced fire risks is being discussed and developed currently. For each step, different kind of software is used, for example FDS(Fire Dynamic Simulation) for fire progression analysis, SAPHIRE[8] for event tree & fault tree analysis, GO-FLOW[9] for system reliability analysis. Input output data of these software are mutually related and also related to data concerning plant, components, earthquake, fire events, and so on. A system to manage complex information, data and software, is necessary to perform well organized analysis, especially for earthquake-induced fire PSA.

Main menu screen is shown in figure 2. The analysis is started by this screen and the items in this screen correspond to the steps shown in figure 1.

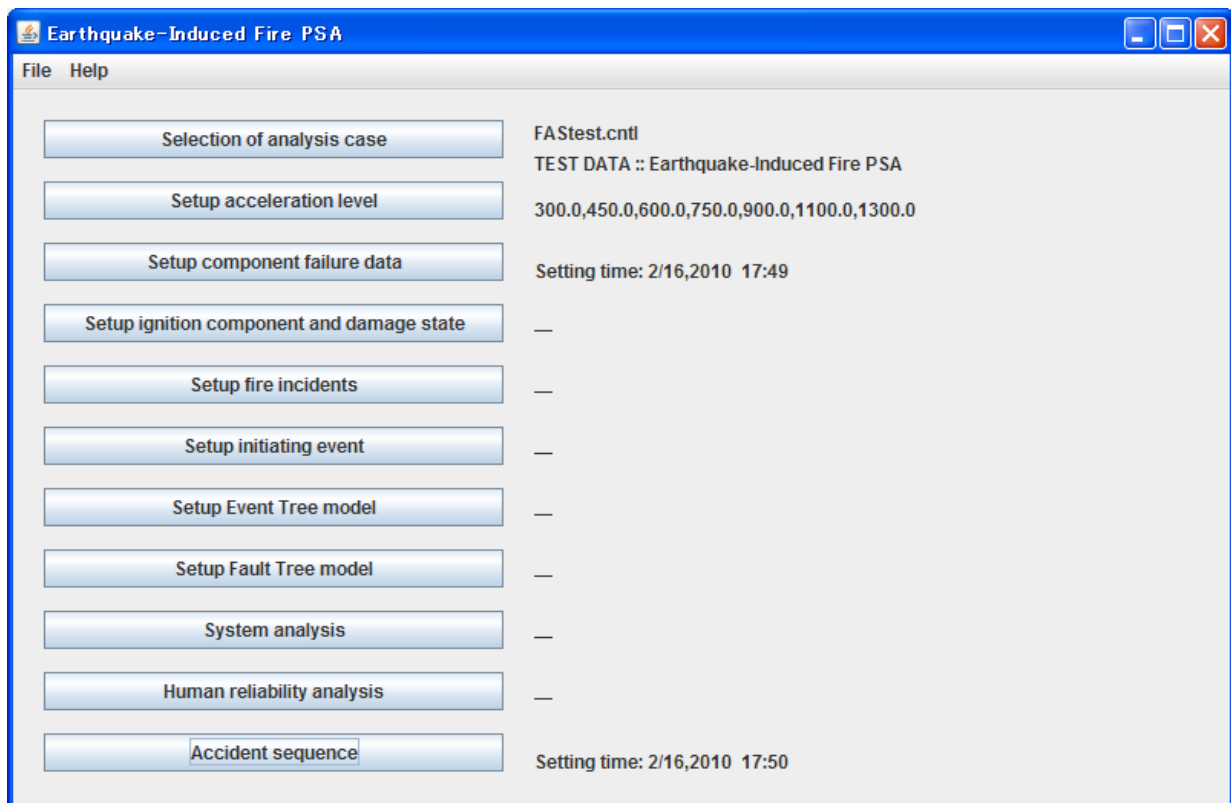


Figure 2. Main menu screen.

For each item in main menu screen, a sub window is prepared, in which necessary data, analysis conditions are given. In the followings, some examples of sub windows are shown and explanations are given. Note that numerical values on the screens are hypothetical.

At the "acceleration level", set seven different ground acceleration levels and give corresponding occurrence frequencies. In the "component failure data" window, give random failure rate, fire occurrence frequency, seismic capacity and its standard deviation, precursory phenomenon capacity and its standard deviation.

In the "ignition component and damage state" window, give a list of components which will ignite at earthquake, and also give ignition component groups which will ignite at the same time. Fire occurrence probabilities at each ground acceleration level are automatically calculated based on the equation (1), and values are put in a table in this window. The damage state by a fire is also given, which is deduced from analysis results of FDS.

Figure 3 shows "initiating event" window. Initiating events are defined and their occurrence frequencies are given for seven ground acceleration levels.

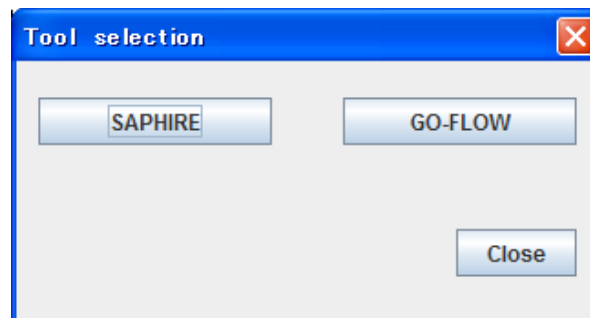
Selection	Initiating Event	code	300.0Gal	450.0Gal	600.0Gal	750.0Gal	900.0Gal	1100.0Gal	1300.0Gal
<input type="checkbox"/>	ISLOCA	ISLOCA	1.00E-03	1.10E-03	1.20E-03	1.30E-03	7.50E-05	1.40E-03	1.40E-03
<input checked="" type="checkbox"/>	LLOCA	LLOCA	1.00E-04	1.10E-04	1.20E-04	1.30E-04	1.40E-04	1.40E-04	1.40E-04
<input type="checkbox"/>	MLOCA	MLOCA	1.00E-05	1.10E-05	1.20E-05	1.30E-05	1.40E-05	1.40E-05	1.40E-05
<input type="checkbox"/>	SLOCA	SLOCA	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03	1.00E-03
<input type="checkbox"/>	SGTR	B2	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
<input type="checkbox"/>	Loss of CCWS	CCWSMF	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
<input type="checkbox"/>	LOSP	LOSP	1.00E-03	1.00E-03	1.00E-03	1.00E-03	8.40E-04	1.00E-03	1.00E-03
<input type="checkbox"/>	ATWS(PCS)	ATWSWITHPCS	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04

Enter Frequency

OK Cancel

**Figure 3. Initiating event window.**

In the "System analysis" window, "Tool selection" dialog box appears, and the click of "SAPHIRE" button or "GO-FLOW" button directly leads the start of the codes.



**Figure 4. Tool selection dialog box.**

The "Accident sequence" window is shown in figure 5. As seen in this figure, a list of accident sequences has been expressed for the condition that "Initiating event" is ISLOCA, "Ground acceleration level" is 900gal and "fire ignition group" is ignition group #1, in this case. There are two tables of accident sequences for "With fire" and "Without fire" conditions. By clicking "Read sequence data", a data file of accident sequences is read, which are produced by SAPHIRE or equivalent analysis code.

If we click the "Calculate the contribution of earthquake-induced fire" button in the "Accident sequence" window (at the lower left in figure 5), calculation begins and "Analysis result for a fire initiating group" window appears as shown in figure 6. The core damage frequency (CDF) increased by earthquake-induced fire, is obtained based on the equation (10) for a specific fire ignition group ("ignition group #1" in this case).

This analysis result is shown in the left end frame of the window (in figure 6). After carefully confirming the result, the values can be added up to previously calculated analysis results. By clicking "Update" button, this result is reflected to all the values in the right side frames of the window.

By repeating this procedure, CDF by earthquake-induced fire is obtained in the lower right text field, which is for a specific fire ignition group, but for all the possible initiating events and acceleration levels.

**Accident sequence**

With Fire  File Name WF\_900.SEQ

sequence name(No.)	Frequency	Status
1	0.00E000	OK
2	0.00E000	OK
3	0.00E000	CD
4	0.00E000	CD
5	1.34E-10	CD
6	1.37E-11	CD
7	1.52E-10	CD
8	1.54E-11	ATWS
9	1.55E-11	CD
10	4.80E-12	CD

Without Fire  File Name WOF\_900.SEQ

sequence name(No.)	Frequency	Status
1	1.30E-10	OK
2	1.27E-11	OK
3	2.60E-11	CD
4	1.45E-12	CD
5	6.71E-12	CD
6	1.37E-11	CD
7	7.61E-12	CD
8	1.54E-11	ATWS
9	1.55E-11	CD
10	4.80E-12	CD

Initiating Event: ISLOCA, LLOCA, MLOCA, SLOCA, SGTR, Loss of CCWS, LOSP, ATWS(PCS)

acceleration: 300.0, 450.0, 600.0, 750.0, 900.0, 1100.0, 1300.0

Selection of Fire ignition group: Ignition Group #1

Figure 5. Accident sequence window.

**Analysis Results**

Fire ignition group: Ignition Group #1

initiating event: ISLOCA

acceleraton level: 900.0

CDF<sub>E-F</sub>: 3.70E-10

CDF<sub>E~F</sub>: 1.70E-10

Contributin from fire: 2.00E-10

Initiating Events: LLOCA, SLOCA

Acceleration: 900.0

CDF<sub>E-F</sub>: 5.00E-10

CDF<sub>E~F</sub>: 2.40E-10

Contributin from fire: 3.10E-10

Initiating event: ISLOCA

Acceleraton levels: 600, 900

CDF<sub>E-F</sub>: 2.50E-9

CDF<sub>E~F</sub>: 1.40E-9

Contributin from fire: 1.10E-9

All Initiating Events

All acceleraton levels

CDF<sub>E-F</sub>: 8.80E-9

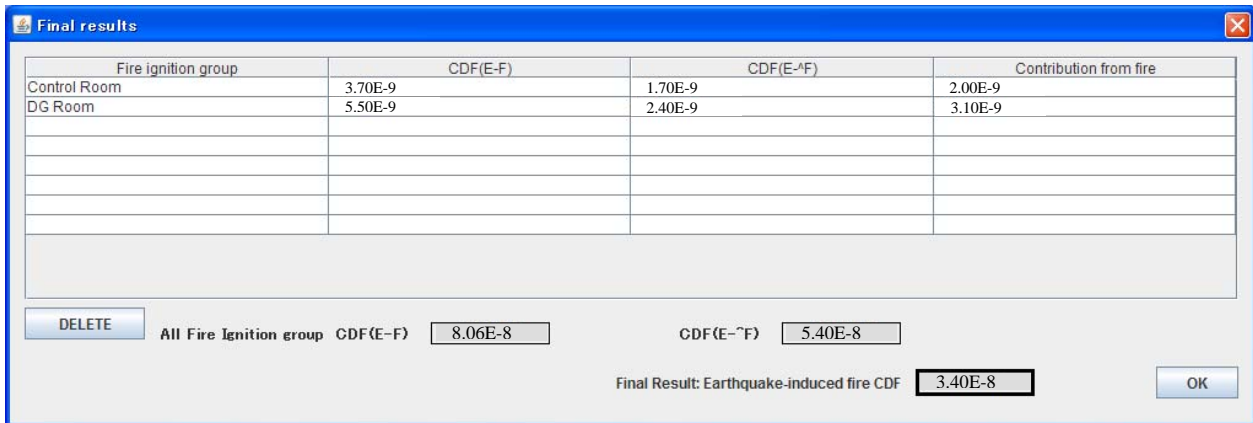
CDF<sub>E~F</sub>: 5.40E-9

Contributin from fire: 3.40E-9

Figure 6. Analysis results for a fire ignition group window.



By clicking “List” button in the bottom of the window in figure 6, "Final result" window appears as shown in figure 7. The table shows a list of fire ignition groups and the corresponding CDFs, which are already evaluated. The summation of CDFs is written in the lower right text field. This value becomes total earthquake-induced fire CDF of a specific plant after the completion of evaluations for all the possible fire ignition groups.



**Figure 7. Final results window.**

In this framework of "earthquake-induced fire PSA", not all the procedure is automatically done, many procedures are manually performed by analysts. For example, construction of event tree, assignment of the occurrence frequencies for initiating events, judgment of core damage status for accident sequence, construction of FDS analysis model or GO-FLOW model, judgment of damaged components by fire, and so on. But, this framework clearly shows and manages the relations between analysis steps, data flow and analysis conditions. This is a very useful tool for the earthquake-induced fire PSA. It will be expected to be applicable to the assessment of nuclear power plants.

## 6. CONCLUSION

A concept of precursory phenomenon capacity is proposed and a formula is presented for the conditional occurrence probability of fire in case of earthquake. A fire incident on the Kashiwazaki-Kariwa NPP is used for determining parameters appeared in the formula.

A relation between the ignition probability ( $\gamma$ ) and fire occurrence frequency ( $f_f$ ) in NPPs is also proposed, and it is used for the assessment of fire occurrence probabilities and Median values of precursory phenomenon capacity ( $A_{Pm}$ ).

Median values of precursory phenomenon capacity ( $A_{Pm}$ ) for important components are calculated by the proposed formula and results are listed up.

A method to calculate increased risks by earthquake-induced fire is presented. The procedure of risk assessment for fires caused by Earthquake is explained with a flow chart. Finally, framework of the earthquake-induced fire PSA, which is now under development, is explained by main menu screen and sub windows.

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