U. S. Department of Justice

Bureau of Alcohol, Tobacco, Firearms and Explosives

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MEMORANDUM TO: Technical Committee Members, NFPA 1901, 1906 and 1961

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SUBJECT: Comparing the Effectiveness of Ultra High Pressure to Traditional Fire Suppression Methods

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Comparing the Effectiveness of Ultra High Pressure to Traditional Fire Suppression Methods

Testing Locations:

Midwestern University Downers Grove, Illinois

Acquired structures in Middleton, Wisconsin

June 14-18, 2015 August 6-7, 2015, December 6, 2015, April 24, 2016 and May 28, 2016

Bureau of Alcohol, Tobacco, Firearms and Explosives

Special Agent Certified Fire Investigator Candidate

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Abstract

Between June 2015 and June 2016, Bureau of Alcohol, Tobacco, Firearms and Explosives, Special Agent Certified Fire Investigator Candidate (CFIC) William Fulton, Madison Wisconsin Field Office, partnered with the Middleton Fire District (Wisconsin) to conduct a research project on Ultra High Pressure Fire (UHP) Suppression Systems. The Middleton Fire District (Wisconsin) utilizes UHP as their first line of attack on the majority of fires they respond to. Their system is mounted on a Chevrolet 3500 rapid response truck (Command Vehicle). The Middleton Fire District's (Wisconsin) protocol is to respond with this vehicle as their first out apparatus. According to their Fire Chief, the rapid response vehicle significantly reduces their response time versus traditional fire truck pumpers. The UHP system also claims to allow faster application of water to the fire, at times with fewer personnel.

The UHP system that was tested was a PTO driven 30 gallon per minute unit that pressurizes water to 1500 psi through an engineered nozzle and hose system. This ultra high pressurization creates smaller water droplets. The application of these smaller water droplets creates more surface area and typically allows heat energy to be absorbed more efficiently than the larger droplets created by lower pressure systems (solid bore or fog nozzles).

As a fire investigator, CFIC Fulton has responded to investigate several fires to date with the Middleton Fire District (Wisconsin) where UHP has been utilized during suppression operations. It was of interest to CFIC Fulton to conduct a series of controlled experiments to determine what impact, if any, that UHP has on the survivability of fire patterns and overhaul damage post fire suppression. In addition, a comparison between UHP and traditional

suppression was also warranted to evaluate the suppression capabilities of this technology. CFIC Fulton developed phases of testing to evaluate this emerging technology. To date, a total of twenty one tests have been conducted for this research project. The research began with a series of eleven burns in single room dormitories which were conducted to establish baseline data for UHP in a single compartment. Additional tests were then conducted in a two-compartment structure with identical fuel packages to evaluate the same variables. Finally, a series of full-scale tests were conducted in a two-story acquired structure with flames extending from the first to the second level.

The research concluded the UHP system reduced temperatures as effectively as traditional low-pressure systems in compartment fires. The distinguishable difference was the UHP system used 1/5 the amount of water than the low-pressure systems. Researchers further concluded that the use of less water during suppression operations was beneficial to the survivability of burn patterns, evidence preservation, less movement of items in a room and other fire affects used to determine the origin and cause of fires. The emerging technology deserves further study and may supplement existing firefighting operations in the future.

Introduction

Between June 2015 and June 2016 a total of twenty one tests were conducted for this research project, the initial research burns were conducted in June 2015, at Aspen Hall, an acquired university dormitory located at Midwestern University in Downers Grove, Illinois. These tests were conducted in single compartment dorm rooms. Two baseline tests (B1 and B2) and nine research tests (T1-T9) were conducted. These tests compared the two traditional methods of fire attack (solid bore and fog nozzles), to UHP. Firefighters flowed water into a single compartment for set time intervals (5, 10 and 20 seconds) and flow rates (150 gpm/30 gpm). The temperatures were recorded as well as the temperature exposure to a mannequin, which was set up at the point of fire attack.

In August of 2015, tests (T10-T13) were conducted in a two room burn trailer, in Middleton, Wisconsin. These tests compared the temperature reduction of a two room fire using a solid bore nozzle compared to UHP.

In December 2015, tests (T14-T16) were conducted in a two story acquired structure. These tests involved a fully developed room fire with fire extending to the second floor. These tests compared the temperature reduction using a fog nozzle compared to the UHP.

In April 2016, tests (T17-T19) were conducted evaluating the effectiveness of UHP with regards to fire attacks from adjacent rooms, attic fires and vehicle fires in attached garages.

In May of 2016, tests (T20-T21) were conducted comparing the deployment time of an 1 ¾” handline to the deployment time of UHP.

The initial tests in June 2015, (B1, B2 and T1-T9), were designed to answer two questions. What is the reduction of the room temperature in a compartment fire after flowing water into the compartment at set time intervals? And, is there a noticeable temperature increase experienced by firefighters when suppressing a compartment fire utilizing solid bore, fog, and ultra high pressure? The additional tests (T10-T19) were designed to systematically increase the parameters of the fuel load and fire conditions. Additional tests (T20-T21), were designed to show the time needed to deploy an 1 ¾" handline compared to deploying the UHP system.

Purpose

The American fire service has used low-pressure water systems to extinguish fires for over 350 years. The first practical low pressure hose-line was invented in Holland in 1673. It was made of leather (or sailcloth) and fastened with brass screw heads. Prior to the invention of the hose, buckets of water were thrown on fires to extinguish them.

Currently a majority of the American fire service uses low-pressure water systems to extinguish most compartment fires. The low-pressure systems are typically delivered by using a 1 ¾" handline, with either a solid bore or automatic fog nozzle. These systems are capable of delivering up to 250 gallons of water per minute.

A technology has been introduced to the fire service called Ultra High Pressure. Ultra High Pressure is a system that delivers water at ultra high pressures (over 1100 psi -NFPA 1901 Standard for Automotive Fire Apparatus 2016 ed.), which creates smaller water droplets than high pressure and low-pressure systems. The creation of these smaller droplets claims to absorb energy more effectively than larger water droplets created by lower pressure systems (solid bore or fog nozzles). The UHP system tested was a PTO driven 30 gallon per minute unit that pressurizes water to 1500 psi through an engineered nozzle and hose system.

The research began by conducting a series of side-by-side tests. Researchers were provided with a dormitory at Midwestern University, Downers Grove, Illinois.

The initial goal of the research was to attempt to answer two questions:

What is the reduction of the room temperature in a compartment fire after flowing water into the compartment at set time intervals? Researchers compared the two traditional methods (solid bore and fog nozzles) to an ultra-high pressure fire suppression system.

In June 2015, a series of eleven tests were conducted in Downers Grove, Illinois, two baseline tests and nine single room compartment tests. Identical fuel packages were placed into identical dorm rooms. The fire was initiated and when the fire plume contacted the ceiling, products of combustion were flowing into the hallway, and the room temperature reached 800 °F measured by a thermocouple located at the six foot level in the right corner of the room the firefighter was placed into the doorway to extinguish the fire. The firefighter flowed water for predetermined times (5 seconds, 10 seconds and 20 seconds), for a total of 9 tests. Researchers measured the reduction of temperature and calculated the amount of water flowed into the rooms. The results of the research in Downers Grove, Illinois determined the UHP system reduced room temperatures as effectively as traditional methods (fog/solid bore). The UHP system utilized 1/5 the amount of water as the other two methods.

The UHP system extinguished the fires utilizing 2.7 gallons to 9.8 gallons of water (5 second flow-20 second flow). The traditional methods used 12.8 to 50.7 gallons of water (5 second flow-20 second flow). Utilizing the UHP system to extinguish fires with 1/5 the amount of water aids in the reduction of water damage and preserves fire patterns for fire investigators.

Fire Investigators who conduct origin and cause investigations in incidents where UHP was utilized to extinguish the fire, describe well-preserved fire scenes. Walls and ceilings are left intact, evidence is preserved, burn patterns are present and overall damage to the structure is reduced.

Researchers addressed the potential for temperature increase at the firefighter's doorway position for all three fire attack methods during the initial nine tests (T1-T9). A mannequin equipped with thermocouples was placed in the doorway to the left of the firefighter's position. The thermocouples were placed under the helmet and under the protective hood of the mannequin. The temperature increase on the mannequin ranged from .5°F - 7 °F, adjacent firefighters were unable to physically detect a temperature increase.

In September 2015, after the research burns in Downers Grove, Illinois researchers systematically increased the parameters of the tests. CFIC Fulton and Fire Protection Engineer Adam St. John conducted additional tests in Middleton, Wisconsin in a two room metal burn trailer. Researchers ignited simultaneous fires in two adjacent rooms and measured the temperature reduction and water flows for these tests. The results were consistent with the single room tests (T1-T9) in June 2015, showing similar temperature reductions (solid bore/UHP) the distinguishable difference was the UHP system used 1/5 the amount of water.

In December 2015, researchers were provided with a two-story residential acquired structure in Middleton, Wisconsin (T14/T15). Researchers ignited a fire on the first floor in the A/D corner of the structure, and the fire progressed through the stairwell to the second division. Researchers created a unidirectional flow path by opening the second story exterior door and window. UHP was compared to an automatic fog nozzle, the results were consistent with the findings in Downers Grove, Illinois. The UHP system extinguished the fully involved room and second floor, utilizing 11 gallons of water. The automatic nozzle utilized 55 gallons to extinguish the same fire.

The December 2015 two story residential acquired structure burn (T16), culminated in a burn in which four bedrooms and hallway on the second floor were furnished with a heavy fuel load. All areas were allowed to progress to full room involvement. The firefighters utilized the UHP system and brought the fire "under control" with 85.5 gallons of water.

Additional tests utilizing various UHP fire attacks methods were conducted in April 2016 at an acquired structure in Middleton, Wisconsin. The strategies included attacking a room fire from an adjacent, unaffected compartment (T17), attacking an attic fire from the living space below (T18) and finally conducting a "capacity" test by igniting a vehicle inside of the attached garage (T19). Researchers captured data with thermocouples and video.

The UHP rapid response methodology that the Middleton Fire District (Wisconsin) uses to incorporate UHP as their first line of attack is notable. They further plan to incorporate several additional UHP rapid response vehicles into their community. This regionalized fire attack model will provide a faster response to fire emergencies within their 55 square mile fire protection district.

The NFPA recognizes UHP in the context of pumps (NFPA 1901 Standard for Automotive Fire Apparatus 2016 ed.) and it's utilization in wild-land fire applications (NFPA 1906 Standard for Wildland Fire Apparatus 2016 ed.). The current NFPA standards do not recognize UHP for structural firefighting. Researchers anticipate that the NFPA will explore how UHP can be incorporated into future editions of the standards.

Literature Review

Fire is a complex process that involves many interactions between chemical and physical processes. Burning will continue until one of the following happens: the combustible material is consumed, the concentration of oxidizing agent (normally oxygen in the air) is lowered to below the concentration necessary to support combustion, sufficient heat is removed or prevented from reaching the combustible material, thus preventing further fuel pyrolysis or the flames are chemically inhibited or sufficiently cooled to prevent further reaction. (NFPA, 2008)

The fire service in North America traditionally utilizes low-pressure water systems to extinguish fires. Currently, the most widely accepted application of water to extinguish fires is the utilizing of a 1¾" handline equipped with either a solid bore nozzle or an automatic fog nozzle. Generally, these handlines are pressurized between 100 psi-200 psi and can deliver over 200 gallons of water per minute.

The thermal characteristics of water makes it ideal to extinguish most types of fires. It is used to extract heat directly from flames, products of combustion or from the surface of the burning fuel. When exposed to heat, water undergoes a phase change from a liquid to a vapor (at 212 °F). This phase change interacts with the combustion process. The combustion process is interrupted by reducing the thermal energy and reducing the oxygen concentration of the surrounding atmosphere, particularly when the fire is confined to a single room (also referred to as a compartment).

Water, in its normal state, is a liquid that can be solidified by the process of freezing, or it can be vaporized by the process of boiling. Heat is released by water in the process of freezing, while heat is absorbed by the water in the process of boiling. Under atmospheric pressure equal to that at sea level, fresh water freezes at 32°F and boils at 212°F. At higher elevations, the atmospheric pressure is less and its boiling point is correspondingly lower. Steam is generated in the process of boiling. Steam is a transparent vapor and remains so until the process of condensation begins. Condensation results from loss of heat and as this process progresses what was formerly steam appears as visible mist. This visible mist is referred to as "condensing steam". (Layman, 1955)

A fraction of the absorbing capacity of water is utilized in the process of raising its temperature to the vaporization point. It is in the process of vaporization, when the water reaches 212 °F that water exerts its cooling action. One gallon of freshwater will absorb approximately 1250 British Thermal Units (BTU) in the process of raising its temperature from 62°F to 212°F. This theoretical gallon of water has reached its boiling point (212°F) and is ready to start changing from a liquid to a vapor. Absorption of additional heat will not increase the temperature of the liquid that will reduce the volume by converting liquid into vapor (steam), which will escape into the surrounding atmosphere. When the last drop has been converted into steam, this gallon of water has absorbed approximately 9333 BTU; 1250 BTU in the process of raising the temperature from 62°F to 212°F and 8080 BTU in the process of vaporization. It should be noted that in the process of vaporization this gallon of water absorbed within six times the volume of heat that is absorbed in the process of raising its temperature from 62°F to 212°F. Based upon the scientific facts the following truism can be stated: the maximum cooling action of a given volume of water is obtained only when the entire volume has been converted into steam. (Layman, 1955)

Vaporization of water results in the production of steam in ratio of 1 to over 1,600. Water in a volume of 1.05 in.^{3}, measured at its boiling point, will expand into 1728 in.^{3} or 1 ft.^{3} of steam. A gallon of water, measured at 62°F, will produce approximately 223 ft.^{3} of steam. This calculation takes into account the liquid expansion that results from increasing the temperature of the water from 62°F to 212°F. If in firefighting operations only 90% of a given volume of water is vaporized, approximately 200 ft.^{3} of steam would be generated per gallon of water used.

Effective extinguishing action is dependent upon instantaneous transfer of heat from the involved and exposed materials to the water being applied. The volume of heat transferred should be sufficient to convert a large percentage of the water into steam. Ideal use of water as a fire extinguishing agent is achieved if water could be applied in a form and at a rate whereby the entire volume is converted into steam.

The rate of heat absorption can be increased by increasing the surface area of water in ratio to its volume. The surface exposure of a given volume of water can be increased by breaking the water into finely divided particles. The surface area of a gallon of water broken into finely divided particles is increased many times over that of a gallon of water in the form of a solid stream. Water can be broken into finely divided particles by passing it through a properly designed nozzle under adequate pressure. The design of the nozzle and the nozzle pressure are the factors that determine the size of the particles or the degree of fineness. The degree of fineness that will produce effective results in firefighting operations may be defined as follows: (a) a large percentage of the particles should be of sufficient degree of fineness that they are buoyant enough to be carried for some distance by air currents; (b) a large percentage of the particles should be of sufficient degree of fineness to vaporize instantaneously upon contact with materials having temperatures above the boiling point of water. The development of equipment that enables firefighting personnel to apply water in the form of finely divided particles was the most progressive advancement in equipment since the advent of the power driven pumping unit. (Layman, 1955)

Extinguishing efficiency of a given volume of water depends upon the percentage converted into steam. Water that fails to vaporize contributes very little to actual extinguishment but is responsible for water damage to exposed materials. The most practical solution to the problem of reducing water damage is to increase the percentage of vaporization. (Layman, 1955)

Ultra High Pressure is a fire suppression system which can be mounted to an all-terrain vehicle, a quick response vehicle, a heavy rescue, or a traditional fire engine. The systems are powered with either a generator or a power take-off (PTO) power train. The power supply engages a pump, the pump pressurizes tank water to between 1200-1500 psi. There are different UHP systems that can deliver water between 10 to 100 gallons per minute. The water is deployed through either a ¾ inch or 1-inch pre-connected hydraulic hose-line that is stored on a reel, similar to a booster line. The hose is manufactured similar to a hydraulic line with an inner tube that carries the water, with a sheath of wire or, with a protective outer layer, which provides protection from thermal damage and abrasion. The pre-connected hose lines tested ranged in length from 150’ to 200’ and there were no couplings located along the hose line.

The UHP system that was tested utilized an engineered pistol grip and bail style nozzle to deliver the water. The nozzle has the general appearance of an automatic fog nozzle. The calibrated fixed gallonage nozzle can be manipulated to deliver a straight stream or a fog pattern. The system has the ability to apply a surfactant (foam), however, no surfactants were used during this research.

The ability to deliver water between 1200-1500 psi creates finer water droplets than those in low pressure systems. The finer water droplet creates more surface area than those created with traditional low-pressure systems. This results in the ability for water to absorb heat energy more efficiently and in a shorter period of time.

Methods and Materials

Single Compartment Tests

Eleven tests (B1/B2 and T1-T9) were conducted at Aspen Hall at Midwestern University, Downers Grove, Illinois in June 2015. Aspen Hall consisted of thirty-six dormitory units. The building was steel frame with concrete block with an exterior brick finish. The floors were poured concrete with two interior stairwells. The interior dormitory rooms were concrete block. The roof was a flat, rubber membrane covered with aggregate rock.

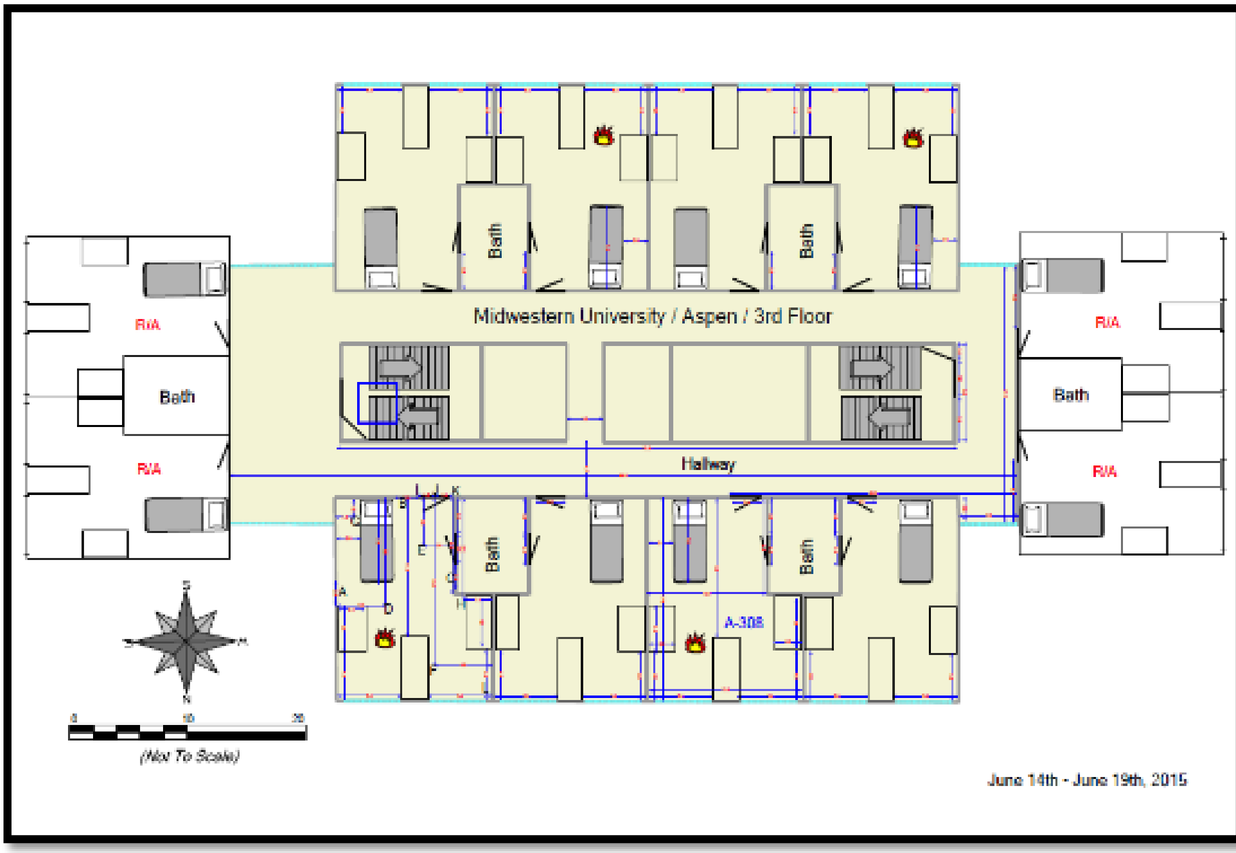

Figure 1-Midwestern University location of B1/B2 and Tests T1-T9

Exterior of Building

Figure 2-Midwestern University A/D corner

Figure 3- Midwestern University Side C

Figure 4-Midwestern University Side A Entry Door

Figure 5-Midwestern University Side D

Interior hallway/test room

Figure 6-Interior Hallway

Figure 7-A Test Room

Figure 8-A Test Room

Figure 9-A Test Room

The configuration of the rooms, furnishings, fuel load and fires were identical. The test rooms were dorm rooms constructed of poured concrete floors and ceilings with concrete block partition walls. The rooms measured seventeen feet (17') by nine feet six inches (9 ½') with a slight two-foot (2’) by eight foot (8’) bump out which gave the rooms a slight left hand “L” shape. The rooms had eight-foot (8’) ceilings.

The furnishings consisted of a single metal frame bed with a mattress louvered hanging closet doors, built-in floor to ceiling dressers, desks and carpeting. The fires were configured by stacking identical drawers with a known quantity of fuel. The fires were initiated in the same location for all nine tests.

Thermocouple Placement

Researchers conducted two baseline burns (B1 and B2). The baseline burns were conducted to calibrate the expected time to room flashover or full room involvement. These baseline burns were outfitted with instrumentation to measure the heat flux and establish the placement of five (5) thermocouple trees. These thermocouple trees were placed in shielded (out of reach of the handline) space within the test room, as well as in the hallway directly outside of the test room.

There were five thermocouple (TC) trees placed in the test room and two thermocouples placed on the mannequin. The mannequin was located to the left of the doorway of the test room.

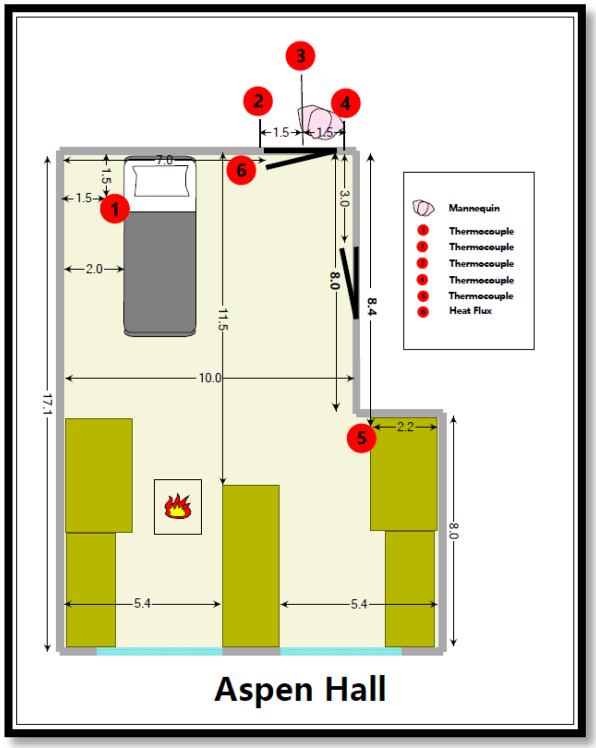

Figure 10-Temperature Measurement Locations

The thermocouples were placed at the floor, 2’, 4’, 6’, and ceiling level (8’ level). There were two thermocouple trees located inside the room where the water flowing from the hose-lines would not affect them.

Three thermocouple trees were located in the hallway just outside of the doorway. One thermocouple tree was located in the center of the doorway and the other two were located 18” to the right and left of center.

A mannequin was equipped with a turnout coat, mask (no air), thermal protective hood and a firefighting helmet. Researchers placed additional thermocouples under the helmet and under the thermal hood. The mannequin was positioned to the left side of the doorway.

Figure 11-Mannequin placement in doorway

<u>Initial Fuel Load</u>

Researchers used wooden drawers from the built-in dormatory dressers as fuel load. They were centered between the built-in dresser and the built in closet door. The drawers were alternated and stacked on top of each other. Researchers placed two stacks of Styrofoam plates (20) in the dresser drawer openings, as well as the first four dresser drawers (counting from the bottom). The fifth dresser drawer in the stack was turned upside down. Researchers pulled out the top dresser drawers to make contact with the stacked drawers. A standard ignition package was used to initate the fire and placed in the bottom drawer closest to the built-in dresser. (figure 12/13)

Figure 12-Fuel Load

Figure 13-Fuel load

Standard Ignition Package

Researchers utilized cotton rounds (20) and placed them into a one-quart plastic bag. The bag was filled with 10 oz. of gasoline (figure 15) and allowed to absorb into the cotton rounds. This standard ignition package was utilized to create a consistent way to initiate the ignition. The standard ignition package was placed into the bottom level of the dresser drawers, next to a stack of foam plates (20).

Figure 14-SIP Quart Bag 10 oz Gasoline 20 Cotton Rounds

Figure 15-SIP Cotton Rounds

Researchers placed single stacks of Styrofoam plates (20) in the five dresser drawers, as well as the five shelves of the dresser. There were five levels of dresser drawers placed between the build-in cabinet and the accordion closet doors. The standard ignition package was placed in the bottom dresser drawer (figure 17).

Fuel package configuration

Figure 16-SIP Placed in Bottom Drawer to Initiate the Fires

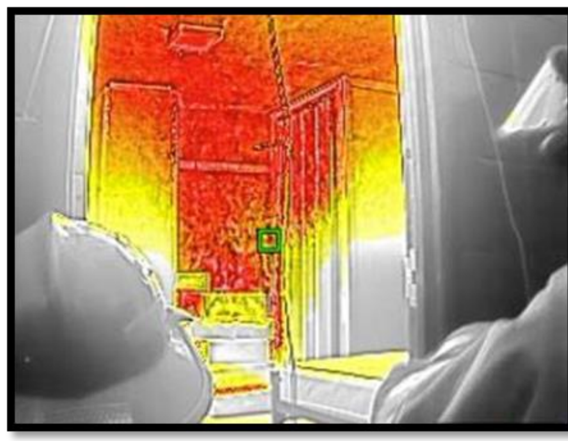

Figure 17-Thermal Image- Fire Plume

Process of ignition for Tests T1-T9

The standard ignition package was placed in the bottom drawer and ignited. Researchers recorded video of the fire's progression.

Figure 18-Fire Plume Reaching the Ceiling

When the temperature of the thermocouple, located in the right corner of the room at the 6' level, reached 800°F, the firefighter flowed water for a set time interval.

<u>The application of water T1-T9</u>

Researchers calibrated the flow rates for each system. The smooth bore and fog nozzles were calibrated to flow 150 gallons per minute (2.5 gallons per second). The Ultra High Pressure system was calibrated to flow 30 gallons per minute (.5 gallon per second) at 1500 psi.

The water was applied from the doorway of the test room. The firefighter was instructed to initially apply water to the ceiling level for approximately one second then apply water in a "Z pattern" for the remainder of the test. The test concluded once the water was remotely shut off.

Figure 19-Firefighter Applying Water from the Doorway. Mannequin to the left

Test Locations by Floor

Researchers considered ventilation, the potential water accumulation, conductive heat transfer and other effects when considering the order in which the test would be conducted. Tests were conducted in the following sequence: T7, T8, T9, (third floor) T1, T2, T3, (first floor) T4, T5 and T6 (second floor).

Third Floor	T7 UHP	T8 UHP	T9 UHP
Second Floor	T4 Fog	T5 Fog	T6 Fog
First Floor	T1 Solid Bore	T2 Solid Bore	T3 Solid Bore

Figure 20-Test Locations by Floor

Test	Nozzle	Flow Time (seconds)	Total flow (gallons)
T2	15/16" solid bore 150 gpm/170 psi	5.10	12.8
T4	Automatic fog 150 gpm/170 psi	6.22	15.5
T7	Ultra High Pressure 30gpm/1500 psi	5.45	2.7
T1	15/16" solid bore 150 gpm/170 psi	8.6	21.5
T6	Automatic fog 150 gpm/170 psi	10.27	25.7
T8	Ultra High Pressure 30gpm/1500 psi	8.32	4.2
T3	15/16" solid bore 150 gpm/170 psi	20.28	50.7
T5	Automatic fog 150 gpm/170 psi	16.4	41
T9	Ultra High Pressure 30gpm/1500 psi	19.6	9.8

Figure 21-Tests 1-9 Flow Times with Total Gallons Flowed

Videos

5 Second Flow Test - Tests: T2 T4 T7

10 Second Flow Test - Tests: T1 T6 T8

20 Second Flow Test - Tests: T3 T5 T9

Researchers examined the results of the tests and determined all nine tests were consistent with the temperature reductions in the test rooms. Temperatures dropped throughout the room and the relative fire suppression times were the same. The notable difference was the amount of water used to reduce the temperatures. All three methods of technology generally lowered temperatures in a consistent manor.

Tests T10-T13

After conducting the research burns in Downers Grove, Illinois in June 2015, researchers systematically increased the intensity of the tests. An additional ten tests were conducted. The tests included adjacent room fires in a metal two room burn trailer, burns in two acquired structures, as well as hoseline deployment tests.

Figure 22-Two-Room Burn T12

Figure 23-Two-Room Burn T12

Video: Two Room Burn Trailer T12 and T13

Test T10 Two-room burn trailer (baseline burn-not enough fuel used)

- T11 Two-room burn trailer (baseline burn)
- T12 Two-room burn trailer (Ultra High Pressure)
- T13 Two-room burn trailer (15/16" Solid bore 150 gpm)

In August 2015, researchers conducted adjacent room burns in Middleton, Wisconsin utilizing a two-room metal burn trailer (T10-T13). The fuel packages consisted of upholstered sofas/chairs, brand new polyester polyurethane foam carpet padding and wooden pallets. Thermocouples were placed at the 2' and 6' level in the furthest room from which the fire attack was initiated.

Test T12 utilized a 200 foot 1 ¾" handline with a 15/16" solid bore nozzle flowing 150 gallons per minute (2.5 gallons per second). The room temperatures measured approximately 1300 °F at the ceiling level and 1250 °F 18" from the floor level, prior to the application of water. Water was applied for approximately 34 seconds. The room temperatures were reduced to 181 °F at the ceiling and 105 °F 18" from the floor level utilizing 85 gallons of water.

Test T13 utilized a 200 foot ¾" handline with the Ultra High Pressure system flowing 30 gallons per minute (.5 gallons per second) at 1500 psi. The room temperatures measured approximately 1600 °F at the ceiling level and 1430 °F 18" from the floor level, prior to the application of water. Water was applied for approximately 34 seconds. The room temperatures were reduced to 453 °F at the ceiling and 108 °F 18" foot from the floor level utilizing 17 gallons of water.

Tests T14-T16

Figure 24-T14/T15 Fuel Load A/D First Floor Room

Figure 25-T14 Side D

Figure 26-T14/T15 Side A Firefighter Entry Point

Video [Two Story Residential - Single Room Tests T14 T15]

- T14 Full room involvement of first floor room A/D corner, UHP side-by-side with T15
- T15 Full room involvement of first floor room A/D corner, automatic fog, side by side with T14
- T16 Four rooms and hallway on second floor of two story acquired structure, UHP used 85.5 gallons of water to bring the fire "under control"

In December 2015, after conducting the tests in Downers Grove, Illinois (Tests T1-T9) and research burns in Middleton, Wisconsin (Tests T10-T13), researchers again systematically increased the parameters of the tests. Researchers conducted three additional tests in an acquired structure. The structure was a two story wood frame residence with a stone foundation. The fuel package was placed on the first floor A/D corner room, which measured 14' x 16'. The fuel load consisted of upholstered sofas/chairs, brand new polyester polyurethane foam carpet padding and wood pallets. Thermocouples were placed on the first and second floors of the residence.

A side-by-side comparison was conducted using an automatic fog nozzle and the UHP system.

Test T14 utilized a 200' ¾" handline with the Ultra High Pressure system using 30 gallons per minute (.5 gallons per second) at 1500 psi. The room temperatures measured approximately 1500 °F at the ceiling and 1037 °F 18" from the floor on the C/D corner of the first division prior to the application of water. Water was applied for approximately 20 seconds. The room temperatures were reduced to 380 °F at the ceiling and 96 °F at the floor level, utilizing 9.9 gallons of water.

Test T15 utilized a 200' 1 ¾" handline with an automatic fog nozzle flowing 150 gallons per minute (2.5 gallons per second). The room temperatures measured approximately 1468 °F at the ceiling and 829 °F 18" from the floor on the C/D corner of the first division prior to the application of water. Water was applied for approximately 20 seconds. The room temperatures were reduced to 459 °F at the ceiling and 86 °F at the floor level, utilizing 49.9 gallons of water.

Video Two Story Residential - 2nd Division - Test: T16

Test T16 was conducted in an attempt to test the potential limits of the Ultra High Pressure system. The fuel load consisted of upholstered sofas/chairs, brand new polyester polyurethane foam carpet padding, mattresses, box springs and wood pallets. These items were placed in the bedrooms on the second floor. The four bedrooms were simultaneously ignited and heavily involved with fire prior to extinguishment. Thermocouples were placed in the second story bedroom in the A/D corner as well as the C/D corner bedroom, both thermocouples were located at the six foot level. The initial temperature in the A/D corner bedroom was 1900 °F, and the C/D corner bedroom was 700 °F. The fire was brought to a manageable level after 171 seconds of total flow time, utilizing 85.5 gallons of water. The volume of fire for this test was impressive, the utilization of the UHP system was remarkable and deserves additional testing for consideration for interior fire attack.

Firefighters initially applied water to the fire while advancing to the second division via the interior stairwell. Once the fire was knocked down in the hallway water was applied in a systematic room by room method to bring the fire "under control". Attack team members did not make entry into any rooms on the 2nd division. All fire attacks were made from the hallway.

April 2016, Middleton, Wisconsin

Figure 27-T17 Lateral Fire Attack

Test T17 was designed to simulate firefighters entering from an unaffected unit (A/B corner room), breaching the wall, and using the UHP to cut through the sheet rock. Thermocouples were placed into the room of fire origin (B/C corner). The room temperature was reduced from 1100 °F at the 6' level to 142 °F after flowing water from the UHP system from the adjacent room for 28 seconds (14 gallons of water).

Figure 28-T18 Attic Fire Attack

The intent of Test T18 was to create a well involved attic fire. The plan was to have the UHP system breach the ceiling below the fire and extinguish the fire. The ceiling was constructed of a wire mesh covered with plaster. The UHP system was not able to penetrate this material unassisted. Additional tests should be conducted where the ceiling is constructed of gypsum board.

Figure 29-T19 Vehicle Fire in Garage

Figure 30-T19 Vehicle Fire in Garage UHP Extinguishment

Test T19 was designed to have a well involved vehicle fire in an attached garage. The UHP system used for this fire was a 20 gallon per minute system flowing at 1200 psi. There were three thermocouples placed in the garage. The highest recorded temperature was 820 °F (at the 5' level, located above the hood of the vehicle). The temperature was reduced to 220 °F after flowing for 180 seconds, utilizing 60 gallons of water.

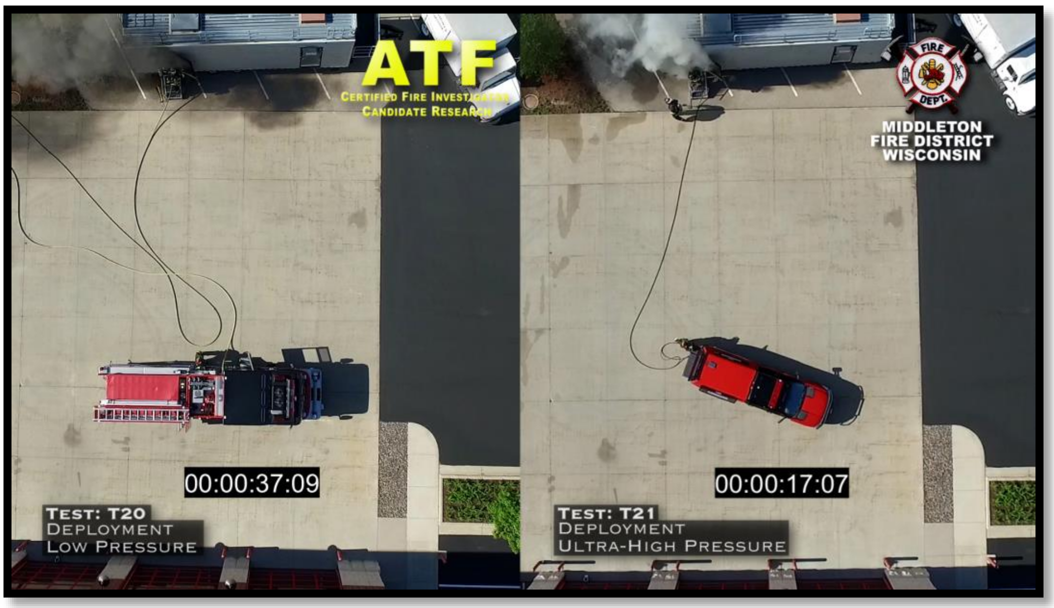

Figure 31-T 20-T21 Traditional Method vs UHP Deployment

Video Speed of Attack: Deployment

Tests T20 and T21 were designed to test the deployment time of a traditional 200', 1 ¾" handline and a UHP system. The test time began when the unit arrived and ended when the firefighter flowed water. The traditional line was laid in a triple layer load and took 37 seconds to deploy. The UHP system is stored on a reel and took 17 seconds to deploy. It should be noted that this simulation is only comparable if the units were to arrive at the same time. The

Middleton Fire District (Wisconsin) has done testing involving acceleration, road conditions, turning radius, braking and other conditions, which concluded the rapid response vehicle deploys considerably faster than a conventional fire attack engine.

Results

The time/temperature curves for Tests T1-T9, were compared to the amount of water flowed during each test. It was determined there was no discernable difference between the tests in regards to the reduction of room temperature.

Test	Nozzle	Flow Time (seconds)	Total flow (gallons)	Temp (begin) (°F)	Temp (end) (°F)	Total Reduction
T2	15/16" solid bore 150 gpm/170 psi	5.10	12.8	858	424	434
T4	Automatic fog 150 gpm/170 psi	6.22	15.5	717	358*	359
T7	Ultra High Pressure 30gpm/1500 psi	5.45	2.7	806	451	355
T1	15/16" solid bore 150 gpm/170 psi	8.6	21.5	830	342	488
T6	Automatic fog 150 gpm/170 psi	10.27	25.7	934	297	637
T8	Ultra High Pressure 30gpm/1500 psi	8.32	4.2	880	319	561
T3	15/16" solid bore 150 gpm/170 psi	20.28	50.7	905	155	750
T5	Automatic fog 150 gpm/170 psi	16.4	41	842	195	647
T9	Ultra High Pressure 30gpm/1500 psi	19.6	9.8	931	184	747

Figure 32-Tests 1-9 Beginning/Ending Temperatures with Total Water Flow/Time. Thermocouple Six Foot Level Right Corner of Test Rooms

* T4-visible fire after test ended

Researchers determined that the UHP system was as effective as the solid bore and fog nozzle at reducing the room temperatures despite only using a fraction (1/5) of the amount of water.

A heat flux gauge was placed 32” from the floor level in the wall to the right of the firefighter’s position. The heat flux gauge was in direct line of site of the fuel package and measured the radiant energy experienced by the firefighters. Researchers measured the firefighter exposure values before, during and after fire attack, using solid bore, fog and ultra high pressure nozzles.

Test	Nozzle	Flow Time (seconds)	Total flow (gallons)	Heat Flux (begin) (kW/m2)	Heat Flux (end) (kW/m2)	Total Reduction
T2	15/16” solid bore 150 gpm/170 psi	5.10	12.8	4	1	3
T4*	Automatic fog 150 gpm/170 psi	6.22	15.5	3	.5	2.5
T7**	Ultra High Pressure 30gpm/1500 psi	5.45	2.7	7	1	6
T1	15/16” solid bore 150 gpm/170 psi	8.6	21.5	5	.5	4.5
T6	Automatic fog 150 gpm/170 psi	10.27	25.7	4	.5	3.5
T8	Ultra High Pressure 30gpm/1500 psi	8.32	4.2	8	1	7
T3	15/16” solid bore 150 gpm/170 psi	20.28	50.7	6	1	5
T5	Automatic fog 150 gpm/170 psi	16.4	41	5	.5	4.5
T9	Ultra High Pressure 30gpm/1500 psi	19.6	9.8	10	1	9

Figure 33-Heat Flux Measurements

** T4-The heat flux eventually increased after water flow as there was still visible fire*

***T7-There was an initial increase after water was applied, then the temperature was reduced.*

A mannequin, equipped with a firefighting hood and fire helmet, was placed to the left of the firefighting position outside the test room doorway. The mannequin was equipped with thermocouples (under the hood/helmet area) to measure exposure temperatures.

The data obtained from the thermocouples on the mannequin indicated slight temperature increases for all nine tests. The increases ranged from .5 °F to 7 °F, eight of the nine tests fluctuated by 1°F.

Test	Nozzle	Flow Time (seconds)	Total flow (gallons)	Temp (begin) (°F)	Temp (end) (°F)	Total Increase
T2	15/16" solid bore 150 gpm/170 psi	5.10	12.8	69.4	70.2	.8
T4	Automatic fog 150 gpm/170 psi	6.22	15.5	71.6	72.1	.5
T7	Ultra High Pressure 30gpm/1500 psi	5.45	2.7	79	86	7
T1	15/16" solid bore 150 gpm/170 psi	8.6	21.5	68.8	70.2	1.4
T6	Automatic fog 150 gpm/170 psi	10.27	25.7	73.5	75	1.5
T8	Ultra High Pressure 30gpm/1500 psi	8.32	4.2	78.6	80	1.4
T3	15/16" solid bore 150 gpm/170 psi	20.28	50.7	69	70	1
T5	Automatic fog 150 gpm/170 psi	16.4	41	73.4	74	.6

T9	Ultra High Pressure 30gpm/1500 psi	19.6	9.8	78	79.5	1.5

Figure 34-Temperature Measurements from Mannequin Placed in Doorway

When analyzing the water application methods (smooth bore, fog and UHP), the notable difference is the pressure and the rate at which the water was applied. The UHP causes the water droplets to sheer, which increases the surface area of the water. As water droplets entered the fire environment, it caused the droplets to change phases from a liquid to a gas. This phase change process inherently absorbs a tremendous amount of heat energy. Smaller water droplets are able to absorb heat energy more efficiently than the water droplets produced by traditional applications. The faster the water droplets convert from a liquid to a gas the more energy is absorbed. When water travels through a compartment and stays in a liquid phase, it doesn't absorb its full potential. The most efficient use of water is to go through a phase change from a liquid to a gas. This is accomplished with UHP as it produces a smaller water droplet, enabling it to absorb heat energy faster.

Discussion

There are different methods of applying water into a fire environment, each application deliveries water droplets at different rates and sizes.

Water absorbs the most energy, and is most effective, when it undergoes a phase change from a liquid to a gas. The surface area of the water droplet affects the efficiency and speed at which energy can be absorbed. Dividing a given volume of water into smaller droplets increases the surface area, allowing heat energy to be absorbed at a faster rate. Steam conversion in a compartment will expand the gas volume. These gases are made up of water vapor, heated smoke, fuel gases, aerosols, and particulates. Some of the steam conversion expansion is offset by contraction of the gases through cooling and continues to absorb heat.

During the course of this research project the UHP system flowing 30 gallons per minute consistently reduced the compartment temperatures using approximately 1/5 the amount of water than the two traditional methods flowing 150 gallons per minute. The researchers are not suggesting that UHP be considered as a replacement for the traditional low pressure methods, it appears to warrant additional testing for interior structural fire attack.

Researchers believe the use of less water at a fire scene can be particularly beneficial to conducting origin and cause investigations. The use of less water creates less damage to the fire scene, preserves fire patterns and is less likely to disturb items during fire suppression.

In addition, the sooner water can be applied to a fire the faster the fire can be extinguished and less damage will occur. The speed of attack capabilities of rapid response vehicles equipped with UHP allow fire departments , such as the Middleton Fire District (Wisconsin) to achieve these desirable on scene and deployment times.

Acknowledgements

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Bureau of Alcohol, Tobacco, Firearms and Explosives Special Agent Certified Fire Investigator Ricky Hankins and Lenwood Reeves

Wisconsin Department of Justice- Office of the State Fire Marshal Special Agent Certified Fire Investigator William Boswell

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Waukesha County Technical College (Wisconsin) –Thomas Schlei, Ph.D

Lyon Illinois Fire Department

Midwestern University, Downers Grove, Illinois

Ohio Attorney General's Office, Special Agent George Staley

References

(1) Alpert, Ronald, Fire Protection Handbook, National Fire Protection Association, Quincy, MA 2008, section 2-1

(2) Layman, Lloyd, *Attacking and Extinguishing Interior Fires*, National Fire Protection Association, Boston, MA, 1955

Video links

5 Second Flow Test - Tests: T2 T4 T7

10 Second Flow Test - Tests: T1 T6 T8

20 Second Flow Test - Tests: T3 T5 T9

Two Room Burn Trailer - Tests: T12 T13

Context of the study

This research focused on fires involving compartments and their contents. Additional research should be conducted to test the limits of the Ultra High Pressure Fire Suppression System in regards to how large of a fire the system is capable of effectively extinguishing. Reach and penetration are immediate considerations when using the UHP system. The fires in the initial testing phase of this research project (Tests T1-T9) were limited to a single compartment.

The researcher has a prior fire department background and was intrigued with how the UHP system was being utilized by the Middleton Fire District (Wisconsin), and discovering its potential effects on fire scene investigations. The researcher involved in this study did not communicate with the manufacturers of the UHP utilized during the course of this research. It is not the intent of the researcher to endorse or promote any manufacturer.

Figure 35-T1 Solid Bore 8.6 second flow 21.5 gallons

Figure 36-T2 Solid Bore 5.10 second flow 12.8 gallons

Figure 37-T3 Solid Bore 20.28 second flow 50.7 gallons

Figure 38-T4 Fog Nozzle 6.22 second flow 15.5 gallons

Figure 39-T5 Fog Nozzle 16.4 second flow 41 gallons

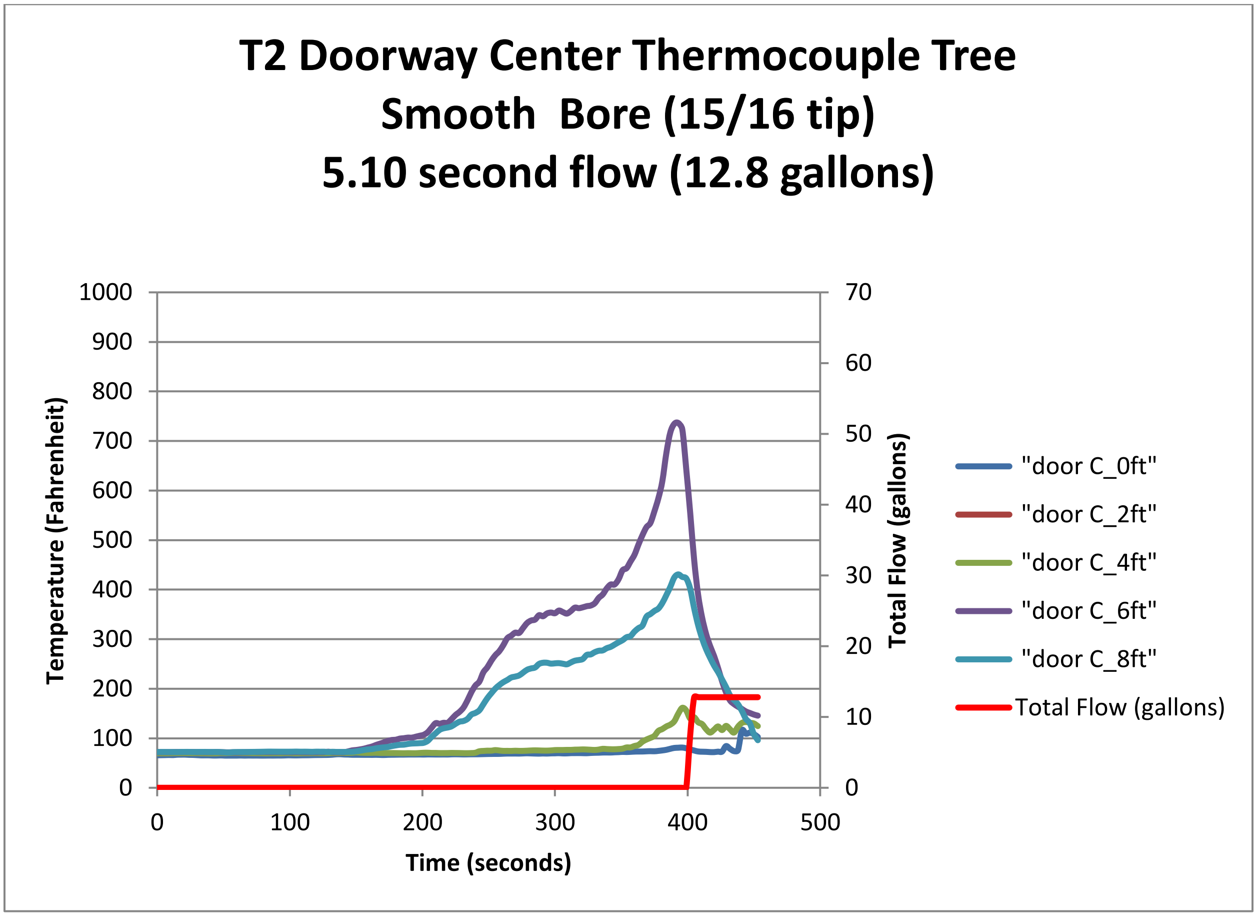
Figure 40-T6 Fog Nozzle 10.27 second flow 25.7 gallons

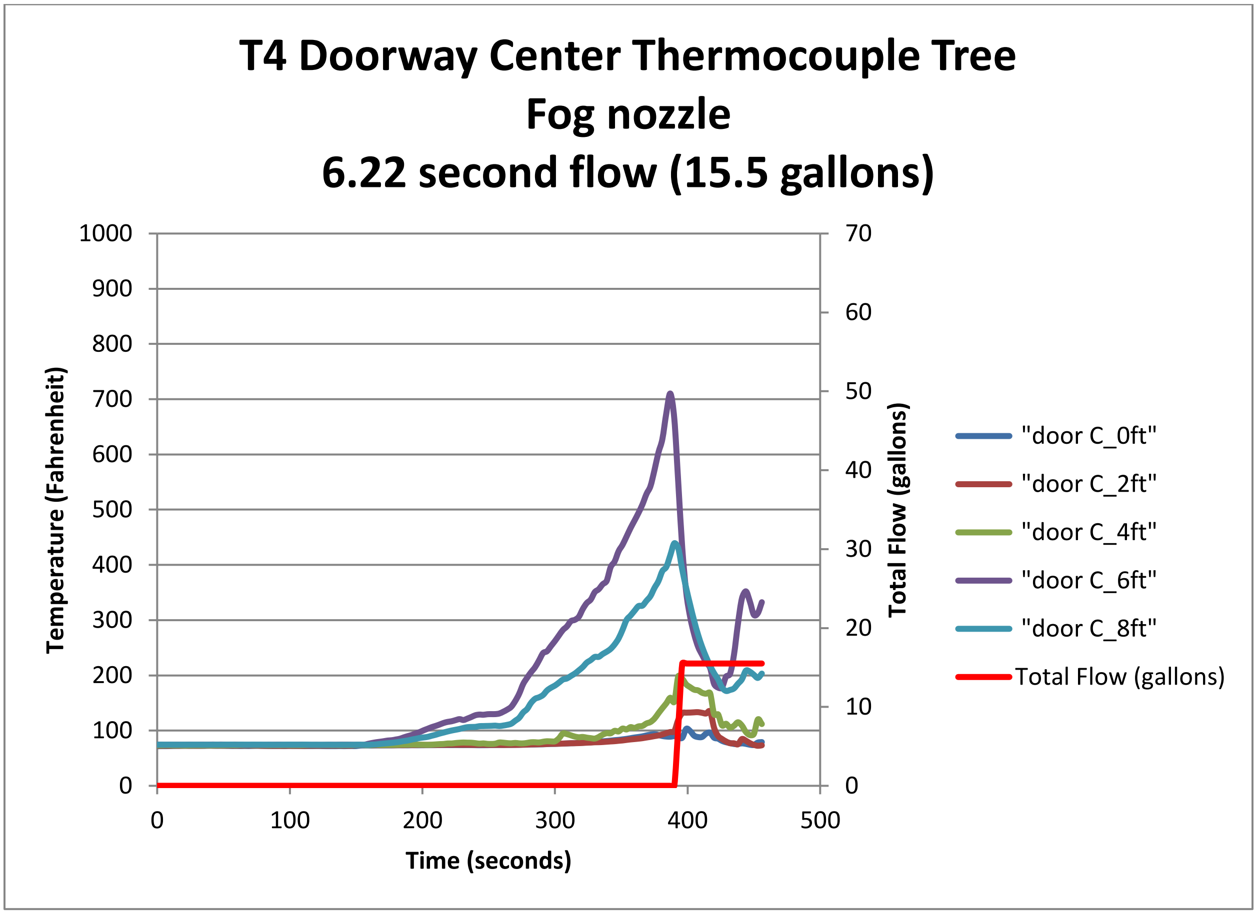
Figure 41-T7 UHP 5.45 second flow 2.7 gallons

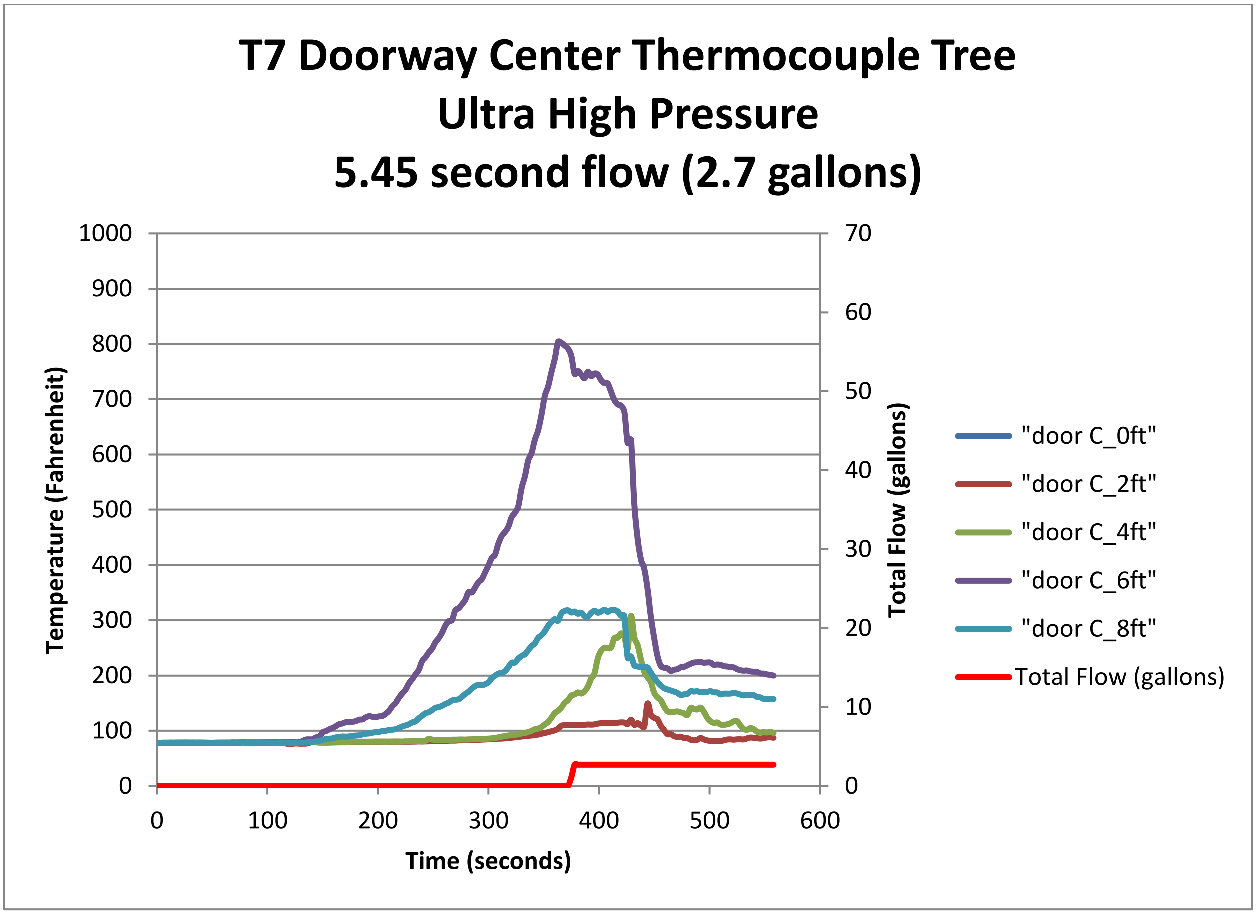
Figure 42-T8 UHP 8.32 second flow 4.2 gallons

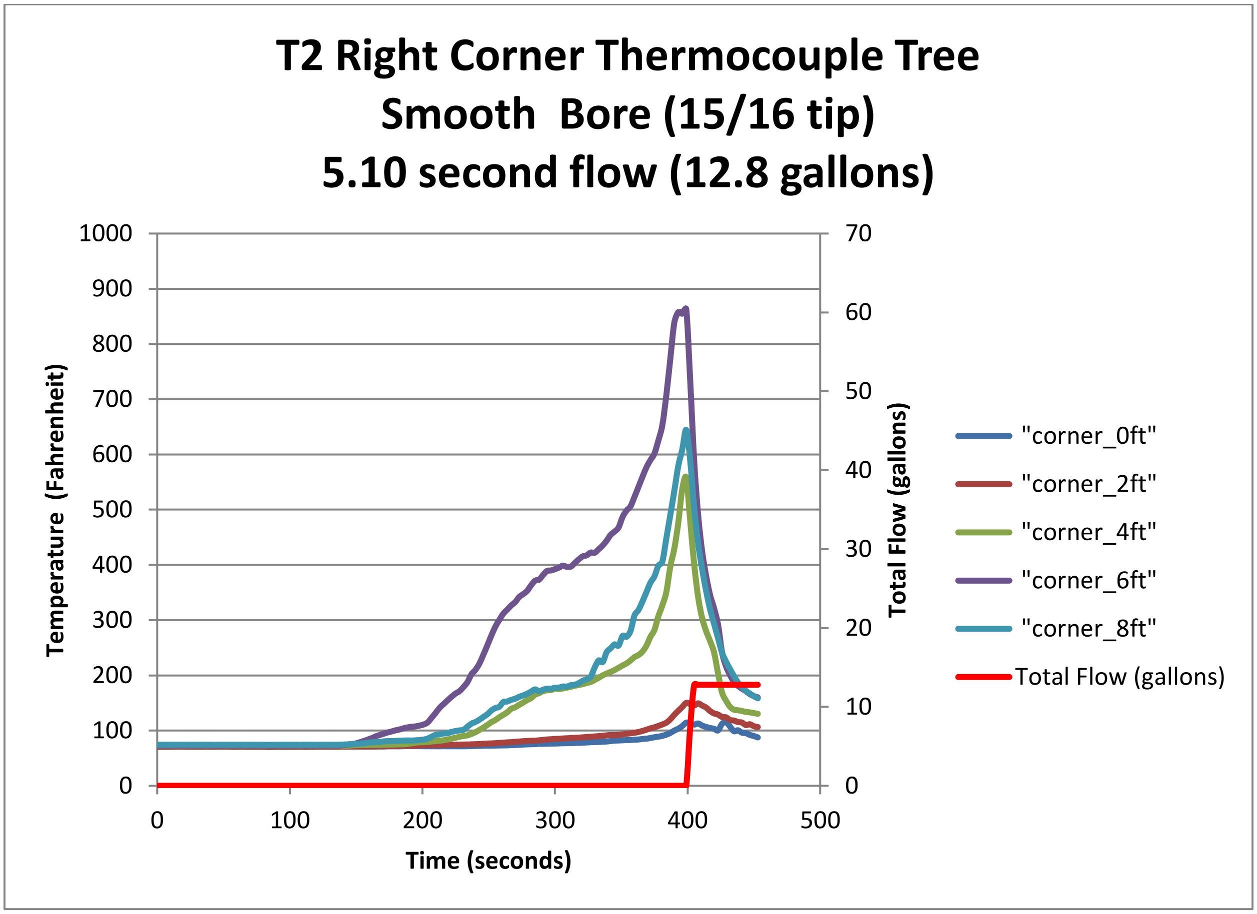
Figure 43-T9 UHP 19.6 second flow 9.8 gallons

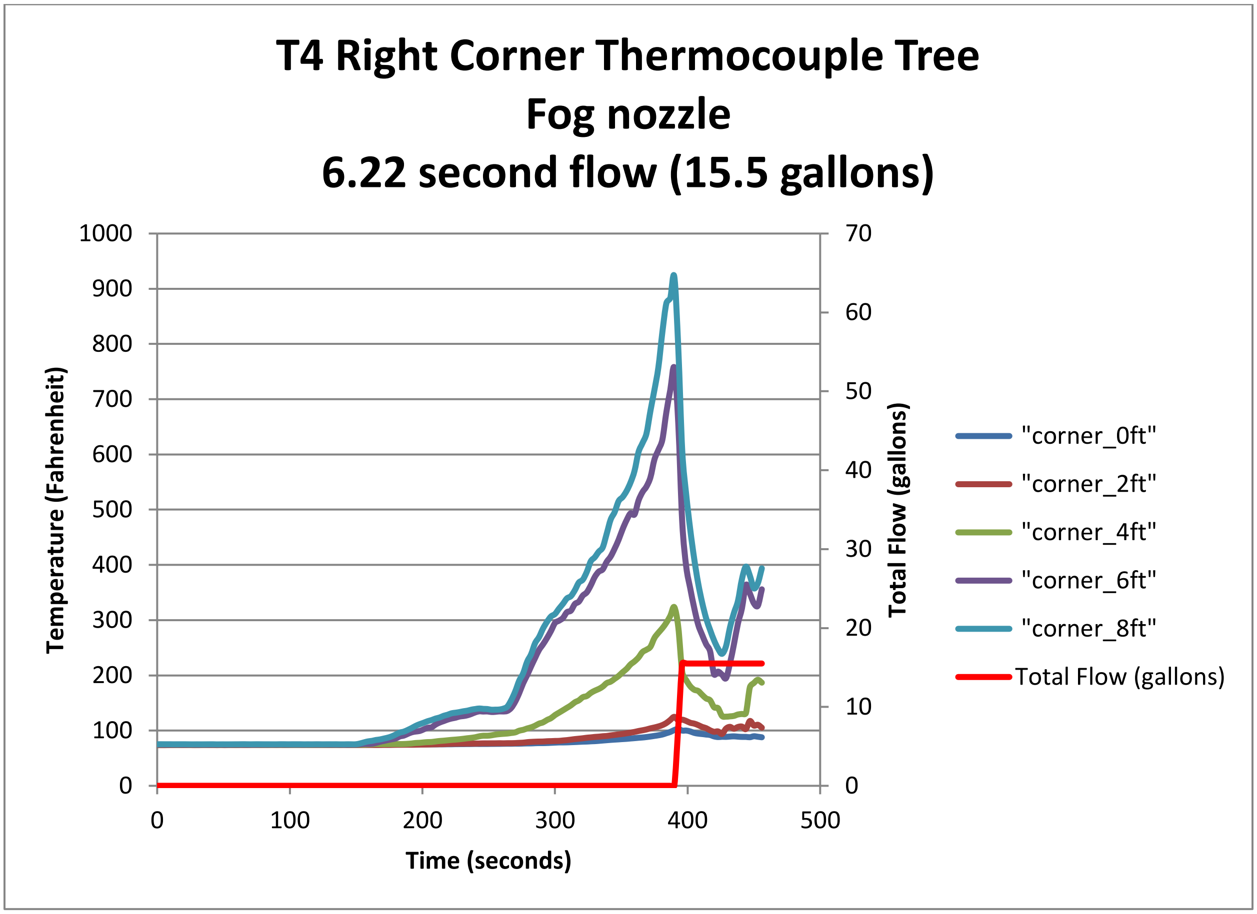
Comparing Test T2, T4 and T7

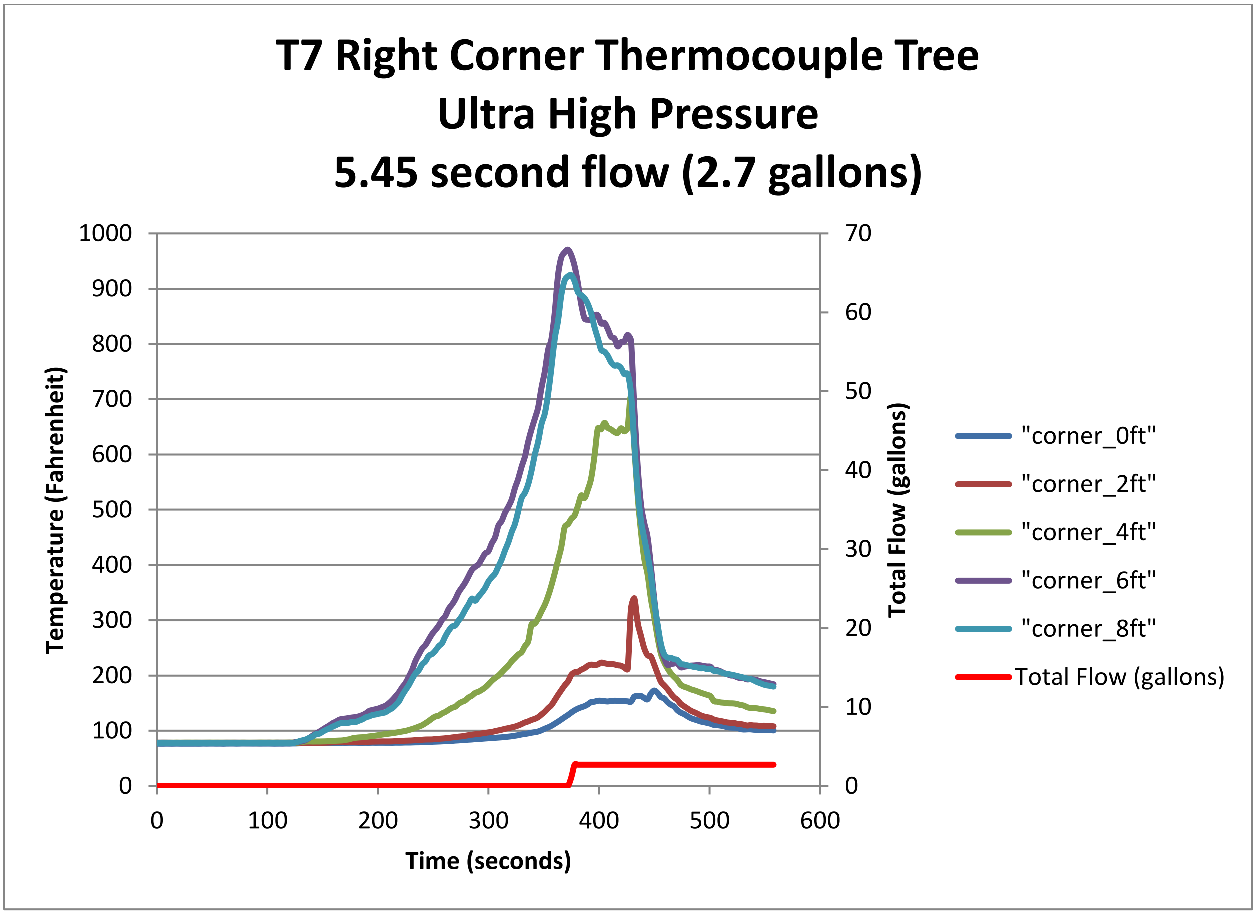


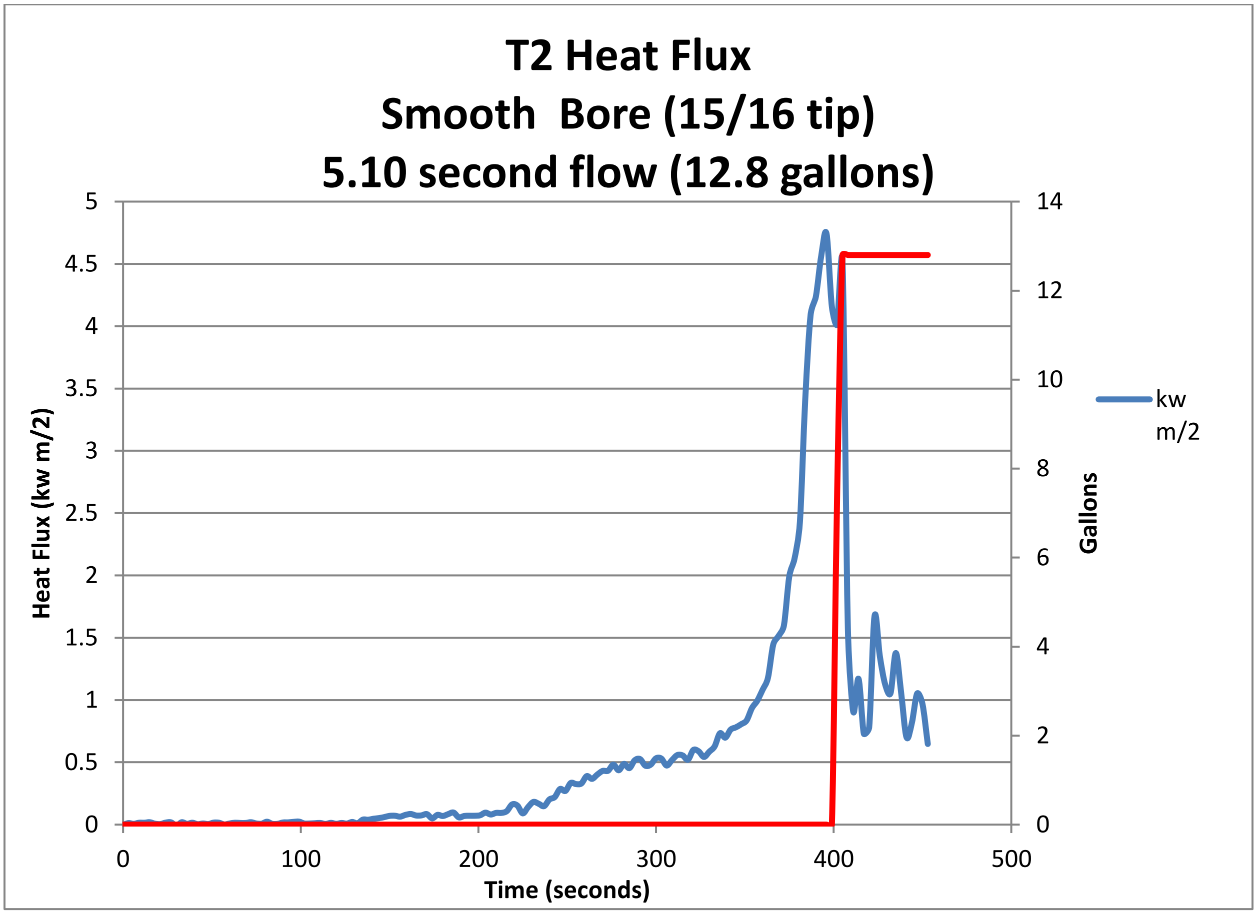

T4 Doorway Center Thermocouple Tree
Fog nozzle
6.22 second flow (15.5 gallons)
Temperature (Fahrenheit)
Total Flow (gallons)
Time (seconds)
0
100
200
300
400
500
600
700
800
900
1000
10
20
30
40
50
60
70
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Flow (gallons)

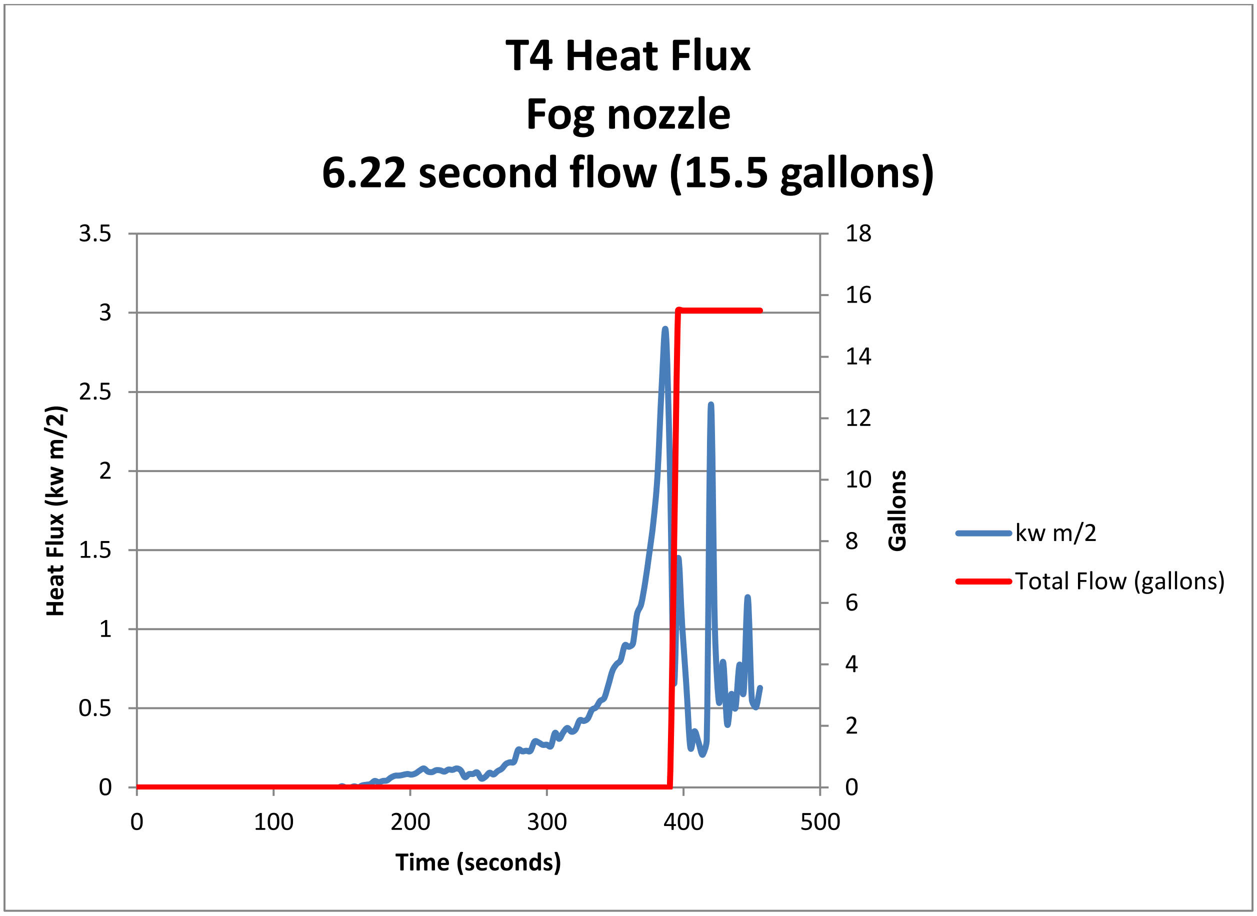

T7 Doorway Center Thermocouple Tree
Ultra High Pressure
5.45 second flow (2.7 gallons)
Temperature (Fahrenheit)
0
100
200
300
400
500
600
700
800
900
1000
Total Flow (gallons)
0
10
20
30
40
50
60
70
Time (seconds)
0
100
200
300
400
500
600
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Flow (gallons)

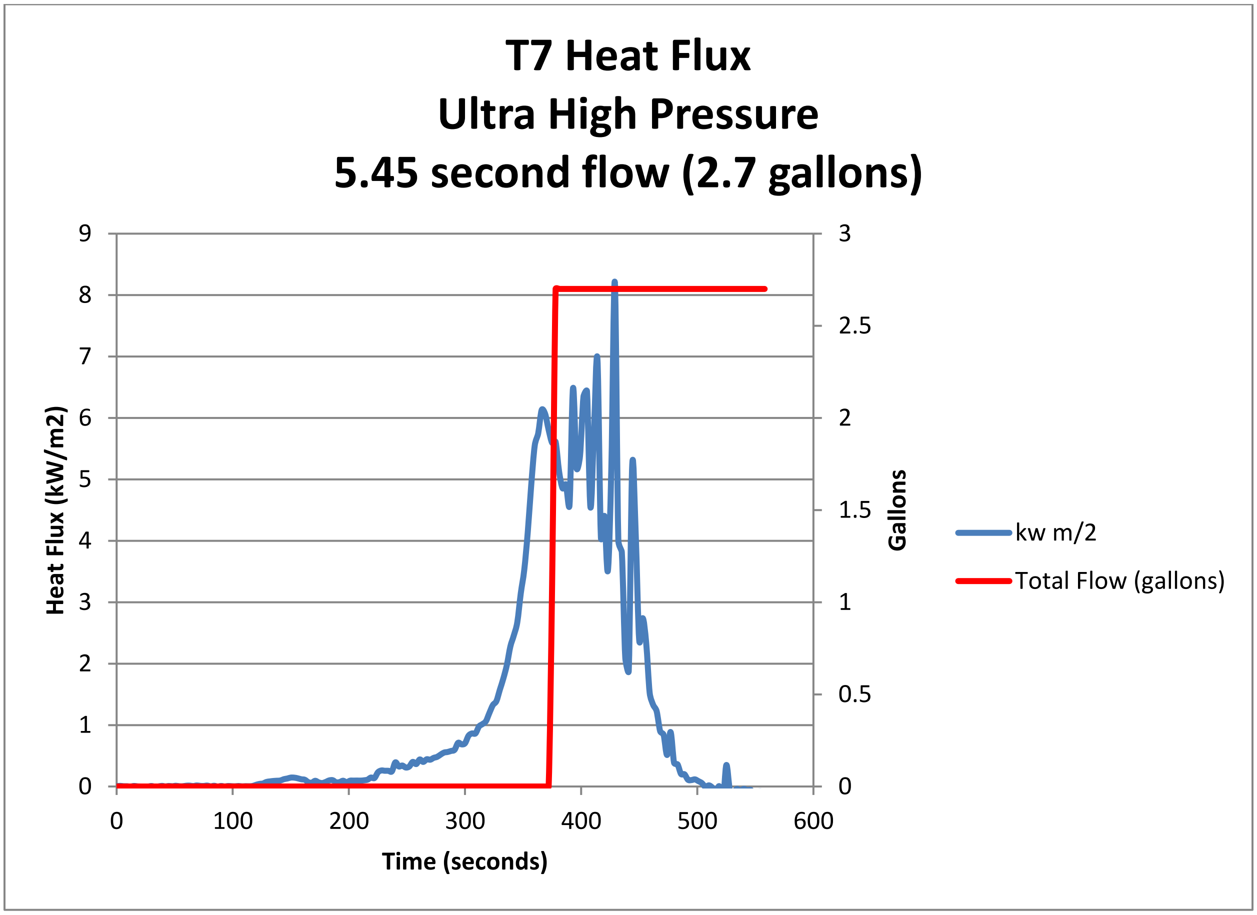

T2 Right Corner Thermocouple Tree
Smooth Bore (15/16 tip)
5.10 second flow (12.8 gallons)
Temperature (Fahrenheit)
0
100
200
300
400
500
600
700
800
900
1000
Total Flow (gallons)
0
10
20
30
40
50
60
70
Time (seconds)
0
100
200
300
400
500
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

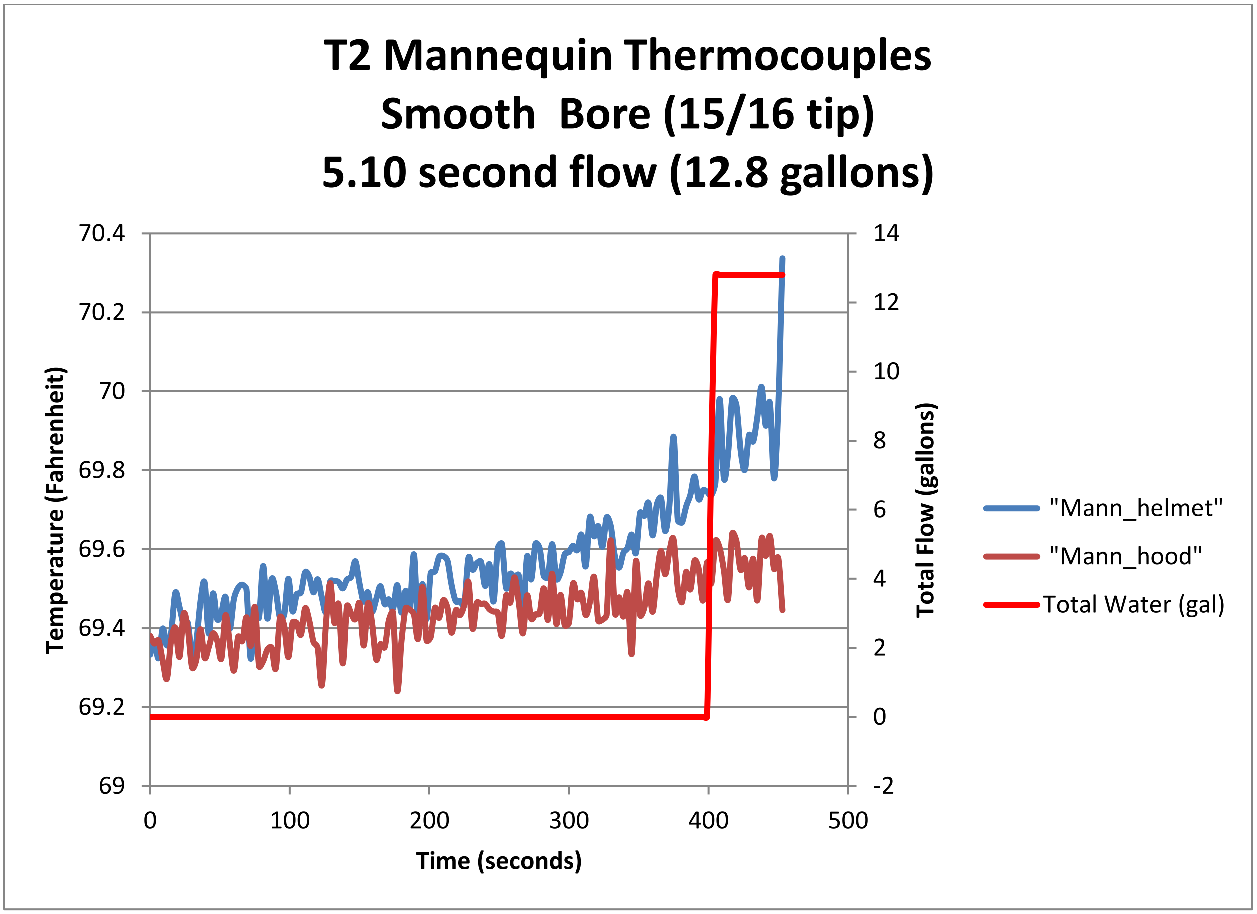

T4 Right Corner Thermocouple Tree
Fog nozzle
6.22 second flow (15.5 gallons)
Temperature (Fahrenheit)
1000
900
800
700
600
500
400
300
200
100
0
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
100
200
300
400
500
Time (seconds)
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

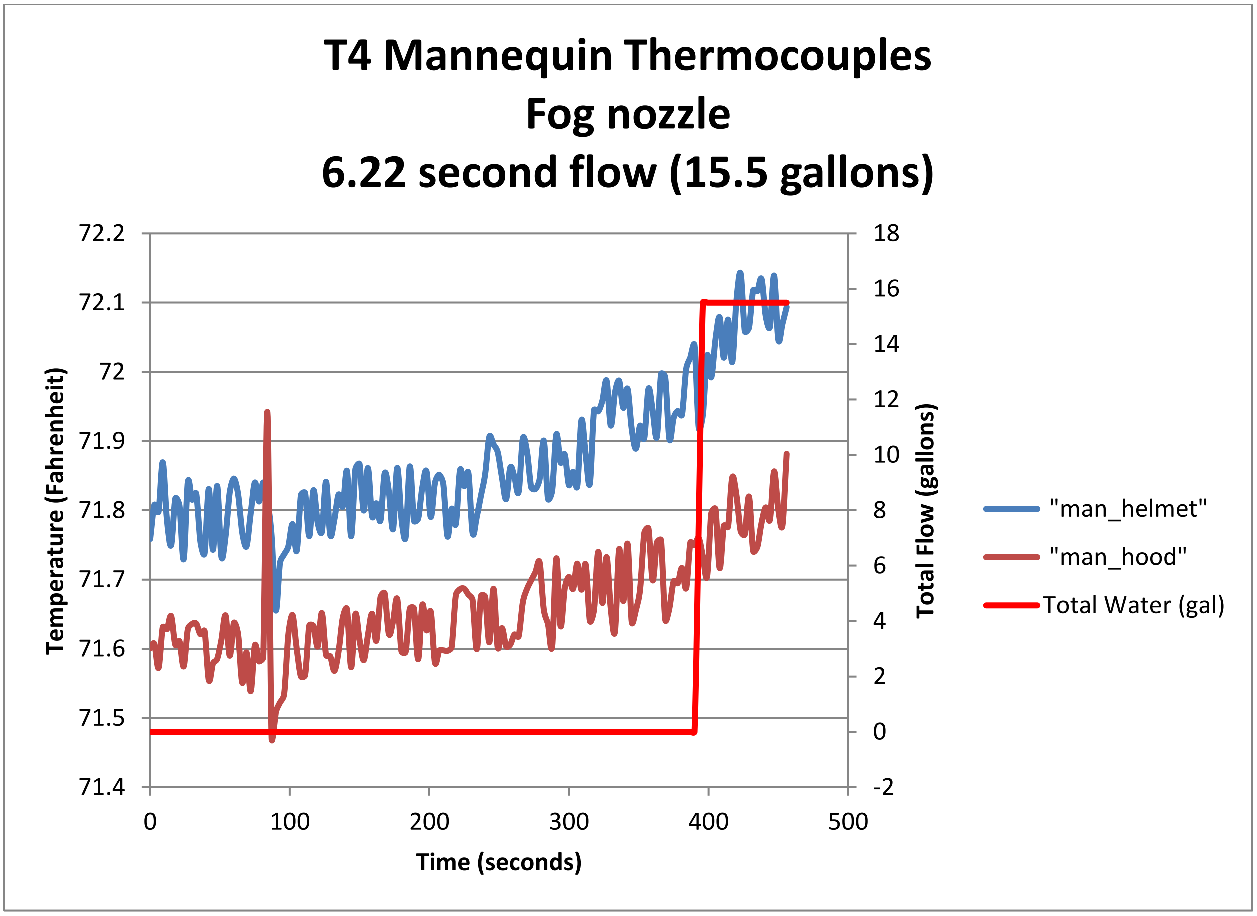

T7 Right Corner Thermocouple Tree
Ultra High Pressure
5.45 second flow (2.7 gallons)
Temperature (Fahrenheit)
Total Flow (gallons)
Time (seconds)
0
100
200
300
400
500
600
700
800
900
1000
10
20
30
40
50
60
70
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

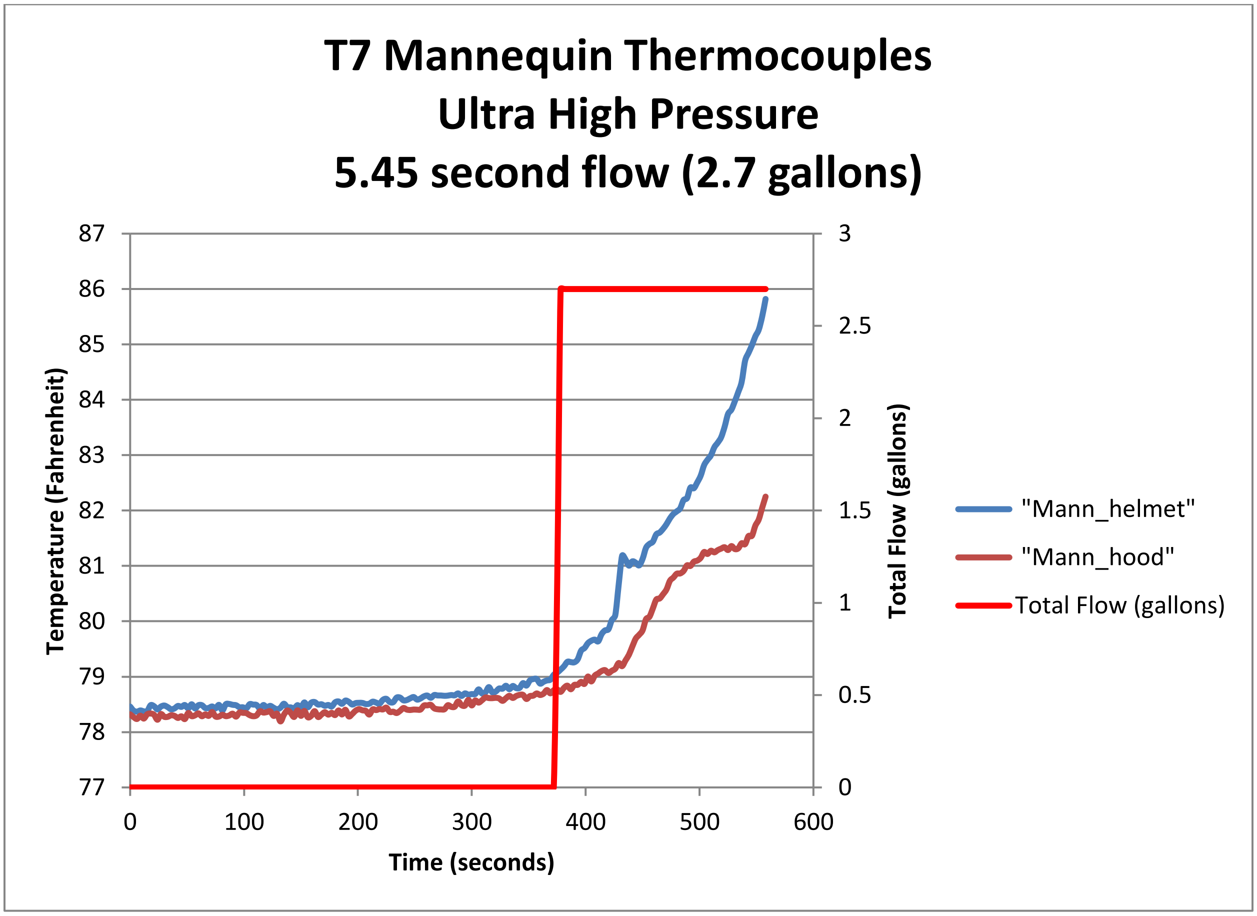

T2 Heat Flux
Smooth Bore (15/16 tip)
5.10 second flow (12.8 gallons)
Heat Flux (kw m/2)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Gallons
0
2
4
6
8
10
12
14
Time (seconds)
0
100
200
300
400
500
kw m/2


T4 Heat Flux
Fog nozzle
6.22 second flow (15.5 gallons)
Heat Flux (kw m/2)
3.5
3
2.5
2
1.5
1
0.5
0
18
16
14
12
10
8
6
4
2
0
Gallons
0
100
200
300
400
500
Time (seconds)
kw m/2
Total Flow (gallons)

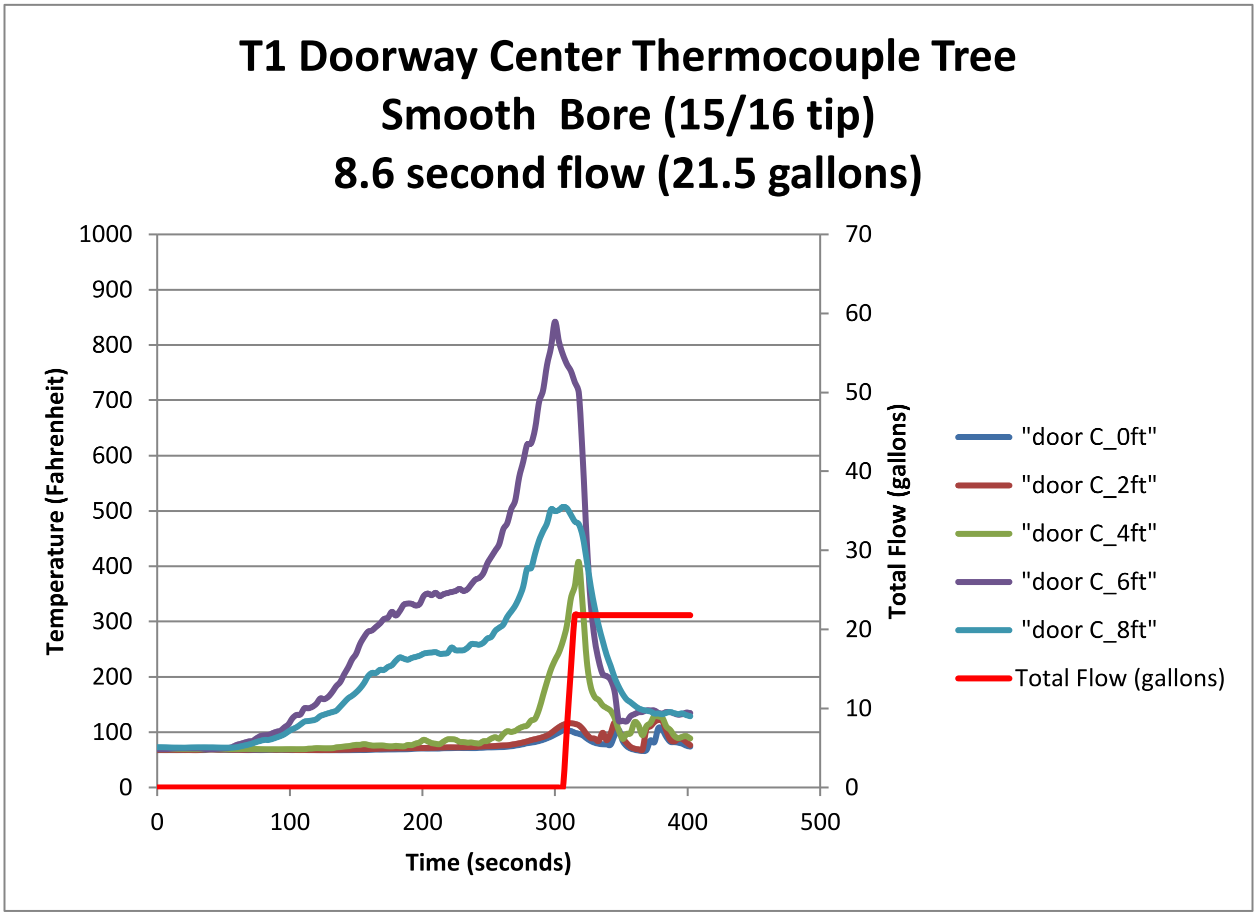

T7 Heat Flux
Ultra High Pressure
5.45 second flow (2.7 gallons)
Heat Flux (kW/m2)
Gallons
Time (seconds)
0
1
2
3
4
5
6
7
8
9
0.5
1.5
2.5
100
200
300
400
500
600
kw m/2
Total Flow (gallons)

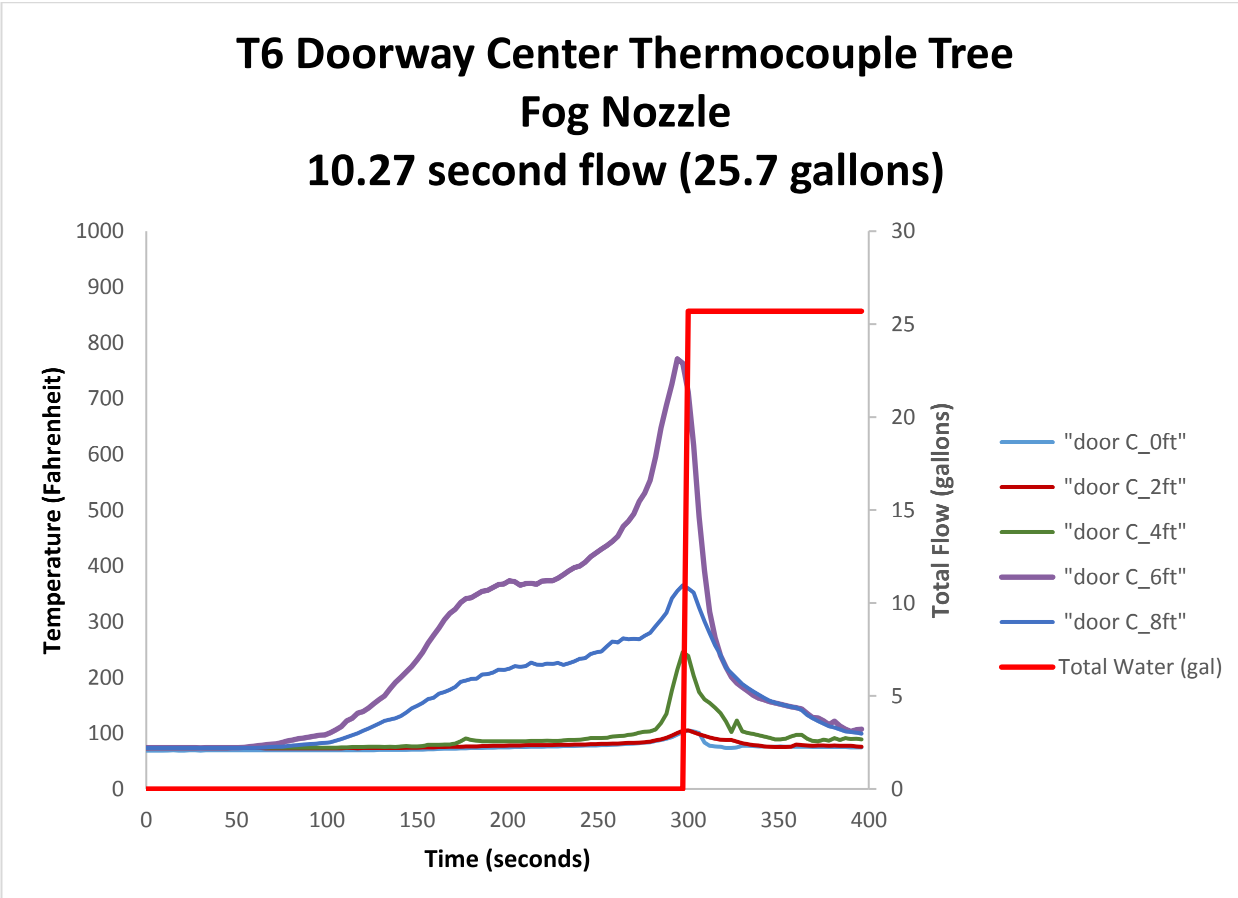

T2 Mannequin Thermocouples
Smooth Bore (15/16 tip)
5.10 second flow (12.8 gallons)
70.4
70.2
70
69.8
69.6
69.4
69.2
69
Temperature (Fahrenheit)
14
12
10
8
6
4
2
0
-2
Total Flow (gallons)
0
100
200
300
400
500
Time (seconds)
"Mann_helmet"
"Mann_hood"
Total Water (gal)

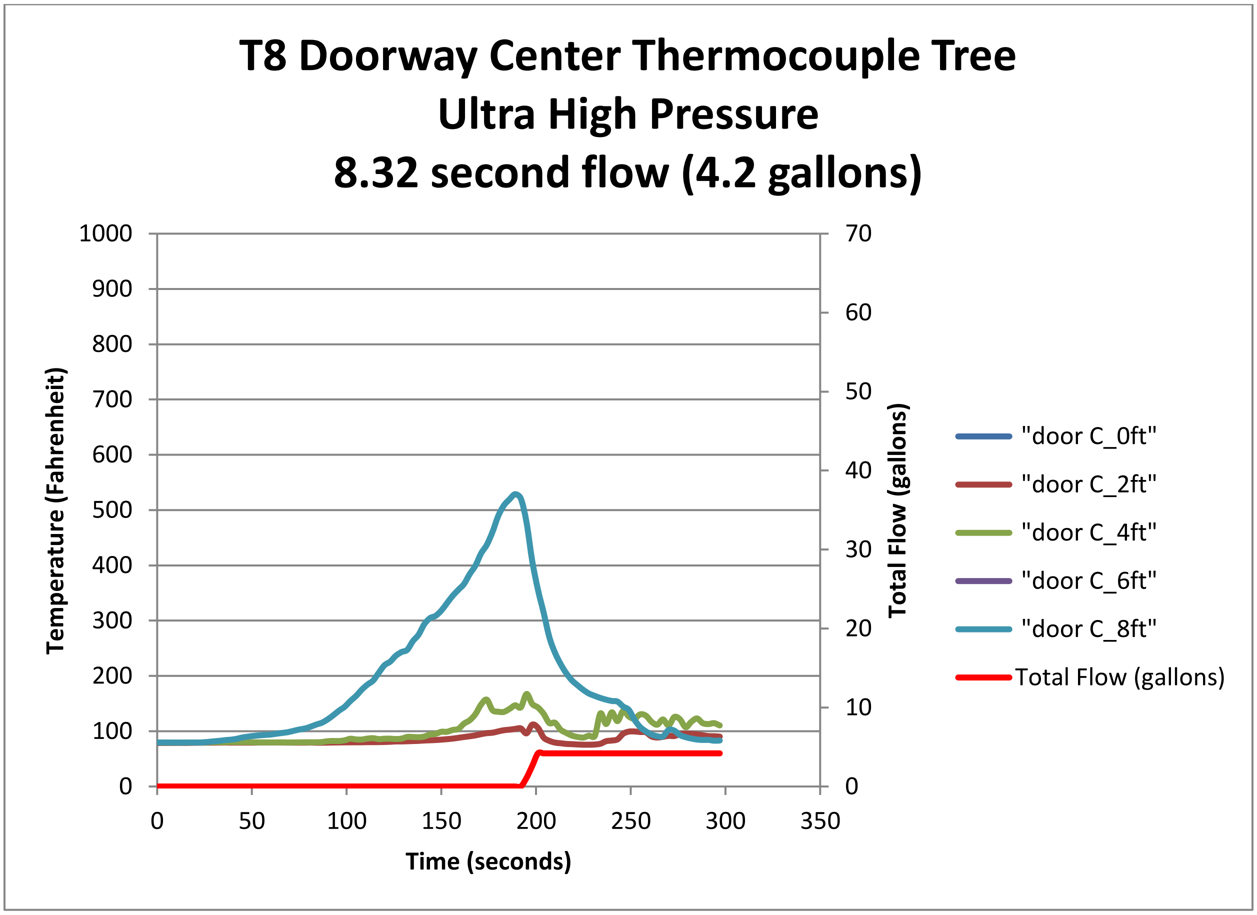

T4 Mannequin Thermocouples
Fog nozzle
6.22 second flow (15.5 gallons)
Temperature (Fahrenheit)
72.2
72.1
72
71.9
71.8
71.7
71.6
71.5
71.4
Total Flow (gallons)
18
16
14
12
10
8
6
4
2
0
-2
0
100
200
300
400
500
Time (seconds)
"man_helmet"
"man_hood"
Total Water (gal)

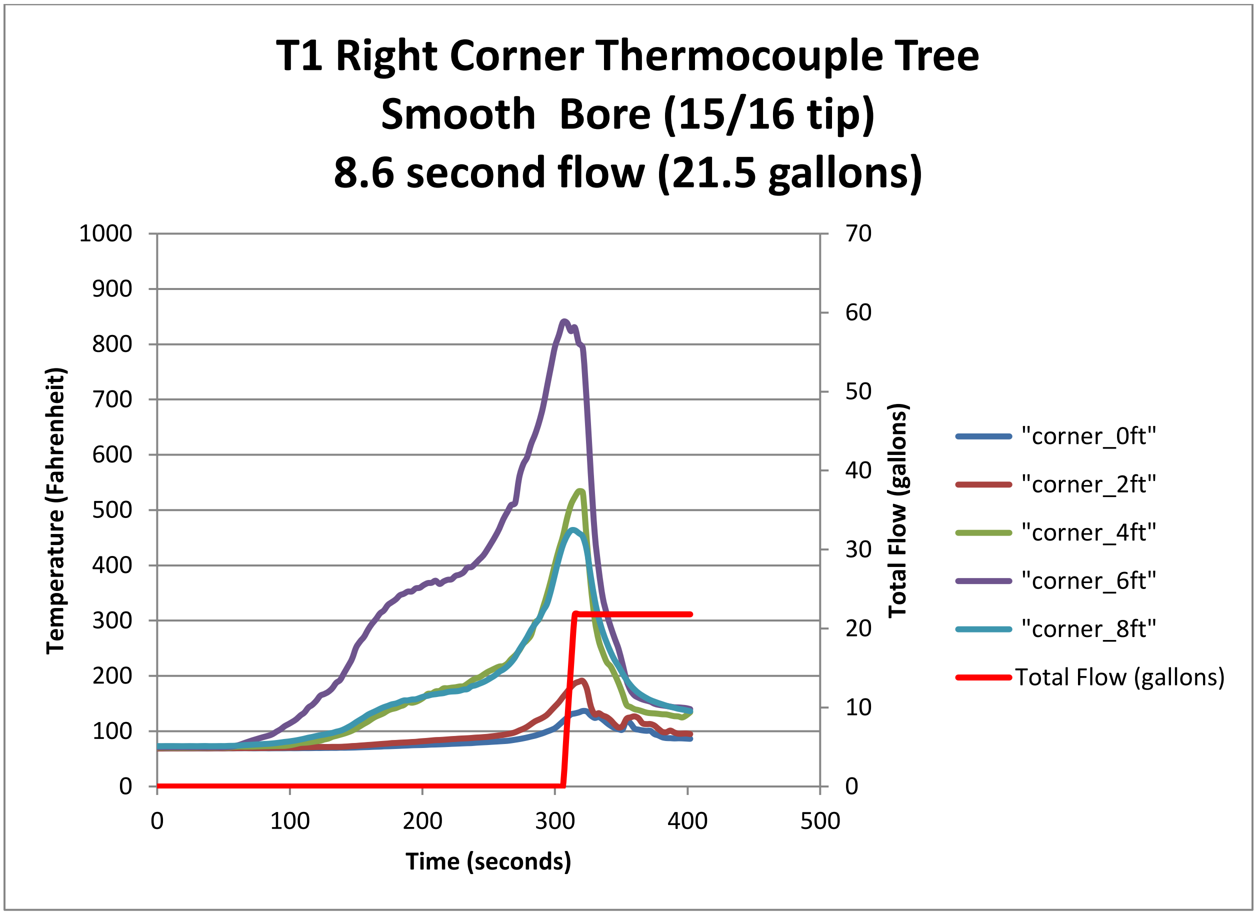

T7 Mannequin Thermocouples
Ultra High Pressure
5.45 second flow (2.7 gallons)
Temperature (Fahrenheit)
87
86
85
84
83
82
81
80
79
78
77
Total Flow (gallons)
3
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
600
Time (seconds)
"Mann_helmet"
"Mann_hood"
Total Flow (gallons)

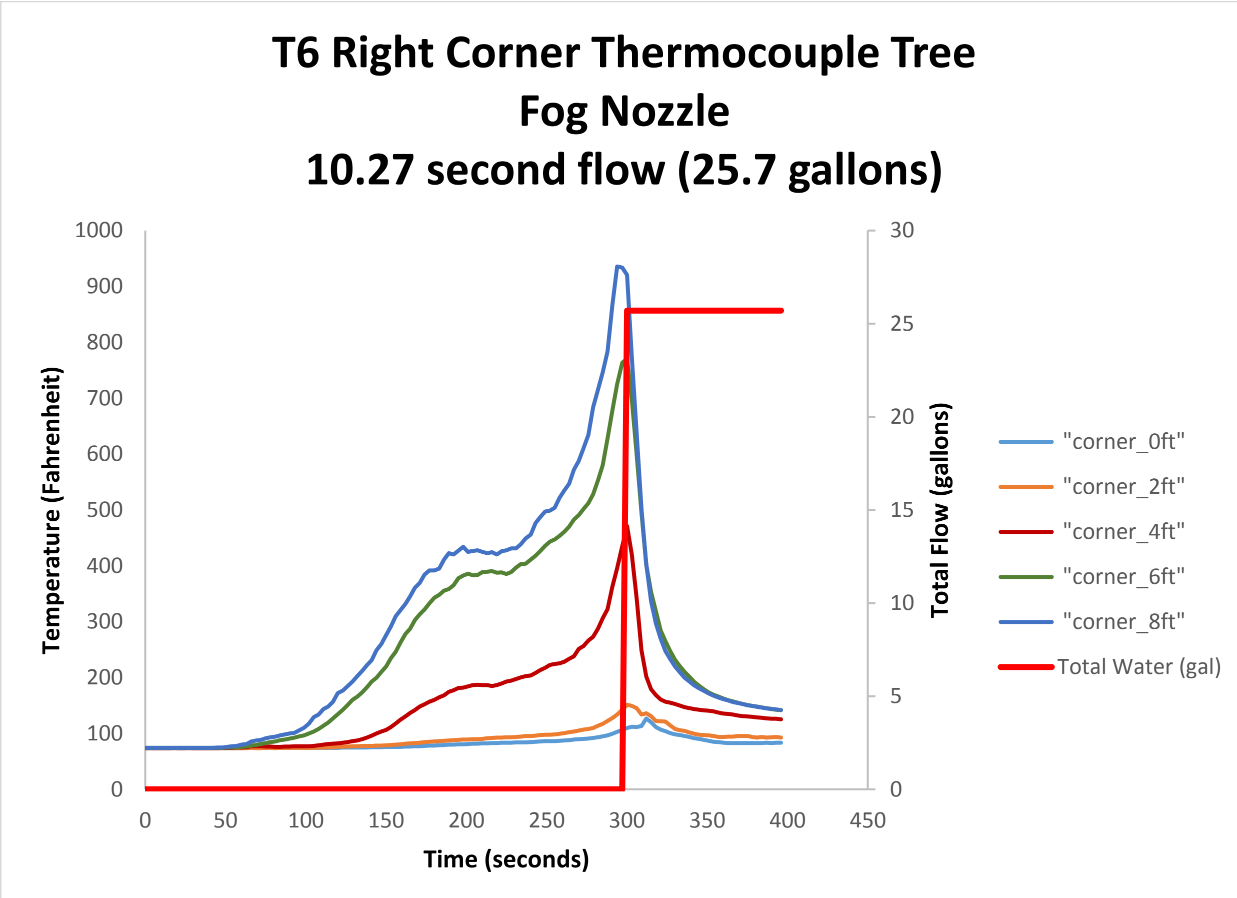
Comparing Tests T1, T6, and T8

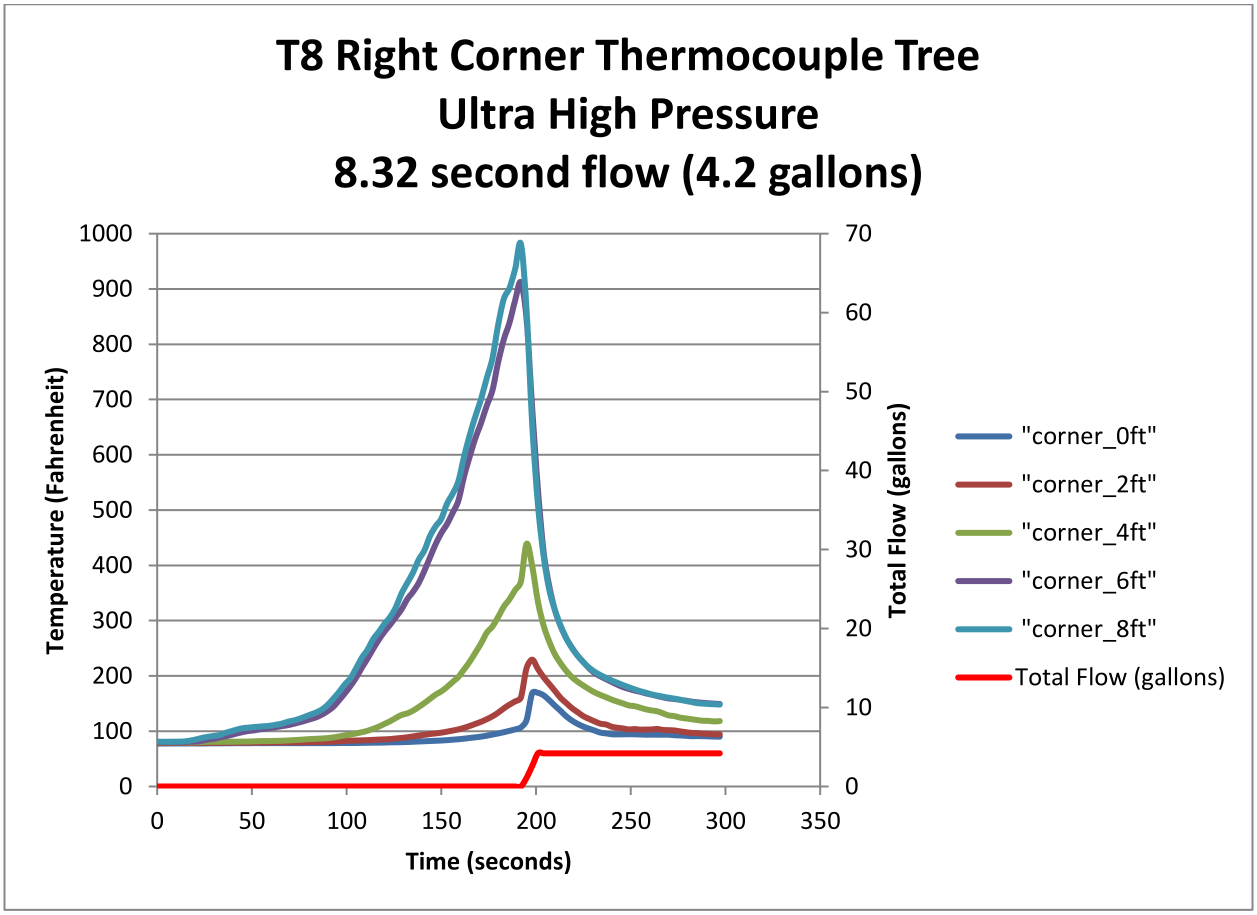


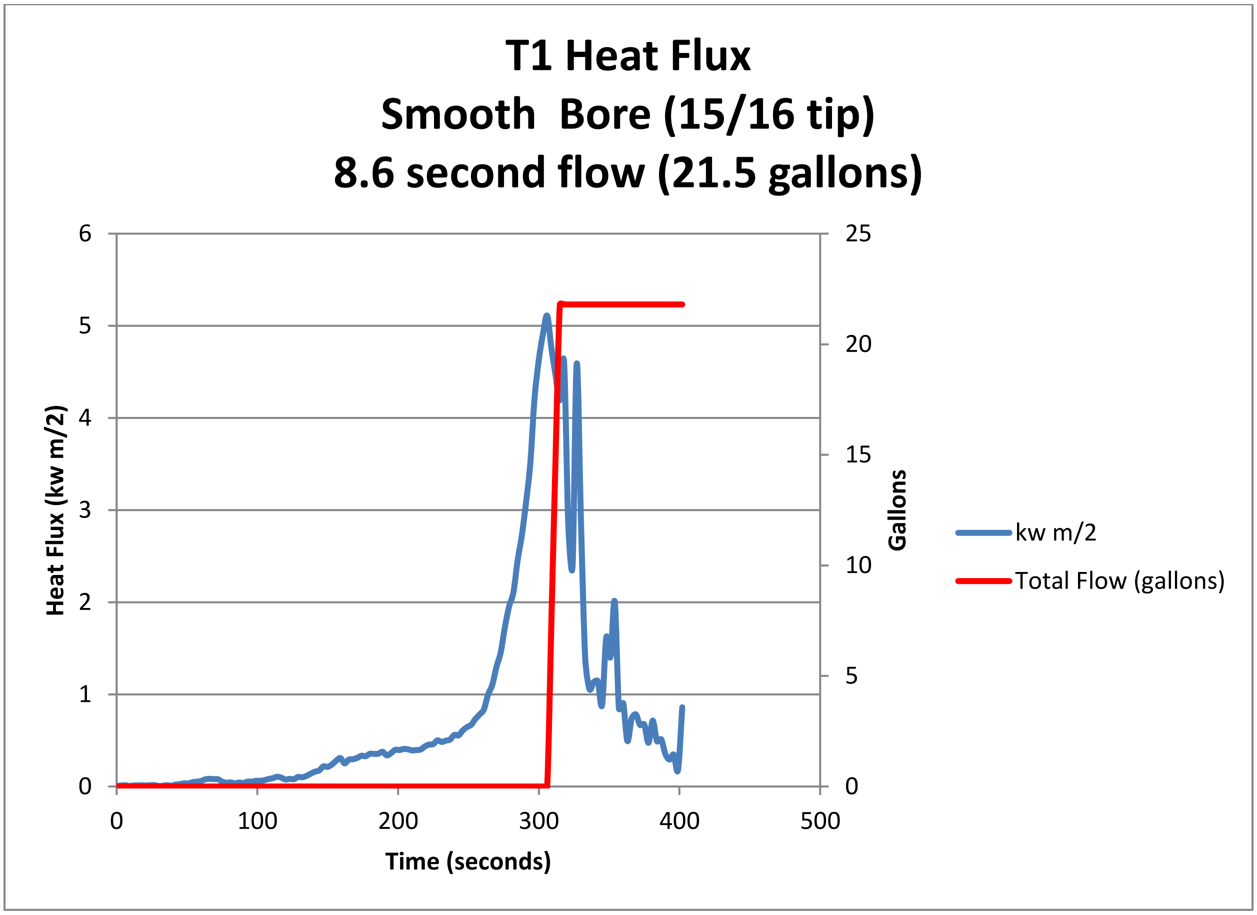

T6 Doorway Center Thermocouple Tree
Fog Nozzle
10.27 second flow (25.7 gallons)
Temperature (Fahrenheit)
0
100
200
300
400
500
600
700
800
900
1000
Total Flow (gallons)
0
5
10
15
20
25
30
Time (seconds)
0
50
100
150
200
250
300
350
400
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Water (gal)

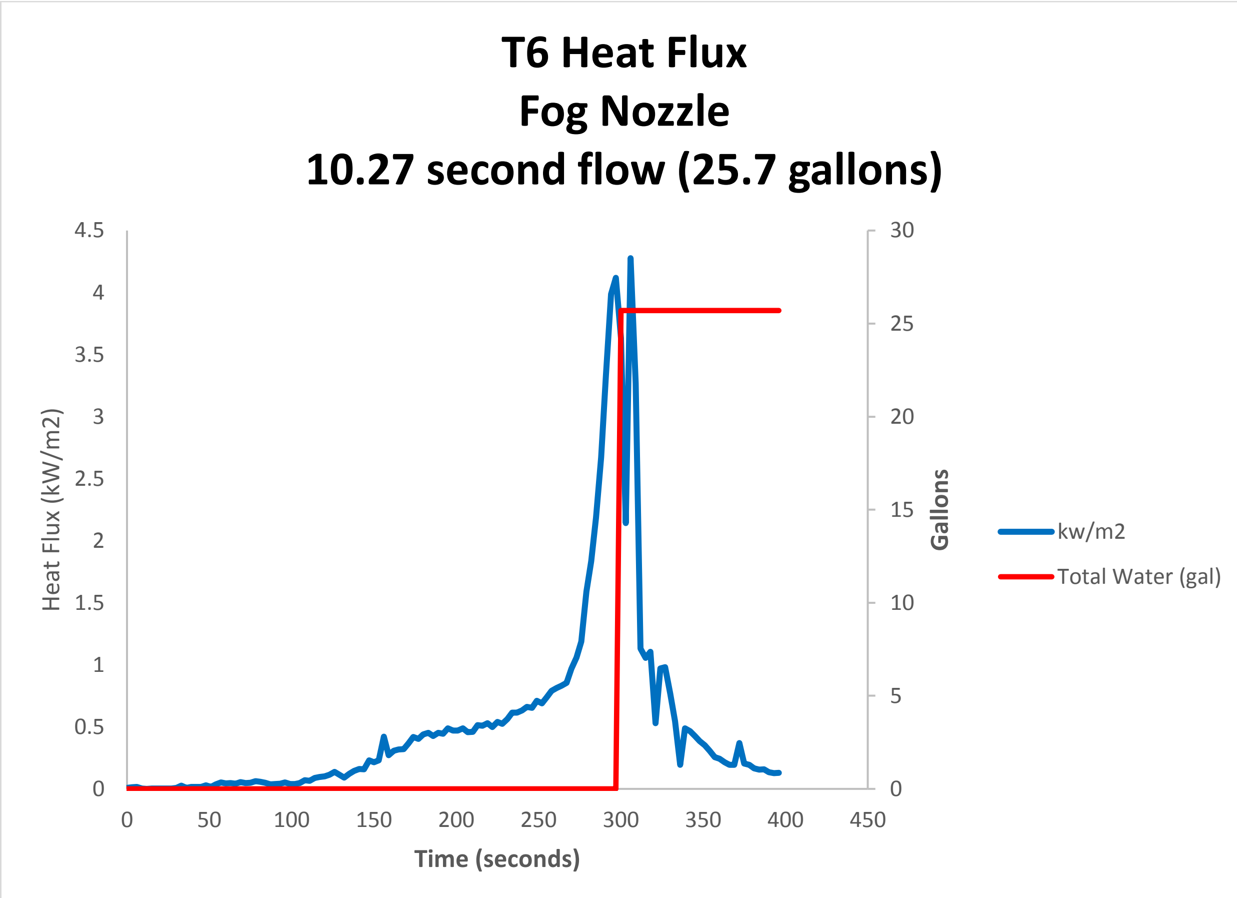

T8 Doorway Center Thermocouple Tree
Ultra High Pressure
8.32 second flow (4.2 gallons)
Temperature (Fahrenheit)
1000
900
800
700
600
500
400
300
200
100
0
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
Time (seconds)
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Flow (gallons)

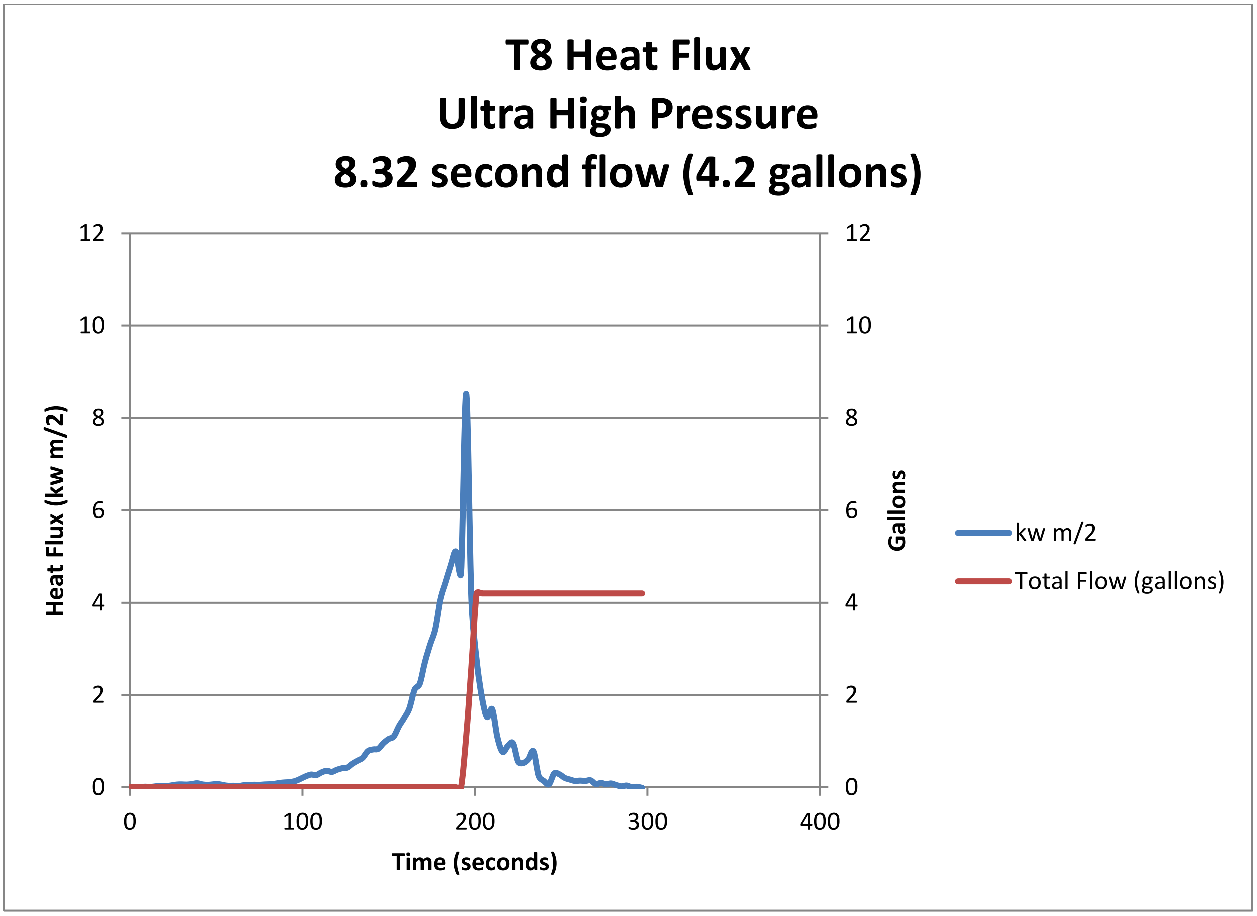

T1 Right Corner Thermocouple Tree
Smooth Bore (15/16 tip)
8.6 second flow (21.5 gallons)
Temperature (Fahrenheit)
1000
900
800
700
600
500
400
300
200
100
0
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
100
200
300
400
500
Time (seconds)
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

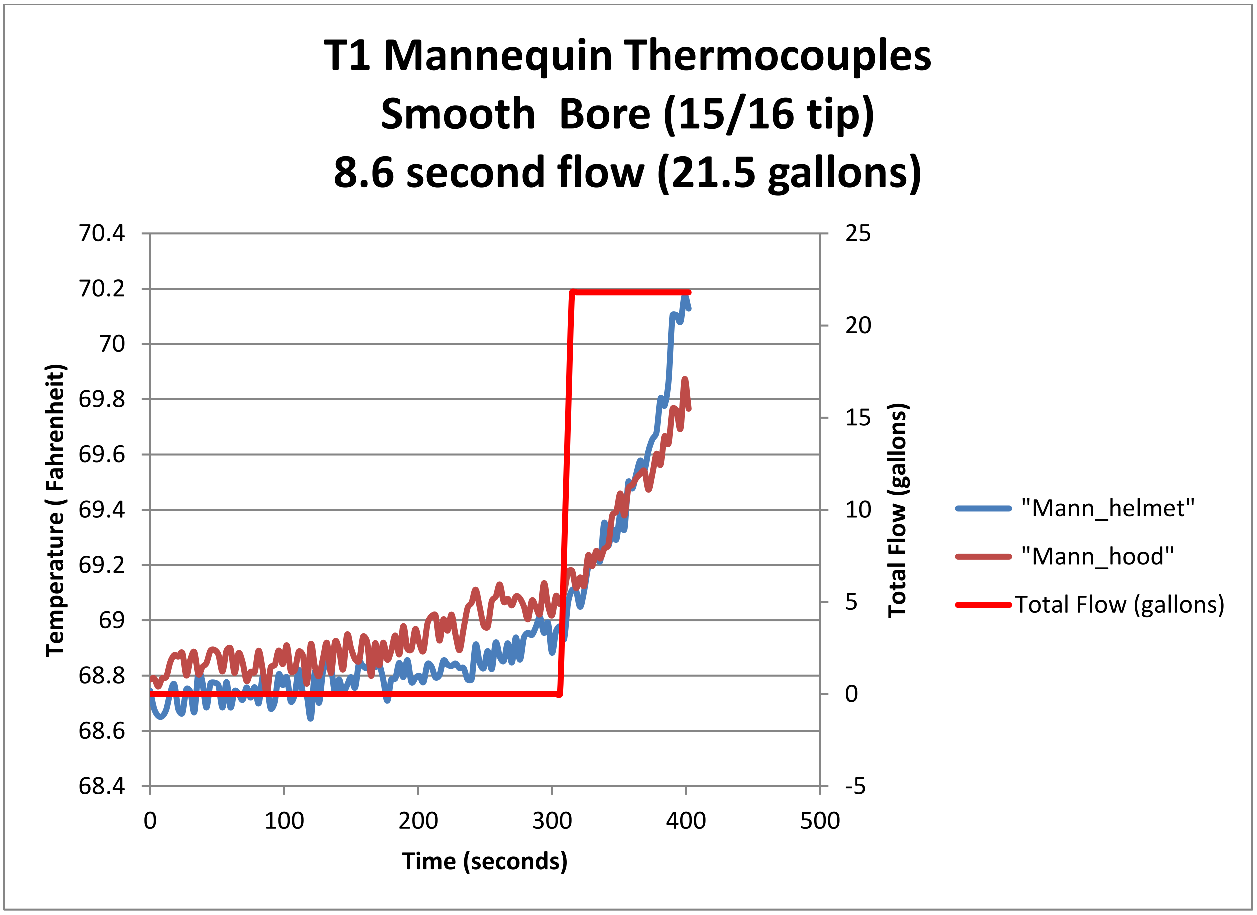

T6 Right Corner Thermocouple Tree
Fog Nozzle
10.27 second flow (25.7 gallons)
Temperature (Fahrenheit)
Total Flow (gallons)
Time (seconds)
0
100
200
300
400
500
600
700
800
900
1000
0
5
10
15
20
25
30
0
50
100
150
200
250
300
350
400
450
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Water (gal)

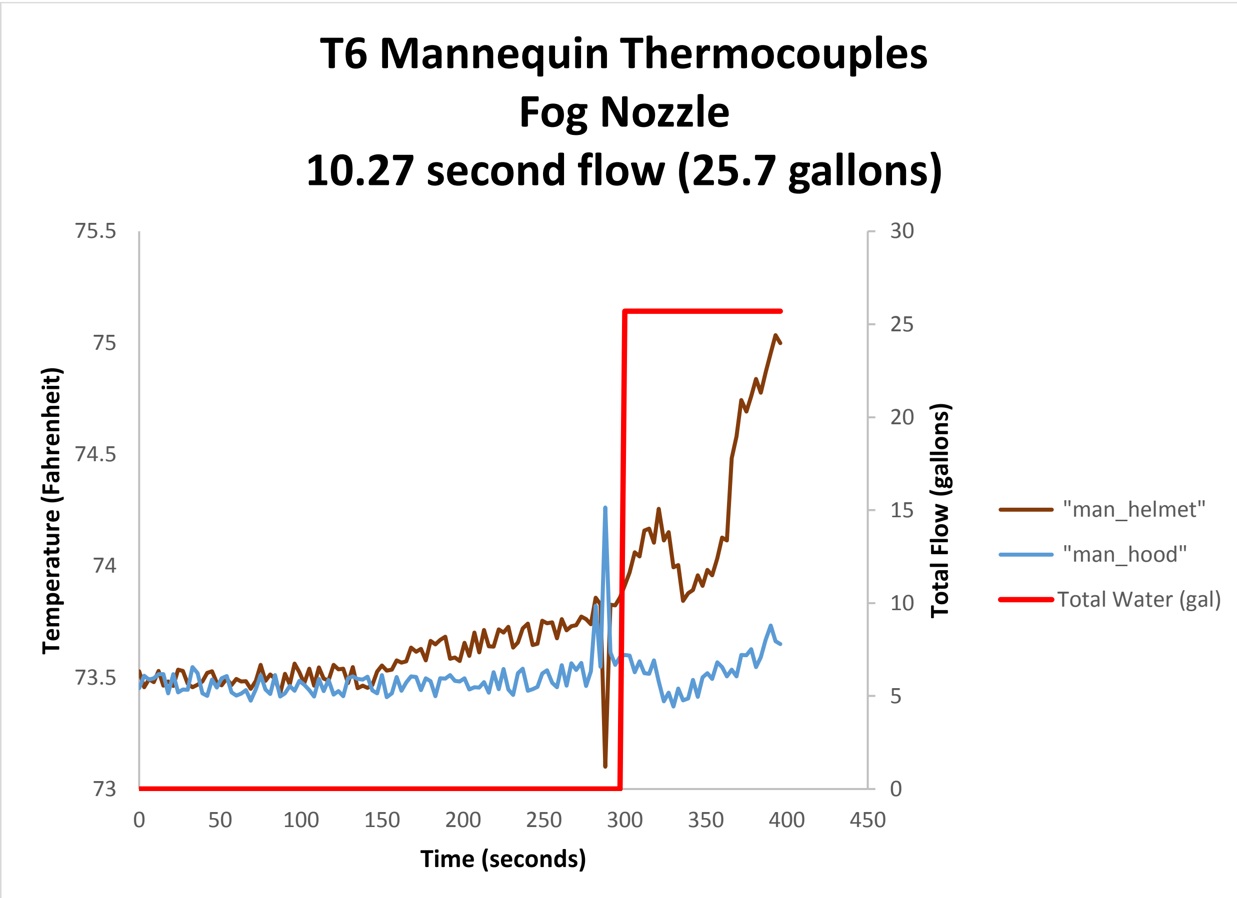

T8 Right Corner Thermocouple Tree
Ultra High Pressure
8.32 second flow (4.2 gallons)
Temperature (Fahrenheit)
1000
900
800
700
600
500
400
300
200
100
0
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
Time (seconds)
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

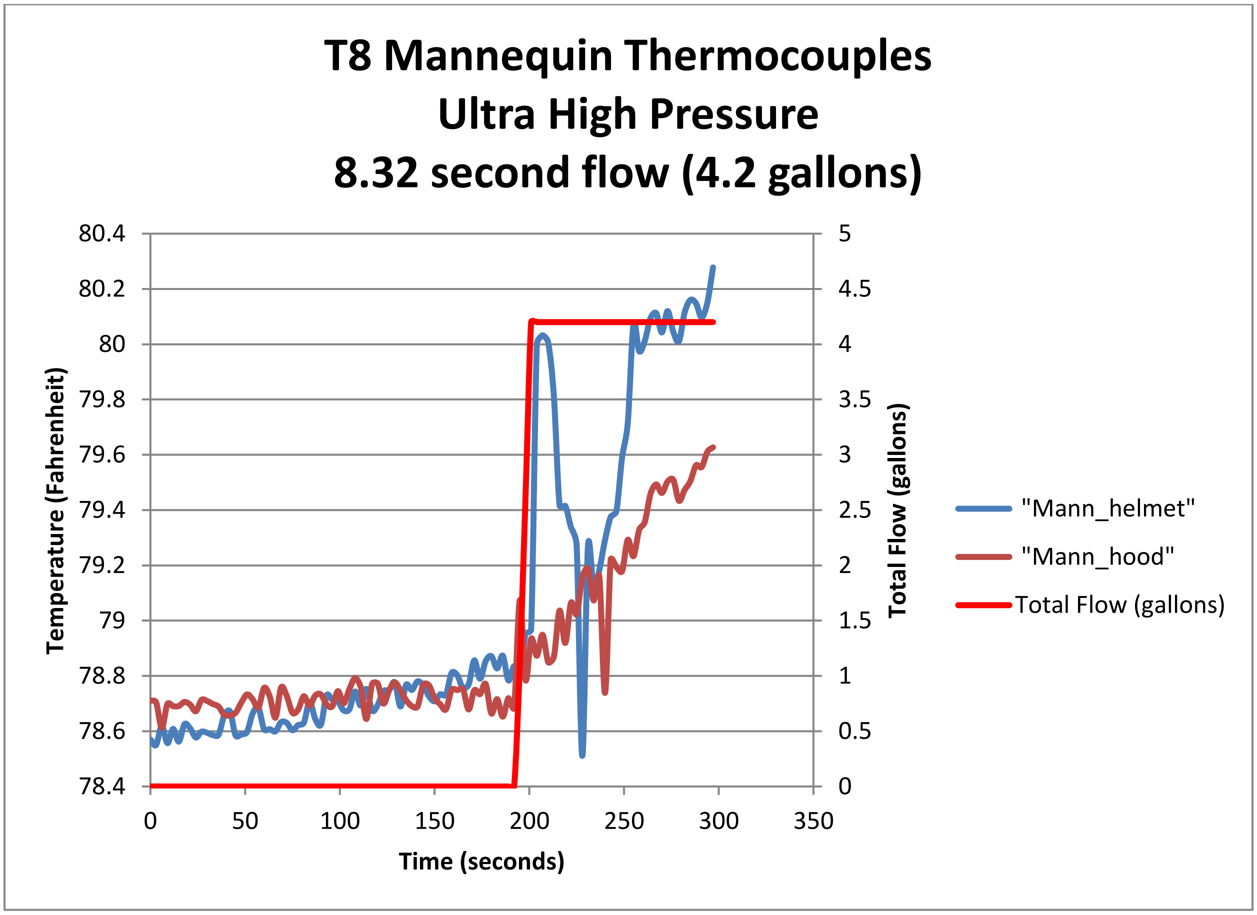

T1 Heat Flux
Smooth Bore (15/16 tip)
8.6 second flow (21.5 gallons)
Heat Flux (kw m/2)
Gallons
Time (seconds)
0
1
2
3
4
5
6
0
5
10
15
20
25
0
100
200
300
400
500
kw m/2
Total Flow (gallons)


T6 Heat Flux
Fog Nozzle
10.27 second flow (25.7 gallons)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Heat Flux (kW/m2)
30
25
20
15
10
5
0
Gallons
0
50
100
150
200
250
300
350
400
450
Time (seconds)
kw/m2
Total Water (gal)

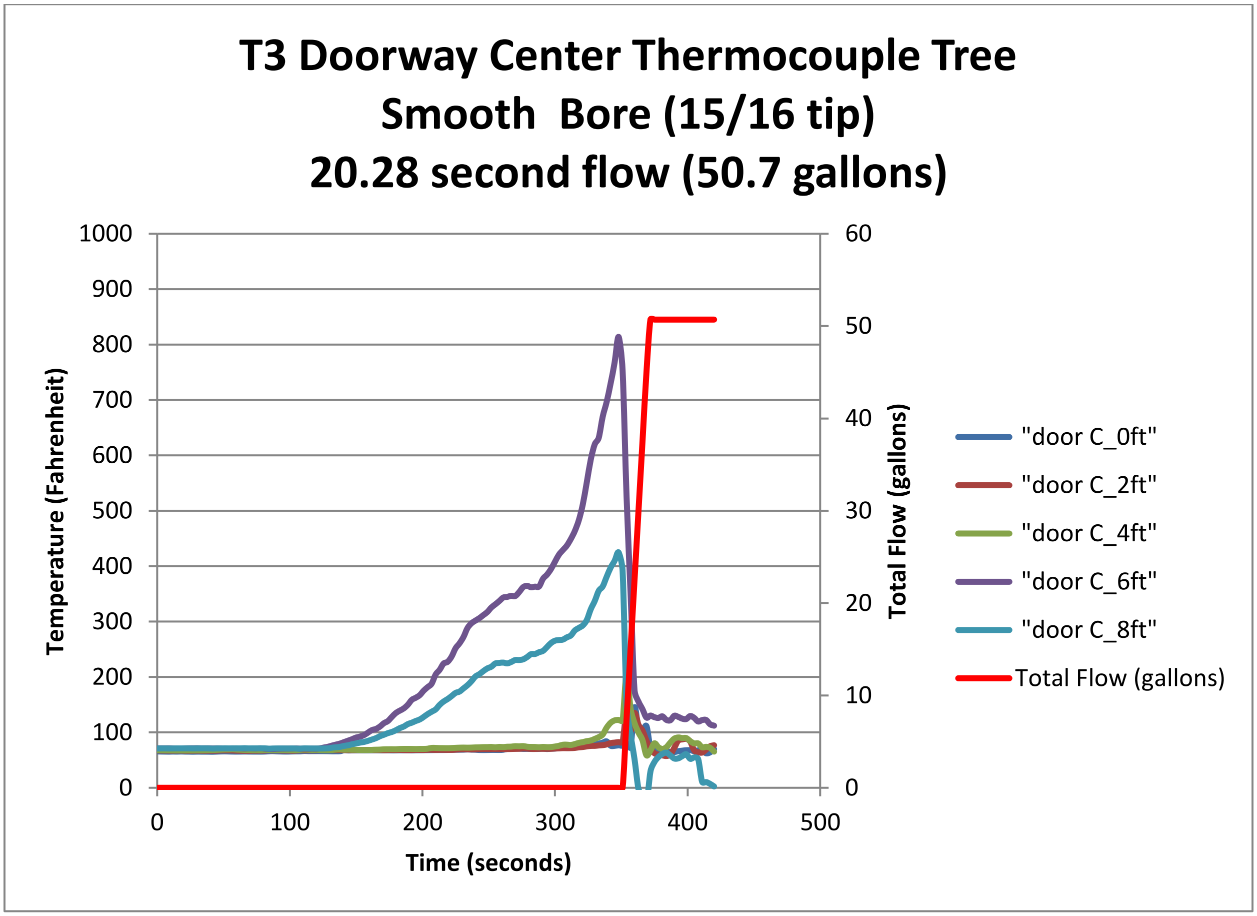

T8 Heat Flux
Ultra High Pressure
8.32 second flow (4.2 gallons)
Heat Flux (kw m/2)
Gallons
Time (seconds)
0
100
200
300
400
0
2
4
6
8
10
12
kw m/2
Total Flow (gallons)

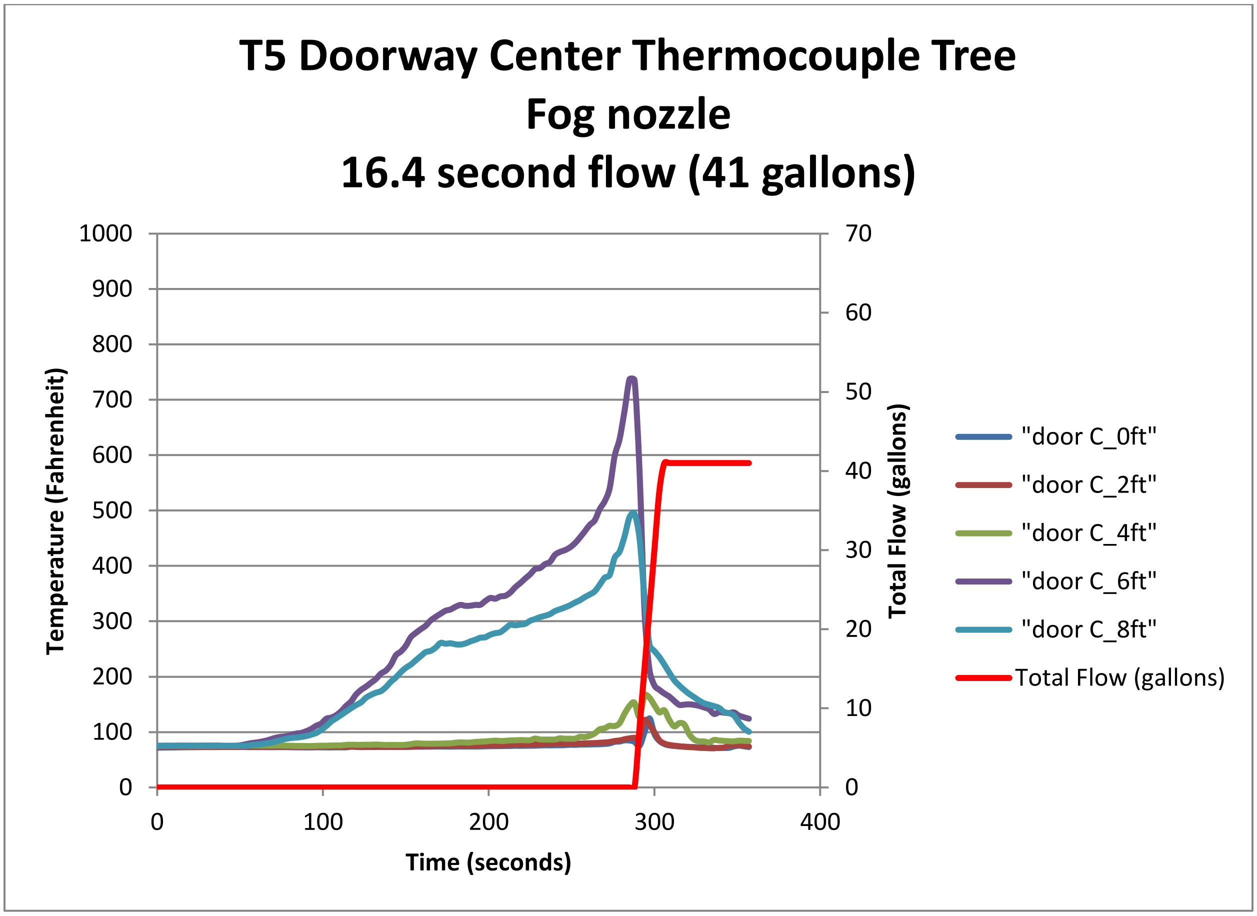

T1 Mannequin Thermocouples
Smooth Bore (15/16 tip)
8.6 second flow (21.5 gallons)
Temperature (Fahrenheit)
70.4
70.2
70
69.8
69.6
69.4
69.2
69
68.8
68.6
68.4
Total Flow (gallons)
25
20
15
10
5
0
-5
0
100
200
300
400
500
Time (seconds)
"Mann_helmet"
"Mann_hood"
Total Flow (gallons)

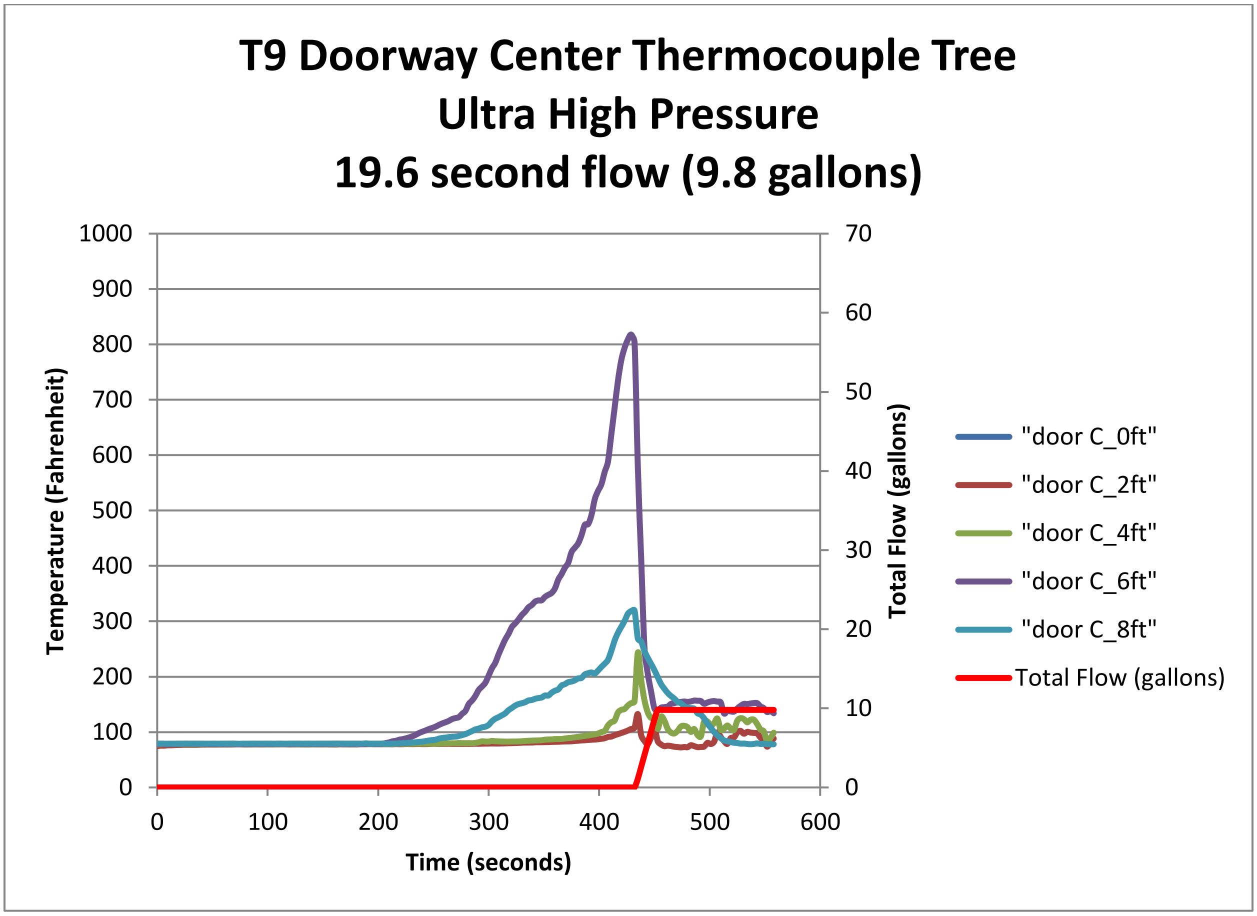

T6 Mannequin Thermocouples
Fog Nozzle
10.27 second flow (25.7 gallons)
Temperature (Fahrenheit)
75.5
75
74.5
74
73.5
73
Total Flow (gallons)
30
25
20
15
10
5
0
0
50
100
150
200
250
300
350
400
450
Time (seconds)
"man_helmet"
"man_hood"
Total Water (gal)

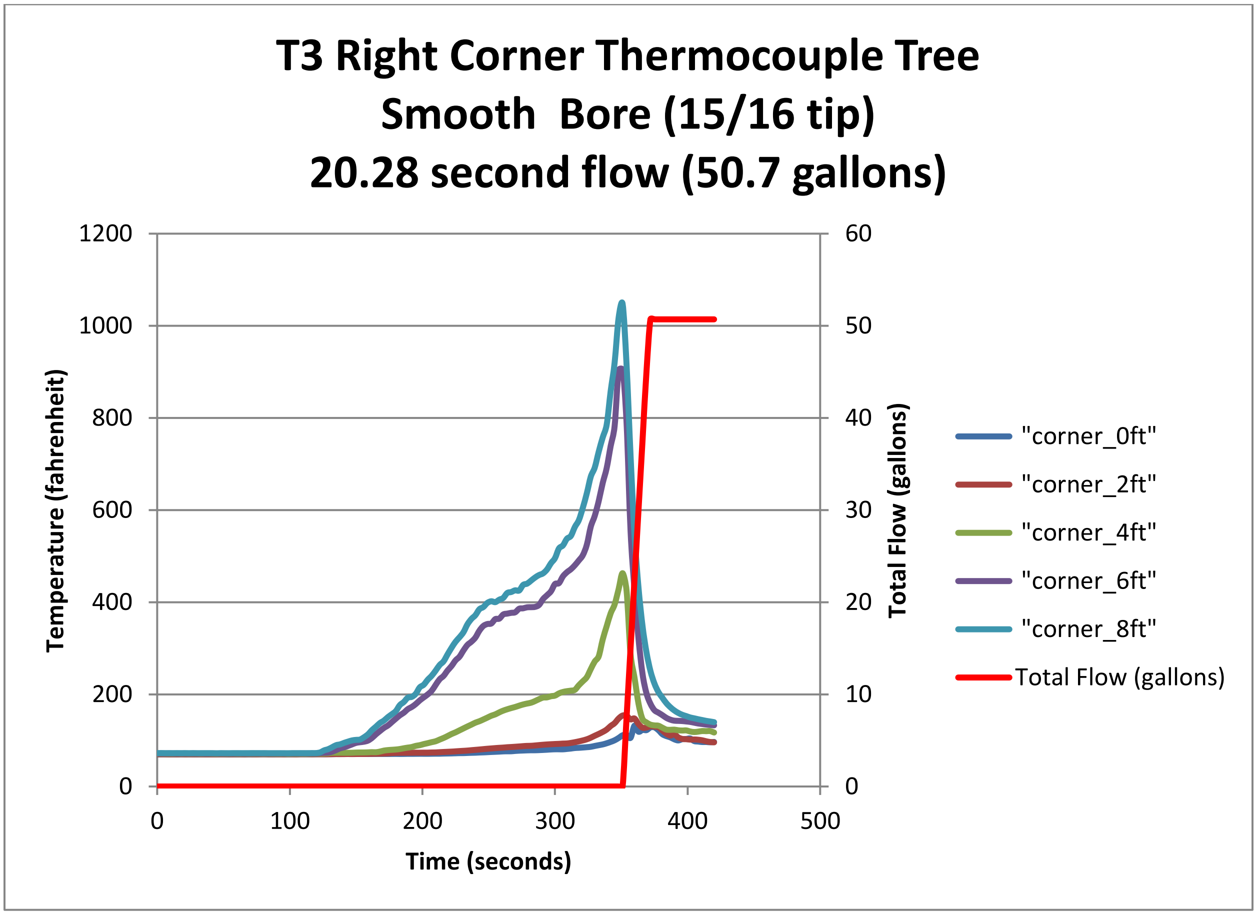

T8 Mannequin Thermocouples
Ultra High Pressure
8.32 second flow (4.2 gallons)
Temperature (Fahrenheit)
80.4
80.2
80
79.8
79.6
79.4
79.2
79
78.8
78.6
78.4
Total Flow (gallons)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
350
Time (seconds)
"Mann_helmet"
"Mann_hood"
Total Flow (gallons)

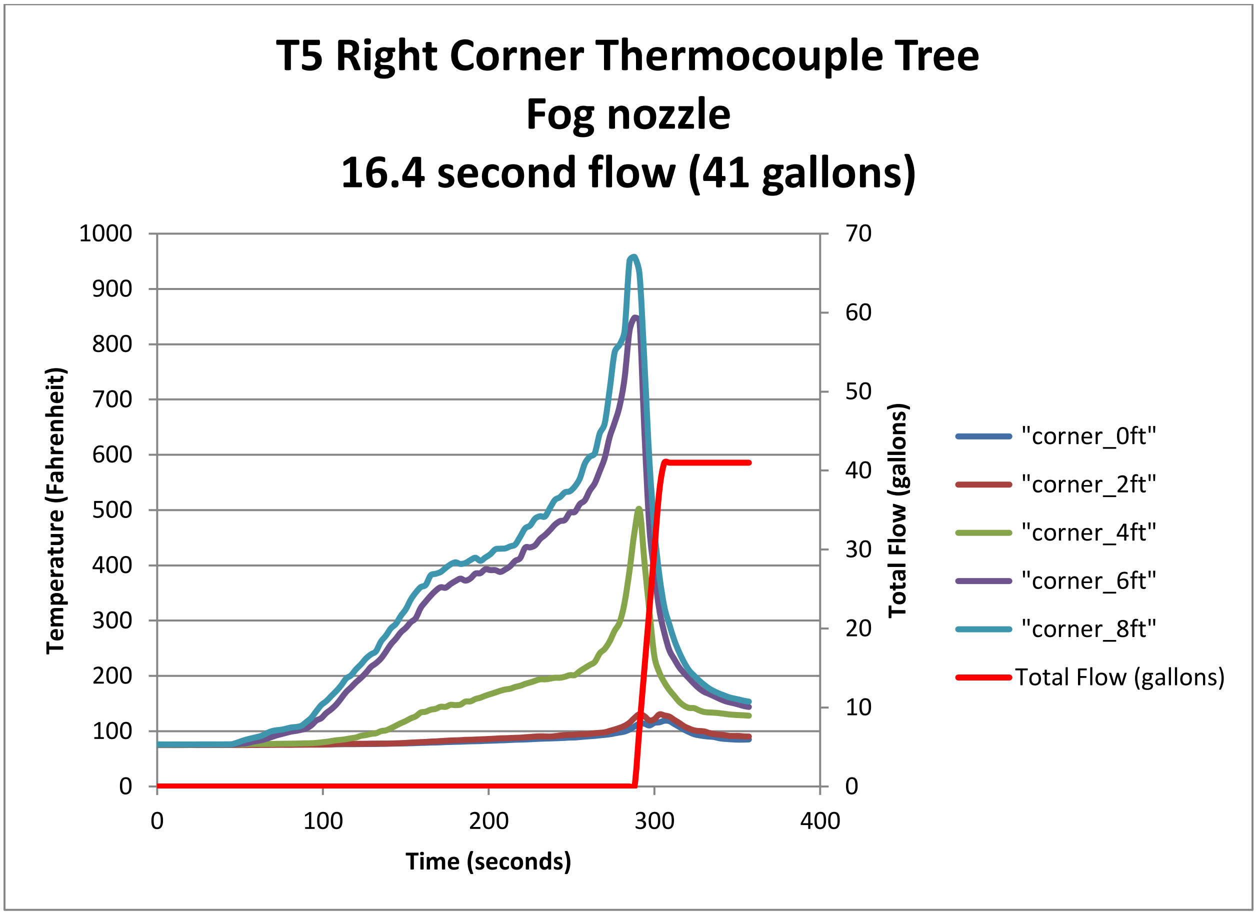
Comparing Tests T3,T5, and T9

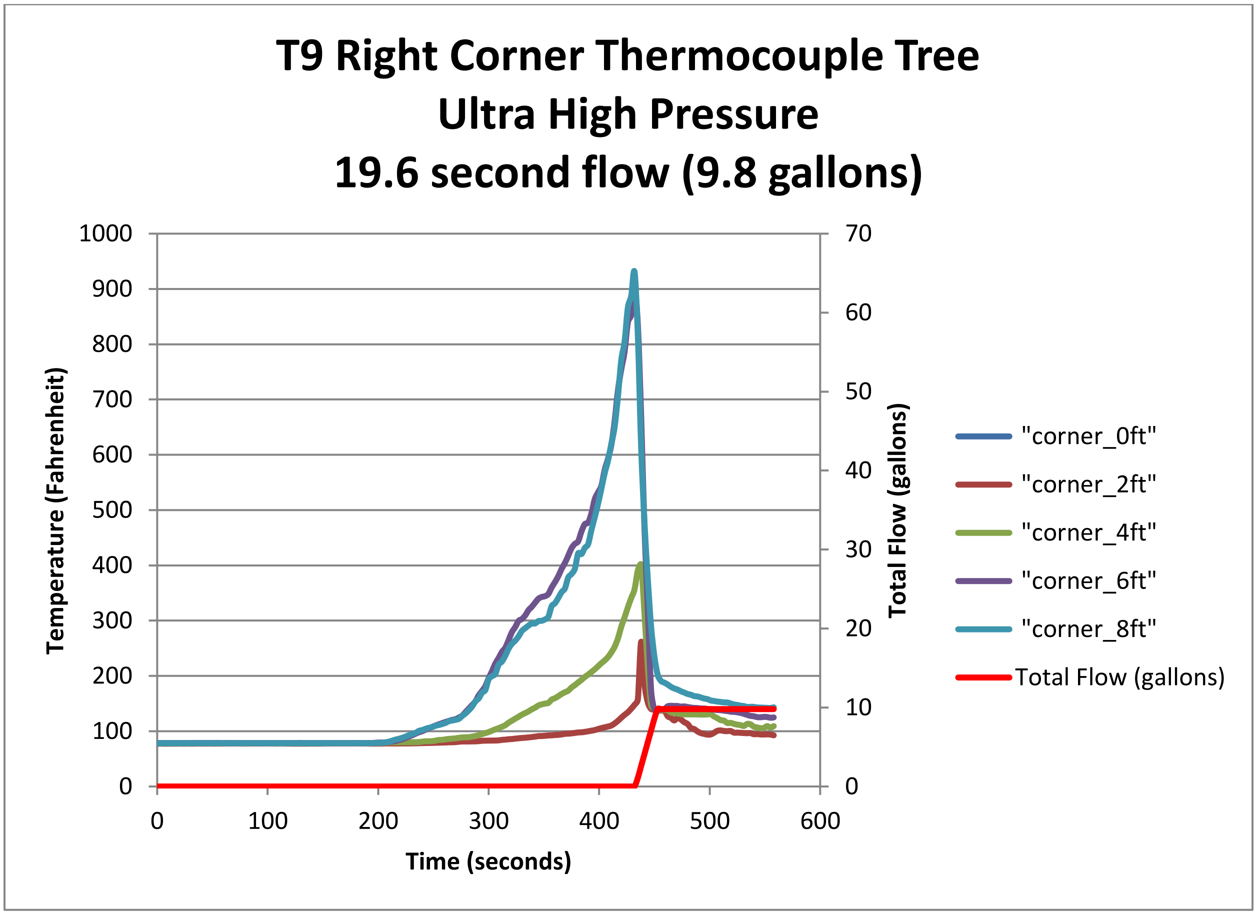


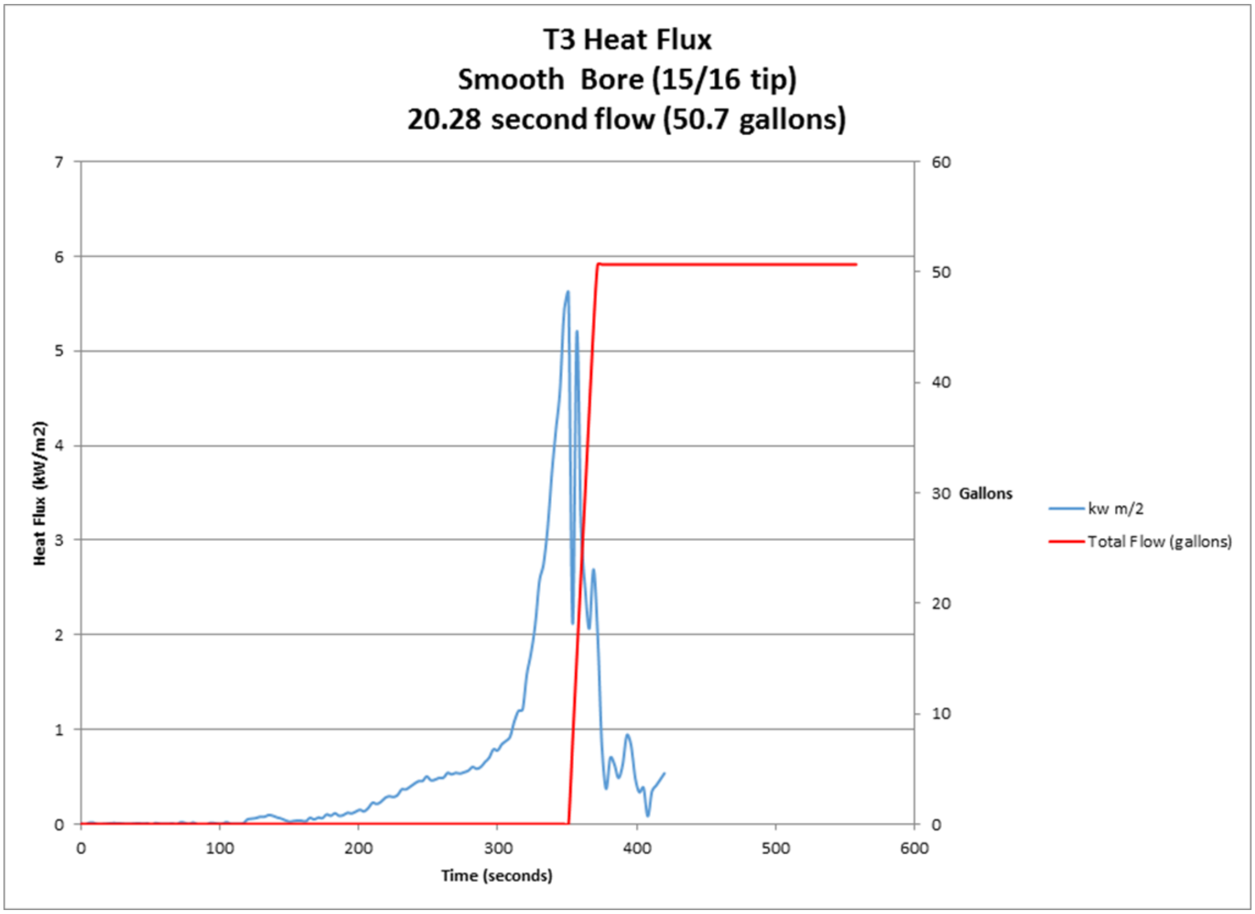

T5 Doorway Center Thermocouple Tree
Fog nozzle
16.4 second flow (41 gallons)
Temperature (Fahrenheit)
Total Flow (gallons)
Time (seconds)
0
100
200
300
400
500
600
700
800
900
1000
0
10
20
30
40
50
60
70
0
100
200
300
400
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Flow (gallons)

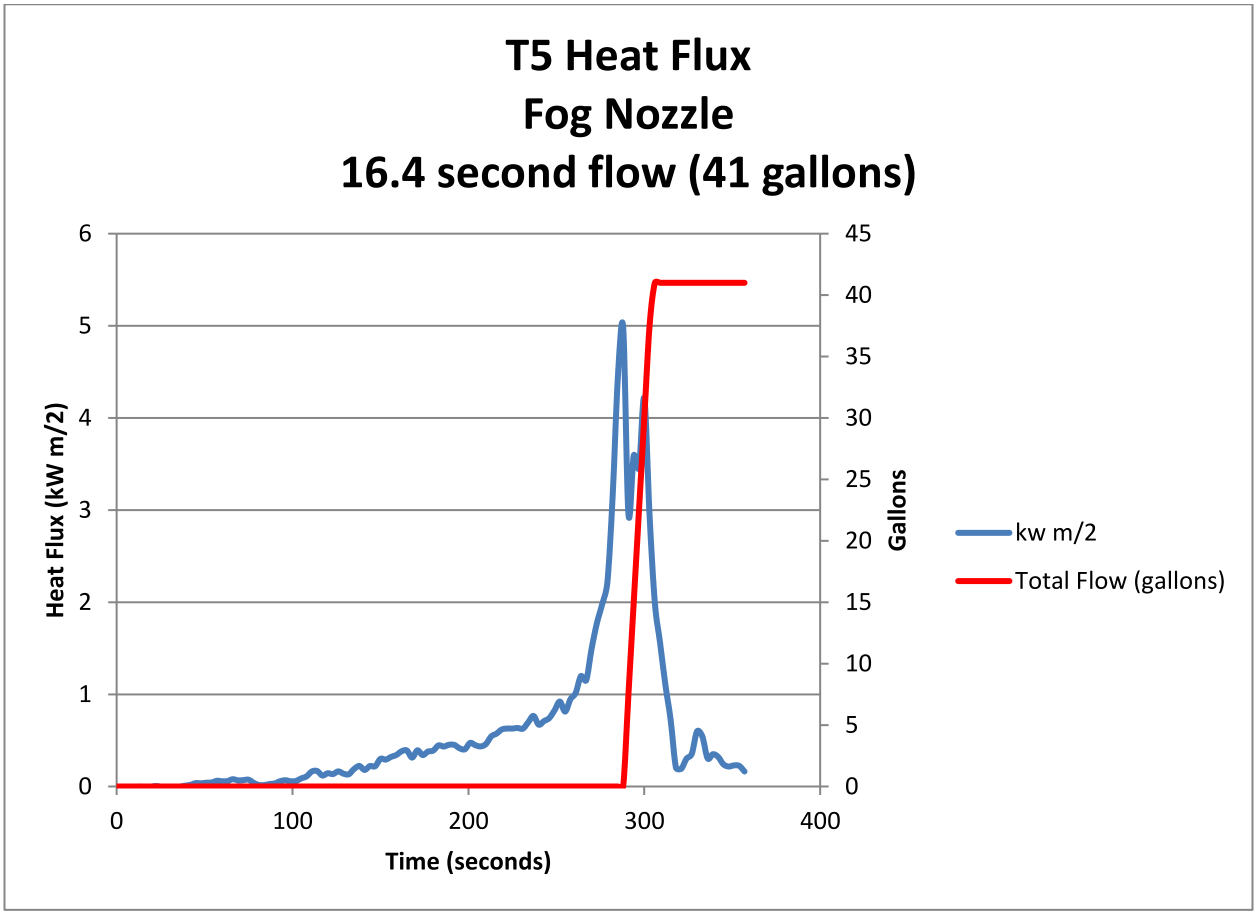

T9 Doorway Center Thermocouple Tree
Ultra High Pressure
19.6 second flow (9.8 gallons)
Temperature (Fahrenheit)
Total Flow (gallons)
Time (seconds)
0
100
200
300
400
500
600
700
800
900
1000
10
20
30
40
50
60
70
"door C_0ft"
"door C_2ft"
"door C_4ft"
"door C_6ft"
"door C_8ft"
Total Flow (gallons)

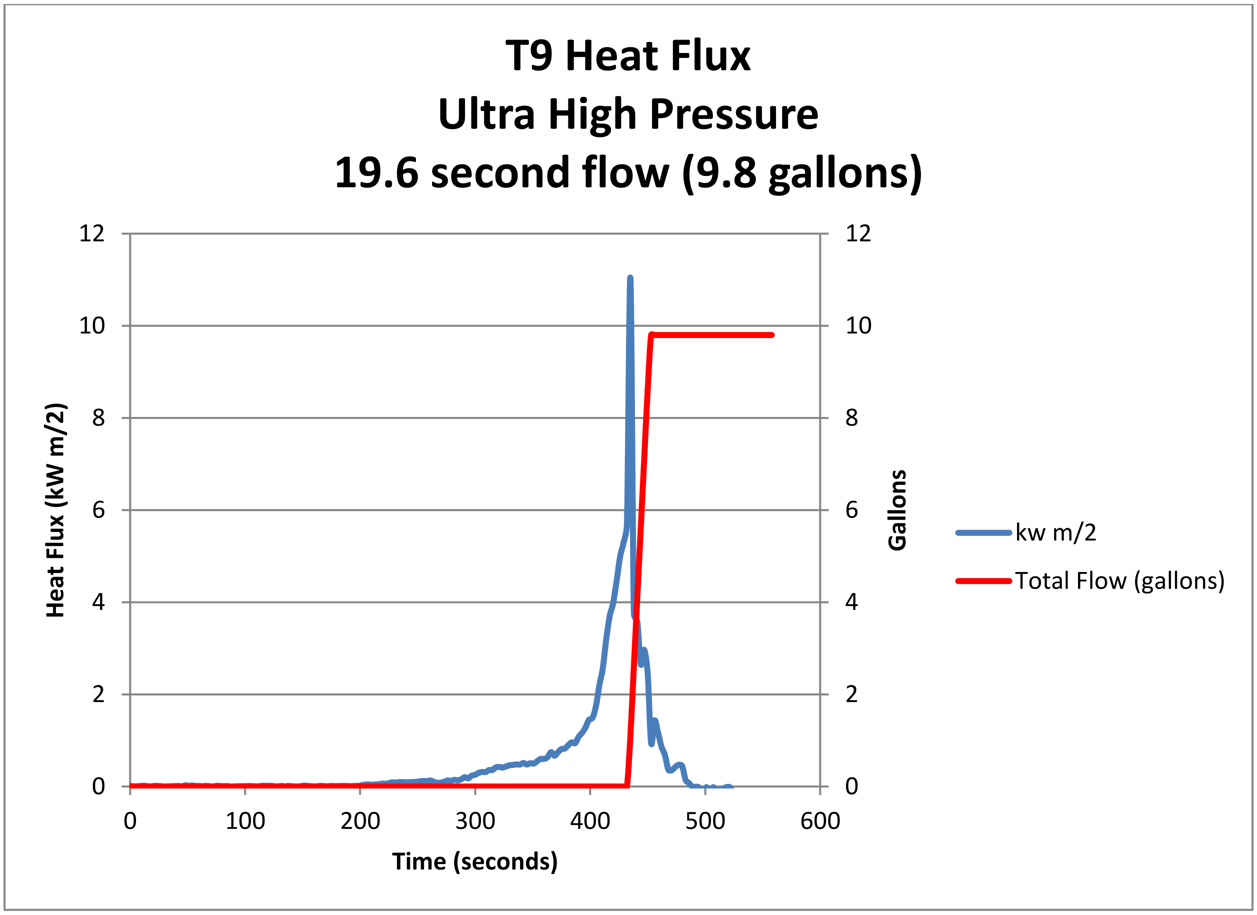

T3 Right Corner Thermocouple Tree
Smooth Bore (15/16 tip)
20.28 second flow (50.7 gallons)
Temperature (fahrenheit)
Total Flow (gallons)
Time (seconds)
0
200
400
600
800
1000
1200
0
10
20
30
40
50
60
0
100
200
300
400
500
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

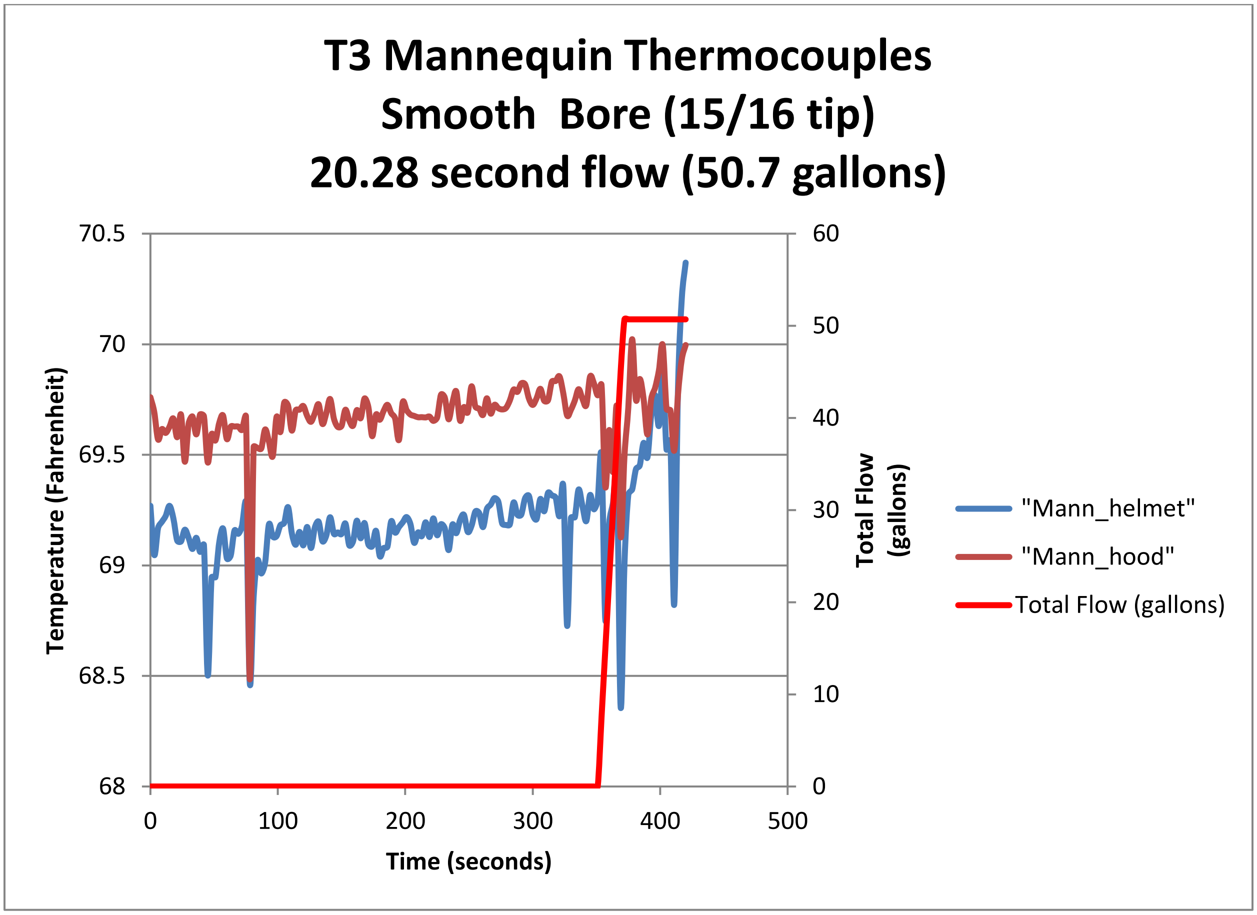

T5 Right Corner Thermocouple Tree
Fog nozzle
16.4 second flow (41 gallons)
Temperature (Fahrenheit)
1000
900
800
700
600
500
400
300
200
100
0
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
100
200
300
400
Time (seconds)
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)


T9 Right Corner Thermocouple Tree
Ultra High Pressure
19.6 second flow (9.8 gallons)
Temperature (Fahrenheit)
0
100
200
300
400
500
600
700
800
900
1000
Total Flow (gallons)
0
10
20
30
40
50
60
70
Time (seconds)
0
100
200
300
400
500
600
"corner_0ft"
"corner_2ft"
"corner_4ft"
"corner_6ft"
"corner_8ft"
Total Flow (gallons)

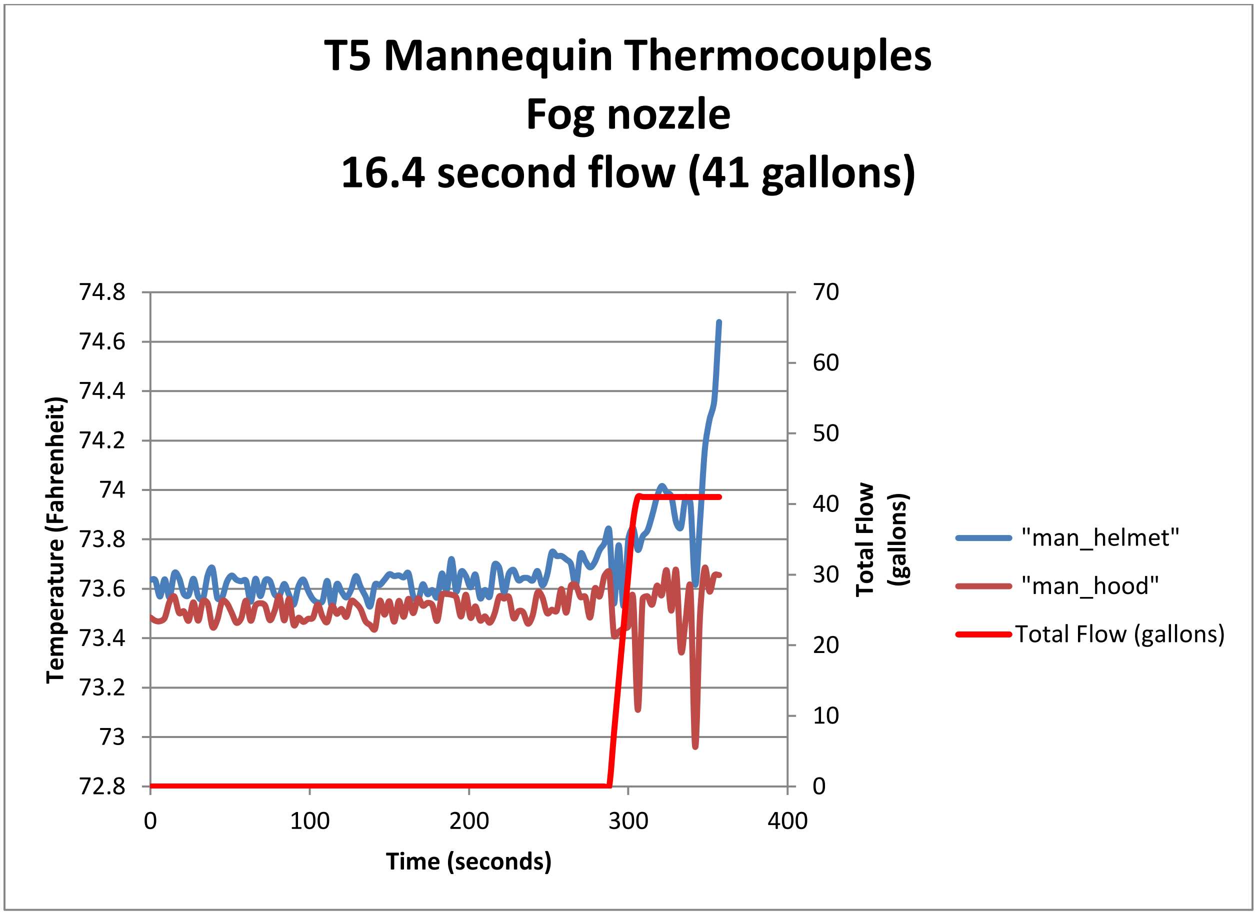

T3 Heat Flux
Smooth Bore (15/16 tip)
20.28 second flow (50.7 gallons)
Heat Flux (kW/m2)
Gallons
Time (seconds)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
0
100
200
300
400
500
600
kw m/2
Total Flow (gallons)

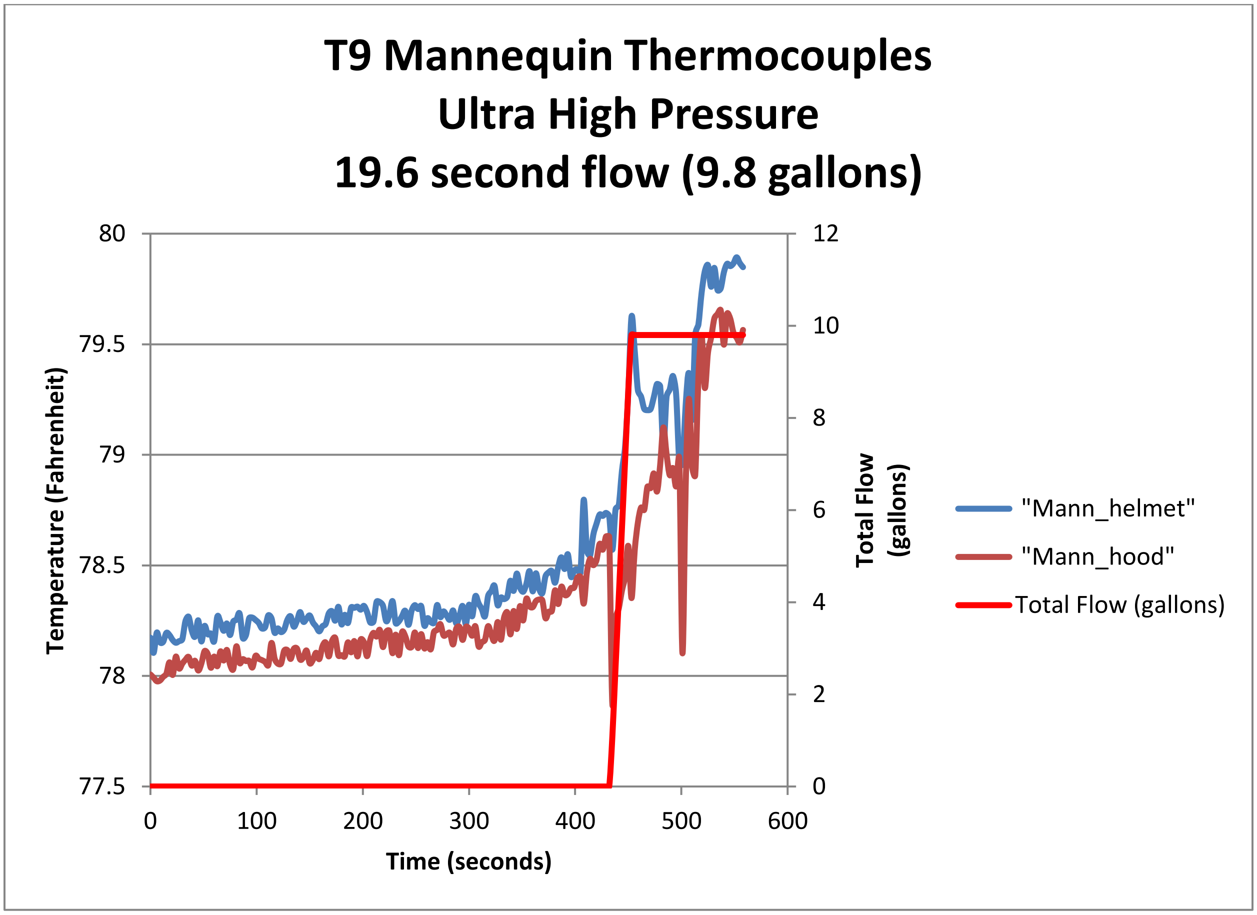

T5 Heat Flux
Fog Nozzle
16.4 second flow (41 gallons)
Heat Flux (kW m/2)
Gallons
Time (seconds)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
40
45
0
100
200
300
400
kw m/2
Total Flow (gallons)


T9 Heat Flux
Ultra High Pressure
19.6 second flow (9.8 gallons)
Heat Flux (kW m/2)
Gallons
Time (seconds)
0
100
200
300
400
500
600
0
2
4
6
8
10
12
kw m/2
Total Flow (gallons)



T3 Mannequin Thermocouples
Smooth Bore (15/16 tip)
20.28 second flow (50.7 gallons)
Temperature (Fahrenheit)
70.5
70
69.5
69
68.5
68
0
100
200
300
400
500
Time (seconds)
60
50
40
30
20
10
0
Total Flow (gallons)
"Mann_helmet"
"Mann_hood"
Total Flow (gallons)


T5 Mannequin Thermocouples
Fog nozzle
16.4 second flow (41 gallons)
Temperature (Fahrenheit)
74.8
74.6
74.4
74.2
74
73.8
73.6
73.4
73.2
73
72.8
Total Flow (gallons)
70
60
50
40
30
20
10
0
0
100
200
300
400
Time (seconds)
"man_helmet"
"man_hood"
Total Flow (gallons)


T9 Mannequin Thermocouples
Ultra High Pressure
19.6 second flow (9.8 gallons)
Temperature (Fahrenheit)
80
79.5
79
78.5
78
77.5
12
10
8
6
4
2
0
Total Flow (gallons)
0
100
200
300
400
500
600
Time (seconds)
"Mann_helmet"
"Mann_hood"
Total Flow (gallons)