A Methodology for Forest Fire Hazard Analysis for External Event PSA

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1. Introduction

During the period of operation of nuclear power plants in South Korea, a total of three failures occurred due to forest fires. All of them ended in a kind of Loss of Off-site Power (LOOP) caused by the forest fire blocking the transmission line [1]. Forest fires are expected to increase both probability and magnitude worldwide due to climate change [2]. Likewise, according to statistics, figures 1 and 2 show that the number of forest fires and the fire size is gradually increasing. Therefore, it is meaningful to evaluate the impact of forest fires from the viewpoint of potential initiating events.

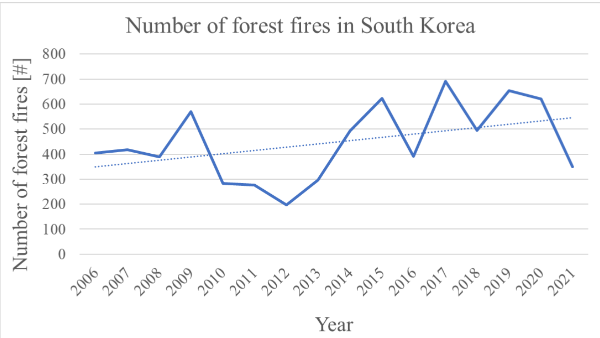

Fig. 1. Number of forest fires in South Korea from 2006 to 2021.

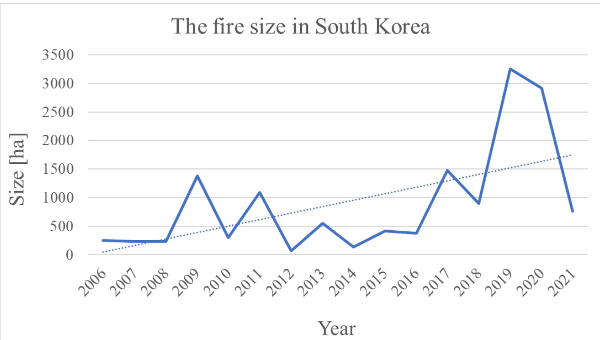

Fig. 2. The fire size in South Korea from 2006 to 2021.

In the case of forest fires, based on statistical data, the frequency of forest fires affecting LOOP can be simply stated as y/x $\#/yr$, where y is the number of forest fires and x is year. However, if the frequency is derived in this way, information other than the frequency cannot be obtained such as, a pattern in accidents or off-site fragile point. Analysis of the forest fire itself is needed to understand potential behavior.

Generally, the step for an external event in probability safety assessment (PSA) is first to perform a hazard analysis, conducts a fragility analysis according to the hazard, and finally quantify the impact of the external event through system analysis. This paper presents a methodology for conducting hazard analysis.

2. Hazard Indicators

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 an earthquake, the horizontal axis is the ground acceleration, and in a tsunami, the horizontal axis is the wave height.

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. From this information, 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 and fireline intensity.

Reaction intensity is defined as the heat emitted per unit area and the formula is as follows.

$$I_R = -\frac{dw}{dt}h \tag{1}$$

where: $\frac{dw}{dt}$ is mass loss rate per unit area in the fire front (kg/m^2s), 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].

Fireline intensity is expressed as heat emitted per unit length, and the formula is as follows.

$$I_B = Hwr \tag{2}$$

where H is the fuel low heat of combustion (kJ/kg), which when reduced for fuel moisture content becomes the net value, w is the amount of fuel consumed in the active flaming front (kg/m^2), and r is the linear rate of fire spread (m/s) [4].

3. Simulation Model

More than 20 forest fire simulators have been developed to date. Among them, FARSITE is considered the most accurate accredited by many government agencies and researchers [5]. This FARSITE is a simulator developed by the Missoula fire sciences laboratory of the United States Fire Administration (USDA). This laboratory developed FlamMap, a simulator that includes three simulation mode ('FlamMap Runs', 'FARSITE Runs', 'SpatialFOFEM'). Wind information is kept constant in FlamMap Runs. Therefore, in this study, FARSITE Runs is used to apply wind information differently by time.

The representative input data required by this simulator is shown in the table 1. Elevation, Slope, Aspect, and Fuel models are determined through topography and forest floor data. Since these are variables independent of time (season), they do not change when the simulation area is specified. However, since the rest are variables that vary according to time (season), they must be entered differently according to the date on which the simulation is to be performed.

Table I: Input of FlamMap

Input	Description
Elevation	Elevation above sea level
Slope	Degrees or percent of inclination from the horizontal
Aspect	Azimuth values (degrees clockwise from north)
Fuel model	Original standard NFFL fuel models and expanded set of standard models
Canopy cover	Horizontal percentage of the ground surface that is covered by tree crowns
Wind	Wind speed and direction at observation time
Temperature	Temperature at observation time
Humidity	Relative humidity at observation time
Precipitation	Precipitation at observation time
Cloud cover	Cloud cover at observation time

4. Case study

The Uljin and Samcheok forest fires, which are the most recent causes of blocking transmission line in the failure history by forest fires in South Korea, had the largest damage area ever with a damage area of 20,923 ha. This size is about 6.4 times the size of the forest fires in 2019 (3,255 ha), which is the highest value in Figure 2. Therefore, the size of the forest fires in Uljin and Samcheok was used as the size of the simulation background. The background of the simulation was set as a circle with the coordinates of the Hanul Unit 1 reactor containment as the origin. Figure 3 shows the simulation area. The blue line stands for the transmission lines in off-site. The forest floor distribution and terrain information of the simulation background referred to GIS data provided by the government, and the initial ignition point of the forest fire was arbitrarily set.

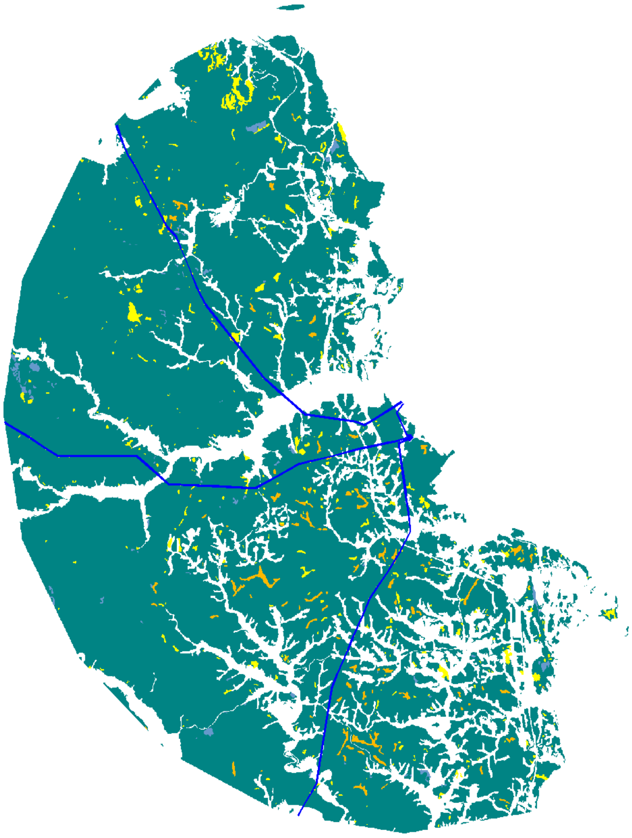

Fig. 3. The simulation area in FlamMap.

Among the simulation results, the fireline intensity is shown in Figure 4, and the reaction intensity is shown in Figure 5. If melting of a transmission line is defined as a failure, the frequency of transmission line failure can be obtained by iterating several times with a random combination of weather and ignition point in the simulation. The annual frequency affecting LOOP can be estimated by the exceedance frequency (i.e., the ratio of the number of trials from simulation) and fragility analysis for the transmission lines:

$$freq = -\int \frac{dH(I)}{dI} F(I) dI \qquad (3)$$

where $H(I)$ is the exceedance frequency at hazard indicator, and $F(I)$ is the failure probability at hazard indicator.

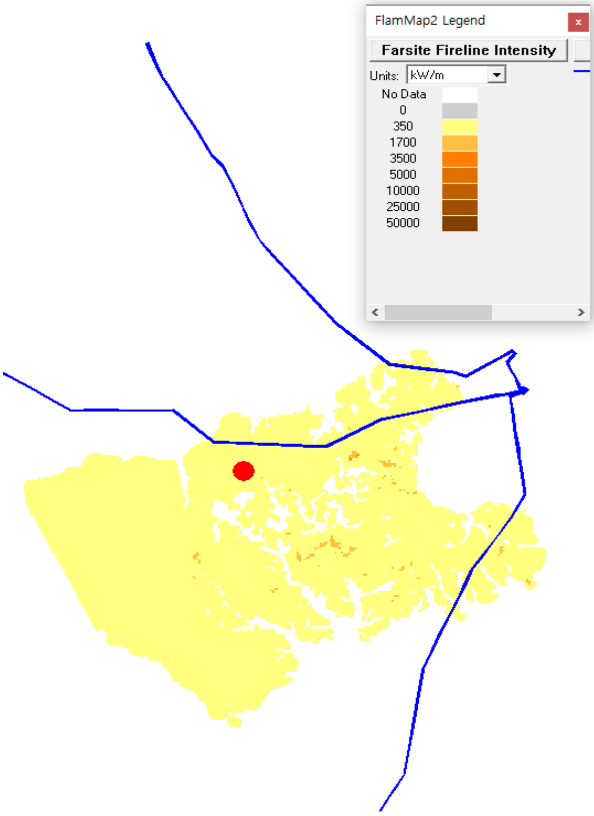

Fig. 4. The fireline intensity in FlamMap, where a red dot is an ignition point.

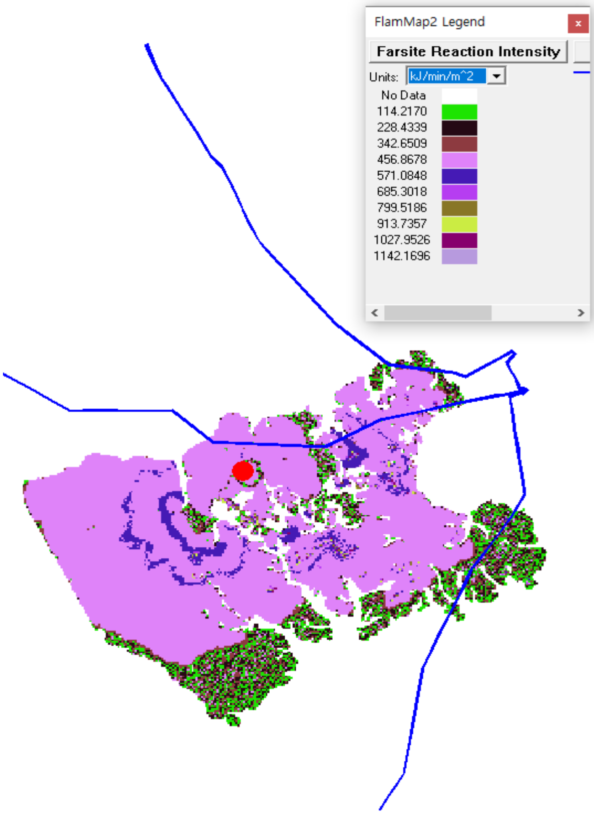

Fig. 5. The reaction intensity in FlamMap, where a red dot is an ignition point.

5. Conclusions

At a nuclear power plant in Korea, there is a history of failure due to a forest fire blocking transmission line. From this motivation, it is required to identify fragile points and major event trends for forest fires. This study attempted to obtain the hazard indicators such as fireline intensity or reaction intensity. In conclusion, using FlamMap, it was possible to obtain a hazard curve for an off-site transmission line, and furthermore, it can be confirmed that a forest fire directly affects a nuclear power plant.

In future research, in order to improve the reliability of the forest fire simulator, a comparative analysis of the simulator results and actual results will be performed for the Uljin and Samcheok forest fires that occurred in March 2022. And Monte Carlo simulation will be conducted by combining random ignition points and weather. We will finally quantify the impact of forest fires on LOOP by performing fragility analysis and system analysis through several derived fireline intensities or reaction intensities.

Acknowledgments

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