

An Analysis of Modern Day Fire Attack Hose

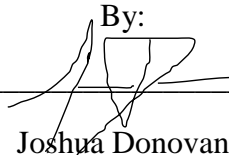
An Interactive Qualifying Project Report

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1.0 Introduction

The fire attack hose serves two important purposes: carrying the water crucial for fire suppression and providing firefighters with a lifeline to safety. In the words of the fire service, “[Fire hoses] allow us to find our way out if we become disoriented, and when used to properly apply water to a fire, they help make conditions within a burning structure more tenable for all inside [1].” Even so, few people pay much attention to the construction of fire attack hoses and their performance capabilities on the fire ground. These hoses are typically made of combustible materials, operate at high pressure, endure extremely harsh and thermally intense environments, face rough storage conditions, and are repeatedly dragged along rough surfaces [2].

Following some recent high profile occurrences of hose burn-throughs on the fire ground, questions are being asked such as:

- How frequently are hose burn-throughs occurring? Do hose burn-throughs occur only in dry hoses or also in those flowing water? Under what scenarios are hose burn-throughs occurring?
- How would today’s firefighters describe their use of and needs for the fire attack hose?
- Does compliance with U.S. fire hose standards ensure fire hose performance when subjected to the intense conditions found on the modern fireground?
- Has fire attack hose construction kept up with advances in material science and manufacturing?
- How do hoses manufactured in the United States compare to those manufactured internationally?
- What qualities should a next generation fire hose have? How can we measure these properties scientifically?

By conducting a thorough analysis of the modern day fire attack hose, this research aims to answer these questions and more, paving the way for the development of a next generation fire attack hose. There are four main areas of research conducted in this study. They are:

1. Design and build the very first fire attack hose burn-through database.
2. Analyzing U.S. and international fire hose codes and standards.
3. Gather the first-hand experience of the fire service with the modern fire attack hose
4. Develop a taxonomy of material properties needed in a next generation fire hose.

Together, the database, standards research, fire service interviews and the taxonomy of performance metrics lay the foundation for the development of a next generation fire attack hose.

2.0 Background

2.1 History of Fire Hose

Organized fire suppression tactics began with the development of “bucket brigades.” These brigades involved two parallel lines of people, one line passing buckets filled with water to the fire, and one line

passing empty buckets from the fire back to the water source. This technique was extremely labor intensive and was not effective in fighting large fires.

The first fire hose was presented in Amsterdam in the early 1670s by Dutchmen Jan Van Der Heiden and his son Nicholaas [3]. Their design, consisting of lengths of leather tubes sewn together, enabled water to be brought to a fire much more efficiently. Even so, these leather strips often leaked and burst under the pressure necessary to deliver adequate water to the fire, and required large amounts of upkeep in order to preserve their integrity [4]. Consequently, the fire attack hose was not widely utilized for well over one-half of a century.

Fire hoses began to spread across Europe during the early to mid-1700s, but the fire hose design did not reach the U.S. until the late 1700s [3]. Adoption of this technology was severely hindered due to the minimal means of communication during this time and the lack of fire department funding necessary to purchase both the new fire hoses and the engines and pumps needed to support this new firefighting technique. Fire hoses were first introduced into the U.S. by the Philadelphia and the Boston Fire Departments in the 1790s [5, 6].

“The original mode of making this hose, by sewing the seams or edges together, remained unchanged from 1672 to about the year 1807,” a period of time spanning 135 years [3]. In this year, James Sellers and Abraham Pennock of the Philadelphia Hose Company developed a method to rivet leather strips together. This new hose design rarely leaked, only losing water at the hose couplings. Although the riveted design was an improvement, the leather material was still extremely heavy, with forty and fifty foot lengths of this leather riveted hose often weighing upwards of eighty five pounds with couplings [4]. The leather hose also still required large amounts of upkeep in order to preserve its integrity. Hoses had to be carefully rinsed with water immediately after use to remove all dirt. After washing, hoses were hoisted up to dry, then taken down and rubbed with oil to preserve the leather material. Lengths were then rolled tightly with the rivet heads downwards, fastened with straps, and deposited in a hose box. If certain lengths of hose were not used for an extended period of time, they then had to be unrolled and re-oiled. Additionally, leather hoses were required to be lubricated with a wax in order to prevent mice and other vermin from ruining their integrity [3].

In 1821, nearly two decades after the introduction of the riveted leather fire hose, Irishman James Boyd patented a rubber lined, cotton webbed hose in Boston, MA. This design included an inner rubber jacket, surrounded by a riveted woven cotton fabric [7, 8]. While this new design did not need to be oiled after every use, it was still riveted and the two layers made lengths of hose just as heavy as their leather counterparts. Additionally, the rubber lining would crack and leak when exposed to extremely high or low temperatures [9, 10].

In the mid-1840s, breakthroughs regarding rubber technologies were achieved by American scientist Charles Goodyear and British scientist Thomas Hancock. The two, working separately, raced to invent rubber that would not melt in high temperatures and would remain flexible in cold temperatures. In 1844, the two scientists were both awarded patents for the invention of the vulcanization process. This process involved the immersion of rubber into melted sulfur, thus modifying the chemical structure of the material. This technique resulted in rubber which better retained its integrity in both hot and cold temperatures [10]. Vulcanized rubber was soon utilized in the design of fire hose. The process of lining cotton fire hoses with

this new rubber was developed by James Bennett Forsyth, the general manager of the Boston Belting Co. [9]. The new vulcanized rubber fire hoses were double jacketed hoses, with an inner rubber liner surrounded by a cotton outer jacket. The first seamless cotton fire hose designed for steam engines was manufactured and sold by the American Fire Hose Manufacturing Company in Chelsea, Massachusetts in 1878, over thirty years after the development of the vulcanization process. These fire hoses were the first to not only rid the design of rivets, but also to function on the modern day steam engine.

These new seamless cotton designs outperformed the leather hose in nearly every sense. As a result, this design, was widely adopted with nearly every fire department using seamless cotton double jacketed fire hose by the late 1890s [5, 6, 9]. As fire hose design progressed, numerous fire hoses of different sizes, couplings, materials, and weights began to be manufactured and sold. In 1898, the NFPA issued a fire hose standard, providing consistency for fire hose thread types, sizes, and weights. Advancements in cotton hose design led to lighter lengths, with a fifty foot, 2 ½ inch double jacketed hose line weighing a maximum of sixty pounds in 1921 [11]. These new hoses required fewer firefighters to operate a line. Also, the cotton lines were able to be more securely attached to the couplings, resulting in less water leakage.

The seamless cotton fire hose remained the norm until the mid-1950s, when advancements in material research led to changes in fire hose construction. In the mid-1940s, companies such as DuPont and Imperial Chemical Industries developed new synthetic materials including polyester, dacron, and nylon. These materials were stronger and much lighter than many natural fibers [12]. By the early-1950s, these new synthetic materials began to be used in the manufacturing of fire hoses and are still used today. Many designs consist of a cotton blend or synthetic outer jacket and a rubber inner liner [13]. Also, these materials began to be used in the development of through-the-weave extrusion fire hoses. This design involves single or double jacketed hose, where the synthetic inner lining is pressed into the inner fiber jacket forming an interlocking weave [2]. The new synthetic materials added strength, reduced weight, and allowed the hose to be more flexible [12, 13]. They did not, however, improve the thermal performance of the hose.

2.2 The Modern Day Fireground

Modern day fireground environments have evolved over the past several decades, resulting in more intense fire conditions [14]. Residential structures have become larger, allowing for increased fuel loads. Also, open floor plans, which lack passive containment, have become more common. Newly-engineered glued beams and synthetic building materials, which ignite more easily and promote faster flame spread, have replaced traditional wood frames. These new beams are much more unstable and unpredictable than dimensional lumber when under thermal attack [15]. Also, household items, such as furniture, electronics and appliances are now more abundant and constructed from more combustible synthetic materials. These new structure designs, building materials, and household commodities have led to more rapid fire growth and intense fire conditions. As a result, modern structures have been determined to reach flashover conditions at a rate eight times faster than structures from fifty years ago [16].

These decreased times to flashover and more unstable structures have led to changes in firefighting techniques. Today, firefighters often arrive at fire scenes after flashover has already occurred [17]. “Prior to flashover, a fire can be extinguished with relative ease and damage will be minor, but extinction of a post-flashover fire requires major resources and will be accompanied by major damage, if not the complete destruction of the contents and combustible linings” [18]. Today, when firefighters arrive at a fire, inside

temperatures often prevent entrance into the structure, thus requiring modern firefighting techniques to evolve. For example, while firefighters were previously trained to first ventilate the structure when arriving at a scene, a study by UL now recommends first applying water on the fire to cool the temperatures [19]. Firefighters have less experience working in buildings constructed from newly engineered synthetic materials, as much of their training focused on older, sturdier building constructions. “Without training and education, firefighters won’t be able to determine a structure’s overall stability and may therefore put occupants’ lives, as well as their own, at risk” [15]. Firefighters are arriving at more involved and unpredictable fire scenes, and it is imperative that they have the appropriate tools to perform under such conditions.

According to *Analysis of Changing Residential Fire Dynamics* published by UL, residential fire room temperatures often reach temperatures of 400°C (750°F), and can even get as hot as 1200°C (2190°F) [14]. Popular fire hose materials such as EPDM rubber and nylon have thermal failure temperatures of about 150°C and 170-260°C, respectively [20, 21]. This discrepancy between the thermal performance capabilities of fire hose materials and the actual thermal environment encountered on the fireground has led to equipment failure. There have been notable instances where a fire attack hose has burned through, preventing the delivery of water to a fire and leaving firefighters without their viable lifeline.

2.3 Fire Hose Burn-Throughs in the News

Some burn-throughs in particular have garnered much attention because, unfortunately, they may have contributed to the death of firefighters and/or civilians. For example, on January 17, 2015 in Altoona, PA, units were dispatched to a structure fire with confirmed entrapment. A hose line was advanced through the building, but there were water source issues due to a water main break. The fire continued to spread due to this lack of water, and a hose line burned through about three feet inside the door resulting in significant pressure loss. A mother and her two daughters, ages one and nine years old, lost their lives in the fire, and two firefighters were sent to the hospital for exertion and smoke inhalation [22].

Also, on March 26, 2014, there was a nine-alarm fire in a four story brownstone building in Boston’s Back Bay. Firefighter Michael Kennedy and Lieutenant Edward Walsh were among those on the scene fighting to contain and extinguish the blaze. Kennedy and Walsh were trapped in the basement and were heard repeatedly calling for water. Firefighter Kennedy and Lieutenant Walsh both died in the line of duty that day. It was later found that their fire hose had burned through, leaving them without water in a rapidly growing fire.

Many questions linger: Were these isolated events? Would the burn-throughs have occurred if the hose had been flowing with water when the firefighters entered the building? Do standards governing the construction of fire attack hoses ensure the safety of the 1.2 million U.S. fire fighters? Could/should fire attack hoses be made of more fire resistant materials?

Although there is no shortage of questions, there is a stark shortage of scientifically and/or statistically verifiable answers. When a fire department experiences a burn-through, they remove the hose from service and replace it. To date, there has been no centralized location for fire departments to report fire attack hose burn-throughs. As a result, the frequency of such burn-throughs is unknown, contributing to a lack of attention to fire hose performance capabilities. WPI’s Fire Protection Engineering Department has taken

the initiative to conduct extensive research to address these issues, starting with the experience of the fire service with their hoses.

3.0 Fire Service Experience

The purpose of this research is to lay the foundation for the potential development of a next generation fire attack hose. The goal in developing a next generation fire attack hose is that such a hose would have performance capabilities such that it would withstand and perform under thermal conditions representative of the fire ground. Since firefighters are the ones who utilize and thus best understand fire hoses, the collection and documentation of their first-hand experience and knowledge is crucial to researchers in understanding the significance of different fire hose functions.

3.1 Gathering Information

WPI toured nineteen firehouses in New England and contacted six departments across the country to speak with fire personnel. The interviews in New England were done in person and ranged from small departments like Essex, MA, protecting only 3,504 people, to large departments like Providence, RI, protecting 177,994 people. The largest department operates fourteen fire stations, whereas the smallest operates only one. Departments also varied in career or volunteer type and the density of the population that they served. The interviews conducted focused on the firefighters' experiences with fire attack hoses and any suggestions for improvement. Fire community publications and standard operating procedures (SOPs) were also analyzed to better understand the performance and usages of fire attack hoses.

Department interviews began with general discussions with neighboring fire fighters. Information gathered from these interviews drove the creation of a structured questionnaire, covering the four primary areas of interest including every day fire hose usages, uncommon uses, problems encountered with hose, and general ideas for improvement. This questionnaire formed the basis of discussion during both the in-person interviews across New England as well as during phone interviews with departments across the country. The research aimed to determine and document the full range of scenarios in which a fire attack hose is used, along with problems that are encountered and what capabilities fire fighters would like to see in their hoses.

3.2 Everyday Use and Maintenance

These interviews sought to determine and document all interactions between a firefighter and a fire attack hose. Input from these interviews categorized the 'life' of a fire attack hose into four sections, each based on a time-dependent stage of usage. These sections are: storage, setup on the fire ground, fire ground usages, and maintenance.

When not in use, hose lengths are folded and stored in a section of the apparatus called the hose bed, or in other compartments. They may also be stored on racks in the firehouse if a department has excess hoses. Upon arriving to a fire scene, the first due engine officer judges the severity of the fire and decides if a hose line is needed. This process is often called a size-up. If a hose line is needed, the firefighters begin the set-up process on the fire ground.

During the set-up, firefighters are responsible for laying out one or more hoses on the fire ground in a manner capable of carrying water from the source to the base of the fire. [23]. Larger supply hoses are dragged and connected to the water source, often a fire hydrant or body of water, to supply water for the attack hoses. The fire attack hoses are pulled off of the apparatus and dragged to the point of entry where they are flaked out before being charged with water. When the hose is properly setup, the firefighters are ready to put the hose to use.

Fire fighters also talked about the next step, approaching the fire. Departments have different tactics on when to charge the hose line with water. One approach is to stretch an uncharged hose to the location of the fire enabling easy transit to the fire location then call for water where another approach is to charge the line before entering the structure providing water for safety during travel [23, 24]. Once inside a building it is very difficult to carry a charged hose around corners, through obstacles, and up-stairs because a fully charged hose is less flexible and significantly heavier than an uncharged hose. Fire departments expressed that a more flexible and lightweight hose would accomplish both goals, allowing for easy transit to the fire while still having the option of spraying water for safety along the way.

Fire-fighters also explained to us how the fire attack hose may serve as a guide to safety. To aid disoriented firefighters, the traditional procedure to help find the way out of a building is to feel for the long lug out [25]. This requires picking up the hose and feeling for the long lug on the coupling, thus guiding firefighters out of the structure. When the hoses are done being used they are checked and maintained for the next time they are needed.

Fire departments reported different levels of compliance with NFPA 1962 *Standard for the Care, Use, Inspection, Service Testing, and Replacement of Fire Hose, Couplings, Nozzles, and Fire Hose Appliances* to maintain their fire attack hoses after use, “so that the reliability of the fire hose, nozzles and fire hose appliances is increased when they are used at an incident” [26]. Much of the variation in NFPA 1962 compliance levels corresponded to how well staffed the station was and how many calls they received, i.e. availability of staffing to perform maintenance. Fire departments reported that when hoses are being repacked onto the apparatus, a visual inspection is performed to ensure the hose is free of burns, debris, and any other imperfections [23, 26]. Also when hoses are being repacked onto the apparatus it is recommended that the hose should be folded on different creases [24, 26]. Fire departments encourage hoses to be washed and dried after every use [26]. Many departments wash their hoses after fires or at the discretion of a commanding officer [34, 26]. Some fire departments have hose dryers or hose drying towers [27, 28]. Other departments simply lay out the hose and wait for it to dry [29]. In addition to day to day maintenance, fire departments call for an annual maintenance test to be performed on every length of hose.

3.3 Uncommon Uses of Fire Hose

In addition to the use of the fire attack house for fire suppression applications, there are other important, less common usages. Departments mentioned how they have used their hose to rescue people out of holes, as an article in Fire Engineering lays out the instruction to properly rescue someone in a hole with a fire hose [30]. Fire hoses have also been inflated with air and used as flotation devices in water rescue scenarios [31]. When an oil spill occurs in a body of water, it is important to prevent the oil from spreading, and a fire attack hose can be inflated with air and be used as a dam [32]. Another important function performed with a fire attack hose is to pump water out of basements. Fire attack hoses are also used for physical

training and for cleaning the fire station [28]. It is important that all of the usages of a fire attack hose, both the everyday uses and the uncommon uses are considered during development of a next generation fire attack hose.

3.4 Problems

During interviews, the fire service expressed any problems encountered with fire attack hoses. Fire personnel described numerous issues from the previously mentioned four sections: storage, setup on the fire ground, usage, and maintenance.

Hoses stored on the apparatus vibrate and rub against both the walls and any debris on the hose bed. As a result, in storage, abrasion can contribute to the weakening of the outer jacket. Also, when stored in the firehouse, vermin have damaged the hose outer jacket making them less reliable on the fire ground.

The fire service also explained that the hose is subject to damage during the setup process on the fire ground. Hoses could be damaged if thrown from the apparatus [29]. The abrasion on the hose from being dragged across concrete, pavement and debris can lead to tears and holes in the outer jacket, often causing the hose to fail [33]. When the hose is not flaked out properly, kinks are more likely to occur. A kink occurs when there is a bend or fold in the hose, preventing the appropriate water pressure from traveling to the nozzle. The hose may be subject to one or more of these potential damage scenarios even before the initiation of suppression.

Once the setup is complete, the firefighter begins to initiate suppression. During suppression the firefighter encounters two main challenges: advancing the hose line to the scene of the fire and avoiding hazards which may damage the hose. Hoses are extremely heavy and difficult to maneuver when charged with water. “An uncharged hose line is stretched more rapidly and it is less fatiguing than attempting to move a charged hose line into position” [23]. Operating a 2 ½ inch fire attack hose efficiently requires three to four firefighters, while operating a 1 ¾ inch fire attack hose is manageable with two to three fire fighters [34, 35]. Many hazards a hose faces on the fire ground, including chemicals, sharp objects, falling debris and extreme temperatures, contribute to significant hose failures. A burn through occurred in Worcester, Massachusetts which was caused by metal debris falling from the roof onto the hose. Once exposed to these hazards, the hoses must be checked and maintained to ensure reliability for the next time they are used.

Fire departments have expressed their concern that if the hose is not properly inspected after each use, then there is a greater possibility of failures going unnoticed which would affect reliability on the fire ground. Damage and permanent folds can also occur to the hose when not folded on different creases before being stored [26, 29]. Fire hoses that are not dried are subjected to increased inner lining failures. In cold temperatures, a fire hose can freeze, and in warm temperatures, mildew grows and deteriorates the hose [36]. Many departments stated that they do not have the time to carefully maintain every length of hose. Volunteer firefighters are called out of their daily job to respond to fires. Upon extinguishing the fire, volunteer firefighters must return to their regular jobs, therefore preventing sufficient time to perform appropriate fire hose maintenance.

Fire attack hoses can be damaged during storage, setup on the fire ground, usage, and because of a lack of maintenance. When considering all fire hose functions and firefighter input, it becomes clear that there could be a better, more reliable fire attack hose designed for the fire service.

3.5 Improvement on Fire Hose

Improvements could be made to the fire attack hose to decrease damage due to storage conditions. Improvements in storage could be made with the use of a hose bed cover. Fire departments have stated that hose bed covers have reduced the amount of debris and eased the vibration of the hoses [27, 37]. NFPA also recommends using a hose bed cover to protect the fire hose, although many fire departments do not have the funding to purchase hose bed covers [26]. The hose bed could also be stripped of fire hoses and cleaned for debris to help prevent damage, but many departments rarely perform this due to a lack of time [34]. Firefighters often utilize different folding techniques to ease the stress on their hose. For example, the flat lay fold minimizes the effects of abrasion [38]. According to several fire departments, if fire hoses are stored on higher racks in the firehouse, then the chances of vermin reaching them are low. Another solution could be a repellent spray, which would not affect the hose in any way. Diminishing the effects on the hose while in storage will allow for a more reliable hose for firefighters on the fire ground.

When arriving to a fire scene, a more durable hose would prevent the possibility of damage occurring when being deployed. While the hose is dragged across concrete, pavement, etc., a more abrasion-resistant outer jacket is crucial to minimize chances of a puncture or failure. When arriving to a highly involved fire, time is always of the essence. The more kink resistant a hose is, the quicker it could be set up. An easier, quicker set-up on the fire ground will help fire fighters get to the fire in earlier stages of fire growth.

While handling a charged fire hose, the fire service expressed the importance of the hose being lightweight. A more lightweight hose would be easier to maneuver and would reduce the fatigue of firefighters on the fireground [34]. The fire service also expressed their concern about how the hose felt in their hands. A good grip on the outer jacket of the hose would benefit the fire service, giving them optimum control when operating the fire attack hose. The fire hose also needs to be able to withstand all exposures encountered on the fireground. As a result, hose must be abrasion, puncture, fire and kink resistant.

To aid with maintenance, the fire service recommended the development of a bright inner liner. This would aid in the firefighters' visual inspection of their hoses; the bright inner liner would more easily identify a failure on the outer jacket to minimize the chances of a failure going unnoticed [39]. Oftentimes firefighters do not have time or the resources to dry every length of hose. A more mildew resistant hose would lower the chance of the hose being damaged from not being dried properly. A hose that is easier to maintain will allow the fire service to be more efficient with their limited time.

The fire service relies on their fire hose to perform at the highest standard in every function explained above. Each function documented from firefighter input has been assigned properties, listed in *6.0 Taxonomy of Performance Metrics*. These properties, if incorporated in the future design, will ensure that the next generation fire hose is designed to meet the needs of the fire service.

4.0 Database

4.1 Database Design, Creation, and Purpose

Previously, when a fire department experienced a fire attack hose burn-through, the department would handle the situation internally. The hose would simply be taken out of service, and no one would record

that a burn-through had occurred. However, researchers at WPI have developed and distributed a fire hose burn-through survey, allowing the fire service to report these events. Survey data was then used to create the first fire attack hose burn-through database. This database will allow the fire community to more accurately understand the frequency of fire hose burn-throughs and the situations which are leading to these events. A burn-through map was also created using the survey data, providing a visual representation for the fire community to see where burn-throughs are occurring. Information gathered from the fire hose burn-through survey and database will be used to draw conclusions about fire hose burn-throughs.

4.2 Populating the Database

In order to identify instances of fire attack hose burn-throughs which are used to populate the database, a communication method was needed to interact with the fire service. To facilitate this communication, a survey was developed so that firefighters could report burn-through events. The survey is composed of twenty questions which allow researchers to gain crucial information relating to each event. After a response was received, it went through a vigorous verification process to ensure that the data was legitimate and that any claims that were made are valid.

4.2.1 Survey Design and Distribution

The survey was developed using a survey software called Qualtrics. Qualtrics provided a means to store and analyze survey data in order to identify trends. The survey is separated into four main categories, each relating to a different aspect of the burn-through event and each designated to provide insight information about the fire hose burn-through problem. The four categories cover descriptions of the type fire department, the environment of the fire event, the thermal conditions and functionality of the hose during the burn-through event, and the properties of the fire hose.

- The fire department questions focus on the type of department and the population served. This data was collected to identify potential trends across department demographics.
- The fire event questions were developed to gain an understanding about the environment the fire hose was operating in, including structure type and level of involvement upon arrival.
- The burn-through event questions were developed with the goal of determining the location and thermal conditions the hose was subjected to when the burn-through occurred. These questions also help determine how the burn-through affected the functionality of the hose.
- The fire hose questions concentrate on the material of the hose jackets and the primary mode of heat transfer. These questions determine if certain hose characteristics contribute to burn-throughs.

Table 1 below shows the four categories of the survey and the corresponding questions that relate to each category. The database categories are also shown to show which category we drew from each question.

Table 1 Database questions

Category	Survey Question	Database Category
Fire Department	On what date did the burn-through occur?	Date
	What is the name of the Department that encountered the burn-through?	Name of Department
	In what city and state is this Department located?	Location
	Which best describes your department?	Type of Department
	What is the size of the community that the department protects?	Size of Community Protected
	Does your department still have the hose that burned-through?	
Fire Event	Please describe the type of structure involvement in the fire event?	Type of Structure
	Please describe the fire event including the level of structural involvement?	Level of Structural Involvement
	What's your job function during this event?	Job Function of Responder
	Were you operating the hose that experienced the burned through?	
	Where there any civilian injuries or deaths at this fire?	Civilian Deaths/ Injuries
	Where there any injuries or deaths at this fire?	FF Deaths/ Injuries
Burn-Through Event	Was the hose inside or outside of the structure at the location of the burned through?	Hose Location
	Please indicate at the time of the burn though whether the hose was:	Hose Status
	Did the burn through result in water leakage from the hose?	Water Leakage
	Did the leakage cause significant pressure loss?	Pressure Loss
	Was the hose in direct contact with a hot object at the location of the burn-through?	Mode of Heat Transfer
	Does your department still have the hose that burned-through?	Pictures
Fire Hose	What was the company and model number of the hose that burned through? If unknown, please provide the jacket and liner material	Company, Inner Jacket, Outer Jacket, Weight, Coating
	What year was the hose manufactured?	Year hose was manufactured
	What was the size of the hose?	Size of Hose

The survey was designed to accommodate the time restraints of the fire service, containing as few questions as possible while still gathering the necessary burn-through information. It was distributed to the fire community through the Secret List, NFPA, WPI and Fire Engineering with responses from all across North America. The Secret List distributed the survey through their email list which reached a large population of the fire service who have experienced a burn-through before and which we received our largest portion

of responses from. The NFPA posted a blog on their website which also reached a large portion of the fire service. With the help of WPI, a section under the Center for First Responders webpage which created a central location for all of the updated information as well as a link to the survey. Fire Engineering has posted several articles on their webpage relating to the research being conducted as well as the link to the survey. All of these distribution services allowed the database to gain crucial information regarding the extent and rate of which burn-throughs are happening.

4.2.2 Incident Verification and Database Entries

The survey asked for a contact number for researchers to follow up with respondents and gather more detailed information about the event. Before the respondent was contacted, researchers conducted a background investigation on the burn-through, searching for news articles or additional information validating the entry. If a response mentioned a firefighter death or injury, NIOSH and USFA reports were cross referenced. This validation process ensured the accuracy of the entries. If a survey response lacked crucial information unable to be gathered from follow up phone calls, it was excluded from the database. Through analyzation of the database, it can be determined if fire hose burn-throughs are a commonality, or if the Boston Back Bay incident stands alone.

4.2.3 Database Design

The first ever fire attack hose burn-through database was modeled after NIOSH’s Fire Fighter Fatality Map and has similar functionality [40]. The database contains 25 categories which were developed from the questions on the survey. Table 1 shows the broad range of information that was gathered from only a 20 questions survey. The burn-through database is completely searchable, making it more user friendly and easier to find information. The user can search for a specific burn-through to find all of the information regarding that instance, or look at all the information about a specific category for all of the burn-throughs. Figure 1 provides a glimpse of the database and how it is structured. In addition to just the database, a map was developed to provide a visual aid of where burn-throughs have occurred. Figure 2 shows what the map looks like with the locations of the reported burn-throughs plotted.

Date Burn-Through Occured	Name of Department	Location of Department	Type of Department	Size of Community Protected
11/12/2013	New Richmond Fire and Rescue Department	New Richmond, WI	Pay-by-Call	10,000 to 24,999
1/13/2013	Boulder Rural Fire Department	Boulder, CO	Combined (Predominately Career)	25,000 to 49,999
2/1/2014	Olympia Fire Department	Olympia, WA	Career	50,000 to 99,999
7/5/2014	La Pine Rural Fire Protection District	La Pine, OR	Combined (Predominately Career)	10,000 to 24,999

Figure 1 Burn-through database example

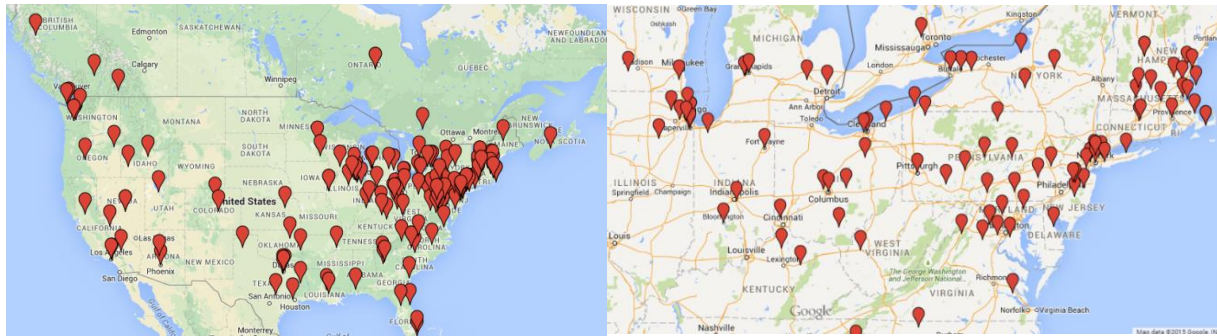


Figure 2 Reported burn-throughs on the map

4.3 Results

As of September 2015, there have been over 172 reported fire attack hose burn-throughs. These reported burn-throughs have been fully analyzed in order to identify trends and inform the fire community of these events.

4.3.1 Range of Scenarios

According to the database, fire hoses are burning through when exposed to a variety of fireground scenarios. The survey has shown that burn-throughs occurring on a range of fire grounds, including residential, industrial, commercial structures and also vehicle fires. Failures are occurring as a result of all three modes of heat transfer. Of the reported burn-throughs, 90% were a result of conductive heat transfer, with the remaining 10% resulting from convection and radiation. Examples of hose failure due to conductive heat transfer include metal/plastic debris falling on the hose, contact with hot coals, contact with melting carpet, and contact with metal handrails. Examples of hose failure due to convective and radiative heat transfer include exposure to hot air flow in the structure, direct contact with flames, and heat radiating from the fire. Fire attack hoses are also burning through not only inside the building but on the exterior of the building. Below are examples of some of the burn-throughs in the database that show the variety of ways an attack hose can burn-through.

Interior Hose Location

In Cranberry, British Columbia, Canada, a fire attack hose burn-through occurred on November 1, 2013. Firefighters entered the building and were conducting interior operations. The nozzleman and his crew spotted fuel leaking from an air vent above. The fuel was suddenly ignited which sparked a fire that would cause their hose to fail. The crew was then able to exit through the side door just before flashover occurred.

Exterior Hose Location

In Worcester, Massachusetts a burn-through occurred on November 8, 2014 in a residential fire. Fire fighters had entered the structure, advancing a hose line up the back staircase when the crew encountered a back draft and was forced to retreat. During this event, another crew outside of the structure noticed their hose had burned through close to the doorway. It was then discovered that the hose had burned through due to metal debris falling on the hose.

Conduction Method of Heat Transfer

In Tonawanda, New York the Brighton Volunteer Fire Department had a burn-through on July 11, 2011. The first interior attack team tried to enter the building from the bar door, near where the fire originated. However, as they opened the door they encountered a back draft. The attack team then regrouped and sprayed water until they were able to enter the building. When they entered the building the two firefighters on the first attack team saw and felt water spraying behind them. They originally thought it was the second attack team spraying them with water but then realized it was their own hose. As they were back tracking out of the building one of the firefighters on the first attack team lost his sense of direction due to smoke inhalation. Thankfully one of the fire chiefs on the scene saw him from the window outside of the structure and pulled him out through the window. After further examination, it was determined that the hose had burned through from the hose laying over the door frame which had heated up due to the fire.

Radiation Method of Heat Transfer

Hull, Massachusetts experienced a burn-through on December 16, 2014, during a residential fire. The burn-through occurred on the front lawn near the structure due to intense thermal radiation.

4.3.2 Status of Hose (Water vs. No Water)

The database includes burn-throughs occurring in both charged and uncharged lines. Of the reported burn-throughs, 68% were flowing with water, 29% were charged but not flowing, 2% were uncharged, and 2% occurred in other unspecified situations. Based on these results, burn-throughs are occurring more often in charged lines than uncharged lines. More than two-thirds of entries occur while the hose was flowing with water, but this situation is not tested for in the standard.

4.3.3 Significant Events (overlap w/ NIOSH)

There are two examples recorded in the database that also have NIOSH reports, since they involve a line of duty death. The first incident occurred on March 3, 2010 in Homewood, Illinois where a firefighter was found tangled in a ruptured hose line. The other incident occurred on April 18, 2008 in Colerain Township, Ohio where two firefighters were trapped in the basement with a burned through hose line [43, 44].

4.3.4 Loss-Near Miss

There have been twenty-seven reported burn-throughs involving either a firefighter injury or death. Other burn-throughs in the database involved a near miss. “A near miss is defined as an unintentional unsafe occurrence that could have resulted in an injury, fatality or property damage” [42]. Fire departments report near misses “to reduce firefighter injury and death by helping the fire service apply local lessons globally” [42]. One example occurred in Columbus, Ohio, when firefighters “dodged a bullet” while operating at a single family residence. A burn-through occurred when a hose came in contact with a hot door jam, nearly contributing to the loss of a firefighter’s life.

4.4 Conclusion

The fire attack hose burn-through database has allowed us to make several conclusions regarding fire attack hose burn-throughs. From the 172-reported burn-throughs it can be determined that the Boston

Back Bay incident is not an isolated incident. With all of the burn-through's reported it also shows that burn-through's are a serious issue within the firefighting community. Of the 172-reported burn-throughs reported they ranged from various locations in the United States and Canada. This proves that burn-throughs don't necessarily happen in one specific demographic but rather are an issue the entire fire service is facing. Also since burn-through's are occurring due to various modes of heat transfer, it shows that the current standards are not enough and that hoses should be subject to tests of various modes of heat transfer. The database also shows that fire hoses are burning through not only inside the building as most people thought but are also occurring on the exterior of the building as well. Lastly the database will be continued and provide a location for the fire community to continue to report burn-throughs. With the continuation of the database more information will be gathered in relation to fire attack hose burn-through's which will provide researchers, manufacturers, and the fire service information to that will improve safety.

5.0 Fire Hose Standards

Nationally published fire hose standards largely drive the design and manufacturing of fire attack hoses. When purchasing fire hoses, fire departments do not have information regarding the performance capabilities of fire hoses; they only know whether or not the hose is stamped NFPA 1961 compliant, and they have no insight on whether the fire hose exceeds the minimum standards or not. The stamp is evidence that the hose has passed all performance tests specified in that standard, thus, when a fire department purchases a hose stamped NFPA 1961 compliant, they trust that the hose has been constructed and tested to ensure successful performance on the fire ground. What they don't know is how well the thermal tests conducted replicate fire ground conditions, and they don't know if the hose just barely passed the test or if the fire hose exceeds the minimum standards. The research will answer the question, "How adequate is current thermal performance testing for fire hose?" in three ways: 1) by analyzing NFPA 1961 *Standard on Fire Hose* to determine what tests for thermal performance are specified in the standard; 2) by comparing the tests specified in NFPA 1961 to the thermal performance tests specified for fire fighter personal protective equipment; and 3) by determining what tests for thermal performance are specified by international fire hose standards.

5.1 U.S. Fire Hose Standards

In the United States, the National Fire Protection Association (NFPA) publishes NFPA 1961: *Standard on Fire Hose* and NFPA 1962: *Standard for the Care, Use, Inspection, Service Testing, and Replacement of Fire Hose, Couplings, Nozzles, and Fire Hose Appliances*. These standards are part of a sub-group of standards which protect the public and minimize the risks from fires. Some of the larger issues that these public safety standards address include standards on fire fighter gear, staffing procedures, and tactical decisions on the fire ground [45].

The 2013 edition of NFPA 1961 outlines nineteen performance tests fire hoses must pass in order to comply with the standard. The tests include: proof, elongation, twist, warp, rise, kink, burst, adhesion, tensile strength and elongation, oven aging, ozone resistance, cold bending, cold flexibility, oil immersion, flexibility and compressibility, abrasion resistance, repeated bending, moisture resistance, and heat

resistance tests. Many of the tests require fire hoses to undergo conditions exceeding actual fire ground conditions in order to assure the hoses' capabilities to perform while in use. For example, the NFPA 1961 burst test requires a three foot hose sample be pressurized to a minimum of 900 psi to test the hose material's ability to withstand high pressures. Fire attack hoses typically operate at a maximum of 275 psi on the fire ground according to NFPA, meaning that NFPA 1961 requires fire hose materials to withstand nearly 330% of its maximum operating pressure on the fire ground. Also, the NFPA 1961 proof test requires fire attack hoses to be pressurized to a minimum of 600 psi to ensure the fire hose couplings are properly secured, a full 220% of the operating pressure when in use on the fire ground [46].

Of the nineteen performance tests specified in NFPA 1961, just one addresses hoses' ability to resist exposure to heat. NFPA 1961 specifies that all fire attack hose must pass the American National Standards Institute (ANSI)/ Underwriters Laboratory (UL) 19: *Lined Fire Hose and Hose Assemblies Heat Resistance Test*. The steps in the NFPA 1961/UL 19 Heat Resistance Test are as follows:

- A steel block (2.5 x 1.5 x 8 inches) is heated in an oven to 260°C (500°F).
- The hot block is then stamped on the fire hose for one minute (the hose is pressurized with water during the test).
- If the hose does not burst or leak, it is said to have passed the test [46, 47].

The primary mode of heat transfer in this test is conduction. Conduction is the most common form of heat transfer and occurs via physical contact between two objects of different temperatures. Conduction transfers heat via direct molecular collision. An area of greater kinetic energy will transfer thermal energy to an area with lower kinetic energy, and higher-speed particles will collide with slower speed particles. The slower-speed particles will increase in kinetic energy as a result. Conduction is one mode of heat transfer responsible for hose failure on the fire ground. Examples would be hot debris falling onto the hose, or the hose being dragged across and/or resting on a hot pole or piece of metal.

While the mode of heat transfer that dominates these particular scenarios is tested for in NFPA 1961, it is only tested for conductive heat transfer from an object at 260°C whereas, as described in 2.3 *The Modern Day Fire ground*, residential fires can reach temperatures upwards of 1200°C (2190°F) [10], or up to four and a half times hotter than the NFPA test. Thus, there is a stark discrepancy, whereas NFPA 1961 requires fire hoses to be pressure tested to conditions far exceeding normal fire ground conditions, it fails to test the fire hose to temperatures commonly seen on the fire ground.

An additional relevant mode of heat transfer for fire hoses is a combination of convection and radiation. Convection occurs when a fluid, such as air or a liquid, is heated and then travels away from the source, carrying the thermal energy along. Thermal radiation generates from the emission of electromagnetic waves. These waves carry the energy away from the emitting object. No contact is necessary between two objects in order for radiative heat transfer to occur. All materials radiate thermal energy based on their temperature. The hotter an object, the more it will radiate. The sun is a clear example of heat radiation that transfers heat across the solar system. When fire hose is brought on the fire ground, it is often exposed to warm convective air currents in the room and to the heat radiating from the fire and, as the fire develops, from the hot upper layer.

Another way that an object may be heated on the fire ground is direct flame impingement. This occurs when an object come in direct contact with flames. Even so, there are no tests in NFPA 1961 for convective and radiative heat or for flame impingement. Since fire attack hose is carried by the fire fighter, it is a solid assumption that the hose and firefighter personal protective equipment (PPE) experience the same or at minimum, remarkably similar thermal conditions. Thus, an analysis of PPE standards and the thermal performance testing they require is instructive as a comparison to how fire attack hoses are tested.

5.2 U.S. Firefighter Personal Protective Equipment Standards

Firefighter PPE is tested for numerous thermal performance criteria as per NFPA 1971: *Standard on Protective Ensemble for Proximity Firefighting* [48]. NFPA 1971 includes ten thermal performance tests with different test procedures corresponding with different elements of the protective ensemble. Firefighter footwear, which operates in a similar environment as fire attack hoses, is required to withstand a flame resistance test, a heat and thermal shrinkage resistance test, two conductive heat resistance tests, a radiative heat resistance test, a thermal protective performance test, and a thread melting test. These tests involve conditions more representative of the three modes of heat transfer found on the fireground. For example, one test requires the footwear to be placed 1 foot from an n-heptane pool fire for 12 seconds, and another exposes the boot to a 280°C (536°F) conductive heat source until the inside of the boot reaches a harmful condition.

A firefighter's PPE is their first line of defense against fire, as it directly shields their body from the harsh conditions on the fire ground [2]. That being said, a fire hose is the firefighter's next lifeline, as the fire hose must go with the firefighter into the burning building. In the words of Duane Leonhardt of Mercedes Textiles, "fire hose faces the same service environment and worse storage conditions than fire." Clearly firefighter PPE is tested at far more rigorous thermal conditions across all modes of heat transfer than fire hoses are. Comparatively, the U.S. standards on fire hose are blatantly weak, testing only for conductive heat transfer and testing well below potential operating conditions. Thus, it is of course a curiosity as to how other countries standards on fire hose specify thermal testing. A search of the international standards was conducted to compare U.S. requirements to those from other countries.

5.3 International Comparison of Fire Attack Hose Standards

Two countries which have standards containing more rigorous thermal performance testing for fire attack hoses are Britain and Germany. The British Standards Institution fire hose standard, BS 6391: *Specification for non-percolating layflat delivery hoses and hose assemblies for fire fighting purposes*, requires two thermal performance tests: the Hot Surface Resistance Test and the Heat Resistance Test. The Hot Surface Resistance Test is a conduction heat transfer test that requires a 300°C (570°F) or 400°C (750°F) filament rod be placed in contact with a fire hose for two minutes. This test mandates higher temperatures and twice the exposure time when compared to the NFPA 1961 Heat Resistance Test. The BS Heat Resistance Test requires a steel cube to be heated to 600°C (1110°F), then stamped on the fire hose for 15 seconds. If the hose does not leak or burst during the duration of the tests, the hose is said to have passed. When compared to the NFPA fire hose thermal performance test, the British tests are more rigorous in that they require a conduction test at a higher temperature, however they still do not accurately represent actual fire ground conditions. Also, like the U.S. fire standard on hose, the British standard also does not require any testing

of a hose's performance when exposed to a convective/radiative heat source nor to a direct flame impingement [46, 50].

The German Institute for Standardization fire hose standard, DIN 14811, *Fire-fighting hoses- Non-percolating layflat delivery hoses and hose assemblies for pumps and vehicles*, includes a fire hose flame test [51]. This test requires fire hoses be impinged by a flame from a Bunsen burner for ten seconds. The hose is said to have passed if it does not leak or burst within the ten seconds, and if the afterflame or afterglow time is no more than three seconds. This procedure tests fire hose for their ability to withstand flame impingement from a fire as well as to self-extinguish when exposed to flames. As shown in 4.3.1 *Range of Scenarios*, flame impingement is a relevant and dangerous mode of heat transfer fire hoses often face on the fireground.

Aside from the more rigorous thermal performance testing, the British and the German fire hose standards both include fire hose classification systems. The goal of fire hose classification systems is to provide fire personnel purchasing fire hose, as well as firefighter who are using the fire hose, with additional insight into the construction and performance capabilities of different fire hoses. An effective classification system should rate hoses in such a way as to provide information on their ability to perform on the fireground. The British system in particular is successful in achieving this goal, with different "types" of fire hose being held to different testing criteria. More durable fire hoses which are ranked as Type 3 hoses must withstand a temperature 100°C greater than the other types during the Hot Surface Resistance Test and are even required to pass an additional heat resistance test. This performance based rating system enables fire personnel to fully understand the quality, be it good or bad, of the hose they are purchasing. Currently in the United States, fire hose can only be "stamped" as NFPA compliant based on a pass/fail criteria from the one thermal test. A fire hose which barely passes the standard's performance tests is rated the same as a fire hose which far exceeds the requirements of the standard; each is simply NFPA 1961 compliant [46, 50, 51].

5.4 Standards Research Conclusion

There is a legitimate problem regarding these standards which have become widely adopted by the fire service. Although the inclusion of fire test for fire hose seems indisputably necessary, NFPA 1961 fails to even mention the importance of a fire hose's ability to perform while under thermal attack from convection, radiation, or direct flame impingement. These standards need to include a more rigorous test for conduction and a rigorous test for convection and radiation. To help meet this need for testing apparatuses and procedures, research teams at WPI are developing a conduction and a separate convection and radiation test which more accurately represent fire ground conditions [51, 52]. Even though fire hoses operate in the same environment as firefighter PPE, the test apparatuses and procedures for PPE are drastically more demanding than those for fire hoses. Additionally, the international comparison supports the inclusion of a fire hose classification system as well as more severe testing, as other countries include a flame impingement test and more demanding conduction tests. NFPA states that their "standards [are] intended to minimize the possibility and effects of fire and other risks" [53]. With that in mind, it is essential that NFPA fire hose standards undergo major revisions in order to maintain and further the safety of firefighters and the residents they protect.

6.0 Taxonomy of Performance Metrics

The many essential functions fire attack hoses perform inevitably expose them to hazards and conditions that ultimately threaten their integrity. As discussed in more detail previously, a fire attack hose is typically made of combustible materials, must operate at high pressures, endure extremely harsh and thermally intense environments, face suboptimal storage conditions, and is repeatedly dragged along pavement [1]. Reports collected in the database of burn-through incidents, results from fire-performance testing in the lab, and findings from post-incident investigations clearly demonstrate the need for a more fire resistant hose. Although a simply fire resistant hose would prevent burn-throughs, this next generation fire attack hose must also be able to complete all necessary fireground tasks. The selection and testing of candidate materials across a distribution of material properties, indicative of performance, will help ensure the hose can complete all of these necessary functions. In order to facilitate this process, this research aims to ultimately identify relevant material properties and organize them into taxonomy. The taxonomy is useful for many stakeholders including but not limited to code making bodies, manufacturers, fire departments, and researchers.

6.1 Methodology

The selection of construction materials is a critical part of any new hose design. Materials selected must have desirable material properties that allow the hose to perform all of the functions documented in section 3.0 *Fire Service Experience*. A taxonomy of these properties was thus created which aids in both hose design and standardized testing. This taxonomy was developed by determining the impact on either the hose or the firefighter for each function described by the fire service. One or more requirements were then specified in order to address the impact. These requirements were then defined scientifically in terms of material properties, indicative of performance, to provide researchers with a list of metrics. For example, when fire attack hoses are deployed, they are pulled from the apparatus to the point of fire attack. During this process, hoses are dragged across pavement, around obstacles, and up stairs. The impact to the hose while performing this function is abrasion from rough pavement and or debris. The requirement is thus that the hose be resistant to abrasion. Material properties that are scientifically accepted to measure abrasion resistance include: hardness, tensile strength, and fracture toughness.

Utilizing this process, each and every function involving a fire attack hose was analyzed, its impacts documented, requirements determined, and material properties defined. The process is shown below in Figure 3 and the full analysis is shown in Table 2.

Function → Impacts → Requirements → Material Properties

Figure 3 Taxonomy of performance metrics process

This analysis consisted of two steps: translating the information provided by the fire service into requirements and then translating the requirements into quantitative material properties. The first process specifies requirements from an analysis of hose functions and corresponding impacts. These requirements describe desirable characteristics to be considered when creating a next generation fire attack hose. The

second process delves a layer deeper by defining these requirements as material properties, which can then be used to compare candidate materials.

6.2 Process for Determining Requirements

As previously discussed in *3.0 Fire Service Experience*, fire hoses perform a variety of demanding tasks on the fireground. The abusive nature of these functions causes the fire attack hose to sustain damage that can compromise hose performance. For example, *4.3.1 Range of Scenarios* describes a situation in Worcester, Massachusetts where a fire attack hose came in contact with hot debris. In this situation, the function of the fire hose was fire suppression. The resulting impact on the hose was thermal damage. As a result, the requirement is that a fire hose be resistant to heat.

Additionally, a fire hose carries the water for necessary for fire suppression. In this example, the fire hose functions as a conduit of water. The impact to the fire hose is repeated exposure to high pressures. The requirement is that fire attack hoses must be able to withstand high pressures. A thorough analysis of all functions and usages documented in *3.0 Fire Service Experience* is summarized in Table 2 along with the corresponding impacts and requirements.

Table 2 Analysis of Fire Hose Functions

Function/Usage →	Impact (on hose or firefighter)	Requirement
Annual Pressure testing	Exposed to high pressures	Withstand high pressures
Stored on apparatus	Vibrates on apparatus/ against debris	Durable
	Folded on same crease	Flexible, durable
	Sits on apparatus, wet	Mildew resistant, corrosion resistant
Pulled off apparatus	Outer jacket abuse	Durable
Dragged into Buildings	Exposed to debris	Abrasion resistant
	Exposed to sharp objects	Puncture resistant
	Exposed to chemicals	Chemically inert
	Exposed to extreme temperatures	Heat resistant, freeze resistant
	Exposed to electricity	Non conductive
	Navigated around corners, obstacles	Flexible, kink resistant
Carried up stairs	Wasted energy getting to fire	Lightweight
	Controlled by less than ideal manpower	Lightweight
Conduit of water	Exposed to high pressure	Flow water, withstand high pressure
'Rope' Rescue	Stressed in an unusual manner	Durable
Damming oil spills	Exposed to chemicals	Chemically inert

Reviewing the list of requirements, it becomes clear that they span across various categories of material properties such as mechanical and physical, chemical and electrical, and thermal. For example, “durability” and “flexibility” describe mechanical performance, whereas “chemically inert” and “degradation resistant” describe chemical performance. These categories of performance were used to define the first level of a taxonomy useful in developing a framework for understanding, identifying, and investigating materials to determine their potential for use in a next generation fire attack hose. Requirements are fully categorized in Table 3.

Table 3 First level of taxonomy: requirements

Next Generation Fire Attack Hose		
Mechanical & physical properties	Chemical & electrical properties	Thermal properties
Requirements		
Durability (NFPA 1961 5.5.1)	Mildew resistance (NFPA 1961 5.3.6, 5.5.1)	Heat resistance (NFPA 1961 7.3.4.2)
Flexibility (NFPA 1961 6.11, 6.13)	Corrosion resistance	Range of use
Abrasion resistance (NFPA 1961 7.3.4.1)	Chemically inert	Thermochemistry performance
Puncture resistance	Low toxicity	Cold resistance and performance (NFPA 1961 6.10, 6.11)
Kink resistance (NFPA 1961 6.4)	Degradation resistance	
Lightweight	Non-conductive	
Tolerate high pressure (NFPA 1961 6.5)		

6.3 Expression of Requirements of Material Properties

The next step in building the taxonomy is defining the requirements in terms of material properties. The list of requirements determined from a study of hose functions and associated impacts is a useful first step, but it does not provide stakeholders with specific quantitative metrics. For example, the meaning of durability can change based on the application. A material may be durable enough to be used in a firehouse bunkroom couch, but may not be durable enough to be dragged along the pavement. To continue our discussion of abrasion resistance from above, the question arises as to how one might measure and compare the abrasion resistance of two different materials. Scientifically, abrasion resistance is measured by the metrics of hardness, tensile strength, and fracture toughness. These metrics have existing testing methods: ASTM E384, ASTM C1557, and ASTM E1820, respectively. Tables 4, 5, and 6 depict the second process of the analysis that was previously discussed in Section 6.1. Table 7 is the completed taxonomy.

Table 4 Mechanical and Physical Properties

<u>Requirements</u>	<u>Material properties</u>
Durability	Fatigue strength, hardness, tensile strength, elongation, yield Strength
Flexibility	Flexural modulus, Young's modulus, shear modulus
Abrasion resistance	Hardness, tensile strength, fracture toughness
Puncture resistance	Hardness, fracture toughness
Kink resistance	Flexural modulus, Young's modulus, shear modulus, fatigue strength
Lightweight	Density
Withstand high pressure	Permeability, fatigue strength

Table 5 Thermal and Fire Properties

<u>Requirements</u>	<u>Material Properties/Performance Metrics</u>
Heat resistance	Thermal conductivity, melting point, auto-ignition temperature, thermal diffusivity, flammability
Range of use	Maximum service temperature, minimum service temperature
Thermochemistry performance	Heat of combustion, thermal expansion
Cold resistance & performance	Specific heat, elongation, flexural modulus

Table 6 Chemical and Electrical Properties

Requirements	Material properties/ performance metrics
Corrosion resistance	Surface roughness, reactivity
Chemically inert	Reactivity
Low toxicity	Toxicity, product of combustion
Degradation resistance	UV radiation, ozone resistance, Mildew resistant
Non-conductive	Electrical resistance

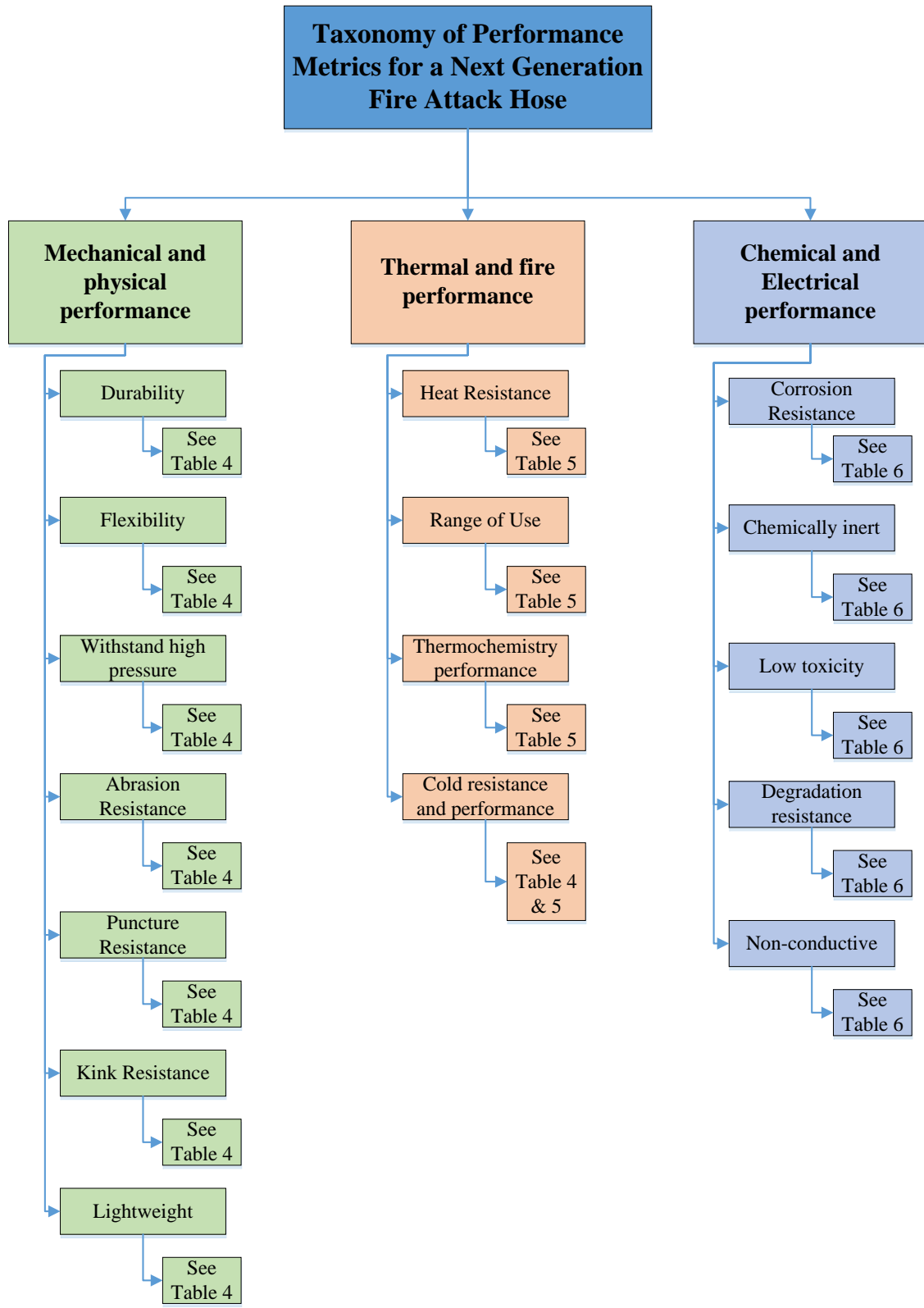


Figure 4 The taxonomy of performance metrics

6.3.1 Mechanical & Physical Properties

As shown in Table 4, mechanical properties important in a fire attack hose include durability, flexibility, abrasion resistance, kink resistance, puncture resistance, and withstanding high pressure. Each of these properties are describe in more detail below.

Durability of a material can be understood and quantified by the material properties/ metrics: fatigue strength, hardness, tensile strength, elongation, and yield strength. All of these metrics are measures of the hoses ability to perform over multiple deployments. Each property is measuring a specific aspect of a material's performance. Fatigue strength is the amount of cyclic loading that a material can withstand before failure, such as a fire hose experiences when repeatedly folded back onto the apparatus. Tensile strength is the maximum amount of stress a material can withstand, in tension, before failure. Hoses experience tension when filled with water or dragged along the ground. Elongation, expressed as a percentage, expresses the strain and object can withstand until necking occurs. Yield strength is the point on a stress-strain curve that is no longer linear, indicating that irreversible damage has been done to the material [54].

Abrasion resistance of a material can be understood and quantified by the material properties/ metrics: hardness, tensile strength, and fracture toughness. Hardness is a materials ability to resist physical shape change. Fracture toughness is the ability of a material to resist fracture where cracks are present. Microscopic cracks are present in all materials but whether these cracks propagate to cause fracture under an applied stress, such as a hose being dragged along the ground, relates to its fracture toughness [2].

The *flexibility* of a material can be understood and quantified by the material properties/metrics: flexural modulus, young's modulus, and shear modulus. The flexural modulus is a stress-strain relationship of a material during flexural deformation, such as a hose being maneuvered around corners [55]. Young's modulus is a measure of the materials elasticity. Shear modulus is a measure of a materials resistance to deformation in shear [54].

The *puncture resistance* of a material can be understood and quantified by the material properties/ metrics: hardness and fracture toughness. These metrics are described above with abrasion resistance and durability.

Kink resistance of a material can be understood and quantified by the material properties/metrics: flexural modulus, Youngs modulus, fatigue strength, and shear strength. These metrics are defined above with flexibility and durability.

A *lightweight* material can be understood and quantified by the material property/metric: density. Density is the mass per unit volume of a material [56]. Lightweight materials are those, which have a low density.

A materials ability to *withstand high pressure* can be understood and quantified by the material properties/metric: fatigue strength. Fatigue strength has been previously defined.

6.3.2 Thermal & Electrical Properties

As shown in Table 5, thermal and fire properties important in a fire attack hose include heat resistance, range of use, thermochemistry performance, and cold weather performance. Each of these are described below in more detail.

The *heat resistance* of a material can be understood and quantified by the material properties/metrics: thermal conductivity, melting point, auto-ignition temperature, thermal diffusivity, and flammability.

Thermal conductivity is the ability of a material to rise in temperature due to an external heat source. The melting point of a material is the temperature at which a material changes state from a solid to a liquid. The auto ignition temperature is the temperature at which materials will combust without an ignition source. The thermal diffusivity of a material “measures the rate of heat transfer from an exposed surface of a material to the inside [57].” NFPA 704 ranks flammability of substances and materials based on volatility [58].

The *range of use* of a material can be understood and quantified by the material properties/metrics: maximum service temperature and minimum service temperature. The maximum service temperature of a material is the highest temperature at which a material can be used before it begins to undergo chemical transformation. The minimum service temperature is the temperature at which a material becomes too brittle for use. There are no universal tests for either of these metrics, and are understood from experience of using a material [55].

The *thermochemistry performance* of a material can be understood and quantified by the material properties/ metrics: heat of combustion and thermal expansion. The heat of combustion is the “amount of heat released when a unit quantity is oxidized completely to yield stable end products [57].” Thermal expansion is “defined as the expansion of unit length of a material when it is raised by one degree in temperature [57].”

The *cold resistance* of a material can be understood and quantified by the material properties/metrics: specific heat, elongation, and flexural modulus. Specific heat is the “amount of heat required to raise the temperature [of a material] of unit mass by one degree Celsius [57].” Flexural modulus and elongation, as defined previously, should also be tested to ensure that the material does not become brittle when exposed to sub-zero temperatures.

6.3.3 Chemical & Electrical Properties

As shown in Table 6, chemical and electrical properties important in a fire attack hose include mildew resistance, corrosion resistance, chemically inert, low toxicity, and degradation resistance. Each of these are described below in more detail.

The *mildew resistance* of a material can be understood and quantified by the material properties/metric: mildew resistance test. An existing mildew resistance test for synthetic materials can be found in ASTM G21 [59].

The *chemical inertness* of a material can be understood and quantified by the material properties: reactivity. Reactivity describes the likelihood of a materials to undergo a chemical reaction when it comes into contact with another substance, such as a hose being used to dam oil spills or coming into contact with chemicals [60].

The *corrosion resistance* of a material can be understood and quantified by the material properties: surface roughness and reactivity. Surface roughness determines the smoothness of a surface, necessary for a conduit of water. Reactivity has been previously defined.

A material with *low toxicity* can be understood and quantified by the material properties/metrics: toxicity and products of combustion. Toxicity is determined by “concentration of toxic product in the target organ

of the body and the time period for which a toxic concentration is maintained [57].” Products of incomplete combustion, which include asphyxiate gases, can lead to serious health problems.

The *degradation resistance* of a material can be understood and quantified by the material properties/metrics: UV radiation resistance, and Ozone resistance. Existing test methods that materials UV and ozone resistances are ASTM D4329 and ATSM D1149, respectively [61, 62].

A material that is non-conductive can be understood and quantified by the material property/metric: electrical resistance. Electrical resistance is the ease of which an electrical current can flow through a material.

6.4 Comparison with Standards

When comparing NFPA 1961 to this taxonomy, there is a discrepancy between what is currently required in the standard and what is needed for reliable fire ground performance. Nine out of the seventeen requirements in the taxonomy are tested for in the current standard. The requirements tested are: durability, flexibility, abrasion resistance, kink resistance, withstands high pressure, degradation resistance, heat resistance, cold resistance, and range of use. Only eight out of twenty nine performance metrics/material properties are mentioned in the standard: fatigue strength, tensile strength, mildew resistance, minimum service temperature, elongation, mildew resistance test, thermal conductivity, and ozone resistance. Although these requirements/material properties are tested for, this does not indicate that the test is comprehensive or accurately represents conditions found on the fireground. For example, although heat resistance is currently tested for, the test is limited to conductive heat transfer. As displayed in section 4.0 *Database*, hoses burn-throughs also occur due to thermal radiation, but the standard does not test for this mode of heat transfer.

Additionally, the current standard does not test the following material properties: hardness, yield strength, flexural modulus, Young’s Modulus, shear modulus, fracture toughness, density, surface roughness, reactivity, toxicity, products of combustion, UV radiation, melting point, auto ignition temperature, thermal diffusivity, flammability, maximum service temperature, heat of combustion, thermal expansion, specific heat, and electrical resistance. Furthermore, the standard does not test for the following requirements: puncture resistance, lightweight, corrosion resistance, chemical inertness, low toxicity, electrical conductivity, and thermochemical performance. Test methods do exist for which both requirements and material properties can be tested on. For example, ASTM E1461 measures thermal diffusivity. Another example is Young’s Modulus is measured using ASTM E111.

6.5 Conclusion

The ultimate goal of this taxonomy is to provide a structured presentation of a set of material properties, each of which can be used to quantitatively measure an aspect of performance of a fire hose. This taxonomy can be used by hose manufacturers and fire personnel to consider when designing or purchasing fire attack hose. These metrics, derived from functions documented in section 3.0 *Fire Service Experience*, more accurately reflect the harsh conditions found on modern firegrounds. The taxonomy provides manufacturers and material researchers with a comprehensive list of properties to test potential materials on before creating a hose. Fire personnel can use this taxonomy to construct a hose specification for a manufacturer or to help

judge whether or not a fire hose will function effectively under certain fireground conditions. Serious consideration must be given before buying a hose that is simply stamped NFPA 1961 approved. The “minimum requirements” set forth by the standard do not account for all the elements faced on the fireground and therefore hoses cannot be expected to perform reliably to firefighter expectations. This taxonomy combines hose standards requirements and firefighter needs into an easily accessible document that’s intent is to improve fire hose.

7.0 Recommendations

Researchers have compiled the following recommendations in order to continue progress towards the goal of developing a next generation fire attack hose

- 1. Transfer the fire hose burn-through database to a nationally recognized organization that will further develop and expand the database and take steps to ensure continual two way communication with the fire service.**

The fire hose burn-through database would benefit from being turned over to a national organization to use its resources to expand the features of database, such that many stakeholders receive valuable information from the data to create recommendations for increasing firefighter safety. The longevity of the database is highly dependent on its presence in the minds of fire fighters so that data is reported.

- 2. Promote dialogue between the fire service, hose manufacturers, code committees and other stakeholders by holding a workshop once a year to discuss the frequency of fire hose burn-throughs, the state of fire hose manufacturing materials and processes, and the progress of the fire hose codes.**

The fire hose burn-through database can be used to promote conversation between all parties involved with fire attack hoses. Bringing these parties together once a year to discuss updates on the current state of fire hoses will ensure that fire hose technology continues to improve.

- 3. Define quantitative fire hose performance expectations via a fire hose workshop.**

Before developing testing procedures, it is first necessary to define exactly what conditions a fire hose should be capable of withstanding. This data can then be used to drive the development of more rigorous fire hose tests.

- 4. Improve the existing fire hose conduction test by creating an apparatus and procedure which reflects temperatures and exposure times representative of those experienced on the fire ground.**

The current NFPA 1961 fire hose conduction test does not adequately reflect conditions found on modern firegrounds. Creating an apparatus capable of exposing fire hoses to these conditions as well as defining realistic testing parameters will drive an increase in fire hose performance capabilities.

5. Develop a convection and radiation test which reflects temperatures and exposure times representative of those experienced on the fire ground.

Fire hoses are exposed to all three modes of heat transfer on the fireground, yet NFPA 1961 does not test for convection or radiation. It is essential that a convection and radiation testing apparatus is developed and adequate parameters are defined. This test should be included in the standard in order to quantify fire hoses' ability to perform under such conditions.

6. Publicize and make publically available the taxonomy of material properties needed in a next generation fire attack hose.

The taxonomy can serve as a guide for fire departments when developing a hose specification. Departments can ask for specific material performance data to compare types of hose before submitting a purchase. Hose manufacturers should utilize the taxonomy when developing new fire hoses to ensure that new fire hose construction can withstand all of the required fireground functions.

7. Improve and strengthen NFPA 1691 by incorporating an evaluation of the material properties identified in the taxonomy of performance metrics.

The taxonomy was developed based on an analysis of functions and usages of fire attack hose and has identified material properties that are indicative of fire hose performance. Researchers can use pre-existing test methods to evaluate the properties of potential new materials for fire attack hose construction.

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