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TECHNICAL NOTES

An Analysis of Firefighter Breathing Air Replenishment Systems

Final Report by:

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Foreword

The criteria for the installation of Firefighter Breathing-Air Replenishment Systems (FARS) is contained in the Uniform Plumbing Code. The 2018 edition of NFPA 1 added Annex F which references the Appendix F provisions of the Uniform Plumbing Code. During the NFPA 1 Fire Code Technical Committee discussions on the issue of firefighter breathing air replenishment systems, numerous questions arose as to the appropriateness of the installation criteria, actual field use by firefighters, safety of such system, maintenance and performance of systems in use. Based on their importance and impact on firefighters, there is uncertainty as to what code or standard should maintain the majority of the requirements for these systems.

The goal of this project is to analyze and review the existing code requirements and literature to provide guidance on the use and effectiveness of these firefighter breathing air replenishment systems. This project is comprised of the following tasks:

Task 1: Literature Review. Provide a background on firefighter breathing air replenishment systems, their use, cost, and inspection, testing, and maintenance requirements, specifically addressing the following:

- What are firefighter breathing air replenishment systems?
- What are the needs and use cases for these systems in specific buildings?
- What are the current code requirements for their installation?
- What are the current code requirements for their ITM requirements?
- What are the costs of installation and ITM for these systems?

Task 2: Cost-Benefit Analysis. Based on the findings of task 1, conduct a cost-benefit analysis for at least two scenarios in which firefighting breathing air replenishment systems may be installed.

Task 3: Packaging and Dissemination. Based on the information collected above, develop a final report that will be published on the Foundation's website.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire

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safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: **air-supply, bottle-brigading, high-rise, air-quality.**

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Executive Summary

The primary goal of this project was to review and analyze the existing code requirements and literature, as well as collect, analyze, and summarize stakeholder input to provide informational guidance to the concerned NFPA committee on the use of Firefighter Air Replenishment Systems (FARS). In brief, the present study included data collection and analysis to provide an understanding of FARS, their use, cost, inspection, testing, and maintenance requirements, and benefits. The study provides an understanding of various components of FARS and its operations by firefighters. Data from a questionnaire survey of 200 fire departments across the nation was collected and analyzed to quantify the benefits of FARS for fire service, the concerns of firefighters, the need for training, and the applicability for various structures. Various real-life cases depicting the issues of FARS were identified and discussed with several fire service officials and the leading FARS technology provider. As air quality, testing, and maintenance were found to be a major concern raised by the participants, current standards and procedures for air quality testing and maintenance of the system have been investigated. Costs of installation and maintenance of FARS have been described and compared with other substitutes and their benefits.

Review of existing code requirements indicate a scope to improve the current code requirements for FARS, the system configurations, its deployment, applicability for various types of structures, testing, and maintenance procedures. The system should be tested, inspected, and maintained on frequent basis. Additionally, the costs of new installation, retrofitting of FARS, and their testing and maintenance have been provided. This cost varies based on the location of construction, size of the structure, cost of the local labor and materials, AHJ requirements, and cost of conducting business in the area. Based on the information gathered during this effort, this preliminary study implies that making compressed breathing air available to firefighters inside the structures to avoid bottle-brigading can be advantageous to fire departments, if properly installed, tested, and maintained. This is also the basic concept and application of FARS. AHJs interested in adopting this system should carefully self-evaluate their resources, requirements, available alternatives, pros and cons of the system before making necessary changes to their codes. When adopted regionally, the AHJ must allocate proper resources to ensure that the system is installed, inspected, tested, and maintained in accordance with local code requirements.

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Authors' Note

This student research project was funded by the Fire Protection Research Foundation, an independent research affiliate of NFPA. In general, the goal of this project is to collect and analyze the information related to Firefighter Air Replenishment Systems (FARS), and provide a report that will be used by the concerned NFPA committee for taking the next steps in relation to standards and regulation. The NYU researchers have not been financially benefited from any of the stakeholders and do not have any personal or organizational interest with the stakeholders. The research budget was used to support student salary and travel for information collection. Adhering to our strong commitment to improving firefighter health and safety, NYU Fire Research Group expended a significant amount of its own resources to collect and provide unbiased information to the fire service and the concerned NFPA committee. However, readers should also note that this is a student project with a limited budget and timeline restriction. The knowledge presented in this preliminary report should be used for information purposes only. The authors are not providing any recommendations regarding the use or discontinuation of FARS. Authorities Having Jurisdiction (AHJ) are encouraged to utilize the information presented at their own discretion to make necessary decisions based on their resources and requirements. Neither the authors nor the Fire Protection Research Foundation are responsible for any kind of loss or gains to anyone resulting from using the information presented in the report. If the information presented in the report conflict with your local SOPs or policies, you should follow your local guidelines. We would like to acknowledge several fire service leaders, fire department officials, and stakeholders who discussed this topic with our research team and provided valuable information. We would also like to thank the leading FARS technology provider for being extremely cooperative in providing information and addressing various issues of importance to the fire service. We appreciate the assistance provided by Ashley, Nanda, Umesh, Rishi, Prabhanshu, and other students from our research group. Finally, we would like to express our gratitude to the Fire Protection Research Foundation for giving us an opportunity to research a topic of paramount interest to the fire service.

Chapter 1: Background

On May 4, 1988, the Los Angeles City Fire Department (LAFD) responded to one of the most destructive high-rise fires in recent United States history. The fire that originated in an open-plan office area in the southeast quadrant of the 12^{th} floor of the modern 62 story First Interstate Bank building in downtown Los Angeles extended upward destroying four floors [1-3]. A total of 383 LAFD firefighters from 64 companies, approximately one-half of the on-duty force of the entire city, successfully controlled the fire by interior suppression efforts in less than four hours. The fire claimed one life, injured approximately 35 occupants and 14 fire personnel, and resulted in a property loss of over 50 million dollars [3, 4].

Urban and suburban fire departments throughout the country have applied many of the lessons learned through this tragic incident in the areas of building construction and engineering, fire prevention, fire suppression, etc. [5]. For example, the building had sprinkler protection only in the basement, garage, and underground pedestrian tunnel as it was built in 1973 - one year before a high-rise sprinkler ordinance went into effect. Although not required by the codes, the sprinkler system was 90% installed at the time of the fire, but was non-functional, awaiting the installation of water flow alarms [3]. This event demonstrated the need for automatic sprinklers to improve fire protection in high-rise structures. Because of this incident, building codes of the city were changed, requiring all high-rises to be equipped with fire sprinklers. This modified a 1974 ordinance that only required new buildings to contain fire sprinkler systems, grandfathering older buildings [6].

The logistical considerations involved in the fire operation were also ginormous. The staging area was located on the 10^{th} floor. At the time, the local standard operating procedures did not allow the use of elevators that have a shaft opening within five floors of the fire floor. Looking at the fire visible from the street, no elevators were used by the firefighters. Without elevators, every piece of equipment was carried up the stairs, including approximately 600 air-bottles. Each firefighter carried hose, nozzles, and other tools up to the 10th floor. Nine companies spent over two hours moving equipment from the street level, through an underground tunnel from a parking garage across the street, up to the lobby, and then up the stairs to the staging area [7, 8].

Although 60-minute air-bottles were available, firefighters were allowed to use only 30-minute air-bottles to avoid the risk of crews overextending their penetration and finding themselves too far above the staging area or too far into a burning floor to reach a safe area before their air supply was exhausted. In each cycle, the companies operated for approximately 20 minutes, returned to the staging area as they were out of the air, and had about 20 minutes for resting, changing the air-bottles, and reassignment to a fire floor. Fatigue became a major concern as several firefighters went through four cycles of fire attack, rest, replacing air-bottles, and reassignment, after walking up 10 floors with all of their equipment. Used empty bottles were stockpiled on the 10th floor and the logistical challenge of two-way movement precluded replenishing bottles at street level [3, 8]. Eventually, as the smoke began to fill the staging area deteriorating its conditions, windows were broken for ventilation.

Following this event, several interventions were proposed and adopted to reduce the impact of such logistical challenges of bottle-brigading including fire equipment (or cache) room near the standpipe to store necessary equipment, replacement, or redesign of the elevator shafts throughout the high-rise structures. Another novel concept that aimed to solve the problem of air-supply without bottle-brigading was Firefighter Air Replenishment Systems (FARS).

The two crucial elements necessary for firefighters to fight any fire are water and air. While water standpipes are widely accessible for firefighting, allowing firefighters to have a reliable immediate water source, the same is not necessarily true for air. FARS is essentially a "standpipe for air" permanently installed within a building aimed to provide emergency personnel with instant access to replenish their bottles [6, 8, 9]. The goal of this project was to analyze and review the existing code requirements and literature to provide guidance on the use and effectiveness of FARS. As per the scope provided by Fire Protection Research Foundation at NFPA, this report provides background on FARS, their installation, use, cost, and inspection, testing, and maintenance (ITM) requirements, specifically addressing the following questions:

- What are FARS?
- What are the needs and use cases for these systems in specific buildings?
- What are the current code requirements for their installation?
- What are the current code requirements for their inspection, testing, and maintenance (ITM)?
- What are the costs of installation and ITM for these systems?
- What are the overall costs vs benefits of these systems?

Chapter 2: Firefighter Air Replenishment System (FARS)

FARS is a breathing air replenishment system permanently installed within a structure and to be used by the firefighters. In very simple words, it is also referred to as a "standpipe for air." The system is designed to provide an ability to refill the air-bottles closer to the fire location instead of allocating resources to carry air-bottles to the fire-staging area designated by the Incident Commander (also referred to as "bottle-brigading"). The proponents of FARS have hypothesized that FARS provides emergency personnel with a safe, efficient, instant, and reliable source of breathing air inside the building structure improving the productivity of fire operations. It can enable the attacking team to focus on fire attack, search and rescue, EMS work, ventilation, and fire control [6, 8-10].

2.A System components: FARS is a modular system that has seven key components as described below:

a) Exterior Mobile Air Connection (EMAC)

b) Interior air fill panels

c) Interconnected tubing

d) Air monitoring system

e) Interior air fill stations

f) Air storage system

g) System isolation valves

The Sunnyvale Department of Public Safety (CA) and a leading FARS technology provider demonstrated the system, its operations, and testing procedures to the NYU research team at a high-rise building in Sunnyvale (CA). The description of each component of the system is provided below:

Exterior Mobile Air Connection (EMAC): It is a locked box mounted on the exterior of the structure or in a remote lockable monument outside the structure that enables the connection between the Mobile Air Unit (MAU) with an on-board air compressor of the fire department and FARS installed in the structure.

Fig. 2.1: Firefighter connecting MAU to EMAC installed in a remote lockable monument. (Picture: With permission from Sunnyvale Department of Public Safety)

With a simple connection to the MAU and a twist of the fill control knob, breathable air flows from the MAU into the FARS for refilling the air-bottles while firefighting. Using the valve at the EMAC, the incident commander (IC) can choose between the air storage system installed in the structure (if available) and the MAU as a source of compressed air. EMAC also includes gauges, digital visual display, and LEDs to monitor the system's pressure, moisture, and CO levels.

EMAC may be installed on a pedestal or kiosk near of point of easier access such that it provides safer parking for MAU. The location and number of EMAC panels may depend on the number of logistical and operational parameters including easy access for MAU, safe parking for MAU, passing traffic, building size, placement for apparatus, etc. Please note that the electric outlet at the bottom of EMAC (see Fig. 2.1) is not necessarily a part of FARS [11]. Similar to other fire protection systems, the components of FARS that require electricity should be connected to the emergency power of the structure. If the fire department requires to have an electric supply, it should meet the requirements of the National Electrical Manufacturers Association (NEMA) [6]. The key for EMAC should be located in the nearby Knox Box.

NYU research team filmed the demonstration of EMAC and has created a video to provide a visual understanding of the use of EMAC in conjunction with MAU of the fire department. This video is available at https://youtu.be/8ZWFFr63Y_s

Interior air fill panels: It is a locked box permanently mounted on the wall inside the fire-rated stairwell that enables firefighters to rapidly refill their SCBA air-bottles. As shown in Fig. 2.2, firefighters can attach a high-pressure fill connection from the interior air fill panel to the Rapid Intervention Universal Air Connection (RIC/UAC) on their SCBA harness to refill empty bottles. Firefighters do not need to remove the air-bottles from their backs and SCBA can be in use while refilling. As per several NFPA standards, the fire department should have Standard Operating Procedures (SOPs) for the use of RIC/UAC fitting.

Usually, these panels are installed 3 to 5 floors apart in high-rise structures and every 150 to 200 feet in large horizontal structures [6, 12]. Local Authority having Jurisdiction (AHJ) should decide the spacing between floors based on available resources, and standard operating procedures of the fire department such that the panels will be available within close proximity of the incident for a quick refill. The panels provide at least 2 connections to refill the air-bottles simultaneously. Typically, these boxes are locked, and the keys to the panel are carried by the local fire department. If needed, firefighters can break the glass on the panel door to get access.

Fig. 2.2: Firefighters refilling air-bottles through connection with interior air fill panel. (Picture: With permission from Sunnyvale Department of Public Safety)

The video created by NYU researchers to demonstrate the visual understanding of the use of interior air fill panels is available at https://youtu.be/i-_wmtZF7ag. In this particular system, it took approximately two minutes to fill the air-bottle at the interior air fill panel. The leading FARS technology provider also confirmed that, on average, these panels fill two air-bottles in approximately three minutes or less. It should be noted that during this demonstration the system was not used at full capacity. The duration for filling may depend on the number of panels being used simultaneously and the source of air supply.

Interconnected tubing: This permanently installed stainless steel tubing (3/8” to 1/2” in diameter) distributes the compressed breathing air from EMAC and air storage system to the air fill panels and the air fill stations. This tubing also connects EMAC and air storage system, and acts as a conduit between the two [6, 8].

This piping distribution system is kept under constant pressure to ascertain the instant supply of air to firefighters and to avoid contamination. In order to protect the tubing from accidental exposure to physical damage, it is hidden behind walls or under floors. All tubing is provided with fire-rated protection, and its bends are secured from mechanical damage. Based on building design, the tubing may be protected by installing it within fire-rated shafts or by locating it within fire-rated stairwells, or by placing it within concrete decks with a minimum 4” concrete cover. It should be noted that the piping protection requirements are not consistent across all jurisdictions [11].

Air monitoring system: FARS may include air-flow monitors (referred to as, “ENMET”) to continuously monitor the quality of air (including but not limited to system pressure, moisture, carbon monoxide) throughout the system. The number of parameters to be measured is specified by the AHJ and the building engineers. The ENMET unit sends information to the fire command center only if and when an air composition reading is detected to be beyond established acceptable levels. There is no intermittent or transient data being sent to fire command or building security [11]. The digital display and pressure gauges on the system depict the measured values enabling the arriving companies to ensure the quality of air and system pressure. The system is similar to the air monitoring system used in fire departments, fire training facilities, and MAUs. The quality of air can also be monitored off-site via web-application.

Fig. 2.3: Air monitoring system.
(Picture: With permission from Sunnyvale Department of Public Safety)

During normal day-to-day operations, if the concerned values exceed safety thresholds, an audible and visual signal is activated to inform local supervisors, fire command center, and web-monitoring station. The building engineer and third-party technicians respond to the alarm and restore the system. A detailed report confirming the air quality and system's readiness for use in emergency situations should be submitted to AHJ. The air monitoring system also acts as a pressure relief in case of accidental over-pressurization of the FARS.

Interior air fill stations: It is a stationary unit in a fire-rated room (such as cache or fire equipment room) that enables firefighters to refill multiple air-bottles simultaneously in a rupture containment chamber. It includes an air control panel for adjusting the system's pressure similar to the fire departments' cascade system. Unlike interior air fill panels, firefighters need to remove the air-bottles from their backs for refilling. Therefore, the appropriate location for installing the air fill station is the interior of the building.

Similar to interior air fill panels, these stations are staged 3 to 5 floors apart in high-rise structures and every 150 to 200 feet in large horizontal structures [6, 12]. The interior air fill stations should be located immediately adjacent to and easily accessible from the stairwell enclosure. Local Authority having Jurisdiction (AHJ) should decide the spacing between floors based on available resources, and standard operating procedures of the fire department such that the stations will be available within close proximity of the incident or the fire staging area.

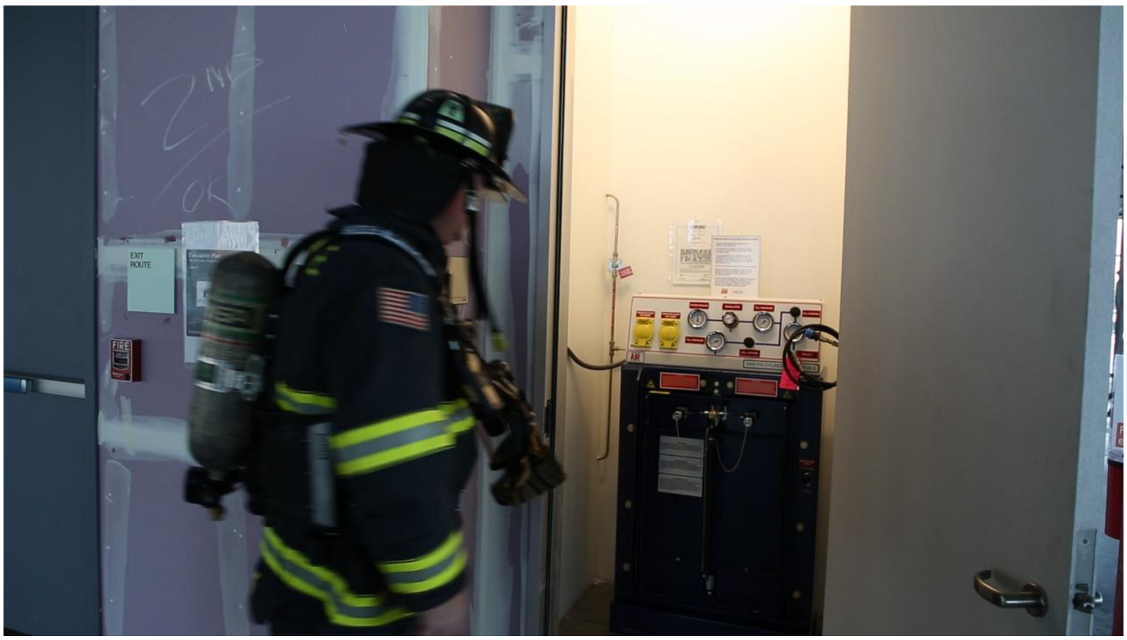

Fig. 2.4: Firefighter using the interior air fill station.
(Picture: With permission from Sunnyvale Department of Public Safety)

Refilling of air-bottles begins by placing empty bottles into a cylinder rupture fill container. Using the air control panel, firefighters can regulate the pressure levels and the period of the refill. After setting the pressure level, the firefighter rotates and locks the fill station door to begin the refilling of pre-loaded bottles. As these bottles are being refilled simultaneously, other empty bottles can be loaded which should reduce the total refilling time.

NYU research team filmed the demonstration of the use of interior air fill stations which can help firefighters to understand their use and operation. The interior air fill station was located within 5 ft. from the stairwell door. This video is available at https://youtu.be/v1SQbV_THk8. In this particular system, it took approximately two minutes to fill two air-bottles at the interior air fill station when the system was not used at full capacity. The leading FAR technology provider also confirmed that, on average, these stations fill two air-bottles in approximately three minutes or less depending on the number of air-bottles being filled, the overall usage of the system, and the source of air supply.

Air storage system: Similar to the fire department's cascade system, it consists of a bank of air-cylinders, booster pump, and other components permanently installed on-site within a structure. This allows the use of interior air fill stations and interior air fill panels to refill the air-bottles without the need for MAU or prior to its arrival and is designed to assist the fire departments with limited manpower for emergency response. This component can provide the ability to refill 50 to 250 air-bottles which depends on the size and capacity of the air storage system. AHJ should specify the capacity of the air storage system based on the building size, and its resources. The capacity of the air-storage system is further enhanced by installing a breathing air compressor that supports the extended operation.

This system is permanently installed within a lockable fire-rated room at the ground or basement level. Using this on-site air storage system, two SCBA air-bottles can be refilled within three minutes or less at the interior air fill station or interior air fill panels. The air monitoring system described earlier is also located in conjunction with the air storage system. Using the valve at the air monitoring system, the incident commander (IC) can choose between the air storage system and the fire department's MAU as a source of compressed air at the interior air fill station and interior air fill panels. At the time of the fire event, in the air storage room, firefighters are essentially responsible for operating this valve and ensuring the system pressure and air quality.

The air storage of FARS used for demonstration included 12 large air-cylinders that could support the refilling of 75 SCBA air-bottles. Additionally, the breathing air compressor was available that could extend the capacity of this system to a total of 105 bottles. Out of the 12 air-cylinders, two primary cylinders are always open and supply the system. The air from two primary cylinders passes through the air monitoring system before it is supplied to the interior air fill stations and air fill panels. As the primary cylinders are depleted, the secondary cylinders supply air to primary cylinders and support their function.

(a) Primary storage with booster pump (b) Secondary storage

Fig. 2.5: Air storage system at FARS demonstration.

(Picture: With permission from Sunnyvale Department of Public Safety)

In order to keep the system pressurized for safety purposes, it has a fundamental requirement of at least two primary cylinders that are open at all times and circulate air in the system. As the air-samples are taken for testing purposes periodically, the pressure in the system decreases. This automatically triggers the operation of the high-pressure pump and commercial-grade air compressor to restore the pressure in the system. Similarly, in the event of a fire, if the system is used without the fire department's MAU then the pump and the compressor begin to operate for maintaining the system pressure to the desired level. The compressor is subject to the same air quality control standards as the air in the system.

System isolation valves: They serve the purpose of isolating certain parts of the FARS system, as needed (e.g., leakage or damage during emergency situations). To prevent tampering, the valves can be locked in an open position. The valves are installed downstream of each interior air fill station and can be operated manually at the air fill station or remotely from the fire command center. It is reported that in the event of leakage during a fire incident, the pressure would still be maintained (though in a lesser amount) and the system will be able to operate due to the size of piping.

2.B Retrofitting FARS: As informed by the leading FARS technology provider, retrofitting of FARS can be accomplished by drilling the holes through stairwell landing for 0.5" stainless steel tubing used to distribute the air. Due to the fact that the route of distribution is typically within the stairwells, the cost of retrofit is usually 2-3% more than the new installation of the system. Based on the building design and requirements from the building owner, in a retrofitted FARS, the interior air fill panels can be surface-mounted directly to the wall or installed by utilizing a rack-mounting system [11, 13]. The piping system in the retrofitted FARS is typically protected by pipe guards.

2.C System design: The FARS system is modular that can be customized based on the requirements of AHJ and building owners. Out of the seven system components, in most cases, every system includes EMAC, interconnected tubing, and an air monitoring system. For refilling the air-bottles, the stakeholders can choose to install interior air fill panels or interior air fill stations, or both. Air storage systems and system isolation valves are optional enhancements for the system and can be installed as required [6].

Interior air fill stations and interior air fill panels should be installed 3 to 5 floors apart in vertical structures allowing firefighters to refill air-bottles in close proximity to the fire incident or as they walk to the fire location and need to wear SCBA because of the contaminated atmosphere. Interior air fill panels should be contained within the stairwell enclosure – the area of refuge for firefighters. Due to the possibility of IDLH (Immediately Dangerous to Life or Health) conditions in the stairwell, the interior air fill panels should be contained within the two-hour enclosure of the stairwell.

The interior air fill station has a footprint of approximately 4ft x 4ft and should not be installed in the stairwell to maintain proper access and egress routes for occupants and firefighters. The interior air fill stations should be located immediately adjacent to and easily accessible (between 5 to 10 ft.) from the stairwell enclosure. The fill station room should have restricted access with a 'fail-safe' latch locking mechanism that can be released from the building's Fire Alarm Control Panel or at the fire command center. AHJ should identify and designate one specific stairwell throughout their response district where the interior air fill stations will be located (e.g. Stair-A), and when necessary coordinate these locations with mutual-aid response groups.

Similar to Fire Department Connection (FDC) for a standpipe or sprinkler system, AHJ should decide the location of EMAC on the exterior wall of the building or in a remote lockable monument outside the structure such that MAU with an on-board air compressor will have unobstructed access to EMAC. During an emergency incident, the MAU Unit may not be able to connect to a single EMAC panel due to falling debris, damage to the hose, and other hazardous conditions. Therefore, AHJ should consider a requirement of a minimum of two EMAC panels that are interconnected and remotely located on opposite sides of the structure. MAU should be closer to the EMAC without having to roll out an extended hose lay. MAU must be provided safer parking away from the structure to avoid falling debris and products of combustion.

MAU operator and IC must ensure that air taken in by the compressor is not contaminated by smoke or other products of combustion at the fire incident. FDC and deployment of hose lines should be away from EMAC. Wind pattern, the prohibition of parking / red-curbing of the surrounding area, and uphill placement on hilly terrain are additional parameters that should be considered by AHJ for the EMAC installations. The air storage system is permanently installed within a lockable fire-rated room at the ground or basement level inside the structure. Depending on the source of air-supply for filling air-bottles, FARS can be operated with (a) MAU with an onboard air-compressor (b) an air storage system installed in the structure (c) a combination of both systems.

The MAU to be connected to FARS should be equipped with an onboard air compressor and compatible with pressure and volume requirements of interior air fill stations and interior air fill panels. Fire departments should develop specific SOPs for MAU's operation in conjunction with FARS and requirements for communication between IC and MAU operators. AHJ should also consider the onboard cascade system in case of failure of the air compressor and absence of the FARS air storage system. Ensuring MAU's functionality on a regular basis is also important. Overall, as recommended by NFPA 1031 and FEMA guidelines, fire departments ensure that emergency planning and preparedness measures are in place, and have been practiced by concerned members through periodic in-field training exercises [6, 8].

Chapter 3: Needs and use cases of FARS

Primarily, the FARS serves the need of firefighters to refill air-bottles in close proximity to the fire incident in a large vertical and horizontal structure. Without FARS, IC would need to deploy a number of firefighters for bottle-brigading. In this bottle-brigading operation, firefighters repetitively (a) transport air-bottles from the mobile air truck to the fire-staging area, (b) carry expended air-bottles down the stairs, (c) fill spare air-bottles at the mobile air truck, and (d) again carry filled air-bottles up the stairs to the fire staging area [6, 8].

The fire dynamics encountered during modern fires differ greatly from those in the past decades. The size and open layouts, new construction techniques, lightweight engineered structural components, and high-heat release-rate furnishings are increasing the risk to firefighters. The cumulative effects of these changes are faster fire propagation, an excessive volume of smoke, shorter escape times, decreased time to flashover, shorter times to structural collapse, and a reduction in time available for effective fire-ground operations. High-rise fires (such as the First Interstate Bank building fire in Los Angeles, One Meridian Plaza fire in Philadelphia) can demand significant resources and time for bottle-brigading [3, 14-16].

The firefighters responsible for bottle-brigading can be used for fire attack, search and rescue, medical and other critical operational needs enhancing the efficiency of fire operations. It is reported that for every four firefighters involved in active firefighting, four firefighters are needed every seven floors to support the operation. In some cases, as many as half of the personnel operating at high-rise fires are used for bottle-brigading [6]. The work involved in high-rise firefighting coupled with the efforts involved in bottle-brigading can demand resources from fire departments that can exceed their capabilities. As the number of supertall structures (above 300 m in height) and large big-box facilities is also increasing, the operation of bottle-brigading can become more challenging for fire service, especially for volunteer fire departments (70% of US fire service) with limited personnel and other resources [17-19].

The availability of an interior air fill station and interior air fill panel in close proximity to fire incident offers an ability to “top-off” the air-bottles just prior to entering the fire floor. This can be useful in situations where firefighters climb to the fire floor while wearing SCBA in a contaminated stairwell and expend the available air. Additionally, if the FARS air storage system is available at the structure, the inefficiencies in fire operation due to possible delays in the arrival of mobile air truck or its logistics can be avoided [6, 11, 20]. In our discussion with the fire service, the use of fire service elevators to facilitate the bottle-brigading operation and the availability of fire equipment or cache room to serve the immediate need for air-bottles were identified as an alternative to FARS. However, the advantages of FARS (if implemented successfully) discussed above also cannot be ignored. Please note the FARS and its alternatives have been discussed in detail in Chapter 5.

Researchers from the University of Waterloo developed two scenarios to test the amount of air used by firefighters during high-rise firefighting. Their report demonstrates the physically demanding and strenuous nature of high-rise firefighting operations that result in the rapid depletion of air and highlights the need for better strategies to manage air supply. In their experiment, 50% of the firefighters’ low-air alarm was activated in 11-12 minutes, even while working at a self-selected pace of operation. In some cases, the low-air alarm was activated in as little as 8 minutes [21]. The low-air alarm implies that 75% of the firefighter’s air has been consumed. Considering varying rates of consuming air for every individual, exiting the work area only upon activation of a low-air alarm can be risky [22, 23].

A survey on FARS conducted between November 2010 and December 2010 indicated that 94.9% of all participants (total count: 39) had a favorable opinion of FARS. 53.8% of their participants never heard of FARS and 79.5% of all participants felt FARS would aid their fire department with the logistical difficulties of high-rise firefighting operations [8].

The need for FARS is evident in several types of structures where bottle-brigading can be challenging due to the requirement of significant personnel effort, duration, and logistical hurdles [24-27]. It can serve the structures including but not limited to:

i. High-rise buildings
ii. Tunnels

iii. Mega horizontal structures (such as big-box retail stores, warehouses, manufacturing / industrial plants, etc.)
iv. Subways
v. Underground structures
vi. Large marine vessels (such as cruise ships, cargo ships, submarines, and large naval crafts)

FARS has been installed in more than 500 buildings across 20 US states, including three subway stations in San Francisco (CA). However, there is no documented case of the use of FARS in a real-life fire event. A leading FARS technology provider also confirmed that fire service has tested and used the FARS system in training exercises (e.g. Phoenix Fire Departments' Training Tower (AZ), Glendale Regional Public Safety Training Center (AZ)), but FARS has not been used in any real-life emergency situation [11].

Since the inception of this project, we discussed FARS with many fire service leaders including the advocates of FARS and fire officials with issues about the system. We also visited several career and volunteer fire departments to learn their perspectives about the topic, and understand their current operation of filling air-bottles, and supplying them to firefighters at the fire incident. We also learned their current process and standards for installation, inspection, testing, and maintenance required for the equipment involved in the air-bottle filling operation, and the associated costs.

In our discussion with fire service leaders, we found that most of them were aware of FARS, its application, and its possible benefits for fire service, if implemented properly. However, several fire officials raised issues about the quality of air, the standards and process followed for inspection, testing, and maintenance (ITM) of the system, costs associated with systems, and its use in real fire incidents. We learned that in some jurisdictions while responding to high-rise fires, firefighters are not comfortable using the hose available at the structure, and they carry their own hose up the stairs. Thus, convincing members to breathe air through a system that is not maintained by them can be challenging. Discussions with a few major career fire departments with a large number of firefighters reported that, in most cases, their members are required to go through rehabilitation after consuming the first air-bottle at the fire and are replaced if the additional crew are available. Conversations with their firefighters also implied that they physically feel tired to efficiently respond to high-rise fire after consuming two or three air-bottles. From their perspective, the necessity of refilling air-bottles and thus the applicability of FARS in their jurisdiction is questionable. Additionally, considering the strong passion of firefighters for public safety, the availability of instant air-supply may encourage them to overexert and place themselves in danger. If building owners fail to test and maintain the system per the standards, it may also pose health issues for firefighters. As FARS has never been used in real-fire incidents, the reliability of the system was also one of the major issues raised by the fire officials.

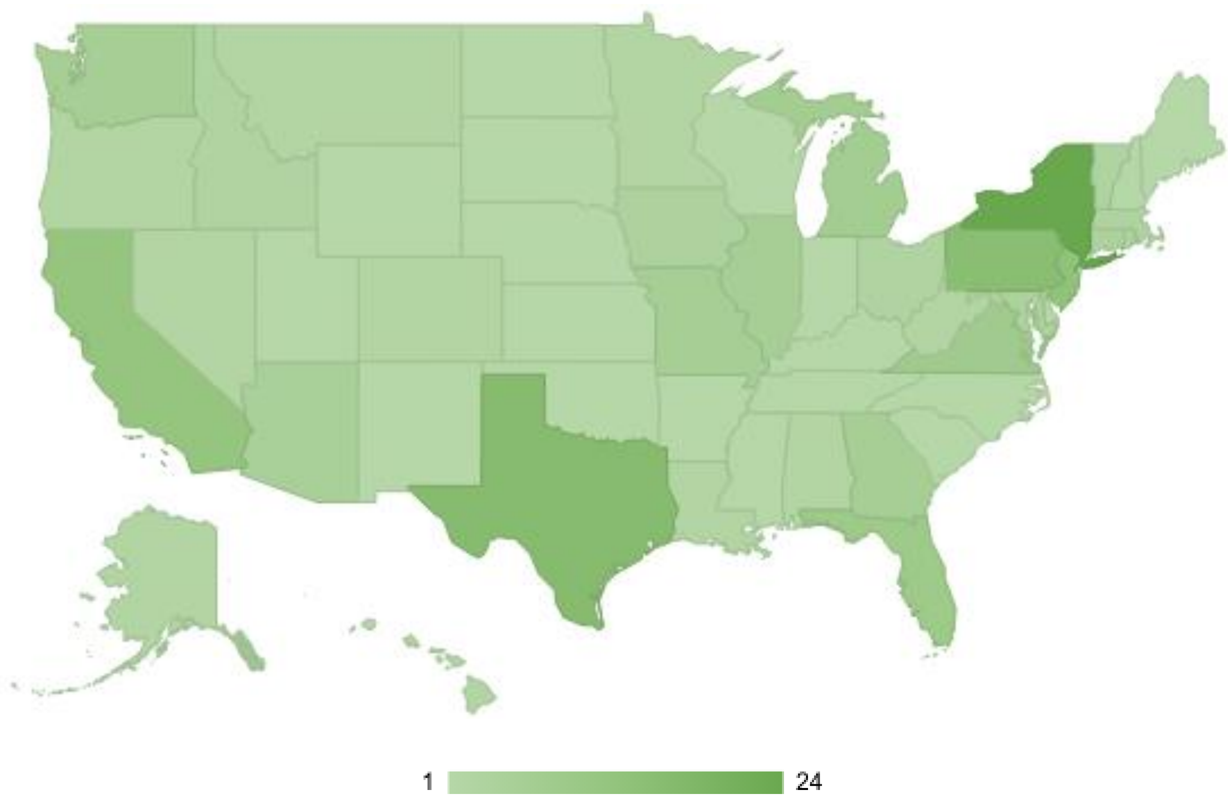

Fig. 3.1: Geographic distribution of fire department participants.

While these inputs were very crucial for the study, we decided to expand our reach and receive unbiased feedback from fire departments across the nation. In consultation with the project panel, a brief questionnaire was developed to collect relevant perspectives of random firefighters across the nation. Instead of collecting the data from our partners in

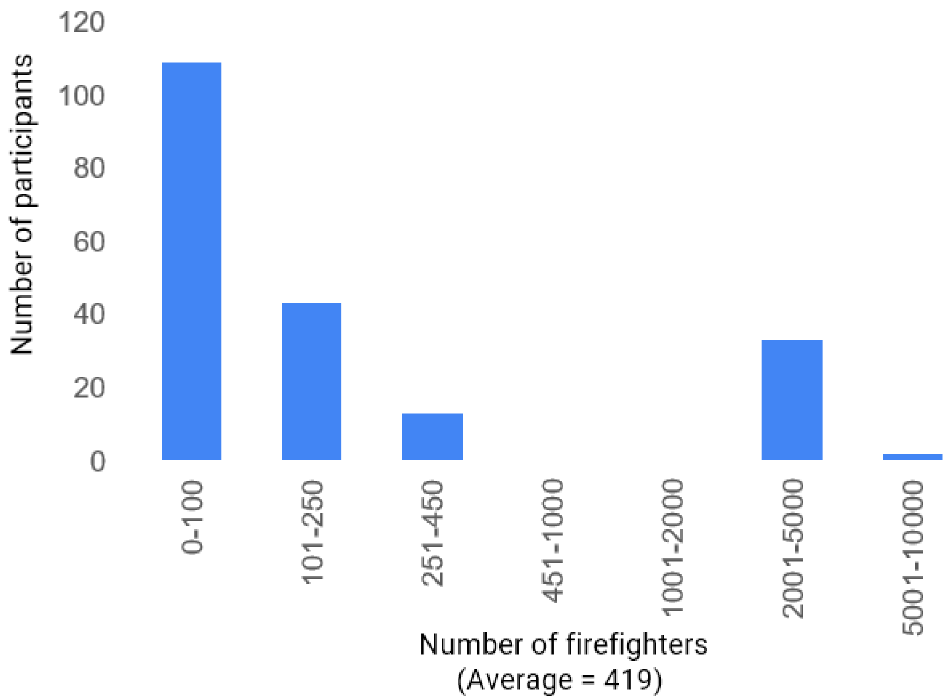

Fig. 3.2: Number of firefighters in participating fire departments.

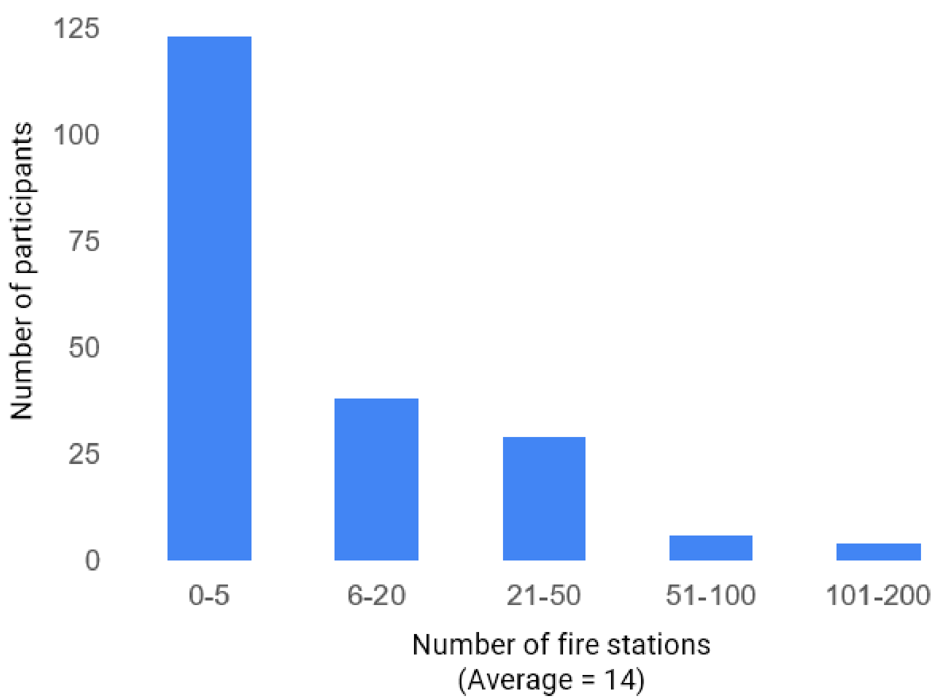

Fig. 3.3: Number of fire stations at participating fire departments.

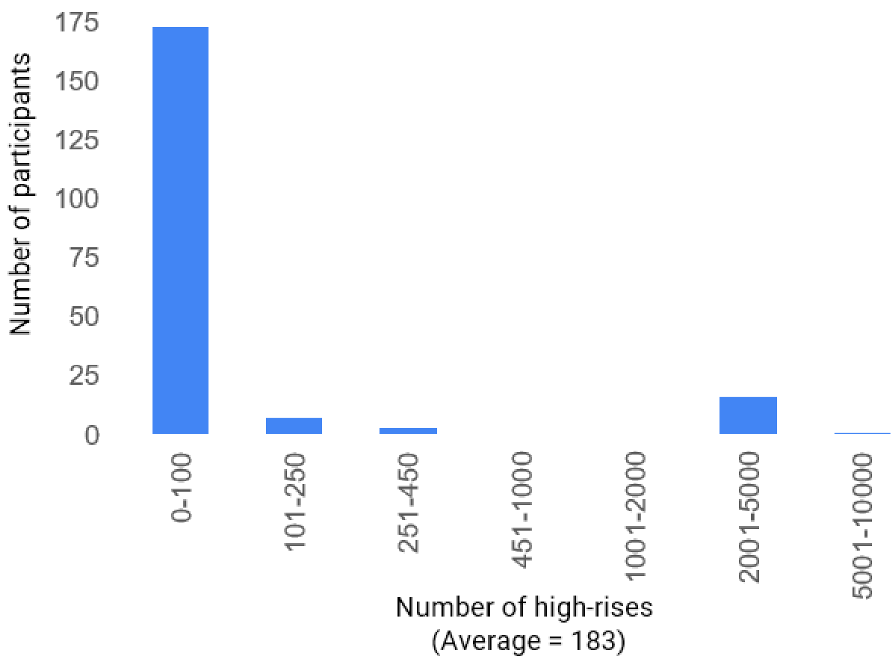

Fig. 3.4: Number of high-rises at participating fire departments.

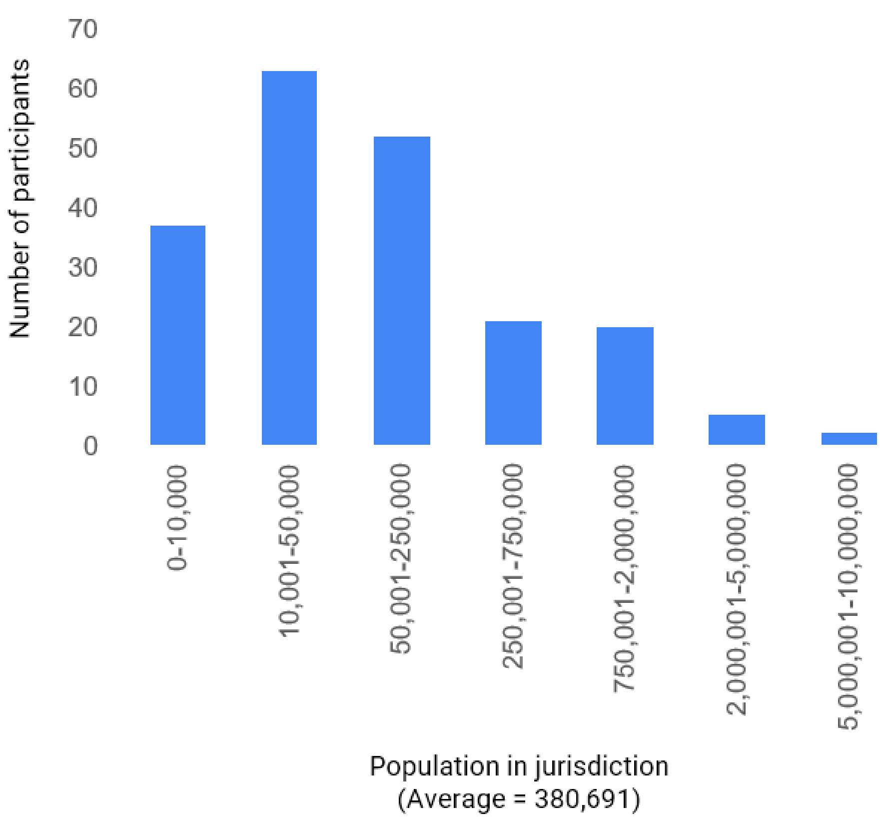

Fig. 3.5: Population in the jurisdiction of participating fire departments.

fire service, the survey was made available to all fire departments in the nation through the SecretList of firefighterclosecalls.com. Considering the timeline restriction of the project, the data collection process was stopped after receiving feedback from representatives of 200 unique fire departments (N = 200). It is very likely that most of the firefighters of fire departments who adopted FARS will have positive opinions about the system or vice-versa. The strategy of one opinion per fire department for data collection assisted the team in reducing the effect of a large number of similar opinions from the same jurisdiction on the outcomes of the questionnaire.

The geographic distribution and demographics of the fire department participants are provided in Fig. 3.1-3.5. 81% of all participating fire departments had less than the average number of firefighters and 88% of all participants' jurisdiction included less than the average number of high-rises. This implies that a few very large and many small fire departments participated in the questionnaire – an overall reflection of the US fire service. Thus, the outcomes of the questionnaire may represent a nationwide opinion about the topic.

All questions were mandatory, and the responses of participants are depicted below. Furthermore, the responses for each question have been analyzed with respect to their background (fire department location, number of firefighters, number of high-rises in the jurisdiction, etc.), and has been provided if a notable useful observation has been identified.

As shown in Fig. 3.6, 59% of all participants were aware of FARS. 73.17% of all participants who were not aware of FARS were located to the east of the Mississippi River. Additionally, 71.05% of participants located to the west of the Mississippi River were aware of FARS. This may be due to the fact that the FARS installations are more prevalent in the west of the Mississippi River.

As shown in Fig. 3.7, 88.5% of all participants were not aware of any structure with the FARS installation. 82.61% of all participants who were aware of any structure with FARS installation were located to the west of the Mississippi River. 96.77% of participants located to the east of the Mississippi River were not aware of any structure with FARS installation. These observations are complementing and confirming the findings of Fig. 3.6. Additionally, 76% of participants whose jurisdiction included more than the average number of high-rises, where FARS is more applicable, were also not were of any structure with FARS installation.

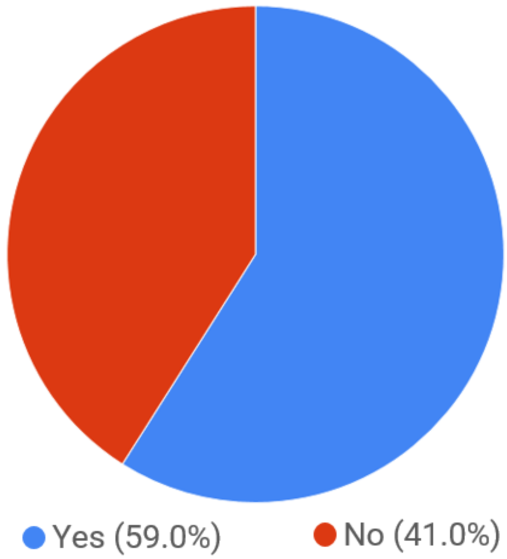

Fig. 3.6: Participants aware of FARS.

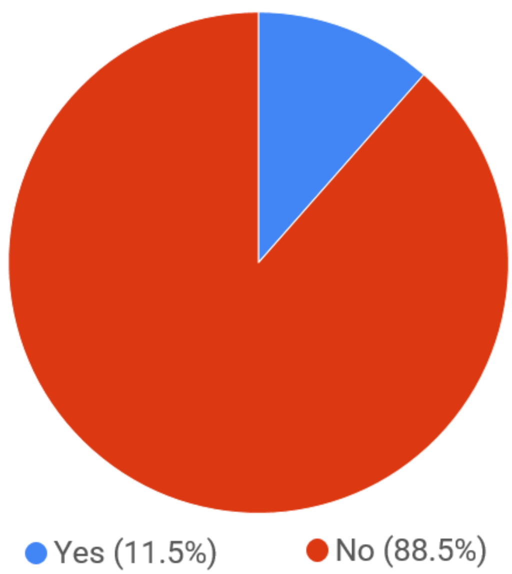

Fig. 3.7: Participants aware of structures with FARS Installation.

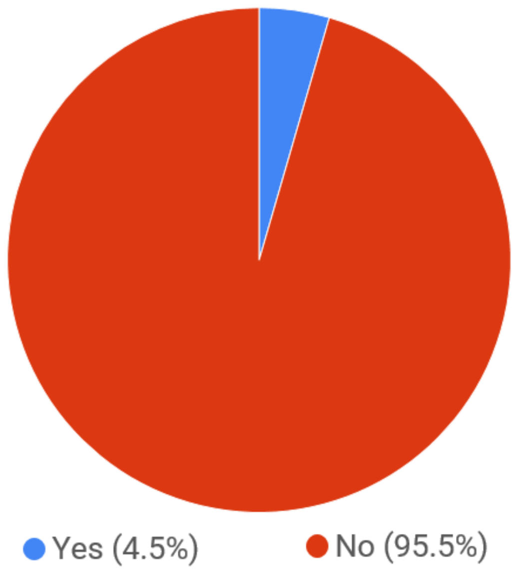

Fig. 3.8: Participants aware of real-life fire incidents where FARS have been utilized.

As shown in Fig. 3.8, 95.5% of all participants did not know of any fire incident where FARS has been utilized by the firefighters. As per the leading FARS technology provider for more than 30 years, FARS has not been deployed in a real-life fire event and it has been used only for training exercises. The finding from Fig. 3.8 is supporting this information. We assume that the other 4.5% of all participants who claimed to know the FARS deployment in a real-life fire incident might be referring to the use of FARS in training exercises.

As shown in Fig. 3.9, 37% of all participants would like to utilize FARS in real fires and another 40.5% may deploy FARS in the field. 68.89% of all participants who do not intend to use the FARS in real fires were located to the east of the Mississippi River. 47.37% of participants west to the Mississippi river would like to deploy FARS in real fires and another 34.2% of participants from the same group may consider using it. These observations are complementing our previous findings related to the geographical location of participants. Additionally, 52% of participants whose jurisdiction included more than the average number of high-rises, where FARS is more applicable, would like to use the system in real-fires and another 28% of participants from the same group may use it. This highlights the need for urban fire departments with a higher concentration of high-rise structures for a solution that may avoid or facilitate the “bottle-brigading” operation.

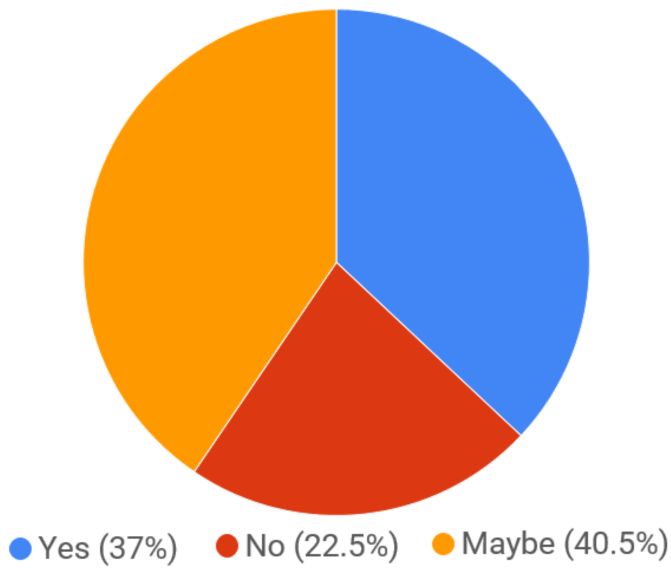

Fig. 3.9: Participants intend to utilize FARS in real fires.

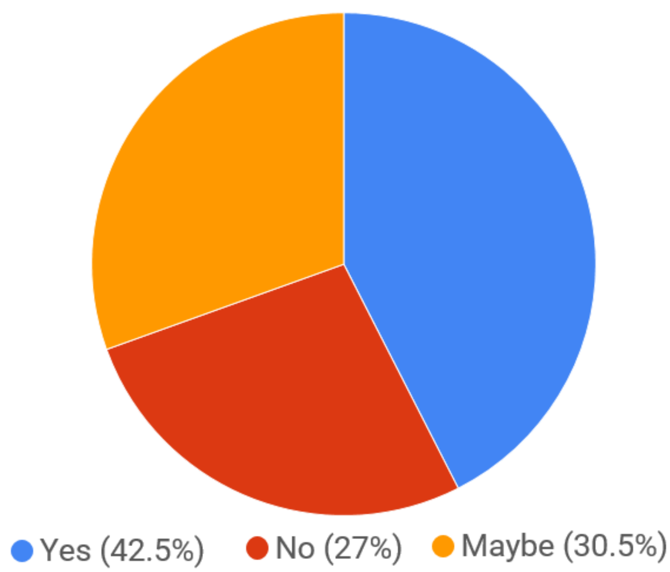

Fig. 3.10: Participants comfortable with the testing and maintenance of FARS performed by a certified third party and coordinated by the building's owner.

As shown in Fig. 3.10, 42.5% of all participants were comfortable with the testing and maintenance of FARS performed by a certified third party and coordinated by the buildings' owner. Another 30.5% of all participants may accept these procedures. 70.37% of all participants who were not comfortable with third-party testing and maintaining the FARS were located to the east of the Mississippi River. Whereas 46.05% of participants west to the Mississippi river were comfortable with third-party testing and maintenance of the system, and another 32.89% may accept this process for testing. These results confirm that acceptance for FARS is higher to the west of the Mississippi River.

Additionally, 43.43% of participants whose jurisdiction included less than the average number of high-rises were comfortable with third-party testing and maintenance of FARS, and another 30.86% of participants from the same group may consider this type of testing and maintenance. Fire departments of jurisdiction with less than the average number of high-rises are located in suburban and rural parts of the nation with limited personnel and financial resources and are possibly more accustomed to the type of testing and maintenance of FARS.

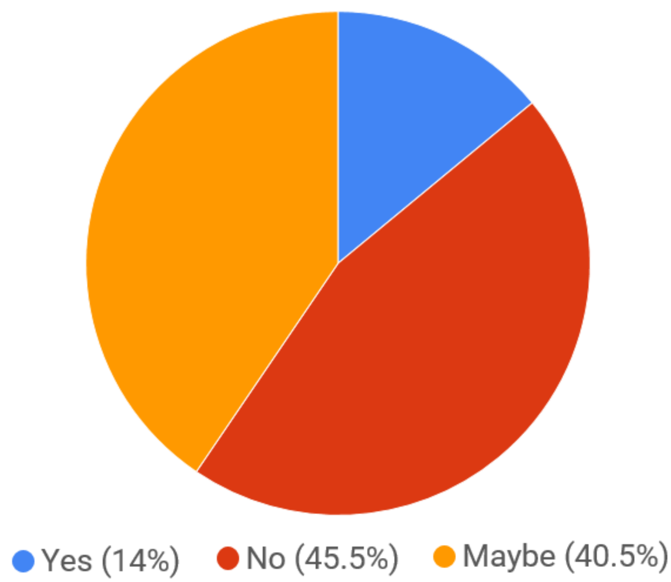

Fig. 3.11: Participants comfortable with existing codes for testing and maintenance.

The criteria for the installation, inspection, testing, and maintenance (ITM) of FARS are contained in the Uniform Plumbing Code (adopted from International Association of Plumbing and Mechanical Officials IGC 220-2005) – Appendix F, and International Fire Code (IFC) – Appendix L by International Code Council (ICC). Additionally, several fire departments that adopted FARS also developed codes for their jurisdictions using UPC and IFC codes. As shown in Fig. 3.11, only 14% of all participants felt that existing codes provide enough standards for testing and maintenance to ensure a suitable quality for breathing air in FARS. 60.71% of this group was located to the west of the Mississippi

River. This observation follows the fact that the installations of FARS are more common to the west of the Mississippi River. However, the need for improvement in codes for ITM of FARS was highlighted by participants irrespective of their size, number of high-rises in the jurisdiction, geographical location, and other demographics.

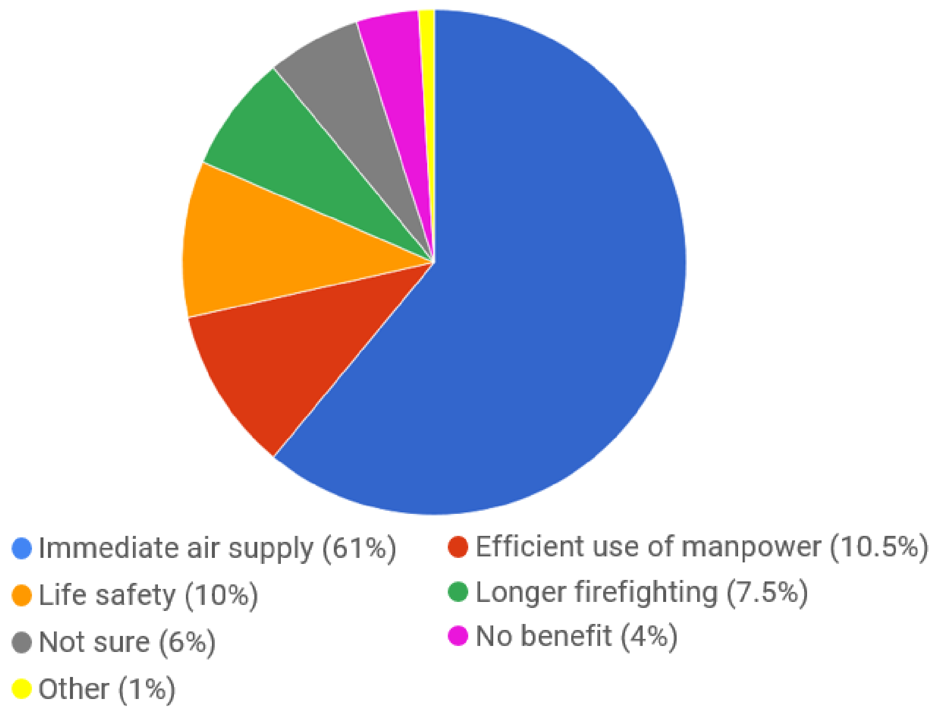

Fig. 3.12: Benefits of FARS reported by participants.

As shown in Fig. 3.12, air supply in close proximity to fire location was reported as the primary benefit by 61% of all participants. Other participants mentioned that FARS can:

- ✓ allow them to efficiently use their manpower by avoiding fatigue and time involved in bottle-brigading (10.5%),
- ✓ save lives by supplying air in the IDLH environment (10%), and
- ✓ allow them to fight fire for a long time without exiting the structure (7.5%).

Few participants (6%) were not sure about the benefits due to their unfamiliarity with the system, and 4% of all participants did not see any benefit of FARS to fire service. 75% of participants who did not see any benefit in FARS were located to the east of the Mississippi river which complements our previous observations related to the effect of geographical location.

Immediate air supply which was found to be the primary benefit of FARS, its quality, and lack of maintenance was the major drawback of FARS as reported by 34% of all participants (see Fig. 3.13). Participants shared their experience of owners not maintaining existing fire protection systems which create unexpected situations for firefighters. Several participants mentioned that if owners properly test and maintain existing fire protection systems periodically, the fire environment can become significantly safer even in the absence of FARS.

Other drawbacks reported by the participants were:

- ✓ Reliability (11.5%): FARS has never been used in real-life fires, and its real-life performance can be questionable. Participants were concerned that the system which is not maintained by them may not work when they will need it the most and reliance on FARS may lead to more chaos.
- ✓ Cost of installation and maintenance (8.5%): Participants assumed that the cost of installation and maintenance of FARS must be high due to which structure owners will follow dubious practices that will compromise the quality of air and performance of the system placing the firefighters at risk.
- ✓ Encouragement for overexertion (8%): Considering the drive of firefighters for the job, participants felt that an unlimited instant supply of air may encourage firefighters to overexert themselves, to avoid rehab, and to aggressively overextend their reach into the burning structures placing themselves in danger.
- ✓ Possible tampering & contamination (3%): High-rise fires can be challenging but may not be a frequent event in most parts of the nation. A system may not be used for decades after the installation. Tampering or contamination of the system within this period may impact its performance during the fire incident, and the health and safety of responding firefighters. Contamination of the system during a fire incident may not allow its reuse or require major repairs incurring significant costs. As the system has not been used in a real-fire, concerned data is not available, and few participants felt that FARS can be a single-time use system.

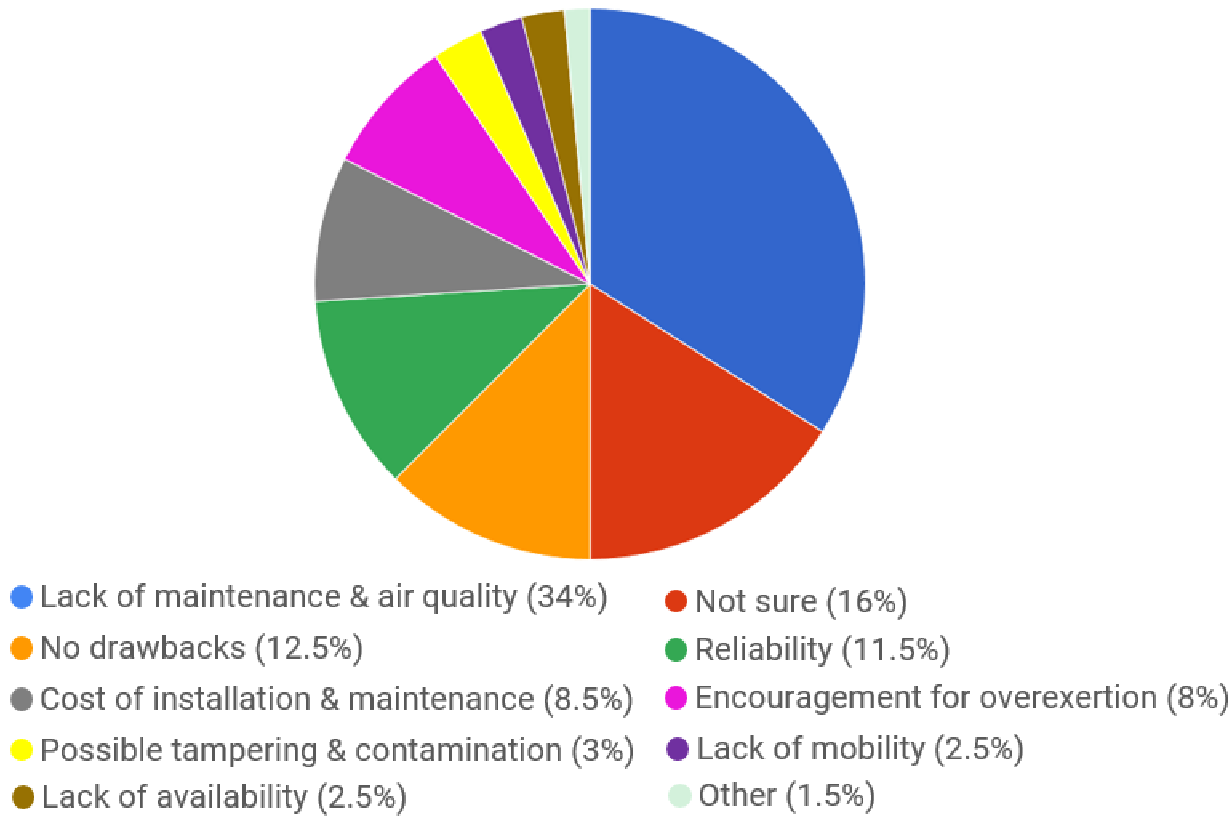

Fig. 3.13: Drawbacks of FARS reported by participants.

- ✓ Lack of mobility (2.5%): FARS is permanently installed within the structure at certain locations such as stairwells, and its components cannot be moved. If the location of interior fill stations or interior air fill panels is compromised during the fire, then filling air-bottles may not be possible. Stairwells are also used for evacuation as well as hoseline activity and few participants were concerned that filling air-bottles inside the stairwell can lead to overcrowding of stairwells and add to the chaos in the fire environment.

- ✓ Lack of availability (2.5%): Few participants reported that the system is not available in all applicable structures. Issues about retrofitting the system in older structures, associated costs, impact on the structure, and system performance were also mentioned.

16% of all participants were not sure about the drawback due to unfamiliarity with the system, and 12.5% of all participants did not report any drawback of the system. 52.63%

of participants with more than the average number of firefighters did not report any drawback of the system.

As shown in Fig. 3.14, the quality of air and maintenance of the system was the major issue reported by the participants. Essentially, the majority of participants (63%) do not trust the owners of the structures for maintaining the system and providing the air of breathable quality adhering to standards. Several participants shared that their firefighters are not even comfortable using the hose available at the structure, and they carry their own hose up the stairs. Therefore, breathing air through the system maintained by the owners that can impact the health of firefighters was found to be the major issue for many participants.

Other concerns reported by the participants were:

- ✓ Real-life performance (5.5%): Participants questioned the real-life performance of FARS as there is no documented case of its use in a single fire-incident. The system may not be used for decades after the installation and may not be maintained properly during this period due to associated costs to be paid by the owners. Additionally, the data on how many air-bottles can be filled simultaneously and the required time, the impact of heat and smoke on the system, the ability of firefighters to operate the system, and the overall performance of the system in a real-life incident is not available.

- ✓ Overexertion (5%): Incident rehabilitation (rehab) is an integral component of firefighting to mitigate the physical, physiological, and emotional stress of firefighting in order to improve performance and decrease the likelihood of injury or death. The availability of immediate plenty of supply of air will allow firefighters to fight the fires for a long time. However, the physical exertion of firefighters was a concern for several participants. Firefighters may continue to refill air-bottles and overexert themselves by avoiding rehab or increase the safety risk by going deep inside the structure.

- ✓ Tampering and contamination (4%): Tampering and contamination of the system may impact the ability of the system to function properly during a fire incident risking the firefighting operations and affect the quality of air delivered through the system endangering the health of firefighters. The data on wear and tear of the system over a prolonged period or after a fire incident, its impact on the system's performance, and quality of air are not available, which was concerning to the participants.

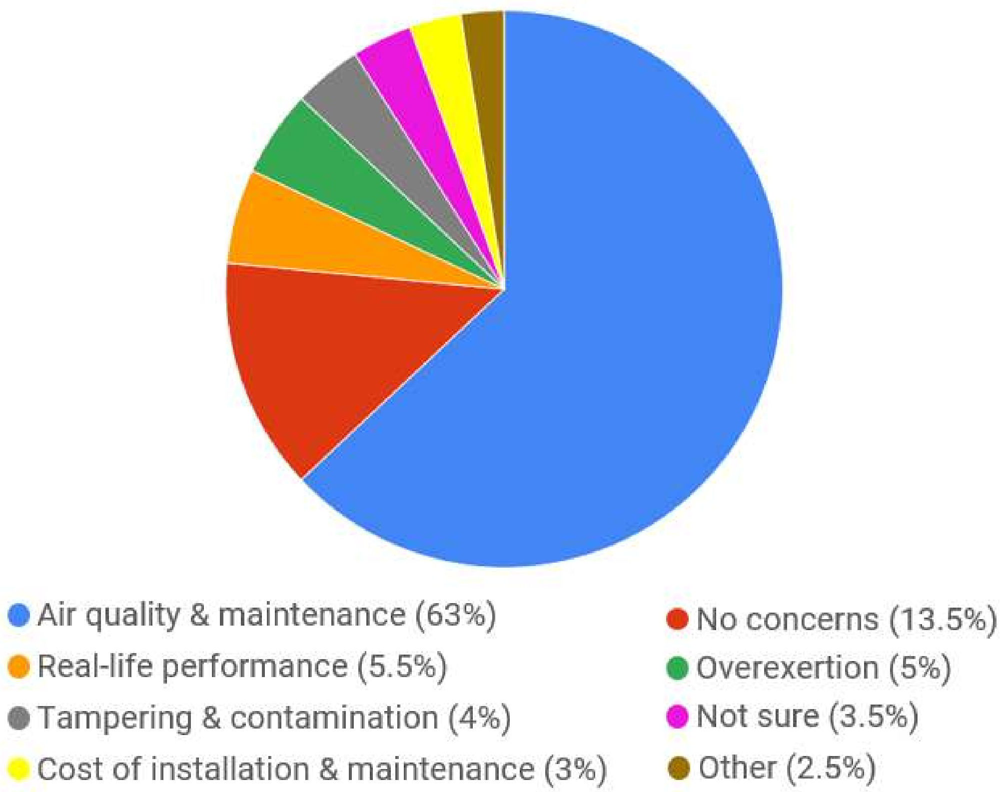

Fig. 3.14: Concerns about FARS reported by participants.

✓ Cost of installation and maintenance (3%): If FARS is mandated by the AHJ, the building owner or management will need to pay the cost of installation and maintenance. Based on experience, several participants felt that first-of-all, building developers will resist the adoption of codes mandating the installation of FARS. Additionally, the procedures for proper installation and maintenance may not be followed in an effort to reduce the associated costs which will risk the firefighting operation during the incident, and the health and safety of responding firefighters. The cost of upgrading the system to fulfill the pressure requirements of new air-bottles was an additional concern.

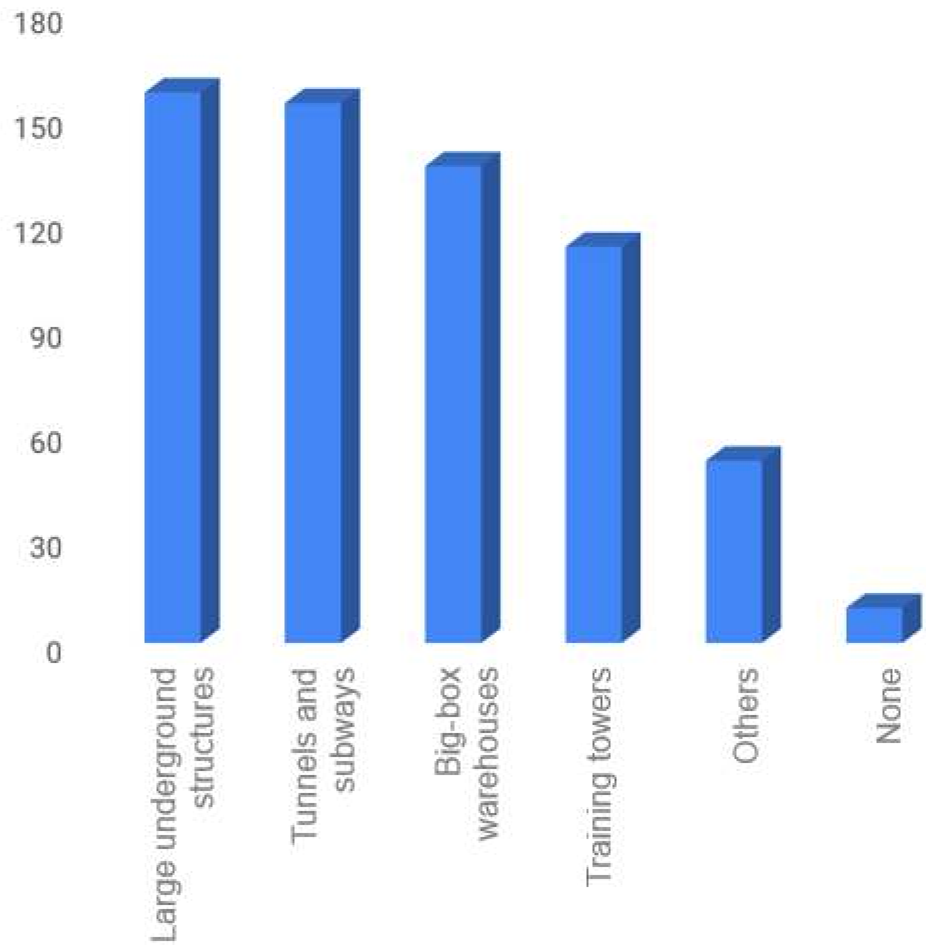

Fig. 3.15: Types of structures in which FARS can be installed and applicable.

While 3.5% of all participants were not sure about their concerns on FARS due to unfamiliarity with the system, 13.5% of all participants were not concerned about the system. This constituted 19.73% of participants west to the Mississippi river in comparison to 9.67% of participants east to the Mississippi River. A few participants were also concerned about the presence of a prominent FARS technology provider that can influence the costs associated with the systems, codes and standards to install and maintain the system, quality of testing and certifications, available options for the stakeholders, and advancements of the system which can ultimately risk the health and safety of firefighters. A few fire officials were more concerned about firefighters' health and safety issues, and not the providers.

FARS can be beneficial in several types of structures where bottle-brigading can be challenging due to the requirement of significant personnel effort, duration, and logistical hurdles. Participants reported that, in addition to high-rise buildings, FARS can be applicable to large underground structures, tunnels and subways, big-box warehouses, and firefighter training towers. The distribution for this multiple-choice question is shown in Fig. 3.15.

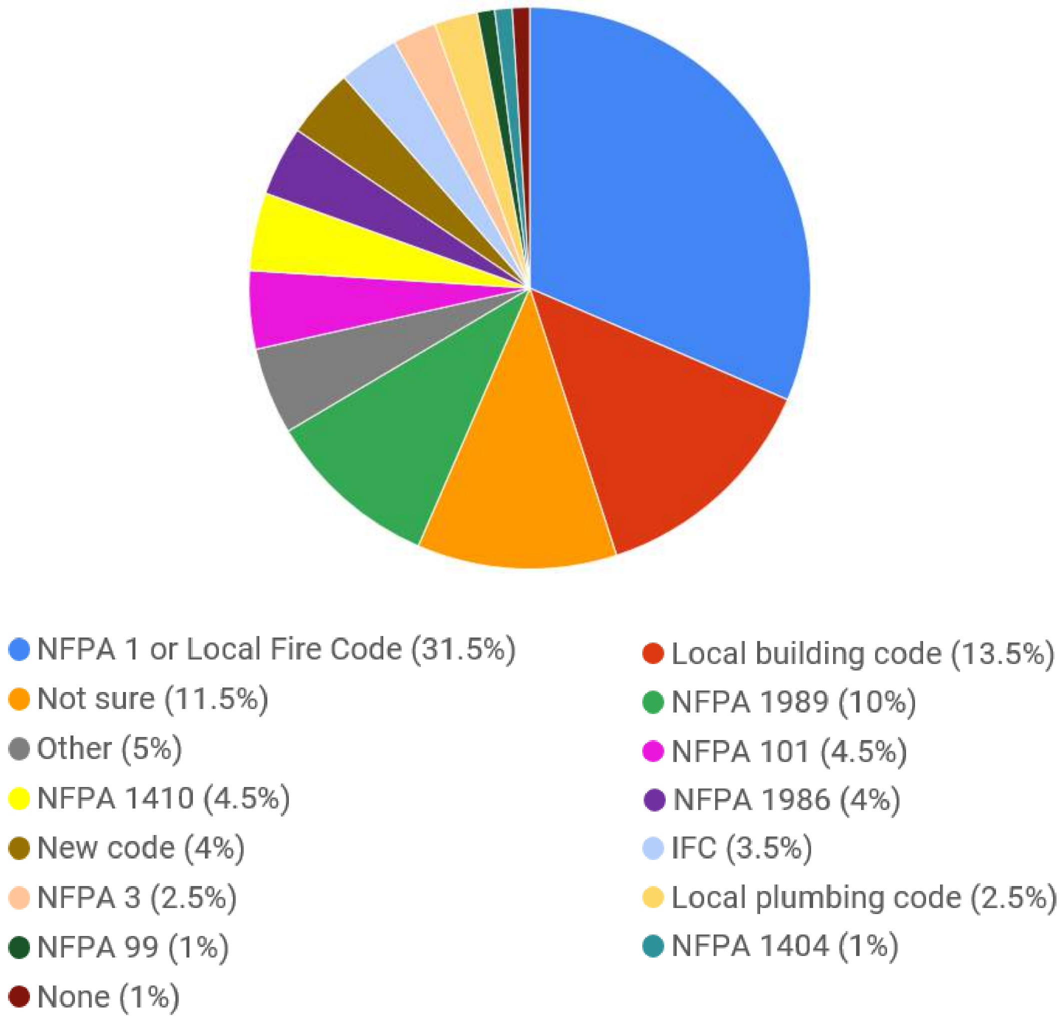

Fig. 3.16: Codes for regulating design, installation, testing, and maintenance of FARS.

Five percent of all participants reported that it should not be installed in any structure. Several participants noticed the application of FARS in a wide variety of structures such as large marine vessels/ships, industrial and manufacturing plants, schools, hospitals, malls, hazmat facilities, aircraft hangers, caves, airports, stadiums, large agricultural buildings, high-fuel-load facilities (mattress shops), etc.

As shown in Fig. 3.16, most participants (31.5%) reported that NFPA 1 or local fire code should incorporate the standards for regulating design, installation, testing, and maintenance of FARS. Another 13.5% of all participants proposed changing local building codes to regulate the FARS system. 11.5% of all participants were not sure due to unfamiliarity with the system. NFPA 1989 can be also modified to ensure the quality of air delivered through FARS, as reported by 10% of all participants. As shown in Fig. 3.16, few other participants suggested changes to several other existing code documents including NFPA 101, NFPA 1410, NFPA 1986, IFC, NFPA 3, NFPA 99, NFPA 1404, local plumbing code, etc. Please note that the criteria for the installation, inspection, testing, and maintenance (ITM) of FARS are contained in the UPC – Appendix F and IFC – Appendix L.

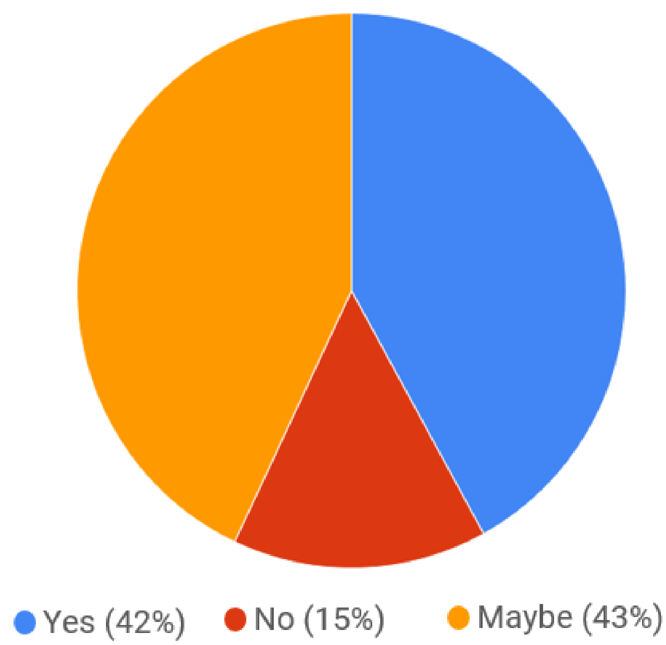

Fig. 3.17: Use of FARS in conjunction with MAU.

As explained in Chapter 2, FARS can be used with the fire department's MAU instead of delivering the air through the air storage system installed in the building. Such use of FARS may reduce the concern of the quality of air provided at the interior air fill station and interior air fill panel. As shown in Fig. 3.17, 42% of all participants were comfortable using FARS in conjunction with their MAU, and another 43% of all participants may consider this option. 15% of all participants were not ready to use FARS with MAU which also included a few small fire departments that may not have MAU. Overall, the use of FARS in conjunction with their MAU was less concerning to the participants.

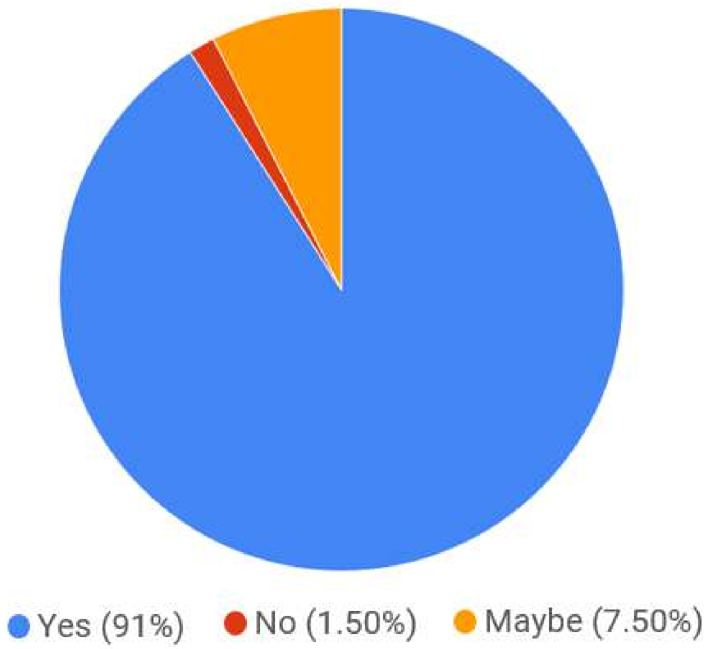

Fig. 3.18: Need for training to use FARS.

The need for training to use the FARS system is evident as shown in Fig. 3.18. Only 1.5% of all participants did not feel the need for training to use FARS. Based on our observations while receiving the demonstration of FARS, we also concur that AHJs planning to implement FARS in their jurisdictions must provide periodic hands-on training for using various components of FARS to their members. This will ensure the efficient use of FARS in real-life fire incidents without any confusion.

Chapter 4: Current code requirements for installation, inspection, testing & maintenance

In 2006, the International Association of Plumbing and Mechanical Officials (IAPMO) included IAPMO IGC 220-2005, “Breathing Air Replacement Systems,” to their Uniform Plumbing Code as a supplement to Appendix F [8, 28]. As recommended by the International Code Council (ICC) Fire Code Action Committee (FCAC) and the International Associate of Fire Chiefs (IAFC) Fire and Life Safety Section, FARS has been also included in Appendix L of the 2015 International Fire Code (IFC) [29]. The UPC and IFC codes intend to standardize the criteria for installation, inspection, testing, and maintenance of the FARS.

It is estimated that 8000 cities from 14 US states that follow the Uniform Plumbing Code should consequently require FARS in the applicable structures within their jurisdiction. However, at present, approximately 100 cities in 20 US states have adopted ordinances requiring FARS which has led to the installation of the system in around 500 structures in the nation [11]. This implies that these code changes are happening at the state and local level instead of adoption through UPC or IFC codes. FARS installations are more prevalent in California, Arizona, Nevada, Oregon, Colorado, and Florida than in other parts of the country. The following sections briefly summarize these codes.

4.A UPC – Appendix F [28]: As per UPC, the FARS shall be installed in (a) high-rise structures (greater than 75 ft. in height) (b) Underground structures (three or more floors below grade with an area greater than 20,000 sq. ft.) (c) Large area structures (area greater than 200,000 sq. ft. and where travel distance from the building centerline to the closest exit is greater than 500 ft.) (d) Underground transportation or pedestrian tunnels (length greater than 500 ft.).

EMAC should be easily accessible and compatible with the fire department's MAU, and protected from vehicular impact. Each building should have at least two panels, and each panel should contain at least two inlet air connections for fire departments’ MAU. EMAC should be located on opposite sides of the structure within 50 ft. of an AHJ approved driveway or other locations. EMAC should be locked and secured in weather and corrosion-resistant enclosure (a metal cabinet constructed of not less than 18-gauge carbon steel or equivalent) with 180 degrees - 6 ft. unobstructed access to the front of the panel.

The UPC document provides detailed specifications for pressure relief valves. Interior air fill panel should be also locked and secured in a metal cabinet constructed of not less than 18-gauge carbon steel or equivalent. It should be located not less than 36 inches but not more than 60 inches above the stairwell landing or finished floor. The depth of the panel and the open door of the cabinet should not obstruct the path of egress. Only pressure gauges, shutoff valve, fill hoses, and ancillary components should be visible at the front of the panel. At the interior air fill panels and interior air fill stations, storing of hose without kinking should be possible. Brackets to coil the hose (if necessary) should be provided such that the hose bend radius is at least 4 inches. The connection to SCBA air-bottles must comply with the requirements of CGS V-1, number 346 (3000 or 2200 PSI air-bottle), or 347 (4500 PSI air-bottle). Interior air fill stations should be locked in a closet or room with emergency lighting and restricted access at a location approved by AHJ. The front of the station should have 180 degrees – 6 ft unobstructed access. The components of FARS should be rated for working pressure of at least 5000 PSI.

Tubing and fittings should be constructed of stainless-steel complying with ASTM A269, or other approved materials that are compatible with the system pressure. The design of tube bends and routes should protect the tubing from mechanical damage. Nonmetallic materials, carbon steel, iron pipe, malleable iron, high strength gray iron, or alloy steel should not be used for breathing air pipe and tubing materials. An electric low-pressure monitoring switch installed in the piping system should alert the supervisors visually and audibly if the pressure of the system drops below 80% of the design pressure.

The system isolation valve should be installed downstream of the interior air fill station located in the panel or within its 3 ft. radius. All components should be provided with at least 2-hour fire-resistive construction, protection from physical damage, and markings by means of tags or labels. Pipe and tubing should be supported at certain intervals.

The system should be capable of filling at least two 66 ft^3 air-bottles simultaneously in 3 minutes or less to a pressure not to exceed 4500 PSI. The interior air fill panel should be installed on the third floor above (for high-rise buildings) and below the ground level floor (for underground structures) and every third-floor level thereafter. This document also provides specific detailed requirements for system assembly and welding. Any component of the system should not be exposed to contaminants, including but not limited to, oils, solvents, dirt, and construction materials.

Upon installation, before placing the system in service, it must pass the acceptance test that includes (a) pneumatic test (of not less than 24 hours) in accordance with ASME B31.3 of the complete system that should be witnessed by AHJ at a test pressure of not less than 7500 psi using oil-free dry air, nitrogen, or argon for possible leaks/defects, (b) low-pressure monitoring switch calibration to at least 3000 PSI, (c) test for compatibility with fire department connections, (d) certifications for materials used for pipe and tubing, and (e) air quality test from at least two interior air fill panels. This air sampling should examine the following requirements for breathing air: (a) oxygen level is between 19.5% and 23.5%, (b) carbon monoxide concentration does not exceed 5 ppm by volume, (c) carbon dioxide concentration does not exceed 1,000 ppm by volume, (d) condensed oil and particulate concentration do not exceed 2.0 mg/m^3 at 72°F and 102 kPa, (e) moisture concentration does not exceed 24 ppm by volume, (f) non-methane volatile organic compound (VOC) content does not exceed 25 ppm as methane equivalents, (g) no pronounced or unusual odor, and (h) nitrogen level is between 75% and 81%. The air fill panel inlet should be secured, and no air should enter into the system during air quality analysis. Air quality must be tested annually to ensure the above requirements. AHJ should also witness the filling of two empty 66 ft^3 capacity SCBA air-bottles simultaneously, at the interior air fill panel or stations farthest from the EMAC, in less than 3 minutes using the fire department's MAU.

The lettering of enclosure marking for all components should not be less than 2 inches high with a 3/8" brushstroke and should be of the color that contrasts with the front of the enclosure. Different and more specific marking specifications are mentioned for isolation valves, tubing, and air-quality testing signs. EMAC, interior air fill panel, and interior air fill station should contain the gauges, isolation valves, pressure-relief valves, pressure-regulating valves, check valves, tubing, fittings, supports, connectors, hoses, adapters, and other components to refill SCBA cylinders.

4.B IFC - Appendix L [29]: This code recommends that AHJs should consider the requirement for FARS based on their staffing level, availability of MAU, building characteristics, and special hazards that require unique accommodations for firefighting operations. The system's minimum design pressure should be 110% of the fire department's normal SCBA fill pressure, and the system pressure should be within 5% of the design pressure. The recommended filling rate is at least 2 SCBA air-bottles simultaneously in 2 minutes or less. A valve to bypass the air storage system must be provided at EMAC if air storage is available. The air storage system should provide the capability of filling 50 air-bottles of AHJ and should be designed in accordance with Chapter 24 NFPA 1901. The document also provides guidance for the installation of isolation valves, pressure relief valves, welded connections, piping protection, the security of the system, and compatibility with fire department MAU.

As per the IFC code, interior fill stations should be provided on the fifth floor above and below the ground level floor and every third-floor level thereafter. These stations should be located adjacent to exit stairs. The specific distance between the station location and the exit stair is not mentioned. The interior fill stations should be installed at a ratio of one fill station for every three stairways, if the structure has three or more exit stairs. They should be provided with (a) pressure gauges, (b) pressure-regulating devices and controls to manage fill-pressure and fill rate, (c) slow-operating valves for controlling fill hoses, (d) separate flow restriction device on each fill hose, and (e) a method for bleeding fill hose. The station must enclose the bottles being filled and flexible fill hoses and protect the personnel. Detailed guidelines for interior air-fill panels were not provided. EMAC should be accessible to the fire department's MAU, protected from vehicular impact, and have a working space of at least 36" x 36" x 78" around it. The air monitoring system should audibly and visually alert the supervisors if (a) carbon monoxide exceeds 5 ppm, (b) carbon dioxide exceeds 1,000 ppm, (c) oxygen level drops below 19.5% or exceeds 23.5%, (d) nitrogen drops 75% or exceeds 81%, (e) hydrocarbon (condensed) content exceeds 5 milligrams per cubic meter of air, (f) moisture concentration exceeds 24 ppm by volume, and (g) pressure falls below 90% of the maintenance pressure. Air quality should be visually displayed at EMAC, electrically supervised, and monitored by an approved supervising station. Upon installation, before placing the system in service, it must pass the acceptance test that includes (a) pneumatic test in accordance with ASME B31.3 for checking system pressure and possible leaks/defects, (b) performance test for refill rate, (c) test for air monitoring system, (d) test for compatibility with fire department connections, and (e) air quality test from at least two interior air fill stations to verify compliance with NFPA 1989. FARS should be maintained and inspected at least annually. Air quality must be tested to verify compliance with NFPA 1989 at least each quarter. The test results should be available on-site and for AHJ’s review.

Several fire departments have adopted and revised these codes as per their requirements, and implemented them in their jurisdiction [9, 30]. Few departments have rewritten the UPC and IFC codes with minor modifications for their jurisdictions, whereas few departments simply referred to the original IFC and UPC appendices [31-37]. These codes do not provide detailed Standard Operating Guidelines as to how the department operates the FARS system during an emergency response. These references may help the NFPA committee and other departments to understand various requirements of fire service and create appropriate standards for FARS, if necessary.

FARS adoption as an Appendix in IFC and UPC has been less effective and less consistent. Few fire departments have referenced IAPMO-IGC whereas others have not mentioned it all. In order to create consistency in FARS installations, inspection, testing, and maintenance practices, a modification to NFPA 1989, “Standard on Breathing Air Quality for Fire and Emergency Services Respiratory Protection,” with a new chapter entitled, “Firefighter Breathing Air Replenishment Systems Installed in Structures” [38] was suggested in the year 2008. This proposal was rejected in November 2012. The 2018 edition of NFPA 1 recognizes FARS in Annex F which references the Appendix F provisions of the Uniform Plumbing Code. If the NFPA committee decides to create standards for FARS, several NFPA standards may need to be modified including but not limited to [39-49]:

- Chapter 5, 6, and 9 of NFPA 1404 - “Standard for Fire Service Respiratory Protection Training,”
- Chapter 7 of NFPA 1500 - “Standard on Fire Department Occupational Safety, Health, and Wellness Program,”
- Chapter 5, 6, and 7 of NFPA 1989 - “Standard on Breathing Air Quality for Emergency Services Respiratory Protection,”
- Chapter 4, 5, and 7 of NFPA 1852 - “Standard on Selection, Care, and Maintenance of Open-Circuit Self-Contained Breathing Apparatus (SCBA),”
- Chapter 6, 7, and 8 of NFPA 1981 - “Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services,”
- Chapter 24 of NFPA 1901 - “Standard for Automotive Fire Apparatus,”
- Chapter 10, 11, and 13 of NFPA 1 – “Fire Code”
- Chapter 9 and 11 of NFPA 101 – “Life Safety Code,”
- Chapter 12 of NFPA 1410 – “Standard on Training for Initial Emergency Scene Operations,”
- Chapter 4, 6, 7, and 8 of NFPA 1986 – “Standard on Respiratory Protection Equipment for Tactical and Technical Operations,”
- Chapter 5 and 6 of NFPA 3 – “Standard for Commissioning of Fire Protection and Life Safety Systems,”

Filling of air-bottles at interior air fill panels is performed without the protection of the fragmentation chamber. As per the National Institute for Occupational Health and Safety (NIOSH) standards, filling of air-bottles on firefighters’ backs is prohibited under normal circumstances, and maybe allowed only in “down firefighter” situations. NFPA 1500 and 1852 also require the operators to be protected from catastrophic failures while filling air-bottles [46, 49]. However, as per NFPA 1500, filling of SCBA air-bottles during emergency situations may be allowed if (i) NIOSH-approved fill operations are used; (b) the risk assessment process has identified procedures for limiting personnel exposure during the refill process and has provided for adequate equipment inspection and member safety; (c) imminent life-threatening situation occurs that requires immediate action to prevent the loss of life or serious injury [49]. Therefore, we propose cross-referencing between the standards of NFPA, OSHA, and NIOSH, if the NFPA committee decides to create standards for FARS. The codes for FARS should also consider contamination of the system during a fire event and procedures to restore it. Upon installation, wherever applicable, the compatibility of the system should be also tested with the equipment of fire departments providing mutual aid. Current codes lack detailed benchmarks for locations and installations of various components of FARS systems. A research study can be conducted to examine the components of the FARS system that was used for fires in training towers for several years and evaluate the effect of combustion products on post-fire air-quality delivered through FARS and the post-fire restoration process.

If FARS is installed, the codes should require its inclusion in the Building Information Card. For large horizontal structures, maritime shipping vessels, tunnels and subways, and other underground structures interior air fill stations and panels should be located every 150 - 200 ft. [6, 12]. Guidelines, standards, and codes for installation, inspection, testing, and maintenance of various components of FARS in these types of structures could be inspired by those for high-rise structures and made more specific based on the requirements of the structures. The inclusion of the air storage system should be considered for maritime applications.

Researchers also visited NYU Langone Medical Center, based in New York City, and studied their medical air distribution system, testing, and maintenance requirements. Their system has rigorous periodic quality checks and maintenance in accordance with NFPA 99 involving significant associated costs, as many patients use it every minute. FARS may or may not be used in the lifetime of a building depending on the occurrence of a fire event. As per their officials, a comparison of FARS with the complex medical air distribution system installed in hospitals may not be valid based on the requirements, usage, and associated costs.

Chapter 5: Cost-benefit review of FARS

The costs associated with FARS can be divided into two main types (i) costs of installation, and (ii) costs for inspection, testing, and maintenance of the system. These costs vary on various factors as described below:

5.A Costs of installation: The cost of FARS system, including design, manufacturing, and installation varies based on the location of construction, size of the structure, building design, cost of the local labor and materials, system components as per AHJ requirements, and cost of conducting business in the area. For example, in Texas, the FARS installation costs about 1/16th of 1 percent of the overall construction cost. Whereas, the cost of a similar installation in California is 1/4th of one percent of the total construction cost [6, 9].

The costs for two FARS systems recently installed in Texas and California were obtained from the report published by the leading FARS technology provider. FARS installation in an 18-story tower (1 million sq. ft.; total construction cost = $325 million) in Texas cost $218,000, which implies FARS cost per sq. ft. in Texas is $0.22. Whereas, FARS installation in two 8-story towers (612,000 sq. ft.; total construction cost = $180 million) in California costed $485,000 (i.e., $242,000 per tower) which implies FARS cost per sq. ft. in California is $0.79. As per the leading FARS technology provider, the FARS system in a typical high-rise structure can cost anywhere between $0.22 to $0.79 per sq. ft. in most parts of the nation [6, 9].

There are no direct costs incurred by the local fire department and the cost of FARS falls squarely on the building's owner. However, the fire department will be responsible to train the firefighters for using the system, inspect the system upon installation, and monitor the system's air-quality testing and maintenance [50].

As per the leading FARS technology provider, the cost of retrofit is 2-3% more than the installation in new construction. The recent cost of retrofitting FARS in a 65-story building in San Francisco was $600,000. This system is comprised of two MAU connections at EMAC, interior air fill stations every third floor, and an air storage system with a 100 SCBA air-bottle capacity [6, 8, 9].

5.B Costs of testing and maintenance: The building owner is also responsible for hiring certified professionals for NFPA 1989 compliant testing and maintenance of the system. This cost is estimated to be $2,000-$4,000 based on the location and size of the structure, cost of the local labor, AHJ requirements, materials required for testing, and other miscellaneous costs such as the shipment of air-samples [9, 11].

5.C Operational benefits of FARS: FARS serves the need of firefighters to refill air-bottles in close proximity to the fire incident in a large vertical and horizontal structure. Without FARS, IC needs to deploy a number of firefighters for bottle-brigading which requires significant personnel resources and time. There is no documented case of the use of FARS in a real-life fire event [11]. Therefore, it is difficult to quantify the benefits of FARS. The benefits of FARS have been described below with the assumption that FARS is installed, inspected, tested, and maintained as desired, and works properly during the fire event.

FARS can allow IC to efficiently use the manpower. The firefighters responsible for bottle-brigading can be used for fire attack, search and rescue, medical and other critical operational needs enhancing the overall efficiency of fire operations [6, 9, 51]. As per the advocates of FARS, in a typical high-rise fire, the system can save at least 15 minutes wasted in transporting the air-bottles. A full-scale research experiment will be needed to verify this time estimate which depends on the size of the structure, fire spread, department resources, civilians trapped, etc. As the structures are increasingly becoming taller and wider, the operation of bottle-brigading can become more challenging for fire service, especially for volunteer fire departments (70% of US fire service) with limited personnel and other resources. Additionally, if the fire department does not have MAU or it is delayed, the air storage system of FARS can play a critical role in firefighting operations.

When firefighters climb to the fire floor while wearing SCBA in a contaminated stairwell and expend the available air, FARS will allow the firefighters to “top-off” the air-bottles just prior to entering the fire floor using interior air fill station and interior air fill panel located in close proximity to the fire incident. FARS will also allow firefighters to fight fires for a long time. However, this may lead to overexertion of firefighters, and AHJs that are interested in adopting FARS need to address this issue in the code. As suggested by several participants in the questionnaire, FARS may supply much-needed air in the IDLH situation and save the life of firefighters or enable firefighters to save the lives of civilians.

The advocates of FARS suggest, in the long-term, the fire department will need to purchase and maintain fewer SCBA cylinders, particularly in jurisdictions with a limited number of high-rises. In their opinion, FARS is a good investment for the builders as it can avoid the potential costs associated with building downtime, property damage, loss of life, and injury in the event of a fire. They recommended that AHJs can offer tax abatements to building owners for voluntary installations of FARS [6, 8].

5.4 Cost-benefits of FARS: In our discussions with fire officials, several alternatives to FARS were proposed, and their pros and cons were discussed as below:

Fire equipment room or cache room: "The training manual for firefighter air replenishment systems" compares the cost of FARS with fire equipment room or cache room [6]. The approach mentioned and the analysis performed in this document have several shortcomings including some numerical errors.

A fire equipment room or cache room is a room dedicated to the storage of necessary fire department equipment including hose, hose fittings, nozzles, communication equipment, building plans, and, in some cases, SCBA air-bottles. It is typically located on every 5th floor or different floors adjacent to the stairwell in a high-rise structure as designated by the local ordinance [52, 53]. First of all, this room is not a requirement for all AHJs where the comparison of FARS with cache room may not be valid. The example of existing code language for the fire equipment storage room provided in Chapter 5 of the training manual also states that these rooms are not required below grade [6].

As described above, cache rooms also store several types of equipment essential for firefighting that cannot be replaced by FARS. Therefore, assuming that FARS will completely prevent the loss of rentable space dedicated to the cache room may not be appropriate. As per our discussion with the builders, the cache room space adjacent to the stairwell is usually a dead-space and cannot be rented. This space can be equivalent to the dead-space used by FARS and its components.

Additionally, Fig. 22 of the training manual has a numerical discrepancy due to which the manual erroneously concluded that the FARS will save $43,000 in initial construction costs. This cost-comparison of FARS with cache room has been cited in several other documents and articles.

Elevators with fire service mode: Several participants in the questionnaire suggested the use of elevators with fire service mode which allows only firefighters to perform essential operations including bottle-brigading. We discussed this topic with several fire department officials across the nation. As per these officials, the elevators with fire service mode do not eliminate the need for bottle-brigading, but it can significantly reduce the resources involved in bottle-brigading. It can also assist firefighters to navigate to different floors with other types of heavy equipment as needed without consuming a significant amount of energy, which is extremely helpful in supertall and megatall structures.

We were informed that these elevators are used by occupants on a daily basis, and fire-service mode is an additional feature that enables the use of such elevators by firefighters only in the event of fire [54-56]. The cost of incorporating fire-service mode and necessary design/manufacturing requirements in elevators to be used by civilians on daily basis is significantly less (even in the most expensive cities) as compared to the new installation of FARS. There have been fire incidents when the elevators with fire-service mode did not work as expected due to a lack of testing and maintenance or the firefighter did not use it due to safety issues and hazardous fire conditions. However, the same situation can occur with any system including FARS, if they are not maintained properly. The fire officials recognized the benefits of FARS and would like to have both - the elevators with fire-service mode and FARS to improve firefighting efficiency. However, considering the resistance from builders' community due to associated costs, in a high-rise structure, they preferred to have elevators with fire-service mode due to their multi-purpose ability.

The advocates of FARS reasoned that elevators with fire service mode are designed for the transition of personnel to conduct fire suppression operations, and not for ferrying air bottles. Elevators with fire service mode do not completely eliminate the need for bottle-brigading. In fact, such elevators deploy more firefighters quickly in the suppression mode and create greater demand for air supply that can be fulfilled by FARS. FARS will also be able to supply air above the fire floor for firefighters involved in search and rescue operations, which may not be possible by using elevators. Additionally, such elevators do not exist in several other types of structures including mega-horizontal structures, tunnels, underground structures, etc.

Insurance premiums: Due to several potential benefits of FARS mentioned before, we investigated the possibility of a reduction in insurance premiums for building owners. Fire officials where FARS have been implemented and the leading FARS technology provider were not aware of any impact on the insurance premium due to FARS. As per our discussions with insurance agents in jurisdictions where FARS have been implemented, we found that insurance companies need quantifiable unbiased data, and possibly real-life fire-event case studies for developing the necessary financial model. From their perspective, FARS can be also a liability to the building owners due to possible tampering and contamination which can increase insurance premiums. A detailed research study to investigate the impact on insurance premiums due to FARS should be conducted.

Bottle-storage space: In order to compare the cost of FARS with an equivalent alternative, we considered a hypothetical scenario where AHJ mandates the builders to provide a number of SCBA air-bottles for firefighting in high-rise structures. A simpler solution can be a closet or room stacked with the required number of air-bottles every certain number of floors, referred to as “bottle-storage space.” As per our discussion with fire officials, firefighters will need 50 bottles every five floors for high-rise firefighting. So, if there is a fire on the 12th floor in a 20-story high-rise, 100 filled air-bottles can be easily available on-site above and below the fire floor, which is also the capacity of the FARS air storage room. These bottles could be stacked in a 10 sq. ft. dead-space area and have no relation to the fire equipment room or cache room. We assumed the yearly inflation rate of 2% for the increase in costs of air-bottles, certifications, testing, and maintenance. The costs of air-bottles, inspections, and certification across different parts of the nation were assumed to be approximately the same and were obtained from the discussions with fire officials and our visits to fire departments' air/mask units. Table 5.1 depicts the cost of a single bottle-storage space (10 sq. ft. with 50 air-bottles) over a period of 45 years in the interval of 15 years.

Cost Items	Rate	15 years	30 years	45 years
Construction cost	$2,000 (one-time cost)	$2,000	$2,000	$2,000
Cost of bottles ($1,500 per bottle)	$75,000 (Bottles should be replaced every 15 years)	$75,000	$175,940	$311,792
Inspections per NIOSH and NFPA 1500	$2000 (per year in 2020)	$35,279	$82,759	$146,661
SCBA Quarterly Air Quality Certification per NFPA 1989	$2200 (per year in 2020)	$38,806	$91,035	$161,327
SCBA Certification per DOT CFR §§ 180.205 and 180.209	$1500 (per certification in 2020 performed every 5 years)	$5,503	$12,910	$22,879
	Total	$156,588	$364,644	$644,660

Table 5.1: Cost of single bottle-storage space.

The cost of FARS in an 18-story high-rise building in Texas described earlier over a period of 45 years with an inflation rate of 2% is calculated in Table 5.2 [6, 9, 11].

Cost Items	Rate	15 years	30 years	45 years
Installation cost	$218,000 (one-time cost)	$218,000	$218,000	$218,000
Annual testing & certification	$2500 (per year in 2020)	$44,098	$103,449	$183,326
Upgrade/Maintenance/ Miscellaneous cost	$1,000 (per year in 2020)	$17,639	$41,379	$73,331
	Total	$279,737	$362,828	$474,657

Table 5.2: Cost of FARS in 18 story high-rise building in Texas.

The 18-story building should require three bottle-storage spaces. Their cost and saving through FARS installation over a period of 45 years in the interval of 15 years is provided in Table 5.3. We have also considered a 2% annual interest on the difference between initial investments.

Cost Items	15 years	30 years	45 years
Cost of 3 bottle storage spaces	$469,765	$1,093,932	$1,933,979
2% annual interest on difference in initial investment	$4,496	$110,787	$290,066
Savings through FARs Installation	$194,524	$841,891	$1,749,388

Table 5.3: Cost-difference between FARS and bottle-storage spaces for 18 story building in Texas.

The cost of FARS in an 8-story high-rise building in California described earlier over a period of 45 years with an inflation rate of 2% is calculated in Table 5.4 [6, 9, 11].

The 8-story building should require two bottle-storage spaces. Their cost and saving through FARS installation over a period of 45 years in the interval of 15 years is provided in Table 5.5.

Cost Items	Rate	15 years	30 years	45 years
Installation cost	$242,000 (one-time cost)	$242,000	$242,000	$242,000
Annual testing & certification	$2500 (per year in 2020)	$44,098	$103,449	$183,326
Upgrade/Maintenance/ Miscellaneous cost	$1,000 (per year in 2020)	$17,639	$41,379	$73,331
	Total	$303,737	$386,828	$498,657

Table 5.4: Cost of FARS in 8 story high-rise building in California.

Cost Items	15 years	30 years	45 years
Cost of 2 bottle storage spaces	$313,177	$729,288	$1,289,319
2% annual interest on difference in initial investment	($30,436)	$28,861	$132,816
Savings through FARs Installation	($20,997)	$371,321	$923,479

Table 5.5: Cost-difference between FARS and bottle-storage spaces for 8-story building in California.

The cost of retrofitting FARS in a 65-story high-rise building in San Francisco (CA) described earlier over a period of 45 years with an inflation rate of 2% is calculated in Table 5.6 [6, 9, 11].

Cost Items	Rate	15 years	30 years	45 years
Installation cost	$600,000 (one-time cost)	$600,000	$600,000	$600,000
Annual testing & certification	$2500 (per year in 2020)	$44,098	$103,449	$183,326
Upgrade/Maintenance/ Miscellaneous cost	$1,000 (per year in 2020)	$17,639	$41,379	$73,331
	Total	$661,737	$744,828	$856,657

Table 5.6: Cost of retrofitting FARS in 65-story high-rise building in San Francisco (CA).

The 65-story building should require thirteen bottle-storage spaces. Their cost and saving through FARS installation over a period of 45 years in the interval of 15 years is provided in Table 5.7.

Cost Items	15 years	30 years	45 years
Cost of 13 bottle storage spaces	$2,035,649	$4,740,373	$8,380,575
2% annual interest on difference in initial investment	$138,693	$640,519	$956,028
Savings through FARs Installation	$1,512,605	$4,636,064	$8,479,945

Table 5.7: Cost-difference between FARS and bottle-storage spaces for 65 story building in San Francisco (CA).

In all three scenarios, in the long-term, FARS was cost-effective in comparison to storing air-bottles on-site. However, a time factor in IDLH situations should be also considered.

Ideally, the bottle-storage space will have all air-bottles already filled and can make them available immediately. Filling 100 air-bottles with FARS in IDLH situations may take a considerable amount of time. It can be argued that firefighters will fill the air-bottles as needed and all 100 bottles may not be required to be filled at the same time. Thus, the system may properly fulfill the air-supply requirement of firefighters. These are research questions that need a full-scale research experiment for verifying the hypotheses.

Chapter 6: Discussions with fire service

During the course of this project, the NYU research team discussed various aspects of FARS systems with several fire service officials, and stakeholders; some of whom supported FARS and others had concerns about FARS. The NYU research team also had discussions with the leading FARS technology provider to provide another perspective. This chapter is a summary of these discussions. The collected information is presented generically to assist the reader by providing the context of issues for consideration related to the FARS system.

6.A Upgrades of FARS: In due course of time**,** upgrades will be necessary to the FARS system and the cost associated with upgrades may be a concerning factor. A case study example implied that a subsequent upgrade to the FARS system may be necessary in order to accommodate the upgrades of air-bottle pressure requirements. One of the fire departments that adopted FARS by incorporating it into their codes has recently decommissioned FARS from the service owing to the issues related to system upgrades and the associated costs. The cost associated with the replacement of system components might be a hurdle for the continuous implementation of these systems.

6.B Diligence in testing and maintenance: The fire departments check and maintain their mobile air every day and feel comfortable using it. The building owner (and not the fire department) is responsible for the testing and maintenance of FARS, which is one of the prominent concerns raised by the fire service. Instances of lapses in ITM have been observed [57]. Once a FARS system is installed, professional testing and maintenance are required to properly maintain the system. The responsibility for the inspection, testing, and maintenance falls to the building owner. Out of concern for the safety of firefighters, the AHJ is often in the position of ensuring the building owner stays current with all such proper maintenance.

6.C Quality of air delivered through FARS: The quality of air delivered through FARS was of great concern to fire service leaders and the participants of our questionnaire. Therefore, this was discussed in detail with the leading FARS technology provider and a laboratory that analyzes air-samples.

The FARS technology provider or a professional licensed by them collects two air-samples from two different interior air fill panels as directed by the AHJ. Few AHJs require the air-samples to be taken from the lowest and highest air fill panels. In most cases, this test is conducted every quarter. The testing professional is equipped with a mobile air unit and portable breathable air compressor to filter and compress outside air, and provide air supply within the building. The sample is then provided to the laboratory for analyzing the air quality as per NFPA 1989 air quality standards. A passing report of the FARS provides various constituents of the sample measured, their allowable limits as per NFPA 1989, and laboratory measurements. Bacterial or microbial contamination testing is not a requirement of NFPA 1989 or NFPA 99 (Standard for health care facilities / Hospitals), and is usually part of pharmaceutical and food-grade testing [47, 58].

Based on the research team's request, the air-quality testing laboratory provided a summary of the air-sample results from January 2013 to September 2019. During this period, a total of 6,723 FARS air-sample reports were processed out of which 118 samples (1.76%) failed to meet NFPA 1989 air quality requirements. Out of these 118 samples, 117 samples failed due to technician error or technician equipment (compressor/filter) failure. The remaining one air-sample may have failed due to contaminated piping, although not definitive as the failure was also attributed to a malfunction of technician equipment (compressor). An additional 41 samples (0.61%) failed due to the sampling technique or sampling hardware malfunction that resulted in the lab unable to perform a complete analysis. As per the summary provided by the laboratory including their air-quality testing with non-FARS compressed breathing air systems, overall, FARS air samples were at least as safe and more compliant with NFPA 1989 air quality standards than non-FARS compressed breathing air samples. Based on further discussion with the laboratory technicians, it was learned that two air-samples are collected for testing, and if any one of those samples passes the air quality test, the FARS system receives a passing certification. Current codes regarding FARS do not provide clear guidelines about this practice.

Additionally, the FARS may include air-flow analyzers that continuously monitor the quality of air as per the requirements from AHJ and building engineers. The digital display and pressure gauges allow arriving companies and building engineers to ensure the quality of air and system pressure. The air monitoring data is also provided to the remote command center, which can respond to system alerts. The leading FARS technology provider provided a summary of warnings received by the air monitoring systems. These warnings were related to carbon monoxide and carbon dioxide sensors which were replaced, and systems' conformity with NFPA 1989 was ensured through air quality tests.

The existing codes have the scope for improvement in regard to the standardization of testing procedures and equipment. Considering the feedback from the leading FARS technology provider and the air-quality testing laboratory that all FARS air-samples failed due to technician error or technician equipment (compressor/filter) failure, there is a need for standards for testing procedures and equipment, especially the specifications of the compressor to be used for testing, its filter, location or placement during testing, replacements of the filter before the testing, etc. A few fire officials suggested that the standards could consider advocating the use of large compressed breathing air-cylinder for air-supply inside the structure during the testing of the system to eliminate the environmental, operational, and equipment errors during testing. This should allow the AHJ to accurately capture the system failures (if any), and but may affect the cost associated with testing.

If fire departments use their own MAU with the breathable air compressor, which is NFPA 1989 compliant and maintained by them on regular basis, to supply air within the structure during a fire event, firefighters may feel more comfortable using FARS. If fire departments do not have MAU, an alternate reliable approach would be the use of an on-site certified breathable air storage system without an air compressor. As per the leading FARS technology provider, the air compressor in the air storage system adds 30 air-bottle capacity to the number of air-bottles (typically, 50 to 75 air-bottles) filled with large certified breathable air-cylinders. These air compressors are located inside the air storage system in a closed room. There is no specific standard on the placement and location of air compressors that may impact the quality of air driven into the system. As per the leading FARS technology provider, very few structures include FARS with a breathing air compressor, and these systems have not failed any air-quality test in at least the last three years. Based on the discussions with the leading FARS technology provider, the laboratory, and analysis of failed test reports, it was observed that the risks, possibilities of error, and contaminations are higher when air compressors are used for providing air-supply during testing or actual fire event, and they could be eliminated, if deemed possible.

Summary

The two crucial elements necessary for firefighters to fight any fire are water and air. While water standpipes are readily accessible to firefighters in high-rises, allowing them to have a reliable immediate water source, the same is not true for air. Firefighter air replenishment systems (FARS) are essentially standpipes for air. Without FARS, in the event of the high-rise fire, firefighters would have to rely on the limited number of air-bottles in the fire-equipment / cache room, if available, or manually haul the air-bottles to the staging area (also called “bottle-brigading”) which can consume a significant amount of time, manpower, and other resources. While FARS seems to be a possible replacement for conventional bottle-brigading techniques, the fire service needs information about the appropriateness, usage, quality, applicability, safety, and maintenance of the system.

The primary goal of this project was to analyze and review the existing code requirements and literature, as well as collect, analyze, and summarize stakeholder input to provide informational guidance to the concerned NFPA committee on the use of FARS. In brief, the present study included data collection and analysis to provide an understanding of FARS, their use, cost, inspection, testing, and maintenance requirements, and benefits. The study provides an understanding of various components of FARS and its operations by firefighters. Data from a questionnaire survey of 200 fire departments across the nation have been collected and analyzed to quantify the benefits of FARS for fire service, the concerns of firefighters, the need for training, and the applicability for various structures. Standards and procedures for air quality testing and maintenance of the system have been investigated. Costs of installation and maintenance of FARS have been described and compared with other substitutes and their benefits.

This modular system has five primary components: exterior fire department mobile air unit connection panel, interior air fill panel, interior air fill station, interconnected piping distribution, and air monitoring device. The FARS may also include a local air storage system and system isolation valves, as needed. The present study provides an understanding of these components, their use, and has produced videos that can educate firefighters about the operation of the system.

A survey of 200 fire departments across the nation was conducted to study the state-of-knowledge of fire service about FARS, the concerns of firefighters, their comfort level for using FARS, the benefits of FARS for fire service, code requirements for the design and installation of FARS, need for training, and the applicability for various structures. While 59% of all participants were familiar with FARS before the survey, 37% of all participants were interested in utilizing the system and another 40.5% of all participants could see their fire department utilizing the system in real-fire events. Additionally, 42% of all participants were comfortable using FARS in conjunction with their MAU, and another 43% of all participants may consider this option. 42.5% of all participants were comfortable with the testing and maintenance of FARS performed by a certified third party and coordinated by the buildings' owner. Another 30.5% of all participants may accept these procedures for their jurisdiction. The need for training to use the FARS system was overwhelmingly evident through participants' responses.

Immediate air supply (61%), efficient use of manpower (10.5%), empowering life-saving efforts (10%), and enabling longer firefighting (7.5%) were found to be prominent benefits of the system. Additionally, the survey established that air quality and maintenance (63%), real-life performance or reliability (5.5%), overexertion from longer firefighting (5%), possible tampering and contamination (4%), and cost of installation and maintenance (3%) are notable concerns of the fire service. Respondents reported that NFPA 1/local fire code (31.5%), local building code (13.5%), NFPA 1989 (10%), NFPA 101 (4.5%), NFPA 1410 (4.5%), NFPA 1986 (4%), NFPA 3 (2.5%), local plumbing code (2.5%), NFPA 99 (1%), and NFPA 1404 (1%) could be changed and regulate the design, installation, testing, maintenance of the system. Participants reported that, in addition to high-rise buildings, FARS can be applicable to large underground structures, tunnels and subways, big-box warehouses, firefighter training towers, large marine vessels/ships, industrial and manufacturing plants, schools, hospitals, malls, hazmat facilities, aircraft hangers, caves, airports, stadiums, large agricultural buildings, high-fuel-load facilities (mattress shops), etc. In general, participants located to the west of the Mississippi River expressed a more favorable opinion about FARS than the participants located to the east of the Mississippi

River. This correlates with the prevalence of FARS to the west of the Mississippi River.

Existing code requirements were studied and have been summarized. There is a scope to improve the current code requirements for FARS, the system configurations, its deployment, applicability for various types of structures, testing, and maintenance procedures. As per the discussions with fire service and survey participants, the system is recommended to be tested quarterly, and inspected and maintained bi-annually. Additionally, the costs of new installation, retrofitting of FARS, and their testing and maintenance have been provided. This cost varies based on the location of construction, size of the structure, cost of the local labor and materials, AHJ requirements, and cost of conducting business in the area. While FARS has never been used in a real high-rise fire event, its operational and cost-benefits, pros and cons in comparison to its alternatives have been outlined.

During this project, various aspects of FARS systems were discussed with several fire service officials, stakeholders that included both who supported FARS, and those who had concerns about FARS, and the leading FARS technology provider. Various real-life cases depicting the issues of FARS were identified and discussed. As air quality, testing, and maintenance were found to be a major concern raised by the participants, current standards and procedures for air quality testing and maintenance of the system have been investigated thoroughly.

Based on the information gathered during this effort, this preliminary study implies that making compressed breathing air available to firefighters inside the structures to avoid bottle-brigading can be advantageous to fire departments, if properly installed, tested, and maintained. This is also the basic concept and application of FARS. AHJs interested in adopting this system should carefully self-evaluate their resources, requirements, available alternatives, pros and cons of the system before making necessary changes to their codes. When adopted regionally, the AHJ must allocate proper resources to ensure that the system is installed, inspected, tested, and maintained in accordance with local code requirements.

Overall, we recognize the potential benefits of FARS to fire service and propose the need for further full-scale research studies and experiments to test various hypotheses in relation to the system before mandating all nationwide applicable structures to install the system. However, as the system is being used in various parts of the nation, the current need for consistent standards and regulations to govern this application is also acknowledged.

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