

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

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Abstract: The fire incident on the Kashiwazaki-Kariwa NPP is briefly described. A concept of fire capacity and calculation formula is presented for the conditional occurrence probability of fire in case of earthquake. The median values of fire capacity 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. Finally, the procedure of risk assessment for fires caused by Earthquake is explained with a flow chart.

Keywords: PSA, Nuclear Facility, Fire PSA, Earthquake PSA.

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, first, this fire incident is briefly described with some statistical data. Next, a calculation form is presented for the conditional occurrence probability of fire in case of earthquake to the important components used in nuclear power plants. The values of parameters used in this form are discussed and estimated based on the data obtained in this earthquake. Third, a formula is given for the calculation of increased risks by earthquake-induced fire.

Finally, the procedure of risk assessment for fires caused by Earthquake is briefly described. The authors are now developing an analysis framework for the earthquake induced fire PSA, and it will be applied to nuclear power plants in Japan.

2. FIRE INCIDENT AT THE KASHIWAZAKI-KARIWA NPP

The Unit 3 in-house electrical transformer fire occurred as one of the consequences of the earthquake. The fire was initiated by sparks from a short circuit caused by large ground displacements between the connecting structure and the transformer foundation. The sparks caused the ignition of oil leaked from the broken porcelain, which was also caused by the earthquake.

There are five oil leakages from transformers and switching station on the site, as well as the fire in the in-house electrical transformer of Unit 3. But the only one fire ignition occurred among the five oil leakage. Total of 40 transformers and switching stations exist on this site.

Vertical and horizontal motions were recorded at various places on the plant site. The recorded maximum acceleration values(gal) are as follows for units 1 to 7 at lowest floor of the reactor building.

852(unit 1), 734(unit 2), 582(unit 3), 672(unit 4), 560(unit 5), 644(unit 6), 569(unit 7)

These values are calculated as the square root of the sum of squares of two horizontal and one vertical recorded motions. The mean of these 7 values is 659 gal. This value is used as the representative value of acceleration at lowest floor of the reactor building.

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3. FIRE OCCURRENCE PROBABILITY DUE TO EARTHQUAKE

3.1. Electrical Transformer

Fire occurrence probabilities(P_f) due to earthquake have to be evaluated for important components. The fire may occur in the following process. 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 γ (ignition probability).

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

For the case of the Unit 3 in-house electrical transformer fire, P_p is estimated as 0.125 at the 659 gal ground motion, because the five oil leakages were observed among 40 transformers etc. The ignition probability γ is estimated at 0.2, because one ignition was observed for 5 oil leakages. Then the fire occurrence probability (P_f) of electrical transformer is estimated at 0.025 at the 659 gal.

3.2. Oil Tank

Oil leakage was observed in the lubricating oil tank room for turbine driven reactor feedwater pump. Fortunately, fire ignition did not occur. There are 49 similar lubricating oil tanks on this site. Therefore, P_p is estimated at 0.0204(=1/49), and γ is estimated at 0.00072, based on the discussion in section 3.4. Then the fire occurrence probability (P_f) of lubricating oil tank is estimated at 1.48×10^{-5} .

The median value of seismic capacity of oil tank is evaluated as 3.4G with uncertainty β equals 0.26. With the assumption of log-normal distribution of the capacity, the acceleration of 2.91G(=2850gal) is obtained for the failure probability of 0.0204. Therefore, if the precursory phenomenon of oil tank is failure, oil tanks might be actually suffered by 2.91G acceleration. The fire occurrence probability (P_f) of lubricating oil tank is 1.48×10^{-5} at the 2850 gal.

3.3. Median Value of Fire Capacity of Components

We introduce the concept of fire capacity of component, and its distribution is assumed as a log-normal distribution like that of seismic capacity. Fire occurrence probabilities(P_f) is derived by the following equation,

$$P_f = \Pr(A_f < M_i) = \gamma_m \int_0^{M_i} f_f(A_f) dA_f = \gamma_m \int_0^{M_i} \frac{1}{\sqrt{2\pi\sigma_f^2} x} \exp\left(-\frac{(\ln x - \ln A_{fm})^2}{2\sigma_f^2}\right) dx \quad (2)$$

where A_f is fire capacity, A_{fm} is a median value of fire capacity, M_i is the magnitude of acceleration act on a component. Logarithmic standard deviation β , which expresses uncertainty, has the following relations to A_{fm} and σ_f .

$$\beta_f = \sqrt{\exp(2 \ln A_{fm} + \sigma_f^2) \{ \exp(\sigma_f^2) - 1 \}} \quad (3)$$

$$\sigma_f^2 = \ln \left\{ \frac{A_{fm} + \sqrt{A_{fm}^2 + 4\beta_f^2}}{2A_{fm}} \right\} \quad (4)$$

The γ_m is the maximum ignition probability. If very large acceleration is applied to a component, the failure probability becomes nearly 1.0, but the ignition probability may not be 1.0. There is some upper limit γ_m . The equation (2) does not contain P_p and γ . Fire occurrence probabilities(P_f) is directly determined by fire capacity.

3.4. Ignition Probability

If we use the equation (1) for calculation of fire occurrence probability (P_f), the value of γ must be known. There was no experience of earthquake induced fire in NPPs, except Kashiwazaki-Kariwa NPP. So the ignition probability (γ) must be deduced from some fire related data. The following relation between the ignition probability (γ) 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 our engineering judgment, put $\gamma_m=0.5$. Electrical transformer has the value of $1.45 \times 10^{-3}/y$ [3] for fire occurrence frequency. And, there is a fact $\gamma=0.2$ for electrical transformer. With these values, equation (5) becomes as follows,

$$\gamma = 0.5 \cdot \{1 - \exp(-353 \cdot f_f)\} \quad (6)$$

Fire event data base[3] has no record of oil tank fire, so 0.5 time fire incident is assumed and f_f is estimated at $4.1 \times 10^{-6}/y$. This value is substituted into the equation (6) and $\gamma=0.00072$ is obtained for ignition probability of lubricating oil tank. This value is used in the section 3.2.

3.5. Estimation of Median Value of Fire Capacity

Median values of seismic capacity(A_m) are estimated for many important components[4], and electrical transformer, oil tank have the values of 0.66G, 3.4G with the uncertainties ($\beta=0.269, 0.26$), respectively. Then, ratios of seismic and fire capacities are 1.54 and 1.12.

In case of no information about the occurrence probability of precursory phenomenon(P_p), we have to directly estimate the median value of fire capacity for specific component. Mean value of the ratio of seismic and fire capacity (1.33) could be used as $A_{fm} = 1.33A_m$. The uncertainty of fire capacity is calculated as the square root of the sum of squares of β (for seismic capacity) and β_f (for fire occurrence frequency). The ignition probability (γ) depends on component, so the modification is also made for the calculation of the median value of fire capacity for specific component.

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

Table 1: Median values of fire capacity for various components

Component	Median value of seismic capacity: A_m	Fire occurrence frequency: f_f	Ignition probability: γ	Median value of fire capacity: A_{fm}	Uncertainty: β
Transformers	0.66G	$1.45 \times 10^{-3}/y$	0.2	1.02G	0.27
Lubricating oil tanks	3.4G	$4.1 \times 10^{-6}/y$	0.00072	3.82G	0.26
Large oil tanks	3.4G	$6.7 \times 10^{-6}/y$	0.023	4.72G	0.26
Main control board	6.5G	$1.2 \times 10^{-3}/y$	0.173	8.56G	0.23
Cable duct and inside cables	7.0G	$5.2 \times 10^{-5}/y$	0.0091	9.67G	0.32
Pipes connecting to a tank	3.4G	$2.0 \times 10^{-3}/y$	0.25	4.44G	0.115
Hydrogen pipes	3.4G	$4.2 \times 10^{-3}/y$	0.39	4.39G	0.115
Diesel generators	2.2G	$4.0 \times 10^{-3}/y$	0.33	2.79G	0.12
Turbines	2.7G	$6.0 \times 10^{-3}/y$	0.44	3.54G	0.045

4. RISKS INCREASED BY EARTHQUAKE INDUCED FIRE

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

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

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. We have to consider all the possible combinations of ignition locations,

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

$n1'$ 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(s) is included in the multiple locations(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 7 groups. The 7th initiating event is defined as "automatic scram with PCS unavailable", being induced by high acceleration signal. $P(S_{f,l}/E_i, IG_j, IE_k)$ 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 there happens no fire incidents. Our 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.

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

Equation (9) gives the core damage frequency produced by earthquake vibration without any fire incident. Summation of $P(IG_j/E_i)$ is the total probability of 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.

Increase of core damage frequency by fires occurred at earthquake incident is expressed in the following equation.

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

5. A FRAMEWORK TO ASSESS EARTHQUAKE-INDUCED FIRE RISKS

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

For all the combinations of ignition sources, we have to estimate the occurrence probabilities, 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)[5]" provided by NIST, USA.

For a specific acceleration level and combination of ignition sources, develop an accident sequence (ET: event trees). Then, quantify this ET with the boundary condition of damaged components by fires, earthquake itself and random failures. Sum up all the CDF over all the combinations of ignition sources.

Almost the same procedure has to be done for the conditions without fire ignition. Finally, subtract the second contribution from the first one. These procedures are expressed in figure 1.

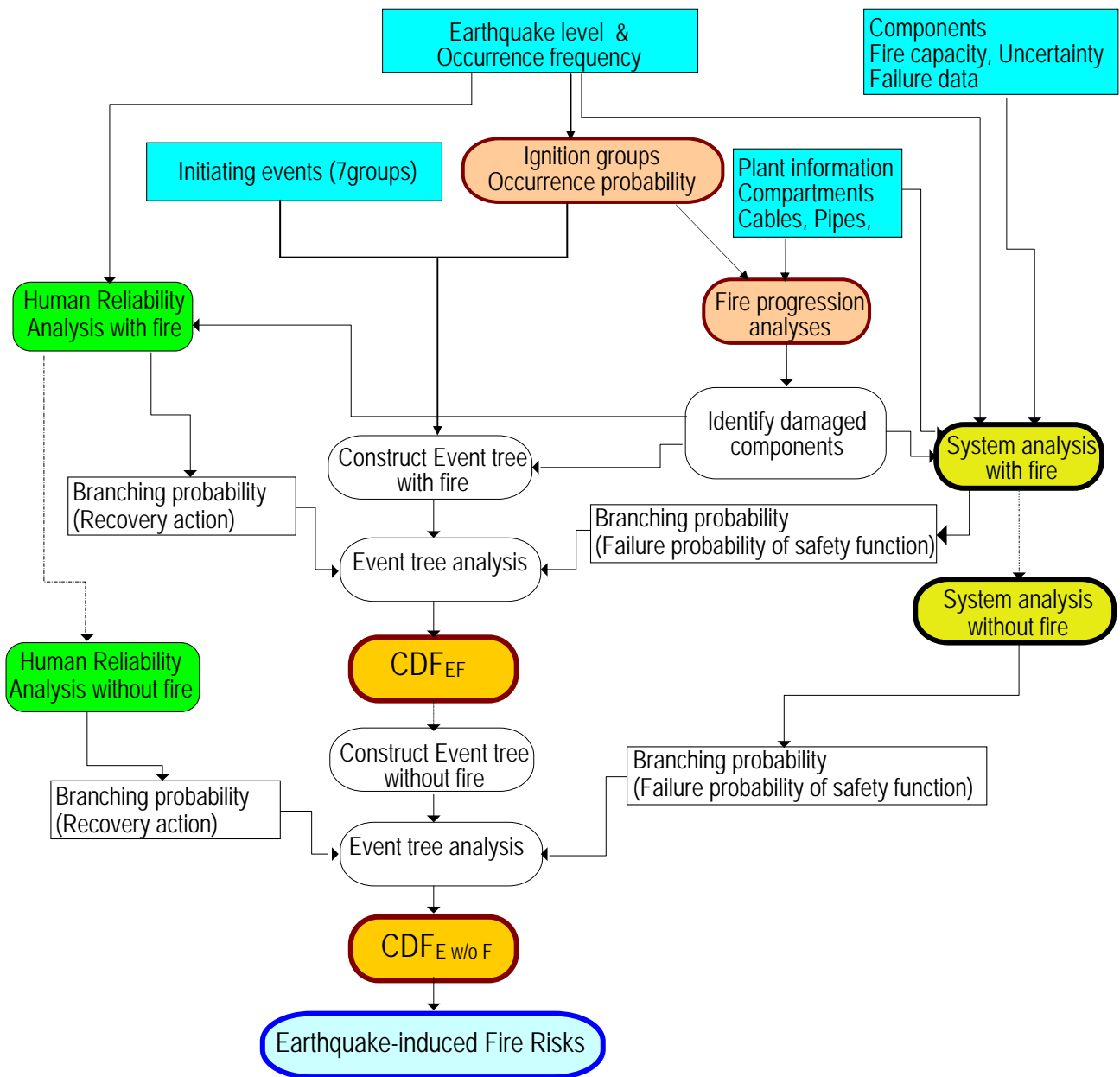


Figure 1. Procedures to assess earthquake-induced fire risks.

The authors are now developing a framework to assess the earthquake-induced fire risks. For each step, different kind of software is used, for example FDS(Fire Dynamic Simulation) for fire progression analysis, SAHIRE[6] for event tree & fault tree analysis, GO-FLOW[7] 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 these complex data and software is necessary to obtain a good quality results with short analysis time. This analysis framework will be applied to nuclear power plants in Japan.

6. CONCLUSION

A concept of fire 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 (γ) 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 fire capacity(A_{fm}).

Median values of fire capacity(A_{fm}) 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. Finally, the procedure of risk assessment for fires caused by Earthquake is explained with a flow chart.

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