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Design a Safe Firefighting Time (SFT) for Major Fire Disaster Emergency Response

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Abstract:

A major fire disaster is hazardous to both occupants trapped in the built environment and firefighters during the firefighting operation. Though various construction codes, technologies, and facilities have enhanced occupants' evacuation in fire, insufficient effort is made to ensure a safe firefighting and rescue environment for firefighters, and their safety is not effectively guaranteed in the process of firefighting. To fill this gap, this work proposes a new concept of safe firefighting time (SFT) in fire safety design, combining the features of firefighting and evacuation behavior. By referring to the available and required safe egress time, ASFT (Available Safe Firefighting Time) and RSFT (Required Safe Firefighting Time) are defined with detailed calculation methods. As a demonstration, safe firefighting time including ASFT and RSFT is evaluated in a fire safety performance-based design of a tunnel. Apart from fire safety design, SFT could contributes to smart firefighting supported by emerging technologies. The framework for future fire safety design and the research needs in smart firefighting with SFT are discussed combining intelligent approaches such as IoT infrastructures and cloud services. In summary, this study introduces the safe firefighting time and application approaches in fire safety design that extends the current fire-safety design framework and lays a foundation for smart firefighting for engineers, firefighters and policymakers.

Keywords: *Smart firefighting; Firefighters behavior; Fire safety design; Tunnel fire; Fire rescue*

1. Introduction

Today, a major building fire disaster is still one of the top safety concerns in modern cities. Fire could significantly change the built environment in a short period, such as temperature, gas composition, luminance, and visibility. Destructive fire accidents have always threatened occupants' safety, and some severe fires have taught us lessons such as the Grenfell Tower Fire (2017) with 72 death, and Jinji Road Tunnel Fire with 40 deaths [1–3]. Various methods have been introduced to reduce the risk of fire since the 1950s, namely active and passive fire protection systems, prescriptive codes, and performance-based fire safety designs [4–6].

Nomenclature

B	Burden during the rescue	ASFT	available safe firefighting time
C	cooperation among groups	CFD	computational fluid dynamics
C_i^t	condition of firefighter i at time t	CO	carbon monoxide
C_N^t	condition of all other firefighters at time t	FDS	fire dynamic simulator
D_j	different duties	FED	fractional effect dose
F_c	fire conditions	IoT	internet-of-things
M_t	movement time	PBD	performance-based design
S	building structures	PPE	personal protective equipment
v	the velocity of firefighters	RSET	required safe egress time
Abbreviations		RSFT	required safe firefighting time
AHJ	authority having jurisdiction	SET	safe egress time
ASET	available safe egress time	SFT	safe firefighting time

Apart from the occupants' safety in fires, firefighters' safety is also a serious problem when fighting against unknown fires and searching for trapped personnel (see Fig. 1a-b). They may encounter tough situations like flashover deriving from changeable fire dynamics, and carrying the injured enhances the difficulty of moving through the fire to a large extent. As a result, firefighters may suffer from falling, burning and coma during their operations, and some tragedies have taught us lessons.

Fig. 1. Firefighters in fire operations (a) Firefighters carried the injured out of the fire, (b) A firefighter was found unconsciously in a fire, (c) Mini-storage fire in Hong Kong, 2016, and (d) City library fire in California, 2020. In both fires, two firefighters lost their lives in firefighting operations.

For example, in the 2016 mini-storage fire in Hong Kong, while there was no occupant injury, two firefighters were dead, and 11 others were injured. In 2020, two firefighters were dead when battling a fire at the city library in Porterville, California (see Fig. 1c-d). The casualties of firefighters have taught us lessons now and then, but insufficient attention has been paid to firefighters' safety during the fire safety design. In specific, limited research has addressed the firefighters' safety such as the required entry and exit time, the safe firefighting time in the buildings, the safe zones, and the route for firefighting.

Though a mass of scientific measurements is applied to enhance evacuation in fires such as wayfinding signages and interval exits, occupants could hardly evacuate with the instructions by themselves owing to their unfamiliarity with the buildings [7]. Moreover, the decreasing visibility from the dense smoke plays an extra adverse role in evacuation [8,9]. Then, assistance from firefighters is essential and advantageous. Their intervention could suppress the growing development of fire by spraying fire extinguishers or setting isolation zones. On the other hand, they could find and rescue trapped occupants [10,11].

Compared to firefighters' irreplaceable assistance in evacuation in fires, much less research on firefighters and their behaviors has been done, except for a few on wildfire firefighting safety [12,13]. Our knowledge of safe firefighting time for the sake of firefighters' safety is still very limited, and their safety has not been considered in the fire safety design, despite their long-time exposure to fire. Insufficient consideration of firefighters' behavior and safe operation time could be a major factor in their casualties. On the other hand, firefighters' uncertainty about their safety also reduces their efficiency in fighting fire, finding trapped occupants and rescuing them [14]. Frankly speaking, firefighters' safety is prone to be underestimated or neglected during the design process, and posing a significant safety flaw and a big knowledge gap.

To enhance the safety of firefighters, two approaches can be applied, (1) considering firefighters' safety as part of the fire-safety design, and (2) developing a smart firefighting system, providing real-time safe firefighting information to the firefighters, guiding their prompt firefighting behavior and adjusting firefighting tactics during the operation. For the firefighter's safety design, it can refer to the performance-based design (PBD) for the evacuation of occupants in fire [15]. The booming of innovative and uncommon architectural design since the 1990s promotes fire safety PBD [16]. One main task is to ensure occupants' safety in potential building fire scenarios. Specifically, fire engineers can calculate occupants' fire safety, based on potential building fire scenarios and occupant evacuation performance via numerical simulation and theoretical analysis [17,18]. Despite the flexibility, the PBD still needs approval from the authority having jurisdiction (AHJ) to ensure the fire-safety requirement is fulfilled.

The concept of PBD promotes research on fire evacuation in the 21st century [19,20]. Research on human evacuation behaviors has been extended from simple structures to high-rise buildings and underground spaces such as tunnels [21]. Scientists now have learned the human beings' basic moving time and speed [22], human behavior and psychology in fire, and their responses to external guidance [23]. The latest research also explores the walking speed and postures with different visibilities and environments for normal and vulnerable people [24–27], social influence's formation and function (Drury, 2009; and the effects of dynamic exit designs and lighting in fire evacuation [30,31].

The smart firefighting system is more challenging because it requires real-time interaction and feedback via i.e. sensor network and a superior capacity for data processing and communication. More recently, the concept of smart firefighting has been proposed driven by Internet-of-Things (IoT) and artificial intelligence [32]. These intelligent sensor networks can monitor real-time fire safety in a three-dimensional Metaverse (or Digital Twin) [11][33]. Also, artificial intelligence can use these real-time sensor data to forecast critical fire events, such as flashover, backdraft, failure of structural components, and so on [34–36]. Then, the real-time critical fire information can be used to calculate the safe-evacuation time for occupants and safe-firefighting time for firefighters. One key function of smart firefighting is to improve firefighters' safety and reduce their casualties by obtaining real-time information (via cloud services) and releasing optimal operations (via IoT network), and firefighters' behavior will also affect the fire scene largely. Thus, firefighters are regarded as a core element in smart firefighting before the massive application of firefighting robots. Thus, it is crucial to define firefighters' safe operation time and then evaluate its safety level.

Driven by recent developments in PBD and smart firefighting, we now can consider the safe firefighting time (SFT) to improve the safety of firefighters. In this paper, the available/required safe firefighting time (ASFT/RSFT) is proposed along with its application in the fire safety design and smart firefighting. These concepts are defined with calculation approaches first, and then demonstrated in the firefighting operations in a simplified tunnel fire scenario. To further improve firefighters' safety in their firefighting and rescue operations, SFT could both contribute to a scientific and accurate fire safety design considering firefighters' involvement and a smart firefighting process in a fire. Aiming to this, the characteristics of SFT in fire safety PBD and smart firefighting are compared and distinguished, and the framework of smart firefighting is proposed correspondingly. This study also aims to call on more attention to the safety of our firefighters who enter dangerous fire scenes to save our lives.

2. Safe Firefighting Time (SFT)

2.1. Review of ASET and RSET for the safety of occupants

Safe Firefighting Time (SFT) refers to the time for firefighters to safely move inside the fire scene with professional suits and facilities considering their location and moving routes. Before introducing SFT in detail, the conventional Safe Egress Time (SET) for occupants is briefly reviewed in advance. SET refers to the time for occupants to evacuate from a building in fire. To evaluate the fire safety performance, researchers have proposed two key factors for occupants, namely "Available Safe Egress Time" (ASET) and "Required Safe Egress Time" (RSET) [37], and several researchers have further developed this concept in the calculation and numerical modelling in various fire safety design including high-rise buildings and underground space [38,39].

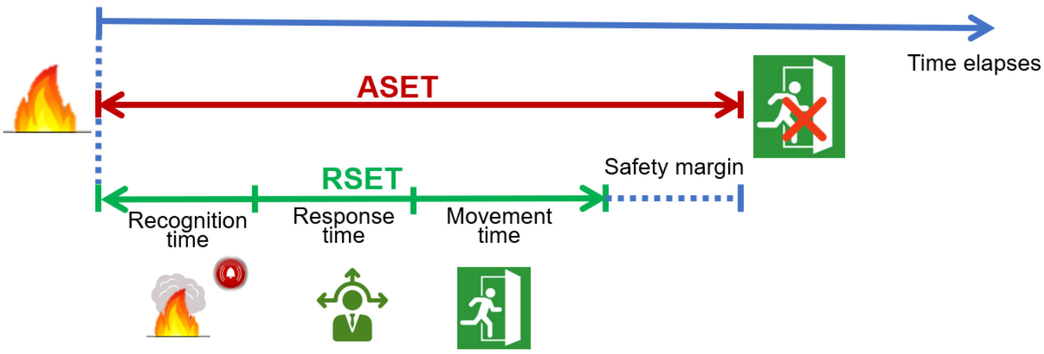

Fig. 2. The illustration of ASET and RSET

As illustrated in Fig. 2, occupant safety could be guaranteed when the fire safety design satisfies Eq. (1) or increases the evacuation safety margin when maintaining the economic costs, see Eq. (2)

$$\text{ASET} > \text{RSET} \quad (1)$$

$$\text{Evacuation safety margin} = \text{ASET} - \text{REST}\ (>0) \quad (2)$$

where ASET expresses the time before the environment becomes too harsh for occupants to stay in, and RSET expresses the required time for occupants to evacuate from the fire to a safety zone.

ASET is controlled by the fire scenarios and building design that can be calculated by Computational fluid dynamics (CFD) fire modelling[40]. Key factors affecting occupants' safety include temperature, visibility, Carbon Monoxide (CO) concentration, and thermal radiation, and their tenable criteria are listed in Table 1 [41]. RSET could be regarded as the issue of pedestrian evacuation consisting of three parts, recognition time, response time and movement time. Those processes can be calculated by evacuation modelling via commercial software like Pathfinder, FDS +Evac, etc., or academic codes adopting social-force and cellular-automaton models [42,43].

Table 1. Tenable criteria for ASET calculation at 2.0 m high [41]

Evaluation indicator	Tolerable value
Temperature (°C)	< 60
Visibility (m)	> 10
CO concentration (ppm)	< 1000
Thermal radiation (kW/m^2)	< 2.5

Scientific research and engineering applications with CFD fire modelling and evacuation modelling promote the PBD in fire safety and have solved a great number of construction problems in practice. However, the role of firefighting is neglected in most current practices that cannot be simply explained by ASET and RSET. Occupants' self-evacuation suffers from the increasingly complex structures, and the dynamic fires will exert extra trouble by irritant gases and decreasing visibility

[44,45]. In consequence, assistance from the fire brigade is essential and advantageous, and by referring to the concept of ASET and RSET, the safe firefighting time should be proposed separately and considered in fire safety PBD.

2.2. Definition of SFT

Firefighters play a central role in firefighting, searching, and rescuing. On the one hand, they can suppress the fire by spraying fire extinguishers or setting firebreaks, which reduces the fire hazard and provides more time for people to evacuate. On the other hand, they could find and rescue trapped occupants. However, these firefighting and rescuing activities also increase firefighters' risk during their close exposure to fire. Hence, it is important to consider the complex role of firefighting and propose a scientific guideline when conducting fire safety PBD. While varied facilities and methodologies are available for firefighters, the fundamental principle is to ensure that firefighters can evacuate safely before the fire scene becomes untenable [46].

By referring to the aforementioned Safe Egress Time (SET), we herein propose the Safe Firefighting Time (SFT). The concept of safety is wide, e.g., no instantaneous injury or no long-term health issue, either physical or mental. In this work, safety emphasizes the physical aspects, that is, no burning on the skin and no injury to the respiratory tract or other organs or tissues. Note that the concept of SFT should be updated for different fire situations and eventually include mental health.

Because of the big differences between firefighting and evacuation behaviors, SFT is fundamentally different from SET in occupants' evacuation (summarized in Table 2). Generally, SFT considers the firefighting task, timeline, moving direction and path, and the influence of behaviors on fire and rescuing trapped occupants.

Table 2. A brief summary of differences between SET and SFT

Aspects	Safe egress time (SET)	Safe firefighting time (SFT)
Tasks	Evacuation	Firefighting, search, rescue
Timeline	A couple of minutes	A few to dozens of minutes
Moving path	From inside to outside	From outside to inside, back-and-forth search, and then from inside to outside
Evacuation	By themselves	Post-firefighting with loads and injured occupants
Influence on fire	Little influence	Big influence on firefighting operations

Task: While the occupants' task is to get out of the building in fire, firefighters enter the fire scene, control the fire, go deep into the fire to search for trapped or injured people, and assist them in moving to a safe area, etc. Nevertheless, firefighters also need to evacuate before the fire reaches a hazardous level or they reach their physical limits.

Timeline: Occupants start to evacuate after they notice the fire from broadcast, smoke, or warning from others, and it commonly takes a couple of minutes [47]. However, firefighters arrive at the building and go deep into the fire within a few minutes to dozens of minutes after the fire occurs, and most people evacuate. At that time, the fire is fierce, the smoke temperature and toxicity are high, and the visibility is low. Generally, the fire scene becomes dangerous to stay and move through.

Moving path: Occupants move out of the building from inside to outside. On the contrary, firefighters have to move into the building in fire first, which is the opposite direction of evacuation. Then, they have to move out of the building after they find and carry trapped occupants, while the search process involves a lot of back-and-forth motion inside the building. In many cases, firefighters are not fully familiar with the building layout themselves.

Evacuation: Occupants move from the fire site themselves. In contrast, although firefighters have undergone professional training and maintained a strong athletic capability, they are still very vulnerable inside the hazardous fire scene, especially after a long-term stay at the fire scene. Moreover, they often need to assist or rescue the trapped people, which results in a heavy burden to carry, especially when the trapped are injured.

Influence on fire: Commonly, the movement of occupants will not affect the fire development during their evacuation to safe places. It is because they seldom (and are not encouraged to) operate fire extinguishers when fire becomes out of control. However, one major operation of firefighters is to control or put off the fire. These activities will change the fire development, the hazardous level, and firefighting strategies and operation. Such a dynamic process needs a real-time smart firefighting system.

2.3. ASFT and RSFT

Referring to ASET and RSET (Fig. 2), the **Available Safe Firefighting Time (ASFT)** and **Require Safe Firefighting Time (RSFT)** should be proposed correspondingly, as illustrated in Fig. 3. ASFT measures the duration of time that elapses after the fire ignition until the presence of smoke, heat and poisonous gases create untenable conditions for firefighters with professional suits and facilities.

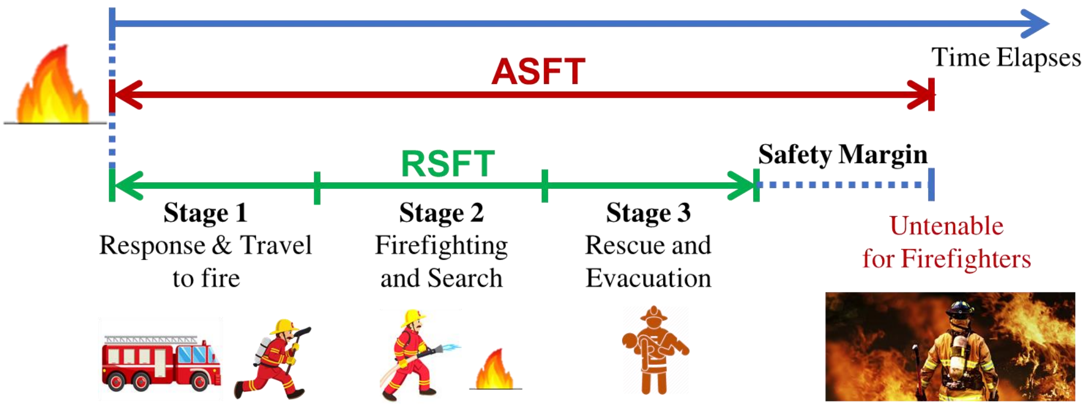

Fig. 3 Diagram of Available Safe Firefighting Time (ASFT) and Require Safe Firefighting Time (RSFT).

Table 3 compares and summarizes the differences between ASET and ASFT in terms of their motivation, objects, and tenable criteria while referring to similar calculation methods. The calculation of ASFT is similar to ASET, where CFD fire modelling can be applied to obtain the ASFT. However, the tenability criteria for firefighters are different from those for occupants, so they should be updated in determining ASFT.

Table 3 Comparison of ASET and ASFT

	ASET	**ASFT**
Motivation	Evacuation	Firefighting and rescue
Object	Trapped occupants	Firefighters
Main methods	CFD modelling	CFD modelling
Tenable criteria	• Accepted by most researchers and engineers • Fixed criteria • All criteria are vital • Consider CO	• Studied by limited researchers and limited recognized criteria so far • Vary from firefighters' suits • Classified as principle and secondary • Do not consider CO with masks

For the ASET calculation, criteria defined by four parameters (temperature, visibility, CO concentration and thermal radiation in Table 1) are used to evaluate the hazardous level of the evacuation environment. These four parameters (but not limited to four) can also be used for the ASFT calculation, but different values should be chosen. For example, if firefighters are equipped with oxygen bottles and professional masks, CO is not a decisive factor. In addition, whether visibility should be set as a criterion is subject to debate. Most firefighters will enter the smoky and low-visibility fire scene, and they are trained to operate in a dark environment with Personal Protective Equipment (PPE). Thus, it is reasonable to believe low visibility near the exit of a building will not pose a vital threat to firefighters or the rescued occupants upon their arrival at the outlets due to plenty of resources and staff nearby. Thus, the thresholds of CO and visibility should be considered secondarily according to firefighters' suits and equipment (see Table 4), though tenable criteria include temperature, thermal radiation, visibility, and CO, and they are applied to obtain four values, where the minimum value is chosen as ASFT, see Eq. (3).

$$\text{ASFT} = \min\{T_T,\ T_R, T_V, T_{CO}\} \tag{3}$$

where

T_T, T_R T_V and T_{CO} refer to the amount of time till the temperature, thermal radiation, visibility and CO reach the threshold, respectively.

In this study, the criteria were proposed (see Table 4) according to past findings [48–50]. The criteria are divided into two parts, principle criteria (i.e. temperature and thermal radiation) and secondary criteria (i.e. visibility and CO). The thresholds of temperature and thermal radiation have increased to 80°C and 5 kW/m^2 from 60°C and 2.5 kW/m, respectively. These increases are acceptable (while open to debate) for firefighters with full sets of PPE (e.g., fire retardant coats, oxygen tank, and mask), considering the original criteria of a conservative fractional effect dose (FED) is set for normal occupants with light clothes with a duration of 30 min [51]. For visibility, a specific value could be set, but it is considered secondary for firefighters with rich darkroom training and firefighting experiences. In terms of CO, if firefighters evacuate with trapped occupants, a critical value should also be set.

Table 4. Tenable criteria for firefighters at 2.0m high (15 min exposure) in the ASFT calculation.

ASFT Criteria	Evaluation indicator	Tolerable value (ASFT)	Reference value (ASET)
Principle	Temperature (°C)	< 80	< 60
	Thermal radiation (kW/m^2)	< 5	< 2.5
Secondary	Visibility (m)	Undetermined	>10
	CO	Not considered (with PPE) < 1000 (rescue task)	< 1000

RSFT (Required Safe Firefighting Time) refers to the duration of time required for the firefighters to fulfill their tasks and withdraw to the safety zone with trapped occupants. RSFT is calculated as the sum of three separate components, (1) the response and travel time to the building in fire, (2) the firefighting time in the building, including fire suppression and searching for trapped occupants, and (3) rescue and evacuation time, during which firefighters are moving out of the building with the injured. RSFT changes with the fire conditions, the firefighting abilities and strategies and the occupants, which can be calculated based on firefighting movement models. In the firefighting practice, RSFT is a dynamic value for each firefighter that varies with fast-changing fire scenes and firefighting tasks. Table 5 compares and summarizes the differences between RSET and RSFT in methods, movement stages and influential factors.

Table 5 Comparison of RSET and RSFT

	RSET	RSFT
Method	Evacuation modelling	Firefighter modelling
Software	Pathfinder, FDS+Evac, etc.	Not available
Models	Many, e.g., social force model, cellular automaton model	Not available
Research	Many since the 1990s	Few
Components	• Recognition time • Response time • Movement time	• Recognition time • Response time • Travelling time to the fire • Firefighting and searching time • Rescue and evacuation time

The RSFT could either be obtained via drills and experiments or by calculating firefighting time via numerical modelling. Compared to masses of evacuation models of RSET, there is little research for firefighting movement modelling nor targeted modules in evacuation software such as Pathfinder or

FDS+Evac. Due to the differences between evacuation and firefighting, RSFT should consider the different tasks, timelines, and moving paths, as shown in Fig. 3. Then, RSFT could be expressed as

$$\text{RSFT} = \sum_{i=1}^{n} f(M_t,\ D_j,\ C,\ B) \tag{4}$$

where

n = 3 and i = 1, 2, 3 refer to the firefighting tasks following the timeline. For i=1 (Task 1), it refers to when firefighters get noticed and arrive at the fire scene; for i=2 (Task 2) refers to when firefighters execute their assigned firefighting and searching trapped people in the building; and for i=3 (Task 3) refers to when firefighters move out of the building and rescue trapped occupants to the outside;

M_t *refers to the movement time for firefighters, and the detailed parameters refer to Eq. (5);*

D_j *refers to firefighters' different duties and tasks;*

C *refers to the cooperation among groups such as communication and support between members;*

B *refers to the burden the firefighters carry during the rescue (firefighting facilities, injured people);*

$$M_t = g(S, F, v, C_i^t, C_N^t) \tag{5}$$

where

S refers to the building structures, including floors, facility layout, and technical installations etc.;

F refers to the fire conditions, including the fire location, comburent etc., and it will be influenced by firefighters' behavior dynamically;

v refers to the velocity of firefighters considering their starting velocity, velocity decay and velocity distribution;

C_i^t *is the condition of firefighter i at time t;*

C_N^t *is the condition of all other firefighters at time t.*

Those equations formulate a framework for calculating RSFT and inspire more investigation into firefighters' movement models. To acquire firefighters' behavior and movement accurately, we need to further study firefighters' speed, trajectories preference, cooperation and mental conditions etc. Moreover, specific models and software are encouraged to establish and applied based on firefighters' characteristics.

Accordingly, the rules of fire safety PBD could be extended from ASET > RSET to Eq. (6):

$$\begin{cases} \text{ASET} > \text{RSET}|\text{F} \\ \text{ASFT} > \text{RSFT} \end{cases} \tag{6}$$

where for the first part, compared to Eq. (1), RSET should be revised as RSET|F, which indicates that with firefighting and rescue, RSET could be modified or shortened. As long as the modified RSET with firefighting is shorter than ASET, the evacuation could be regarded as successful, and occupants are safe. Then, ASFT should be larger than RSFT so that the firefighters' safety could be guaranteed, and the firefighting safety margin could be defined as the difference between ASFT and RSFT.

3. Demonstration of ASFT and RSFT in a tunnel fire

To further illustrate ASFT and RSFT, a simplified firefighting process in a tunnel fire is presented as a demonstration of the safe-firefighting PBD. The ASFT is estimated via CFD fire modelling, and the RSFT is evaluated via a firefighting drill. The tunnel dimensions are 300 m (L) ×10 m (W) ×5 m(H), as shown in Fig. 4 (a), which keeps the same for the fire modelling and the drill. Fire Dynamic Simulator (FDS) version 6.7.6 developed by NIST is adopted to conduct the fire simulation, and SmokeView is used to view the fire simulation results. There is no slope variation along the tunnel, and the smoke ventilation system is not considered. To point out, the demonstration below is to provide an example for ASFT and RSFT based on the current and limited understanding of firefighters, and several factors of firefighting are still missing due to insufficient research. Thus, it is expected to raise following attention on this topic for the sake of firefighters' safety.

3.1. Estimating Available Safe Firefighting Time (ASFT)

To estimate ASFT, a few assumptions are made in the fire modelling. Specifically, the tenable criteria are critical in obtaining the time stamp when the environment is no longer suitable for firefighters to withstand and move through (see Table 4).

The fire model is filled with concrete blocks as linings, and both ends of the tunnel are open inlets with no extra longitudinal wind speed. The atmospheric pressure of the environment was set as 1 atm and the initial air temperature 15°C, which represents the average temperature in Shanghai annually. The walls of the model are set as inert walls. On account of the relatively simple structure of this tunnel, the grid meshing was set as 0.5 m×0.5 m×0.25 m, which balanced the computational time and mesh quality. Consulting with other simulations with more complex structures, including jet fans in grids larger than 0.2m, the meshes in this study could yield relatively reliable and accurate results [52]. No ventilation is adopted in these simulation cases to consider the worst situation. The t-squared fire is set by defining the time to peak heat release rate (HRR) value to mimic the real fire growth. In the present study, the ultrafast fire growth coefficient (0.1876 Kw/s^2) is adopted as the worst case, and the time to peak HRR for different cases is displayed in Table 6.

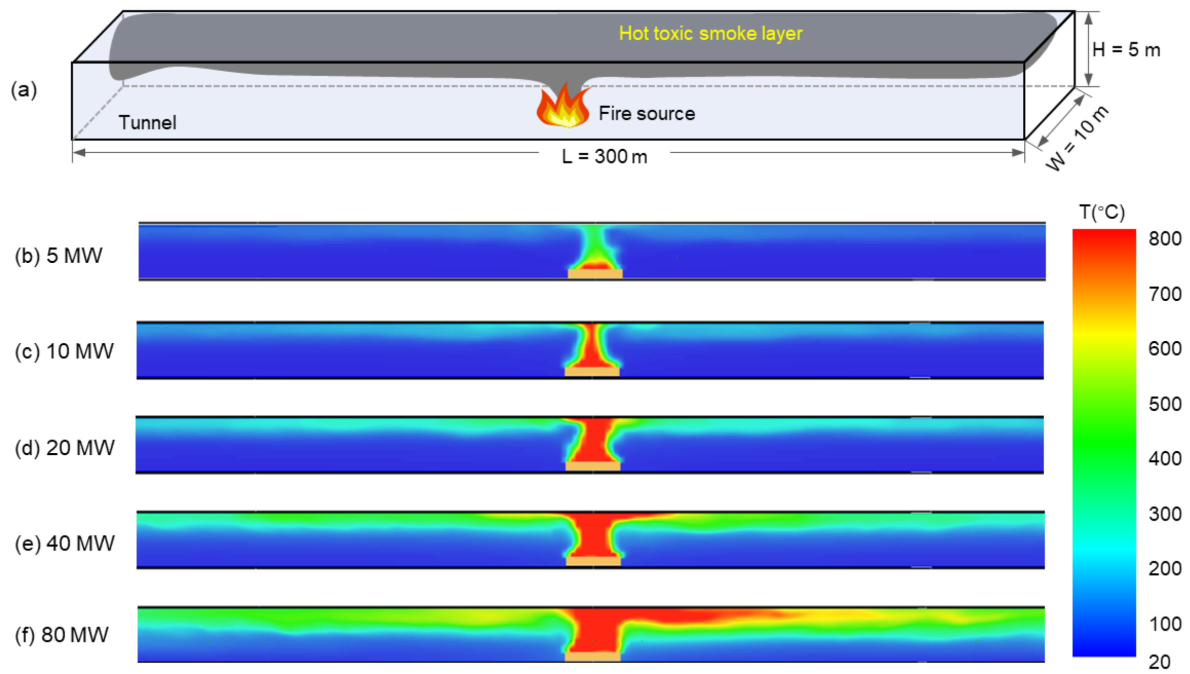

Fig. 4. (a) Geometry of the tunnel model and (b-f) temperature contour at the vertical symmetry plane under different fire HRRs ranging from 5 MW to 80 MW.

Table 6. Five fire scenarios of ASFT in the demonstration, where ∞ means not reaching critical condition after the fire scene reaches the steady state.

HRR	Possible fire cases	Time to peak	Temperature		Thermal radiation		ASFT	ASET
			Near the fire	Outlet	Near the fire	Outlet		
5MW	Car	164 s	∞	∞	∞	∞	∞	∞
10MW	Two cars	231 s	∞	∞	∞	∞	∞	275 s
20MW	Bus	327 s	∞	∞	∞	∞	∞	235 s
40MW	Truck	462 s	560 s	∞	350 s	∞	350 s	230 s
80MW	Oil tank	654 s	505 s	559 s	350 s	∞	350 s	230 s

In the simulated case, scenarios are applied to obtain ASFT till the environment in the tunnel is stable (see Fig. 4b-f). Five tested fire scenarios represent the typical burning of a single car (5 MW), two cars (10 MW), a bus (20 MW), a truck (40 MW), and a large truck or oil tank (80 MW), respectively [53]. Different from ASET, ASFT considers two key locations in the tunnel in this case. The former is close to the fire source because firefighters have to put out the fire or rescue the trapped occupants near the fire with a tolerable temperature and thermal radiation. The distance to the fire source is chosen as 5m, equal to the half-width of the tunnel. The latter is near the exit of the structure, i.e., the outlets of the tunnel so that they can run out of the tunnel successfully. Therefore, both 5 m away from the fire source and the outlets of the tunnel (150 m from the fire source) should be evaluated for ASFT. The safety height is set to 2.0 m considering the human height.

The simulated temperature and radiation heat flux profiles are presented in Figs. 4-6 and summarized in Table 6. When the temperature is regarded as the tenable criterion, all the cases meet the criterion, i.e., the ASFTs are infinity for all cases after the fire scene reaches the steady state, as shown in Figs. 4 and 5. Based on the threshold of 60 °C and 80 °C, the temperature value is divided into three risk levels: low (<60 °C), medium (60-80 °C), and high (>80 °C), as shown in Fig. 5. For all scenarios, both the temperature at 5 m from fire and at the tunnel outlet is less than 100°C, and only the temperature at 5m from fire (40 MW) hits over 80°C. The results indicate that the temperature is a rather tolerant factor in fire scenarios. The proposed risk levels (low, medium and high) in the present study are closely related to the fire HRRs, and the critical HRRs between low risk and medium (based on the temperature) are around 20 MW for the outlet and a bit higher (between 20MW and 40MW) for the region near the fire, and the transition time around 400s. Thus, the time to reach the critical HRR is similar, and the transition time is similar for larger HRRs (i.e., HRR 40MW or 80MW). Moreover, it can be seen from Fig. 5 that the temperature at the outlet is higher than the temperature near the fire in low HRR (<20 MW) due to complex motion and mixing of hot smoke.

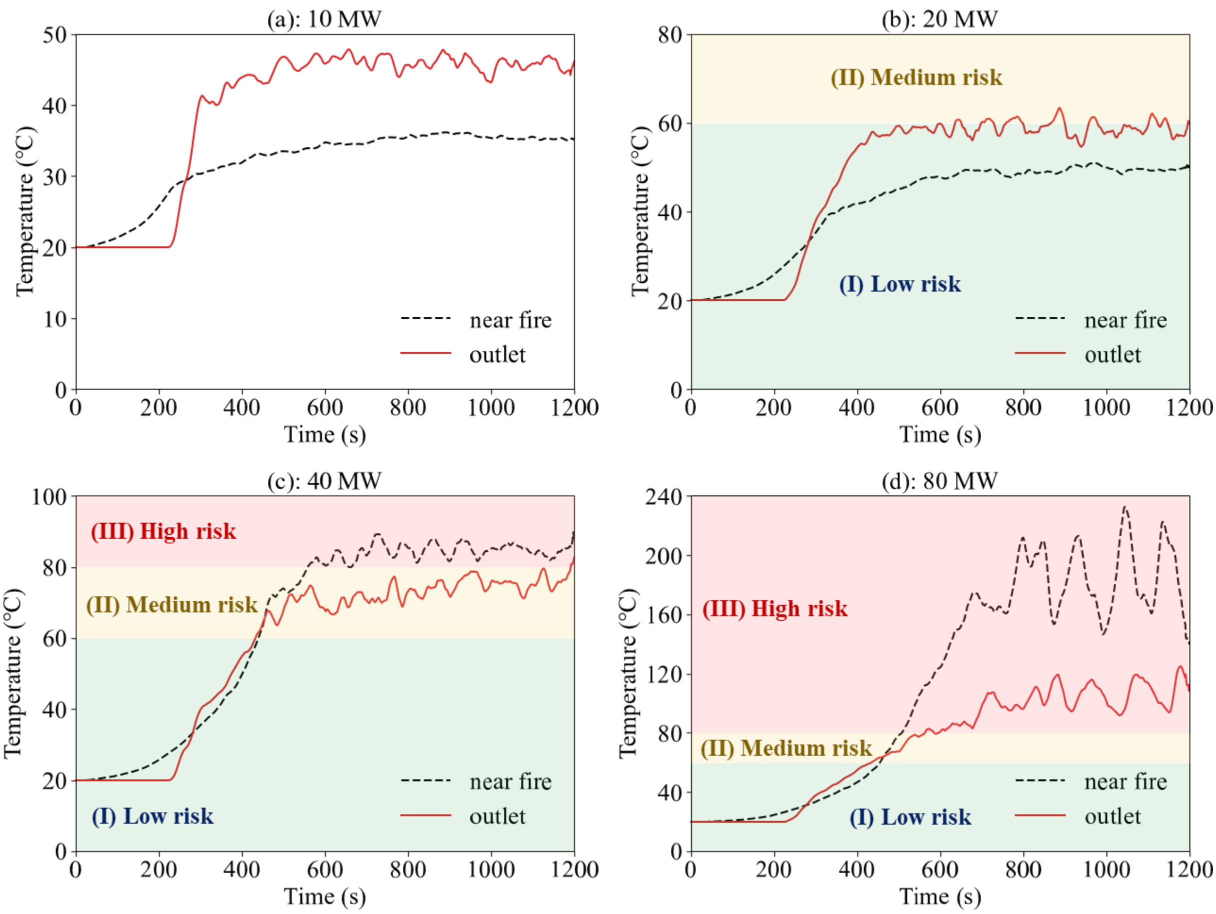

Fig. 5 The temperature evolution near the fire (5 m) and at the outlet under HRRs of (a) 10 MW, (b) 20 MW, (c) 40 MW, and (d) 80 MW.

The radiation heat flux profiles under different fire HRRs are shown in Fig. 6. As to the criteria of thermal radiation, the heat flux value at the outlet is small enough to ignore. As to the location near the fire, the heat flux value is divided into three different levels: heat flux less than 2.5 KW/m^2 is classified as low radiation heat, which can be tolerated by the trapped people; radiation between 2.5 KW/m^2 and 5 KW/m^2 is classified as medium, which can be tolerated by equipped firefighters; the high level is defined as the radiation flux higher than 5 KW/m^2, which is beyond the limit of equipped firefighters.

In the case of 10MW, the maximum heat flux values near the fire source are much smaller than the critical value, as shown in Fig. 6(a). For the scenario of 20 MW, the radiation heat flux at 5 m from fire approaches 5 KW/m^2 at around 360 s, as illustrated in Fig. 6(a), then the heat flux will decrease to about 3 KW/m^2. The heat flux of 40 MW exceeds the critical value from 350 s to 700 s and will finally keep constant at around 4 KW/m^2, as shown in Fig. 6(b). During this period, the firefighting and rescue process is much more dangerous. The decrease in radiation values is caused by the smoke spread and the drop in smoke level that blocks the radiation. For the scenario of 80MW, the heat flux exceeds 5 KW/m^2 at 350 s and remains a high radiation value, as displayed in Fig. 6(b). The large fluctuations in radiation values may be caused by the enhancement of smoke movement.

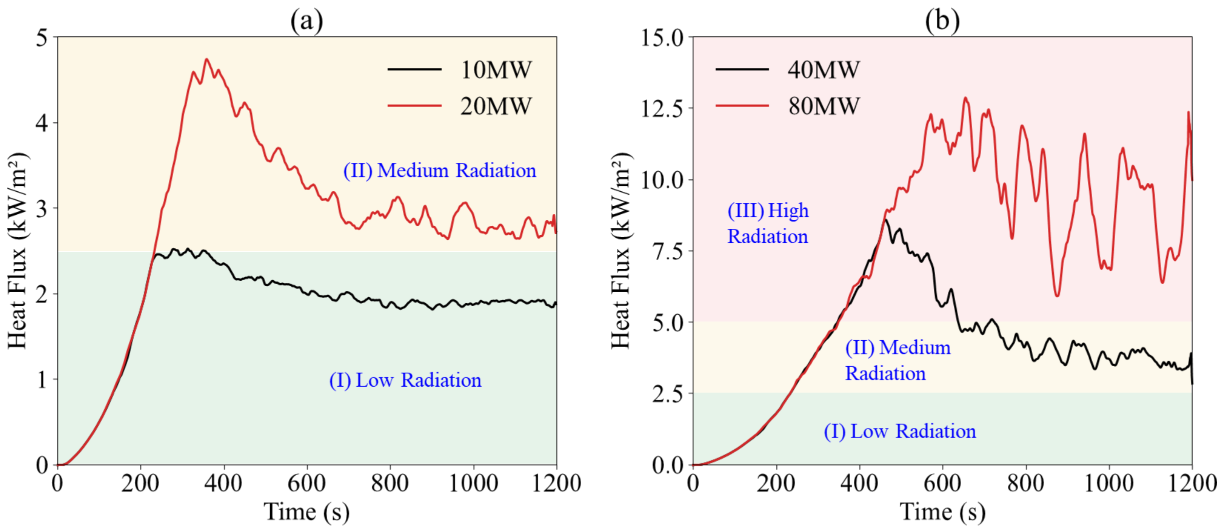

Fig. 6 The radiation heat flux evolution near the fire (5 m) under different HRRs.

3.2. Estimating Required Safe Firefighting Time (RSFT)

The below case introduces a firefighting drill of a tunnel fire, and the drill's RSFT is proposed correspondingly. The drill focuses on the process from firefighters reaching the entrance of the tunnel till they finish the firefighting in the tunnel and move back to the original entrance, see Fig. 7. The response time and driving time from the fire station to the tunnel is referred from commanders and added as the total RSFT.

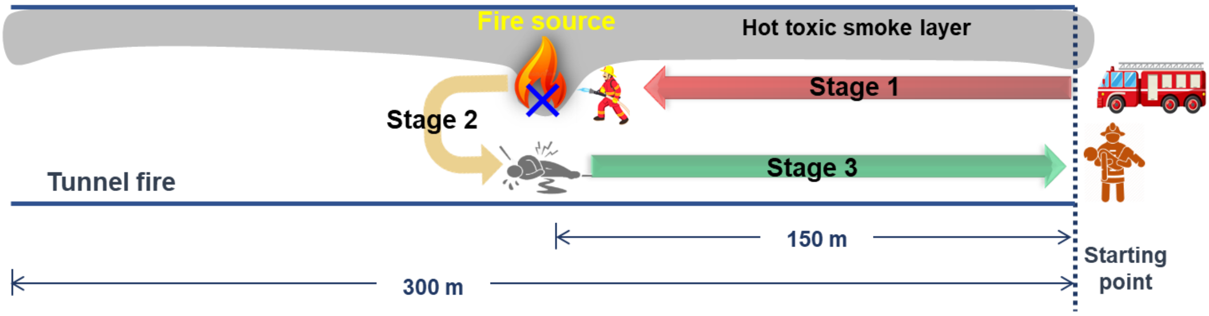

Fig. 7 The diagram of three firefighting stages

A firefighting drill for a tunnel fire was conducted in the Beidi Road Tunnel, Shanghai by firefighters from Changning District. The total length of the tunnel is 2300m and a part of 300m containing two standard sections were applied in this experiment due to the construction restriction and the convenience of firefighters. The tunnel is a bi-directional tunnel, consisting of three lanes in each direction. The slope of the tunnel is less than 1 degree, and any influence of slope is disregarded in this experiment. The experiment was carried out before the tunnel opened to the public officially. To simulate traffic congestion in a tunnel fire, traffic cones were placed in groups of four on three traffic lanes to form cordoned-off areas assumed to be vehicles, and firefighters had to travel through the cordoned-off areas, and the firefighting scene is shown in Fig. 8.

Fig. 8 The firefighting scene (a) The fire engine, (b) the tunnel in fire

The experiment was conducted in two scenarios: with fire (smoke) and without fire (smoke), and the visibility was 5-10 m (with smoke) and larger than 50 m (without smoke), respectively. It represented the condition where a fire occurs and the condition where no fire but needs intervention from professional rescue teams (i.e. fire brigades). For the scenario with fire, the fire (smoke) location was set in the middle of the experimental section. Smoke cakes were burnt to simulate fire to minimize the environmental impact and influences on surrounding residents because the tunnel is located in a central urban area.

Fig. 9 Firefighting process in test drill (a) Firefighters started running in the tunnel, and (b) Firefighters made turns in the tunnel

The firefighting campaign was divided into three stages (see Fig. 7). In Stage 1, firefighters gathered at the entrance and moved towards the fire source in the tunnel. In Stage 2, firefighters put off the fire and found trapped or injured occupants. In Stage 3, firefighters rescued the occupants and moved out of the tunnel. The response time and driving time were set as X s and Y s. By excluding the driving time, the time was 367 s (without smoke) and 517 s (with smoke), as listed in Table 7.

Table 7 The detailed time distribution for firefighting movement

Stages	Total time(s)	Stage 1 (s)		Stage 2 (s)	Stage 3 (s)
		Driving time	Running time		
Without smoke	368+X	X	67	220	81
With smoke	517+Y	Y	80	320	117

The time for each firefighter was almost the same since they started together and reached the fire source within several seconds. Therefore, we did not distinguish individual time but chose average time instead. Without smoke, the average time for Stages 1 to 3 was 67 s, 220 s and 81 s, respectively. With smoke, the average time for Stages 1 to 3 was 80 s, 320 s and 117 s, respectively. To point out, during the movement, the firefighters had to pass through the obstacles and make turns continuously (see Fig. 9), which consumed a large time and increased the actual distance to cover. It led to more difficulty for firefighters when they were in smoke and carried injured people.

For Stage 1, without smoke, firefighters made five turns on average and per turn took 3-4 s, and the running speed was 3.03m/s. With smoke, per turn took 4-5s, and the average speed 2.6 m/s. Referring to the data from daily training of Changning fire brigade, the average running speed for short and medium distances was 3.0 - 3.5 m/s without smoke and 2.5 - 3.0m/s with smoke. For Stage 3, firefighters spent a longer time than entering the tunnel. Turns took a longer time, so their running speed was slower. Generally, per turn took one more second than entering and the running speed was 2.6 m/s (without smoke) and 1.7 m/s (with smoke). The speed both without smoke and with smoke declined to a large extent with burdens to carry.

To point out, the time from the fire ignition till the firefighters assembled at the entrance of the tunnel consisted of a large portion of the whole firefighting time (labeled as driving time in Table 7). It includes the time when the fire engines get noticed of the fire accidents from the control system, the driving time on the road, and the preparation and assembly. This resulted from the simple setting of this tunnel fire scenario and the simulative rescue scene in this experiment. If the fire scenarios were more complicated with a great number of trapped and injured people, the time for Stages 2 and 3 may extend largely, and total RSFT would vary widely. The experiment is used as a demonstration of the proposed RSFT initiatively, and more detailed studies with diverse fire scenarios, tunnel structures, and evacuation situations will be conducted in the future.

3.3. Usage of ASFT and RSFT

The above modelling and experimental drill could be regarded as a basic demonstration to explain ASFT and RSFT further based on the concept and formulas. It presents the fundamental elements and processes to consider for ASFT and RSFT, while some other elements are not fully considered due to a lack of data and knowledge of firefighters' behavior so far. There are several issues to deliberate on before embedding them into firefighting strategies.

(1) **Controversial criteria of ASFT**. The limiting values of temperature, heat flux and CO concentration have a close relationship with firefighters' suits, and the provided criteria are reasonable and relatively conservative based on the occupants' criteria. Though we have sufficient evidence to believe firefighters are safe with these criteria, advanced suits may extend the thresholds furthermore and may change the ASFT differently.

(2) **Dynamic ASFT with different locations and routes.** Currently, the ASFT considers two key locations in the tunnel. Though it is well simplified with finite key locations to determine the ASFT, we recommend that more numerical modelling could be built to consider the time span and harmful materials in different places. For example, if one location is not tolerable for firefighters to move through, we could find out and evaluate the possibility of moving through alternative routes until no route is available. It is of critical importance for complex buildings with several evacuation routes.

(3) **Injury accumulates with time exposure to fire.** The hurt to firefighters is an accumulation of both time and place, which suggests it is insufficient to consider the firefighters' location for their safety. Apart from that, their time exposed to such an environment should be considered meanwhile. For example, both 5 kW/m^2 and 80°C or even higher could be tolerable within several seconds in extreme conditions if firefighters have to pass through a deteriorative zone, but a long residence time in such circumstances may not be a wise choice for firefighters. We should also think about the possibility of receiving guidance and choosing the correct paths for firefighters when they are trapped in danger.

(4) **Post psychological harm in fire.** In addition, an accurate and scientific evaluation of firefighters'

psychological harm is necessary. Reports have claimed the huge mental damage to firefighters during operations and it is one of the most intractable issues to be solved [54,55]. Although long-term exposure to extreme heat, low visibility, and smoke may not cause significant physical harm, it could induce severe injury to firefighters mentally, which should be taken into full consideration.

(5) **Firefighters' diversified work and distribution.** To note, the division of work for firefighters is commonly strictly distributed in advance, and their duty varies widely. It sometimes occurs when a squad withdraws from the fire while another is still searching for occupants, which results in varied RSFT. Before outputting RSFT for a specific fire and fire brigade, it is crucial to investigate these factors in detail.

The points above mentioned should be considered and evaluated carefully before it plays a demanding role in a firefighting plan and action officially. In addition, a thorough understanding of ASFT and RSFT is indispensable and imperative before it is embedded as a decisive factor in smart firefighting systems, as discussed below.

4. Perspectives for Future Fire Safety Design and Smart Firefighting

SFT is a significant factor in evaluating the safety of firefighters in firefighting, both in fire safety design and smart firefighting. The above demonstration provides examples of SFT with ASFT and RSFT for fire safety design. To point out, it shares some limitations due to our insufficient research and understanding of firefighting and firefighters currently. The demonstration is based on a tunnel fire drill, and the structure of a tunnel is relatively simple compared to those complex buildings. Thus, the drill focuses on the firefighter's behavior at different stages, and the speed range indicated the firefighting drill was in accordance with daily training. Firefighters' behavior, status and safety level should be modified correspondingly, if a fire occurs in other forms of buildings or metro stations. Note that various factors may affect the firefighting process, and then affect the ASFT, and the RSFT, such as the sprinkler systems, the exit signages, and the building layout. This demonstration is a novel and preliminary attempt to evaluate ASFT/RSFT. More real-scale fire tests and modeling need to be conducted in the future. Unfortunately, a majority of firefighting drill data are confidential that are not open for research use. Researchers are encouraged to collaborate more with fire brigades and collect more data on firefighting operations and firefighters' behaviors, which can help systematically build firefighter behavior models under different fire scenarios and infrastructures.

Apart from the proposed ASFT and RSFT to be involved in fire safety PBD, the element of SFT also contribute to conducting smart firefighting. Although studies about SFT could play an active role in both fire safety PBD and smart firefighting, there are some significant differences between these two aspects, and worth distinguishing before applying them into smart firefighting (see Table 8).

For fire-safety PBD, introducing the concept of SFT first includes firefighters' impact on fire development. Based on this, engineers could design the newly-built structures and facilities, or optimize existing buildings, so that they could protect firefighters sufficiently. In additional, SFT plays an essential role in smart firefighting practices, that is, the best firefighting strategies can be decided by balancing safety of all parties. While engineers consider SFT in fire safety PBD during the design period of buildings with hours' or days' modelling, SFT in smart firefighting could guide engineers, firefighters and decision-makers in a fire accident, thus has a higher requirement on calculation time due to the urgency in a fire operation.

Although it is the first time proposing SFT in fire safety design, we need to constantly acquire more knowledge of fire dynamics and keep understanding firefighters' behavior. Such a continuous learning process could benefit mature applications in a short period. The use of SFT in a smart firefighting system demands prompt data collection and transfer in fire from the sensor network, robust interaction between different parts of the firefighting system, and a database of thousands of cases with fire dynamics and firefighters' behavior for artificial intelligence modelling training in advance. More effort should be put in through smart facilities, massive data collection, and better understanding of firefighters. Researchers and engineers should also work together to enhance the safety of both occupants and firefighters by applying emerging technologies, such as the AI-driven real-time fire forecast and smart firefighting [33][56].

Table 8. Comparison between SFT application on fire safety PBD and smart firefighting

	Fire safety PBD	Smart firefighting
Principle	Model fire scenarios and firefighters to design and optimize settings	Choose the best or optimal strategies from thousands of possibilities
Aim	To ensure the structures and facilities for firefighting are sufficient	To ensure firefighters' safety and their decisions are wise and feasible
Users	Engineers	Engineers, firefighters, decision makers
Process time	Hours to days	Seconds to minutes
Prerequisite	Knowledge of fire dynamics and firefighters' behavior	Database of thousands of cases with fire dynamics and firefighters' behavior
Development	Mature and commercialized	Early stage

One essential feature of smart firefighting is the access and use of real-time information on fire dynamics and evacuation processes via IoT and digital twin systems [57]. Sensors networks collect massive data in a fire accident and transfer it to a smart firefighting center. The center with an AI engine then handles the data and makes prompt feedback such as predictions and decisions. To copy with fast-changing fire scenes, the sensors network should support real-time data collection and low-latency information transfer. Moreover, firefighters' behaviors affect the fire development, but they are also influenced by real-time fire dynamics and evacuation progress. Therefore, a core function of future smart firefighting system is to obtain precise SFT (ASFT and RSFT) in real-time, which can lead to more functional and explicit firefighting strategies and vice versa. Thus, SFT should be regarded as an indispensable element in a smart firefighting framework.

According to the newly proposed SFT, the modified smart firefighting system consist of the following parts, namely sensors network, a cloud data server, a computing center with an AI engine, and the user interfaces, and the details are as below (see Fig. 10).

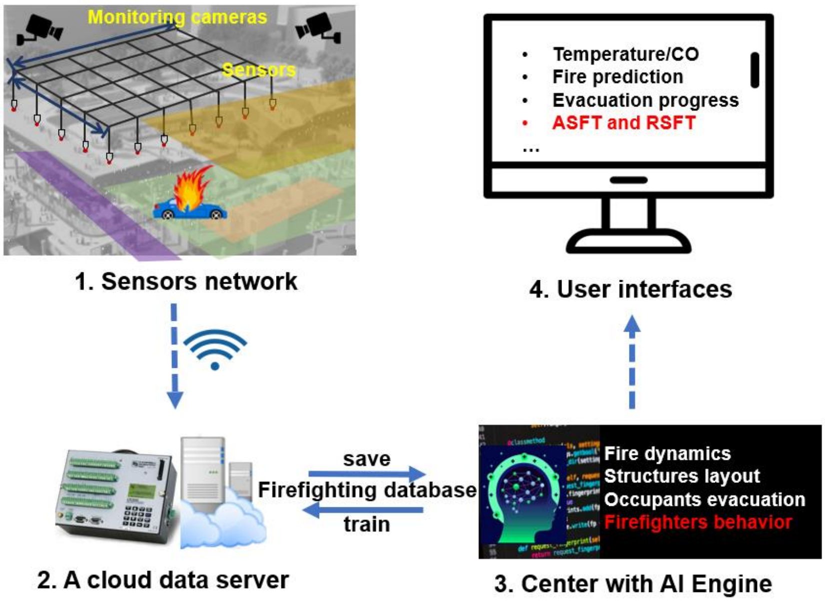

Fig. 10 The framework of SFT in Smart Firefighting design and operation.

1) Sensors network. Sensors are installed in the buildings and monitor the environment, including the temperature, CO concentration, etc., along with the CCTV camera monitoring systems. Once there is an accident, the sensors will upload the real-time data of fire processes, occupants' evacuation process, and firefighters' operations to the cloud server.
2) A cloud data server. The server reads the data from the sensors remotely, clears the noise of the data via multiple filter algorithms, and stores them in standard formats. Then a cloud database is formed by organizing massive data from previous and possible fire scenarios. To be mentioned, the server has collected massive data on firefighters' behavior for further AI training.
3) Computing center with AI engine. The computing center equipped with an AI algorithm could use massive data from previous and possible fire scenarios with evacuation and firefighters' models and train the predicted movement [57]. Once in fire, apart from original items i.e. fire dynamic, structure layout, and occupant's evacuation, the AI engine could now pay attention to firefighters' behavior and their SFT. Specifically, the engine could calculate the ASFT and RSFT according to the fire development, the trapped occupants, and the time stamp when firefighters arrive at the fire scene via the trained model. The center will upload the trained data to the cloud data server to be saved.
4) User interfaces. With the firefighter's behavior and SFT, the interface could show the following information such as the fire scene, evacuation scene, and rescue scene with different modules and elements, and present ASFT and RSFT for firefighters. It will then output corresponding

strategies such as the optimal firefighting route, and the latest time to leave, and provide suggestions for commanders to carry out and adjust firefighting strategies dynamically.

5. Conclusions

With increasingly complex and high-density buildings, firefighting plays a rising-significant role in protecting occupants in fire when self-evacuation is insufficient. However, limited research has paid attention to firefighters' safety, which on the one hand, causes firefighters' injury; and on the other hand, restricts the effectiveness of smart firefighting. Therefore, the safe firefighting time (SFT) is put forward in fire safety performance-based design and smart firefighting. In this study, the rules of ASFT and RSFT have been proposed along with a demonstration of ASFT and RSFT in a tunnel fire. Some main contributions are below:

(1) The concept of available/required safe firefighting time (ASFT/RSFT) is proposed, which emphasizes the significance of firefighting and firefighters' safety in fire safety design.
(2) ASFT and RSFT, along with their calculation approaches and procedures, are put forward in buildings' fire safety design.
(3) The study conducts a demonstration of ASFT and RSFT from a tunnel firefighting case, and it is expected to attract more research on ASFT and RSFT.
(4) SFT could be embedded into a smart firefighting framework, and via emerging technologies (IoT sensors, cloud server, 5G communication, and AI engine), fast ASFT and RSFT prediction could be obtained in real-time according to the sensor data from fire scenarios.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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