DOI: 10.5516/NET.2011.43.3.271

FIRE PROPAGATION EQUATION FOR THE EXPLICIT IDENTIFICATION OF FIRE SCENARIOS IN A FIRE PSA

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Received July 02, 2010
Accepted for Publication January 25, 2011

When performing fire PSA in a nuclear power plant, an event mapping method, using an internal event PSA model, is widely used to reduce the resources used by fire PSA model development. Feasible initiating events and component failure events due to fire are identified to transform the fault tree (FT) for an internal event PSA into one for a fire PSA using the event mapping method. A surrogate event or damage term method is used to condition the FT of the internal PSA. The surrogate event or the damage term plays the role of flagging whether the system/component in a fire compartment is damaged or not, depending on the fire being initiated from a specified compartment. These methods usually require explicit states of all compartments to be modeled in a fire area.

Fire event scenarios, when using explicit identification, such as surrogate or damage terms, have two problems: (1) there is no consideration of multiple fire propagation beyond a single propagation to an adjacent compartment, and (2) there is no consideration of simultaneous fire propagations in which an initiating fire event is propagated to multiple paths simultaneously.

The present paper suggests a fire propagation equation to identify all possible fire event scenarios for an explicitly treated fire event scenario in the fire PSA. Also, a method for separating fire events was developed to make all fire events a set of mutually exclusive events, which can facilitate arithmetic summation in fire risk quantification. A simple example is given to confirm the applicability of the present method for a 2x3 rectangular fire area. Also, a feasible asymptotic approach is discussed to reduce the computational burden for fire risk quantification.

KEYWORDS : Fire Event, Fire PSA, Fire Propagation

1. INTRODUCTION

When performing a fire probabilistic safety assessment (PSA) in a nuclear power plant (NPP), an event mapping method, using a fault tree (FT) for the internal event PSA model, is widely used to reduce the resources needed for fire PSA model development [1, 2, 3]. Feasible initiating events and component/system failure events due to fire are identified to transform the FT for an internal event PSA into one for a fire PSA. A surrogate event or damage term [1,2] method is used to condition the FT for the internal PSA. The surrogate event or damage term plays a role of flagging whether the component/system is damaged or not, depending on the fire being initiated from a specified fire compartment. These methods should explicitly search for all the states of a fire compartment in the fire area. Then, the failure or success of the component/system in the compartment is determined by considering various parameters that are usually related to the fire source, the fire intensity, the distance from the fire source, and so on. In order to facilitate the quantitative fire risk estimation by an analyst, the fire compartment is considered as an artificially divided sector of an entire fire area. A fire is assumed to occur in a single compartment in a fire PSA.

When a compartment has a fire event and there are adjacent compartments to which the fire from the initial compartment can be propagated, the surrogate or damage term method considers two types of events. One is for its own fire without any propagation to any adjacent compartment (see the first term on the right-hand side of Eq. (1)). The other is for the propagation to the next compartment to which it is assumed that the fire can be propagated (see the second term on the right-hand side of Eq. (1)). The general form of fire risk due to a fire event is written as [3,4]:

$$CDF = \sum_i \left(f(R_i) CCDP_i + \sum_j f(R_{ij}) CCDP_{ij} \right) \qquad (1)$$

where the index “i” in the first summation notation indicates the number of compartments in the fire area and the index “j” indicates the number of compartments adjacent to the i'th compartment. $CCDP_i$ and $CCDP_{ij}$ represent conditional core damage probability (CCDP) under the condition of a fire in the i'th compartment only and a fire in i’th and j’th compartment, respectively. Eq. (1) has been written differently from the original equation in Reference 4, in which summation indexes were not clearly defined for the propagation term. In Eq. (1), the first term on the right-hand side represents a fire event without any propagation. The second term in Eq. (1) represents a single propagation event adjacent to the i'th compartment where the fire event originated. Eq. (1) has two problems in its expressing of fire event risk.

1. There is no consideration of multiple fire propagation beyond a single propagation to an adjacent compartment.
2. There is no consideration of simultaneous fire propagations in which a fire is transferred to multiple compartments.

A fire event can usually be catastrophically expanded by successive propagation to the next region. If the propagation likelihood among compartments is relatively high, the effect of multiple fire propagations may not be eliminated by the simple relationship shown in Eq. (1). Therefore, this simplification may lower the overall fire risk in addition to distorting the fire risk profile.

A fire can also be simultaneously propagated to multiple compartments adjacent to the compartment. This may also under-estimate the real fire risk in two ways in terms of effects. A simultaneous fire event is not quantified in the conventional method and that simultaneous fire can invoke multiple successive failures of components; thereby, an initiating event may be directly related to a core damage event.

The present paper suggests an analytic fire propagation equation to identify all possible fire events for an explicitly treated fire event scenario in a fire PSA. In section 2, a simple example calculation for fire risk assessment is performed to show the inappropriateness of conventional fire risk assessment. A fire propagation equation for the general geometry of a fire area is developed in section 3. Also, a method of separating fire events is introduced to make all fire events a set of mutually exclusive events that facilitate arithmetic summation in their frequency quantification.

In section 4, a simple case study is given to explain the applicability of the present method for a 2X3 rectangular fire area. All fire events are indentified using the developed fire propagation equation. Then, the events are reformulated to yield mutual exclusiveness. Finally, the limitations of the present method are discussed in view of the fact that, when a fire area becomes larger and more complex, all the possible fire events increase exponentially. In this case, a computational analysis using this method would be impossible. A feasible asymptotic approach is discussed to reduce the computational burden.

2. ILLUSTRATIVE EXAMPLE OF PROBLEMS IN A FIRE RISK ASSESSMENT

As an illustration of the problems above, we provide a simple example, as shown in Figure 1. The figure shows a fire area with four compartments. The Arabic numbers indicate compartment numbers. The initiating fire is assumed to occur in compartment 2. It is assumed that the fire can propagate among any and all of the compartments.

According to Eq. (1), the fire risk from a fire in compartment 2 in terms of core damage frequency is written as:

$$\begin{aligned} CDF_2 &= f(R_2) CCDP_2 + \sum_j f(R_{2j}) CCDP_{2j} \\ &= f(R_2) CCDP_2 + f(R_{21}) CCDP_{21} + f(R_{23}) CCDP_{23} \end{aligned} \qquad (2)$$

As shown in Eq. (2), the total fire risk is composed of three events, that is, the fire event in compartment 2 without any propagation, fire events in compartments 2 and 1 in which the initiating fire in compartment 2 is propagated to compartment 1, and fire events in compartments 2 and 3 in which the fire in compartment 2 is propagated to compartment 3. The total CDF is obtained by simply adding all three events multiplied by their CCDP. However, although the first event, R_2, is an exclusive event separate from the other two events, R_{21} and R_{23}, the propagated events are not mutually exclusive, and so they cannot be added arithmetically. Also, Eq. (2) does not include any multiple propagation term more than a single propagation.

As an alternative approach, we consider all possible events when an initiating fire event occurs in compartment 2. We define R_{ij} as an event in the sense of Boolean algebra. From Figure 1, all possible fire events (FE) can be written as:

$$FE_2 = R_2 + R_{21} + R_{23} + R_{234} \qquad (3)$$

Since Eq. (3) is a Boolean equation, the fire risk cannot be obtained by a simple arithmetic summation of all possible event frequencies multiplied by their CCDP. To obtain the fire risk, the term in Eq. (3) should be separated into mutually exclusive events. Eq. (3) can be reformulated with an exclusive event set as:

$$\begin{aligned} FE_2 &= R_2 + R_{21} + R_{23} + R_{234} \\ &= R_2 + R_{21} \cdot \left(\overline{R_{23}} \cdot \overline{R_{234}} \right) \\ &\quad + \left(R_{23} + R_{234} \right) \cdot \overline{R_{21}} + R_{21} \cdot \left(R_{23} + R_{234} \right) \end{aligned} \qquad (4)$$

In Eq. (4), the following rule was used to express the exclusiveness among events.

$$R_{ij} \cdot R_{ijk} = 0 \tag{5}$$

In Eq. (5), R_{ij} is defined as a fire event in which the fire event initiated from the i'th compartment and propagated to the j'th compartment with no further propagation. In a similar manner, R_{ijk} is an event in which the initiating fire event propagated to the k'th compartment through the j'th compartment. The two events are mutually exclusive. As shown in Eq. (4), the fire event initiated in compartment 2 has six sub-events that are mutually exclusive.

1. Single fire event with no propagation
2. Event that is propagated to compartment 1 only.
3. Event that is propagated to compartment 3 only
4. Event that is propagated to compartment 4 through compartment 3 only
5. Event in which simultaneous propagation to both compartments 1 and 3 occurs.
6. Event in which simultaneous and multiple propagation to both compartments 1 and 4 occurs

Since the events in Eq. (4) are mutually exclusive, the total fire risk in term of CDF can be obtained as:

$$\begin{aligned} CDF_2 &= f(R_2)CCDP_2 + f\left(R_{21}\cdot\overline{R_{23}}\cdot\overline{R_{234}}\right)CCDP_{21} \\ &+ f\left(R_{23}\cdot\overline{R_{21}}\right)CCDP_{23} + f\left(R_{234}\cdot\overline{R_{21}}\right)CCDP_{234} \\ &+ f(R_{21}\cdot R_{23})CCDP_{213} + f(R_{21}\cdot R_{234})CCDP_{2134} \end{aligned} \tag{6}$$

Comparing Eq. (3) with Eq. (6), it can be easily seen that Eq. (3) does not have simultaneous and multiple propagation terms. Also, Eq. (3) has a problem in that it uses an arithmetic sum while the event should be expressed with Boolean algebra.

3. FIRE PROPAGATION EQUATION

3.1 State Vector of a Fire Area

As mentioned in the previous section, a fire area is divided into compartments among which an initiating fire event in a single compartment can be propagated depending on its propagation characteristics such as propagation probability. A fire event from a compartment can have multiple fire propagation scenarios according to its geometry in relation to other compartments and propagation characteristics. In order to evaluate the risk of a fire event using an explicit method (surrogate event, damage term) , the status of all fire compartments should be known in order to assign a flag that is used to indicate the operability of the system/function located in this compartment. Depending on the fire propagation route, the fire area could have numerous states in its compartments. The state of a compartment in a fire area can be replaced with a state vector, as follows:

$$\vec{S} = \left(s_1, \cdots s_i \cdots s_M\right) \tag{7}$$

where s_i represents the state of the i'th compartment. A compartment in a fire area can have a value of 0 or 1. According to the Boolean notation convention, 1 indicates that a fire event occurs or another fire event is propagated to the i'th compartment. "0" indicates that there is no fire event or propagation from another compartment to the i'th compartment. The subscript M in Eq. (7) denotes the total number of compartments in a fire area. This state vector is an input to the conditioning of an internal event FT to evaluate the core damage frequency (CDF). By mapping the state vector to the internal event FT, a CCDP of a fire propagation scenario of the initiating fire event in the i'th compartment can be obtained.

As an example, a fire area with four fire compartments is considered, as shown in Fig. 1. Assuming an initiating fire event from compartment 2, there can be six exclusive state vectors, as shown in Table 1. In some cases, two or more fire event scenarios can have an identical state vector. Although some fire event scenarios have identical state vectors, if the fire event scenarios are mutually exclusive and one of them is not subsumed into another fire event scenario, they should be treated independently to estimate fire risk.

3.2 Fire Propagation Equation

For the development of the fire propagation equation, the following things are assumed

1. A compartment cannot allow more than one propagation path simultaneously.
2. Fire propagation cannot progress backwards.

Assumption 1 indicates that, if a compartment has a

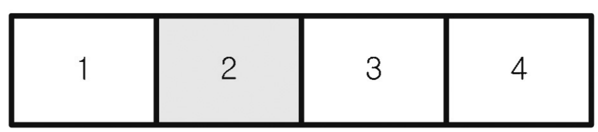

Fig. 1. Fire Area with Four Compartments

Table 1. State Vector of a Fire Area with Four Compartments (Fig. 1)

Fire event scenario	State vector
R_2	(0,1,0,0)
$R_{21}\cdot\left(\overline{R_{21}}\cdot\overline{R_{234}}\right)$	(1,1,0,0)
$R_{23}\cdot\overline{R_{21}}$	(0,1,1,0)
$R_{234}\cdot\overline{R_{21}}$	(0,1,1,1)
$R_{21}\cdot R_{23}$	(1,1,1,0)
$R_{21}\cdot R_{234}$	(1,1,1,1)

fire caused by another fire via a propagation path, no other propagation path through this compartment can exist simultaneously. Assumption 2 says that a propagation path already visited cannot be revisited.

It is defined that FE_i is an initiating fire event in the i'th compartment, and f_{ij} is an event in which a fire initiated from the i'th compartment is propagated to the j'th compartment. These two events have the following relation using Boolean expression.

$$FE_i = f_{ii} + \sum_{j \neq i}^{C_i} f_{ij} \tag{8}$$

where summation notation indicates an "OR" operation in the Boolean algebra and the summation index, C_i represents the total number of compartments adjacent to the i'th compartment. The first term on the right-hand side of Eq. (8) indicates that the fire event from the i'th compartment was not propagated to any other adjacent compartment. The repeated subscript thereafter is defined as a fire event that was stopped at the compartment indexed last. The second term on the right-hand side of Eq. (8) is the sum of all events that are propagated to adjacent compartments. The two terms on the right-hand side of Eq. (8) are mutually exclusive because a fire event that is not propagated to another compartment and a fire event that is propagated to another compartment cannot occur simultaneously.

Eq. (8) can be further expanded considering fire propagation to the next compartment from the j'th compartment, as follows:

$$FE_i = f_{ii} + \sum_{j \neq i}^{C_i} \sum_{k}^{C_j} f_{ijk} \tag{9}$$

where the index, C_j represents the number of compartments adjacent to the j'th compartment. The second term on the right-hand side can be separated into two event groups. One is for events in which no further propagation occurred and the other is for events that are propagated to the k'th compartment. The separated equation can be written as follows:

$$FE_i = f_{ii} + \sum_{j \neq i}^{C_i} f_{ijj} + \sum_{j \neq i}^{C_i} \sum_{k \neq i,j}^{C_j} f_{ijk} \tag{10}$$

This expansion can be repeated until there is no compartment into which the fire can be propagated. The final form of the fully expanded fire propagation equation can be written as:

$$\begin{aligned} FE_i &= f_{ii} + \sum_{j \neq i}^{C_i} f_{ijj} + \sum_{j \neq i}^{C_i} \sum_{k \neq i,j}^{C_j} f_{ijkk} + \\ &\cdots + \sum_{j \neq i}^{C_i} \cdots \sum_{k \neq i,j \cdots m}^{C_m} f_{ijk \cdots n} \end{aligned} \tag{11}$$

As an example, fire propagations and their sub-events are considered in a simple geometry, as shown in Fig. 2. Figure 2 is a fire area composed of six compartments. It is assumed that the fire was initiated in compartment 1. Applying Eq. (8), the fire event can be separated as:

$$\begin{aligned} FE_1 &= f_{11} + \sum_{j \neq 1}^{C_1} f_{1j} \\ &= f_{11} + f_{12} + f_{14} \end{aligned} \tag{12}$$

The second and third term can be further expanded, as shown in Eq. (10), as:

$$\begin{aligned} FE_1 &= f_{11} + f_{12} + f_{14} \\ &= f_{11} + \left(f_{122} + f_{123} + f_{125}\right) + \left(f_{144} + f_{145}\right) \end{aligned} \tag{13}$$

The expansion can be repeated until there is no compartment to be visited, thus:

$$\begin{aligned} FE_1 &= f_{11} + \left(f_{122} + f_{123} + f_{125}\right) + \left(f_{144} + f_{145}\right) \\ &= f_{11} + \\ &+ \left(f_{122} + \left(f_{1233} + \left(f_{12366} + \left(f_{123655} + f_{123654}\right)\right)\right)\right) \\ &+ \left(f_{1255} + f_{1254} + \left(f_{12566} + f_{12563}\right)\right)\Big) \\ &+ \left(f_{144} + \left(f_{1455} + \left(f_{14522} + \left(f_{145233} + f_{145236}\right)\right)\right. \\ &+ \left(f_{14566} + \left(f_{145633} + f_{145632}\right)\right)\Big)\Big) \end{aligned} \tag{14}$$

As shown in Eq. (14), there are five fire propagation paths: (1→2→3→6→5→4), (1→2→5→4), (1→2→5→6→3), (1→4→5→2→3→6), and (1→4→5→6→3→2), with eighteen fire events in their paths.

The fire events in Eq. (11) are not mutually exclusive. In order to obtain the state vector for each fire propagation scenario, the events in Eq. (11) should be modified to an event set in which all fire events are mutually exclusive among each other. Once the fire propagation scenarios are classified as exclusive events exclusive event, one can estimate the fire risk in terms of CDF by simply adding all possible fire propagation scenario frequencies multiplied by their CCDP. The method is explained in section 3.3.

3.3 Exclusive Event Set

To obtain state vectors that are mutually exclusive, the fire events in Eq. (11) should be reformulated. From Eq. (11) and Eq. (14), one can see that events in the same propagation path are mutually exclusive. For example, the events in the first path of Eq. (14) are f_{11}, f_{122}, f_{1233}, f_{12366}, f_{123655}, and f_{123654}. These six events are mutually exclusive. The fire event f_{11} indicates that a fire event is initiated at compartment 1 and it is not propagated to any other compartment. Therefore, the fire event f_{11} is mutually exclusive with other events in the same propagation path. Similarly, the fire event f_{122} is mutually exclusive with other fire events since there is no propagation from compartment 2. This relation can be applied to all fire events in the same propagation path.

Since fire events in the same propagation path are mutually exclusive, a state vector can be easily obtained if the fire events are grouped according to their propagation paths. The fire propagation path can be represented with a vector. A path vector in which the propagation path starts from i'th compartment and ends at n'th compartment through j, …, m'th compartment is defined as follows:

$$P_k = (i, \quad j, \quad \cdots, m, \quad n) \tag{15}$$

where the subscript k denotes the serial number of the path vector. As an example, a fire event initiated from compartment 1 in the fire area of Fig. 2 has five path vectors. Table 2 shows each path vector and its fire events. As shown in the table, some fire events may belong to multiple path vectors. If a fire event belongs to a path vector, this event can be eliminated from the other path vector because the same fire event can be absorbed in the Boolean manipulation of events.

The path vectors can be obtained by inspecting the last terms of Eq. (11). The subscript of a fire event that is fully developed to the point where it has no further propagation path indicates a path vector of the fire event.

A group of events belonging to the kth path vector is defined as Φ_k.When an initiating fire event of a fire area has the number of path vectors "m", the equation of the fire event can be written as follows:

$$FE_i = \sum_{i=1}^{m} \Phi_i \tag{16}$$

The next step is to make each fire event group Φ_i mutually exclusive among other events. For simple illustration, let's suppose that there are three event groups, A_1, A_2, and A_3. It is assumed that each event group has two states, that is, occurrence or non-occurrence. If one wants to find all states of the event group, they can be divided by all possible combinations of all event groups. By using a Venn diagram, all possible combinations can be illustrated as in Figure 3. The group of events in Fig. 3 can be formulated as:

$$\begin{aligned} FE_i &= \sum_{i=1}^{m} A_i \\ &= \sum_{i=1}^{3}\left(A_i \cdot \prod_{\theta \neq i}^{3} \overline{A_\theta}\right) + \sum_{i=1}^{3}\sum_{j=i+1}^{3}\left(A_i \cdot A_j \cdot \prod_{\theta \neq i,j}^{3} \overline{A_\theta}\right) + \prod_{\rho=1}^{3} A_\rho \end{aligned} \tag{17}$$

Eq. (17) can be generalized for an arbitrary number of event sets. For a number of event sets m, the groups of events can be divided so as to be mutually exclusive, as follows:

$$\begin{aligned} FE_i &= \sum_{i=1}^{m} \Phi_i \\ &= \sum_{i=1}^{m}\left(\Phi_i \cdot \prod_{\theta \neq i}^{m} \overline{\Phi_\theta}\right) + \sum_{i=1}^{m}\sum_{j=i+1}^{m}\left(\Phi_i \cdot \Phi_j \cdot \prod_{\theta \neq i,j}^{m} \overline{\Phi_\theta}\right) + \cdots \\ &\quad + \sum_{i=1}^{m} \cdots \sum_{l=k+1}^{m} \prod_{\rho=i}^{l} \Phi_\rho \cdot \prod_{\theta \neq i,\cdots l}^{m} \overline{\Phi}_\theta + \cdots + \prod_{\rho=1}^{m} \Phi_\rho \end{aligned} \tag{18}$$

In Eq. (18), each term is mutually exclusive. This can be easily seen by multiplying two arbitrary terms in the sense of Boolean algebra. Eq. (18) is the final form for fire event separation for explicit treatment. The total number of terms in Eq. (18) is 2^m for a number of path vectors m. As the number of events or path vectors increases, it is difficult to apply this method for fire risk

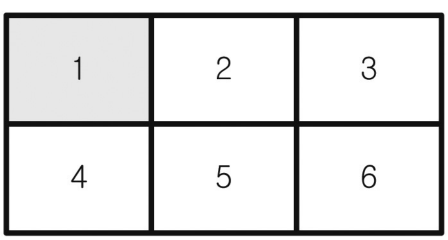

Fig. 2. Fire Area with Six Compartments

Table 2. Path Vector and Events for 2X3 Fire Area

Propagation Path	Events in the path
P_1=(1,2,3,6,5,4)	f_{11}, f_{122}, f_{1233}, f_{12366}, f_{123655}, f_{123654}
P_2= (1,2,5,4)	f_{1255}, f_{1254}
P_3= (1,2,5,6,3)	f_{12566}, f_{12563}
P_4= (1,4,5,6,3,2)	f_{144}, f_{1455}, f_{14566}, f_{145633}, f_{145632}
P_5= (1,4,5,2,3,6)	f_{14522}, f_{145233}, f_{145236}

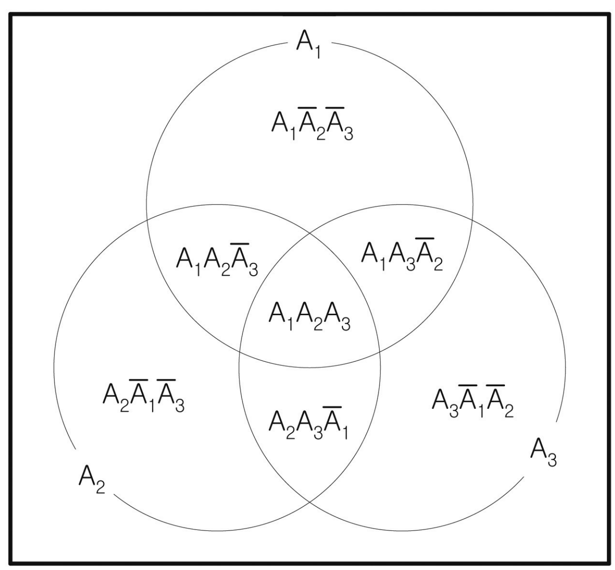

Fig. 3. Venn Diagram for the Exclusive Subdivision for Three Events

quantification. Some asymptotic approaches are discussed in section 5.

4. CASE STUDY FOR THE SIMPLE GEOMETRY OF A FIRE AREA

The present fire propagation equation is applied to a 2X3 geometry as shown in Fig. 2. As in the example of section 3.2, the fire is assumed to be initiated in compartment 1. Path vectors for this fire event in compartment 1 have already been identified and are given in Table 2. As explained in section 3.3, the fire events in an identical path vector are mutually exclusive. The event group belonging to each path vector is written as follows (see Table 2)

$$\begin{aligned}\Phi_1 &= f_{11} + f_{122} + f_{1233} + f_{12366} + f_{123655} + f_{123654}\\ \Phi_2 &= f_{1255} + f_{1254}\\ \Phi_3 &= f_{12566} + f_{12563}\\ \Phi_4 &= f_{144} + f_{1455} + f_{14566} + f_{145633} + f_{145632}\\ \Phi_5 &= f_{14522} + f_{145233} + f_{145236}\end{aligned} \tag{19}$$

Applying Eq. (18), the initiating fire event is divided by 32 events in terms of the group of events in a path vector since there are five path vectors, as follows:

$$\begin{aligned}FE_i = &\sum_{i=1}^{5}\left(\Phi_i \cdot \prod_{\theta\neq 1}^{5}\overline{\Phi_\theta}\right)\\ &+\sum_{i=1}^{5}\sum_{j=i+1}^{5}\left(\Phi_i \cdot \Phi_j \cdot \prod_{\theta\neq i,j}^{5}\overline{\Phi_\theta}\right)\\ &+\sum_{i=1}^{5}\sum_{j=i+1}^{5}\sum_{k=j+1}^{5}\left(\prod_{\rho=i}^{k}\Phi_\rho \cdot \prod_{\theta\neq i,j,k}^{5}\overline{\Phi_\theta}\right)\\ &+\sum_{i=1}^{5}\sum_{j=i+1}^{5}\sum_{k=j+1}^{5}\sum_{l=k+1}^{5}\left(\prod_{\rho=i}^{l}\Phi_i \cdot \prod_{\theta\neq i,j,k}^{5}\overline{\Phi_\theta}\right)\\ &+\prod_{\rho=1}^{5}\Phi_i\end{aligned} \tag{20}$$

Table 3 shows all possible exclusive fire events and their state vectors. As shown in the table, there are eighteen events of a single propagation path and 27 simultaneous events with more than a single propagation path. Since

Table 3. Exclusive Event Sets for 2X3 Fire Area in Figure 2

Event combination	Events
$\sum_{i=1}^{5}\left(\Phi_i \cdot \prod_{\theta\neq i}^{5}\overline{\Phi_\theta}\right)$	$\Phi_1(f_{11}, f_{122}, f_{1233}, f_{12366}, f_{123655}, f_{123654})$
	$\Phi_2(f_{1255}, f_{1254})$
	$\Phi_3(f_{12566}, f_{12563})$
	$\Phi_4(f_{144}, f_{1455}, f_{14566}, f_{145633}, f_{145632})$
	$\Phi_5(f_{14522}, f_{145233}, f_{145236})$
$\sum_{i=1}^{5}\sum_{j=i+1}^{5}\left(\Phi_i \cdot \Phi_j \cdot \prod_{\theta\neq i,j}^{m}\overline{\Phi_\theta}\right)$	$\Phi_1 \cdot \Phi_2(f_{1233}{}^{x} f_{1255}, f_{1233}{}^{x} f_{1254}, f_{12366}{}^{x} f_{1255}, f_{12366}{}^{x} f_{1254})$
	$\Phi_1 \cdot \Phi_3(f_{1233}, f_{12566})$
	$\Phi_1 \cdot \Phi_4(f_{122}{}^{x} f_{144}, f_{122}{}^{x} f_{1455}, f_{122}{}^{x} f_{14566}, f_{122}{}^{x} f_{145633}, f_{1233}{}^{x} f_{144}, f_{1233}{}^{x} f_{1455}, f_{1233}{}^{x} f_{14566}, f_{12366}{}^{x} f_{144}, f_{12366}{}^{x} f_{1455}, f_{123655}{}^{x} f_{144})$
	$\Phi_2 \cdot \Phi_3(f_{1254}{}^{x} f_{12566}, f_{1254}{}^{x} f_{12563})$
	$\Phi_2 \cdot \Phi_4(f_{1255}{}^{x} f_{144})$
	$\Phi_3 \cdot \Phi_4(f_{12566}{}^{x} f_{144}, f_{12563}{}^{x} f_{144})$
	$\Phi_4 \cdot \Phi_5(f_{14566}{}^{x} f_{14522}, f_{14566}{}^{x} f_{145233}, f_{145633}{}^{x} f_{14522},)$
$\sum_{i=1}^{5}\sum_{j=i+1}^{5}\sum_{k=j+1}^{5}\left(\prod_{\rho=i}^{k}\Phi_\rho \cdot \prod_{\theta\neq i,j,k}^{5}\overline{\Phi_\theta}\right)$	$\Phi_1 \cdot \Phi_2 \cdot \Phi_3(f_{1233}{}^{x} f_{1254}{}^{x} f_{12566})$
	$\Phi_1 \cdot \Phi_2 \cdot \Phi_4(f_{1233}{}^{x} f_{1255}{}^{x} f_{144}, f_{12366}{}^{x} f_{1255}{}^{x} f_{144})$
	$\Phi_1 \cdot \Phi_3 \cdot \Phi_4(f_{1233}{}^{x} f_{12566}{}^{x} f_{144})$
$\sum_{i=1}^{5}\sum_{j=i+1}^{5}\sum_{k=j+1}^{5}\sum_{l=k+1}^{5}\left(\prod_{\rho=i}^{l}\Phi_i \cdot \prod_{\theta\neq i,j,k}^{5}\overline{\Phi_\theta}\right)$	None
$\prod_{\rho=1}^{5}\Phi_i$	None

there are some fire events belonging to multiple propagation paths, the number of fire events is fewer than expected. As an example, let's consider the case of $\Phi_1 \cdot \Phi_2$ at or fire event frequency second law of Eq.(20). Boolean multiplication can be done as follows

$$\begin{aligned}\Phi_1 \cdot \Phi_2 &= \left(f_{11} + f_{122} + f_{1233} + f_{12366} \right.\\ &\qquad \left. + f_{123655} + f_{123654}\right) \cdot \left(f_{1255} + f_{1254}\right) \\ &= f_{11} \cdot \left(f_{1255} + f_{1254}\right) + f_{122} \cdot \left(f_{1255} + f_{1254}\right) \\ &\quad + f_{1233} \cdot \left(f_{1255} + f_{1254}\right) + f_{12366} \cdot \left(f_{1255} + f_{1254}\right) \\ &\quad + f_{123655} \cdot \left(f_{1255} + f_{1254}\right) + f_{123654} \cdot \left(f_{1255} + f_{1254}\right)\end{aligned} \quad (21)$$

The two terms of the second law in Eq. (21) are eliminated since they are mutually exclusive. Although fire events f_{11} and f_{122} were not included in Φ_2 in Table 2, they have the same fire propagation path as the fire event in Φ_2. Also, the two terms of the fourth law in Eq. (21) are eliminated since they have the same compartment in their propagation path as defined in the assumptions of section 3; a compartment cannot allow more than one propagation path simultaneously. Compartment 5 exists in the propagation path of f_{123655}, f_{1255}, f_{1254} and f_{1255} simultaneously. Also, compartments 5 and 4 are the simultaneous propagation path in $f_{123654} \cdot f_{1254}$. As a result, $\Phi_1 \cdot \Phi_2$ can be reduced as follows

$$\Phi_1 \cdot \Phi_2 = f_{1233} \cdot \left(f_{1255} + f_{1254}\right) + f_{12366} \cdot \left(f_{1255} + f_{1254}\right) \quad (22)$$

Unexpectedly, there is no simultaneous propagation event with more than four propagation paths. This is due to the fact that there is no case of meeting assumption 1 in section 3.2.

Under this condition, a fire risk analyst should repeat the fire risk quantification 45 times for 45 state vectors for the fire risk quantifications initiated from compartment 1.

5. LIMITATION OF EXPLICIT IDENTIFICATION METHOD AND AN ALTERNATIVE

As shown in section 4, an explicit fire scenario identification method requires a large number of iterative quantifications for each state vector. If there is no limitation in the propagation numbers, there will be an exponential increase in the number of calculations. According to the process above, as the number of compartments in a fire area increases, the number of path vectors becomes larger. Furthermore, to make a fire event mutually exclusive, the event should be separated by using Eq. (18). Finally, the events in the path vector should be multiplied by the other path vector to generate all possible scenarios. From the fire propagation equation and the pilot example, there can be two types of asymptotic approach.

1. Truncation of events in a path vector depending on their propagation probability
2. Truncation of the combination of the path vector.

Applying approach 1, one can reduce the number of events in a path vector. By this truncation, the number of calculations will be significantly reduced. The second approach is to truncate the multiple combinations of events in the path vectors. If one propagation path is combined with another propagation path, its occurrence frequency will be reduced. As shown in the example in section 3.3, if the propagation number is limited, the number of state vectors can be reduced significantly.

Table 4 shows an example of a truncation of fire event scenarios. A limiting frequency of 1E-9 was applied to eliminate fire event scenarios of low occurrence frequency. The initiating fire event frequency and the propagation probability were assumed to have 1E-2 identically. As shown in the table, there remain sixteen fire event scenarios with an occurrence frequency larger than 1E-9. As the truncation limit of the occurrence frequency becomes larger, the fire event scenarios will be reduced. If one

Table 4. Fire Events and Their State Vectors Truncated by a Frequency Limitation of 1E-9

Combination of PV	Event	State vector
Single Path	$\Phi_1(f_{11}, f_{122}, f_{1233}, f_{12366})$	(1, 0, 0, 0, 0, 0), (1, 1, 0, 0, 0, 0) (1, 1, 1, 0, 0, 0), (1, 1, 1, 0, 0, 1)
	$\Phi_2(f_{1255}, f_{1254})$	(1, 1, 0, 0, 1, 0), (1, 1, 0, 1, 1, 0)
	$\Phi_3(f_{12566})$	(1, 1, 0, 0, 0, 1)
	$\Phi_4(f_{144}, f_{1455}, f_{14566})$	(1, 0, 0, 1, 0, 0), (1, 0, 0, 1, 1, 0), (1, 0, 0, 1, 1, 1)
	$\Phi_5(f_{14522})$	(1, 1, 0, 1, 1, 0)
Double Path	$\Phi_1 \cdot \Phi_2(f_{1233} \times f_{1255})$	(1, 1, 1, 0, 1, 0)
	$\Phi_1 \cdot \Phi_4(f_{122} \times f_{144}, f_{122} \times f_{1455}, f_{1233} \times f_{144})$	(1, 1, 0, 1, 0, 0), (1, 1, 0, 1, 1, 0), (1, 1, 1, 1, 0, 0)
	$\Phi_2 \cdot \Phi_4(f_{1255} \times f_{144})$	(1, 1, 0, 1, 1, 0)

applies a truncation limit of 1E-7, which is the commonly used value for the fire scenario truncation, seven fire scenarios will remain.

6. CONCLUDING REMARKS

A fire propagation equation was developed to identify the explicit states of the compartments of a fire area. The initiating fire event in an arbitrary compartment in a fire area was subdivided into sub-events according to their propagation paths. Then, the fire event was regrouped to obtain an exclusive fire event set depending on the fire's propagation path. Finally, the grouped fire event in a path vector was reformulated to confer exclusiveness to each fire event. To show the appropriateness of the developed fire propagation equation, an example calculation for a simple 2X3 rectangular fire area was performed.

Although the developed equation can be applied to the explicit identification of all possible fire events, it has some difficulty when the number of compartments in a fire area increases because there is an exponential increase of fire event scenarios as a function of the number of compartments.

The problem of the exponential increase of fire event scenarios, however, can be mitigated by applying an approximation method in the development of fire propagation path vectors and their associated events and the combination of path vectors for generating an exclusive fire event set.

It is expected that, by applying this fire propagation equation, fire risk assessment can be more realistic and, in some cases, there may be an increase of the estimation of fire risk due to an increase in fire event scenarios.

ACKNOWLEDGEMENTS

This study was performed under the Long-term Nuclear R&D Program sponsored by the Ministry of Science and Technology.

NOMENCLATURE

- CDF : Core damage frequency
- CDF_i : Core damage frequency by a fire in the i'th h compartment
- R_i : Fire event in the sense of Boolean or fire event frequency
- R_{ij} : Fire event or frequency propagated from the i'th compartment to the j'th compartment
- $f(R_i)$: Frequency of event R_i
- $CCDP_i$: Conditional core damage probability of a fire event in the i'th compartment
- $CCDP_{ij}$: Conditional core damage probability of fire event propagated from i'th compartment to j'th compartment
- FE_i : An initiating fire event in the i'th compartment
- $\vec{S}$: State vector of a fire area
- s_i : State of the i'th compartment, 0 for no fire event, 1 for a fire event in the i'th compartment
- f_{ij} : A fire event propagated from the i'th compartment to the j'th compartment in the Boolean algebra
- f_{ii} : A fire event stopped at i'th compartment
- $f_{ij}\ldots ll$: A fire event stopped at the l'th compartment
- C_i : Number of compartments adjacent to the i'th compartment
- P_k : k'th path vector for a fire propagation path
- Φ_i : A group of events belonging to the i'th path vector

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