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Short communication

Forest fire propagation simulations for a risk assessment methodology development for a nuclear power plant

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ABSTRACT

After the Fukushima Daiichi nuclear power plant [NPP] accident, there has been an increased concern with the safety of NPPs in terms of external hazards, one of which is a forest fire which can create potential challenges to safety functions and the structural integrity of an NPP. As a part of the development of a risk assessment methodology for forest fires as an external hazard, forest fire propagation simulations have been performed by using the FARSITE simulator. These simulations have been used to evaluate two intensity parameters (i.e. fireline intensity and reaction intensity) and three other key parameters (i.e. flame length, rate-of-spread, and forest fire arrival time) which are related to "heat" and "flame" effects on an NPP. Sensitivity analyses for a wide range of weather conditions were performed in order to identify the variable ranges of the intensity and other key parameters. The location studied was selected from among areas with typical topographical and vegetation surrounding NPPs in Japan. The NPP is facing the sea and surrounded by hills, distanced from an urban area, with mostly broad leaf forests, several paddy fields and a few pasture areas.

Low-to-high frequency weather conditions have been utilized in this analysis; forest fire propagation simulations were performed "with/without prevailing wind" (i.e. 0–24 m/s wind speed) and "high/low values for ambient temperature and relative humidity" (−4.3 to 37 °C and 5–99%, respectively) according to the recorded data ranges for the typical NPP site. The maximum values of fireline intensity and rate-of-spread are 4.7×10^2 kW/m and 2.4 m/min and they depend very much on prevailing wind speed and relative humidity (around 2.3 and 1.8 times respectively) but less on ambient temperature (around 1.1 times). Reaction intensity and flame length change within relatively narrow ranges (around 1.7 and 1.5 times respectively) even for all the variation in weather parameters. The forest fire arrival time at the site is reduced by a factor of 5 with changing prevailing wind speed from the recorded-highest to zero. The arrival time increases some 3.4 times with the highest humidity compared to the recorded-lowest conditions, although it is changed little even by varying ambient temperature.

Given that this study shows that the maximum height of a flame on a canopy top is close to the range of power line height, a loss of offsite power is recognized as a possible subsequent event during a forest fire.

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1. Introduction

The safety of a nuclear power plant [NPP] is ensured by continuous improvement in the safety approach through obtaining up-to-date operational experience and technical knowledge. After the Fukushima Daiichi NPP accident [1], there has been an increased concern with the safety and exposure of NPPs to external hazards [2], one of which is a forest fire. Conventional safety assessments of a forest fire have been performed in a conservative manner through application of typical deterministic envelope methods and boundary conditions. A new methodology for a risk assessment of a forest fire on an NPP is being developed [3] based on a probabilistic risk assessment methodology as an effective technique for qualitative evaluation of occurrence frequency and corresponding consequence analysis as a result of exposures of NPPs to various hazards.

The new methodology consists of two parts; the first one is a hazard assessment to obtain a "hazard curve" of fireline intensity and reaction intensity due a forest fire [4], and the second one is an event sequence analysis to obtain plant damage frequency due to the challenges by such a forest fire. For these assessments, it is necessary to clarify what phenomena of a forest fire might become challenges to an NPP and what intensities and parameters correspond to the challenges, which is the purpose of this paper. According to the existing deterministic assessments of effects on an NPP by an external fire [5] and by a wild fire [6], "fireline intensity" and "reaction intensity" are mainly considered as the important quantitative indexes.

In this study, physical phenomena related to a forest fire were analyzed in relation to the potential impacts on an NPP in order to identify "intensity" and key parameters especially related to "heat" and "flame" which may potentially have an effect on the NPP and to the external electrical power supply of the NPP. Forest fire simulations were performed for a range of typical NPP site conditions, and the strength values of the intensity and other key parameters were evaluated.

The FARSITE (Fire Area Simulator) software [7] was utilized for the forest fire propagation simulations in this study because of its wide applicability in relation to forest fire management and firefighting actions. However, the most applications of FARSITE have been related to vegetation, topographical and weather conditions of North America [8] and Europe [9,10]. These conditions are different to those in Japan (e.g. humid subtropical climate with rainy and typhoon seasons, wide areas of deciduous tree forest and paddy fields, and mountains/hills near to the seashore). As a result the database needed for FARSITE simulations was consolidated as part of this study.

The FARSITE simulations were performed on a reference condition of high ambient temperature [AT] and low relative humidity [RH] without a prevailing wind. A possible subsequent event important to NPP safety in relation to power line exposure was investigated as well. The sensitivity analysis was performed with changing weather parameters and forest fire breakout points in order to evaluate the range in variation of the forest fire intensity and the other key parameters of flame length, rate-of-fire spread [ROS] and forest fire arrival time.

2. General analysis of forest fire challenges to a power plant

2.1. Forest fire physical phenomena and potential challenges to a power plant

Physical phenomena during a forest fire spread [11] are raised by heat, flame, smoke and flying sparks (otherwise called embers or fire brands). The relation between the physical phenomena, forest fire intensity and these key parameters, resulting in possible consequential effects and potential challenges to an NPP are summarized in Fig. 1. This paper

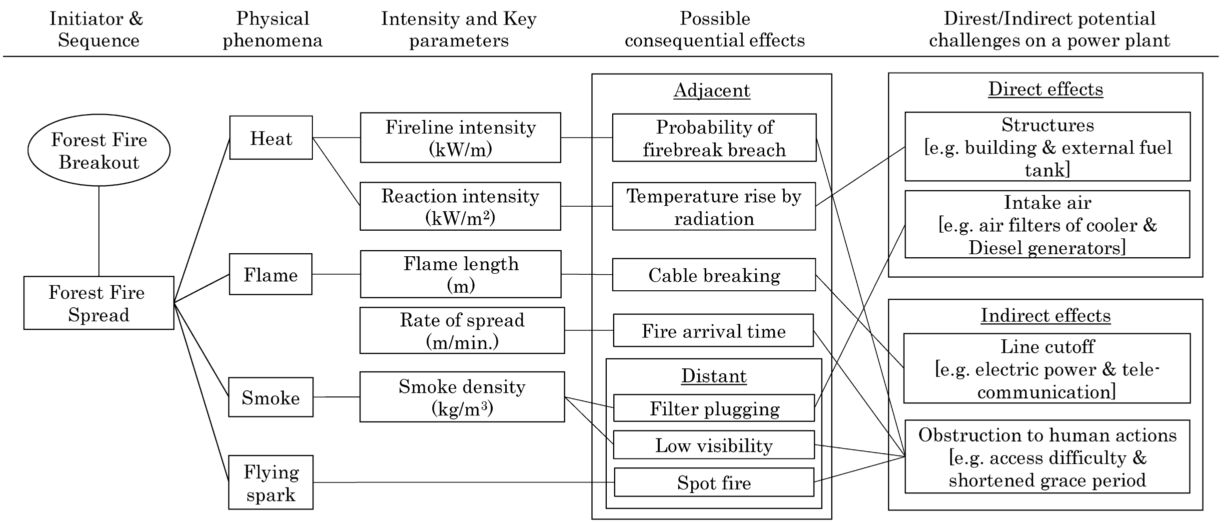

Fig. 1. Forest fire related physical phenomena, intensity and key parameters, possible consequences and potential challenges to a power plant.

specifically deals with the "adjacent" impacts of "heat" and "flame" and not the "distant" impacts of "smoke" and "flying sparks" which are less important for an NPP with essentially non-combustible construction. The parameters of "heat" and "flame" are quantitatively evaluated in this paper by the FARSITE simulator.

The index of "heat" is obtained from the heading "fireline intensity" and the "reaction intensity". A firebreak width is determined from a predicted fireline intensity, and a breaching probability of the firebreak increases with the fireline intensity [12,13]. The width of a firebreak for an NPP in Japan, if a firebreak is provided, corresponds to the breaching possibility below 1% [6]. Once after a breach has occurred, a grace period until the forest fire arrival at an NPP site is an important issue.

The "reaction intensity" is utilized to evaluate temperature rises of external wall surfaces of NPP facilities. There is generally a wide space consisting of a road pavement or concrete on the ground around a typical building and external fuel tanks of an NPP. As a result, a possible consequential impact will be created as a result of radiation and not by convection. Radiation heat flux is calculated from the reaction intensity [5] through multiplying the yield of radiative heat as a fraction of the total heat of combustion.

The index of "flame" is characterized by "flame length". An NPP has many connection lines of cables for external electric power and telecommunication. In a case where a forest fire flame height reaches up to these lines, the lines may be destroyed and disconnected. Normally these lines have redundancy (e.g. multiple lines along separated paths) and an NPP has alternative diesel power generators and emergency batteries just in case of these situations. Nevertheless, these potential consequences during a forest fire spread need to be assessed. "ROS" is an important index to determine a grace period for preparative actions prior to the arrival of the forest fire front at the NPP after the breakout. For the distant effects of "smoke" and "flying sparks", quantitative evaluations have been performed in other studies [14].

2.2. Location and database for forest fire propagation simulations

The location studied is depicted in a topographical map in Fig. 2. The location was selected to represent typical topographical and vegetation conditions near NPPs in Japan. The NPP site faces the sea and is surrounded by hills and ridge lines, and distant from an urban area. The topographical and vegetation maps were prepared for a 20 km × 20 km area, although the maps in Fig. 2 are magnified to around 7 km × 6 km. The ridge lines are around 200–400 m in height, and the peak of the mountain line across from south-to-north is above 700 m in height. There are several villages, small forest roads and beaches as shown in the map. There is a high-voltage electrical power line from south-to-north which cuts across the middle of the ridge lines.

Publicly available databases were proactively used for objectivity and generality in this analysis. For the parameters that do not change through the duration of a forest fire (e.g. over days or a week), stable values were selected from the databases or previous studies, where they existed. In case of absence of data, conservative values were set to produce an overestimated or conservative intensity.

For the topography, elevation data was obtained from the Fundamental Geospatial Data of Japan [15] and the data has a 10 m × 10 m mesh structures. ArcGIS10 software [16] was applied to calculate the slope angles and the directions from the elevation data. High-resolution data was necessary to evaluate local terrain features (e.g. hills and valleys), and the 10 m × 10 m mesh structure used results in a higher resolution than the other FARSITE case studies [8,9]. Non-vegetation areas less than the mesh size, such as narrow roads, and all the firebreaks, have been removed from the simulation for conservative evaluations on forest fire arrival times.

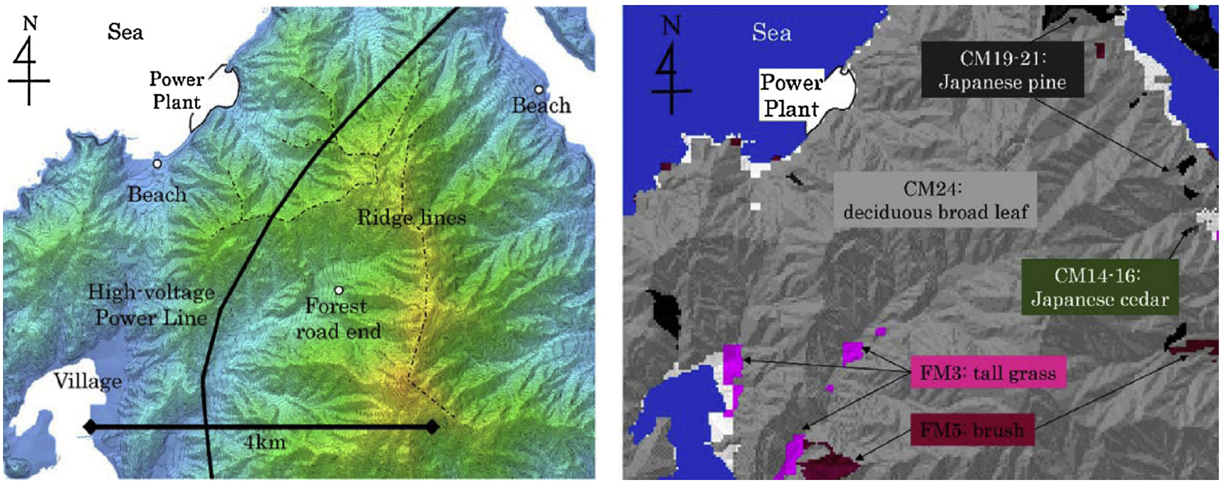

Fig. 2. Topographical (left) and vegetation (right) maps of the studied location for the forest fire propagation simulations. [The map images are made from the original elevation data [15] and modified to include point-of-interests and fuel models.]

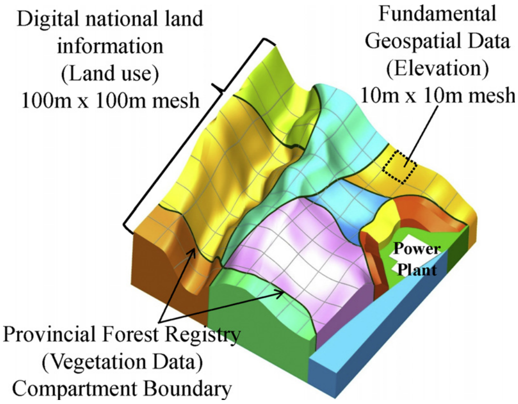

Fig. 3. Image of structure of overlapped topographical and vegetation data for forest fire propagation simulations.

For the vegetation, a database from Digital National Land Information [17] and provincial forest registry [18] were utilized. The digital national land information provides general land use data (e.g. forest, paddy field, town, river, etc.) with a relatively coarse 100 m × 100 m mesh structure. The provincial forest registry data provides specific maps of forest tree species (e.g. Japanese cedar with a category of age of stand) for each compartment of land. The vegetation map is shown in Fig. 2, and there are large deciduous broad leaf forests in most areas of the location studied, as shown on the map.

These topographical and vegetation data were overlapped for the analysis. Fig. 3 shows the image of use of the data, overlapping the resolutions and mesh structures. These data are static and do not change during the forest fire duration.

Fuel models were prepared for this custom utilization. The fuel model parameters of "deciduous broad leaf tree", "Japanese cedar" and "Japanese pine tree" and related input parameters are summarized in Table 1. The fuel model parameters of dead/live heat contents, moisture of extinction, and surface-area-to-volume [SAV] are based on reference data [19] where experimentally measured fuel data had been characterized for Rothermel's model. The fuel model parameters of dead fuel loads for 1-/10-/100-h are referenced from the NFEL fuel models of FM2: Timber (grass and understory) and FM10: Timber (litter and understory). Woody live fuel load was calculated for each species in the category of the forest registry by the product of a specific gravity of a categorized tree species [20] and a total timber volume per area [18], assuming there is no deadwood in the area. Live herbaceous and woody SAVs and live fuel load of herbaceous material are from the data of FM10. Fuel bed depth was set 182.9 cm (6 ft) by referring to FM4: Chaparral which is in the same range of grassland of around 60–180 cm [19] but was overestimated for the deciduous broad leaf forest of around 2–20 cm [19]. The canopy cover

Table 1
Input variables and parameters of custom fuel models applied to forest fire propagation simulations by FARSITE.

Fuel mode code	CM24	CM14	CM15	CM16	CM19	CM20	CM21
Vegetation	DB	JC	JC	JC	JP	JP	JP
Species type	Average of 28 species	Below 10 years	10 years	20 years	Below 10 years	10 years	20 years
Dead fuel load 1-/10-/100-h (ton/ha)[b]	6.75/4.48/11.23	6.75/4.48/11.23	4.48/2.24/1.12	4.48/2.24/1.12	6.75/4.48/11.23	6.75/4.48/11.23	4.48/2.24/1.12
Live fuel load herbaceous[b]/woody (ton/ha)	0/62.66	0/15.71	0/41.71	0/108.2	0/15.71	0/44.24	0/75.03
Fuel model type	Static	Static	Static	Static	Static	Static	Static
Dead 1-h SAV (1/cm)[a]	149.5	60.51	60.51	60.51	70.44	70.44	70.44
SAV live herbaceous/woody (1/cm)[b]	59/48	59/48	59/48	59/48	59/48	59/48	59/48
Fuel bed depth (cm)[c]	182.9	182.9	182.9	182.9	182.9	182.9	182.9
Moisture of extinction (%)[a]	25	32	32	32	31	31	31
Dead/live heat content (J/kg)[a]	18,524/18,524	20,963/20,963	20,963/20,963	20,963/20,963	19,958/19,958	19,958/19,958	19,958/19,958
Fuel moisture							
Dead fuel 1-/10-/100-h (%)	5/8/12	5/8/12	5/8/12	5/8/12	5/8/12	5/8/12	5/8/12
Live fuel herbaceous/woody (%)	100/100	100/100	100/100	100/100	100/100	100/100	100/100
Canopy cover category	3	3	3	3	3	3	3
Adjustment	1	1	1	1	1	1	1

DB, deciduous broad leaf tree; JC, Japanese cedar; JP, Japanese pine tree.
[a] Goto et al. [19].
[b] NFEL FM2: Timber (grass and understory) and FM10: Timber (litter and understory).
[c] NFEL FM4: Chaparral.

Table 2
Forest fire simulation input parameters and outputs of intensity and key parameters at the power plant boundary.

Parameters (Unit)	Inputs parameters				Output parameters at the power plant boundary				
	BP Dis.&Dir. (km, -)	PWS (m/s)	AT (°C)	RH (%)	Reaction intensity (kW/m^2)	Rate of spread (m/min)	Fireline intensity (kW/m)	Flame length (m)	Fire arrival time (h)
Reference (no prevailing wind)	2.5, SSE	0	37	5	1.2×10^3	9.9×10^{-1}	1.9×10^2	8.6×10^{-1}	97
90 percentile of AT frequency	2.5, SSE	0	27	5	1.1×10^3	1.3	2.3×10^2	9.5×10^{-1}	1.0×10^2
99% RH	2.5, SSE	0	37	99	6.9×10^2	1.2	1.8×10^2	8.4×10^{-1}	3.3×10^2
Worst weather overlapping	2.5, SSE	24	37	5	1.0×10^3	2.3	4.3×10^2	1.3	19
99 percentile of PWS frequency	2.5, SSE	11.6	37	5	1.2×10^3	1.4	3.1×10^2	1.1	52
50 percentile of PWS frequency	2.5, SSE	4.7	37	5	1.2×10^3	1.2	2.2×10^2	9.2×10^{-1}	82
90 percentile of AT frequency	2.5, SSE	24	27	5	9.9×10^2	2.2	3.9×10^2	1.2	19
50 percentile of AT frequency	2.5, SSE	24	16	5	1.1×10^3	2.4	4.7×10^2	1.3	20
Lowest AT	2.5, SSE	24	-4.3	5	9.4×10^2	2.4	4.6×10^2	1.3	20
99% RH	2.5, SSE	24	37	99	7.0×10^2	1.7	2.4×10^2	9.6×10^{-1}	62
50 percentile of RH frequency	2.5, SSE	24	37	73	7.1×10^2	1.9	2.7×10^2	1.0	60
Fire breakout point sensitivity									
East of the power plant	3.5, E	9.2	37	5	1.2×10^3	1.8	4.3×10^2	1.3	82
South-west of the power plant	1.0, SW	12.3	37	5	1.1×10^3	1.4	3.2×10^2	1.1	12

PWS, prevailing wind speed; AM, ambient temperature; RH, relative humidity; BP, breakout point; Dis., distance; Dir., direction; SSE, south–southeast; E, east; SW, south-west.

category was selected as "3" according to the definition of "forest" in Japan (i.e. the minimum cover ratio above 0.3 [21]). Fuel moisture of dead fuel and live fuel is 5/8/12% and 100% respectively which are from the default inputs of FARSITE. It is reported that the herbaceous and woody live fuel moistures of deciduous broad leaf trees are around 150–250% [22] and around or over 100% [23], respectively.

For the weather database, the Automated Meteorological Data Acquisition System [AMeDAS] [24] was utilized. Hourly data from January 1990 to December 2012 for the studied location was utilized to prepare a weather database, including AT, RH, prevailing wind speed [PWS] and prevailing wind direction [PWD]. For the location studied, the most frequent PWDs are from south–southeast and north throughout the year.

The purpose of the broader risk assessment methodology is to derive a "hazard curve" which indicates "intensity-frequency" combination. The intensity is taken from one FARSITE simulation, whereas the frequency is taken from the "appearance frequency of a set of weather condition" as an input to the simulation. A series of weather conditions is needed to cover a wide range to include "low frequency–high intensity" conditions as well as "high frequency–low intensity" conditions. Sensitivity analyses were performed for recorded low-to-high values of AT, RH, and RWS.

3. Forest fire simulation conditions and results

3.1. Simulations input parameters

In the analysis on forest fire models using the FARSITE model, the key conditional weather parameters are AT, RH, and PWS, and their variable ranges and appearance frequencies were taken into account in selecting a reference and sensitivity cases for this study. The input parameters for the FARSITE simulations used in this study are summarized in Table 2. The recorded lowest-to-highest ranges were set as −4.3 °C to 37 °C for AT, 5% to 100% for RH, and 0 m/s to 24.0 m/s for PWS. These weather parameters were set uniquely in the spatial volume and were kept constant in each simulation case. The other weather parameters were set conservatively: i.e. zero cloud cover ratio and zero precipitation. As a reference case, 0 m/s PWS was selected because low PWS condition (i.e. 0–5 m/s) occurs most frequently in comparison with the other PWS conditions over 5 m/s, and AT and RH sensitivities were varied. The other sensitivity studies were performed with changing the value of PWS and the location of the forest fire breakout point. 100/90/50 percentiles of PWS appearance frequency (i.e. 24.0/11.6/4.7 m/s), 100/90/0 percentiles of AT (i.e. 37/27/−4.3 °C), and 100/50/0 percentiles of RH (i.e. 99[1]/73/5%) were utilized.

The main causes of forest fires in Japan are related to human activities such as rubbish burns, controlled burns, arson, smoking, and playing with fire [25]. The forest fire breakout points were postulated considering these causes and the topographical features, land use and weather conditions in the location studied. The highest recorded PWS of 24 m/s was from the south-southeast [SSE], and a forest road ending in the SSE direction with 2.5 km distance from the NPP was selected as a reference breakout point as shown in Fig. 2. The high-voltage power line was located between the breakout point and the NPP site. Aside from the reference case, two beaches located in east (3.5 km distant) and south-west (1.0 km distant) from the NPP site were also selected as breakout points. The PWD was set so that the NPP site became in the

[1] The maximum value within a FARSITE input parameter range was applied.

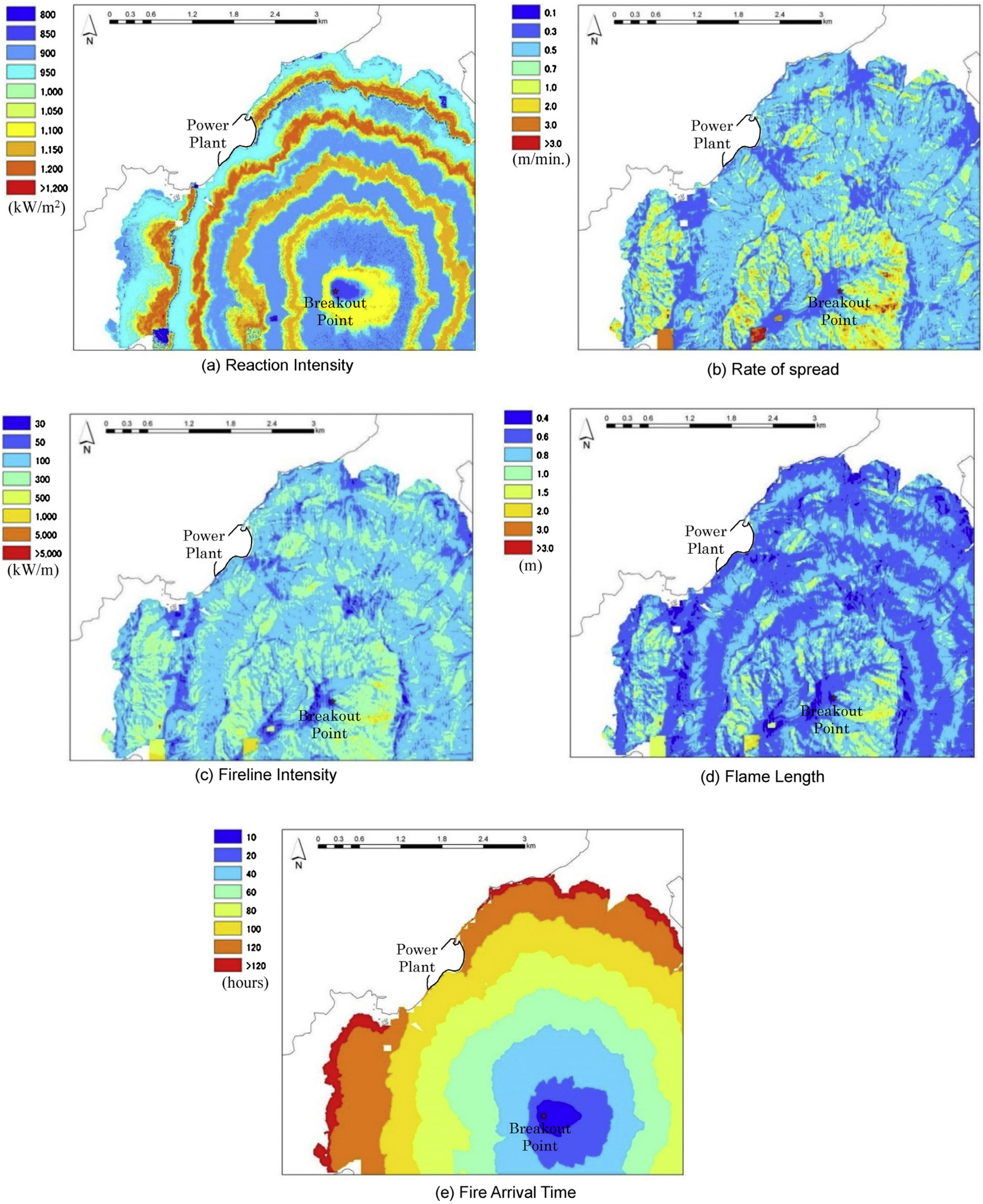

Fig. 4. FARSITE simulation result of the reference case. [Prevailing wind speed of 0 m/s, ambient temperature of 37 °C, and relative humidity of 5%].

leeward direction from the breakout point in each case, and the PWS was set to the recorded highest value in the corresponding PWD.

3.2. Summary of the Simulations by FARSITE

3.2.1. Reference case

All the maximum intensity parameters at the NPP site boundary obtained through the FARSITE simulations are summarized in Table 2. Fig. 4(a)–(e) depicts the reference case simulation results in terms of the parameters of reaction intensity, ROS, fireline intensity, flame length, and forest fire arrival time.

The theoretical point estimation of the intensity at the site boundary is not enough alone to assess the forest fire "heat" and "flame" effects because spatial values of all the five parameters are necessary. Specifically, the "fire arrival time" is the cumulative result of a distance divided by ROS, and the ROS depends on the "reaction intensity". The spatial values of "flame length" along the length of the high-voltage power line depend on the "fireline intensity".

The results of the simulation have shown that the forest fire propagates while keeping almost similar shape to a concentric circle, with deformation due to topographic effects (e.g. slope angle). The range of the reaction intensity was found to be of the order of 8.0×10^2–1.2×10^3 kW/m^2, and varied in accordance with the time condition (day/night) which influences the sunlight, and hence it forms the image like tree annual growth ring patterns. In comparison with the reaction intensity of day time only, the outer ring showed a relatively higher reaction intensity because the moisture content of the intact trees decreased with time under very low humidity. ROS was shown to be in the range 1.0–2.0 m/min and depended on the topographical effect, that is, it increased when spreading uphill and decreased when spreading downhill. The fireline intensity in the daytime was approximately 5.0×10^2 kW/m which is twice as large as that in the night (around 3.0×10^2 kW/m). Flame length varied around 0.8–2.0 m according to the strength of the fireline intensity. The forest fire arrival time for the propagation distance of 2.5 km was approximately 97 h. The reason for such a long arrival time is due to low ROS resulted from the range of the fireline intensity and corresponding fire mode based on the vegetation conditions simulated. The forest fire was evaluated as a surface fire mode in most of the simulated area because the fireline intensity was below the threshold for transition to passive crown fire [7].

3.2.2. Worst weather overlapping case

For a strong prevailing wind (PWS of 24 m/s), the forest fire arrival time was shortened to 19 h with the 2.5 km distance. Reaction intensity at the NPP site boundary was 1.0×10^3 kW/m^2 which was in the same range with the reference case (1.2×10^3 kW/m^2) because static vegetation data dominated in the calculation of the reaction intensity. The maximum ROS at the NPP site boundary was 2.3 m/min which was around 2.4 times greater than the reference case (0.99 m/min). The fireline intensity was 4.3×10^2 kW/m, which is around 2.3 times higher than the reference case (1.9×10^2 kW/m). The range of the fireline intensity was below the threshold in large parts of the simulated area, which resulted in low ROS and relatively long arrival time even under the high PWS condition. As shown in Fig. 5(a) and (b), the forest fire arrived at the high-voltage power line located at the midpoint around 10 h and the flame length along the high-voltage power line reached up to around 3 m. The analysis in this study would suggest the preparatory actions for the threat of a forest fire related to a possible offsite power loss would require action within a grace period of around 9 h for this worst weather scenario.

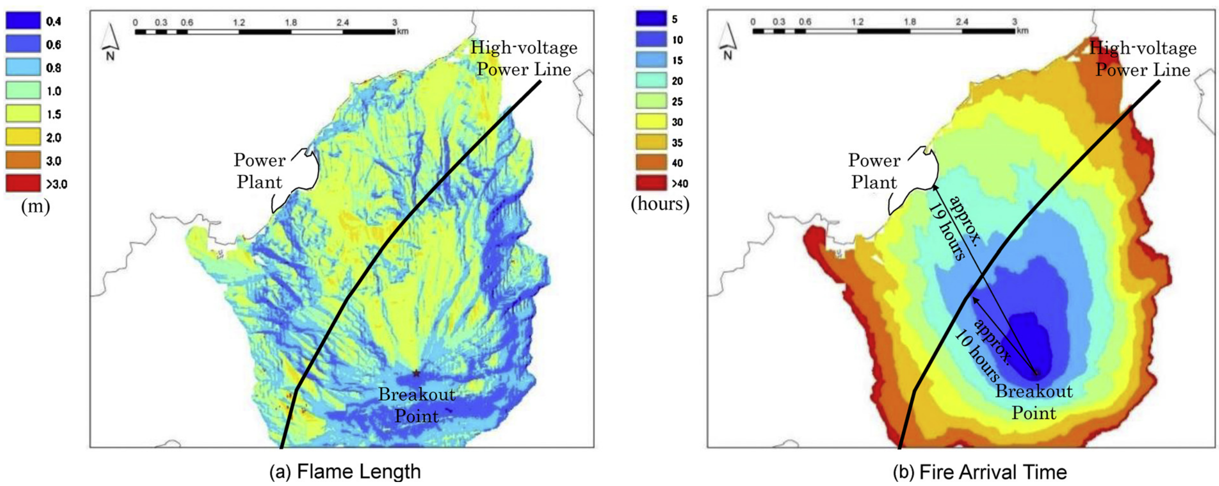

Fig. 5. FARSITE simulation result of the worst weather overlapping case. [Prevailing wind speed of 24 m/s, ambient temperature of 37 °C, and relative humidity of 5%]

3.2.3. Sensitivity study cases

For the sensitivity cases in this study, relative changes in the peak values of reaction intensity, fireline intensity, and the key parameters along the NPP boundary as well as the weather parameters are summarized in Fig. 6(a)–(e) where the horizontal scale is normalized to for values of PWS from 0 to 24 m/s, AT from −5 to 40 °C, and RH from 0 to 100%. Very low

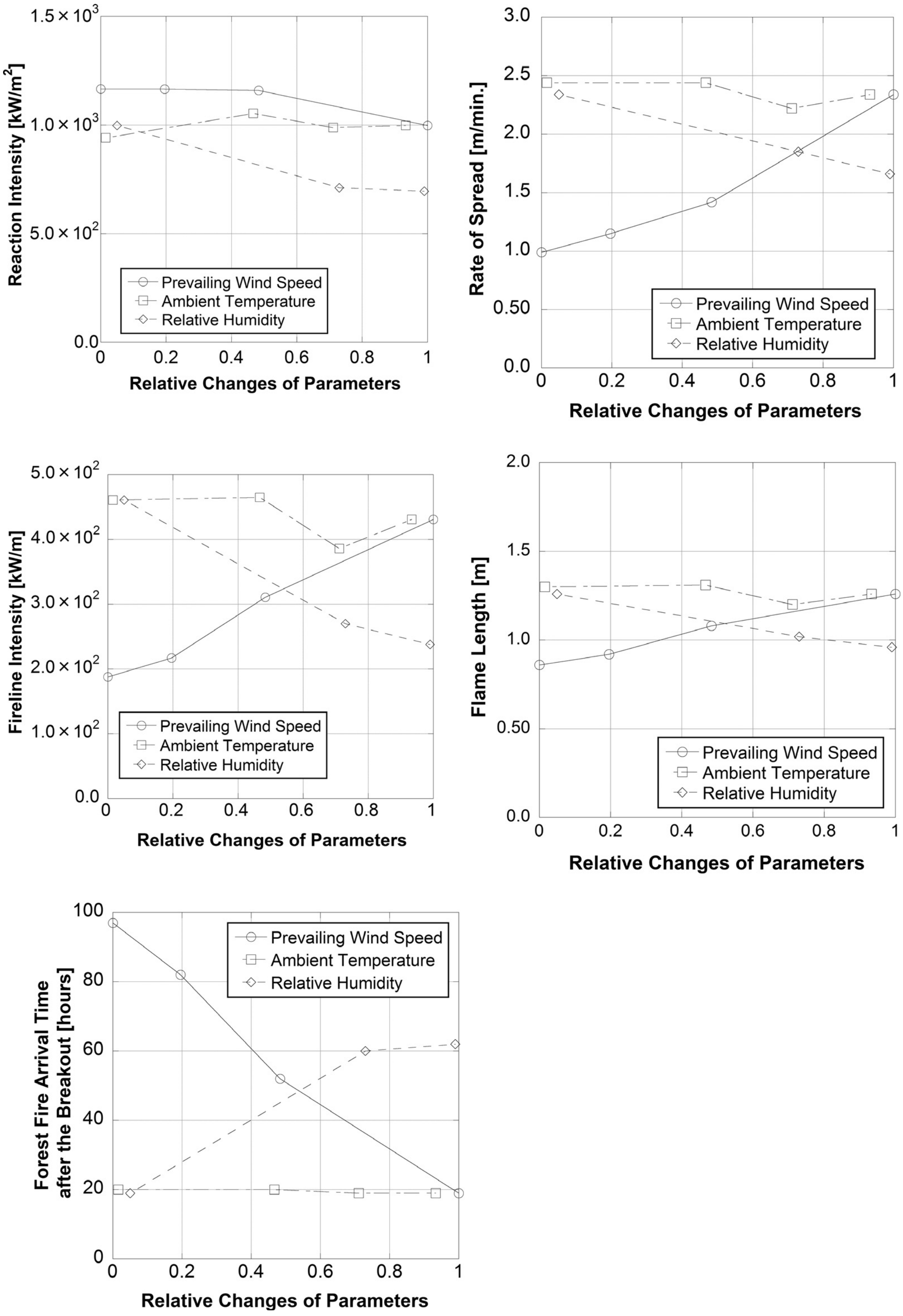

Fig. 6. Intensity and key parameters changes to the weather parameters. [Horizontal scale is normalized to prevailing wind speed (0–24 m/s), ambient temperature (−5 to 40 °C), and relative humidity (0–100%).]

sensitivity was seen to changes in AT; e.g. 19 h for 27 °C and 20 h for −4.3 °C under the same PWS condition. On the other hand, variations in RH had a significant effect on the results, especially on the fireline intensity and the forest fire arrival time. For example, the fireline intensity decreased almost half from 4.3×10^2 to 2.4×10^2 when RH was increased from 5% to 99%, and the forest fire arrival time was prolonged from 97 h to around 330 h for the same RH change. The effect of variation in PWS was significant as well on the ROS, fireline intensity and forest fire arrival time. For an increase in ROS from 0.99 m/min to 2.3 m/min, the fireline intensity varied from 1.9×10^2 to 4.3×10^2 kW/m, and the arrival time reduced from 97 h down to 19 h. That is, the PWS had a significant influence on the forest fire arrival time. However, the time is not exactly in inverse proportion to the PWS.

For the sensitivity to different forest fire breakout points, the forest fire arrival time varied according to the distance between the breakout point and the NPP site, but was not in direct proportion to the distance. For the similar PWS values of 11.6/9.2/12.3 m/s for three breakout points, the reaction intensity, ROS and fireline intensity were approximately in the same range. This is because vegetation and topological conditions near the NPP site are dominant factors for these values.

The maximum reaction intensity and fireline intensity at the NPP boundary were approximately 1.2×10^3 kW/m^2 and 1.0×10^3 kW/m, respectively. These values included the topographical effect, where the NPP was located in a downhill location and surrounded by deciduous broad leaf forests. These values are higher than the range of the existing studies of around 1.5×10^2–6.0×10^2 kW/m for the particular PWSs [19] and due to the conservative conditions in this study, e.g. the values selected for the PWS.

4. Conclusions

As a part of the forest fire risk assessment methodology, key parameters of a forest fire hazard as a risk for NPP safety were identified in this study to be fireline intensity, reaction intensity, flame length, ROS, and forest fire arrival time. Fuel model parameters of deciduous vegetation were based on deciduous broad leaf trees, Japanese cedar and Japanese pine tree, and vegetation, topographical, and weather databases for a typical NPP sites in Japan were consolidated for the FARSITE simulation.

This study showed that the intensity and the key parameters depend significantly on PWS and RH, but less on AT. The reaction intensity and fireline intensity were of the order of 7.0×10^2–1.2×10^3 kW/m^2 and 5.0×10^2–1.0×10^3 kW/m, respectively.

The reaction intensity has been utilized in other research to evaluate temperature increases of NPP structures in the study of failure modes and fragility (i.e. probability of failure due to high structural temperature) of the NPP structures [26].

The flame length was found to be in the range of 1–3 m and deciduous broad leaf trees reach typically around 20 m height [27], so that the possible reaching height of the flame is around 25 m and a loss of offsite power is a possible subsequent event during a forest fire, based on this study.

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