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A Study on Prediction of Time Required in Firefighting Activities Through Fireground Field Experiments

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Abstract: Fire stations strive to suppress fires and save lives by arriving at fire points as quickly as possible after receiving a report of fire in order to reduce human casualty and property damage. The time required to arrive at a fireground depends on the road conditions and distance. The fire point detection time, however can be reduced through efficient arrangement and training of firefighting personnel. A number of studies have been conducted on the methods for the fast arrival of fire brigade's to a fire point. However, there have not been a sufficient number of studies on reducing the time required in fire point detection and fire suppression. Therefore, in this study, a Standard Operating Procedure (SOP) for firefighters was developed targeting residential fires and the time required in each task was standardized through fireground field experiments. In addition, the fire suppression time and effect were measured and analyzed by temperature and the number of fire nozzles used. Through the experiment and analysis, empirical formulas to predict the time required in firefighting activities were derived.

Key words: Fire suppression time, fire fighting activity, fireground field experiments, crew size, fire point, analysis

INTRODUCTION

In line with the advancement of the industrial society as of late, buildings are becoming taller and multiplexed. This results increased human casualties and property damage in the event of a fire.

At this, Korea introduced the golden time system in May, 2010 with a goal to ensure arrival at a fireground by fire engines and ambulances within 5 min (Anonymous, 2014).

With the introduction of this system, a supporting system was established to control traffic signals, open the road for fire engines and assist fire engine drivers (Lee, 2016; Anonymous, 2015).

The fire authorities have set up a goal to improve the rate of fireground arrival by fire engines and ambulances within 5 min from 58% in 2013-74% in 2017.

However, studies on securing the golden time through reduction of firefighting activities after arrival at a fireground have not been conducted sufficiently. In this study, the term "fire point detection time" refers to the time from the firefighter's arrival at a fireground to the fire point detection and the term "firefighting time" refers to the time required in performing the 13 tasks developed on the basis of the NIST's time-to-task as well as the firefighting standards and manuals currently applied in Korea.

In addition, "fire suppression time" refers to the time between from the commencement of water spraying using fire nozzles (one or two) to a state where re-ignition is not detected within three minutes from the disappearance of flames. Figure 1 shows firefighter's response activities by stage from the reception of a fire report.

Therefore in this study, we will measure the time required in fire point detection such as from arrival at a fireground to fire suppression. For this, an SOP suitable to the conditions in Korea was developed through an analysis of domestic and overseas data targeting residential facilities subject to high fire occurrence frequencies and serious casualties and the fire point detection time was measured (Kim, 2015; Anonymous, 2016a-c).

In addition by calculating the average time required in each task and the fire suppression time according to the number of mobilized personnel such as through an analysis on the fire suppression time by temperature and the number of fire nozzles (personnel) used, it was intended to suggest the equations for predicting the fire point detection time and fire suppression time Table 1.

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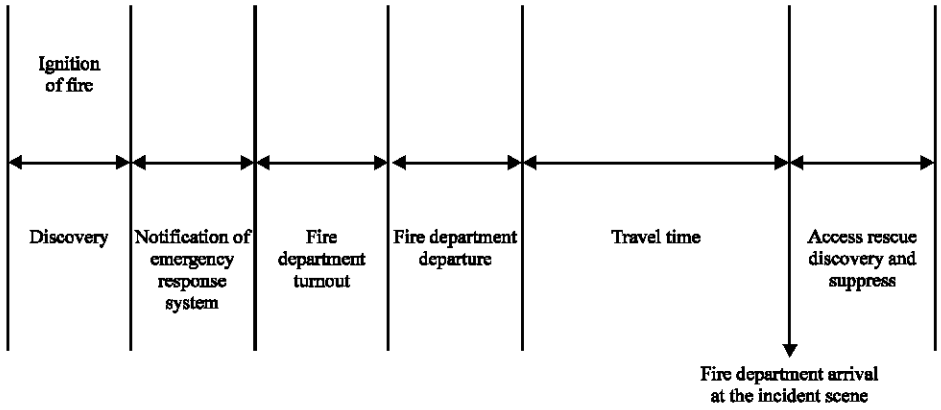

Fig. 1: Hypothetical timeline of fire department response to structure fire

Table 1: Regulations on standards of firefighters and equipment

Fire engine (1st team)		Fire engine (2nd team)		Water tank vehicle		Aerial ladder		Foam truck		Head	
Driver	Fire fighter	Driver	Fire fighter	Driver	Fire fighter	Driver	Fire fighter	Driver	Fire fighter	Driver	Fire fighter
3	9	3	6	3	3	3	6	3	9	3	-

MATERIALS AND METHODS

Korean-style SOP development method: As for the fire suppression technology standards in Korea (Anonymous, 2012), fire service academies and fire departments are providing internal training and educational programs (Anonymous, 2016a-c). However, a standardized guideline has not been established.

Therefore, in this study, the measuring variables associated with time-to-task goals which were developed by NIST of the US for job competency assessment and the 22 related items were analyzed (Anonymous, 2010).

For this study, fire response assessment items were set based on the analysis result according to the conditions in Korea. In addition, measurement items were selected on the basis of the photographs taken at the actual firefighting sites. Then, through a questionnaire survey and an FGI (Focus Group Interview) with professional firefighters, a Korean-style SOP was suggested.

Fire point detection time measuring: In this study, fire point detection time refers to the time from the firefighter's arrival at a fireground to the time of fire point detection and firefighting time refers to the time required in performing the 13 tasks developed on the basis of the NIST's time-to-task as well as the firefighting standards and manuals currently applied in Korea.

As for the fire point, the light of an electric bulb was used. In addition, using a smoke generator, an environment similar to that of a fireground was created. As a location of the fire point, one compartment was randomly selected from compartments 1-4 shown in Fig. 1. Then, firefighters searched for the fire point in order starting from compartment 1.

Table 2: Conditions for fire point detection time measuring

Items	Description
Test location	Gyeonggi Fire Service Academy fire test building
Fire source	3rd floor (compartments 1-4)
Firefighter experience	Over 5 years of experience as a instructor firefighter
Crew size	2-6 firefighters
Number of tests	3 times by crew size (15 times in total)
Number of SOP evaluation Items	13

As for the firefighting time, each firefighter performed the firefighting activity three times. The number of firefighters is prescribed as in Table 1 (Anonymous, 2016a-c). A total of six firefighters are assigned to the first mobilization to operate one fire engine (one firefighter for driving the fire engine and three for fire suppression) and one water tank truck (one for driving and one for fire suppression) (Anonymous, 2016a-c).

However, in reality, there are cases where a smaller number of firefighters are sent to a fireground. Therefore, the firefighting test was conducted by varying the number of firefighters as 6, 5, 4, 3 and 2.

Test conditions: The conditions for fire point detection time measuring are as listed in Table 2 and the test location is shown in Fig. 1. Figure 2-6 show the key activities of the firefighting force for fire point detection.

Full-scale fire suppression test

Test conditions: The conditions for the fire suppression test are as listed in Table 3. As for the water

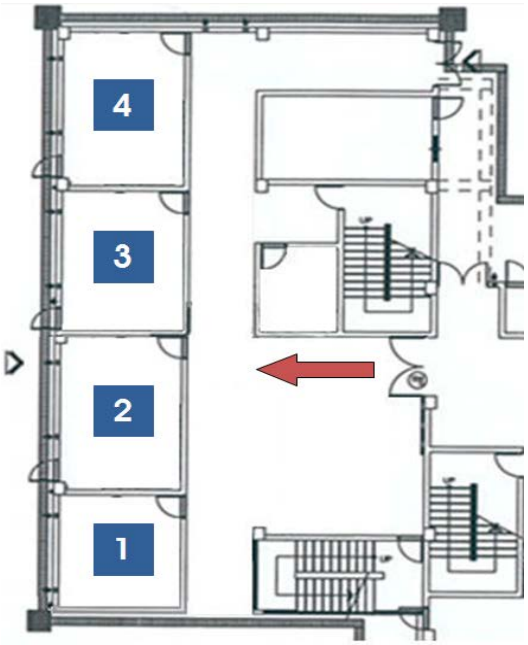

Fig. 2: Gyeonggi Fire Service Academy fire test building

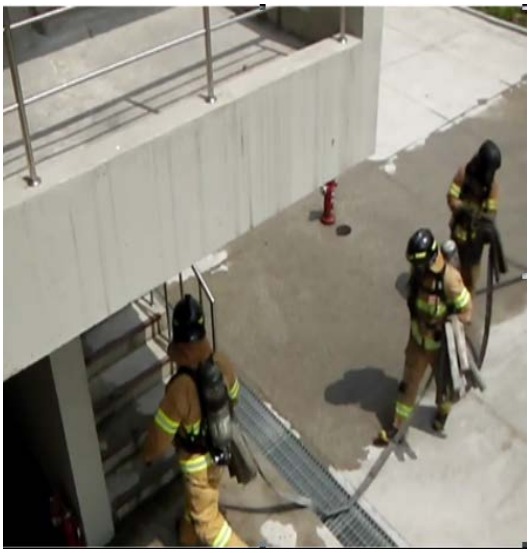

Fig. 3: Firefighters taking out a hose

discharge, a disperse type method was used and the water discharge pressure was 0.5 MPa. To each nozzle, one each of a hose man and an assistant was assigned (Chun *et al*., 2008).

The temperature for suppression commencement was divided into an initial phase 300°C, development phase 500°C and peak stage 700°C according to the fire growth curve (Kwon *et al*., 2014). Under these conditions, the fire suppression test was conducted 30 times in total. Fire

Fig. 4: Firefighters arriving at the upper level

Fig. 5: Firefighters ready to discharge water

Fig. 6: Firefighters opening door

Table 3: Conditions for fire suppression test

Items	Description	Remarks
Test location	Gyeonggi Fire Service Academy, Fire test building	
Usage	Residence	
Fire test room size	28.05 m^2	
Fire load (kg/m^2)	Combustibles equivalent to wood, 19.0 (kg/m^2) (Yun, 2008)	
Placing of thermocouple	Located 1 m away from the entrance with one at every 0.3 m height up to 3 m	
Combustibles	Wood pallets	
Placement of combustibles	No separation from walls (Seo, 2015)	Residence
Firefighter experience	Over 5 years of experience as a firefighter instructor	
Discharge water pressure	0.5 MPa	
Discharge water type	Disperse type	
Temperature at suppression commencement (°C)	300, 500, 700°C (temperature measured at 1.8 m height)	3 times average
Suppression completion time	The time it takes for the flames to be invisible after water discharge Flames not re-ignited within 3 min from fire suppression	
Hose men	2 firefighters per hose	Hose man 1, Assistant 1

extinguishing as defined for the test, refers to the time from the commencement of water spray to the flames being no longer visible to the eyes and it was measured only when the flames did not re-ignite within three minutes from a decision that the fire extinguishing was completed.

Lastly, the test was conducted using one nozzle when there were 2-4 firefighters and two nozzles when there were 5 and 6 firefighters.

RESULTS AND DISCUSSION

Korean-style SOP development: Through an in-depth analysis of the firefighting personnel arrangement standards applied in overseas countries and the time-to-task items developed by NIST, an SOP of 13 items as listed in Table 4 was developed based on the firefighting standards and manuals used in Korea.

Fire point detection time: The time calculated in Table 5 refers to the time to complete all 13 tasks from the choke installation to the fire point detection in a randomly selected compartment. According to the test result when six firefighters were mobilized, the firefighting time reduced by approximately one minute and 10 sec compared to when only two were used. This shows that the fire point detection time can be shortened when two search teams are mobilized rather than one.

In addition, by filming a video of the process, the time required in each task listed in Table 4 was averaged in Fig. 7. Table 6 shows the input variables by task and according to the No. of firefighters.

Fire suppression test result: Figure 8 is a graph showing the time to reach the set temperatures (300, 500 and 700°C) in a complete ombustion test using wood pallets (Kwon *et al*., 2014). Figure 8 shows the scenes of combustion and water discharging. With the set temperature of 300°C, it took approximately 766 sec to reach the temperature from fire ignition. As for 500 and 700°C, the time from ignition to reaching the temperature was approximately 910 and 1,083 sec, respectively. In the case of complete combustion, the maximum temperature was measured at around 780°C.

In the fire suppression test when one nozzle was used as in Table 7 fire extinguishing was completed in 24, 64 and 103 sec from the commencement of water discharging when the set temperatures were 300, 500 and 700°C, respectively. When two nozzles were used, fire extinguishing was completed in 19, 49 and 74 sec for 300, 500 and 700°C, respectively (Fig. 9).

In comparison to the use of one nozzle, the fire extinguishing completion time reduced by approximately 21% from 24-19 sec when two nozzles were used at an indoor temperature of 300°C. Similarly, in the case of 500 and 700°C, the time decreased by approximately 25% from 65-49 sec and by approximately 29% from 102-74 sec, respectively.

In addition, the fire suppression time using one nozzle increased by approximately 2.7 times from 24 sec at the temperature of 300°C to 65 sec at 500°C as shown in Table 8. At a temperature of 700°C, the time increased by 4.25 times to 102 sec. In the case of two nozzles, the time also increased from 19 sec at 300°C to 49 sec at 500°C which is by approximately 2.6 times and to 74 sec at 700°C which is an increase by approximately 3.9 times.

Firefighting activity and fire suppression time Prediction equation development (Tt)

Firefighting time prediction equation (Task): The firefighting time can be predicted by entering the values in Table 6 to the Eq. 1 derived from the fire point detection and fire suppression tests and adding up the results:

$$Task_t = Prepare_t + Stair_t + Move_t + Detect_t \quad (1)$$

Table 4: List of tasks for measuring firefighting time

Tasks	Start	Stop
Chocking	Firefighters get off the fire engine	Firefighters install chocks at wheels of the fire engine
Wearing gear	Firefighters install chocks at wheels of the fire engine	Firefighters wear the gear
Entering building	Firefighters take out the hose	Firefighters enter the front door
Ascending stairs	Firefighters enter the front door	Firefighters arrive at upper level
Arranging hose	Firefighters arrive at each level	Firefighters are ready to use the hose
Ready to discharge water	Firefighters are ready to use the hose	Firefighters arrive at the door of the household in fire
Filling fire water	Firefighters arrive at the door of the household in fire	Firefighters are ready to discharge water
Discharging on wall	Firefighters are ready to discharge water	Firefighters discharge water toward the wall
Entering inside	Firefighters discharge water toward the wall	Firefighters open its door
Discovering a compartment	Firefighters open its door	Firefighters discover the 1st compartment
Searching inside (for people)	Firefighters enter the compartment	Firefighters finish to search inside (people)
Traveling between compartments	Firefighters finish to search inside (people)	Firefighters discover the other compartment
Detecting fire point	Firefighters enter the compartment on fire	Firefighters discover the fire point

Table 5: Firefighting time measurements

Items	2 people	3 people	4 people	5 people	6 people
Average	06:42	06:19	05:53	05:34	05:32
Once	06:34 (2nd room)	05:57 (2nd room)	05:03 (1st room)	05:41 (1st room)	05:58 (2nd room)
Twice	08:11 (4th room)	05:12 (1st room)	05:37 (3rd room)	05:45 (3rd room)	05:50 (3rd room)
Three times	05:22 (1st room)	07:47 (4th room)	07:00 (4th room)	05:11 (4th room)	04:5 (1st room)

Table 6: Input variables for firefighting time according to the no. of firefighters

Tasks	Chocking	Wearing gear	Entering building	Ascending stairs	Arranging hose	Preparing discharge water	Filling fire water	Discharging water to walls	Entering inside	Discovering a compartment	Searching inside (for people)	Traveling between compartments	Detecting fire point
2 people	21.6	33.6	13.8	16.2	6.6	37.2	40.8	4.8	33.6	77.4	25.2	24.6	1
3 people	19.2	9.6	27.6	15.0	0	40.8	39.6	5.4	24.6	72.6	24.0	33.0	1
4 people	13.2	9.6	24.6	16.2	0	40.2	27.6	10.2	24.0	75.6	25.8	25.8	1
5 people	11.4	15.6	22.8	17.4	0	53.4	46.2	6.6	22.8	67.2	24.0	21.6	1
6 people	11.4	15.6	19.8	20.4	0	52.8	40.2	7.8	24.6	62.4	25.2	23.4	1

Table 7: Average fire suppression time according to room temperature and No. of hoses

Hose (ea)/Room temp. (°C)	1 sec	2 sec	Reduction rate compared to 1 hose (%)
300	24	19	21
500	65	49	25
700	102	74	29

Table 8: Comparison of fire suppression time increasing rates by temperature

Hose (ea)/Room temp. (°C)	1	2
300	24 sec	19 sec
	-	-
500	65 sec	49 sec
	Increase by 2.7 times compared to that of fire suppression at 300°C	Increase by 2.6 times compared to that of fire suppression at 300°C
700	102 sec	74 sec
	Increase by 4.25 times (1.57 times) compared to that of fire suppression at 300°C (500°C)	Increase by 3.9 times (1.51 times) compared to that of fire suppression at 300°C (500°C)

$Task_t$: Fire-fighting time (sec)
$Prepare_t$: Chocking~entering building (sec)
$Move_t$: Ready to discharge water~entering inside (sec)
$Detect_t$: Detecting fire point (sec)

$$Stair_t = \{(B_{floor}-1)\times B_s\} + \{(B_{floor}-2)\times H_p\} [sec] \quad (2)$$

B_{floor} : Fire point floor
B_s : Ascending stairs
H_p : Arranging hose

Using Eq. 1, the time required in fire point detection according to the No. of firefighters can be calculated using the 13 items from choking immediately after arrival at the fireground to detecting fire point.

Equation 2 is used to calculate the time required in ascending stairs after entering a building. For instance, to suppress fire on the fourth floor, firefighters need to climb three flights of stairs. Therefore, the time required in ascending stairs can be calculated as fire point floor-1×stair ascending time.

In the case of two firefighters, it is necessary for the firefighters to arrange the hose when ascending the stairs. Therefore, the time for arranging the hose is additionally required.

The time for arranging the hose is calculated as fire point floor in the building-2×hose arranging time. To suppress fire on the fourth floor, firefighters climb up the stairs 3 times. However, what they do first when arriving on the fire point floor is to arrange the hose and prepare for water discharge. So, for the last floor, the time for hose arrangement is not added. In the case of one search team (comprised of 2-4 members):

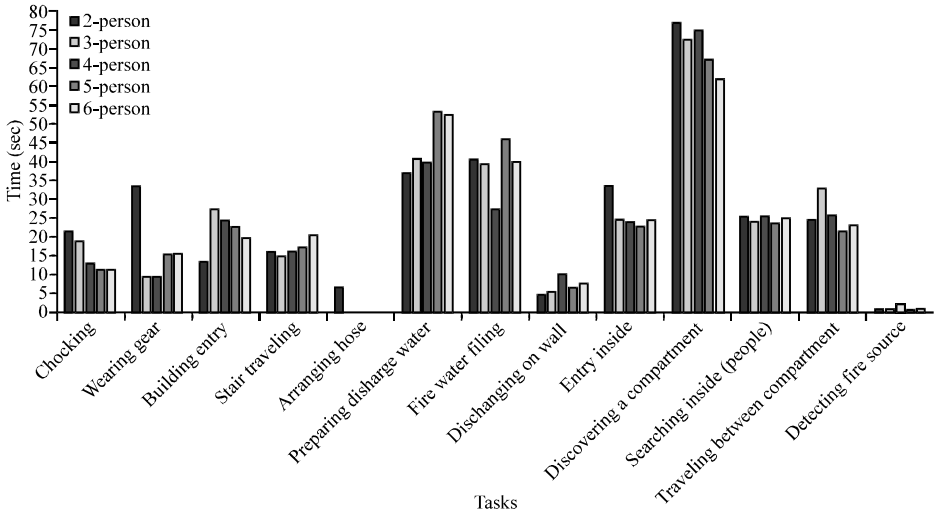

Fig. 7: Average firefighting time according to the No. of firefighters

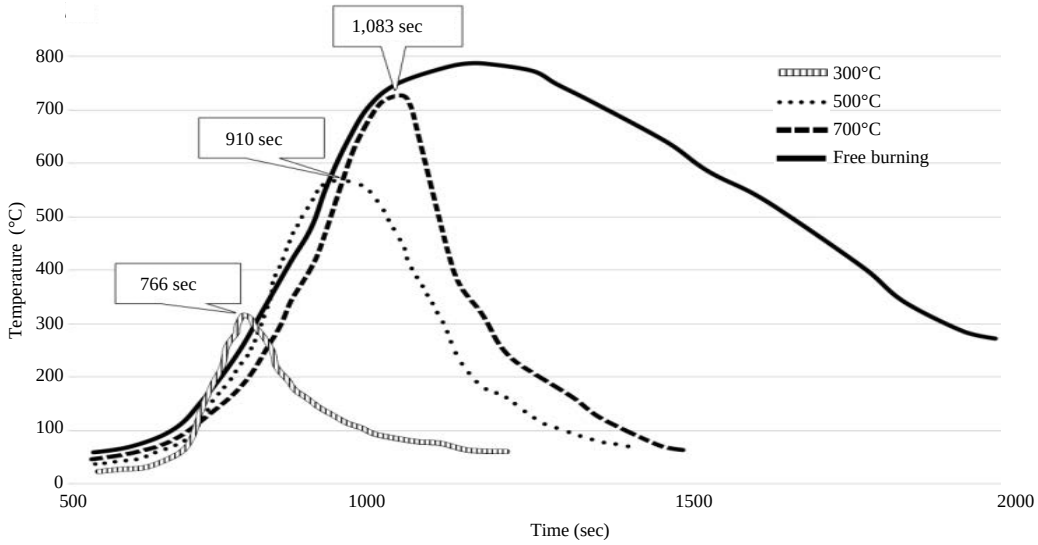

Fig. 8: Results of wood pallet combustion test

Fig. 9: Combustion of wood pallets and discharging water

$$Detect_t = T1_t + \{T2_T \times (N-1)\} + [T3_t \times (N-1)\} + T4_t \quad (3)$$

In the case of two search teams and an odd-numbered compartment (5 or 6 members):

$$Detect_t = T1_t + \frac{\{T2_t \times (N-1)\} + \{T3_t \times (N-1)\}}{2} + T4_t \quad (4)$$

In the case of two search teams and an even-numbered compartment (5 or 6 members):

$$Detect_t = T1_t + \frac{\{T2_t \times (N-2)\} + \{T3_t \times (N-2)\}}{2} + T4_t \quad (5)$$

$Detect_t$: Time for searching inside (sec)
$T1_t$: Discovering compartment (sec)
$T2_t$: Searching inside (for people) (sec)
$T3_t$: Traveling between compartments (sec)
$T4_t$: Detecting fire point (sec)
N : Number of compartments

In the case of the time for searching inside, a separate prediction equation was developed due to the differences in searching methods between one and two teams. Considering a worst case scenario, it was assumed that a fire compartment is discovered following a search for people in each compartment by one team as in Fig. 10 and two teams as in Fig. 11.

Equation 3 is used when there is one search team. It was suggested considering the time required from entering inside a building to discovering the first compartment and also the time required in traveling to the next compartment by following the walls after completing the search inside the first compartment.

With two search teams, the search is carried out in the same method. However, the search teams concurrently search two compartments following discovery of the first, the search speed doubles from that with one search team. In the case there are an odd number of compartments, Eq. 4 was suggested by applying the total No. of compartments (N)-1. As for the case with even-numbered compartments, Eq. 5 was suggested by applying the total No. of compartments (N)-2 as one team searches another compartment concurrently with the other discovering the fire compartment.

Suggestion for fire suppression time prediction equation: Based on the fire suppression test results in Table 7 and Table 8, Eq. 6 to calculate the total of the fire point detection time and fire suppression time according to the temperature and the number of firefighters is suggested:

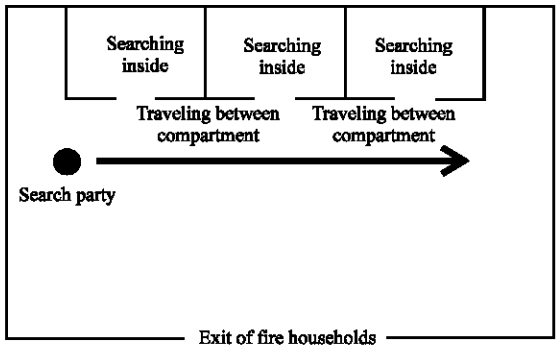

Fig. 10: Method of searching inside one search team

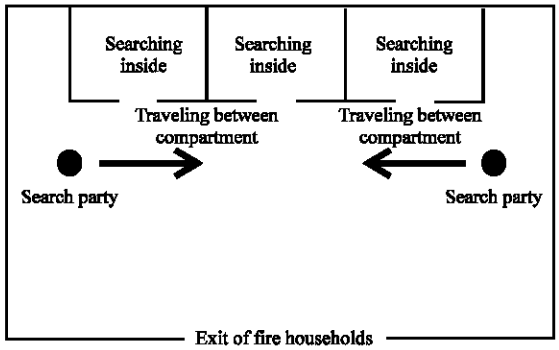

Fig. 11: Method of searching inside two search teams

$$T(t) = Task_t + Te \quad (6)$$

T (t) : Fire point detection and fire suppression time (sec)
$Task_t$: Fire point detection time (sec)
T (e) : Fire suppression time by temperature and No. of hoses (sec)

CONCLUSION

The following conclusion has been reached. First, based on the time-to-task developed by NIST, a Korean style SOP was developed through a questionnaire survey and an FGI with the firefighter instructors of fire service academies in Korea. In addition, on the basis of the SOP, a standard for assessing activities that must be performed in the event of a fire was suggested.

Second, as the target of fireground field experiments, residential buildings subject to the highest rate of human casualties in Korea were selected. In addition, the fire loads for residential buildings were calculated through a

study of existing literature and the actual fireground investigations. Based on the fire load by unit area of residential buildings, the fire suppression speed was measured according to the number of nozzles at the fire compartment temperatures of 300, 500 and 700°C by using wood pallets. When one nozzle was used, the speed of fire suppression at 300°C increased by 4.25 times compared to that at 700°C. In the case of two nozzles, the speed at 300°C increased by 3.9 times compared to that at 700°C.

Third, through the Korean style SOP development, the fire suppression time decrementing each time the number of firefighters is decreased by one from the six which is legally prescribed according to the conditions in Korea, was measured and on the basis of the measurements, equations to calculate the fire point detection and fire suppression time were suggested. When the time required in mobilization from a fire station to a fireground is derived using the internet and mobile phones and the value is entered into the equation, the time from mobilization to fire suppression can be predicted. In addition, Eq. 7 can be suggested:

$$T = Ts + Task_t + Te \quad (7)$$

Where:

T = Time from mobilization to fire suppression (sec)
T(s) = Mobilization time using the internet or navigation system (sec)
$Task_t$ = Firefighting time (sec)
T(e) = Fire suppression time by temperature and no. of hoses (sec)

The results of this study can be used as the basic data for the establishment of fire department allocation and firefighting personnel arrangement guidelines in the future.

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