# A Case Study of Probabilistic Safety Assessment of Radioactive Materials Transport at Tunnel Fires

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## INTRODUCTION

The Construction of a nuclear-cycle facility at Rokkasho-mura in Aomori Prefecture in Japan is being planned, and a uranium enrichment plant is already operating there. Vehicle carriers and ships are used to transport SF, UF6, LLW, etc., within Japan and from overseas. As Japan is very mountainous, it is important to investigate the possibility of tunnel fires and a fall from a bridge in evaluating the safety of transporting radioactive materials (RAM). Accident scenario probabilities and their environmental effects should be investigated, particularly since some routes pass through urban areas.

On the first step, in order to establish Probabilistic Safety Assessment (PSA) for transport of RAM in Japan, we proposed our concepts of PSA at PATRAM'92 (N. Watabe, H. Suzuki., et al, 1992). Our approach of PSA for transport of RAM has two views, one all-inclusive and the other local. The all-inclusive PSA examines the entire route to assess latent risks. The local PSA checks critical sites to discuss emergency plans. Table 1 describes the comparison between them. On the second step, we were collecting the data of dangerous traffic accident and were checking the fault tree and the probabilistic data. But to determine the probability of severe accident, the raw data is insufficient and it is necessary to combine some data for using in our PSA.
This paper describes a method of calculating the remote probability of a severe accident and investigates compliance with IAEA transport regulations on fire by using a tunnel fire simulation .

**Table 1. Comparison Between All-inclusive and Local**

| | Target | Main Methods | Purpose |
|---|---|---|---|
| All-inclusive PSA | Whole route | Fault Tree Analysis | Assess latent risks,etc |
| Local PSA | Critical sites | Fault Tree Analysis<br>Event Tree Analysis | Check emergency plans,etc |

## APPROACH

In our previous study, "fire of the vehicle used to transport dangerous articles" or "fire involving more than three vehicles" was defined as a "severe fire of 800℃ for 30 minutes," and an accident scenario was developed. In this study, we modify the fault tree and calculate the probability of exceeding 800℃ for 30 minutes when a self-combustion or single-vehicle fire occurs in a tunnel (see Fig. 1).

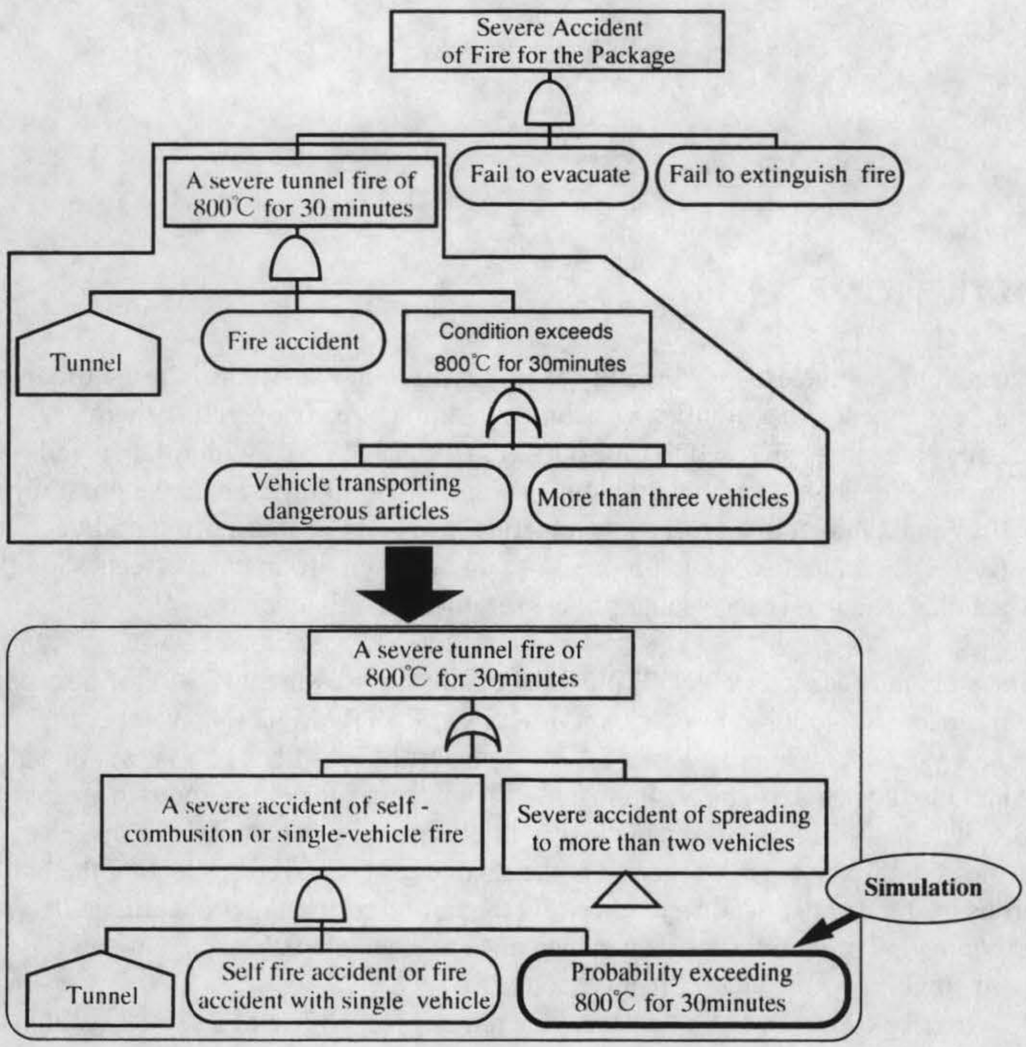


**Fig. 1. Fault Tree of Severe Tunnel Accident**

Figure 2 shows the approach of this study. The approach of this study consists by seven steps and the third step divides into two steps. One is the case studies of target parameters which are selected by the first step. And the other is the simulation at 800℃ for 30 minutes for comparison. From the fourth step to sixth step are to calculate the heat quantity of the package which is reasonable criterion of tunnel fires in this study for treat various tunnel fires by unific way and to determine the probability of the heat quantity. Finally, we estimate the probability of exceeding 800℃ for 30 minutes.

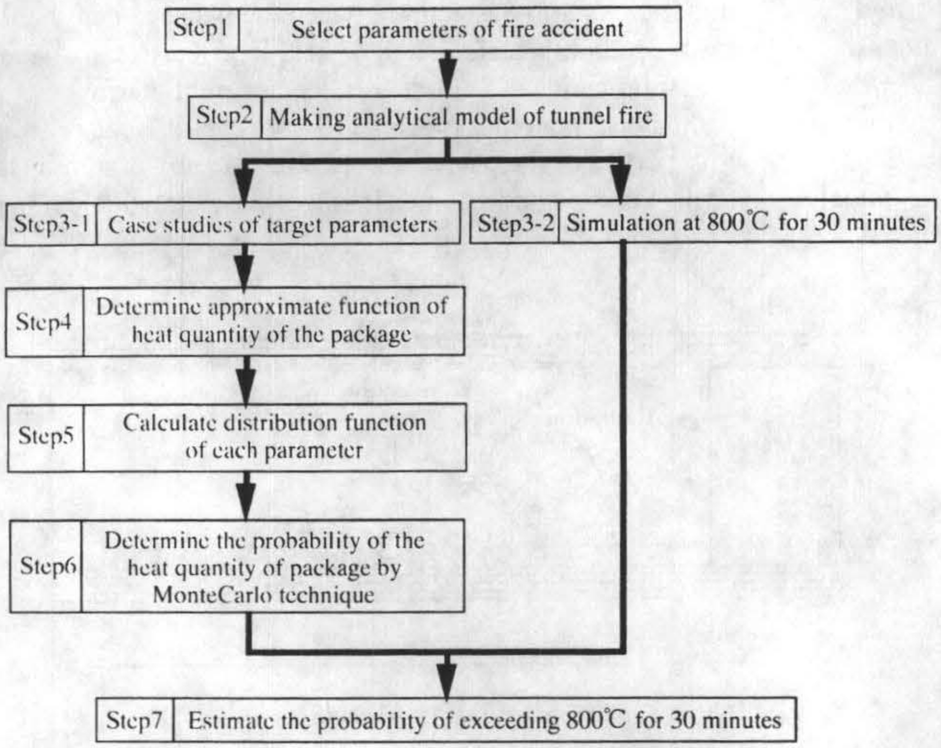


**Fig. 2. Approach of This Study**

# TUNNEL FIRE SIMULATION

## Selection of Analytical Parameters

The required parameters of the simulation of a tunnel fire are described in Table 2. In this simulation, "heat generation of the flame," "distance between the package and the flame," and "fire duration" were selected, because these parameters are related to the accident scenario and directly control the heat quantity of the package. A 48Y cylinder filled with UF6 was assumed as the transport package. FEM code "ABAQUS" was used for the analysis.

**Table 2. Parameters of Tunnel Fire**

| | Parameter related to fire condition | Parameter related to package |
|---|---|---|
| Parameter considered in this paper | Heat generation,Duration of fire | Distance from the flame |
| Other parameters | Inflammables, shape of the flame, emissivity of the flame, wind velocity, tunnel length, incline of the tunnel, emissivity of the wall, etc. | Package size, emissivity of the package surface, contents of the package, etc. |

## Analytical Model

The 2D model shown in Figure 3 was used to investigate the influence of a tunnel fire on the transport package. The accident situation is that the other vehicle or the transport truck is destroyed by fire and there are no obstacles between the package and the flame. The emissivity of each surface used in the calculation of heat transfer is shown in Table 3. To consider the effect of natural convection of the air, the apparent thermal conductivity multiplied by the Nuselt number ($=9.7 \times 10^2$) was used. Heat generation of the flame and the physical properties of the package were converted by assuming the width of the tunnel to be 10 m. Figure 4 shows an example of the finite element mesh used for analysis.

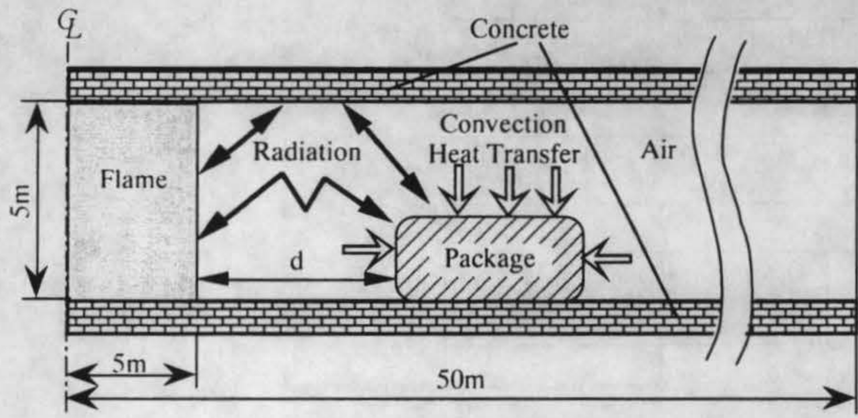


**Fig. 3. Simulation Model**

**Table 3. Emissivities of Each Surface**

| Flame Surface | Package Surface | Tunnel Wall |
|---|---|---|
| 1.0 | 0.6 | 0.6 |

**Fig. 4. Finite Element Mesh of Tunnel Fire (d=1 meter)**

## Case Studies

The parameters considered in the case studies are the heat generation of the flame (q), the distance between the package and the flame (d), and the duration of the fire (t). Three cases of heat generation are considered because Fire Research Institute lists the heat generation of a car, truck, and vehicle that transports dangerous articles as 3MW, 10MW, and 20MW, respectively, for public use (M. Kawasaki, K. Satoh, et al, 1988).
The distance between the package and the flame is assumed to be from 1 to 10 m, because we assume the distance of most collision accidents is within 5 m according to the statistic of the Ministry of Transport. Furthermore, the heat quantity of the package that is more than 10 m apart is negligible. The duration of fire is assumed to be from 0 to 60 minutes.

**Table 4. Parameter Value of the Case Studies**

| Parameter | | Numerical Value |
|---|---|---|
| Flame heat generation | q | 3MW,10MW,20MW |
| Distance between flame and the package | d | 1m,2m,3m,5m,10m |
| Duration of fire | t | 0-60min |

The heat quantity of the package in each case is calculated by the following equation :

$$Q_{in} = \sum_{i=1}^{n} \left\{ \rho_{cyl} \times Cp_{cyl} \times V_i \times (T_i - T_0) \right\} + \sum_{j=1}^{m} \left\{ \rho_{UF6}(T_j) \times Cp_{UF6}(T_j) \times V_j \times (T_j - T_0) \right\} \ldots \quad (3.1)$$

where,

$Q_{in}$: Heat Quantity of Cylinder
$Cp$: Heat Capacity
$T$: Temperature of Each Mesh
Subscription cyl: About the Cylinder
$\rho$ :Density
$V$ : Volume of Each Mesh
$T_0$: Initial Temperature
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The heat quantity of the package at 800℃ for 30 minutes is simulated as the condition of the transport regulation Figure 5 shows an example of the analyzed distribution of temperature.

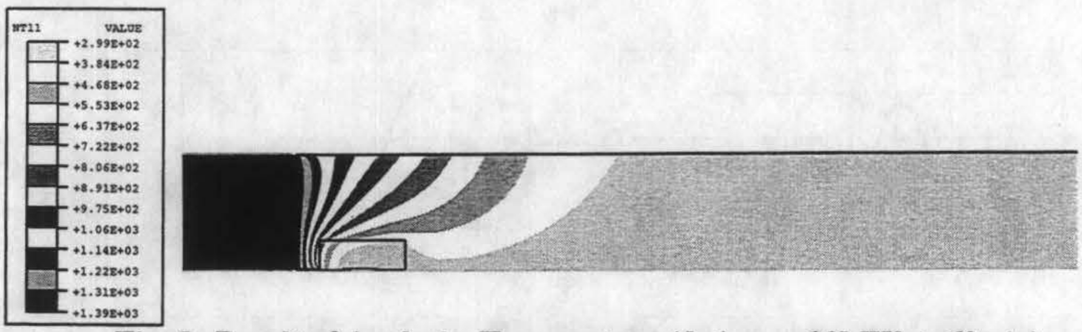


**Fig. 5. Result of Analysis: Temperature (d=1m, q=20MW, t=60min)**

# RISK CURVE

## Approximation of Heat Quantity

Using the result of the case studies, the approximate equation for the heat quantity of the package was determined by multiple regression analysis. The heat quantity of the package (Qin) is defined by equation (4.1) as the summation of up to the 2nd power of three parameters, which are the heat generation of the flame (q), the distance between the package and the flame (d), and the duration of the fire (t).

$$Q_{in} = \sum_{i=0}^{2} \sum_{j=0}^{2} \sum_{k=0}^{2} a_{ijk} \frac{q^i t^j}{d^k} \quad \ldots \quad (4.1)$$

It was thus shown that even if the package is exposed within 1 m from a dangerous article vehicle fire for 30 minutes, the heat quantity of the package ($2.62 \times 10^8$J) is less than that of calculated under IAEA regulation condition ($3.02 \times 10^8$J).

## Probability Density Function of Parameters

The probability density function of fire scale reported by the Sandia National Laboratory was used (Clarke, R.K., Foley, J.T., et al, 1976). Figure 6 shows the relation between the fuel quantity of the truck and probability. Since the heat generation is chosen for the flame scale in this paper, the fuel quantity is converted at the rate of 1MW to 30 liters, and equation is shown as follows:

$$P_q = 1.363 \times 10^{-4} q^{2.68} \exp\left\{-\left(q^{2.68}/16\right)^{3.68}\right\} \quad \ldots \ (4.2)$$

where,

$P_q$: Probability of heat generation $\quad$ $q$: Heat generation

The probability density function of duration of fire reported by Sandia National Laboratory was also used. The following equations and Figure 7 show the relations:

(i) t $\leqq$ 20 minutes

$$P_t = 0.032 t^{0.38} \exp\left\{-(t/15.3)^{1.38}\right\} \quad \ldots \ (4.3)$$

(ii) t $>$ 20 minutes

$$P_t = \left\{0.023/(t-20)^{0.448}\right\} \exp\left[-\left\{(t-20)/24.3\right\}^{0.552}\right] \quad \ldots \ (4.4)$$

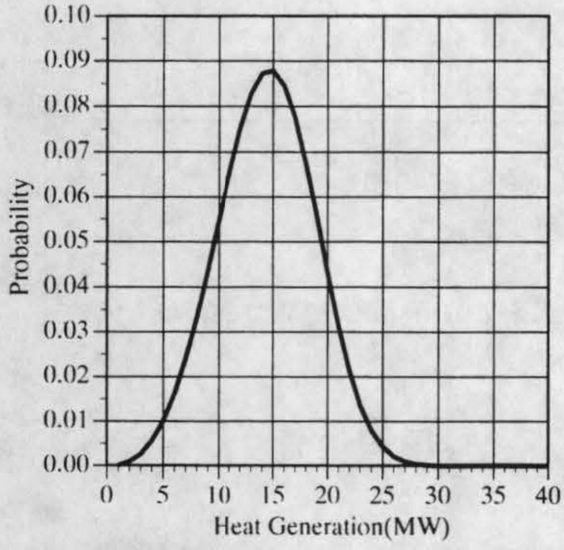


Fig. 6. Probability of Flame Heat Generation

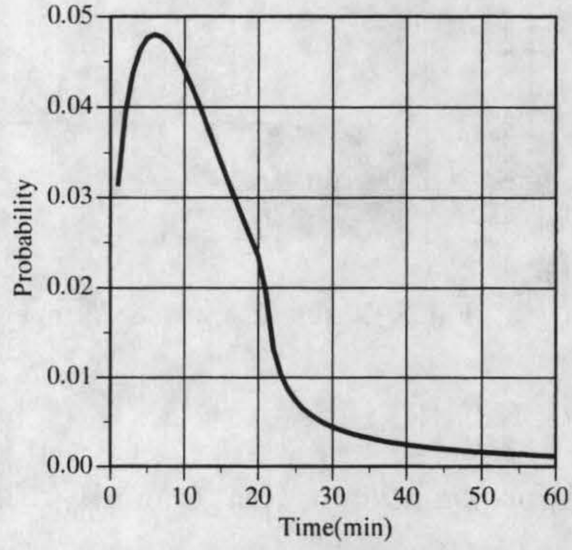


Fig. 7. Probability of Fire Duration

The distance between the package and the flame is set as shown in Table 5 by using statistics of accidents.

**Table 5. Relation between Accident and Distance**

| | Accident situation | Distance (d) | Percentage |
|---|---|---|---|
| Case1 | Single-vehicle accident | 0-1 (m) | 35% |
| Case2 | Colision accident and not separated | 1-5 (m) | 45% |
| Case3 | Colision accident and separated | 5-10 (m) | 20% |

We assessed the three situations, self-combustion or a collision accident with a separation of less than 1 m, 1 to 5 m, and 5 to 10 m, respectively. As the statistics show, 35% of accidents are within 1 m (Regional Traffic Bureau of the Ministry of Transport, 1991). We considered that 70% of collision accidents are 1 to 5 m, and hence the probability of the distance is as shown in Figure 8.

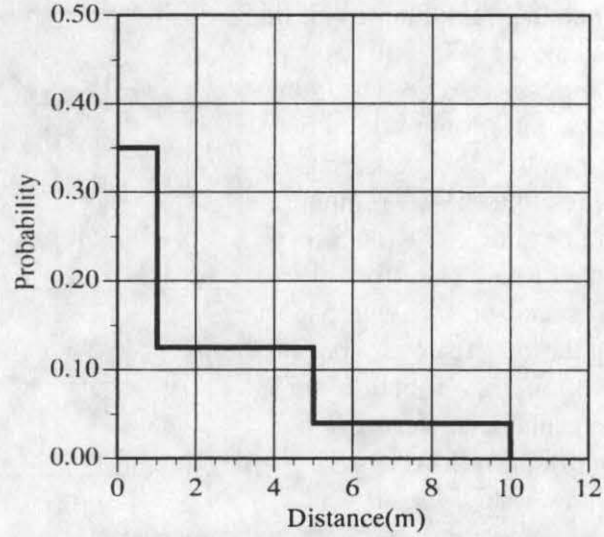


**Fig. 8. Probability of Distance from Flame**

## Risk Curve of Tunnel Fires

Assuming that each parameter is independent, the probability of the heat quantity of the package can be calculated by Monte Carlo technique. This technique uses random numbers depending upon probability distribution of heat generation, distance, and duration. The risk curve of tunnel fires shown in Figure 9 is based on the probability of the parameter and equation (4.1) is determined from the simulation result. Figure 10 shows the probability of heat quantity of the package.

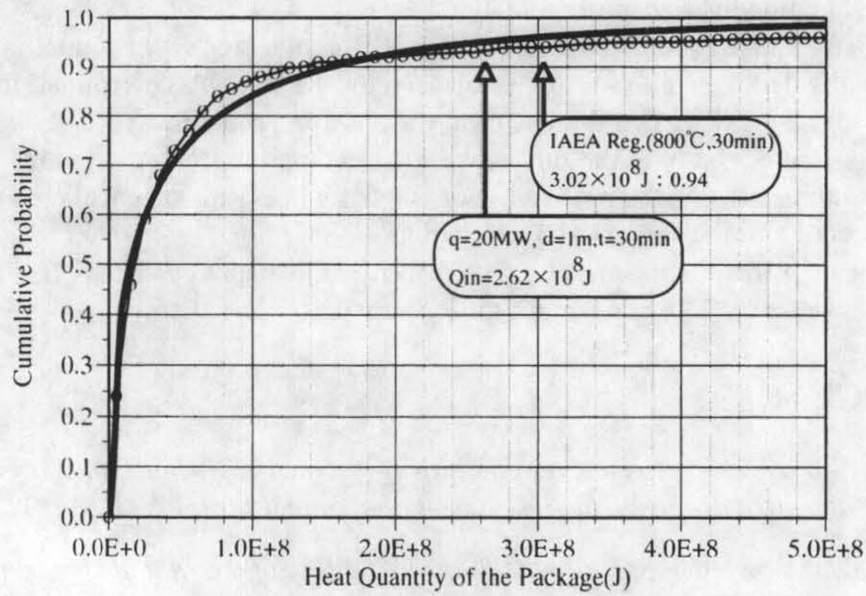


**Fig. 9. Risk Curve (Heat Quantity of the Package VS. Cumulative Probability)**

The approximate equation is shown as follows:

$$F = 1 - \exp\left\{-\left(Q_{in} / 3.009 \times 10^{7}\right)^{0.5103}\right\} \qquad \ldots (4.5)$$

where,

$F$: Cumulative Probability $\qquad Q_{in}$: Heat quantity of the Package (J)

Since the heat quantity of the package at 800℃ for 30 minutes is $3.02 \times 10^8$ J, on this simulation model, it is known that the packages designed to IAEA regulations will be safe in 94% of all tunnel fires. The probability of exceeding IAEA transport regulation of fire is 0.06. In addition, the probability of the package suffering condition of 800℃ for 30 minutes is $2.14 \times 10^{-10}$.

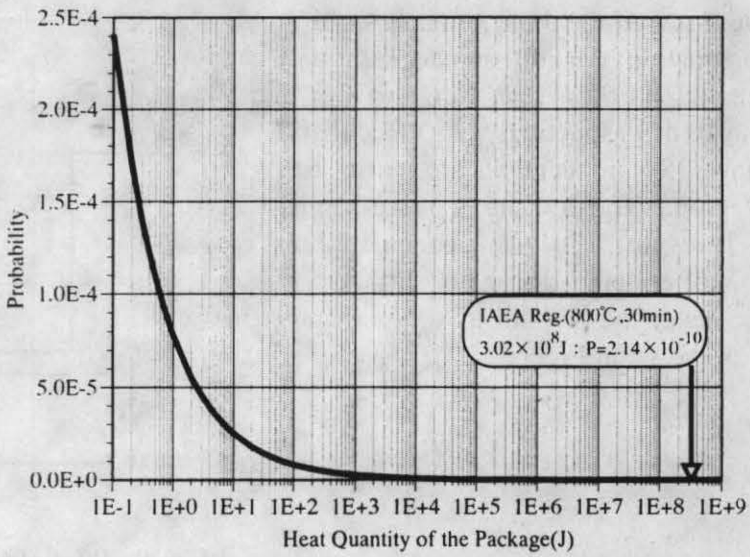


**Fig. 10. Probability of Heat Quantity of the Package**

## CONCLUSIONS

It was shown that even if the package is within 1 m of a fire with a vehicle transporting dangerous articles for 30 minutes, the heat quantity of the package ($2.62 \times 10^8$J) is less than that calculated under IAEA regulation conditions ($3.02 \times 10^8$J). This result will be used to draw up an emergency plan in near future. The risk curve shows that the packages designed to IAEA regulations will be safe in 94% of all tunnel fires. This result will be used for the evaluating the transport regulations.

Assuming the situation of a single-vehicle fire or self-combustion in the tunnel in this paper, we investigated the conditions that exceeded the regulation's determinations. And as the result of this study, we could make clear the obscure probability of severe accident. The probability is about 0.06. In the future, we will develop the simulation model to consider a spreading fire and the probability of whole tunnel fire accidents. We will also study the effects of extinguishment and evacuation.

Finally, we consider that the methodology described in this paper can be applied to other accidents, and we would like to extend it to real transportation situations.

## REFERENCE

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