Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Study on the Loss of Off-site Power Frequency under Forest Fire

Joonseok Lim, Seungsu Han, Hyungdae Kim, Gyunyoung Heo*
Department of Nuclear Engineering, Kyung Hee Univ., Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea
**Corresponding author: gheo@khu.ac.kr*

***Keywords :** forest fire, hazard analysis, fragility analysis, reaction intensity, loss of off-site power

1. Introduction

Forest fires are natural or human-caused disasters that have environmental and economic impacts such as biodiversity loss, agricultural damage, and property damage. Moreover, forest fires are a global phenomenon, affecting numerous countries including Canada, Siberia and Indonesia [1]. According to the Korea Meteorological Administration, the amount of precipitation has increased over the past 109 years, but the number of days with precipitation has been reported to have decreased. This means that the land becomes dry as more days do not rain continuously, resulting in an increase in the probability of forest fires.

According to the Korea Forest Service, as of the end of 2020, Korea's forest area occupies 6,290,000 ha, or 62.6% of the total land area. In addition, forests are located close to nuclear power plants (NPPs) and off-site transmission lines. In fact, a total of three events of NPP due to forest fires have been reported in Korea, and are shown in Table I. The common points of the three failures are 'Occurrence at the NPP in the Hanul site' and 'Loss of off-site power (LOOP) due to shutting down of off-site transmission lines.' In a previous study, a hazard analysis methodology for forest fires as an external event was presented [2]. Therefore, in this paper, hazard and fragility analysis which is similar to an external event probabilistic safety assessment (PSA) was conducted to estimate the contribution on the LOOP frequency due to forest fires at the NPPs in the Hanul site.

Table I: Records of NPP events caused by forest fire in Korea

Unit	Date	Event Title	Cause
Hanul 6	2022. 03.04. 14:21	Automatic start of emergency diesel generator by low voltage of Hanul unit 6 safety bus (A)	External impact
Hanul 2	2000. 04.11. 11:28	Shutdown of transmission lines due to forest fire at Hanul Unit 2, turbine shutdown due to continuous turbine speed reduction, and reactor shutdown	External impact
Hanul 1	2000. 04.07. 12:40	Shutdown of transmission lines due to forest fire at Hanul Unit 1 and reactor shutdown due to high rate of increase in neutron flux of excore detector	External impact

2. Hazard Analysis Method and Results

2.1 Hazard Indicator of Forest fire

The available output of the hazard analysis is the hazard curve. In this curve, the intensity of disasters is shown on the horizontal axis, and the frequency according to the intensity is shown on the vertical axis.

In the statistical data provided by the Korea Forest Service, information on forest fires includes the fire size, the amount of damage, and the time taken to extinguish the fire. In spite of this information, unfortunately, it is not possible to calculate the direct impact of forest fires on site or off-site transmission lines. In other words, this information cannot be physically interpreted. Therefore, in practice, statistical data is unavailable to be used as an intensity for forest fires.

In order to be connected with fragility analysis, the indicators related to heat transfer are needed. Forest fire intensity typically expressed as reaction intensity. Reaction intensity is defined as the heat emitted per unit area and the formula is as follows.

$$I_R = -\frac{dw}{dt}h \qquad (1)$$

where: dw/dt is mass loss rate per unit area in the fire front $(kg/m^2 \cdot s)$, h is heat content of fuel (kJ/kg). The reaction intensity is a function of such fuel parameters as the particle size, bulk density, moisture, and chemical composition [3].

2.2 Forest Fire Simulation

More than 20 forest fire simulators have been developed to date worldwide. Among them, FARSITE is considered the most accurate accredited by many government agencies and researchers [4]. FARSITE is a simulator developed by the Missoula fire sciences laboratory of the United States Department of Agriculture (USDA). This laboratory developed FlamMap, a simulator that includes three simulation mode ('FlamMap Runs', 'FARSITE Runs', 'SpatialFOFEM'). Wind conditions are kept constant in FlamMap Runs. Therefore, in this study, FARSITE Runs is used to apply wind information differently by time.

Elevation, slope, aspect, etc. are determined through topography and forest floor data. Since these are time-independent variables (season), they are invariant when the simulation area is specified. However, since wind direction, temperature and so on are variables that vary according to time (season), they must be entered differently according to the date (weather) on which the simulation is to be performed.

Buk-myeon, which encompasses the Hanul site, and its surroundings, Jukbyeon-myeon and Uljin-eup, were set as simulation targets. After modeling the topography of the Hanul site in FlamMap, the simulation was performed by randomly combining the weather and ignition point of the forest fire. Using off-site transmission line GIS data created in a previous study, the highest reaction intensity at the point where the transmission line and the forest fire were in contact was evaluated as the hazard of the forest fire [2]. The simulation was performed 100 times, and the results are shown in Figure 1.

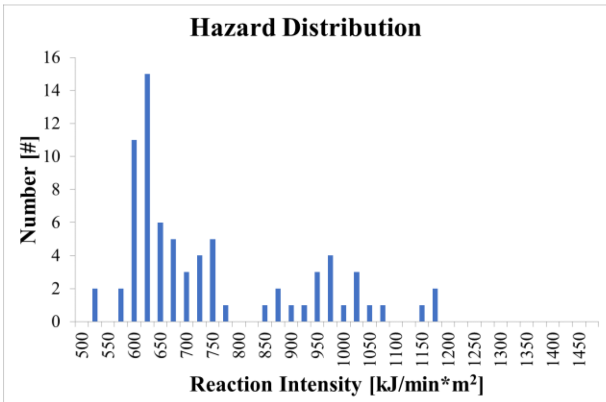

Fig. 1. Result of simulation

2.3 Hazard Curve

The hazard curve is generally presented in the form of hazard on the horizontal axis and annual rate of exceedance (ARE) on the vertical axis. An ARE value corresponding to an arbitrary hazard means a frequency that a hazard greater than or equal to the hazard occurs. In order to create the hazard curve, it is necessary to estimate the probability density function (PDF) for the histogram derived in the previous section. For PDF estimation, the Kolmogorov-Smirnov test was performed for various probability distributions. The test results are shown in Table II, and the higher the p-value, the more accurately it is fitted, so it was judged that the Weibull distribution was the most appropriate. The form of the Weibull distribution and the 95% confidence level of parameters are shown in Equation 2 and Table III.

Table II: p-value by probability distribution

Probability Distribution	p-value
Normal	7.84×10^{-3}
γ	1.40×10^{-1}
β	7.20×10^{-8}
χ^2	1.40×10^{-1}
Exponential	2.97×10^{-3}
t	7.84×10^{-3}
f	2.11×10^{-2}
Weibull	1.50×10^{-1}
Lognormal	8.01×10^{-39}

$$f(x) = \frac{b}{a}\left(\frac{x-c}{a}\right)^{b-1} exp\left(-\left(\frac{x-c}{a}\right)^{b}\right),\ a,\ b,\ x > c \qquad (2)$$

Table III: Parameter of Weibull distribution and its confidence interval

Parameter	Mean value and 95% confidence interval
scale parameter, a	243.59 (203.91, 290.99)
shape parameter, b	1.34 (1.13, 1.60)
location parameter, c	508.70

The ARE is derived by multiplying the PDF by the frequency of forest fires, $Fq_{forest\ fire}$ occurring in the simulated area. This frequency could be obtained from the Korea Forest Service and was investigated 9 times over 7 years. Figure 2 shows the ARE with the mean, maximum, and minimum among the combinations of parameters expressed in the form of Weibull distribution.

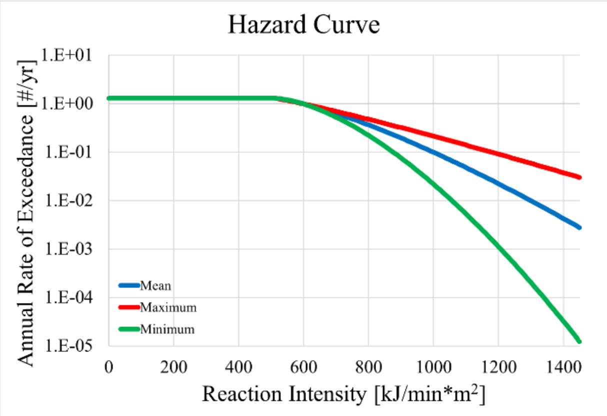

Fig. 2. Hazard Curve

3. Fragility Analysis Method and Results

The reaction intensity derived from FlamMap has the same size of $60m \times 60m$ per pixel as input data. Accordingly, it was assumed that the heat flux equal to the reaction intensity would be released from the high-temperature flat plate with the size of $60m \times 60m$, A_f.

The transmission line was assumed to be a commonly used Aluminum Conductor Steel Reinforced (ACSR) $480\ \mathrm{mm}^2$. According to a study examining the function of this transmission line according to temperature, it was found that the function was lost when the transmission line was exposed to about 300℃. In addition, the distance between the transmission line and the hot plate was conservatively set to about 3.2 m, which was investigated as the lowest height [5].

In this paper, it was assumed that only radiation existed in the heat transfer between the forest fire and the transmission line, but a computational fluid dynamics (CFD) analysis will be conducted to consider the effect of convection in the future. A heat transfer model considering only radiation can be shown in Figure 3. The goal of this section is to derive the reaction intensity of a wildfire required to reach 300℃, the temperature at which transmission lines fail.

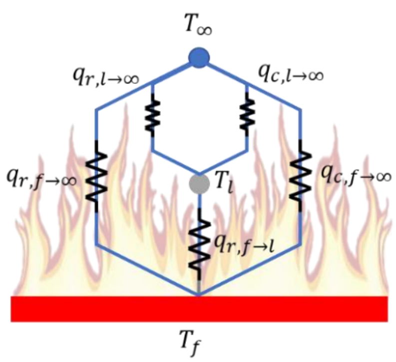

Fig. 3. Heat transfer model

The description of each element in Figure 3 is as follows: $q_{r,\,f\to l}$ is the part where the forest fire heats the transmission line through radiation, and the temperature of the forest fire is a necessary and sufficient condition. Since the temperature of the forest fire is not provided by FlamMap, it was derived by balancing $q_{r,\,f\to l}$ with $q_{r,l\to\infty}$ and $q_{c,\,l\to\infty}$ representing the part of the transmission line cooled by radiation and convection. Since forest fires transfer heat to the atmosphere as well as transmission lines, the amount of heat due to radiation and convection to the atmosphere must be calculated. $q_{r,\,f\to\infty}$ and $q_{c,f\to\infty}$ represent the heat transfer from the forest fire to the atmosphere. Therefore, the heat transferred by the forest fire is the sum of $q_{r,\,f\to l}$, $q_{r,\,f\to\infty}$, $q_{c,f\to\infty}$. Dividing this by the area of the forest fire, that is, the size of the hot plate, is the minimum heat flux, q''_{min} that causes the transmission line to fail, and can be expressed as Equation 3. As a result of the analysis, q''_{min} was found to be 1,390 $kJ/min \cdot m^2$.

$$q''_{min} = (q_{r,f\to l} + q_{r,\,f\to\infty} + q_{c,f\to\infty})/A_f \qquad (3)$$

4. Contribution on LOOP Frequency

By integrating Sections 2 and 3, the LOOP frequency of the Hanul NPP site is derived. To summarize each, Section 2 assumed that a forest fire occurs in the area surrounding the Hanul NPP site with random weather and location and investigates the highest reaction intensity among the areas where the forest fire and off-site transmission lines meet through simulation. The investigated reaction intensity, q''_{min} was reconstructed into a hazard curve as shown in Figure 2. Section 3 calculated the reaction intensity of a forest fire that causes a transmission line to fail using a static heat transfer model that only considers radiation.

The values obtained by substituting q''_{min} into the hazard curve refers to the frequency with which the transmission line loses its function. In order to consider the uncertainty of the parameters of the hazard curve, $3.88 \times 10^{-5}\ \#/yr$ and $3.91 \times 10^{-2}\ \#/yr$ were obtained by substituting q''_{min} into the maximum and minimum hazard curves presented in section 2. The meaning of this value is a kind of conditional frequency of LOOP to forest fires. Finally, if the unit is converted to the frequency of the initiating event (#/Reactor year) used in PSA, they are $6.47 \times 10^{-6}\ \#/RY$ and $6.51 \times 10^{-3}\ \#/RY$ respectively. This is 2.3×10^{-3}~23 % of the frequency of LOOP at the existing Hanul site, $2.83 \times 10^{-2} \#/RY$ [6].

5. Conclusions

Worldwide, forest fires cause numerous damages to facilities and humans. South Korea is also affected and the possibility of forest fires is expected to increase. Since the units 1, 2, and 6 of the Hanul NPPs have a history of LOOP due to forest fires, safety evaluation of NPPs due to forest fires is a necessary part. Among the safety evaluations, this paper conducted a safety evaluation of the off-site transmission lines shown in the event history.

Borrowing an external event PSA methodology, hazard analysis and fragility analysis were conducted. In the hazard analysis, a forest fire simulator called FlamMap was used to measure the intensity of forest fires. As a result of performing Monte Carlo simulation by randomly combining ignition points and weather, the hazard curve was obtained.

A fragility analysis was conducted to determine the reaction intensity of a forest fire that could heat a transmission line to a temperature where it would fail. Only radiation was considered for heat transfer between the transmission line and the forest fire, and an analysis including convection will be conducted in a future study.

As a result, the frequency of an event in which an off-site transmission line loses its function due to a forest fire, that is, a LOOP, was derived as a range by reflecting the confidence interval of the hazard curve parameters.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT and Future Planning) (No. NRF-2021M2D2A1A02044210)

REFERENCES

[1] Milanović, S., Marković, N., Pamučar, D., Gigović, L., Kostić, P., & Milanović, S. D. (2020). Forest fire probability mapping in eastern Serbia: Logistic regression versus random forest method. Forests, 12(1), 5.

[2] Lim, J., Heo, G. (2023, May). A Methodology for Forest Fire Hazard Analysis for External Event PSA, In *KNS Spring meeting* 2023.

[3] Rothermel, R. C. (1972). A mathematical model for predicting fire spread in wildland fuels (Vol. 115). Intermountain Forest & Range Experiment Station, Forest Service, US Department of Agriculture.

[4] Papadopoulos, G. D., & Pavlidou, F. N. (2011). A comparative review on wildfire simulators. IEEE systems Journal, 5(2), 233-243.

[5] Lee, W. K., Lee, J. W., & Kim, B. G. (2010). Mechanical and Electrical Properties of Aluminum Wires of ACSR Conductors due to Forest Fire. Journal of the Korean Institute of Electrical and Electronic Material Engineers, 23(9), 730-735.

[6] Jin, K., Heo, G., et al. (2017). Analysis of Multi-unit Shutdown Events in Korea Using Open Sources. NSTAR-17NS11-02.