

**NIST Technical Note 1969**

# **Investigation of Residential Cooking Fire Suppression Technologies**

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## NIST Technical Note 1969

# Investigation of Residential Cooking Fire Suppression Technologies

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## Abstract

A series of cooking fire experiments were conducted to examine the effectiveness of residential kitchen fire suppression systems. A series of experiments provided data on the hazard associated with cooking oil fires. Then, a series of real-scale fire suppression experiments followed, using scenarios outlined in the UL 300A draft standard. Various fire suppression systems were tested. Experiments were conducted in a full-scale residential kitchen with dimensions 3.6 m x 3.4 m x 2.4 m high with an open doorway. Both gas and electric ranges were used. Several types of cooking pans were tested.

The suppression systems tested included both automatic and manual suppression technologies. The manual devices included wet and dry chemical type extinguishers. The automatic systems included room-wide and range hood installed systems. The room wide systems included water mist and a residential sprinkler system. The hood installed systems included water mist and wet and dry chemical systems.

Manual extinguishers consistently suppressed the oil fires while maintaining tenable conditions in the mock-up kitchen. One hood-installed wet chemical system tested demonstrated success in extinguishing the oil fires in all experiments, and maintained tenability in the mock up kitchen throughout most of the experiments. The hood-installed dry chemical system tested failed to extinguish the oil fire in all experiments, and introduced tenability hazards not present prior to the system activation. All other system types provided mixed results; they either could not reliably suppress the fire, or they consistently generated tenability hazards in the test kitchen.

The effectiveness of ionization smoke alarms to provide early warning of fire were also tested as part of this study. The results showed that the smoke alarms inside, or just outside, the kitchen fire scenarios considered here generally activated several minutes before auto-ignition occurred, but not for all cases.

The results of the experiments demonstrate the need to develop other approaches to kitchen fire safety such as ignition prevention technologies and reliable, early, and nuisance-free warning of pre-ignition conditions possibly through the development of specialized sensors or sensor combinations.

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# 1 Introduction

A 2016 study conducted by the National Fire Protection Association on home fires involving cooking equipment over the five year period from 2010 to 2014 indicates that U.S. fire departments responded to an average of 166,000 structure fires annually associated with cooking [1]. The damage caused by these fires included an annual average of 480 civilian deaths, 5500 civilian injuries, and \$1.1 billion in direct property damage. Cooking equipment was involved in 46 %, that is almost one-half of reported home fires, 19 % of home fire fatalities, and 44 % of reported home fire injuries with U.S. Fire Departments responding to more than 450 home cooking fires per day during this period. While there has been significant progress in reducing home fire fatalities over the last 30 years, there has been relatively little progress in home cooking fire fatalities with home fire fatalities dropping by about half, while cooking fire deaths have been reduced only 4 % over the same period.

Cooktops, or ranges, have been involved in the majority of the cooking fires and associated losses [1]. In reported home fires, involving cooking equipment, ranges or cooktops accounted for 62 % of fires, 88 % of the civilian cooking fire deaths, 79 % of the civilian cooking fire injuries, and 73 % of the direct property damage. Electric ranges are associated with a higher risk of cooking fires, as compared to gas ranges. Whereas about 60 % of households cook with electric cooktops, 80 % of cooktops involved in reported cooking fires were powered by electricity. Using this information, NFPA reports that the rate of reported fires per million households was 2.6 times higher with electric ranges [1]. In addition, the study reports that unattended equipment was a leading cause contributing to the ignition of 34 % of cooking fires. More than half (55 %) of non-fatal civilian cooking fire injuries occurred when the victims tried to fight the fire themselves.

Cooking fires are a significant problem and are unlikely to go away on their own - without significant educational and/or technological advances. In April 2006, a workshop was held at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD that outlined the kitchen fire problem and worked to identify the factors that limit the use of localized kitchen fire suppression systems [2]. The workshop identified the popularity of kitchen suppression systems and the fire control effectiveness of these devices as key factors that will affect the kitchen fire problem through this technology. The workshop suggested research into the effectiveness of existing systems could improve these factors by educating consumers about potential benefit as well as by helping to improve the cost of kitchen suppression systems by aiding technological development. Education of consumers was identified as an important means to prevent kitchen fires and how research could help characterize the hazard of a cooking fire as a means to educate consumers on kitchen fire prevention [2].

In 2014, an abnormal cooking test to prevent ignition during cooking was added to the UL 858 standard for new electric coil cooktops [3]. At the same time, an ignition-prevention standard for gas ranges is currently not in place. Therefore, significant fire losses associated with stovetop cooking can be expected to continue for the next couple of decades as older electric cooktops are gradually replaced and a standard for gas ranges is developed. This suggests that means other than ignition prevention need to be considered to address these fires, which compose a significant fraction of the U.S. fire loss profile.

Recently, Johnsson conducted experiments to examine kitchen photoelectric smoke detectors to warn of approaching ignition of food during unattended cooking [4]. An electric range, range hood, and cabinets were installed in a mock-up kitchen. Commercially available photoelectric smoke detectors were found to activate at least 2 min before ignition. The experiments, however, were conducted for a closed compartment established with non-conventional ventilation conditions.

The acceptance of residential fire suppression systems by industry and the public will require the development of a standard test method. Existing standard suppression test methods designed for residential sprinklers (UL 1626) and commercial systems (UL 300) are not optimized for devices developed specifically for residential cooktop fires [5, 6]. Introduction of suppression systems to the market may be hindered without the development of an accepted standard test method to certify their effectiveness. Although there is currently no accepted standard test method for residential kitchen fire hazards, UL has a “pre-standard” method that it has developed to examine the performance of automatic fire suppression and control systems for kitchen stovetop residential applications [7].

To address these issues, an investigation was conducted to characterize various types of cooking fires and the parameters that might be used to determine successful fire control or suppression. This report describes experiments intended to characterize range fires and examine the performance of suppression systems applied in a full-scale residential kitchen scenario. Based on discussions from the NIST workshop, there was an emphasis on getting a baseline on the suppression performance of existing technologies that were available for retrofit. Cost was also a concern of the group, however given the use of prototype products that are not readily available for sale, direct cost comparisons were difficult to make. This report is broken into several parts that describe the experimental setup, apparatus, instrumentation, experimental procedure, results, and analysis of all experiments. In Section 2, the suppression system technologies considered in this study are described. In Section 3, the nature of cooktop fires is investigated experimentally. In Section 4, the results of full-scale kitchen fire experiments are described. Section 5 provides a summary and conclusions of the study. Appendix 1 presents the detailed results for each of the suppression experiments and Appendix 2 lists the environmental conditions during each of the suppression experiments.

## 2 Suppression System Technologies

A variety of suppression systems were used in these experiments, representing a range of current technologies available to address residential kitchen fires. Two types of suppression strategies were considered. The first approach focused on range hood systems, deploying systems that address the fire at its source – on the cooktop. The range hood technologies tested included wet and dry chemical systems as well as water mist. The second approach considered automatic fire protection for an entire room, addressing not just the stovetop surface but also nearby cabinets and other materials that may be involved in the fire. The room fire protection technologies tested included wet and dry chemical systems, water mist, and a water sprinkler. In all cases, the

technologies were installed and deployed following manufacturer guidance in accord with applicable standards, if any.

Following the UL 300 A pre-standard, cooking oil fires were the focus of the experiments conducted here. These were challenging scenarios in terms of fire suppression as the temperature of the fuel was extensively preheated, such that the stored energy in the liquid fuel can present a challenge in terms of re-ignition. Thus, both suppression and prevention of re-ignition must be considered when evaluating these systems.

## 2.1 Range Hood Protection Systems

Range hood protection systems were installed specifically to suppress a fire originating from the range surface. They activated automatically based on a thermal triggering mechanism or in one case a multi-sensor triggering mechanism.

### 2.1.1 Wet chemical Systems 1- 4

The automatic, self-contained, wet chemical systems delivered aqueous fire suppressant designed for Class K fires. Three of the systems tested in these experiments were commercially available systems or a system composed of listed components which could be installed with limited modification to an existing cooking range and exhaust hood. The fourth system was a novel prefabricated system that could be installed onto the wall behind a cooking range. The pressure pan in all four systems used Class K suppression agent, which contained a solution of potassium carbonate and water; the exact compositions were proprietary.

**Table 2-1. Activation temperatures for automatic wet chemical system tests**

Suppressant	Test	Activation Temp (°C)	Suppressant	Test	Activation Temp (°C)
Auto Wet Chem 1	KSE 02	100	Auto Wet Chem 2	KSE 06	182
	KSE 03	100		KSE 07	182
	KSE 04	100		KSE 08	182
	KSG 02	182		KSE 09	182
	KSG 03	182		KSG 05	182
	KSG 04	182		KSG 06	182
	KSG 19	182		KSG 07	182
Auto Wet Chem 3	KSE 05	Not Specified	Auto Wet Chem 4	KSE 10	121
	KSG 08	Not Specified		KSE 11	121
	KSG 18	Not Specified		KSE 21	121
		KSE 22		121	



**Figure 2-1. Components of an automatic, self-contained, wet chemical system (AWC1) including the automatic gas stovetop shutoff valve, which was not used in these experiments.**

The self-contained, wet chemical suppression agent systems were comprised of three basic components related to fire detection, agent storage, and agent delivery. The multi-component systems typically used (1) temperature or heat detector(s) located above the range surface in the exhaust hood, (2) a pressure vessel, which was slightly remote from the range surface in a cabinet or box, and (3) nozzle(s), which was either permanently fixed above the range surface or was mechanically deployed there. These elements can be seen in Figure 2-1 for the AWC1 system. System activation was managed by the system detector; the manufacturer specified activation temperature for each system is given in Table 2-1. The Auto Wet Chem 1 (AWC1) was supplied with two types of eutectic solder links with different activation temperatures (100 °C and 182 °C). AWC2 exclusively used links that activated at 182 °C. AWC3 was a commercial system commonly used in parts of Asia, which was equipped with a proprietary electronic thermal sensor and a smoke sensing system. AWC4 was a prototype system that used a frangible glass bulb with an activation temperature of 121 °C. The test identifiers all include “KS” for Kitchen Suppression and either an “E” for electric range or a “G” for gas range.

The fire detection systems utilized different technologies. AWC1 and AWC2 utilized a mechanical cable/chain device in concert with two thermal links. The links and the cable were under tension. One thermal link was located above each side of the range surface. The cable

was attached to a rigid anchor point at one end, while the other end of the cable was attached to the pressure vessel. When the thermal link activated, it released tension on the cable and the pressure vessel valve opened allowing agent to discharge from the pressure vessel and out of the nozzles. As the agent in the vessel was deployed, the discharge rate slowed until it stopped completely. AWC1 and AWC2 both utilized two nozzles that were positioned near the side edges of the hood, directed such that the agent discharge covered the area on the top of the range. A portion of the cable arrangement and one nozzle from AWC2 can be observed in Figure 2-2.

AWC3 utilized a proprietary electronic thermal system to detect the presence of a fire and used an electro-mechanical mechanism to activate the pressure vessel. The electronics simplified the installation of the system. AWC3 utilized a single nozzle that was positioned above the center of the range. The single nozzle is seen in Figure 2-3 positioned near the hood.



**Figure 2-2.** One side of a “typical” wet chemical system; two thermal links and a nozzle are shown, the opposing side was similarly configured.



**Figure 2-3.** AWC3 was a single nozzle system that used an electrical thermal trigger.

Three of the systems were mounted with the thermal activation links (or sensors) and agent delivery hardware positioned within the exhaust hood of the range; the fourth system, AWC4 was wall-mounted behind the range. A typical arrangement of the wall mounted system can be seen in Figure 2-4. The pressure vessels for the hood-mounted systems were located in a cabinet above the hood for all experiments. For the wall-mounted system, the pressure vessel was integral to the wall mounted structure. The nozzle hardware for all three hood-mounted systems was permanently fixed above the range with each nozzle directed downward, in contrast to the wall-mounted system, which had a spring-loaded deployment mechanism. The wall-mounted system used two nozzles, but the nozzles were essentially co-located on the end of a single tube in the deployment arm. Each nozzle was directed towards the opposite side of the range surface. When one or both of the thermal links activated, the tension on a cable restraining agent



deployment was released. As a spring pulled the deployment arm to the discharge position, a valve mounted on one end of the pressure vessel opened and the agent begins to discharge.

All four of the automatic, self-contained, wet chemical suppression systems were designed to incorporate an automatic range disabling switch, which would remove the heat-production functions of the range either by disabling the electrical input, in the case of an electrical range, or by disabling the gas input, in the case of a gas range. In all experiments for which the suppression system being tested included a disabling device, the range was manually de-energized when the system activated. The commercially available systems also had the capability to de-energize the range either by automatically shutting off the gas or by disconnecting the electricity. In these experiments, power shut-off was accomplished manually within 5 s of the initial activation of the suppression system.



**Figure 2-4.** A wall-mounted, wet chemical system with arms containing heat sensitive bulb used to trigger agent deployment. Thermocouples mounted on the arms were not an intrinsic part of the device.

## 2.1.2 Dry Chemical Systems

The automatic, self-contained, dry chemical systems delivered sodium bicarbonate powder to the range surface. The systems used in these experiments could be installed quickly with limited or no modification to an existing range exhaust hood.

The dry chemical system used for these experiments consisted of two or more self-contained suppression devices. Each device incorporated a flame activated fuse trigger, storage for the dry chemical suppressant, and a small pyrotechnic charge for deploying the suppressant to the range surface. Direct flame impingement on the fuse of the device caused activation. Each device consisted of a canister, approximately 89 mm (3.5 in) in diameter and 86 mm (3.4 in) in height, containing 282 g of sodium bicarbonate powder. In these experiments, two devices were used, each positioned to protect about half of the range surface.

The canister systems were installed directly above the cooking surface in the exhaust hood of each range, as specified by the manufacturer. This allowed the dry chemical to directly fall onto the fire that is being suppressed. Unlike the automatic, wet chemical systems, the dry chemical system was capable of partial activation, only discharging one of the two devices. The dry chemical systems are not equipped with a stovetop power disabling device. Thus, the range continued to heat the fuel during and after deployment of the automatic, dry chemical suppression systems. A typical manufacturer-recommended installation of an automatic, dry chemical system in the vent hood is seen in Figure 2-5.



**Figure 2-5. Autonomous dry chemical system installed above the stovetop. The thermocouples seen in the image were added and were not an intrinsic part of the device.**

### 2.1.3 Water Mist Systems (Water Mist 2 & 3)

The automatic water mist systems delivered water at high pressure through a specialized nozzle designed to achieve sub-mm droplet sizes. Following manufacturer guidance, water was supplied using the laboratory supply line with supplementary pressurization provided by a gas cylinder of nitrogen. The system was electronically activated using a thermocouple mounted several inches from the nozzle with an activation temperature set to 250 °C (482 °F). The supplied gauge gas pressure was maintained at 448 kPa (65 psi) to 483 kPa (70 psi). The single nozzle was installed in the center of the exhaust hood of the range. The water flow rate was mechanically adjustable.



Figure 2-6. Plumbing for a water mist system above the range exhaust hood.

## 2.2 Automatic Room Protection

The automatic suppression systems activated using a thermal triggering mechanism. They were configured so as to protect not only the range surface, but also the kitchen area. Of the two systems used in these experiments, one was a residential sprinkler system installed in accordance with NFPA Standard 13D, whereas the other was a commercially available water mist system for use in industrial and commercial structures. Consideration of its use in residential structures was novel. The water supply for both systems was provided by pressurized water tanks, making both systems independent of the laboratory water supply.

## 2.2.1 Residential Sprinkler

The single water sprinkler used in this system was installed at the center of the room's ceiling. The water supply provided 0.6 L/s (9 gpm) of flow at 0.58 bar (8.4 psi) suitable for a 3.7 m by 3.7 m room as per the sprinkler's listing. The sprinkler was a typical commercially available surface mounted pendant sprinkler fashioned with a heat-sensitive bulb as a thermal trigger. The sprinkler had a nominal K-Factor of 3.1 and an activation temperature listed as 68 °C (155 °F). The sprinkler head used in these experiments is shown in Figure 2-7.

## 2.2.2 Water Mist (Water Mist 1)

This system used a single mist nozzle located at the middle of the ceiling of the experimental structure. The system was supplied with water at 450 kPa (65 psi) to 480 kPa (70 psi) from pressurized tanks. As with the residential sprinkler, a heat sensitive bulb served as a thermal trigger for the nozzle. The nominal activation temperature was 79 °C (175 °F). The multi-nozzle water mist head used in these experiments is shown in Figure 2-8.



Figure 2-7. Water sprinkler head.



Figure 2-8. Water mist nozzle.

## 2.3 Handheld Extinguishers

Handheld extinguishers suppress a fire when the contents are sufficient in amount and are appropriately directed at the fire. Tests using handheld extinguishers were conducted by staff with extensive experience in handheld fire suppression techniques per manufacturer's instructions and NFPA 10 [8].

### 2.3.1 Dry Chemical

The handheld dry chemical suppression device consisted of a pressurized tank filled with a Class B and Class C powder suppressant and a nozzle to deploy the agent manually. The device could

be activated by a trigger on the handle and aimed into a kitchen fire where the suppressant will be deployed. This device can project the dry chemical suppressant nearly 5 m (16 ft) allowing it to be deployed from a safe distance. However, because of the high velocity of the suppressant, this type of extinguisher can be dangerous when used on an oil fire at close range because significant agitation of the oil can result, causing spatter and potentially serious injury. The dry chemical suppression device tested here is shown in Figure 2-9.



**Figure 2-9. Discharge of manual dry chemical extinguisher.**

### **2.3.2 Wet Chemical**

The handheld wet chemical suppression device consisted of a pressurized tank filled with a Class K aqueous suppressant and a nozzle to deploy the agent manually. The device could be activated by a trigger on the handle and aimed into a kitchen fire from a safe distance. Although this device could not be deployed from as great a distance as the dry chemical extinguisher, it provided no significant danger of spatter related injury. A typical wet chemical suppression device is shown in Figure 2-10.



**Figure 2-10. Discharge of manual wet chemical extinguisher.**

## 2.4 Suppression System Characterization

The suppression systems were characterized in terms of the distribution and rate of agent delivery to the fire source, presumed to be the area defined by the stovetop itself. Measurements were made by deploying the suppression system in the absence of a fire for a given amount of time onto an array of square (0.15 m by 0.15 m) containers stationed about the stovetop. The mass flux distribution and delivery rates were determined by weighing the mass of the containers before and after suppressant deployment. Figure 2-11 shows typical measurement results. Here, a normalized gray-scale image of the distribution of water droplets delivered to various sections of a gas stovetop and its surroundings by a water sprinkler. The image is normalized such that pure black represent the maximum local water flux, which was  $180 \text{ g/m}^2\text{-s}$ . The measured average value of the water sprinkler delivery on the surface of the stovetop was  $69 \text{ g/m}^2\text{-s}$  and the standard deviation of this spatial average was  $\pm 80 \%$ . Reporting the average and standard deviation is a reasonable way to characterize the magnitude and uniformity of suppressant application, but it only provides a temporal and spatial average in the absence of a fire. It does not fully define suppressant performance. Optimal suppressant application would be spatially uniform and temporally constant in the presence of the target fire. In addition, the application would need to maximize fuel containment so that splashing of burning fuel beyond the confines of the vessel would not present a hazard.

**Table 2-2** shows results for the mass delivery rate distribution of the suppressants. There was large variation in average delivery rate among the various suppressant types and the products within one technology type. The largest and smallest mass fluxes were the dry chemical and the water mist, respectively. The largest variance in the spatial distribution over the stovetop was for the dry chemical, which was a value of almost 200 %. Low uniformity of agent delivery can impact suppression system performance. It should be noted that these measurements were

conducted in the absence of the oil vapor plume or a fire, which may significantly impact the trajectory and ultimate distribution of any agent, particularly for large fire plumes.

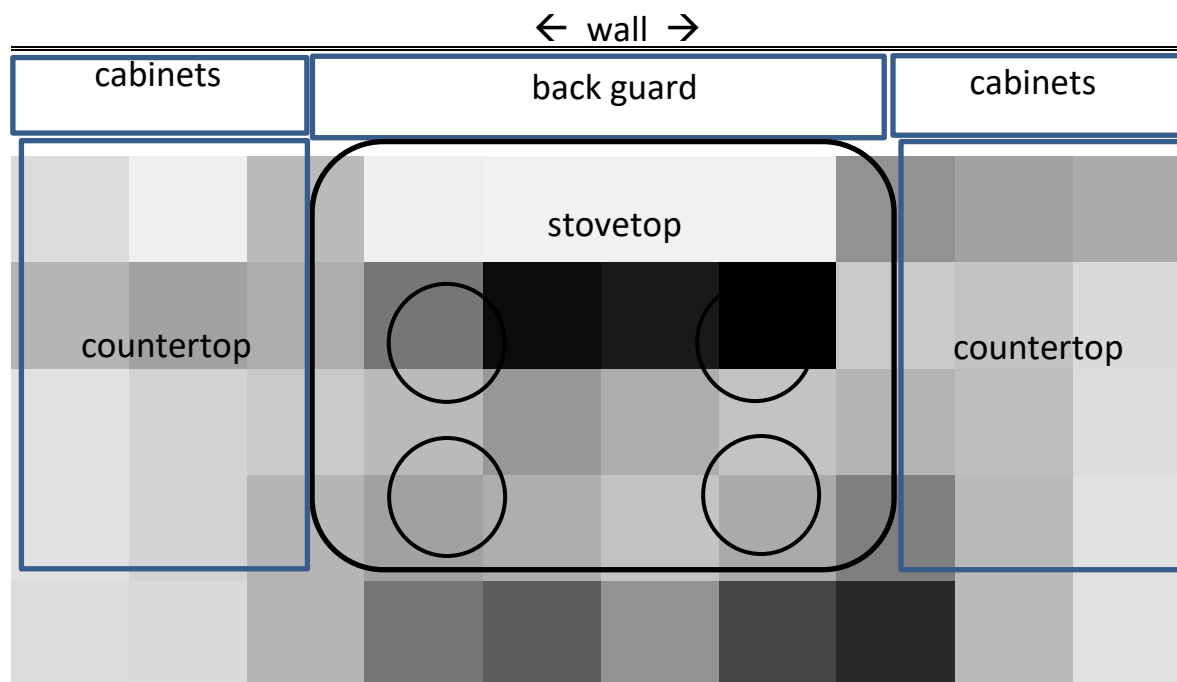


Figure 2-11. Gray-scale map of the measured mass distribution of water delivered by the sprinkler onto the gas stovetop and surroundings normalized by the maximum local water flux ( $180 \text{ g/m}^2\text{-s}$ ) represented as pure black. Nearby wall, cabinets and countertops are also shown.

**Table 2-2. Mass delivery rate, spatial variance and total mass of the suppressants**

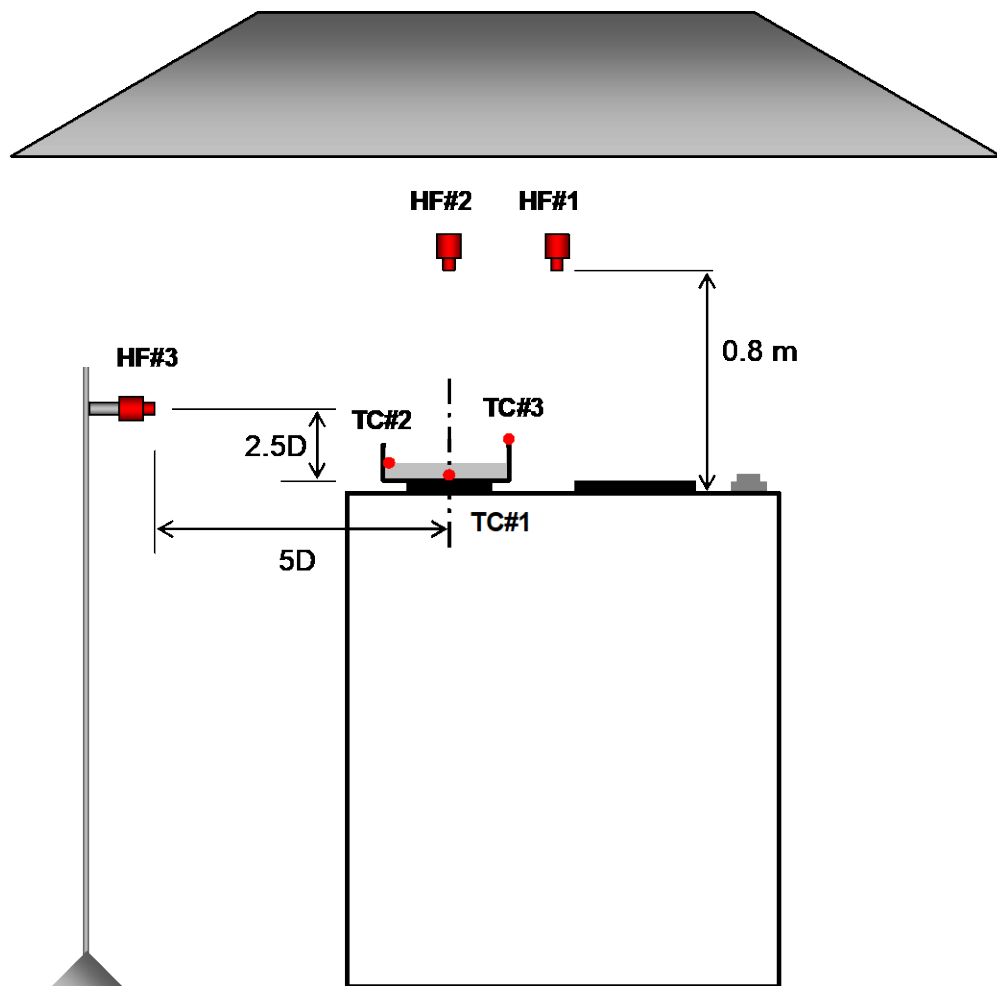
Suppression System	Average Delivery Rate ( $\text{g/m}^2\text{-s}$ ) *	Spatial Variance (Percentage)	Total Mass Available (kg)
Sprinkler	69	80	Unlimited
Water Mist 1	3.7	50	64
Water Mist 2	14	170	1.2
Water Mist 3	210	68	2.0
Wet Chem 1	28	94	1.1
Wet Chem 2	50	59	1.4
Wet Chem 3	5.0	210	0.4
Wet Chem 4	34	107	2.0
Dry Chem	145 **	210	0.3

\* the spatial variation (see column to the right) is a representation of the uncertainty  
 \*\* based on a 10 s delivery time (estimated based on observations)

### 3 Cooktop Fire Characterization

A series of experiments designed to characterize cooking oil fires on kitchen cooktop burners was conducted. Oil type, oil volume, pan type, and cooktop type were varied to quantify the heat release rate, mass loss rate, heat flux, and time to auto-ignition.

#### 3.1 Experimental Apparatus and Configuration



**Figure 3-1. Schematic diagram of the apparatus used in the cooking oil fire characterization experiments.**

Figure 3-1 shows a schematic diagram of the experimental configuration and a photo of the experimental arrangement is presented in Figure 3-2. A single burner, either electric or gas, was used to provide energy to heat the test pan. The (a) electric and (b) gas stovetops are seen in Figure 3-3. The electric cooktop was furnished with two large (195 mm diameter) and two small (150 mm diameter) coiled heating elements.





**Figure 3-2. Photograph of the experimental configuration and instrumentation during Test 1.**



**(a) Electric stovetop**

**(b) gas stovetop**

**Figure 3-3. Photographs of the electric and the gas cooktops used in the cooking oil fire characterization experiments.**

The experimental set-up included the pan sizes and oil volumes specified by UL300A [7]. Four kinds of pans were tested to examine their effect on the character of fires burning cooking oils.

The pan sizes and materials were specified in UL300A [7]. The test pans varied in size, shape, and material composition, as shown in Table 3-1. Pans A, B, and C were actual commercial cookware and included a cast iron skillet, a deep pot or “Dutch oven”, and a sauce pan, respectively. Pan D was a fabricated 53 cm by 46 cm rectangular pan with a 7.6 cm depth. The pan was designed to cover a large portion of the cooktop surface, representing an oil spill fire.

Pans A, B, and C were placed on the left side of the electric cooktop with Pan C placed on the small front heating element and Pans A and B placed on the large rear heating element. The power delivered to the electric stovetop heating elements was specified by the manufacturer as 2400 W and 1500 W for the larger and smaller coiled elements, respectively. The larger heating element was composed of 5 spirals of Inconel rod in a 8 in (20 cm) diameter round, whereas the smaller heating element was composed of 4 spirals in a 6 in (15 cm) diameter round. For the gas stovetop, the flow rate of natural gas was measured to estimate the power output. The flow rate was measured as 0.043 L/s ± 0.002 L/s, which was equivalent to approximately 1400 W.

**Table 3-1. Test pan summary**

Type	Shape	Width (cm)	Depth (cm)	Material	Pan Mass (g)	Oil depth (cm)	Oil Volume (ml)
Pan A	round	33*	5	Cast iron	4230 ± 10	2.5 ± 0.2	1650 ± 10
Pan B	round	25*	18	Stainless Steel	1250 ± 10	10.0 ± 0.2	4500 ± 10
Pan C	round	10*	5	Stainless Steel	1420 ± 10	2.5 ± 0.2	215 ± 5
Pan D	rectangular	53 x 46	7.6	Steel	3000 ± 800	0.6 ± 0.1	1600 ± 20

\* inner diameter at uppermost portion of the rim (or lip) of the pan

The cooking oils specified by the UL 300A method were peanut and vegetable oil. Commercial vegetable oil is typically a blend of various types of oils. In this study, fresh commercial 100 % corn oil was substituted for the vegetable oil in an effort to improve repeatability. Table 3-1 lists the volume of oil used in each pan and the resulting oil depth. Table 3-2 lists the thermophysical and combustion properties of the oils including their density, flash point, and auto-ignition temperature. The auto-ignition temperature of corn oil is significantly lower than that of peanut oil [9].

**Table 3-2. Thermophysical and combustion properties of oils [9]**

Oil type	Density (kg/m <sup>3</sup> )	Flash point (°C)	Auto ignition temperature (°C)
Corn	918	254	392
Peanut	920	282	445

## 3.2 Apparatus

The behavior of the ignition event and subsequent fire were characterized by measuring the ignition time, heat flux, heat release rate, pan temperature, and oil mass loss rate. The entire test was recorded using a digital video camera including the period before ignition that involved oil heating, the moment of ignition, and fire growth. The camera was positioned about 5 m from the stove. The power for the gas cooktop was measured using a dry test meter and stopwatch, while the power for the electric cooktop was based on manufacturer information.

The open burn tests were performed under the 3 m x 3 m exhaust hood in the NIST Furniture Calorimeter. The heat release rate was determined using oxygen consumption calorimetry which involved the measurement of many quantities as described in Ref. [10]. The response time of the system is such that it can accurately resolve dynamic heat release rate events of 15 s or more. The expanded uncertainty was estimated as  $\pm 11\%$  for fire sizes larger than 400 kW and about 15% for smaller fires, based on calibration and repeat measurements.

Three thin (1.6 mm) stainless steel-sheathed type K thermocouples were spring-loaded such that they made contact at various positions on the pan surface to monitor the temperature (see Figure 3-1). Thermocouples were positioned at the center of the pan bottom, on the inner side wall at the oil-fill level, and on the pan rim. The standard uncertainty of the temperature measurement was 2 °C, as specified by the manufacturer [11]. Unless stated otherwise uncertainties reported here are Type B standard uncertainty [12].

Three calibrated water-cooled Schmidt-Boelter heat flux gauges were used to measure the local time varying heat flux emitted by the fire. The gauges had a wide view angle (150 ° view angle) and were coated with a high emissivity paint that had a flat spectral response in the infrared. The gauges had a time response of approximately 2 s [13]. A gauge (HF#3 in Figure 3-1) was directed towards the fire and positioned a approximately 5 times the pan diameter (D) in the horizontal direction (from the pan center) and 2.5 times the pan diameter above pan rim. Two gauges (HF#1 and HF#2 in Figure 3-1) were oriented downward and placed 0.8 m above the center of the pan and above the center of the cooktop, respectively. The heat flux gauges were calibrated using a secondary standard in a well-characterized radiometer facility and the expanded uncertainty of the measurement was estimated as 8% [14].

The fuel mass loss rate due to evaporation and burning of the cooking oil was measured using a load cell that was positioned under the stove. Based on repeated calibration measurements, the standard uncertainty in the load cell was about 10 g with a stove tare weight of about 50 kg.

## 3.3 Test Procedure

The fire tests were performed for different combinations of pan type, oil type and stove type, following the UL300A test guidance [7]. The test procedure involved the following steps. The hood exhaust was opened and the calorimetry system prepared. The instruments were zeroed and the data acquisition system initiated. The volume of oil used in each test was measured using

a graduated cylinder. The oil was carefully introduced into the pan to avoid spillage. The cooktop element or burner was energized to its highest level and the time was noted.

As the pan heated, a vapor cloud was generated above the liquid oil, which became visible with time. For most of the experiments, the cooktop power was stopped shortly after ignition was observed to prevent thermal damage to the instrumentation. For tests using small amounts of oil (those using Pan C; Tests 1, 2, 4, 11, and 12), the experiments continued until flaming ceased and no oil was observed to remain in the pan. The peak heat release rate was measured in these experiments using oxygen consumption calorimetry. For the other tests, burning was stopped before fuel burnout due to safety concerns. In these cases, the maximum value of the measured heat release rate is listed in Table 3-3.

### 3.4 Results

Twelve full scale fire tests were conducted to investigate ignition and stovetop fire characteristics, such as ignition time, mass loss rate, heat release rate, and heat flux emitted by the fire. Table 3-3 lists the mass of oil tested and the experimental conditions, including the types of cooktop, oil, and pan used. Corn oil was used in 7 tests and peanut oil was used in 5 tests. Pan C was used in 5 experiments, which was the most, followed by Pans A and B, which were used 3 times each. Pan D was used once.

**Table 3-3. Summary of tests**

Test No.	Stove type	Power (kW)	Oil type	Pan <sup>B</sup>	Initial oil mass (g)	Time to ignition (min:s)	Peak HRR <sup>D</sup> (kW)
1	Electric	1.4 ± 0.3	Corn	Pan C	187 ± 10	17:52 ± 5	73 ± 20
2 <sup>A</sup>	Electric	1.4 ± 0.3	Corn	Pan C	187 ± 10	20:00 ± 5	101 ± 20
3	Electric	2 ± 0.5	Corn	Pan B	4000 ± 10	77:40 ± 5	472 ± 20 <sup>E</sup>
4	Gas	1.6 ± 0.2	Peanut	Pan C	185 ± 10	16:14 ± 5	66 ± 20
5	Gas	1.6 ± 0.2	Corn	Pan A	1476 ± 10	> 93 <sup>C</sup>	C
6	Gas	6.4 ± 0.8	Corn	Pan D	1432 ± 10	24:20 ± 5	91 ± 20 <sup>E</sup>
7	Gas	1.6 ± 0.2	Peanut	Pan B	4200 ± 10	145:30 ± 5	26 ± 20 <sup>E</sup>
8	Electric	2 ± 0.5	Peanut	Pan A	1454 ± 10	61:10 ± 5	16 ± 20 <sup>E</sup>
9	Electric	2 ± 0.5	Corn	Pan A	1477 ± 10	57:24 ± 5	30 ± 20 <sup>E</sup>
10	Electric	2 ± 0.5	Peanut	Pan B	4004 ± 10	79:35 ± 5	35 ± 20 <sup>E</sup>
11	Electric	1.4 ± 0.3	Peanut	Pan C	186 ± 10	19:10 ± 5	100 ± 20
12 <sup>A</sup>	Electric	1.4 ± 0.3	Corn	Pan C	191 ± 10	18:17 ± 5	115 ± 20

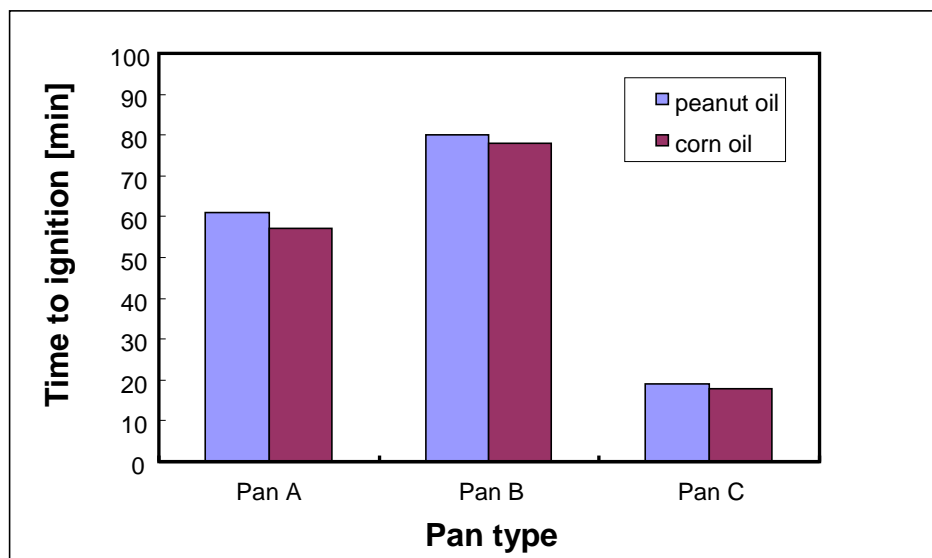
A. repeat of Test 1  
 B. see Table 3-1 for a description of the pans  
 C. ignition not observed  
 D. HRR is the heat release rate; here, measured by oxygen consumption calorimetry  
 E. value of HRR when test was stopped (due to safety concerns)

### 3.4.1 Ignition

Table 3-3 also lists the time at which ignition was observed. Ignition took a significant amount of time and lots of oil vapor was generated before ignition. Figure 3-4 shows the plume of cooking oil vapor above the pan before ignition during Test 2. The time to ignition varied from 18 min to 145 min, depending on test conditions. Generally, the time to ignition was a function of the initial mass of the cooking oil, the mass of the pan, and the cooktop power. The conditions from Test 1 were repeated two additional times (Tests 2 and 12), and the time to ignition was observed to be repeatable with in about 10 % (standard deviation equal to about 10 %). Test 5 was terminated after 93 min, because ignition was not observed and the temperature of the pan did not significantly increase, according to the thermocouple measurements monitoring the pan temperature.



**Figure 3-4. Plume of cooking oil vapor above pan before ignition during Test 2.**



**Figure 3-5. Comparison of the measured time to ignition as a function of pan and oil type on the electric cooktop.**

Figure 3-5 presents the time to ignition of the corn and peanut oils in the three pans (Pans A, B, C) on the electric cooktop. For each of the pans, the time to ignition of the corn oil was 5 % to 10 % lower than that of the peanut oil consistent with its lower auto-ignition temperature (see Table 3-2).

Ignition took somewhat longer on the electric cooktop for Pan B as compared to the gas cooktop, whereas there was little difference in the time to ignition for Pan C. This is attributed to the lower power output of the gas cooktop used in these experiments but other factors may have played a role. Understanding the details of the heat transfer processes to the pan and the oil was beyond the scope of this study.

### 3.4.2 Heat release rate of cooking oil

Figure 3-6 shows the time varying heat release rate  $\dot{Q}(t)$  from the calorimetry and the 20 s running average of the mass loss rate (or mass burning rate) as a function of time of corn oil during Test 2. As expected, the maxima of the heat release rate and the corn oil mass burning rate occur at about the same time. The average burning rate of cooking oil is calculated as follows:

$$\dot{m}_{avg} = \frac{\Delta m}{\Delta t} \quad (1)$$

where  $\dot{m}_{avg}$  and  $\Delta m$  represent, respectively, the average mass loss rate of the cooking oil and the change in the mass of the oil over that time period, typically taken as the test duration ( $\Delta t$ ). The average heat release rate ( $\dot{Q}_{avg}$ ) is related to the average mass burning rate ( $\dot{m}_{avg}$ ), the heat of combustion ( $H_c$ ), and the combustion efficiency ( $\chi_a$ ):

$$\dot{Q}_{avg} = \chi_a \cdot H_c \cdot \dot{m}_{avg} \quad (2)$$

Because Tests 2 and 11 were conducted using an electric stove, no correction was necessary for combustion due to natural gas associated with powering the gas stove. A comprehensive discussion of the measurement uncertainty, using the NIST furniture calorimeter, is given in Ref. [10].

Figure 3-6 and Figure 3-7 present the measured heat release rate and the mass burning rate,  $\dot{Q}(t)$  and  $\dot{m}(t)$ , as a function of time during Tests 2 and 11, respectively. The maximum values of the heat release and mass burning rates during Tests 2 and 11 were roughly 100 kW and 2 g/s in both experiments. Both tests were carried out with Pan C, but with peanut oil for Test 2 and corn oil for Test 11. Previous oxygen bomb calorimetry measurements report a value of about 37 kJ/g to 41 kJ/g for edible oils [9]. Thus, the similarity in the measured heat release rates is not unexpected.

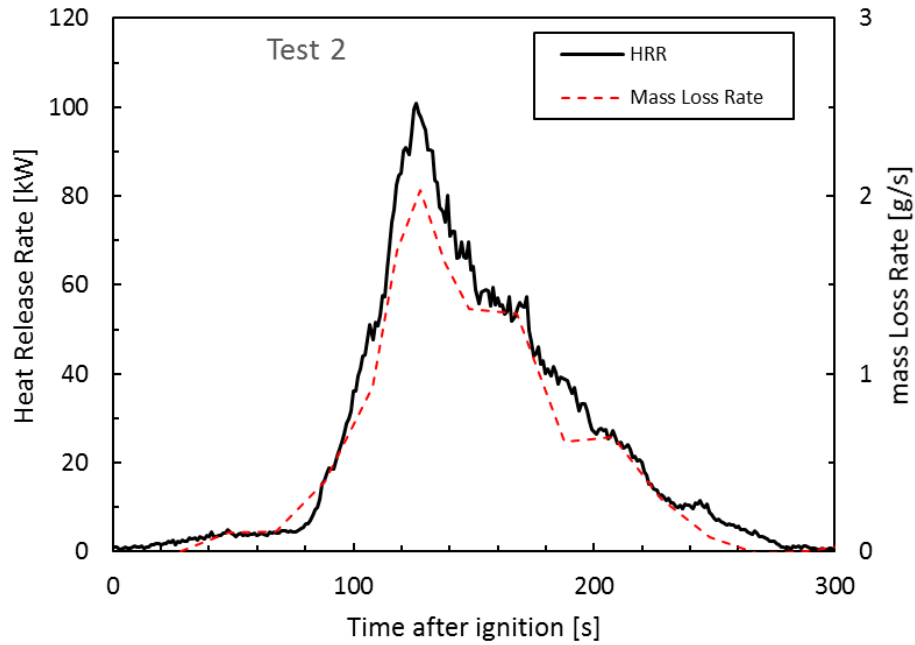


Figure 3-6. Measured heat release rate and mass loss during Test 2 (corn oil in Pan C).

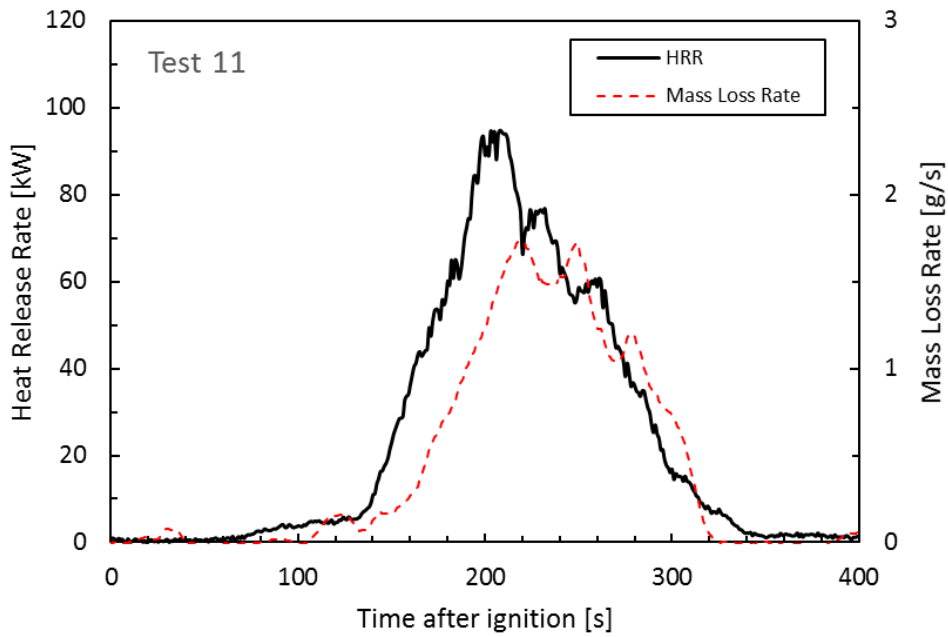
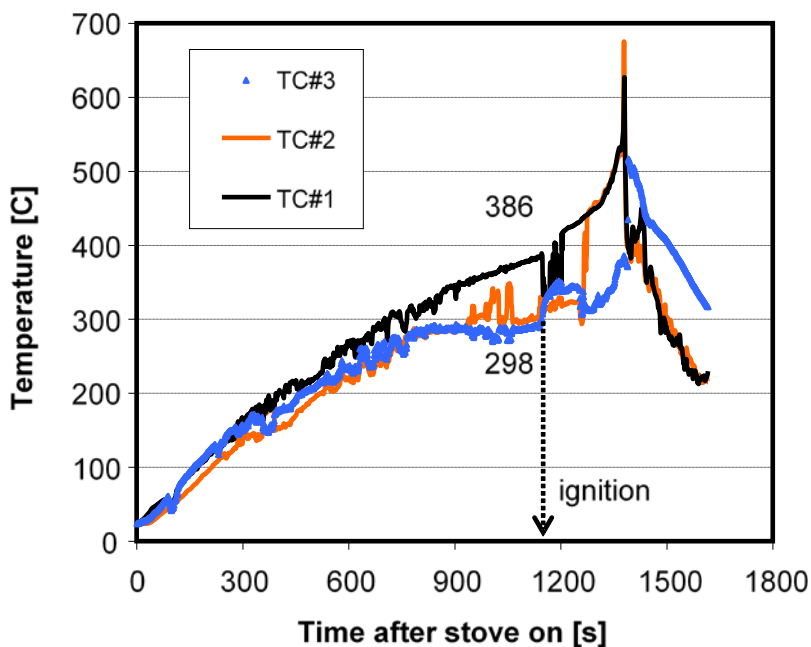


Figure 3-7. The measured heat release rate and mass burning rate during Test 11 (peanut oil in Pan C).

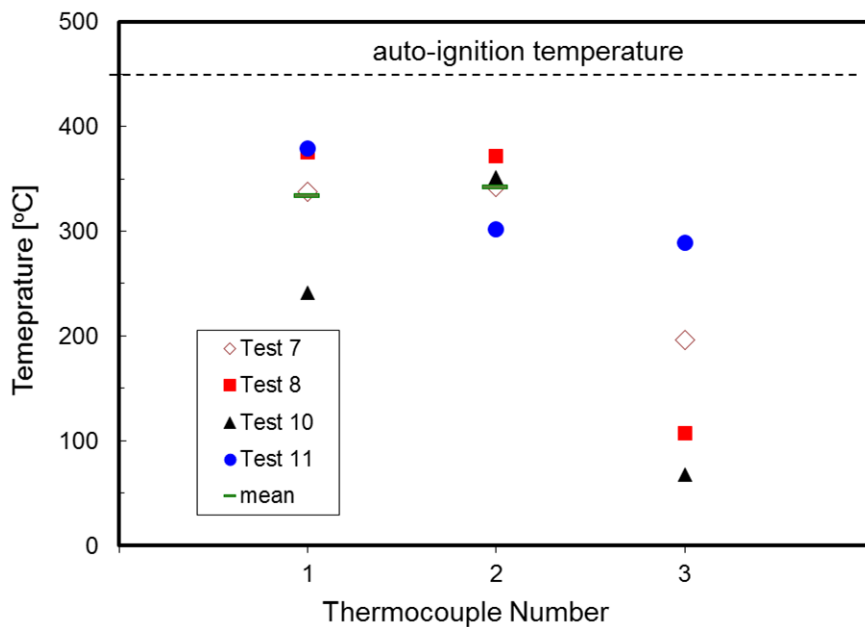


### 3.4.3 Ignition surface temperature and fire characteristics

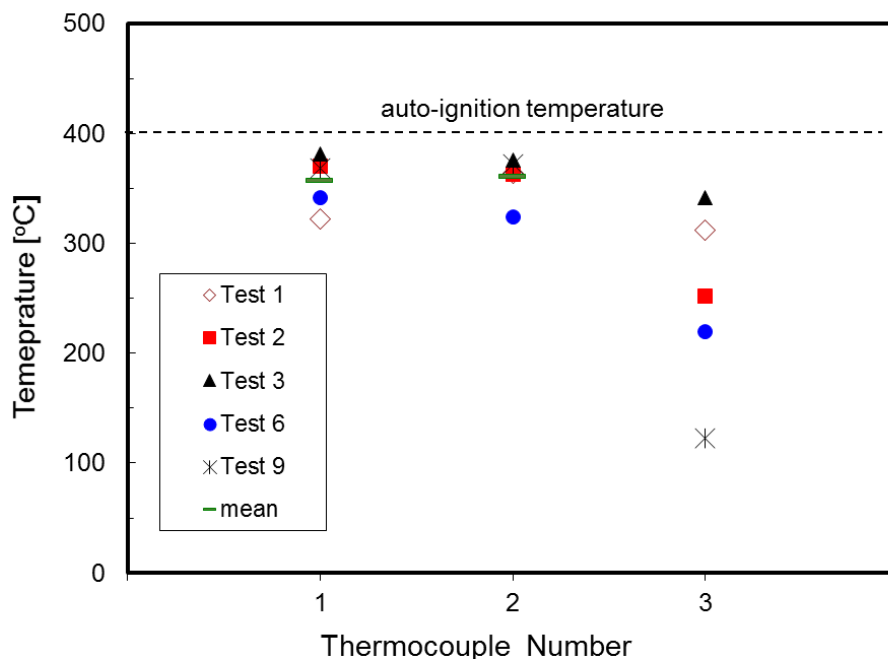
The time history of the fuel temperatures during Test 11 (peanut oil) is presented in Figure 3-8 as a function of time after stove start-up. Figure 3-1 shows the locations of thermocouples 1, 2, and 3, which were located at the bottom of the pan, on the inner side-wall of the pan halfway between the rim and the pan bottom, and at the top of the rim, respectively. The temperature slowly increased until ignition occurred at about 1150 s. At that time, the oil surface temperature (TC#3) abruptly increased and the fire was observed to quickly grow. Figure 3-9 and Figure 3-10 show the measured pan temperatures at the time of ignition for each of the tests. This information is also summarized in Table 3-4. Tests 6 and 7 were conducted using the gas stovetop burner, whereas the other tests used the electrically powered stovetop burner. No discernable difference was evident between gas and electric stovetop results. Both figures indicate that the pan temperature at ignition varied as a function of location. For the given temperature measurement locations, ignition generally occurred significantly below 381 °C, a value lower than the reference auto-ignition temperatures (see Table 3-2). This result is attributed to the fact that the temperature was measured at only three positions and apparently not at the exact ignition location where the local temperature was expected to exceed the auto-ignition temperature. The temperature at the pan rim showed the most variation. At the time of ignition, the mean sidewall temperature (TC #2) was nearly equal to the mean temperature at the pan bottom (TC #1). The pan bottom temperatures at ignition were somewhat below previously reported results for auto-ignition experiments that used less volumes of oil [15].



**Figure 3-8** The evolving temperatures measured at three locations on the cooking vessel (see Figure 3-1) during Test 11 (peanut oil in Pan C).



**Figure 3-9.** Measured mean temperatures on the cooking pan (see Figure 3-1) at the time of peanut oil ignition during Tests 7, 8, 10, and 11.



**Figure 3-10.** Measured mean temperatures on the cooking pan (see Figure 3-1) at the time of corn oil ignition during Tests 1, 2, 3, 6, and 9

**Table 3-4. Pan surface temperatures at the time of ignition.**

Oil Type	Test No.	Thermocouple Results *		
		T <sub>1</sub> (°C)	T <sub>2</sub> (°C)	T <sub>3</sub> (°C)
Corn oil	Test 1	322	312	364
	Test 2	370	252	363
	Test 3	381	341	375
	Test 6	342	220	324
	Test 9	368	123	372
Peanut oil	Test 7	337	196	342
	Test 8	375	107	371
	Test 10	241	68	351
	Test 11	379	289	302

\* the standard uncertainty of the measurement is 2 °C based on manufacturer information.  
locations of the thermocouples on the pan surface are shown in Figure 3-1.

Figure 3-11 shows the measured heat fluxes measured at three locations about the fire. The locations of the gauges are shown in Figure 3-1, which were positioned to the side and above the pan. The maximum heat flux was recorded in the plume directly above the pan, which was larger than 20 kW/m<sup>2</sup>. Figure 3-12 shows the concentration of CO and CO<sub>2</sub> measured in the exhaust duct during Test 1. The CO volume fraction produced by the burning of the cooking oil was 30 μL/L, which occurred during the peak of the heat release rate, whereas the CO<sub>2</sub> mole fraction reached a value of 3000 μL/L. A CO concentration of 30 μL/L is not particularly severe in terms of human physiology with the 8-hour total weight average permissible exposure limit listed as 50 μL/L for CO [16]. During most of the test, the CO/CO<sub>2</sub> volume fraction ratio was less than 1 % except during the peak heat output period, when a maximum value of 1.4% was obtained.

Figure 3-13 shows photographs of the evolving corn oil fire in Pan C as a function of time along with the measured heat release rate during Test 2. As the cooking oil and the pan were heated, copious amounts of oil vapor was generated above the liquid fuel surface, until ignition was observed. When ignited, the initial flame height was very small and the flame was observed to reside within the pan. With time, the liquid oil temperature increased and the fire grew with the flame height larger than 4 times the pan diameter due to the increased mass-burning rate of the fuel. Finally, the fuel began to visibly boil. Bubbling oil was observed overflowing the pan, falling onto the stovetop. Flames then spread along the stovetop, serving to heat the outside of the pan, further heat the oil and increase the heat release rate. The instantaneous flame height was larger than 10 times the diameter of the pan at the time of the peak heat release rate. As the oil was consumed, the fire size diminished and smoke from the fire appeared very dark. Finally, the fire extinguished due to complete consumption of the fuel.

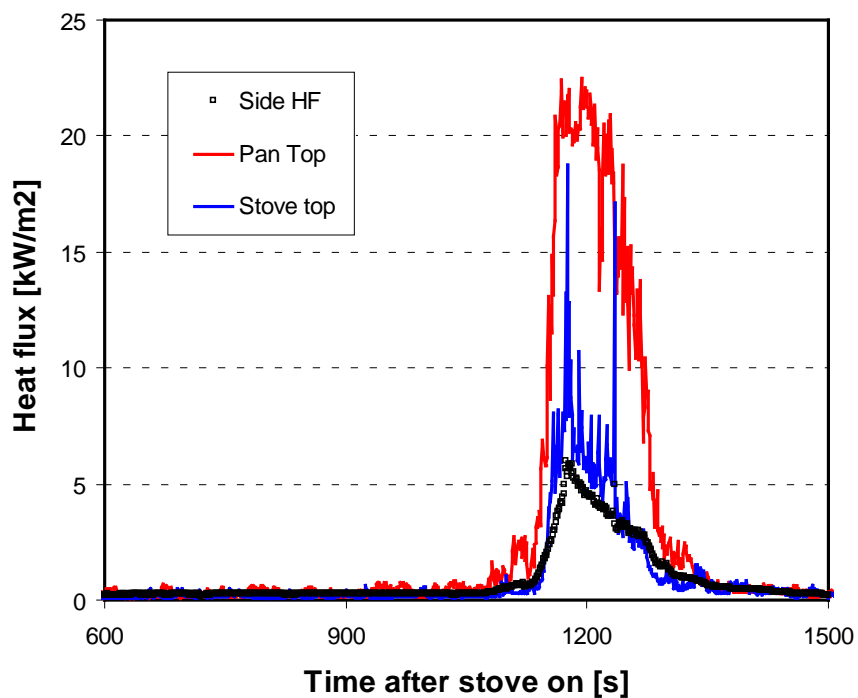


Figure 3-11. The measured heat flux at three positions near the stove (see Figure 3-1) during Test 1 (corn oil in Pan C).

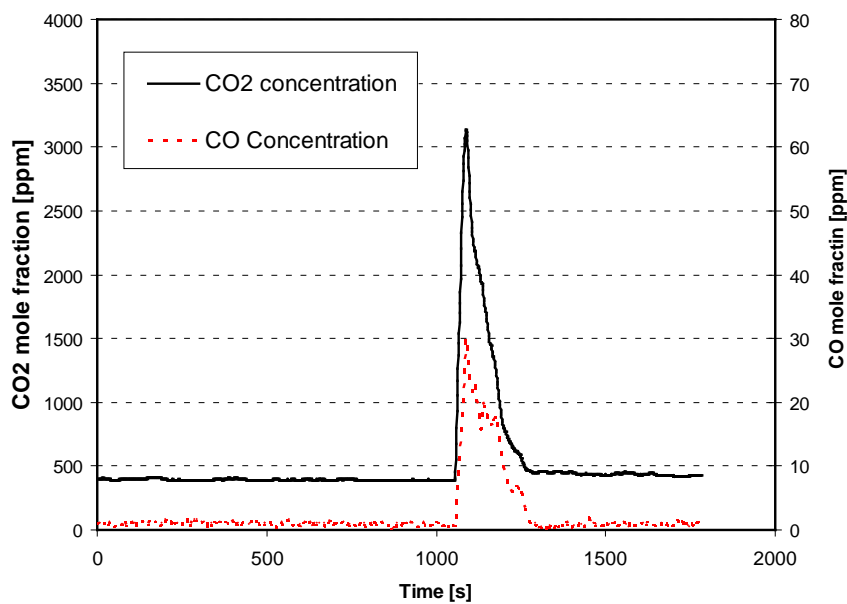


Figure 3-12. The measured CO and CO<sub>2</sub> volume fraction in the exhaust hood as a function of time during Test 1 (corn oil in Pan C).

Figure 3-14 shows photographs of a corn oil fire in Pan B as a function of time along with the measured heat release rate during Test 3. Experimental observations of the ignition and initial fire characteristics were like the results shown in Figure 3-13 for Test 2, except there was a longer pre-heating time associated with the more massive Pan B. After ignition, the fire heat release rate steadily increased until it reached about 50 kW, at which time the heat release rate rapidly increased to about 500 kW as the corn oil boiled and overflowed the pan. At that time, the fire was manually suppressed.

### 3.5 Summary of Cooktop Fire Characterization Experiments

Experiments were conducted to investigate the ignition and burning characteristics associated with the cooktop fire scenarios defined in UL300A. From a safety perspective, the pan with the smallest amount of oil (Pan C) was the easiest to ignite, because it did not require a long pre-heat time. Once the oil began to boil-over, the pan with the largest amount of oil (Pan B) appeared to be the most hazardous, producing a sudden jump in the heat release rate, flame height, and radiative flux. Although the stove was de-energized and hand-held portable CO<sub>2</sub> fire extinguishers were deployed to suppress the fire, suppression efforts were fruitless once boil-over occurred. This was a key lesson from this set of experiments.

The large value of the heat release rates and associated flame lengths were unexpected, considering that the steady burning heat release rate for a hydrocarbon (e.g., heptane) pool fire of the same diameter as used in these tests is typically an order of magnitude smaller than that measured here [17]. Using the value of the ratio of the heat of combustion to the latent heat of vaporization for corn oil (=54) [18], and applying the results shown in Fig. 12 in Ref. [17], the expected heat release rate for a steadily burning 0.1 m diameter corn oil pool fire was about 9 kW, which is a factor of 11 times less than that measured during Test 2 (see Figure 3-13). Thus, a pool fire heated from below represents a significant fire hazard in terms of flame length, heat release rate, the potential to spread to nearby items and to injure people attempting to extinguish such a fire. This will be discussed further in the next section in terms of the full-scale experimental results.

A critical consideration in designing a strategy to mitigate stovetop fires is that suppression must be attempted at an early stage of fire development. An effective fire prevention strategy might consider detection of fuel vapor and de-energization of the stovetop, even before auto-ignition takes place.

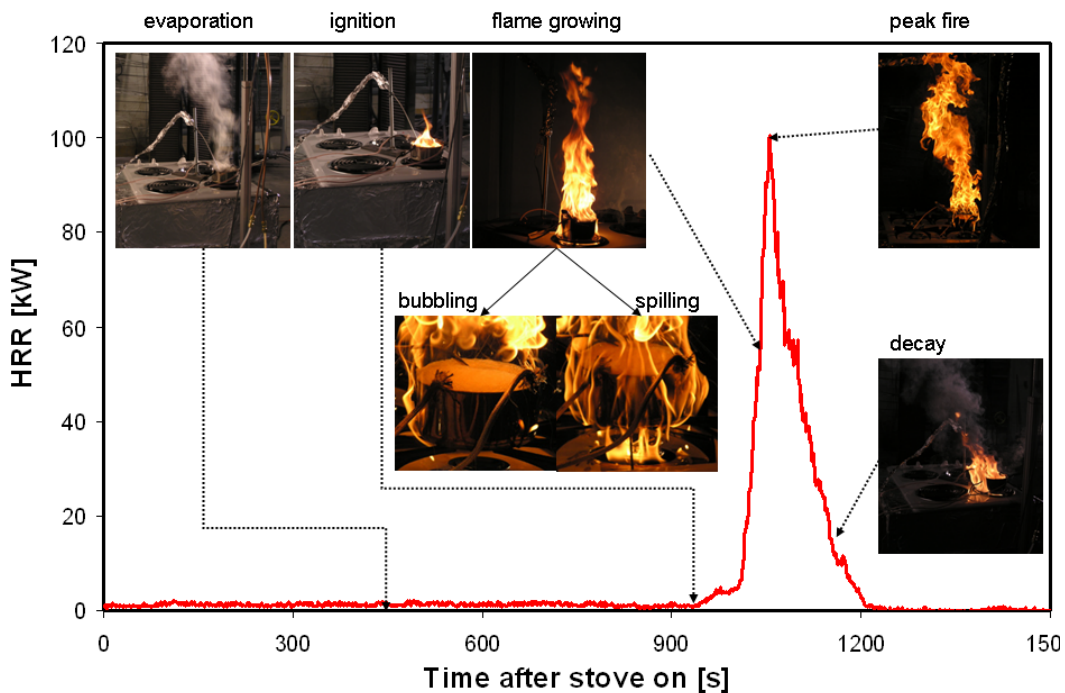


Figure 3-13. The measured heat release rate as a function of time during Test 2 (corn oil in Pan C). Photographs of the fire behavior are also shown.

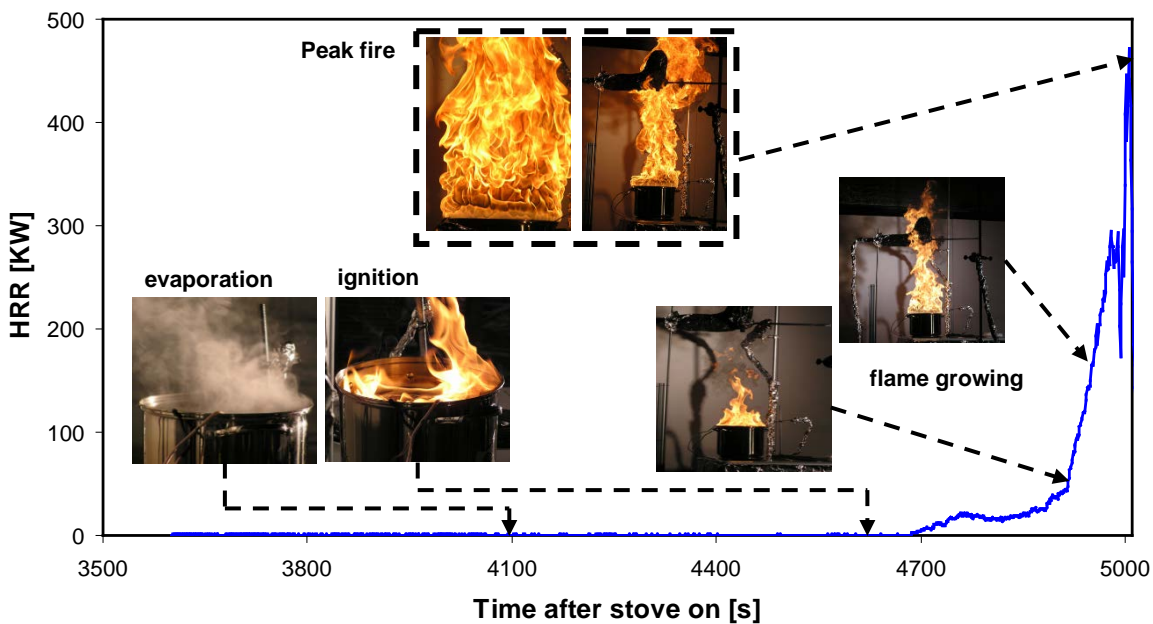


Figure 3-14. The measured heat release rate as a function of time during Test 3 (corn oil in Pan B). Photographs of the fire behavior are also shown.

## 4 Description of Kitchen Fire Suppression Experiments

A series of laboratory experiments were designed to characterize the effectiveness of a variety of commercially available and prototype suppression systems on range-top cooking oil fires. Corn oil was used, as it was assessed to be an adequate representation of cooking oil used in the home.

The suppression systems tested included automatic and manual suppression technologies. The intent of these experiments was to identify factors which limited the success of suppression technologies in controlling and suppressing stove-top fires and maintaining occupant tenability. The experimental series included 42 tests and 11 different suppression devices. Room size, ventilation, the type and layout of room contents, and other factors can influence fire development and fire suppression. A representative configuration was selected for testing that included an open door, a moderately sized room, and the placement of cellulose-based cabinets adjoining the cooktop.

Heat flux, gas concentration, and temperature measurements were conducted to assess the tenability of the kitchen area before and during suppression. Several additional temperature measurements were made to document the progression of the oil heating and ignition process.

### 4.1 Experimental Set-up and Procedure

The fire suppression experiments were conducted using a full-scale residential kitchen arrangement. The dimensions of the test room were 3.6 m x 3.4 m x 2.4 m high. A doorway (0.90 m x 2.03 m) provided ventilation and access to a partial “hallway” situated just outside the door (see

Figure 4-1). The entire room was situated under a large exhaust hood. The mock-up kitchen was built using two layers of 12.7 mm thick gypsum board over steel studs and joists and was furnished using typical materials. The room used vinyl sheet flooring over a nominal 19 mm plywood sub floor. The cabinets were vinyl covered medium density particle board with wooden doors. The counters were medium density particle board with a plastic laminate coating. A vent was located above the range in all tests. This vent was 0.54 m (1.8 ft) above the surface of the range and connected to an exhaust hood. In most tests, the fan was off or the duct system was removed to make room for the suppression system. Schematics of the test compartment and the arrangement of the room contents are shown in Figure 4-2 to Figure 4-4.



Figure 4-1. View of kitchen and adjoining hallway through doorway (left) and side view of the kitchen under a canopy exhaust hood (right). The burning corn oil on the stovetop and the smoke alarm outside the kitchen are visible in the image on the left.

Both gas and electric ranges were tested. The stoves were commercially available for residential use. Twenty-two of the forty-two tests were conducted using an electric range, which heated food using resistance coils; these tests were labeled with the abbreviation “KSE”. The remaining twenty tests were conducted with a cooktop that heated food using natural gas flames; these tests were labeled with the abbreviation “KSG”. The model of range used varied between experiments as did the output of the burners on those ranges, as specified in Table 4-1.

Both automatic and manual suppression system technologies were tested, including commercially available systems and systems under development. The manual devices included wet and dry chemical type extinguishers. The automatic systems included room-wide and range hood installed systems. The room wide systems included one water mist suppression system and one residential sprinkler system. The hood installed systems included water mist, wet chemical, and dry chemical suppression types. Many of the automatic suppression systems incorporated a device that disabled the cooktop power upon activation of the suppression system.

For the tests evaluating the automatic suppression systems, once the suppressant delivery system was activated, the scene was observed for several minutes to determine if re-ignition would occur. If it did occur, the fire was manually suppressed. In the 9 tests in which reignition occurred, the fire was allowed to burn for 100 s, then suppressed manually using a handheld extinguisher.



A skillet or pot containing 100% corn oil was heated to auto-ignition. Several types of cooking pan were used as specified in UL 300A, holding different amounts of oil as characterized in the cooktop fire experiments reported in Section 3. They included cast iron and stainless steel skillets, and a stainless steel Dutch oven listed in Table 3-1. The results from Section 3 of this report suggest that these fires represent a significant tenability hazard.

Various instruments were used to measure the thermal environment and gas concentrations within the kitchen, enabling an assessment of tenability. Commercially available, single station, battery powered, ionization smoke alarms were installed on the ceiling at the center of the room and on the ceiling 0.3 m outside the doorway in the mock hallway as indicated in Figure 4-1. The alarm signal was connected to the data acquisition system, indicating the stage of fire development when occupants would be alerted.

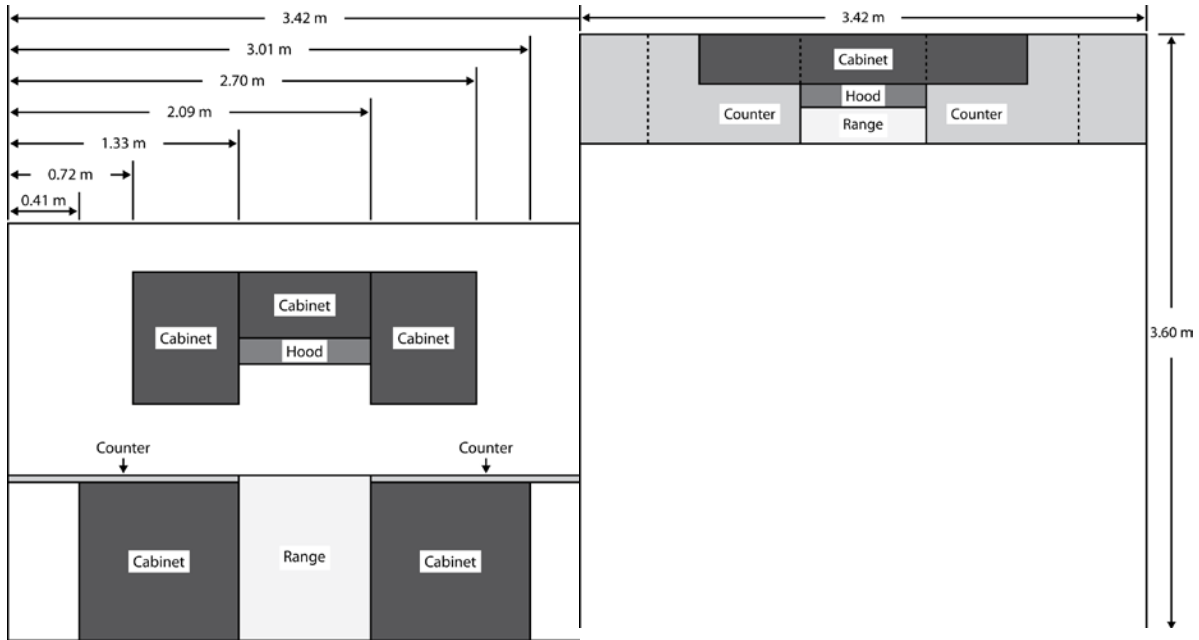
**Table 4-1. Power output of the electric and gas burners**

Suppression Type	Test	Burner Output (kW)	Suppression Type	Test	Burner Output (kW)
Auto Wet Chem 1	KSE 02	2.4	Auto Dry Chem	KSE 01	2.4
	KSE 03	2.4		KSE 14	1.5
	KSE 04	2.4		KSG 01	1.4
	KSG 02	1.4		KSG 11	1.4
	KSG 03	1.4		KSG 16	1.4
	KSG 04	1.4		KSG 17	1.4
	KSG 19	1.4		Free Burn	KSG 15
Auto Wet Chem 2	KSE 06	2.4	KSG 20		1.4
	KSE 07	2.4	Manual Dry Chem	KSE 15	1.5
	KSE 08	2.4		KSG 12	1.4
	KSE 09	2.4	Manual Wet Chem2	KSE 12	1.5
	KSG 05	1.4		KSE 13	1.5
	KSG 06	1.4		KSG 09	1.4
	KSG 07	1.4		KSG 10	1.4
Auto Wet Chem 3	KSE 05	2.4	Sprinkler	KSE 17	1.5
	KSG 08	1.4		KSG 14	1.4
	KSG 18	1.4	Water Mist 1	KSE 16	1.5
Auto Wet Chem 4	KSE 10	2.4	Water Mist 1	KSG 13	1.4
	KSE 11	2.4		Water Mist 2	KSE 18
	KSE 21	2.4	KSE 19		1.5
	KSE 22	2.4	Water Mist 3		KSE 20
		Electric Range			
	Gas Range				

Each cooktop surface had 4 burners, only one of which was used during a single test. Table 4-2 lists the specified maximum power output of the burners, which was 2.6 kW for the electric stoves and varied from 2.8 kW to 3.5 kW for the natural gas stoves. The burner, pan, and volume of oil used in each test are presented in Table 4-2. All tests used corn oil. Three types of cooking pans were used in these experiments. In 33 of the tests, Pan B was used, which was a 25 cm diameter, 18 cm deep stainless steel pot that was filled with 4.5 L of oil. In 9 tests, Pan A was used and Pan C was used once. Pan A was a 30 cm diameter, 6 cm deep cast iron skillet filled with 1.62 L of oil and Pan C was a 25 cm diameter, 5 cm deep filled with 0.5 L of oil. To shorten the time to achieve auto-ignition, an extra torch was applied to the bottom portion of the cooking pan during the early part of some of the tests. By monitoring the cooking oil temperature, the supplemental heating was removed at least 10 min before auto-ignition was achieved.

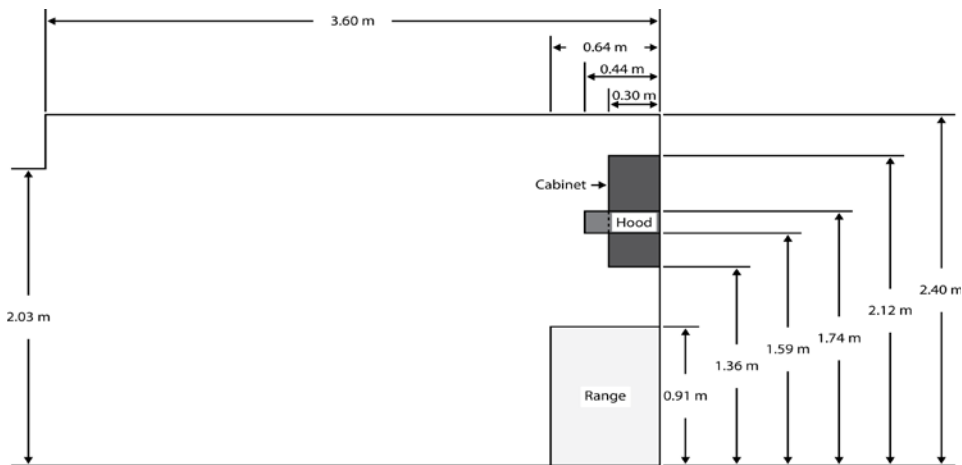
Two experiments were “free burns,” in which the fire burned unabated. In those experiments, fire spread to the surrounding cabinets and other flammable materials (such as items in the range hood) and flashover occurred.

Since the experiments were conducted over the course of a year, the ambient temperature and relative humidity significantly varied among the tests. These variables were recorded during each of the experiments, as listed in Appendix 2. The ambient temperature and relative humidity were not found to have a significant correlation to any of the experimental results.



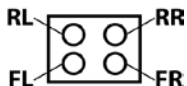
**Figure 4-2. Elevation view schematic with dimensions of the mock kitchen looking toward the range**

**Figure 4-3. Plan view schematic with dimensions of the mock kitchen**



**Figure 4-4. Elevation view schematic with dimensions of the mock kitchen oriented parallel to the countertop**

**Table 4-2. Experimental arrangement including, the burner, pan, and volume of fuel**

Suppressant Type	Test	Burner*	Pan+	Fuel	Suppressant Type	Test	Burner*	Pan+	Fuel
Auto Wet Chem 1	KSE 02	FL	Pan B	4.5 L	Free Burn	KSG 15	FR	Pan B	4.5 L
	KSE 03	FL	Pan B	4.5 L		KSG 20	FR	Pan A	1.6 L
	KSE 04	RR	Pan B	4.5 L	Manual Dry Chem	KSE 15	FR	Pan B	4.5 L
	KSG 02	FL	Pan B	4.5 L		KSG 12	FR	Pan B	4.5 L
	KSG 03	FL	Pan B	4.5 L	Manual Wet Chem	KSE 12	FR	Pan B	4.5 L
	KSG 04	RL	Pan B	4.5 L		KSE 13	FR	Pan B	4.5 L
	KSG 19	FR	Pan B	1.6 L		KSG 09	FR	Pan B	4.5 L
				KSG 10		FR	Pan B	4.5 L	
Auto Wet Chem 2	KSE 06	FL	Pan B	4.5 L	Sprinkler	KSE 17	RL	Pan B	4.5 L
	KSE 07	FL	Pan B	4.5 L		KSG 14	FR	Pan B	4.5 L
	KSE 08	RR	Pan B	4.5 L	Water Mist 1	KSE 16	RL	Pan B	4.5 L
	KSE 09	RR	Pan B	4.5 L		KSG 13	FR	Pan B	4.5 L
	KSG 05	FL	Pan B	4.5 L	Water Mist 2	KSE 18	FR	Pan A	1.6 L
	KSG 06	FL	Pan B	4.5 L		KSE 19	FR	Pan A	1.6 L
	KSG 07	RR	Pan B	4.5 L		KSE 20	FR	Pan A	1.6 L
Auto Wet Chem 3	KSE 05	FL	Pan B	4.5 L	Water Mist 3	KSE 01	FL	Pan B	4.5 L
	KSG 08	FL	Pan B	4.5 L		KSE 14	FR	Pan B	4.5 L
	KSG 18	FR	Pan A	1.6 L	Auto Dry Chem	KSG 01	FL	Pan B	4.5 L
Auto Wet Chem 4	KSE 10	FL	Pan B	4.5 L		KSG 11	FR	Pan B	4.5 L
	KSE 11	FL	Pan B	4.5 L		KSG 16	FR	Pan A	1.6 L
	KSE 21	FL	Pan A	1.6 L		KSG 17	FR	Pan C	0.5 L
KSE 22	FL	Pan B	4.5 L						
* Burner Positions:					+ Pan A: Cast Iron 33 cm dia.; 5 cm deep + Pan B: Stainless Steel 25 cm dia.; 18 cm deep + Pan C: Stainless Steel 10 cm dia.; 5 cm deep				

## 4.2 Instrumentation

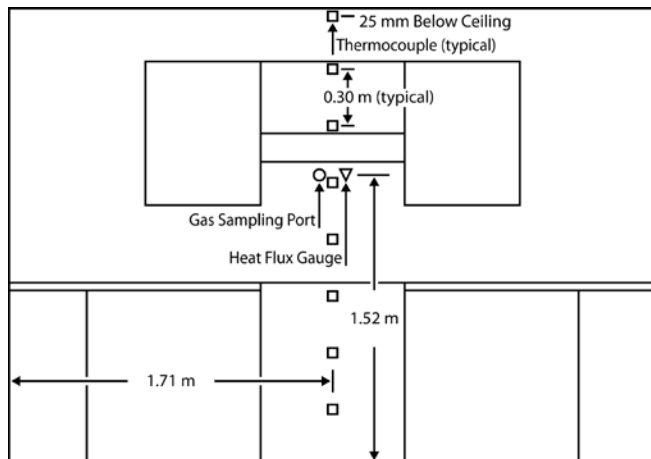
Thermocouples and total heat flux gauges were used to measure the thermal environment within the mock kitchen. The temperature of the cooking oil was measured by a thermocouple suspended within the oil; this thermocouple was similarly placed during every experiment.

The instrumentation locations are schematically shown in Figure 4-5, Figure 4-6, and Figure 4-7. The arrangement was similar for all tests. A linear array of thermocouples stretching from ceiling to floor was used to measure the gas temperature at various heights in the room. The array was located on the centerline of the room, 0.97 m (3.2 ft) from the range. Type K thermocouples were used with a 0.51 mm (0.02 in) bare-bead nominal diameter. The thermocouples were

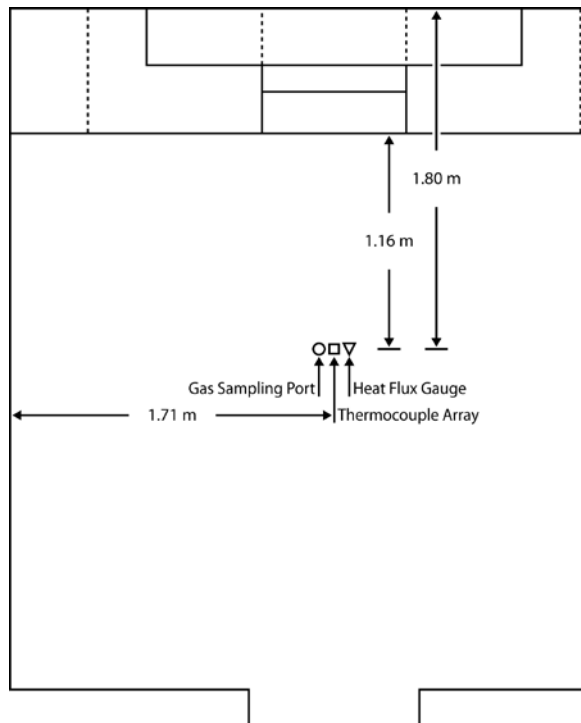
located 0.025 m, 0.305 m, 0.610 m, 0.920 m, 1.22 m, 1.52 m, 1.83 m, and 2.13m (nominally, 1 in, 1.0 ft, 2.0 ft, 3.0 ft, 4.0 ft, 5.0 ft, 6.0 ft, and 7.0 ft) below the ceiling.

Total heat flux measurements were made with water-cooled Schmidt-Boelter gauges. One Schmidt-Boelter total heat flux gauge was installed facing the range on the centerline of the room, 1.19 m (3.90 ft) from the range and 1.52 m (5.00 ft) above the floor of the structure, or 0.92 m (2.87 ft) below the ceiling. Another gauge was installed in the upper cabinets facing the range. Each had a maximum heat flux range of 57 kW/m<sup>2</sup> (5 Btu/ft<sup>2</sup>·s).

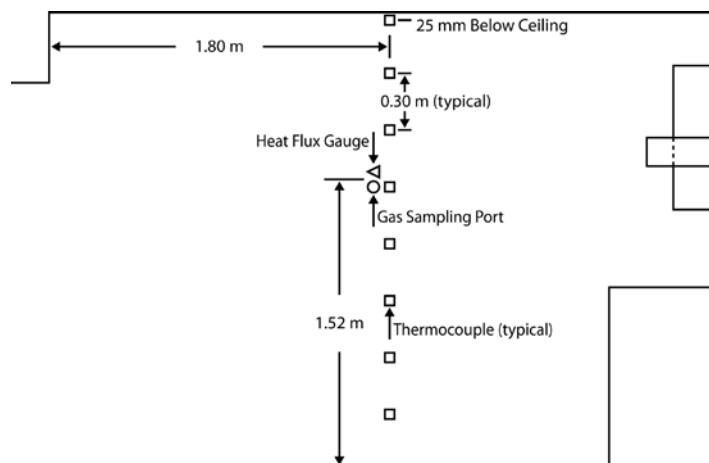
Gas concentrations were sampled from a port located about the centerline of the room, 1.19 m (3.90 ft) from the range and 1.52 m (5.00 ft) above the floor of the structure. The sampling lines were connected to calibrated vacuum pumps which moved the gas samples through a conditioning manifold, which consisted of two in-line filtered cold traps to remove soot particles and moisture. The sampling line had a nominal internal diameter of 9.5 mm. The cold traps were approximately 190 mm long with an internal diameter of 60 mm for an approximate volume of 500 cm<sup>3</sup> for each trap. The sampling system volume was minimized to avoid damping important peak values in the gas concentration measurements. The volume of each cold trap was reduced by approximately 70 % with the addition of glass wool and glass beads [19]. The dry gas samples were drawn through a series of gas analyzers. Oxygen was measured using a paramagnetic analyzer, while carbon monoxide and carbon dioxide were measured using non-dispersive infrared analyzers.



**Figure 4-5. Elevation view schematic with instrumentation, oriented toward the range**



**Figure 4-6. Plan view schematic with instrumentation**



**Figure 4-7. Elevation view schematic with instrumentation, oriented parallel to the countertop**

### 4.3 Measurement Uncertainty

There are different components of uncertainty in the mass, length, temperature, heat flux, gas concentrations, mass and flow rate described in this report. Unless otherwise stated, uncertainty is reported as the expanded uncertainty with an expansion factor of 2. The expanded uncertainties are composed of two components involving statistical methods typically measurement variance and estimates of systematic factors such as instrument specifications (or estimates of instrument uncertainty) [12].

Length measurements such as the room dimensions and instrumentation array locations, were made with a tape measure with a resolution of  $\pm 0.5$  mm (0.02 in). Conditions affecting the measurement, such as levelness or tautness of the device, yield an estimated uncertainty of  $\pm 0.5$  % for measurements in the 0 to 3.0 m (9.8 ft) range. For longer distances (in excess of 3.0 m or 9.8 ft), the expanded uncertainty was estimated as  $\pm 1$  %.

The standard uncertainty in the measured thermocouple temperature was  $\pm 2.2$  °C at 277 °C, increasing to  $\pm 9.5$  °C at 871 °C as specified by the manufacturer [11]. Temperature variance in the zone near the thermocouple is typically much greater than that of the wire uncertainty [20, 21]. And radiation effects in a compartment can significantly impact the measured reading - much more than that of the wire uncertainty [20,21]. Small diameter thermocouples (0.5 mm diameter) were used to limit the impact of radiative heating and cooling in the compartment. The expanded uncertainty for temperature in these experiments was typically  $\pm 15$  %, which was dominated by measurement variance.

The total heat flux gauges had a manufacturer reported expanded calibration uncertainty of  $\pm 3$  % [13]. A comprehensive international study on total heat flux gauge calibration and response demonstrated that the expanded uncertainty of heat flux gauges is typically  $\pm 8$  % [14].

Gas measurement instrumentation and sampling system used in this series of experiments have an expanded uncertainty of about  $\pm 1$  % when compared with calibration span gases. Measurement variance determined through repeat measurements in a typical room fire dominate the expanded uncertainty which is typically  $\pm 10$  % [19,22].

In the following sections, the measurements are presented in graphic and tabular form with a measurement uncertainty as described above.

## 5 Experimental Results

This section presents the results of the kitchen fire experiments. First, the suppression system technologies are characterized in terms of suppressant delivery. Then, Section 4.4.2 describes the results of the fire suppression measurements. Sections 4.4.3 and 4.4.4 discuss the performance of the systems are considered in terms of room tenability including heat flux, temperature, fuel containment and fuel spatter. Measurements on the effect of the hood fan on

the wet chemical agent performance is examined in Section 4.4.5. Section 4.4.6 discusses the measurements of the effectiveness of smoke alarms in providing warning to occupants about the impending oil fires.

## 5.1 Suppression System Effectiveness

The performance of the suppression systems was tested on the oil fires. Data collected during the experiments are presented in Appendix 1 for each test. The results include the experimental timelines based on observations (e.g., time to auto-ignition and suppression system activation times), temperature measurements, gas concentrations, and heat flux measurements.

The results of the suppression experiments are summarized in Table 5-1. Auto-ignition took a significant amount of time to occur and depended on the burner power, the mass of the pan, the mass of oil, and other factors. In a few experiments, a torch was used to hasten heat-up. On the electric stovetop, auto-ignition in Pan B (the stainless steel Dutch oven with 4.5 L of oil) and Pan A (the cast iron skillet with 1.6 L of oil) required about 62 min ( $\pm 13$  min) and 46 min ( $\pm 12$  min), respectively. On the gas stovetop, auto-ignition in Pan A and Pan B required about 89 min ( $\pm 12$  min) and 37 min ( $\pm 5$  min), respectively.

The time of suppressant deployment for both automatic and manually controlled systems are listed in the table as well as the outcome of suppressant delivery. The suppression systems were allowed to fully discharge. Successful extinguishment was confirmed if flaming combustion ceased and the oil cooled to below the auto-ignition temperature. In several tests, the suppression system extinguished the fire for a short period, but not long enough to allow the oil to cool below the auto-ignition temperatures, resulting in reignition. In other tests, the suppression system failed to disrupt the combustion of oil and the fire was not suppressed. Of the 40 suppression experiments, suppression was accomplished 40 % of the time (17 tests) and unsuccessful in 30 % of the cases (12 tests). In 23 % of the tests (9 tests), the fire was successfully extinguished, but reignition occurred. In 2 tests (5 %), the suppression devices did not activate (KSE05 and KSE08) and the fire was manually extinguished. There were an additional two free burns” during which suppression was not attempted (KSG 15 and KSG 20). During the free burns, the oil fire was allowed to spread to the surrounding furnishings.

On average, suppressant activation initially occurred 84 s and 158 s after ignition for cases in which the fire was extinguished and not extinguished, respectively. Thus, extinguishment was associated with earlier suppressant activation. Manual suppression of the oil fires using the wet and dry chemicals were successful on every attempt with 6 tests in total (2 dry chemical and 4 wet chemical). The automatically delivered wet chemical was used to suppress the fire on every attempt with 7 tests in total (3 electric and 4 gas). There was only one test of Water Mist System 3, which was successful. The other two water mist systems tested did not successfully suppress the fires.



**Table 5-1. Time of suppression system deployment after ignition and its outcome**

Type	Test	Time (s)*	Outcome	Type	Test	Time (s)	Outcome	
Water Mist 1	KSE 16	129	Not Extinguished	Auto Wet Chem 1	KSE 02	61	Extinguished	
	KSG 13	294	Not Extinguished		KSE 03	102	Extinguished	
Water Mist 2	KSE 18	86	Not Extinguished		KSE 04	47	Extinguished	
	KSE 19	78	Not Extinguished		KSG 02	118	Extinguished	
Water Mist 3	KSE 20	92	Extinguished		KSG 03	74	Extinguished	
Manual Dry Chem	KSE 15	69	Extinguished		KSG 04	181	Extinguished	
	KSG 12	73	Extinguished		KSG 19	92	Extinguished	
Manual Wet Chem	KSE 12	63	Extinguished		Auto Wet Chem 2	KSE 06	206	Re-Ignition
	KSE 13	63	Extinguished			KSE 07	192	Re-Ignition
	KSG 09	65	Extinguished			KSE 09	131	Re-Ignition
	KSG 10	61	Extinguished	KSG 05		149	Re-Ignition	
Sprinkler	KSE 17	176	Extinguished	KSG 06		84	Extinguished	
	KSG 14	307	Not Extinguished	KSG 07		178	Re-Ignition	
Auto Dry Chem	KSE 01	171	Not Extinguished	Auto Wet Chem 3		KSG 08	140	Re-Ignition
	KSE 14	198	Not Extinguished		KSG 18	160	Re-Ignition	
	KSG 01	111	Re-Ignition	Auto Wet Chem 4	KSE 10	46	Not Extinguished	
	KSG 11	229	Not Extinguished		KSE 11	144	Not Extinguished	
	KSG 16	116	Not Extinguished		KSE 21	5	Extinguished	
KSG 17	57	Re-Ignition	KSE 22	102	Not Extinguished			

\* time of suppressant deployment after auto-ignition (expanded uncertainty = ± 2 s)

Although Wet Chem 1 was most effective, Wet Chem 2 and 3 also extinguished all the fires – but most of the time, these fires re-ignited. Wet Chem 4 was less successful despite its relatively large average delivery rate – possibly due to the large spatial variance of the suppressant application (see Table 2-2).

The discussion below considers tenability in terms of benchmark values for thermal injury and incapacitation due to inhalation of combustion products. A qualitative discussion of additional hazards including oil spatter, fire containment, and visibility is also presented.

## 5.2 Tenability

Burn injuries can be caused by convection of combustion products (such as hot gases and smoke) and by radiative heat transfer. The hazard related to heat transfer from a fire environment to an object or human body can be simplified as an exposure temperature for a prescribed duration.

UL 1626 specifies estimated practical limits for tenability based on temperature. Two limits are specified: a limit at which tenability is instantly compromised and a limit at which tenability is compromised after 2 min of exposure. The estimated instantaneous and 2 min\* tenability limits due to temperature are 54 °C (130 °F) and 93 °C (200 °F), respectively [16]. The SFPE Handbook of Fire Protection Engineering estimates the tenability limit due to heat flux as 2.5 kW/m<sup>2</sup> for which the time to burn unprotected skin is less than 20 s [23]. These limits are not absolute, since clothing, humidity, skin composition, and other factors can mitigate or exacerbate the impact of the thermal energy for a given heat level and exposure time. These values are helpful benchmarks and are considered here.

Based on individual exposures, incapacitation can occur due to low oxygen (10 % to 13 %) or a high level of carbon dioxide (7 % to 8 %) or carbon monoxide (0.6 % to 0.8 %) after approximately a 5 min exposure [16]. Lower concentrations of oxygen and higher concentrations of carbon dioxide and carbon monoxide, or synergistic effects involving all multiple combustion products can lead to incapacitation in a shorter time. Following the SFPE Handbook, the following values are taken as the limits of tenability: oxygen < 10 %, carbon dioxide > 8 %, or carbon monoxide > 1 %. Measurements were made of the temperature, heat flux, and gas concentrations at approximately 1.5 m (5 ft) above the floor (0.9 m below the ceiling) at the center of the room. This elevation can be considered face height of a typical, standing person. Table 5-2 lists the tests when the tenability limits based on heat flux or temperature were exceeded. In the table, “Time” is the time elapsed between ignition and when the tenability limit was first exceeded.

Tenability limits for low oxygen, elevated levels of carbon monoxide, or elevated levels of carbon dioxide were not reached in any of the tests. All these conditions, however, are dependent upon the amount of ventilation in the kitchen, as well as the volume of the room. Under realistic conditions, these factors could vary significantly from these experiments. Of the 38 suppression experiments in the table, the instantaneous temperature tenability limit of 54 °C (130 °F) was exceeded 5 times (or 13 %), whereas the 2 min temperature tenability limit of 93 °C (200 °F) was exceeded only twice (or 5 %) - both times only after the suppression system had activated. The heat flux tenability limit was exceeded 16 times (or 42 %). Temperature and heat flux tenability limits were exceeded for the free burn tests in the table, which provide a reference for the other gas stovetop tests. Of the 17 tests in which suppression was successful, tenability limits were exceeded in 3 of those cases. Temperature based tenability limits were exceeded only by the water-based suppression systems. For the two free burn experiments, the limits of tenability were exceeded 350 s and 160 s after ignition.

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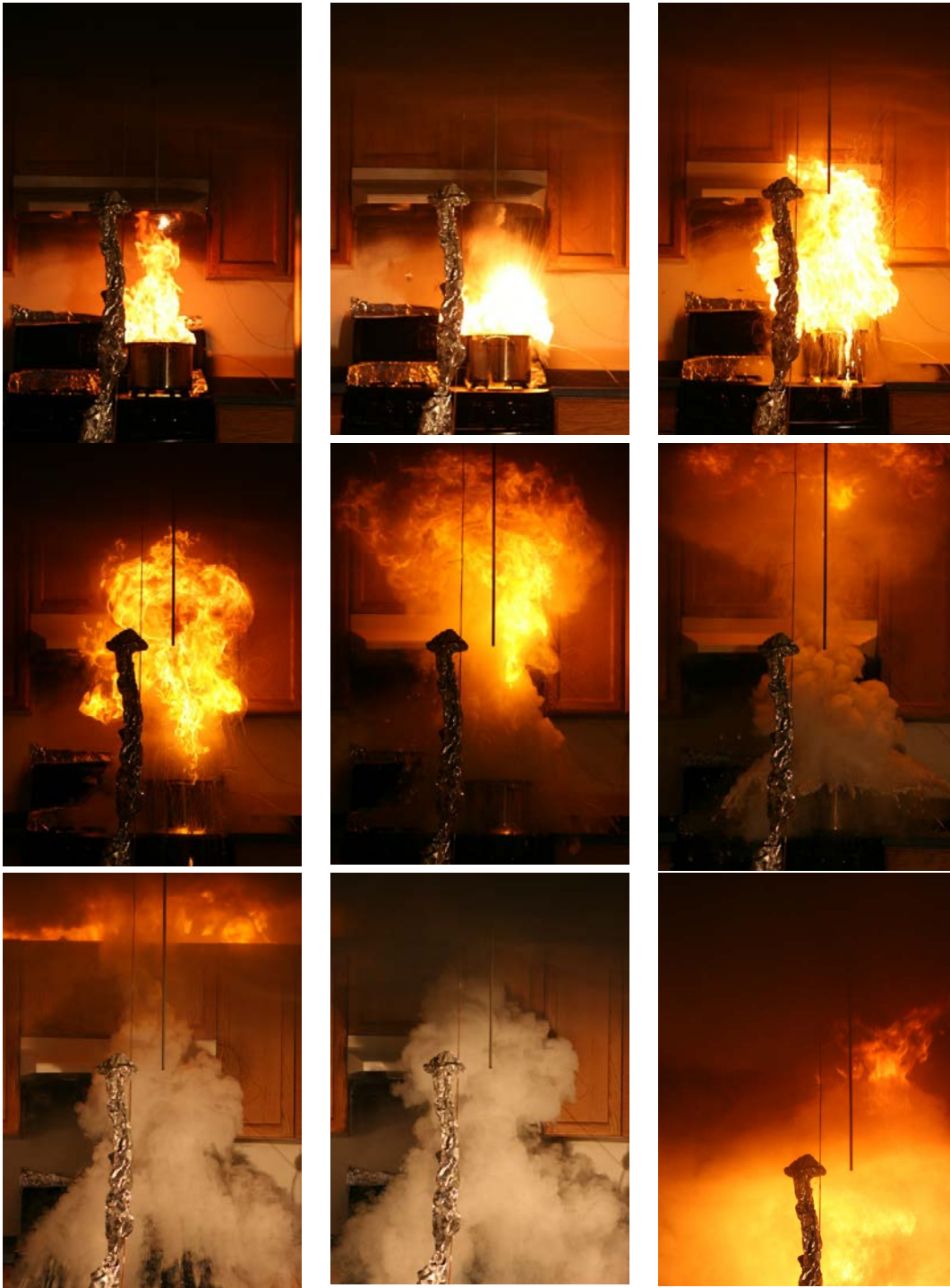
\* the two min tenability limit requires that the temperature be above 93 °C for a two min period.

**Table 5-2. Tenability**

Type	Test	Instant <sup>a</sup>	2min <sup>b</sup>	Heat Flux <sup>c</sup>	Time <sup>d</sup> (s)	Type	Test	Instant	2min	Heat Flux	Time (s)
Sprinkler	KSE17	No <sup>e</sup>	No	Yes <sup>e</sup>	169	Auto Wet Chem 2	KSE06	No	No	Yes	209
	KSG14	Yes	Yes	Yes	307		KSE07	No	No	Yes	194
Water Mist 1	KSE16	Yes	Yes	Yes	145		KSE09	No	No	No	
	KSG13	Yes	No	Yes	315		KSG05	No	No	No	
Water Mist 2	KSE18	Yes	No	Yes	73		KSG06	No	No	No	
	KSE19	No	No	Yes	162		KSG07	No	No	Yes	176
Water Mist 3	KSE20	Yes	No	Yes	70		Auto Wet Chem 3	KSG08	No	No	No
Auto Wet Chem 1	KSE02	No	No	No		KSG18	No	No	No		
	KSE03	No	No	No		Auto Wet Chem 4	KSE10	No	No	No	
	KSE04	No	No	No			KSE11	No	No	No	
	KSG02	No	No	No			KSE21	No	No	No	
	KSG03	No	No	No		KSE22	No	No	No		
	KSG04	No	No	No		Manual Dry Chem	KSE15	No	No	No	
	KSG19	No	No	Yes	95		KSG12	No	No	No	
Auto Dry Chem	KSE01	No	No	Yes	162	Manual Wet Chem	KSE12	No	No	No	
	KSE14	No	No	Yes	201		KSE13	No	No	No	
	KSG01	No	No	No			KSG09	No	No	No	
	KSG11	No	No	Yes	235	KSG10	No	No	No		
	KSG16	No	No	Yes	165	Free Burn	KSG15	Yes	Yes	Yes	350
	KSG17	No	No	Yes	59		KSG20	Yes	Yes	Yes <sup>f</sup>	160

a. 'Instant' represents the instantaneous tenability limit for temperature exposure to 54 °C  
 b. '2 min' indicates the 2 min tenability limit for temperature exposure to 93 °C  
 c. 'Heat Flux' indicates a 20 s heat flux exposure to 2.5 kW/m<sup>2</sup>  
 d. 'Time' is the time elapsed between ignition and when the tenability limit was first exceeded  
 e. 'yes, or no' indicates that the tenability limit was, or was not, exceeded for that test  
 f. Heat flux data not available; the temperature data, however, suggests that 2.5 kW/m<sup>2</sup> was exceeded

The tenability limits for heat flux were sometimes exceeded after activation of the suppression system, which agitated the oil fire causing a large, but momentary increase in the heat release rate and a corresponding increase in the heat flux. An example of a flare-up due to a test using automatic dry chemical suppressant delivery is shown in Figure 5-1. Enhanced temperature in the middle of the room due to suppressant delivery was also experimentally observed. Other fire enhancement effects included the observation that small oil droplets were ejected from the cooking pan in the form of spatter. On other occasions, burning oil splashed out of the container onto the range leading to a dramatic increase in the fire size. Delivery of the suppressant was also observed to lead to gas-phase effects, displacing hot gasses away from the range towards the center of the kitchen, where a person could be exposed.



**Figure 5-1. Photo of the burning oil just prior to activation of an auto dry chemical system (upper left), followed by 8 photos of the scenario taken within 3 sec of the initiation of suppressant (dry chemical) delivery.**

### 5.3 Spatter, Loss of Containment, and Visibility

In addition to heat flux and temperature, several other phenomena observed during the experiments could present a tenability hazard. They are qualitatively described here. In a free burn scenario, the burning oil eventually boiled, causing the oil to cascade over the top of the pan, which enhanced the fire size, causing direct flame impingement on other items present in the kitchen that might otherwise not be exposed to flame. The suppression systems always activated before boilover was observed. Loss of containment of the fuel could occur in other ways. Loss of containment occurred due to suppressant delivery, apparently due to the momentum of the suppressant displacing the oil in the container. Instances of observed loss of containment are documented in Table 5-3. Loss of containment could accelerate fire spread or impact tenability. In many cases, loss of tenability occurred within 20 s after initiation of suppressant delivery. This was generally not the case for the most successful suppression types, such as manual suppression or the automatically delivered wet chemical.

Loss of containment occurred for the automatic dry chemical and water based systems. The dry chemical systems caused loss of containment as oil splashed out of the pan immediately after suppressant activation. The momentum of the dry suppressant into the oil caused some oil to splash out of the container. The sprinkler system produced containment losses due to the violent vaporization of water droplets on the oil surface. The hood mounted water mist systems (water mist 2 & 3) provided a high velocity jet of nitrogen which was used to produce fine water droplets. This caused visible agitation of the oil as the flames were pushed down and away from the nozzle, ultimately leading to containment failure in these cases. Since a shallow skillet (Pan A which was 5 cm deep) was used during all hood-mounted water mist system tests, it is unclear whether a deeper container would have led to different results. The ceiling mounted water mist suppression system (water mist 1) led to a containment failure, but the mechanism was not clear in these experiments.

For most tests, a high degree of visibility was maintained within the kitchen at 1.5 m (5 ft) throughout the experiment, but the hood mounted water mist systems reduced visibility within the kitchen to zero within seconds of activation. This could inhibit the ability of occupants to evacuate the kitchen area and increase the risk occupants will approach the fire or encounter hot surfaces or burning oil. However, the significance of this risk was not studied.

**Table 5-3. Fuel containment results**

Type	Test	Suppression Status	Contained <sup>a</sup>	Type	Test	Suppression Status	Contained
Auto Dry Chem	KSE01	Not Extinguished	No	Auto Wet Chem 3	KSE05	No Activation	N/A
	KSE14	Not Extinguished	No		KSG08	Re-Ignition	Yes
	KSG01	Re-Ignition	Yes		KSG18	Not Extinguished	Yes
	KSG11	Not Extinguished	No	Auto Wet Chem 4	KSE10	Not Extinguished	Yes
	KSG16	Not Extinguished	No		KSE11	Not Extinguished	Yes
	KSG17	Re-Ignition	No		KSE21	Extinguished	Yes
			KSE22		Not Extinguished	Yes	
Auto Wet Chem 1	KSE02	Extinguished	Yes	Manual Dry Chem	KSE15	Extinguished	Yes
	KSE03	Extinguished	Yes		KSG12	Extinguished	Yes
	KSE04	Extinguished	Yes	Manual Wet Chem	KSE12	Extinguished	Yes
	KSG02	Extinguished	Yes		KSE13	Extinguished	Yes
	KSG03	Extinguished	Yes		KSG09	Extinguished	Yes
	KSG04	Extinguished	Yes		KSG10	Extinguished	Yes
	KSG19	Extinguished	Yes				
Auto Wet Chem 2	KSE06	Re-Ignition	Yes	Sprinkler	KSE17	Extinguished	No
	KSE07	Re-Ignition	Yes		KSG14	Not Extinguished	No
	KSE08	No Activation	N/A	Water Mist 1	KSE16	Not Extinguished	No
	KSE09	Re-Ignition	Yes		KSG13	Not Extinguished	Yes
	KSG05	Re-Ignition	Yes	Water Mist 2	KSE18	Not Extinguished	No
	KSG06	Extinguished	Yes		KSE19	Not Extinguished	Yes
	KSG07	Re-Ignition	Yes	Water Mist 3	KSE20	Extinguished	No

a. 'no' indicates loss of fuel containment; 'yes' indicates no loss of containment

The different types of extinguishers tested here fared better or worse in terms of tenability and containment of the burning fuel. The handheld extinguishers, for example, were quite effective and created no apparent tenability hazards to their potential users beyond what the oil fire presented prior to their usage. The results were mixed for the automatically discharged Wet chemical 1, which had one test in which tenability was a significant issue and 6 tests in which it wasn't.

Deployment of the wet and dry chemical handheld extinguishers can create a hazard, however, due to several factors. First, the manufacturer instructions may not be necessarily satisfied by a user in a realistic scenario due to lack of training or when in a panic. The wet chemical extinguishers may be manually deployed from a limited distance and thus require that the user be somewhat intimate with the fire, presenting a potential hazard if burning fuel is agitated. The dry

chemical systems were capable of discharging from a significant distance. If discharged near an oil fire, however, splashing could occur, presenting a hazard to the user.

## 5.4 Effect of Hood Fan

The hood/vent system installed above each range was equipped with a fan, which was not used except in the series of tests for the auto wet chemical systems 1 and 2. For these tests, the effect of the fan on fire suppressant effectiveness was investigated. The fan extracted air from the hood at a maximum flow speed of 90 L/s. It was anticipated that the fan would influence hood temperatures, and possibly suppression system activation time. The results are given in Table 5-4.

The discussion below considers tenability in terms of benchmark values for thermal injury and incapacitation due to inhalation of combustion products. A qualitative discussion is also presented of additional hazards including oil spatter, fire containment, and visibility. The difference in the time between auto-ignition and system activation is denoted as “Activation Time” in the table. No significant correlation was apparent between fan status and activation time.

**Table 5-4. Activation times and fan status for tests using automatically delivered wet chemicals**

Suppression Type	Test	Nominal Suppressant Activation Temperature (°C)	Burner Position	Fan	Activation Time (s)
Auto Wet Chem 1	KSE 02	100	Front Left	Off	61
	KSE 03	100	Front Left	On	102
	KSE 04	100	Rear Right	On	47
	KSG 02	182	Front Left	Off	118
	KSG 03	182	Front Left	On	76
	KSG 04	182	Rear Left	On	181
	KSG 19	182	Front Right	Off	102
Auto Wet Chem 2	KSE 06	182	Front Left	Off	206
	KSE 07	182	Front Left	On	192
	KSE 08	182	Rear Right	On	155
	KSE 09	182	Rear Right	On	131
	KSG 05	182	Front Left	Off	151
	KSG 06	182	Front Left	On	84
	KSG 07	182	Rear Right	On	178

## 5.5 Smoke Alarm Activation

The time of smoke alarm activation relative to the time of auto-ignition is shown in Table 5-5. On average, the smoke alarms inside and just outside the kitchen activated an average of 24 min and 20 min before auto-ignition, respectively. There were three cases when the smoke alarm activated after auto-ignition, indicated by a negative value in the table. This only occurred for electric stoves when the range fan was operating (see entries highlighted in the table). The range fan (90 L/s) extracted smoke from the room over the period before auto-ignition occurred, pulling fresh air from outside the room through the doorway, into the room, and diluting oil vapor to such a level that the smoke alarms didn't activate.

**Table 5-5. Time difference between activation of smoke alarms (inside and outside of kitchen) and auto-ignition**

Test	Inside (s)	Outside (s)	Test	Inside (s)	Outside (s)
KSE 01	197	1047	KSG 01	1151	78
KSE 02	1540	1320	KSG 02	*	*
KSE 03	995 **	360	KSG 03	2010	1995
KSE 04	-26	-44	KSG 04	1126	1116
KSE 05	1100	986	KSG 05	470	332
KSE 06	1860	1677	KSG 06	501	478
KSE 07	958	826	KSG 07	460	676
KSE 08	-32	-24	KSG 08	2616	1536
KSE 09	-75	-90	KSG 09	3585	2585
KSE 10	2061	2684	KSG 10	1889	1889
KSE 11	2002	1848	KSG 11	2556	2266
KSE 12	1503	1375	KSG 12	2400	1408
KSE 13	1475	1378	KSG 13	2055	1374
KSE 14	1532	1336	KSG 14	2195	1590
KSE 15	1417	1127	KSG 15	2628	772
KSE 16	1034	879	KSG 16	1652	1540
KSE 17	2037	1838	KSG 17	340	240
KSE 18	975	962	KSG 18	483	453
KSE 19	1322	1308	KSG 19	1020	952
KSE 20	1295	1295	KSG 20	1443	293
KSE 21	2624	2395			
KSE 22	3100	2760			

\* manual ignition used  
 \*\* highlighted entries represent experiments when the range fan was operational  
 \*\*\* negative values represent time to alarm after ignition



Recently, Johnsson [4] experimentally found completely different results for photoelectric alarms, which consistently activated about 2 min before stovetop ignition of peanut and canola oils under a hood fan operating at 104 L/s in a small room. Differences in room ventilation conditions may explain the difference in results from this study. Further research is needed to clarify these conflicting results.

## 6 Discussion of Results

The experiments described in this report focused on residential cooking and particularly on general purpose ranges and cooktops. The experiments were conducted using full-scale scenarios and commercially-available suppression system technologies addressing realistic fire scenarios. Several types of fresh (previously unused) cooking oil were assessed, and corn oil was selected as a reasonable representation of the hazards associated with cooking oil fires. The pans tested complied with UL300A and included a deep pot and shallow skillets. Both natural gas and electric ranges were tested. Successful performance was deemed to necessitate both fire suppression and prevention of re-ignition. In these terms, some suppression system technologies performed better than others in the full-scale kitchen fire suppression experiments reported here.

Complete extinguishment of cooking oil fires would not only prevent property damage, but would also protect occupants from potentially fatal hazards. During the process of suppression, however, fire conditions could be exacerbated, introducing additional risks to occupants that did not exist prior to suppressant application. Many of the tested systems did not completely extinguish the fire.

The time to ignition was found to vary significantly based on the type of burner, properties of the pan, type of oil, and volume of oil. The peak heat release rate was found to vary based on these same properties - which affected the thermal exposure of nearby furnishings (or tenability) in the room. The volume and type of oil, as well as the pan geometry, affected the ability of a suppression system to effectively lower the temperature of the oil below its auto-ignition point. The capability of a system to depower the stovetop was of critical importance.

Three of the suppression systems successfully extinguished the oil fire in all experiments, 3 systems were successful in some experiments, and 4 systems were not successful in any experiments. One system was tested only once, so the results are inconclusive. Considering all systems, three of the systems consistently provided notable benefits over a no-suppression scenario.

### 6.1 Manual Extinguishers

Both types of manual extinguishers were successfully used to extinguish the oil fires. The use of a manual extinguisher, however, precludes immediate egress and puts the user at some risk, depending on the fire scenario and the performance of the user. In this regard, it should be noted

that kitchen fires lead to a large excessive number of injuries - probably due to people attempting to control the fires. In addition, a large fraction of range and cooktop fires involve unattended cooking. Consequently, a manual extinguisher cannot be considered a substitute for an effective automatic suppression system, fire alarm warning system, or an ignition prevention device.

Successful application of the manual extinguishers suggests that an automatic system should be able to extinguish these fires – if properly engineered.

## **6.2 Automatic Systems**

The automatic systems tested in this study included room protection in the form of ceiling mounted water sprinklers and water mists, and localized systems that were hood mounted, including wet chemical, dry chemical, and water mist systems. All the automatic systems exacerbated the fire somewhat when activated; this translated to an increase in heat flux, and in some cases, an increase above the tenability limit.

### **6.2.1 Automatic Wet Chemical Systems**

Automatic wet chemical 1 was successful in all 7 experiments tested, making it the most reliable automatic system to successfully extinguish oil fires. Although wet chemical 1 was consistently able to suppress the fire, it did pose a tenability issue in 1 of the 7 tests. Automatic wet chemical 2 demonstrated some success in suppressing the fire, achieving temporary extinguishment in all tests and permanent extinguishment in one test. Automatic wet chemical 3 was unsuccessful in permanently extinguishing the oil fire in any tests, but it did successfully cause temporary extinguishment in one test. Automatic wet chemical 4 was less successful, as it did not provide extinguishment in 3 of 4 tests. This system did however successfully extinguish the oil fire during one test in which the volume of oil was smaller, using the cast iron skillet.

### **6.2.2 Automatic Dry Chemical System**

The automatic dry chemical system was not successful in extinguishing the oil fires in any of the experiments, and it introduced tenability hazards which were not present prior to system activation.

### **6.2.3 Water Mist Systems (Room and Hood Protection)**

Water mist system 1 (room protection) and water mist system 2 (hood protection) were not successful in extinguishing the oil fire in any experiments and each of these systems introduced tenability hazards which were not present prior to system activation. Water mist 3, a hood mounted water mist system, was successful in the one experiments in which it was tested, which was on the smaller volume of oil. It was a high pressure system, and was associated with both fuel containment and tenability problems.

## 6.2.4 Sprinkler Room Protection

The residential sprinkler was successful in extinguishing the fire in the first test and unsuccessful in the second test. Unlike some of the other systems, the stovetop power source was not shut as the suppressant (water) was deployed. Neither room protection system tested (water sprinkler and mist) could provide suppression without producing some hazard to occupants. This is partly due to the slower activation times of the room protection systems, which resulted in a larger fire prior to activation. The sprinkler system was able to delay the tenability limit in one test. In the second test, tenability became an issue after sprinkler activation. In general, room protection systems provide suppressant to a wide area, controlling or slowing fire spread to nearby items even when they are not successful in extinguishing the fire. Because of this, sprinklers provide benefit beyond simply cooktop protection, but the delay in application and the lack of a way to depower the cooktop present issues that challenge the performance of these systems.

## 7 Summary and Conclusions

Experiments were conducted investigating a common class of kitchen fires, involving oil burning in a pan that was heated on a cooktop. The performance of real-scale fire suppression systems was tested. Various emerging and commercially-available retrofit fire suppression systems for residential application were tested. The fire scenarios tested are outlined in the UL 300A draft standard. Experiments were conducted in a full-scale residential kitchen with dimensions 3.6 m x 3.4 m x 2.4 m high with an open doorway. Several types of cooking pans and oils were tested for both gas and electric cooktops. The suppression systems tested included automatic and manual suppression technologies using either local or total flooding type suppressant application. Manual devices that were tested included both wet and dry chemical type extinguishers. Automatic systems included total flooding whole-room and range hood installed systems. The total flooding systems provided whole-room protection; the systems tested included a water mist and a residential sprinkler system. The hood installed systems were positioned in the kitchen cabinets above the exhaust hood or in the hood itself, delivering agent onto the cooktop; these included wet and dry chemical systems, and water mist. A series of measurements provided data characterizing the hazard associated with cooking oil fires. The hazard associated with cooktop fires was characterized in terms of the rate of fire growth, and tenability proximate to the cooktop in terms of heat flux, temperature, gas concentration, and the splatter of hot burning oil.

Experimental characterization of the kitchen cooktop fires considered in this study showed that they were quite hazardous. The experiments showed that the performance of the automatic suppression technologies tested in this study faced challenges in terms of the fire intensity, propensity of the fuel to re-ignite, and tenability. Control experiments conducted without the application of a suppressant demonstrated that the cooktop fires exhibited ultra-fast  $t^2$  fire growth behavior. Smoke alarms inside, or just outside, a kitchen may provide early warning of fire, but not for all cases. The results showed that the performance of the commercially available automatic suppression technologies that were tested was problematic due to fire intensity, re-ignition, and tenability issues. While it is surely possible to mitigate the hazards associated with

cooking oil and range fires with large fire suppression systems, the results of these experiments suggest that delivering sufficient agent for a long enough duration to a hot oil burning within a pan located somewhere on the cooktop is quite challenging.

The results of the suppression and tenability experiments are summarized in Table 7-1. They show significant variation in the overall effectiveness of the various technologies and the collateral effects such as tenability and lack of fuel containment among the suppression systems tested. The automatically deployed systems demonstrated a mixed set of outcomes, some performing better than others in suppressing the fire, preventing reignition, and minimizing tenability issues near the cooktop. One type of automatic wet chemical system was particularly effective. This is not entirely unexpected as this type of wet chemical system is common in commercial applications. This wet chemical system did present some tenability issues. The hood-installed dry chemical system tested failed to extinguish the oil fire in all experiments, and introduced tenability hazards not present prior to system activation. The water mist automatic systems provided generally inadequate performance; they either could not reliably suppress the fire, or they consistently generated tenability hazards. Whole room systems fared no better. The water sprinkler and water mist systems were not particularly effective for the rapidly growing cooking oil fires.

Table 7-1 shows that the only suppressant types that were fully successfully were the manually applied wet and dry chemicals. For every other suppressant type either failed to suppress the fire, reignition occurred, the suppressant system did not properly activate, or there were issues in terms of tenability or fuel containment. Manual extinguishers consistently suppressed the oil fires while maintaining tenable conditions in the mock-up kitchen. In this sense, control of the direction, rate, and amount of suppressant delivery was advantageous.

The effectiveness of ionization smoke alarms to provide early warning of fire were also tested as part of this study. The results showed that the smoke alarms inside, or just outside, the kitchen fire scenarios considered here generally activated several minutes before auto-ignition occurred, but not for all cases. Further research is needed to determine if kitchen or nearby alarms may be a viable approach, adding to kitchen fire safety. Other approaches for kitchen fire safety should also be considered. This may include consideration of ignition prevention technologies and reliable, early, and nuisance-free warning of pre-ignition conditions possibly through the development of specialized sensors or sensor combinations. The best means to control the fire may be “smart” cooktops that prevent ignition from occurring such as mandated by the recent UL 858 standard for electric cooktops [3]. Future research should consider the best ways to evaluate kitchen fire prevention technologies. In addition, the results of this study suggest that further work is needed to examine the limits of the effectiveness of sprinkler fire protection systems for stovetop fire protection.

Table 7-1. Summary of Suppression and Tenability Measurements. <sup>a</sup>

Type	Test	Suppressed	Tenable and Contained <sup>b</sup>	Type	Test	Suppressed	Tenable and Contained <sup>b</sup>
Auto Dry Chem	KSE01	No	No	Auto Wet Chem 3	KSE05	No Activation	N/A
	KSE14	No	No		KSG08	Re-Ignition	Yes
	KSG01	Re-Ignition	Yes		KSG18	No	Yes
	KSG11	No	No	Auto Wet Chem 4	KSE10	No	Yes
	KSG16	No	No		KSE11	No	Yes
	KSG17	Re-Ignition	No		KSE21	Yes	Yes
Auto Wet Chem 1	KSE02	Yes	Yes	KSE22	No	Yes	
	KSE03	Yes	Yes	Manual Dry Chem	KSE15	Yes	Yes
	KSE04	Yes	Yes		KSG12	Yes	Yes
	KSG02	Yes	Yes	Manual Wet Chem	KSE12	Yes	Yes
	KSG03	Yes	Yes		KSE13	Yes	Yes
	KSG04	Yes	Yes		KSG09	Yes	Yes
	KSG19	Yes	No		KSG10	Yes	Yes
Auto Wet Chem 2	KSE06	Re-Ignition	No	Sprinkler	KSE17	Yes	No
	KSE07	Re-Ignition	No		KSG14	No	No
	KSE08	No Activation	N/A	Water Mist 1	KSE16	No	No
	KSE09	Re-Ignition	Yes		KSG13	No	No
	KSG05	Re-Ignition	Yes	Water Mist 2	KSE18	No	No
	KSG06	Yes	Yes		KSE19	No	No
	KSG07	Re-Ignition	No	Water Mist 3	KSE20	Yes	No
<p>a. see Table 5-1, Table 5-2, and Table 5-3</p> <p>b. 'no' indicates that there was a loss of fuel containment or tenability; 'yes' indicates no loss of containment</p>							

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## Appendix 1: Experimental Results

This appendix provides details on the individual results of the full-scale kitchen fire suppression experiments. The following table lists the tests in this series and the pages on which their results can be found.

Table A1-1. Summary of suppression test name, fuel quantity, suppression system, and page number where results are presented.

Test Name	Fuel	System	Page
KSE 1	4.5 L	Auto. Dry Chem	54
KSE 2	4.5 L	Auto Wet Chem 1	55
KSE 3	4.5 L	Auto Wet Chem 1	56
KSE 4	4.5 L	Auto Wet Chem 1	57
KSE 5	4.5 L	Auto Wet Chem 3	58
KSE 6	4.5 L	Auto Wet Chem 2	59
KSE 7	4.5 L	Auto Wet Chem 2	60
KSE 8	4.5 L	Auto Wet Chem 2	61
KSE 9	4.5 L	Auto Wet Chem 2	62
KSE 10	4.5 L	Auto Wet Chem 4	63
KSE 11	4.5 L	Auto Wet Chem 4	64
KSE 12	4.5 L	Manual Wet Chem	65
KSE 13	4.5 L	Manual Wet Chem	66
KSE 14	4.5 L	Auto Dry Chem	67
KSE 15	4.5 L	Manual Dry Chem	68
KSE 16	4.5 L	Water Mist 1	69
KSE 17	4.5 L	Residential Sprinkler	70
KSE 18	1.62 L	Water Mist 2	71
1KSE 19	1.62 L	Water Mist 2	72
KSE 20	1.62 L	Water Mist 3	73
KSE 21	1.62 L	Auto Wet Chem 4	74
KSE 22	4.5 L	Auto Wet Chem 4	75

Test Name	Fuel	System	Page
KSG 1	4.5 L	Auto. Dry Chem	76
KSG 2	4.5 L	Auto Wet Chem 1	77
KSG 3	4.5 L	Auto Wet Chem 1	78
KSG 4	4.5 L	Auto Wet Chem 1	79
KSG 5	4.5 L	Auto Wet Chem 2	80
KSG 6	4.5 L	Auto Wet Chem 2	81
KSG 7	4.5 L	Auto Wet Chem 2	82
KSG 8	4.5 L	Auto Wet Chem 3	83
KSG 9	4.5 L	Manual Wet Chem	84
KSG 10	4.5 L	Manual Wet Chem	85
KSG 11	4.5 L	Auto Dry Chem	86
KSG 12	4.5 L	Manual Dry Chem	87
KSG 13	4.5 L	Water Mist 1	88
KSG 14	4.5 L	Residential Sprinkler	89
KSG 15	4.5 L	Free Burn	90
KSG 16	1.62 L	Auto Dry Chem	91
KSG 17	0.5 L	Auto Dry Chem	92
KSG 18	1.62 L	Auto Wet Chem 3	93
KSG 19	1.62 L	Auto Wet Chem 1	94
KSG 20	1.62 L	Free Burn	95

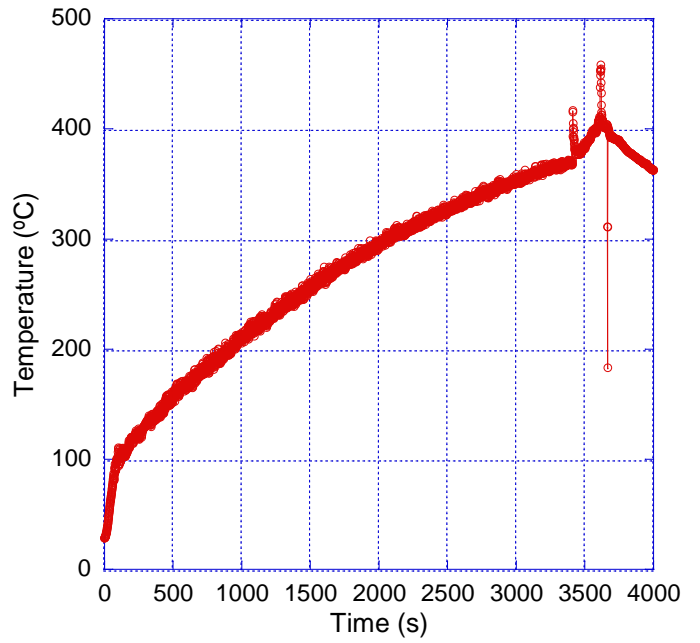
The uncertainty of data presented in this appendix is presented in Section 4 of this report. The expanded uncertainty in the measured temperature, heat flux, and time is approximately  $\pm 15\%$ ,  $\pm 8\%$ , and  $\pm 5\text{ s}$ , respectively.



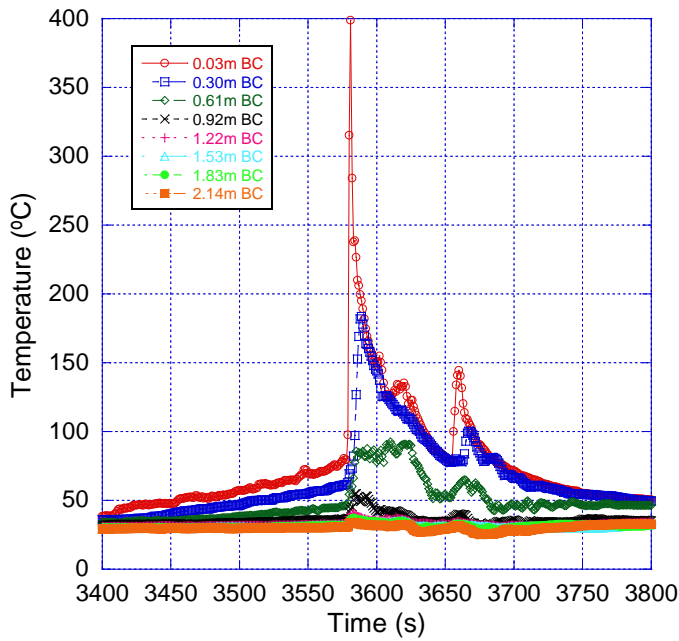
**KSE 1 Timeline  
Automatic Dry chemical**

Time	Event
0	Burner On
3407	Auto Ignition
3578	Auto Suppression (Canister 1)
3583	Auto Suppression (Canister 2)
	Fire Not Extinguished
3603	Manual Suppression
3654	Re-Ignition
3659	Manual Suppression 2
	Fire Extinguished

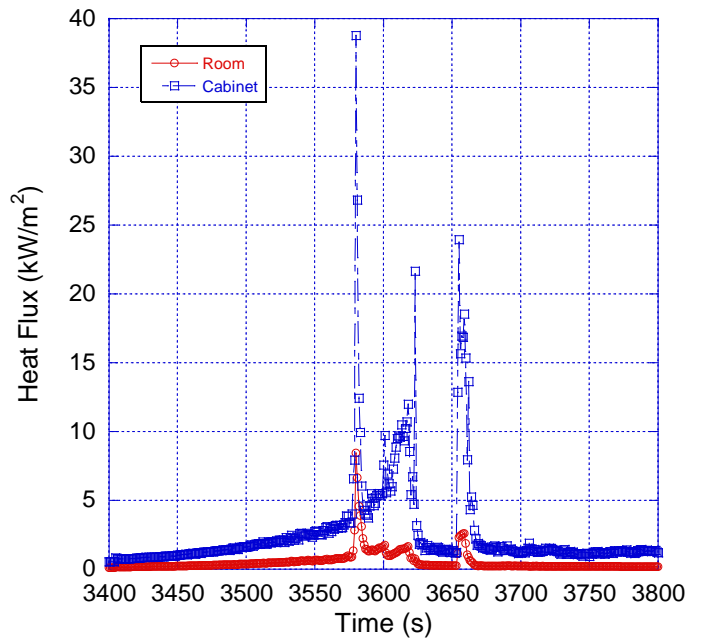
**Oil Temperature**



**Room Temperature**



**Heat Flux**

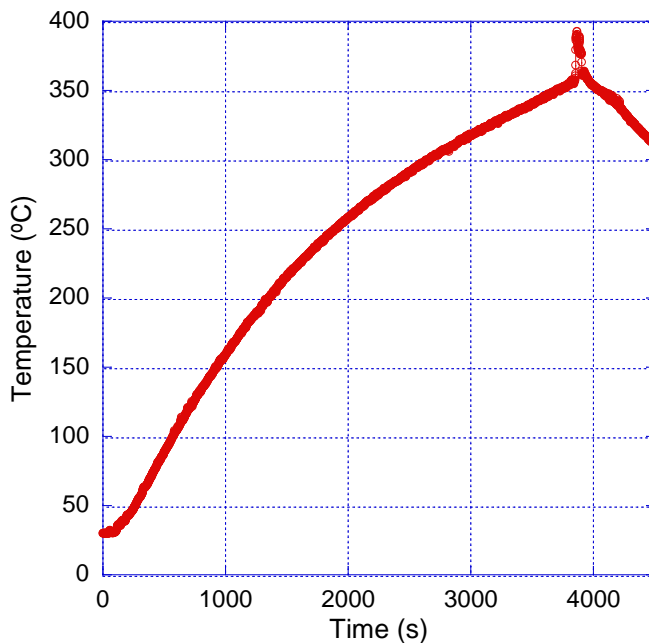


**Figure A1-1. Experiment KSE 1 timeline and data**

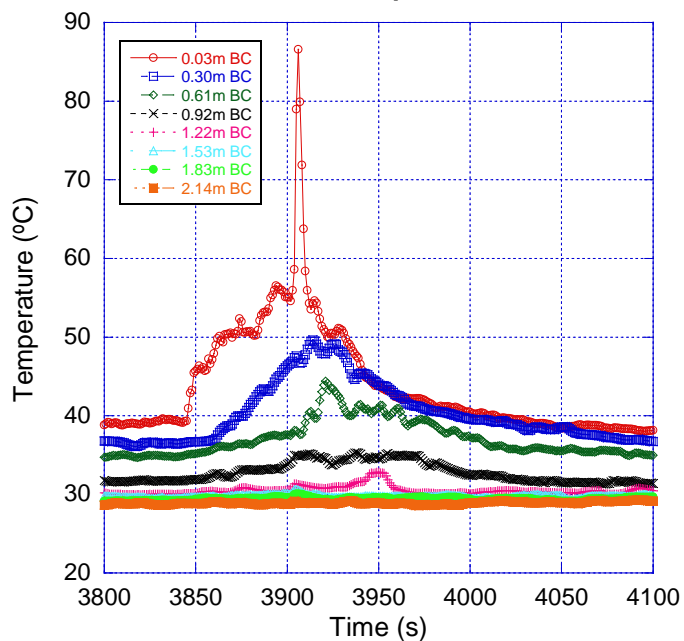
**KSE 2 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
3845	Auto Ignition
3906	Auto Suppression
	Fire Extinguished

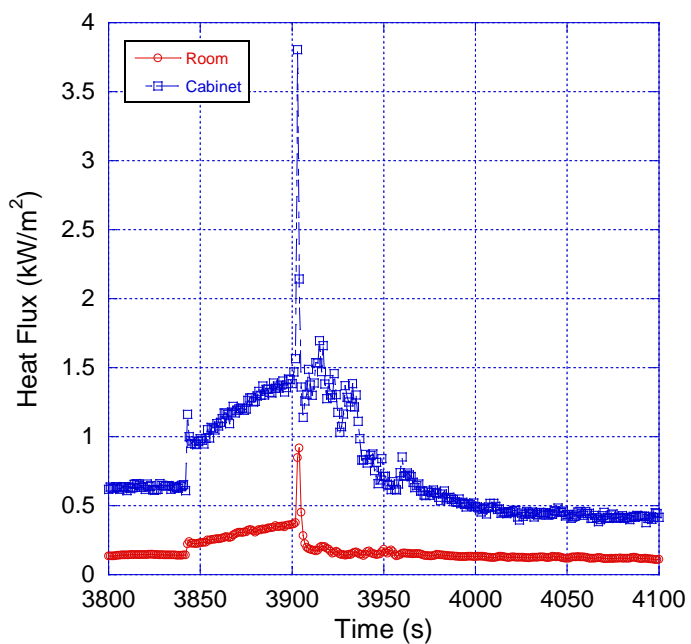
**Oil Temperature**



**Room Temperature**



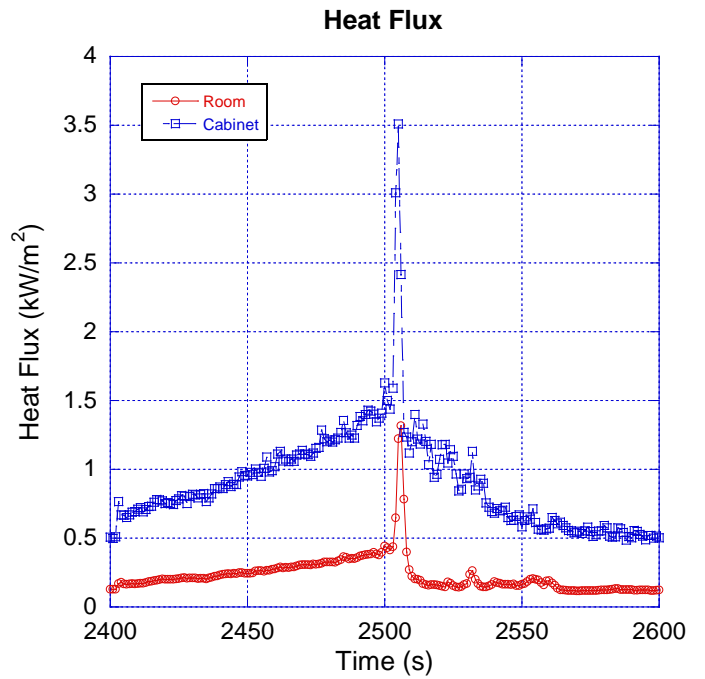
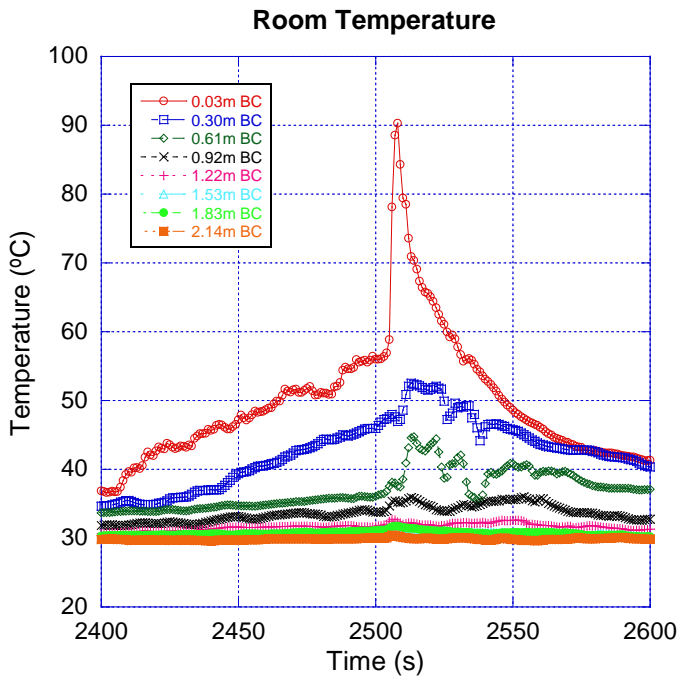
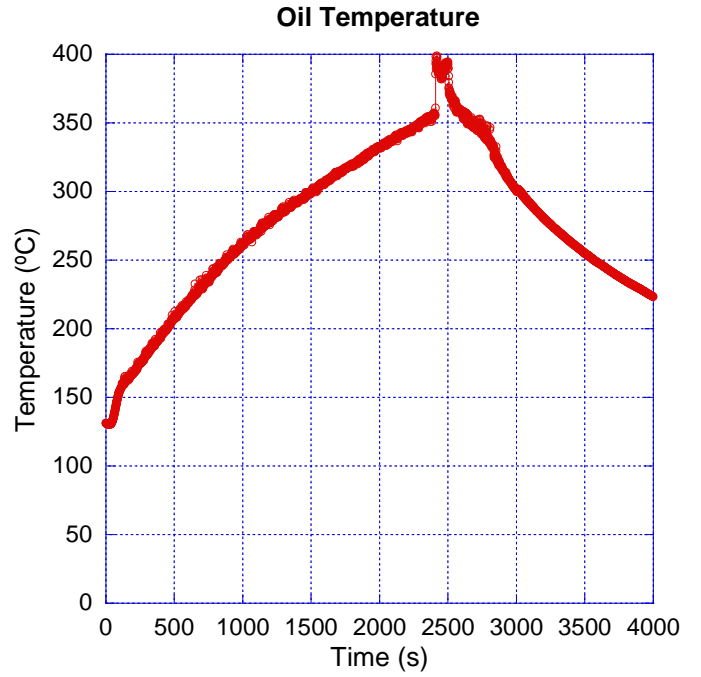
**Heat Flux**



**Figure A1-2. Experiment KSE 2 timeline and data**

**KSE 3 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
2405	Auto Ignition
2507	Auto Suppression
	Fire Extinguished

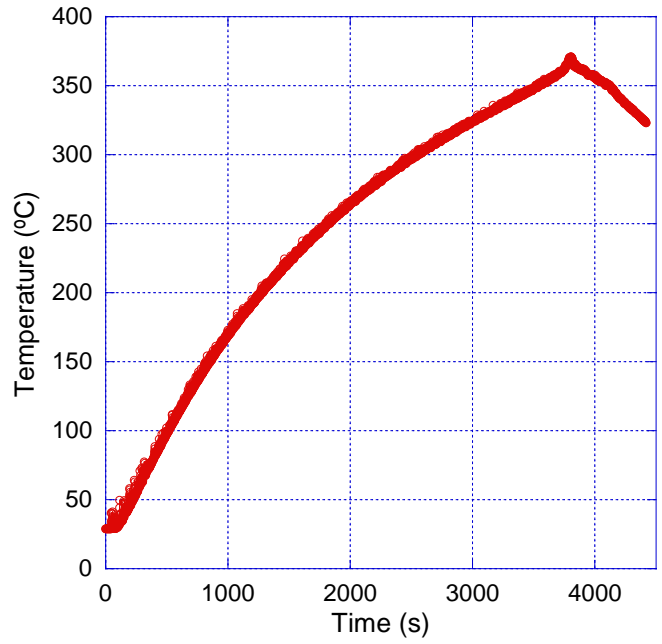


**Figure A1-3. Experiment KSE 3 timeline and data**

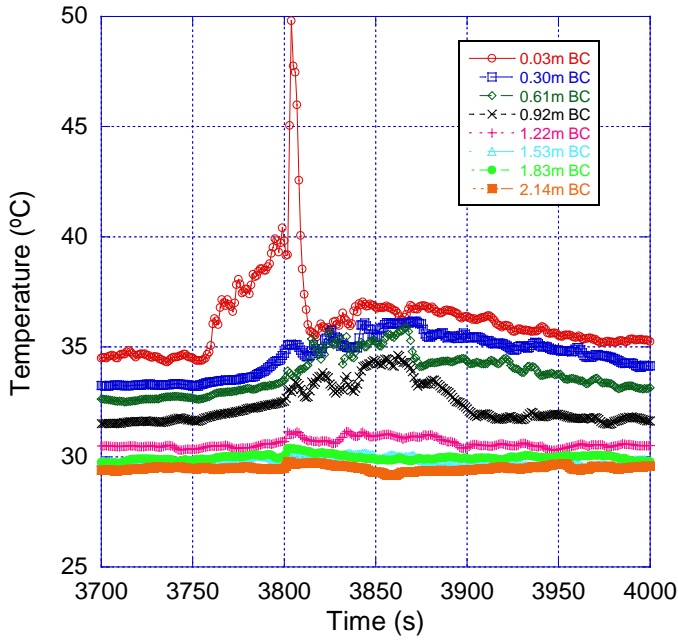
**KSE 4 Timeline  
Automatic Wet Chemical**

Time	Event
0	Burner On
3753	Auto Ignition
3800	Auto Suppression
	Fire Extinguished

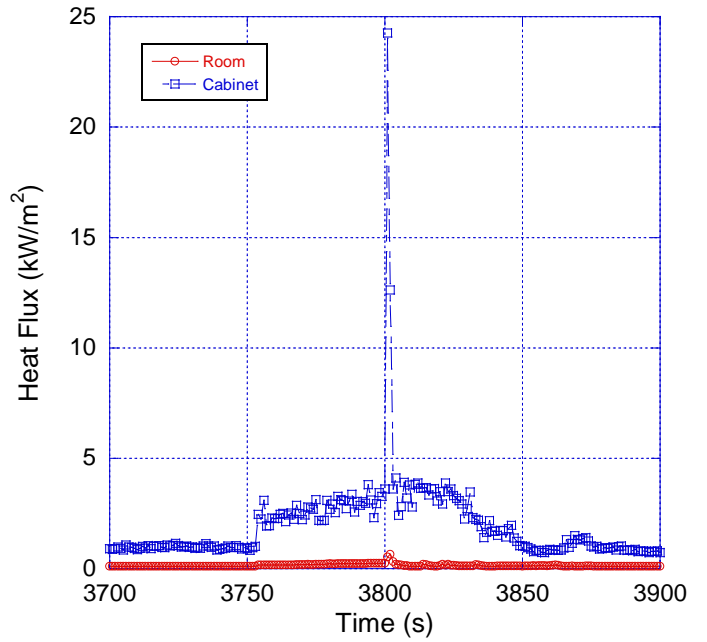
**Oil Temperature**



**Room Temperature**



**Heat Flux**

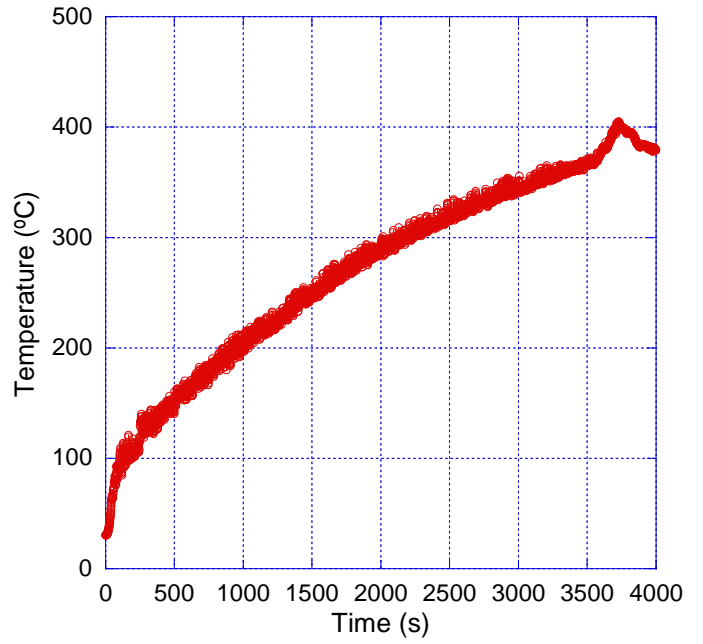


**Figure A1-4. Experiment KSE 4 timeline and data**

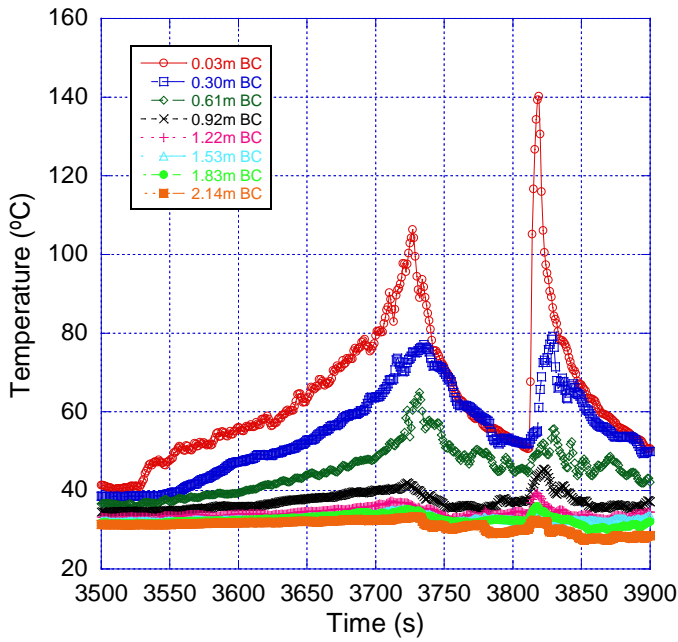
**KSE 5 Timeline  
Automatic Wet Chemical 3**

Time	Event
0	Burner On
3524	Auto Ignition
3707	Manual Suppression
3775	Auto Suppression
3811	Re-Ignition
3816	Manual Suppression 2
	Fire Extinguished

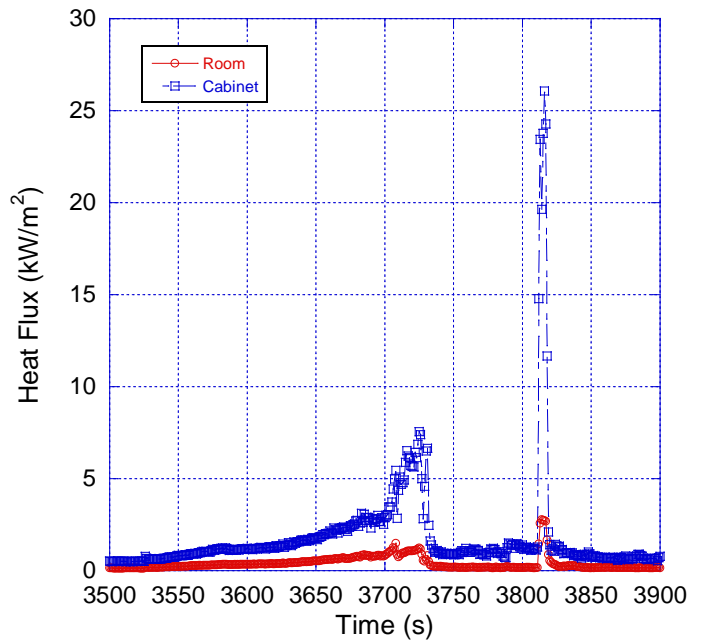
**Oil Temperature**



**Room Temperature**



**Heat Flux**

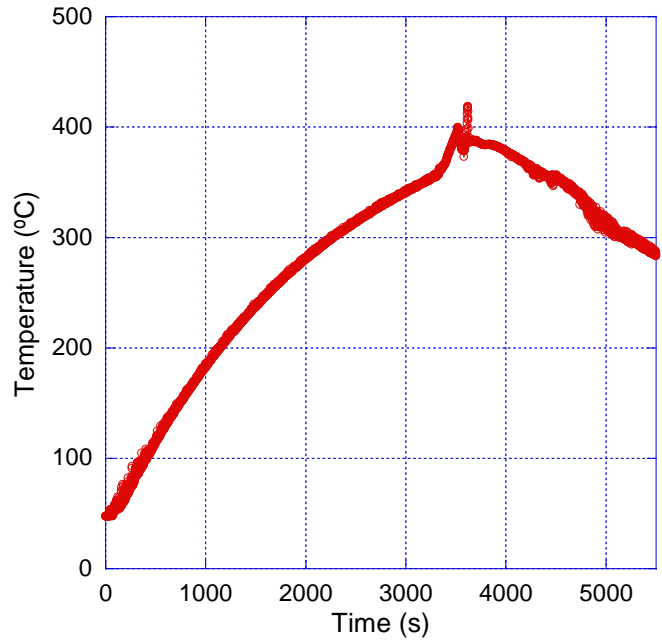


**Figure A1-5. Experiment KSE 5 timeline and data**

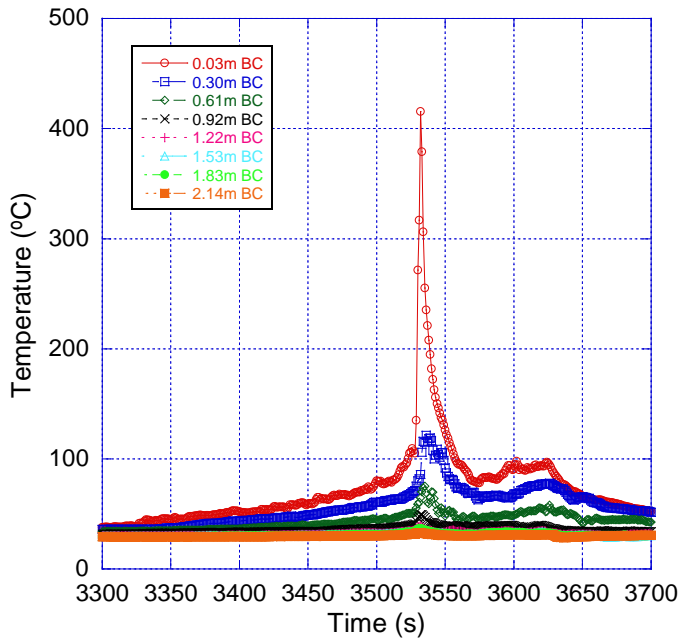
**KSE 6 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
3320	Auto Ignition
3526	Auto Suppression
3570	Re-Ignition
3598	Manual Suppression
	Fire Extinguished

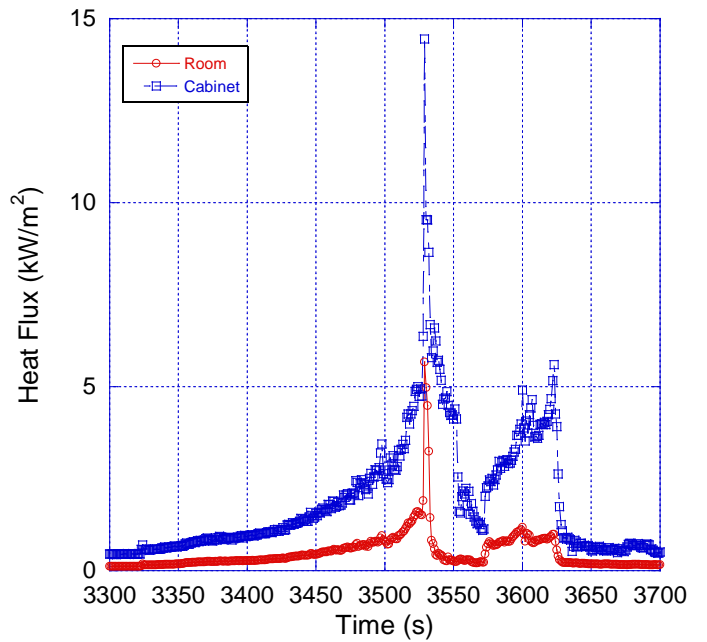
**Oil Temperature**



**Room Temperature**



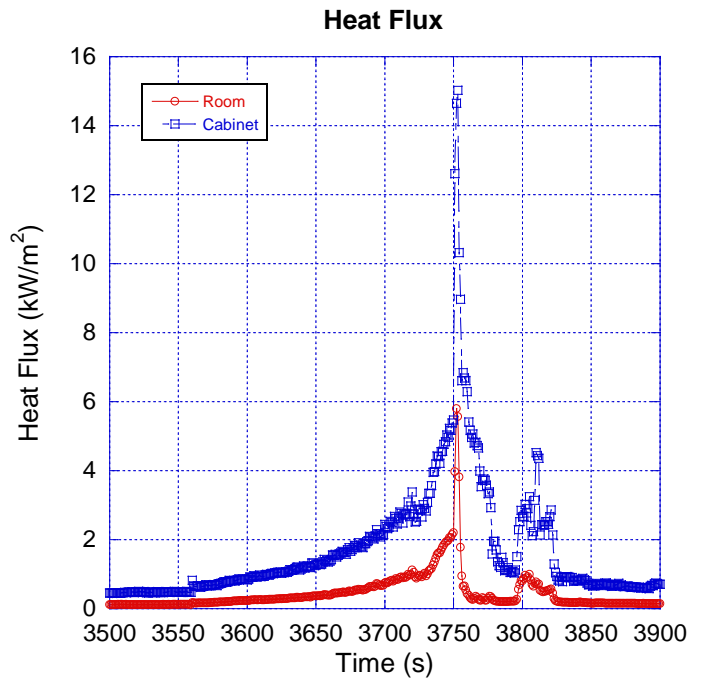
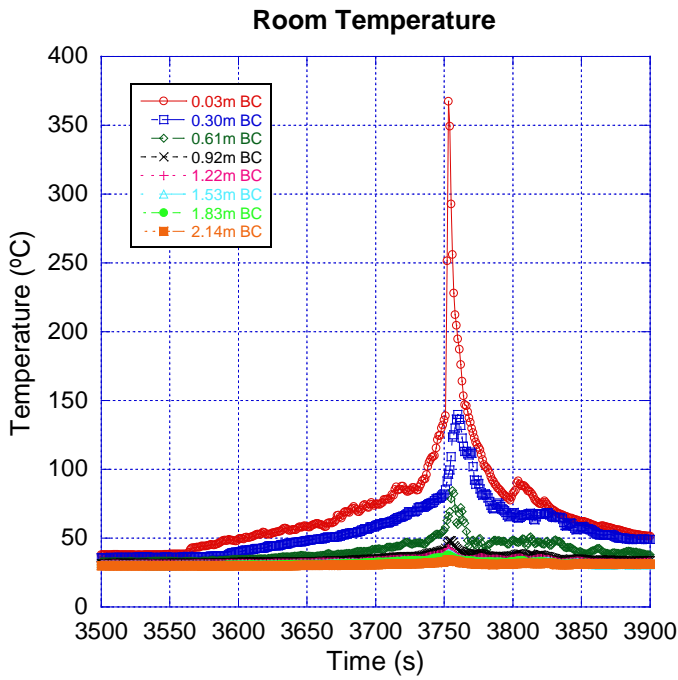
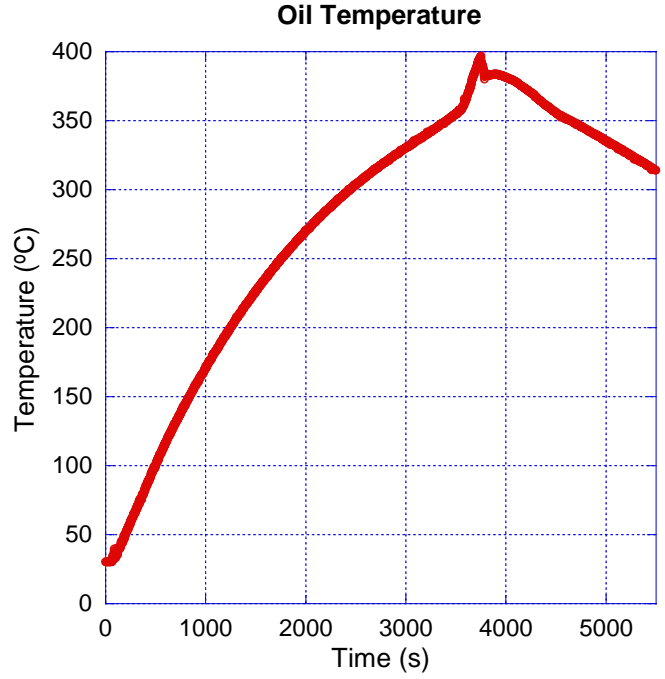
**Heat Flux**



**Figure A1-6. Experiment KSE 6 timeline and data**

**KSE 7 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
3557	Auto Ignition
3749	Auto Suppression
3793	Re-Ignition
3808	Manual Suppression
	Fire Extinguished

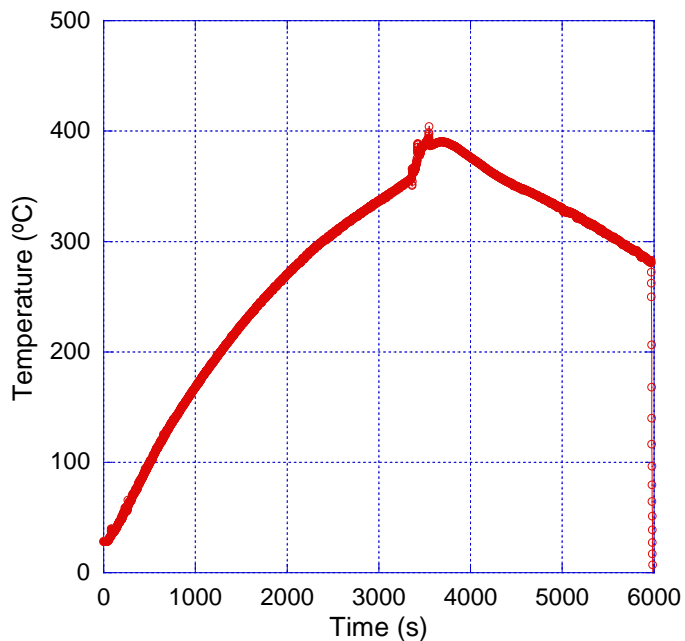


**Figure A1-7. Experiment KSE 7 timeline and data**

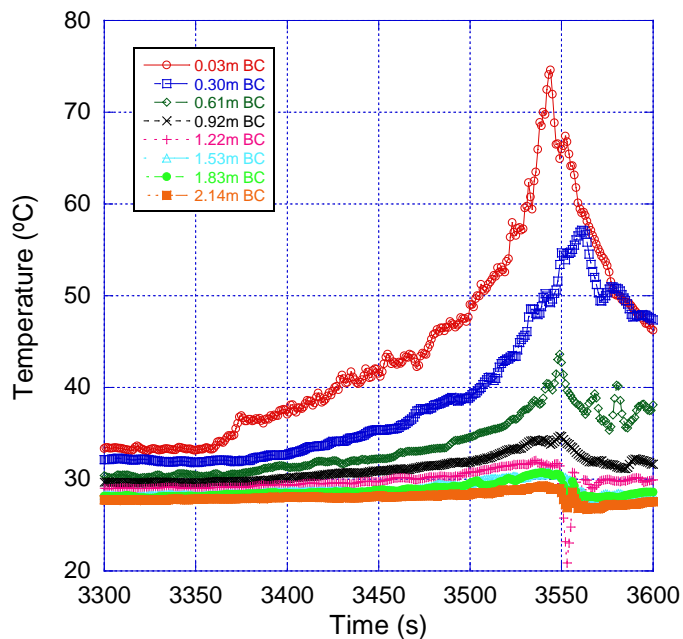
**KSE 8 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
3358	Auto Ignition
3513	Auto Suppression (No Discharge)
	Fire Not Extinguished
3546	Manual Suppression
	Fire Extinguished

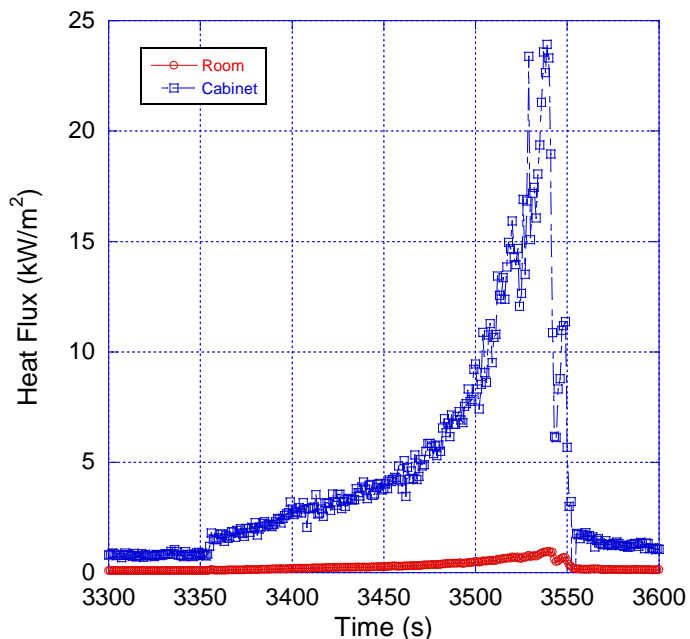
**Oil Temperature**



**Room Temperature**



**Heat Flux**



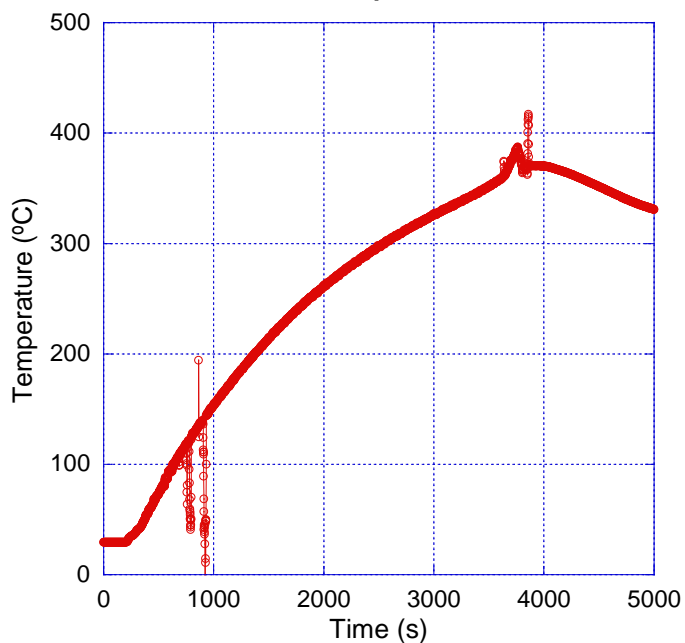
**Figure A1-8. Experiment KSE 8 timeline and data**



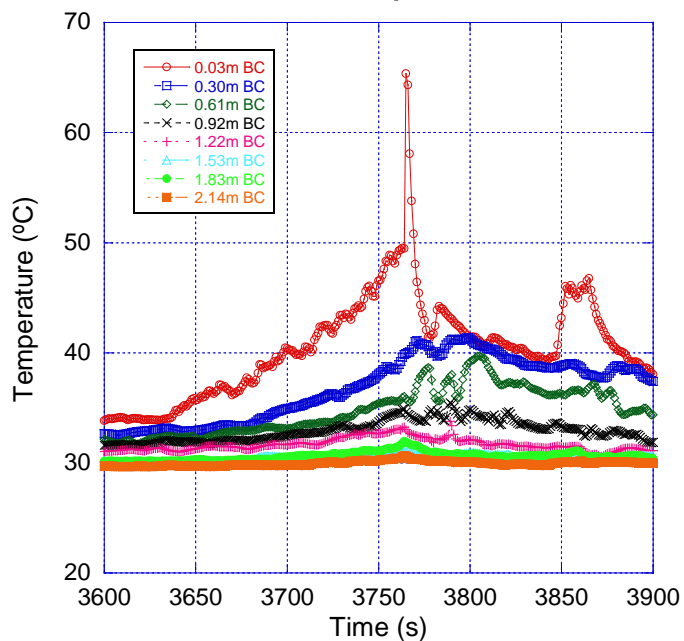
**KSE 9 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
3632	Auto Ignition
3763	Auto Suppression
3844	Re-Ignition
3862	Manual Suppression
	Fire Extinguished

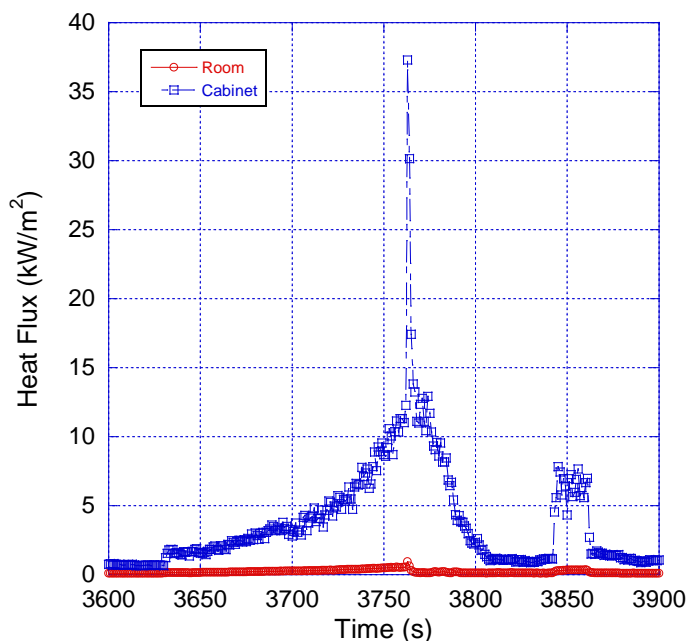
**Oil Temperature**



**Room Temperature**



**Heat Flux**

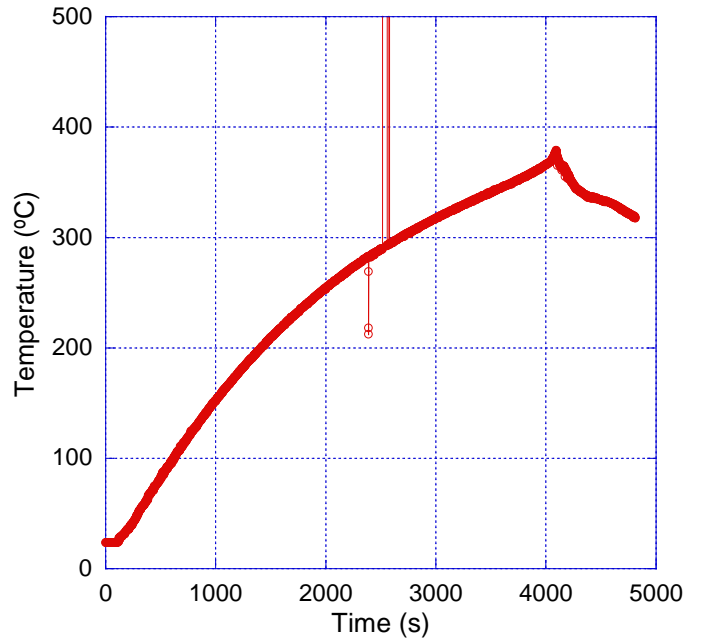


**Figure A1-9. Experiment KSE 9 timeline and data**

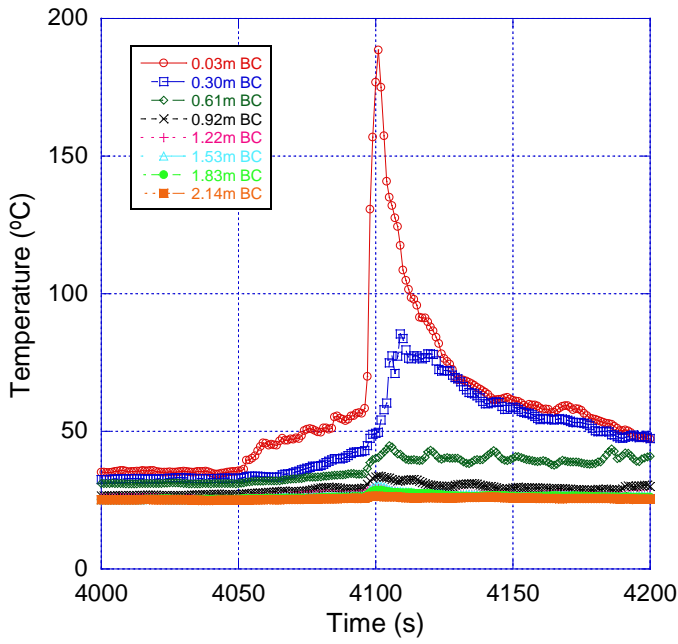
**KSE 10 Timeline  
Automatic Wet Chemical 4**

Time	Event
0	Burner On
4045	Auto Ignition
4091	Auto Suppression
	Fire Not Extinguished
4170	Manual Suppression
	Fire Extinguished

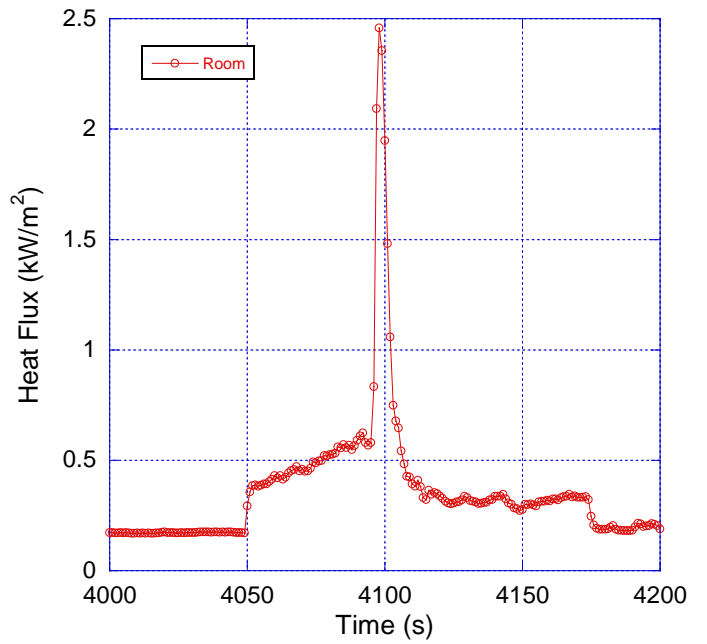
**Oil Temperature**



**Room Temperature**



**Heat Flux**

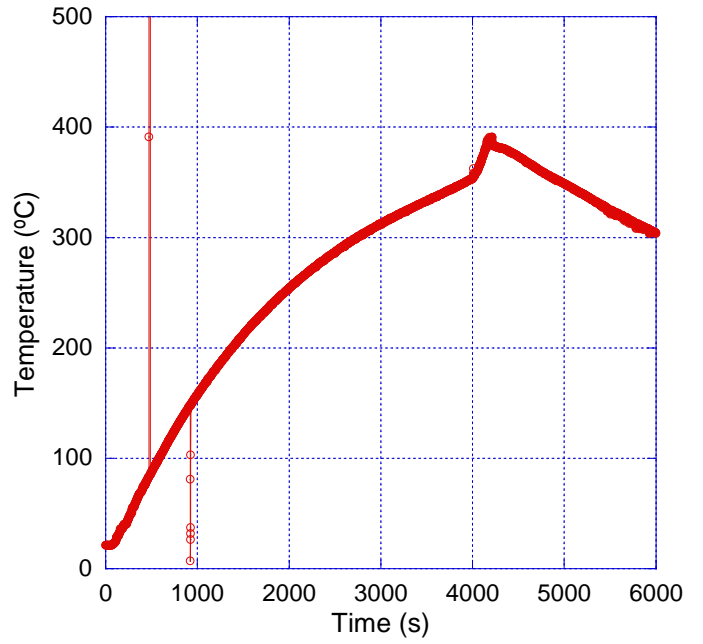


**Figure A1-10. Experiment KSE 10 timeline and data**

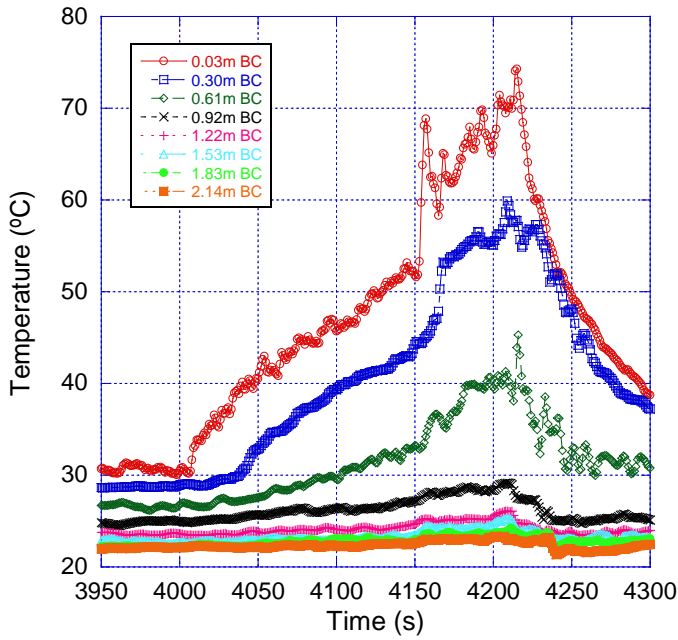
**KSE 11 Timeline  
Automatic Wet Chemical 4**

Time	Event
0	Burner On
4008	Auto Ignition
4152	Auto Suppression
	Fire Not Extinguished
4229	Manual Suppression
	Fire Extinguished

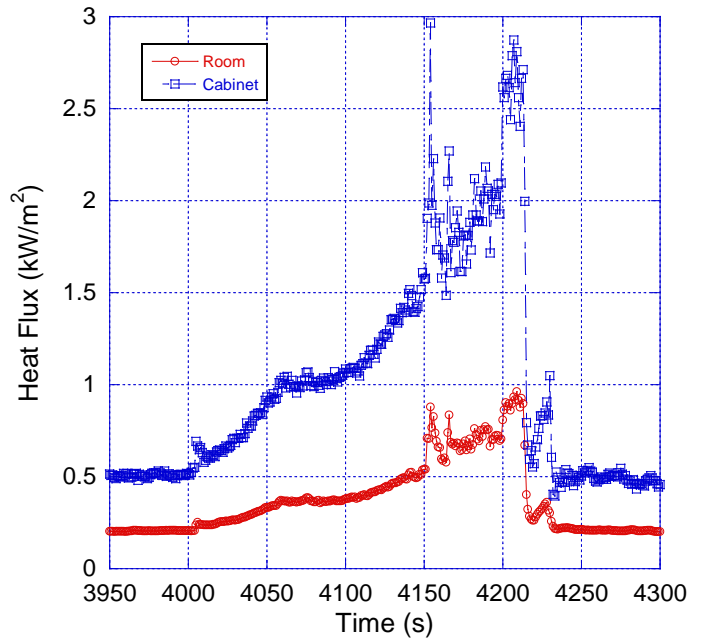
**Oil Temperature**



**Room Temperature**



**Heat Flux**

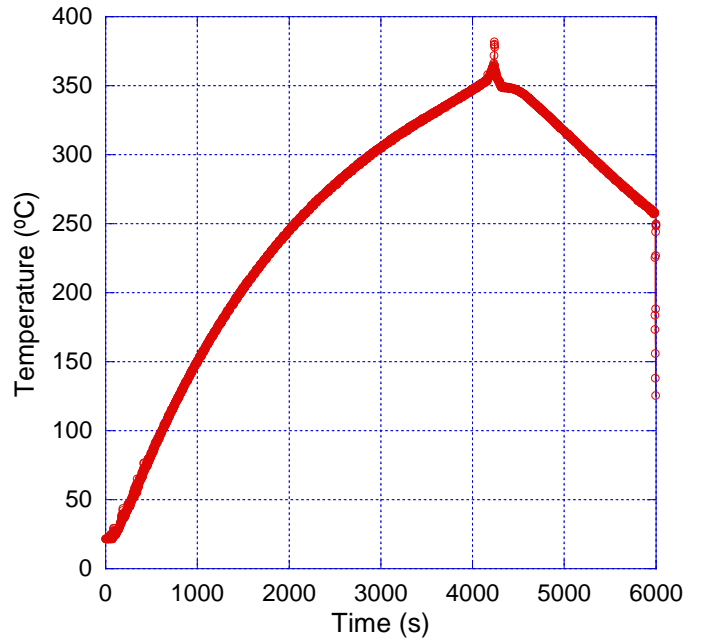


**Figure A1-11. Experiment KSE 11 timeline and data**

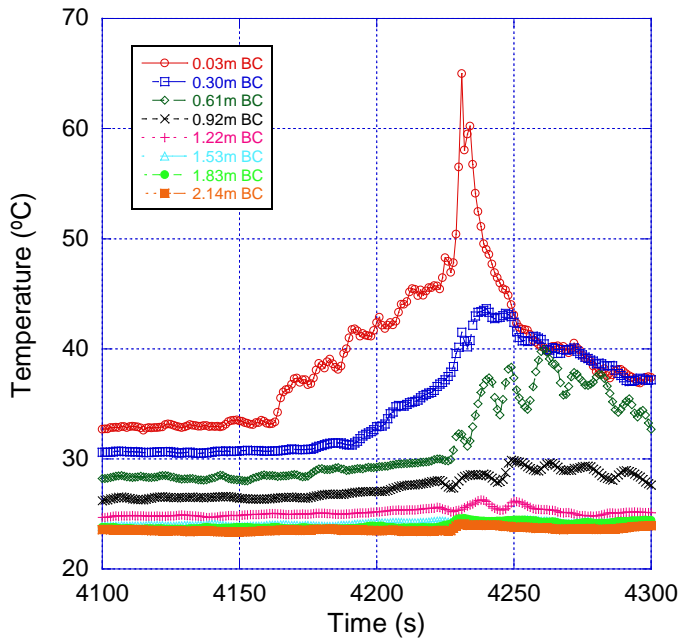
**KSE 12 Timeline  
Manual Wet Chemical**

Time	Event
0	Burner On
4158	Auto Ignition
4221	Manual Suppression
	Fire Extinguished

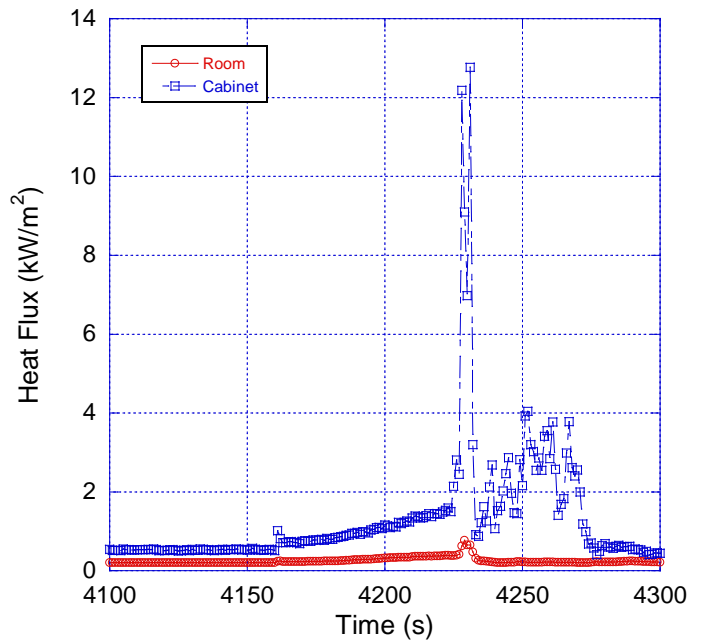
**Oil Temperature**



**Room Temperature**



**Heat Flux**

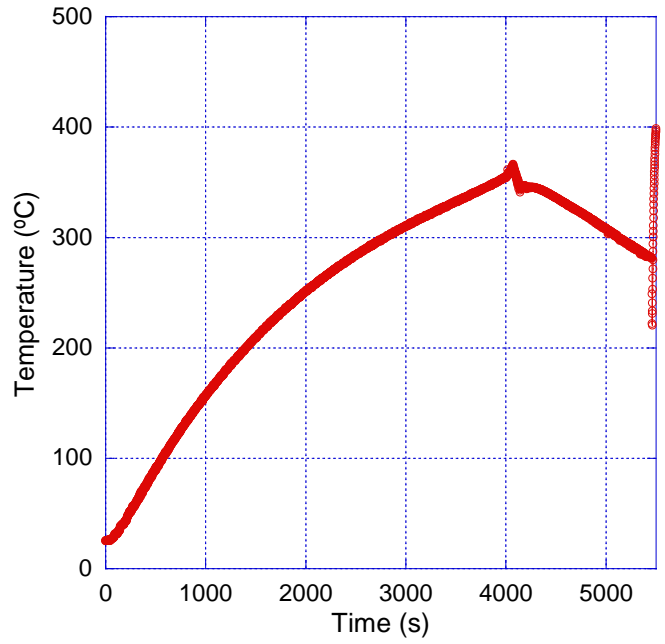


**Figure A1-12. Experiment KSE 12 timeline and data**

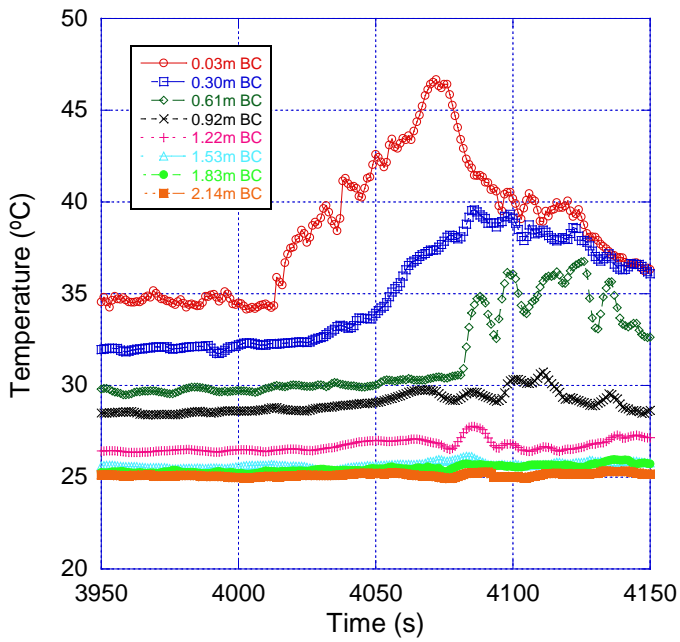
**KSE 13 Timeline  
Manual Wet Chemical**

Test	Event
0	Burner On
4010	Auto Ignition
4073	Manual Suppression
	Fire Extinguished

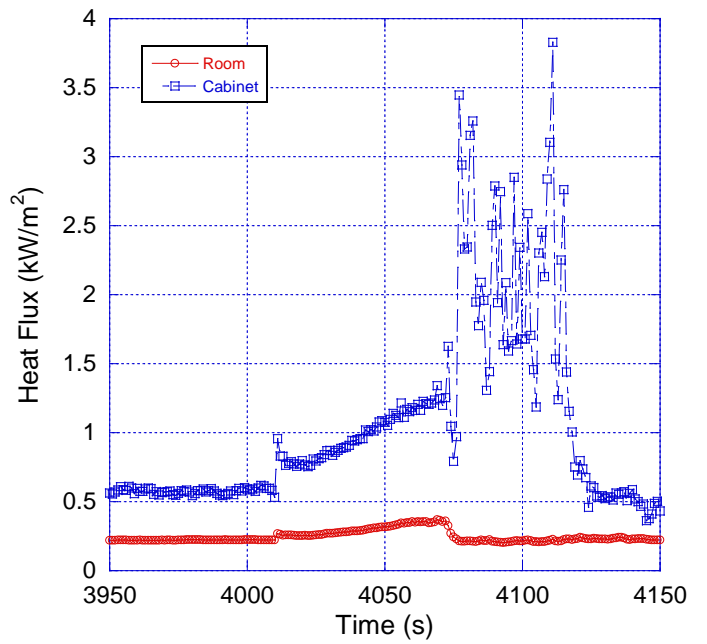
**Oil Temperature**



**Room Temperature**



**Heat Flux**

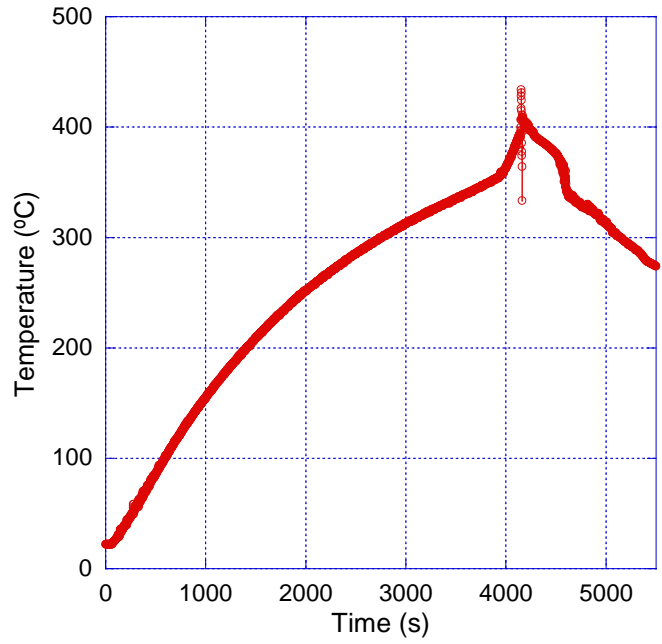


**Figure A1-13. Experiment KSE 13 timeline and data**

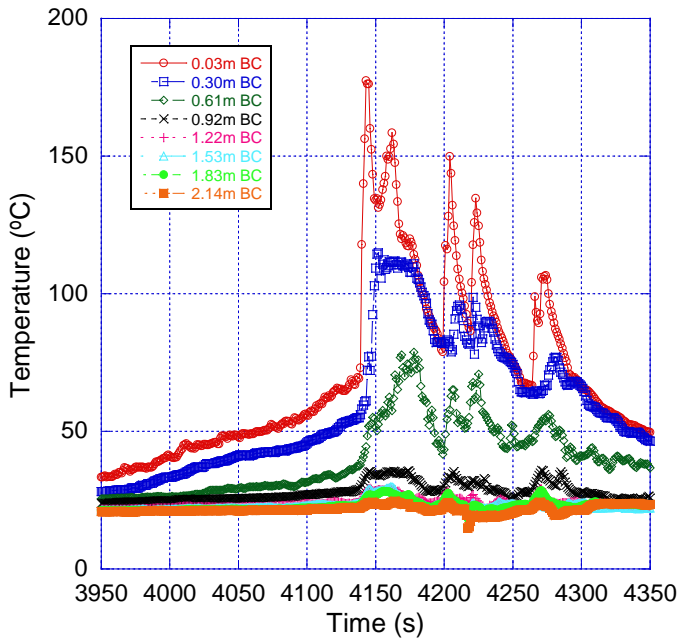
**KSE 14 Timeline  
Automatic Dry Chemical**

Time	Event
0	Burner On
3940	Auto Ignition
4138	Auto Suppression
	Fire Not Extinguished
4162	Manual Suppression
	Fire Extinguished

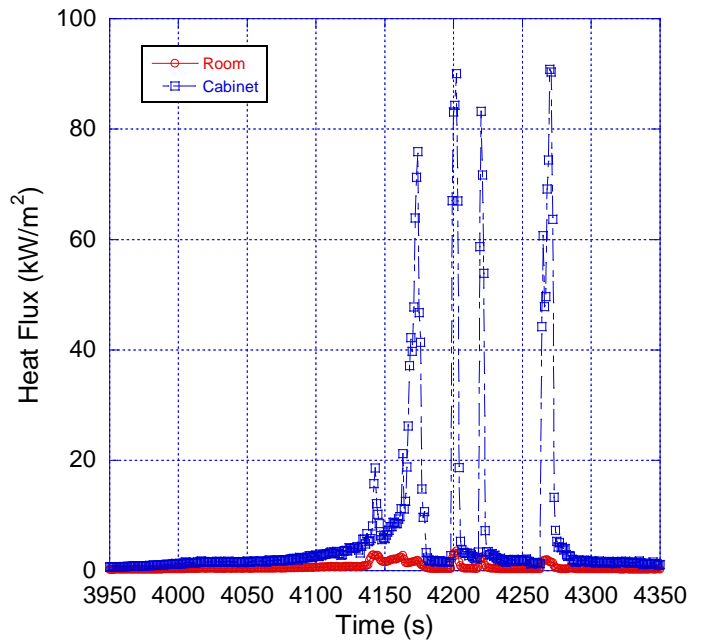
**Oil Temperature**



**Room Temperature**



**Heat Flux**

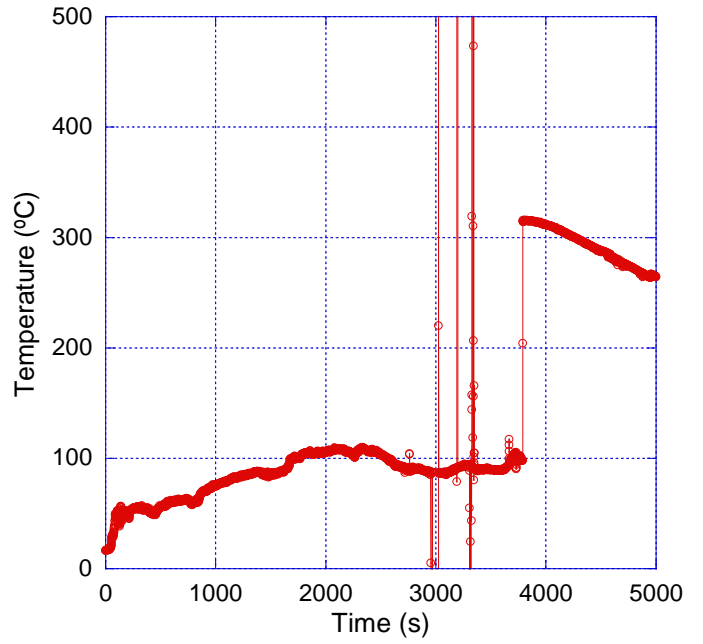


**Figure A1-14. Experiment KSE 14 timeline and data**

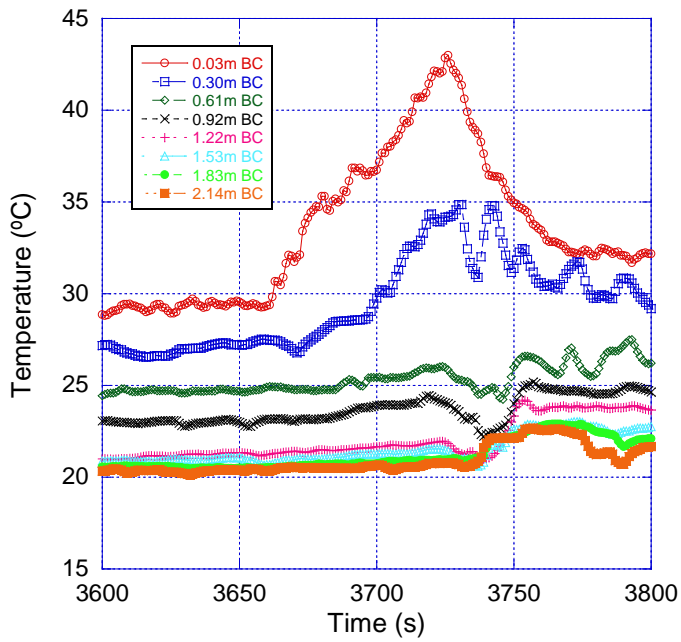
**KSE 15 Timeline  
Manual Dry Chemical**

Time	Event
0	Burner On
3647	Auto Ignition
3716	Manual Suppression
	Fire Extinguished

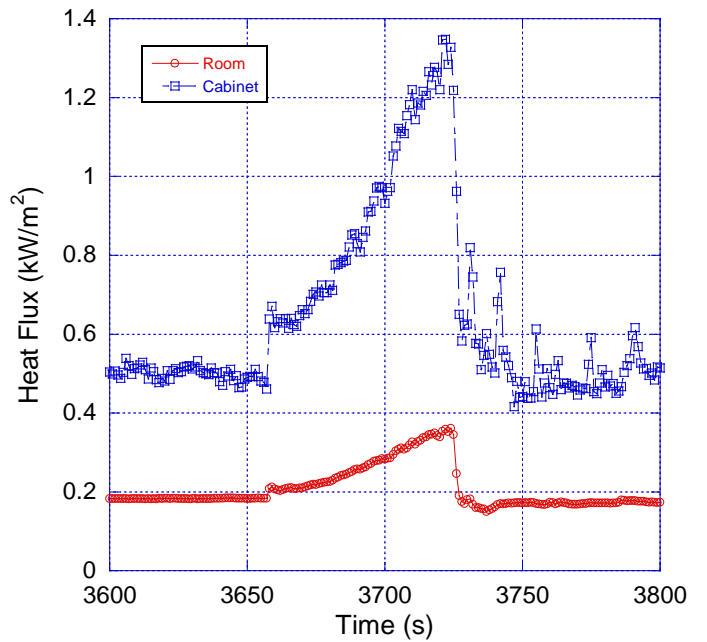
**Oil Temperature**



**Room Temperature**



**Heat Flux**

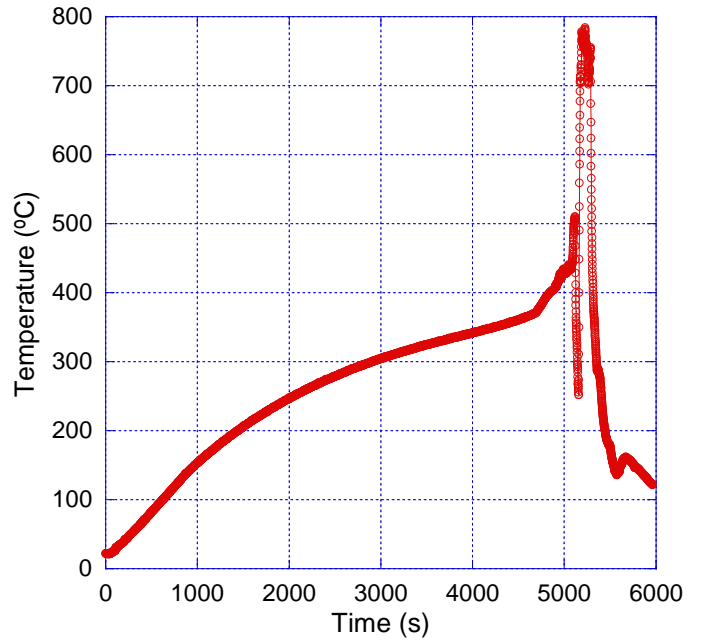


**Figure A1-15. Experiment KSE 15 timeline and data**

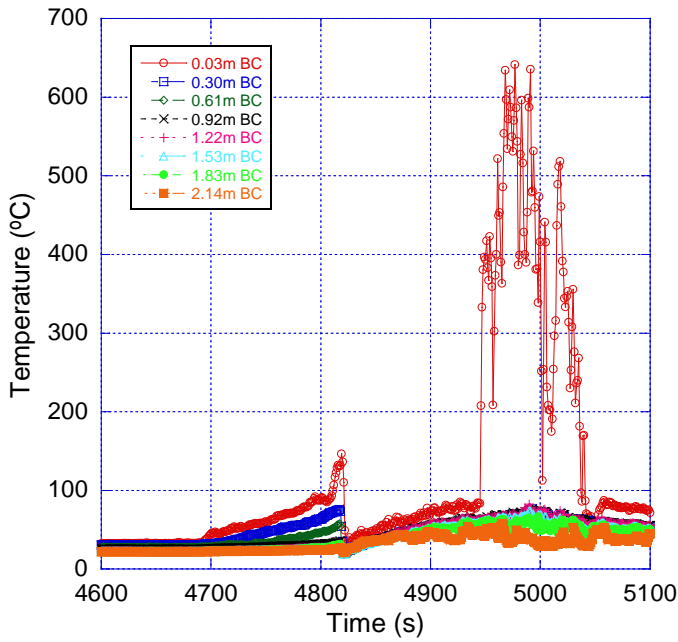
**KSE 16 Timeline  
Water Mist 1**

Time	Event
0	Burner On
4694	Auto Ignition
4823	Auto Suppression Activation
	Fire Not Extinguished
4991	Manual Suppression
	Fire Extinguished

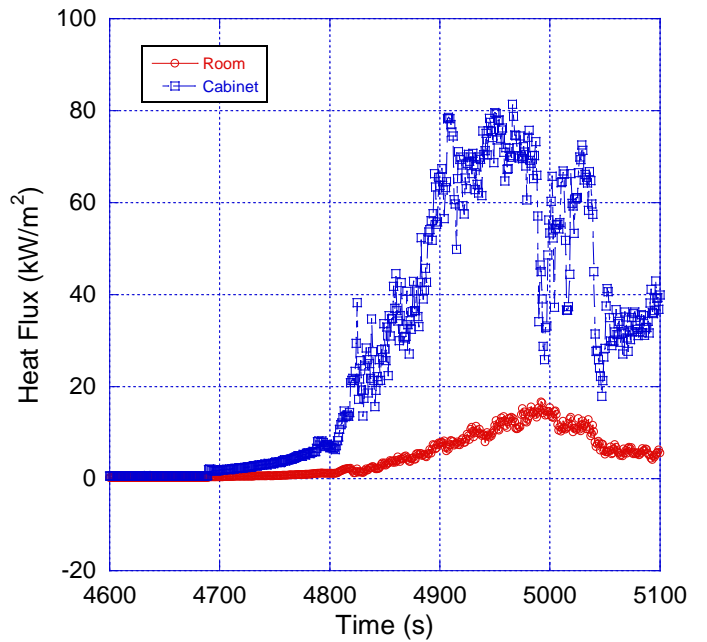
**Oil Temperature**



**Room Temperature**



**Heat Flux**



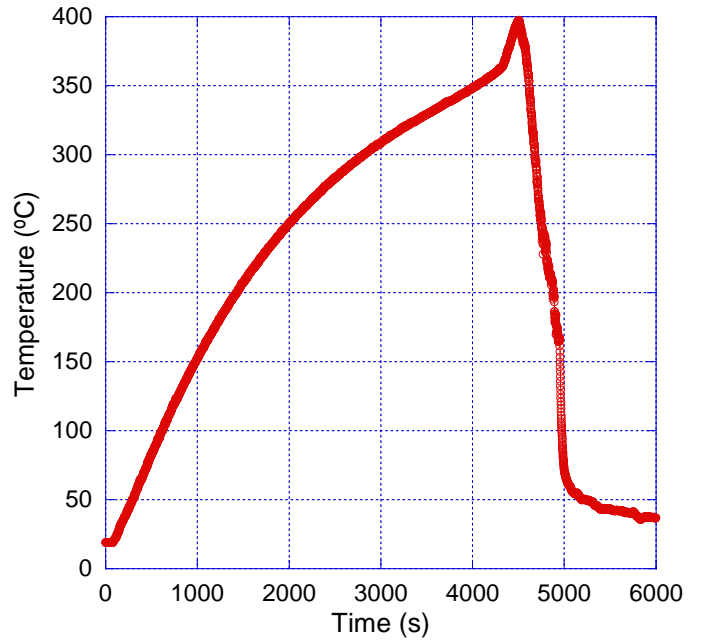
**Figure A1-16. Experiment KSE 16 timeline and data**



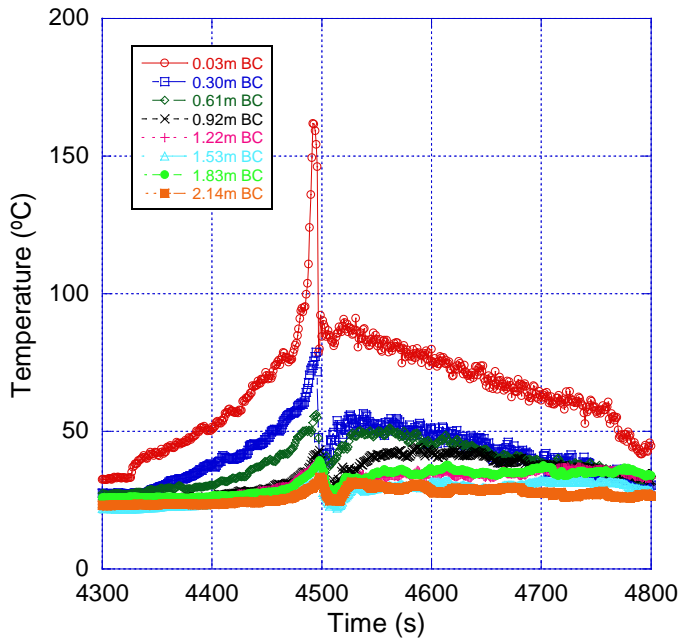
**KSE 17 Timeline  
Residential Sprinkler**

Time	Event
0	Burner On
4318	Auto Ignition
4494	Auto Suppression Activation
4765	Fire Extinguished

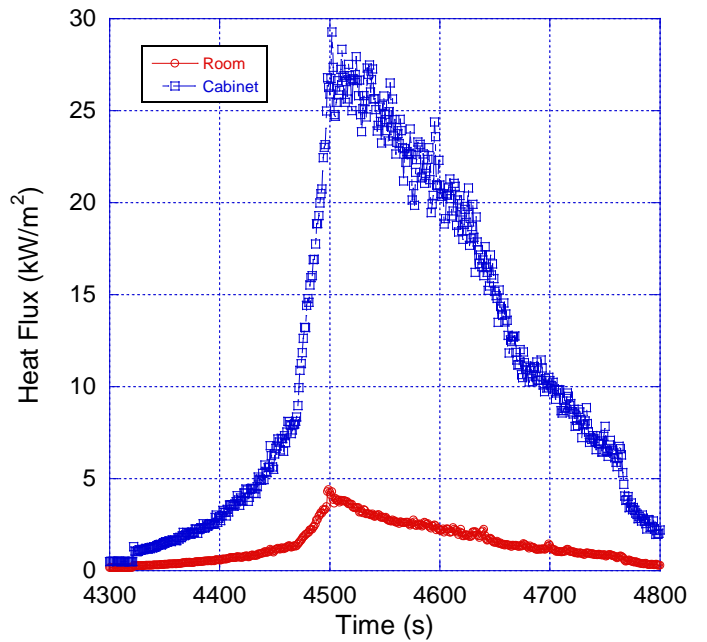
**Oil Temperature**



**Room Temperature**



**Heat Flux**

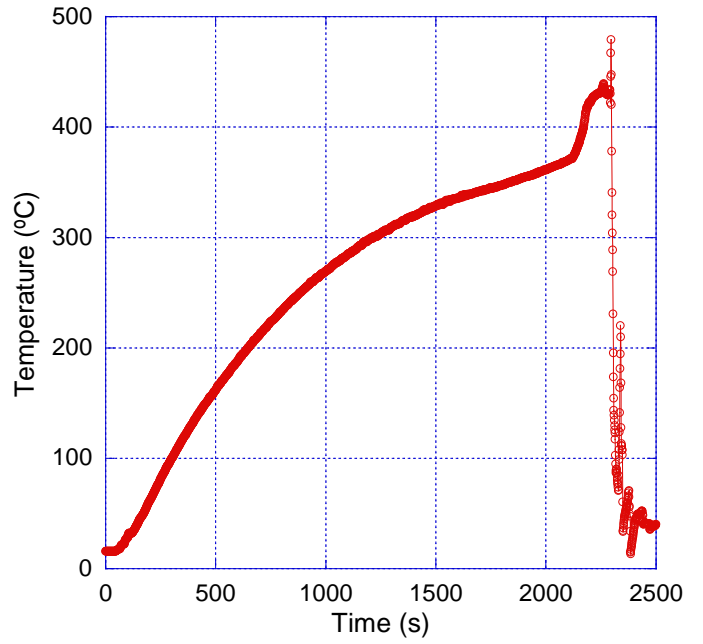


**Figure A1-17. Experiment KSE 17 timeline and data**

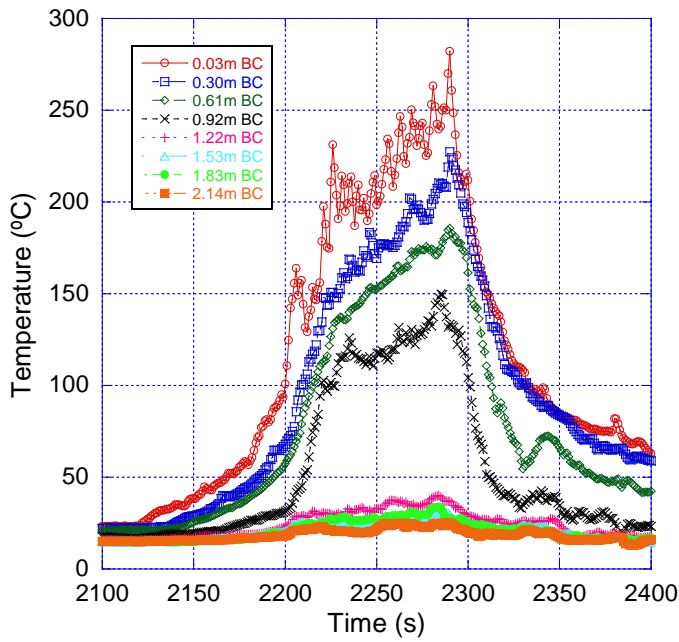
**KSE 18 Timeline  
Water Mist 2**

Time	Event
0	Burner On
2130	Auto Ignition
2216	Auto Suppression Activation
	Fire Not Extinguished
2300	Manual Suppression
	Fire Extinguished (Several Tries)

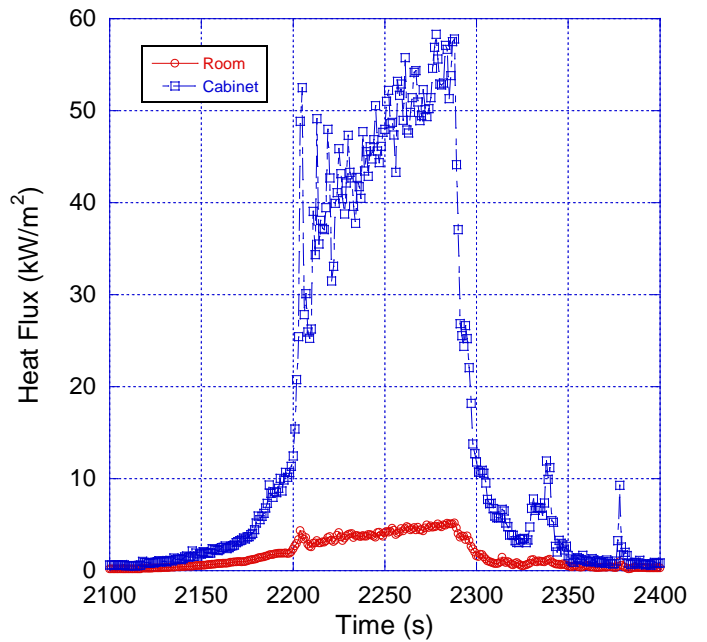
**Oil Temperature**



**Room Temperature**



**Heat Flux**

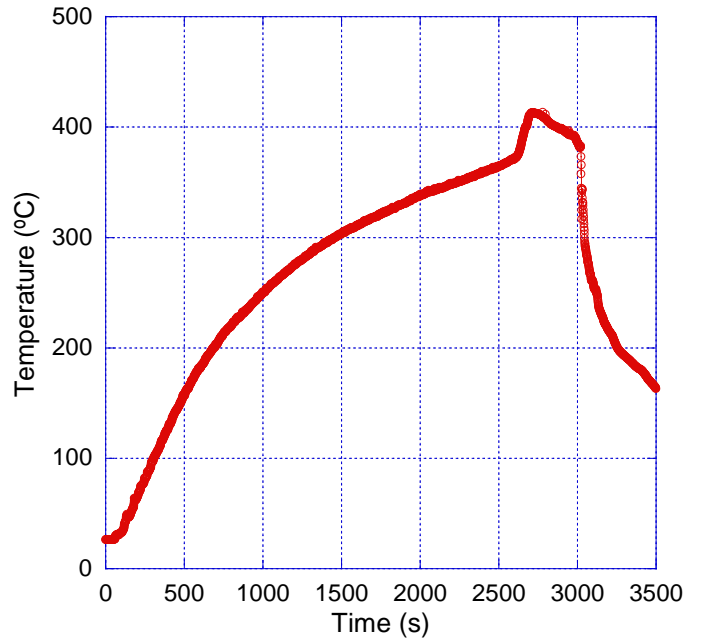


**Figure A1-18. Experiment KSE 18 timeline and data**

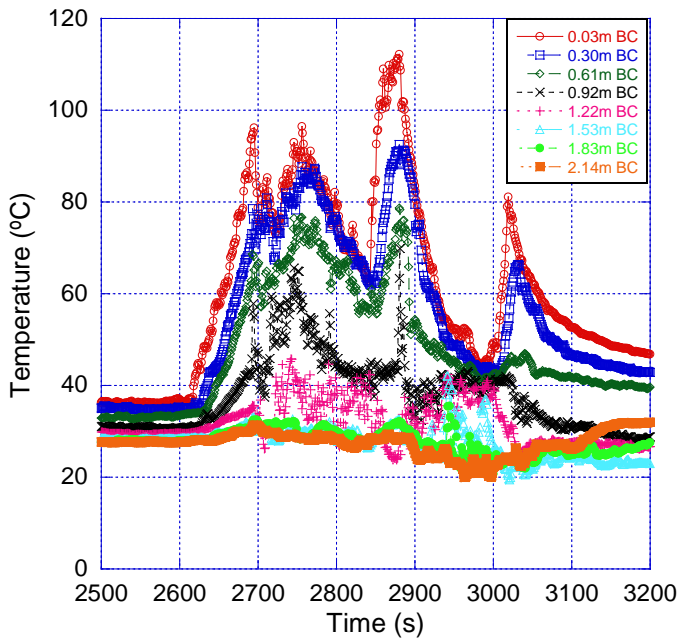
**1KSE 19 Timeline  
Water Mist 2**

Time	Event
0	Burner On
2610	Auto Ignition
2688	Auto Suppression
	Fire Not Extinguished
3018	Manual Suppression
	Fire Extinguished

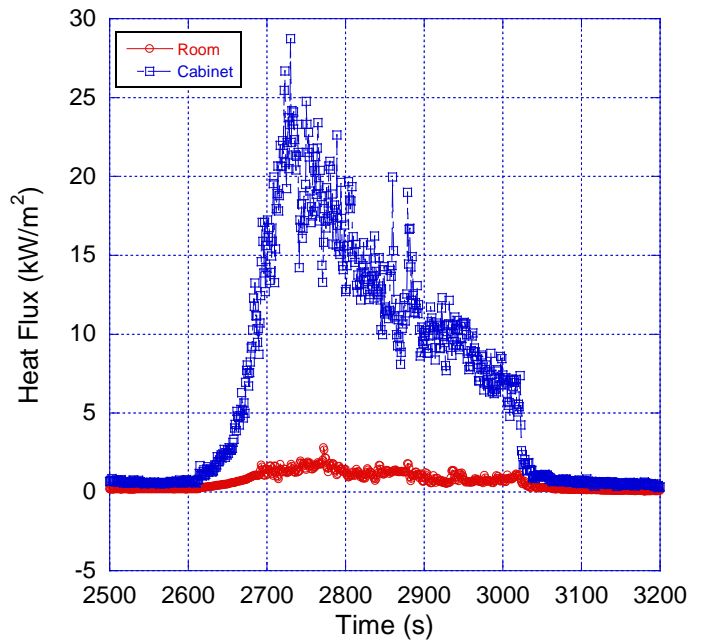
**Oil Temperature**



**Room Temperature**



**Heat Flux**

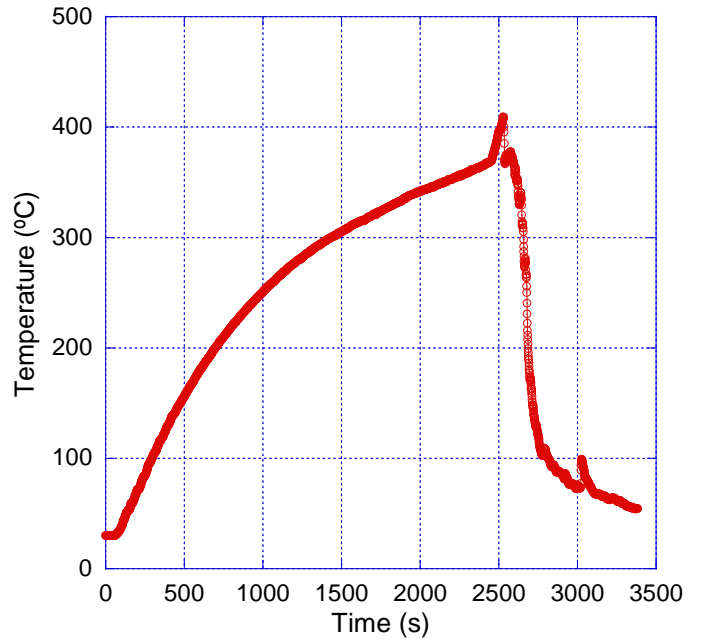


**Figure A1-19. Experiment KSE 19 timeline and data**

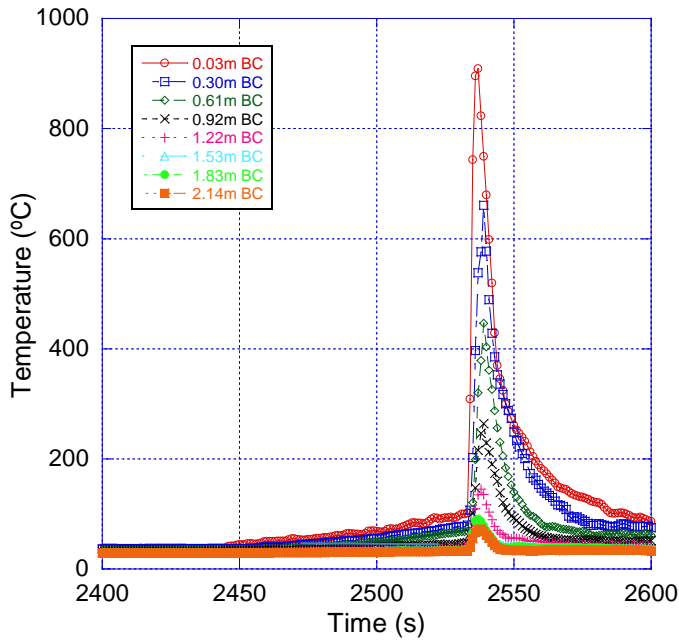
**KSE 20 Timeline  
Water Mist 3**

Time	Event
0	Burner On
2445	Auto Ignition
2537	Auto Suppression
	Fire Extinguished

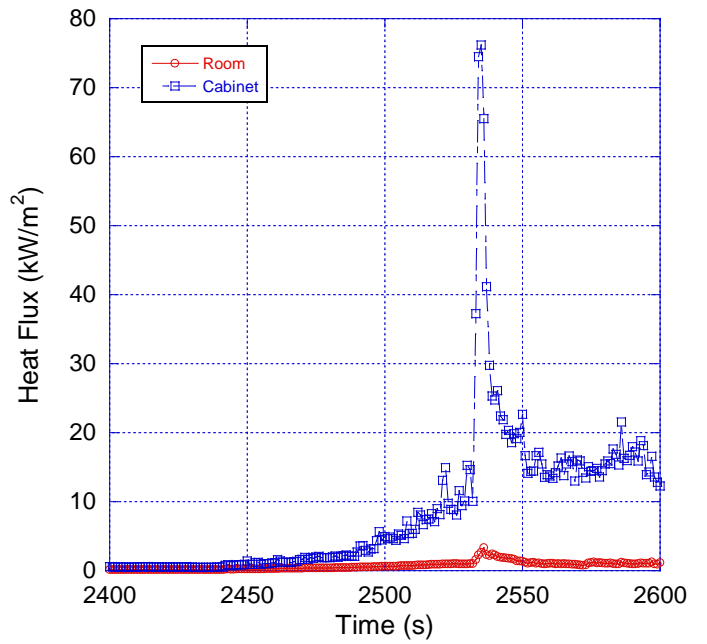
**Oil Temperature**



**Room Temperature**



**Heat Flux**

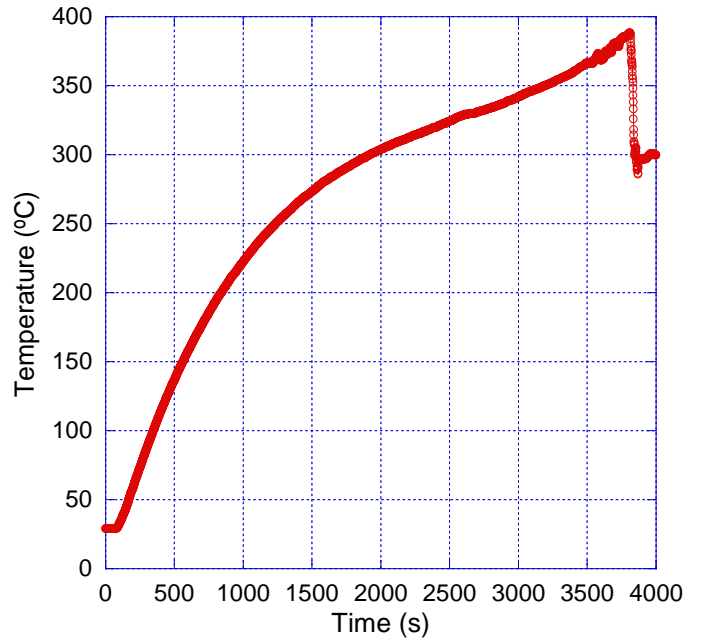


**Figure A1-20. Experiment KSE 20 timeline and data**

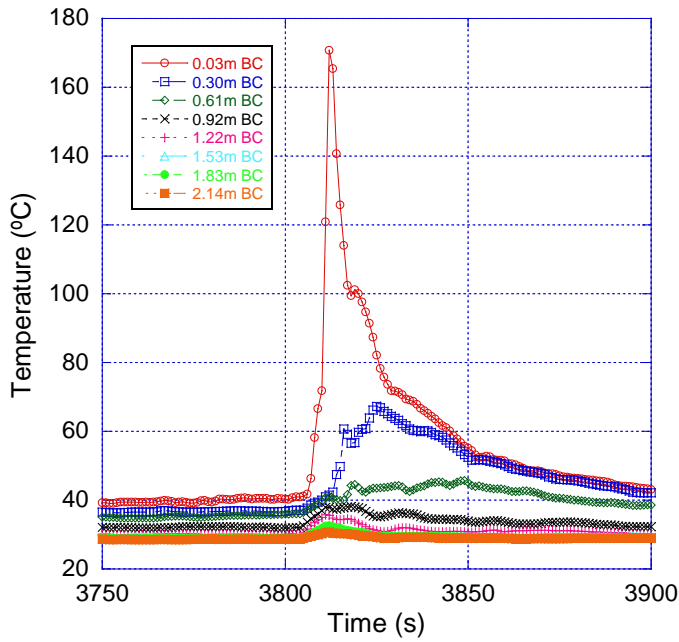
**KSE 21 Timeline  
Automatic Wet Chemical 4**

Time	Event
0	Burner On
3805	Auto Ignition
3810	Auto Suppression
	Fire Extinguished

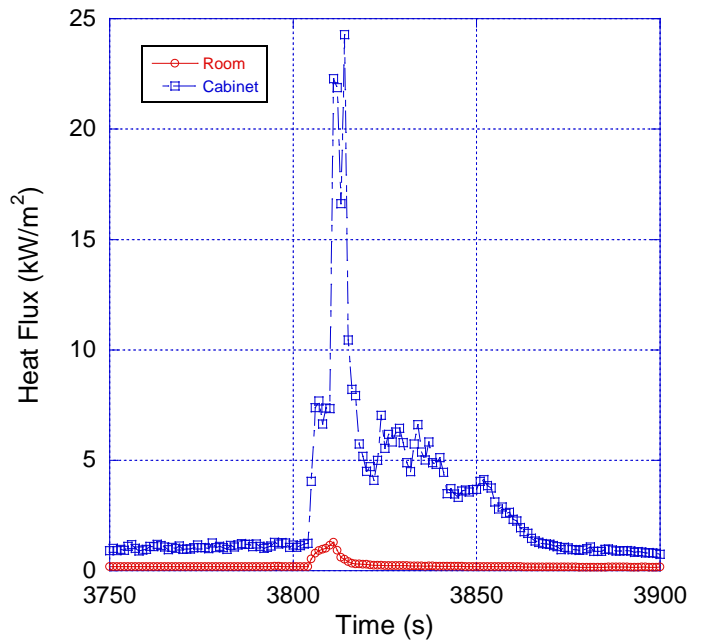
**Oil Temperature**



**Room Temperature**



**Heat Flux**

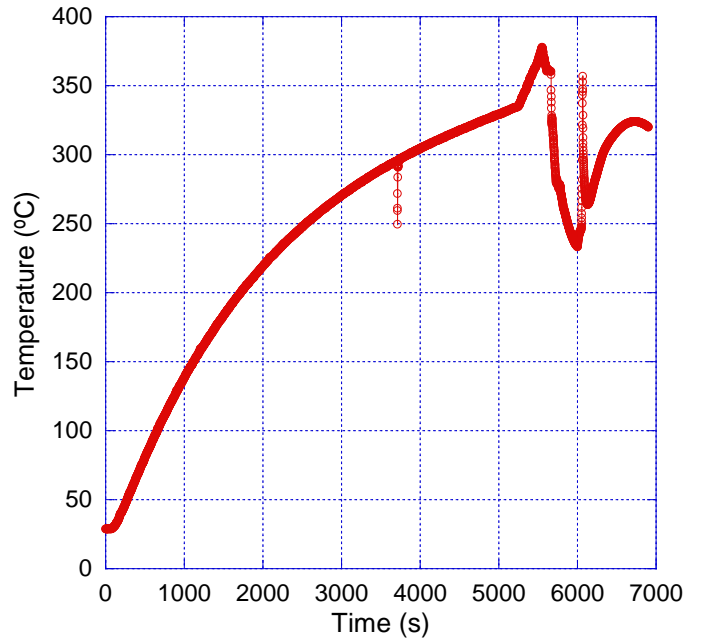


**Figure A1-21. Experiment KSE 21 timeline and data**

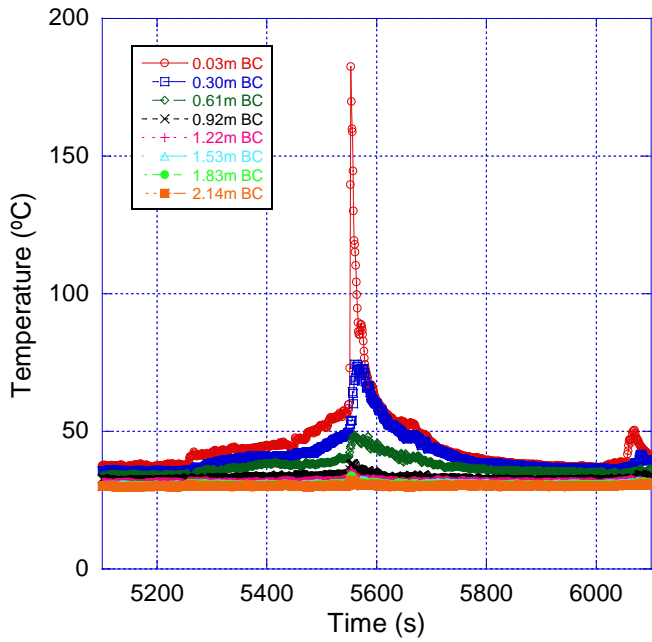
**KSE 22 Timeline  
Automatic Wet Chemical 4**

Time	Event
0	Burner On
5456	Auto Ignition
5558	Auto Suppression
	Fire Not Extinguished
5675	Manual Suppression
6021	Re-Ignition
6078	Manual Suppression 2
	Fire Extinguished

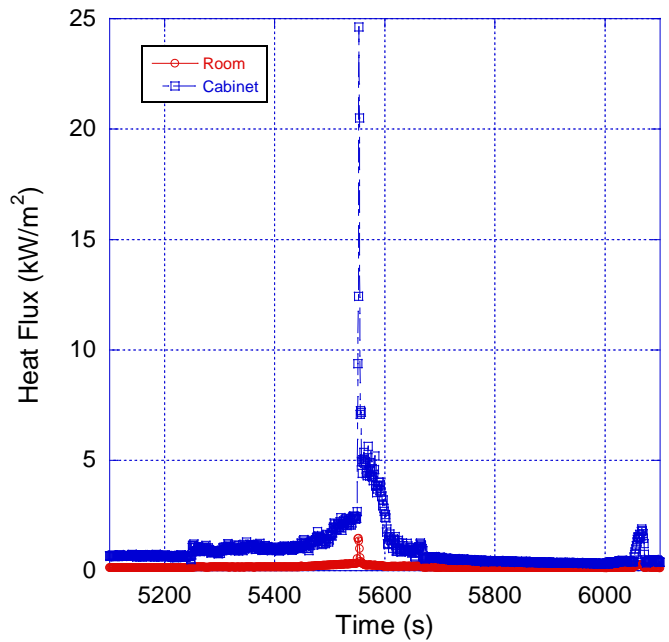
**Oil Temperature**



**Room Temperature**



**Heat Flux**

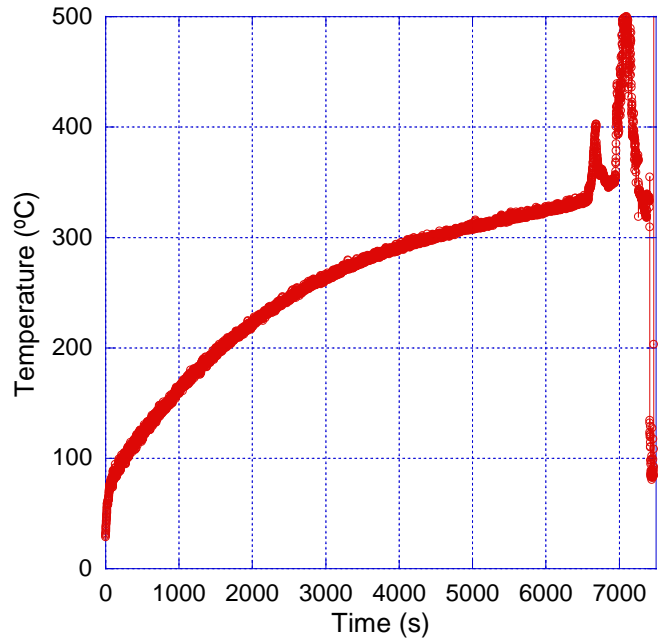


**Figure A1-22. Experiment KSE 22 timeline and data**

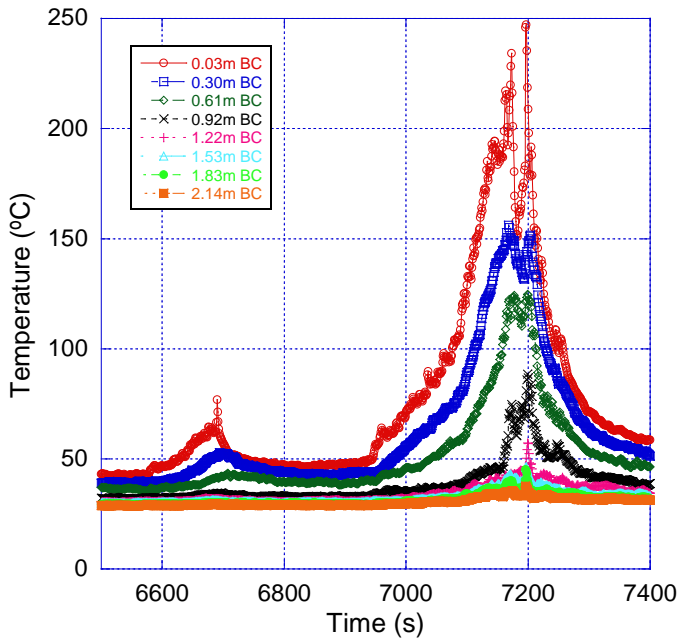
**KSG 1 Timeline  
Automatic Dry Chemical**

Time	Event
0	Burner On
6585	Auto Ignition
6696	Auto Suppression
6952	Re-Ignition
7162	Manual Suppression
7203	Oil Spill (During Suppression)
	Fire Extinguished (Several Tries)

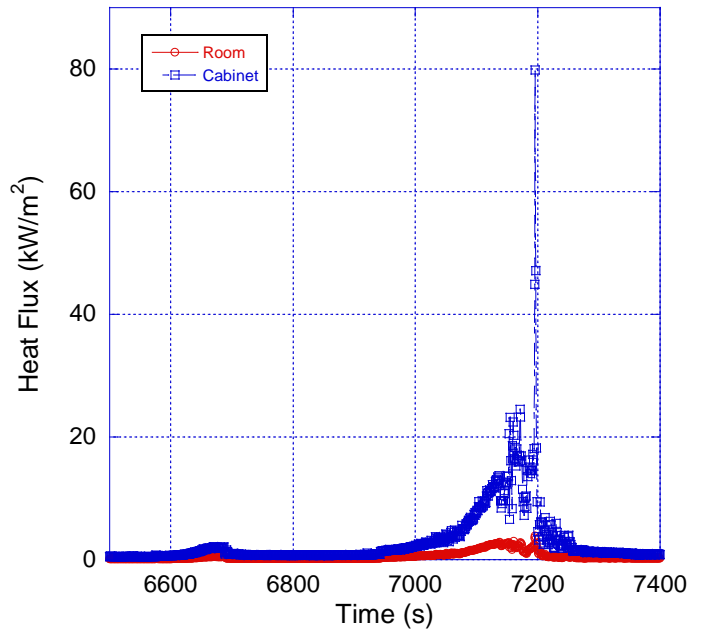
**Oil Temperature**



**Room Temperature**



**Heat Flux**

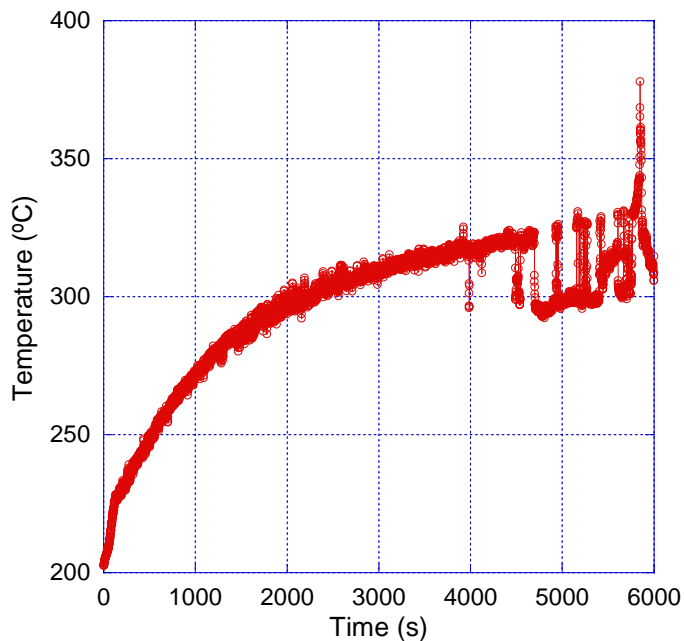


**Figure A1-23. Experiment KSG 1 timeline and data**

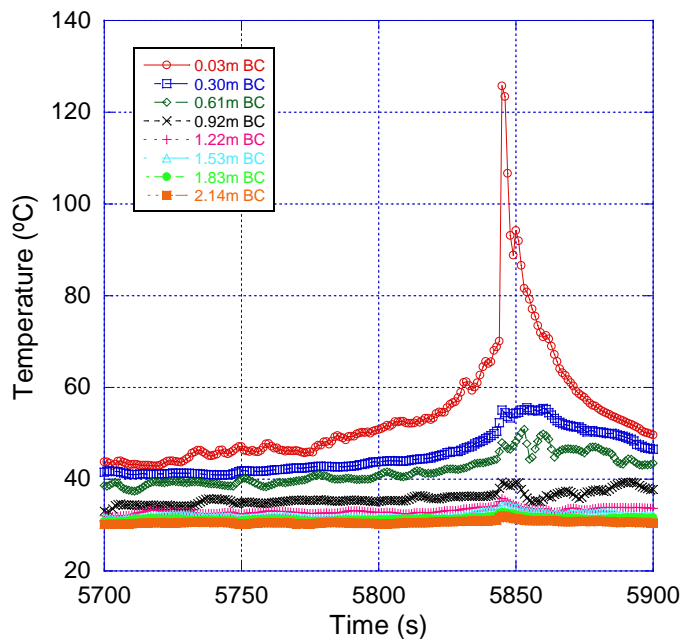
**KSG 2 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
5725	Manual Ignition
5843	Auto Suppression
	Fire Extinguished

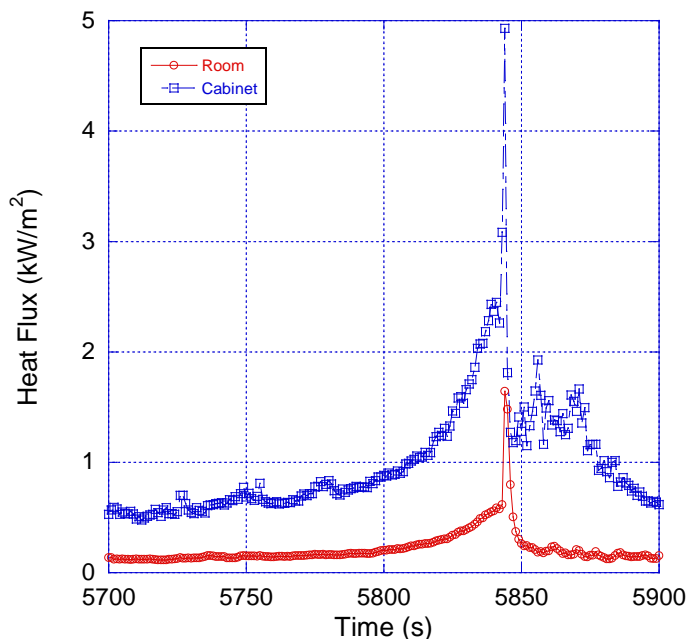
**Oil Temperature**



**Room Temperature**



**Heat Flux**



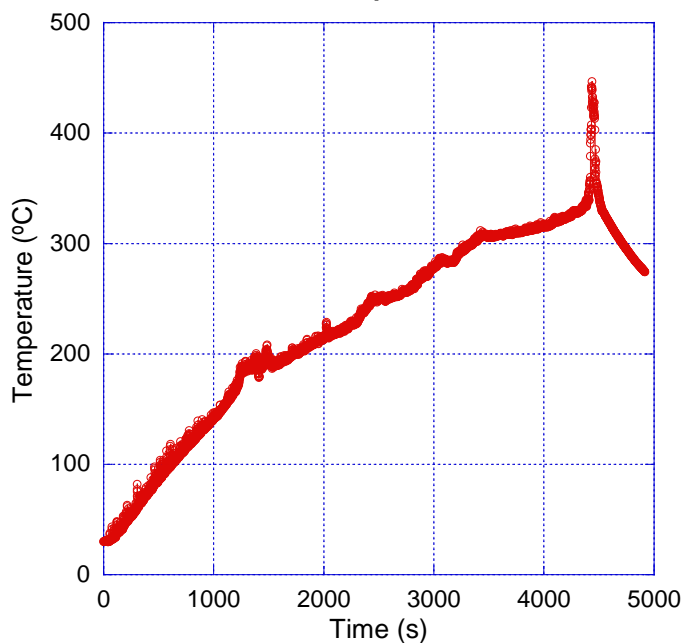
**Figure A1-24. Experiment KSG 2 timeline and data**



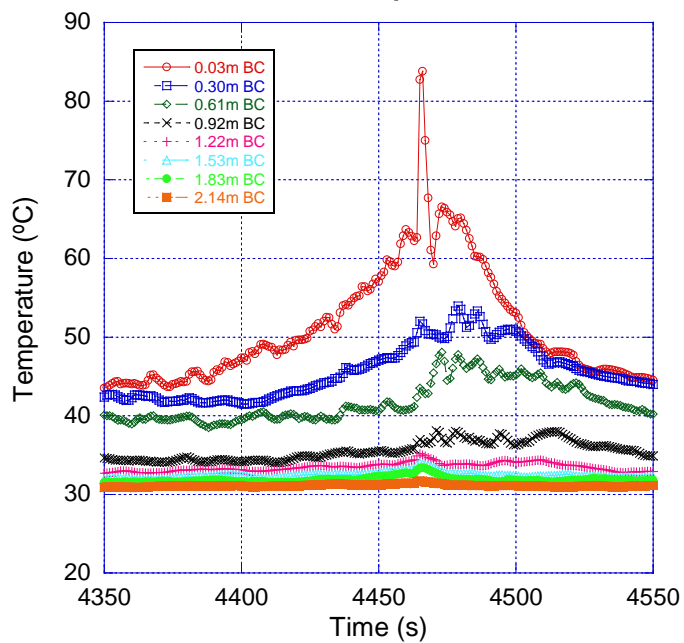
**KSG 3 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
4380	Auto Ignition
4456	Auto Suppression
	Fire Extinguished

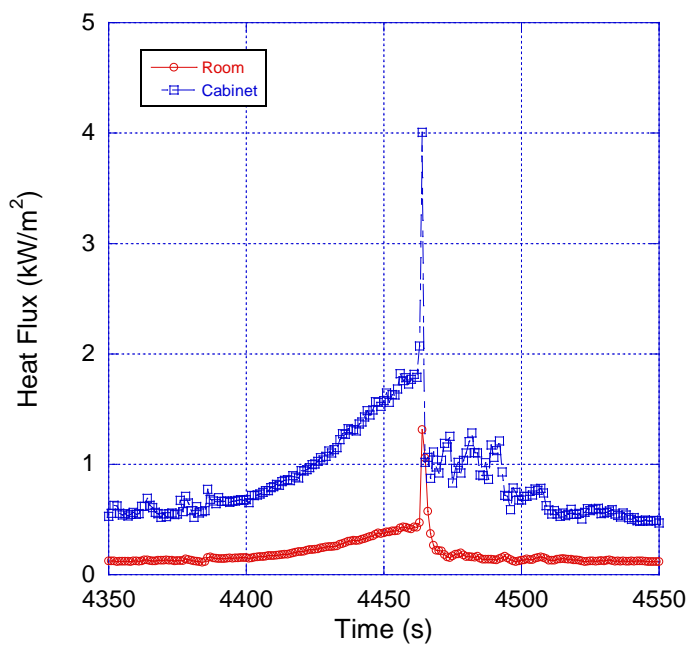
**Oil Temperature**



**Room Temperature**



**Heat Flux**

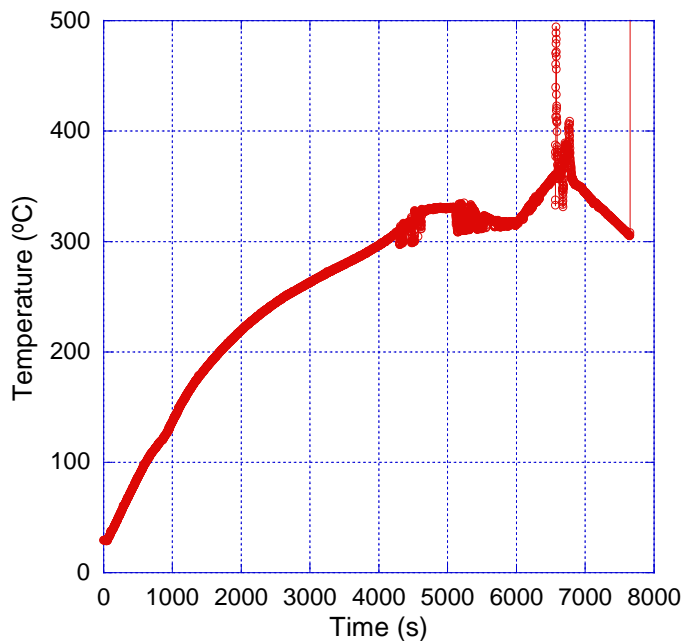


**Figure A1-25. Experiment KSG 3 timeline and data**

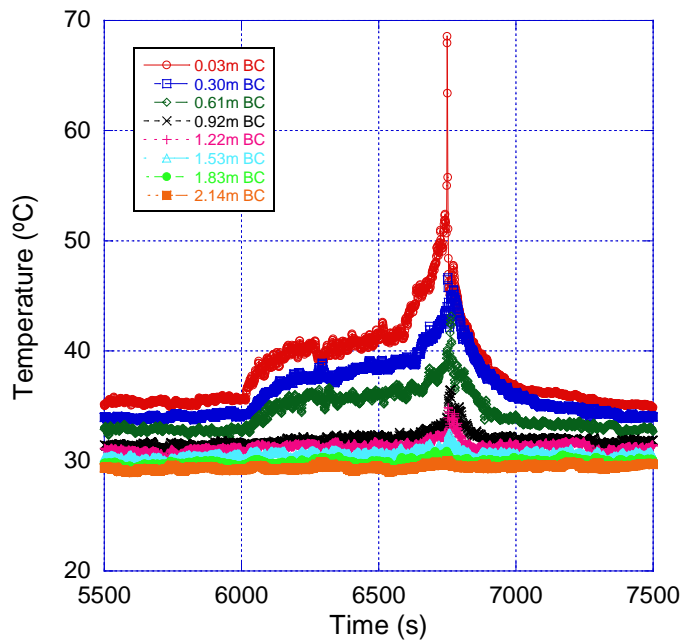
**KSG 4 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
6617	Auto Ignition
6798	Auto Suppression
	Fire Extinguished

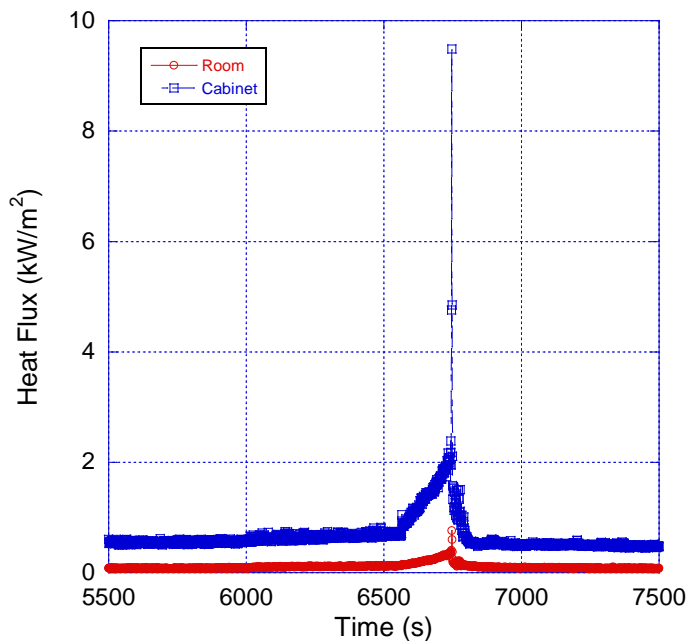
**Oil Temperature**



**Room Temperature**



**Heat Flux**

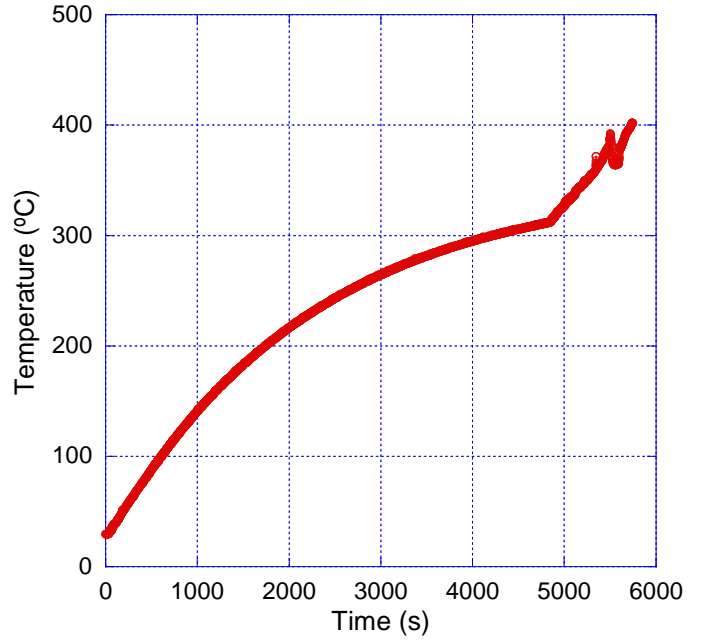


**Figure A1-26. Experiment KSG 4 timeline and data**

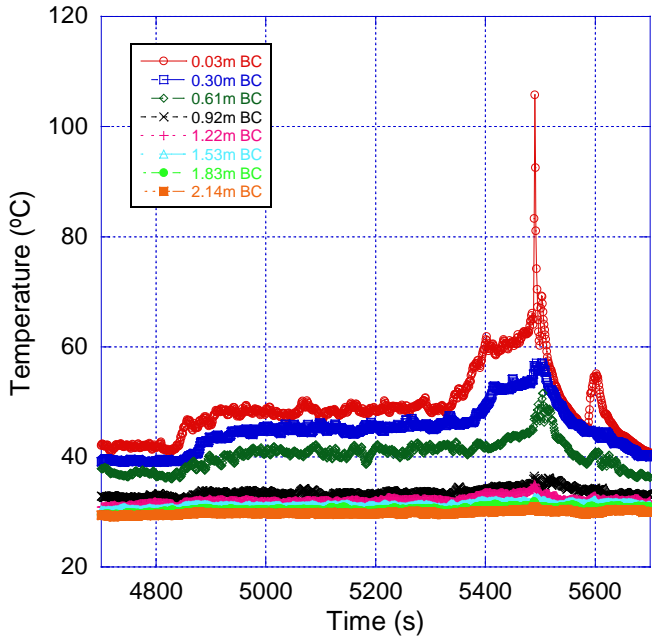
**KSG 5 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
5329	Auto Ignition
5480	Auto Suppression
5576	Re-Ignition
5594	Manual Suppression
	Fire Extinguished

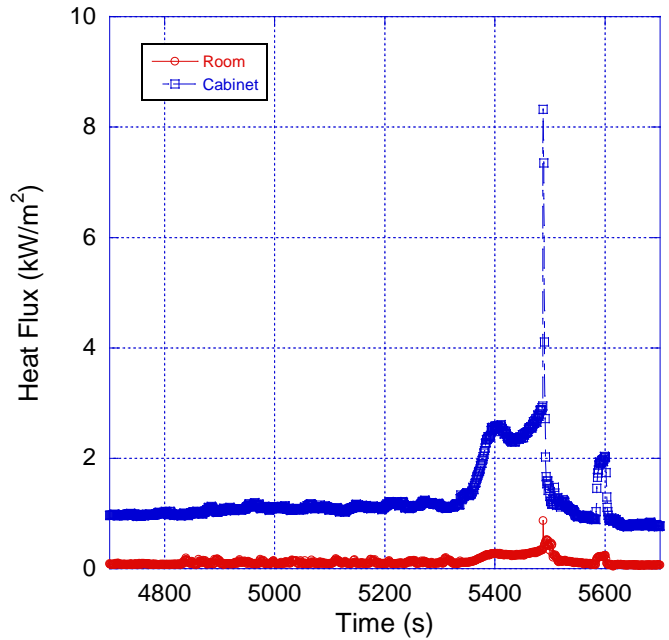
**Oil Temperature**



**Room Temperature**



**Heat Flux**

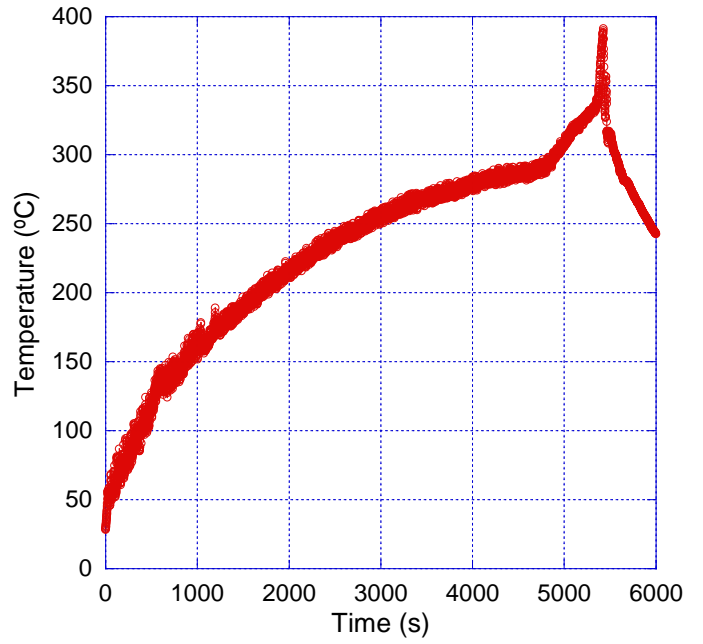


**Figure A1-27. Experiment KSG 5 timeline and data**

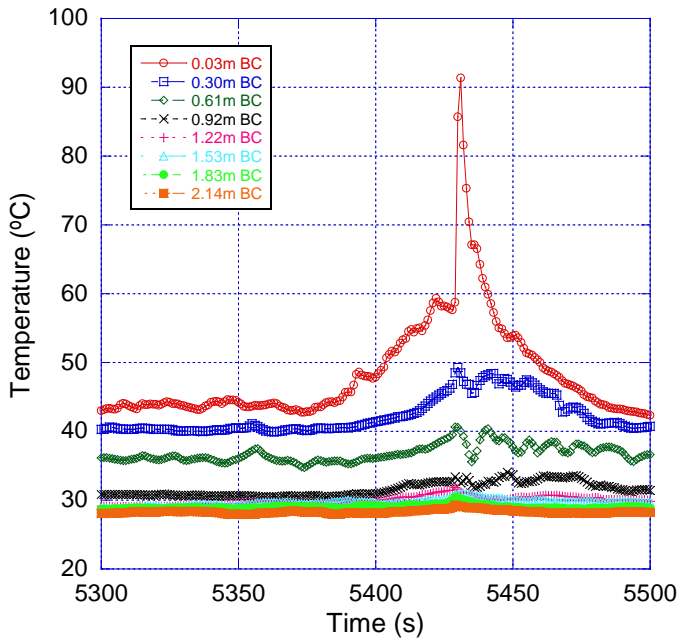
**KSG 6 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
5347	Auto Ignition
5431	Auto Suppression
	Fire Extinguished

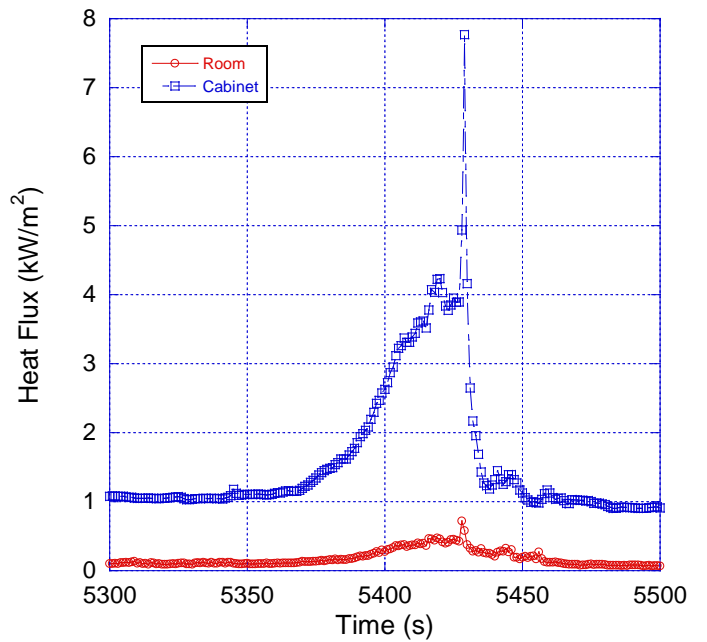
**Oil Temperature**



**Room Temperature**



**Heat Flux**

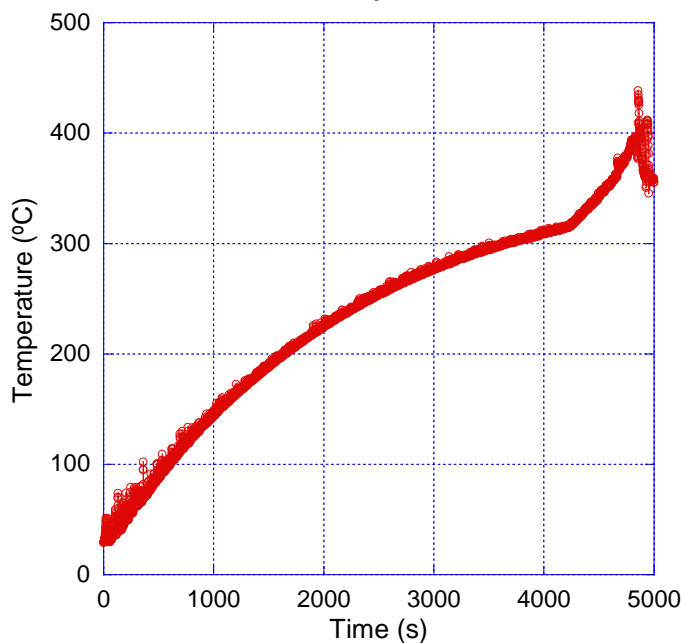


**Figure A1-28. Experiment KSG 6 timeline and data**

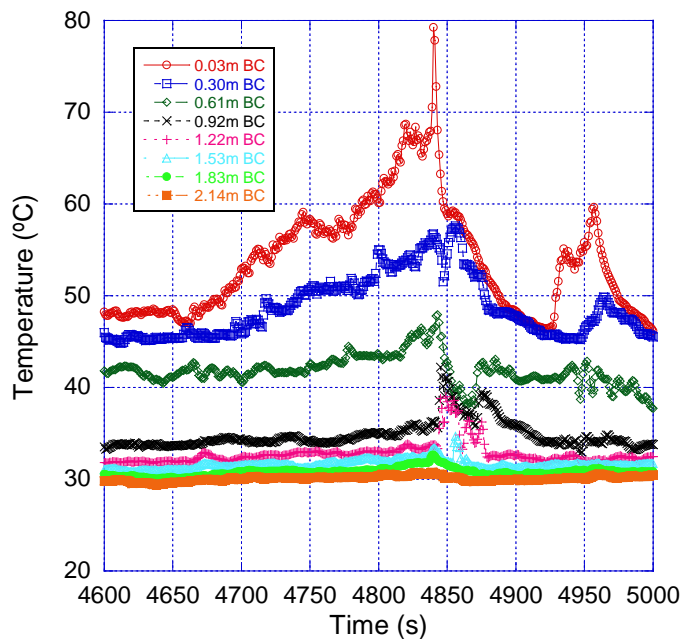
**KSG 7 Timeline  
Automatic Wet Chemical 2**

Time	Event
0	Burner On
4661	Auto Ignition
4839	Auto Suppression
4924	Re-Ignition
4957	Manual Suppression
	Fire Extinguished

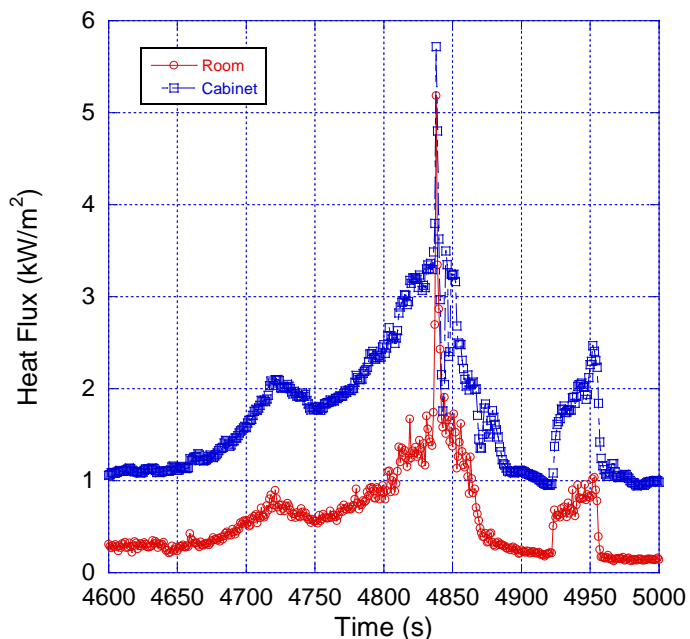
**Oil Temperature**



**Room Temperature**



**Heat Flux**

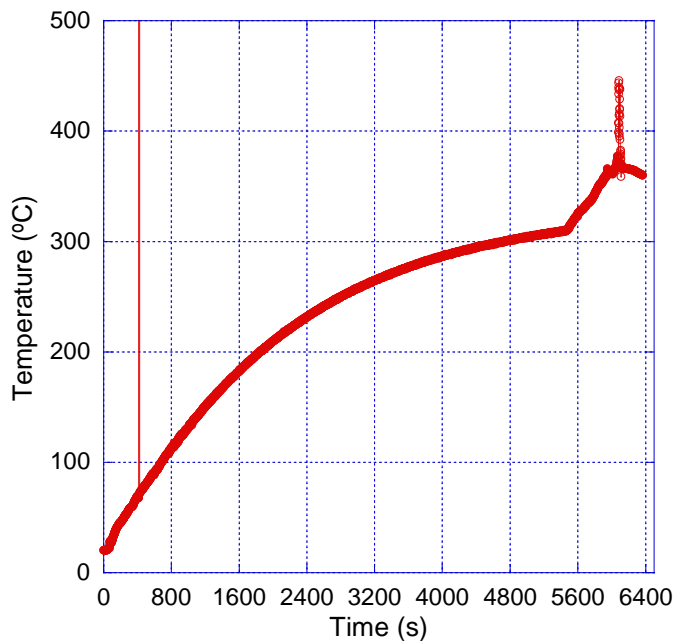


**Figure A1-29. Experiment KSG 7 timeline and data**

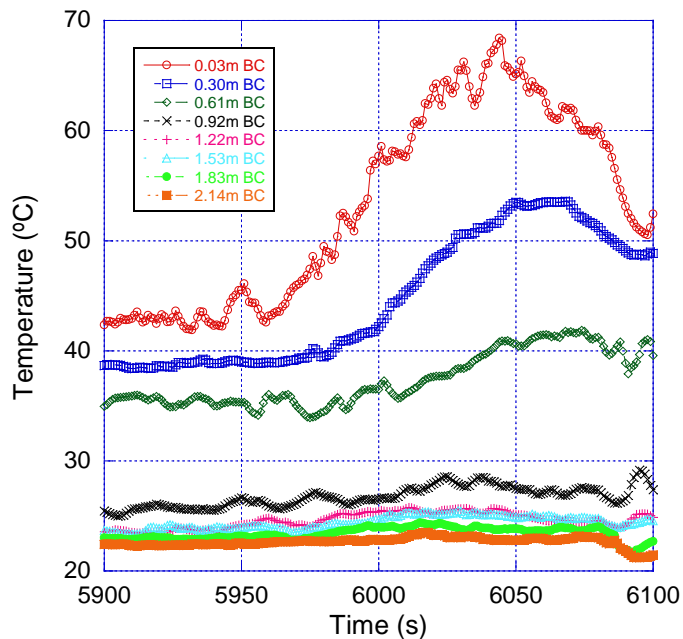
**KSG 8 Timeline  
Automatic Wet Chemical 3**

Time	Event
0	Burner On
5906	Auto Ignition
6046	Auto Suppression
6059	Re-Ignition
6077	Manual Suppression
	Fire Extinguished

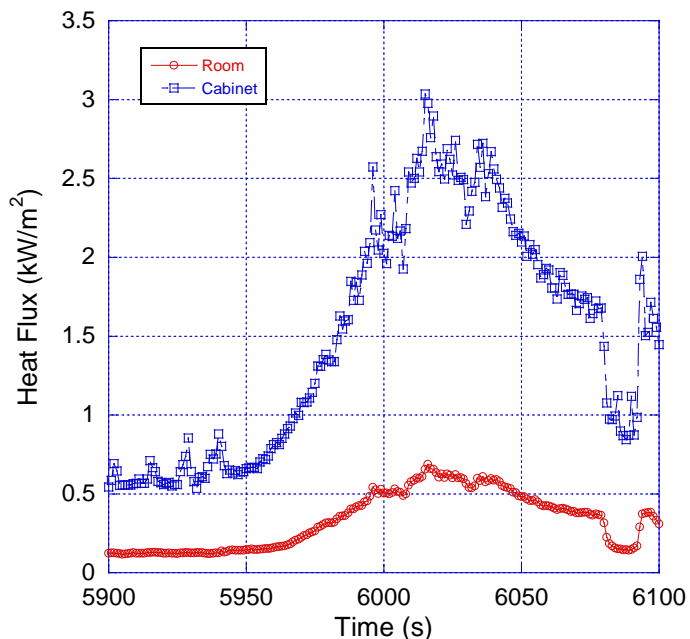
**Oil Temperature**



**Room Temperature**



**Heat Flux**

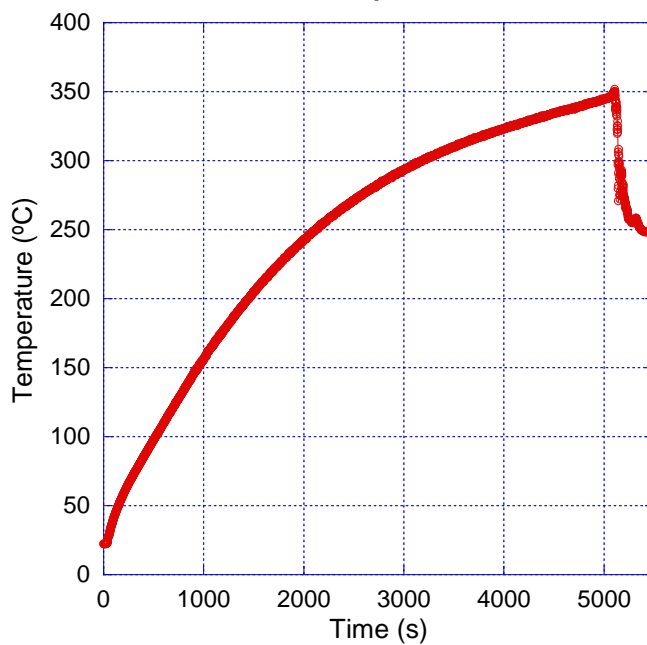


**Figure A1-30. Experiment KSG 8 timeline and data**

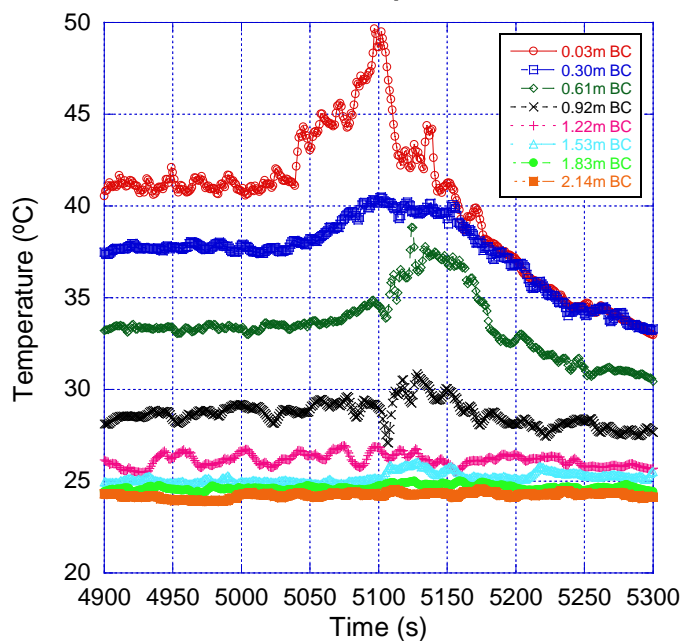
**KSG 9 Timeline  
Manual Wet Chemical**

Time	Event
0	Burner On
5038	Auto Ignition
5103	Auto Suppression
	Fire Extinguished

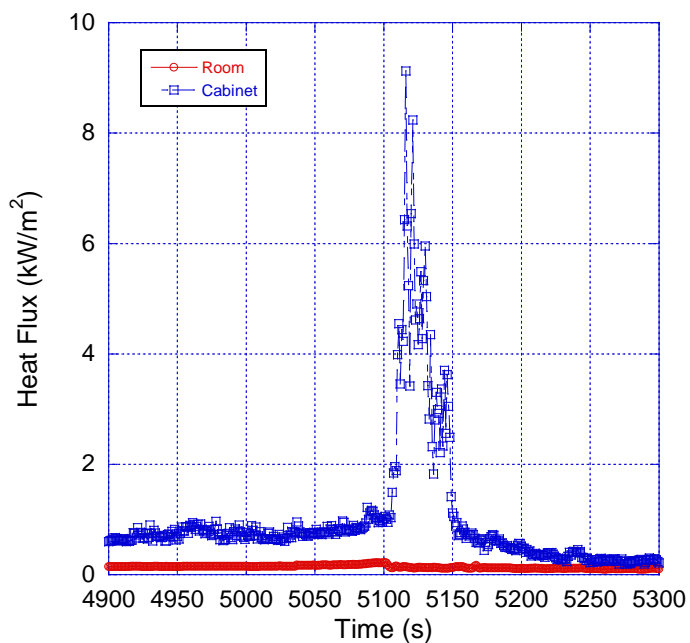
**Oil Temperature**



**Room Temperature**



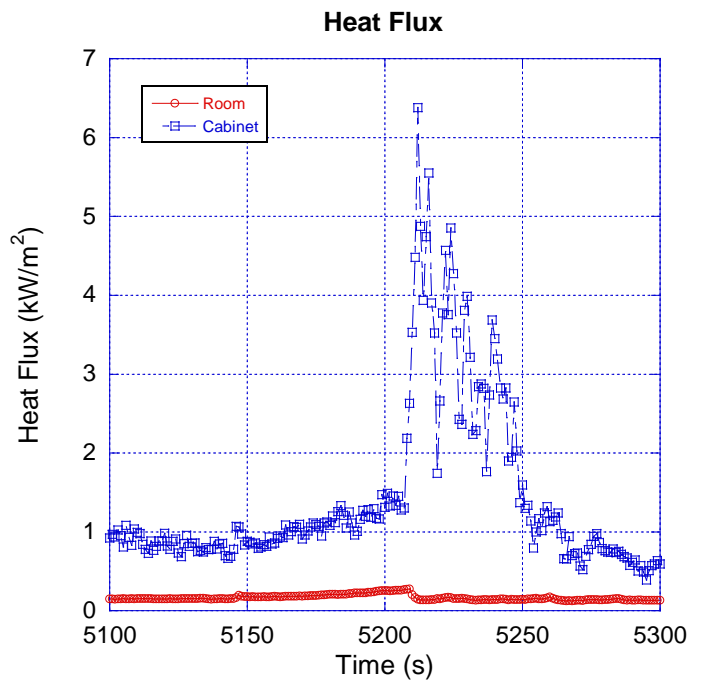
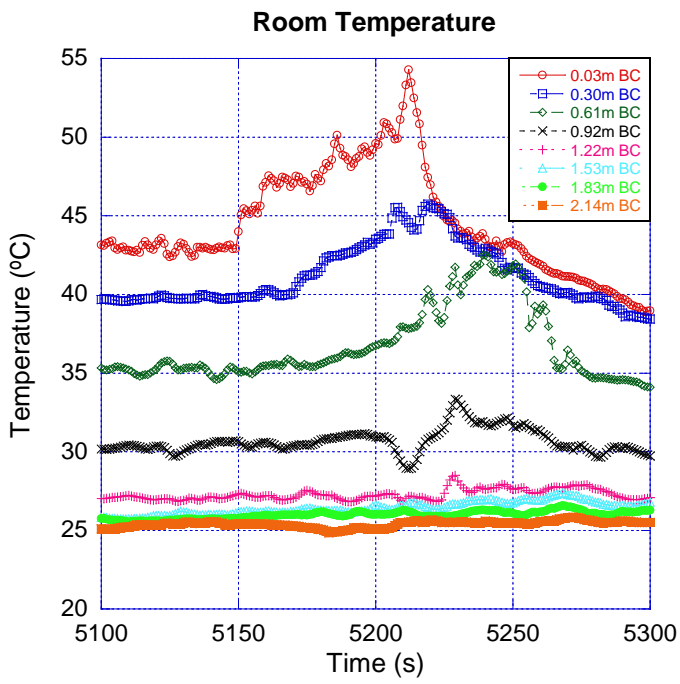
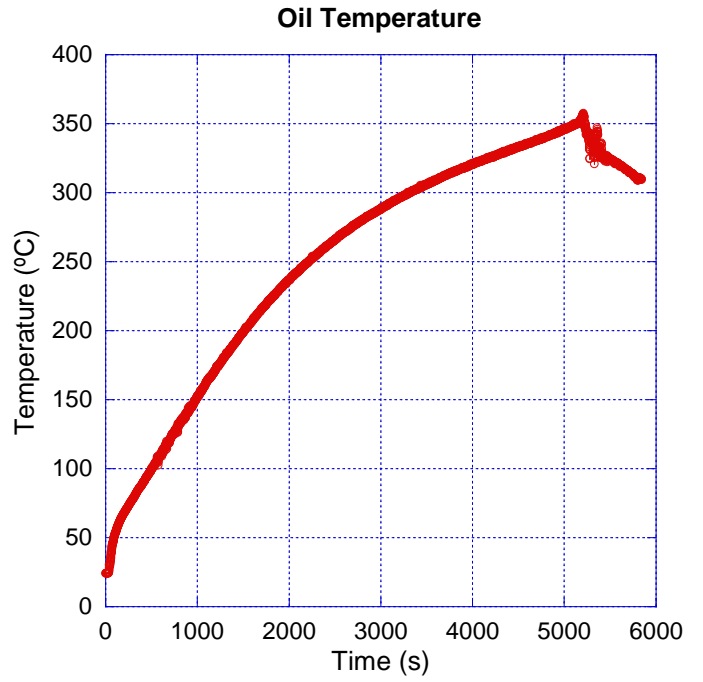
**Heat Flux**



**Figure A1-31. Experiment KSG 9 timeline and data**

**KSG 10 Timeline  
Manual Wet Chemical**

Time	Event
0	Burner On
5145	Auto Ignition
5206	Auto Suppression
	Fire Extinguished



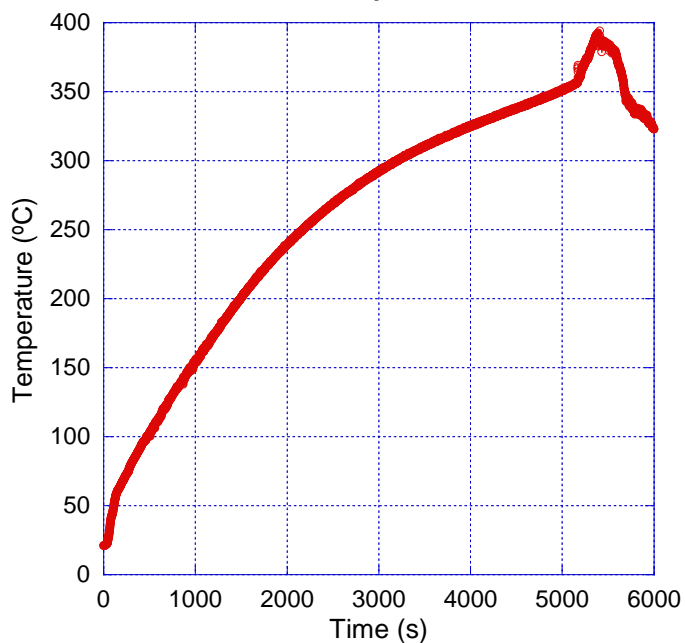
**Figure A1-32. Experiment KSG 10 timeline and data**



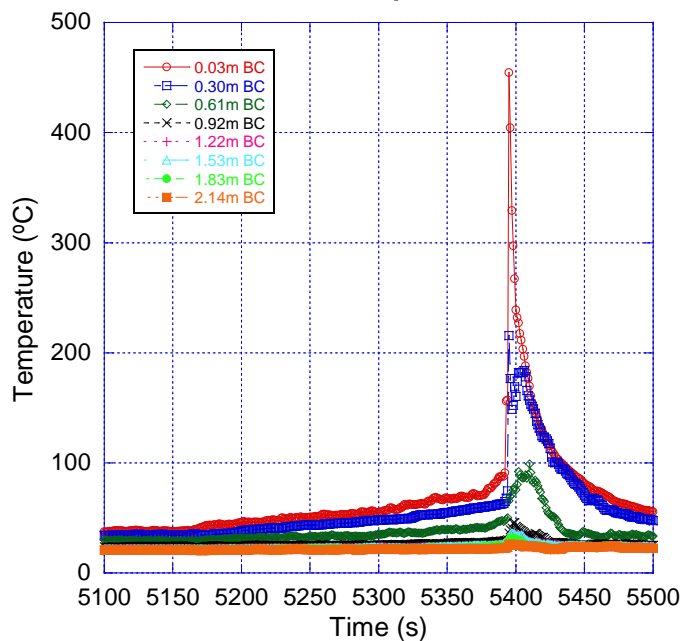
**KSG 11 Timeline  
Automatic Dry Chemical**

Time	Event
0	Burner On
5160	Auto Ignition
5389	Auto Suppression
	Fire Not Extinguished
5402	Manual Suppression
	Fire Extinguished

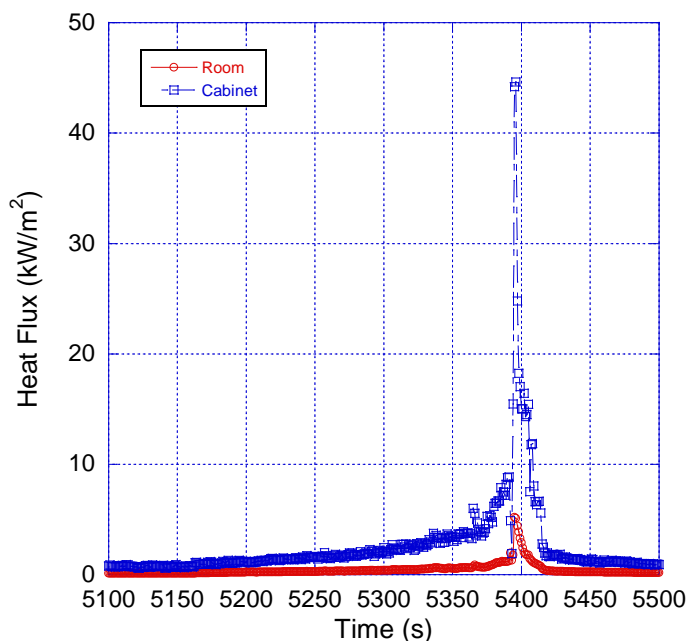
**Oil Temperature**



**Room Temperature**



**Heat Flux**

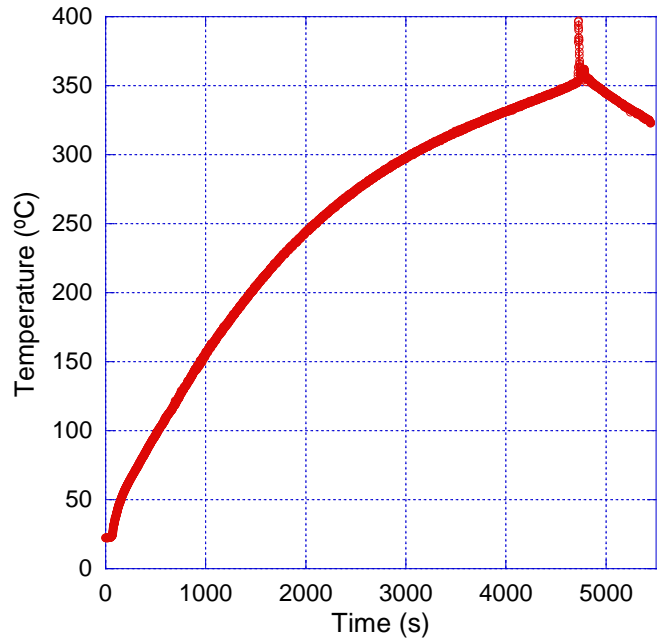


**Figure A1-33. Experiment KSG 11 timeline and data**

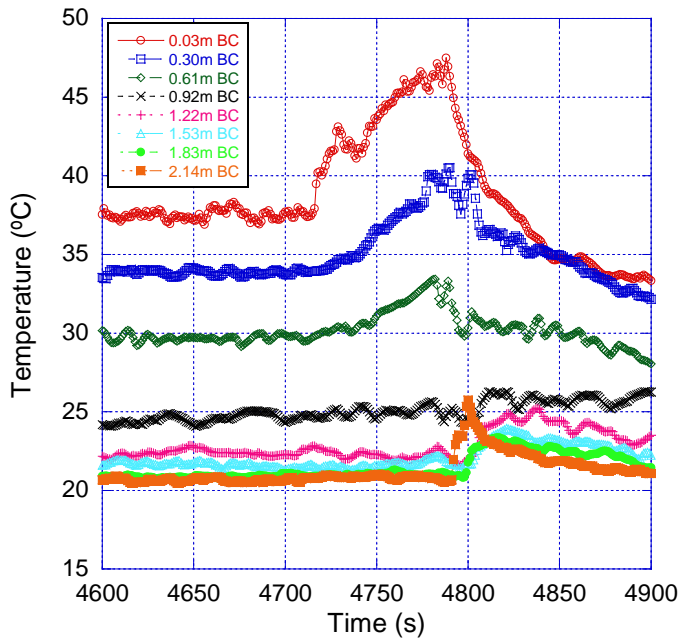
**KSG 12 Timeline  
Manual Dry Chemical**

Time	Event
0	Burner On
4689	Auto Ignition
4762	Manual Suppression Activated
4774	Manual Suppression Completed
	Fire Extinguished

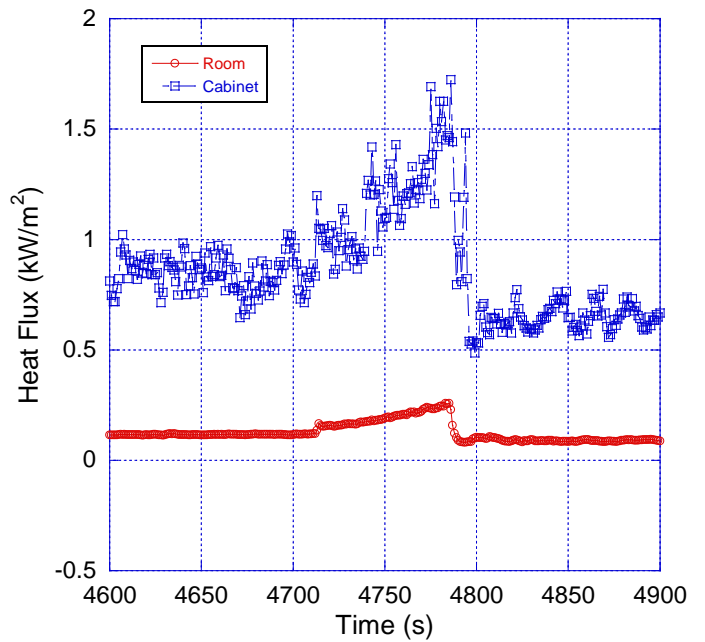
**Oil Temperature**



**Room Temperature**



**Heat Flux**

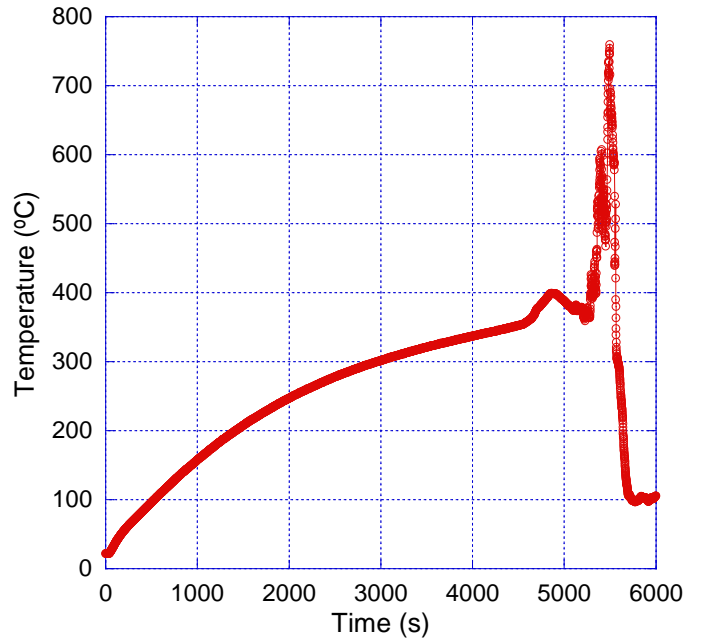


**Figure A1-34. Experiment KSG 12 timeline and data**

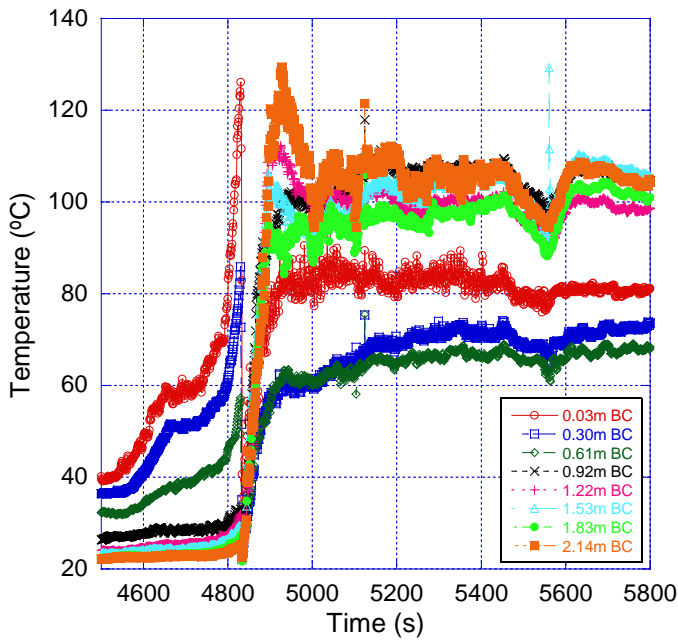
**KSG 13 Timeline  
Water Mist 1**

Time	Event
0	Burner On
4535	Auto Ignition
4829	Auto Suppression Activated
5512	Auto Suppression Completed
	Fire Not Extinguished
5545	Manual Suppression
	Fire Extinguished (Two Tries)

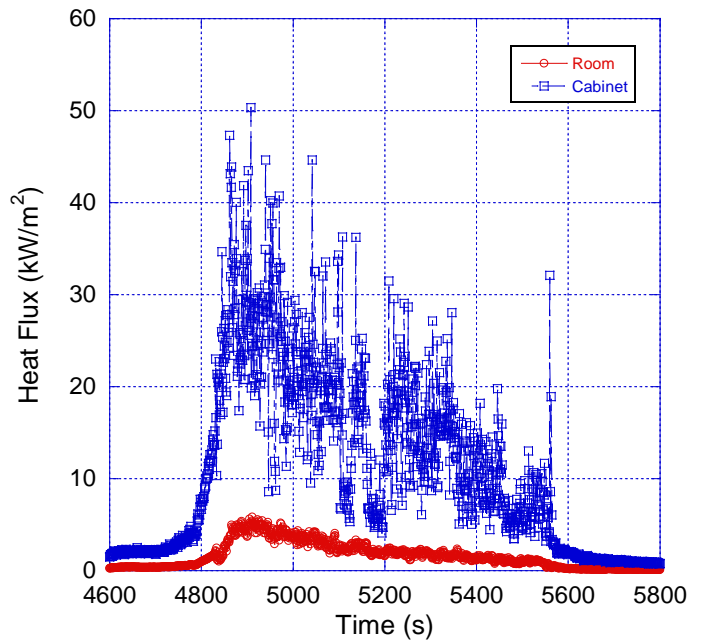
**Oil Temperature**



**Room Temperature**



**Heat Flux**

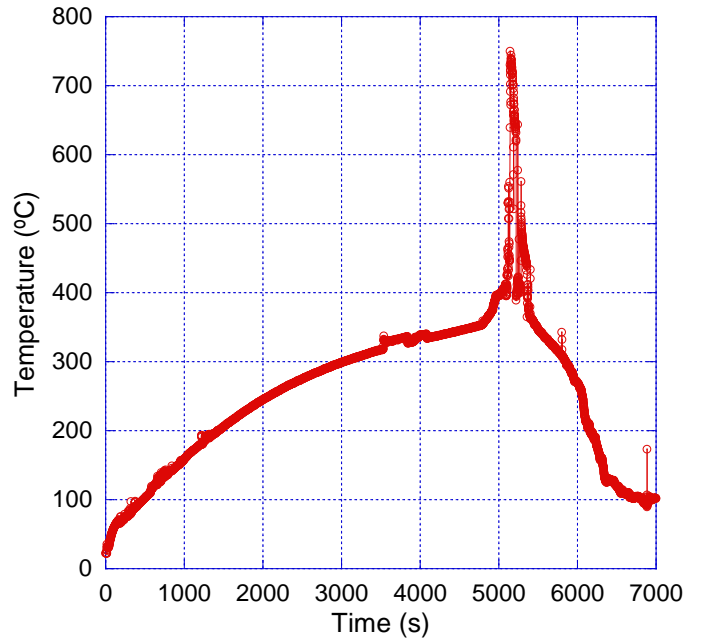


**Figure A1-35. Experiment KSG 13 timeline and data**

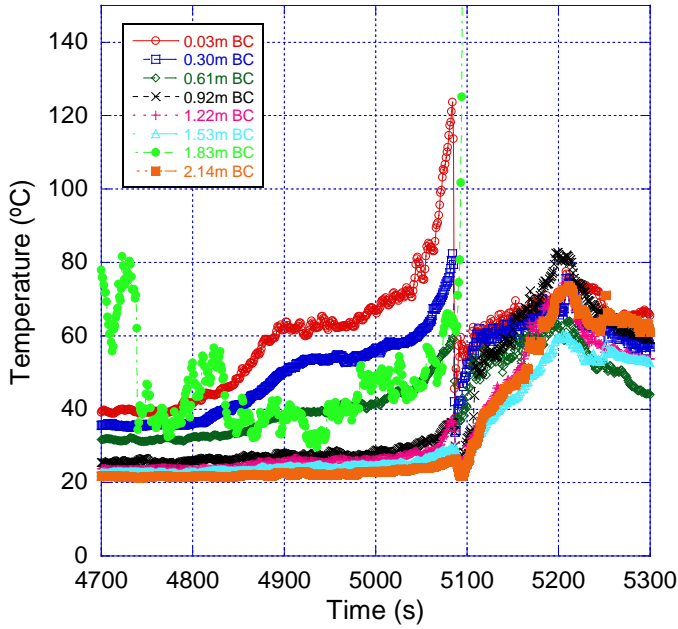
**KSG 14 Timeline  
Residential Sprinkler**

Time	Event
0	Burner On
4780	Auto Ignition
5083	Auto Suppression Activated
5204	Auto Suppression Completed
	Fire Not Extinguished
5244	Manual Suppression
	Fire Extinguished

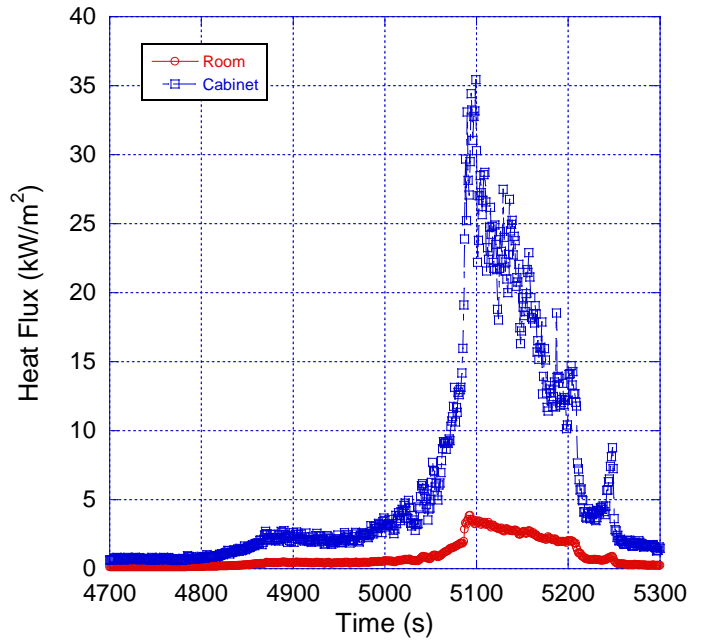
**Oil Temperature**



**Room Temperature**



**Heat Flux**

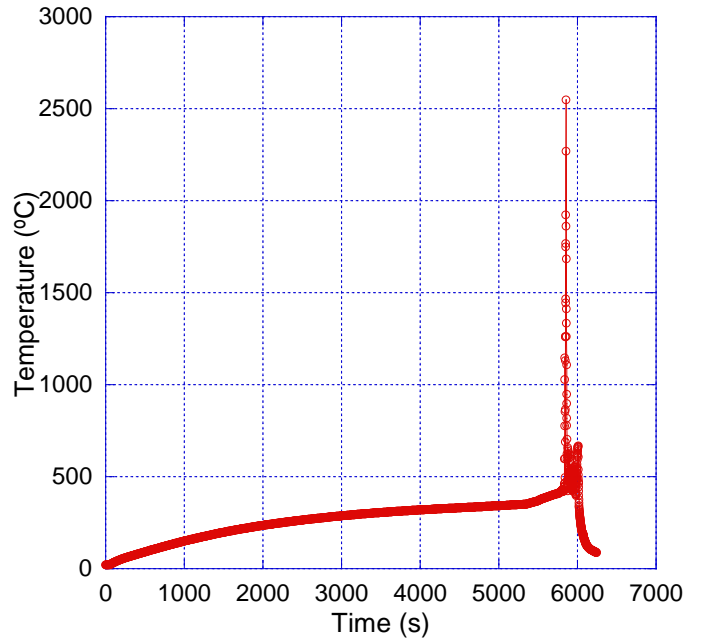


**Figure A1-36. Experiment KSG 14 timeline and data**

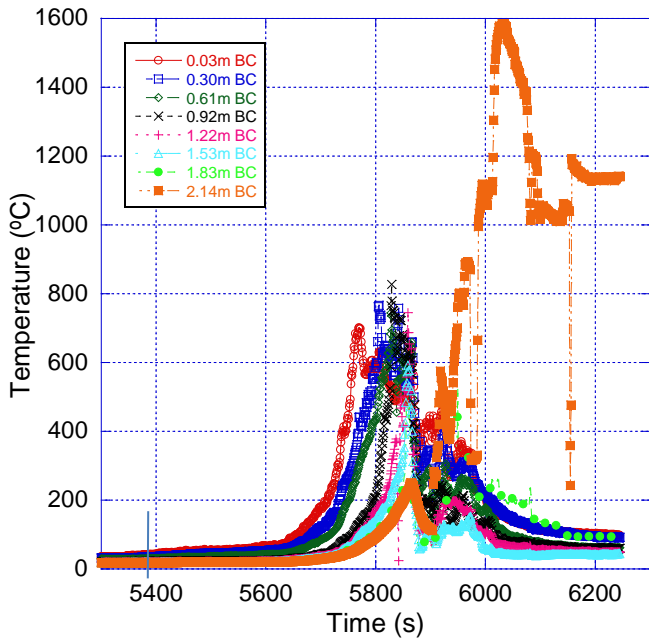
**KSG 15 Timeline  
Free Burn**

Time	Event
0	Burner On
5339	Auto Ignition
5853	Manual Suppression Start
6056	Manual Suppression End
	Fire Extinguished

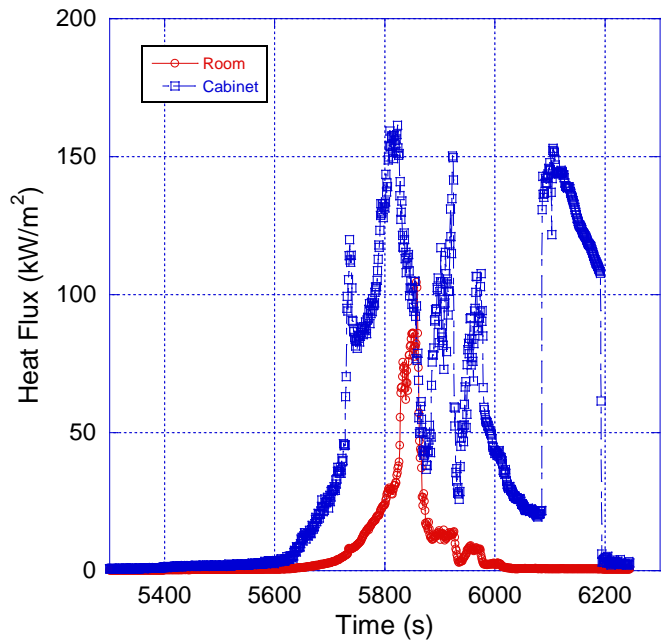
**Oil Temperature**



**Room Temperature**



**Heat Flux**

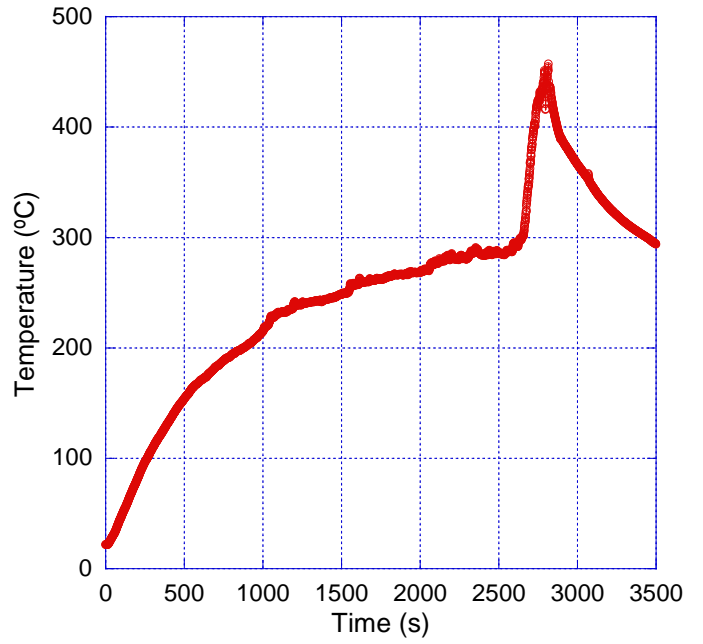


**Figure A1-37. Experiment KSG 15 timeline and data**

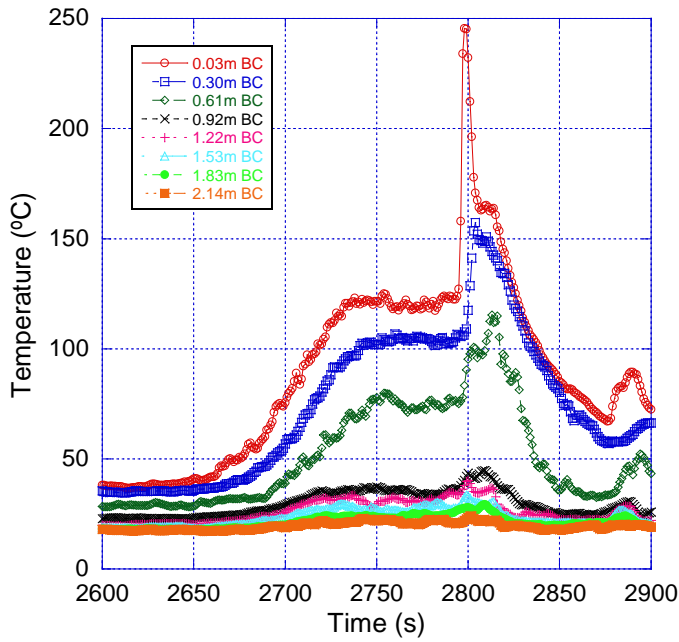
**KSG 16 Timeline  
Automatic Dry Chemical**

Time	Event
0	Burner On
2630	Auto Ignition
2796	Auto Suppression
	Fire Not Extinguished
2826	Manual Suppression
	Fire Extinguished

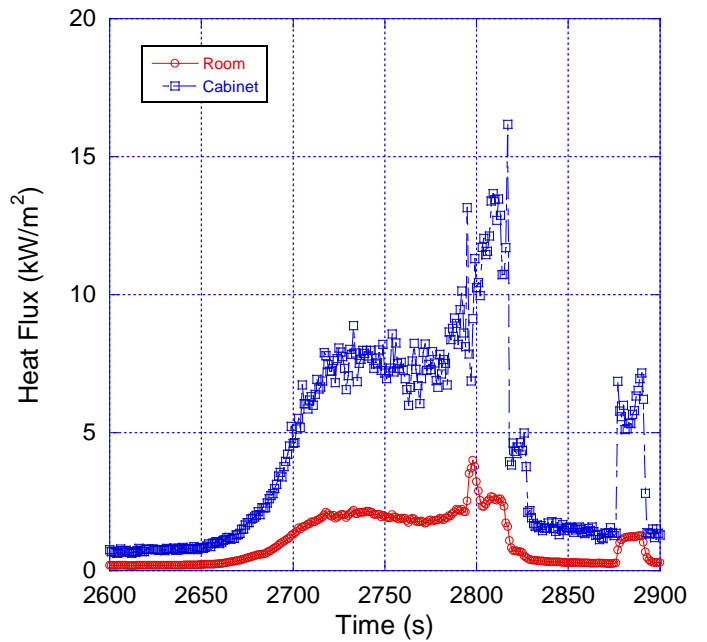
**Oil Temperature**



**Room Temperature**



**Heat Flux**

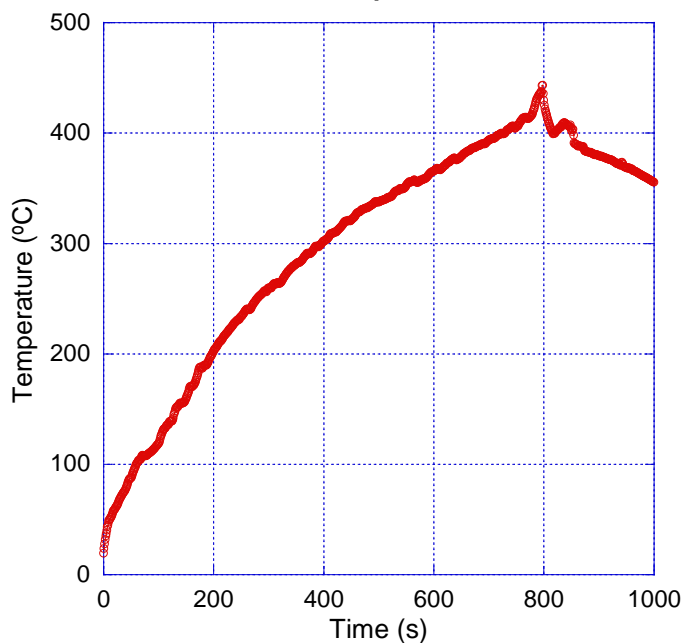


**Figure A1-38. Experiment KSG 16 timeline and data**

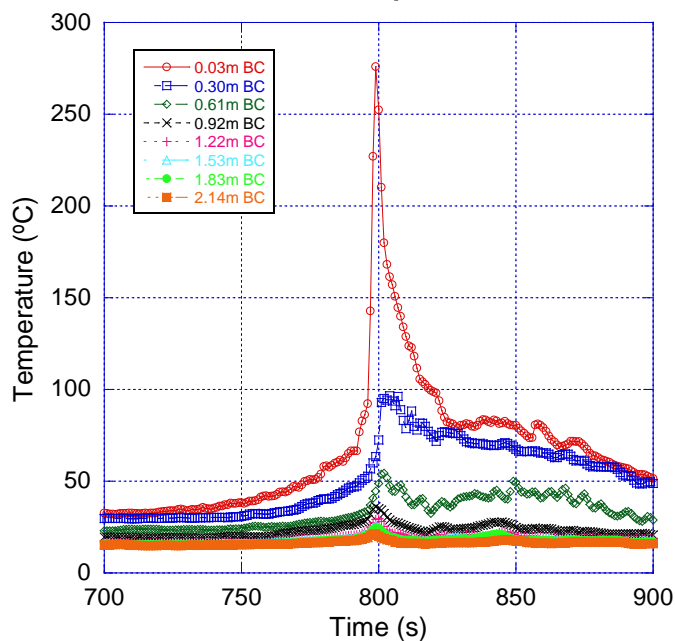
**KSG 17 Timeline  
Automatic Dry Chemical**

Time	Event
0	Burner On
738	Auto Ignition
795	Auto Suppression
823	Re-Ignition
853	Manual Suppression
	Fire Extinguished

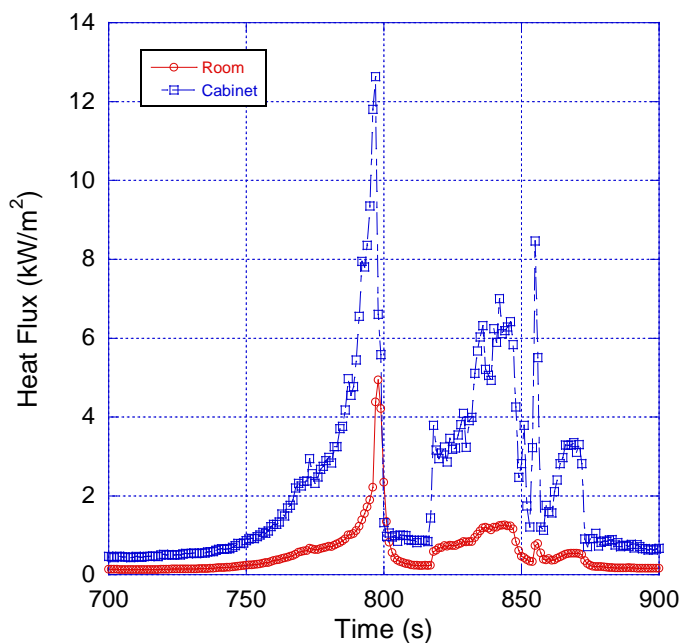
**Oil Temperature**



**Room Temperature**



**Heat Flux**

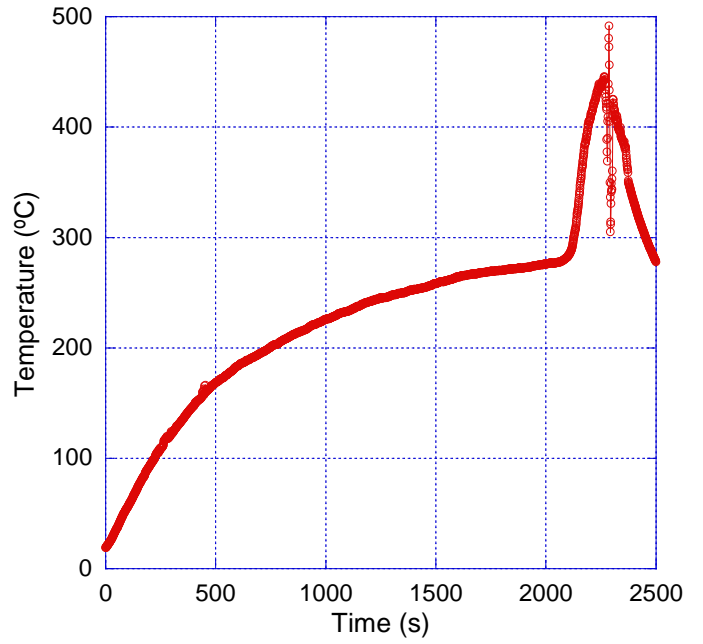


**Figure A1-39. Experiment KSG 17 timeline and data**

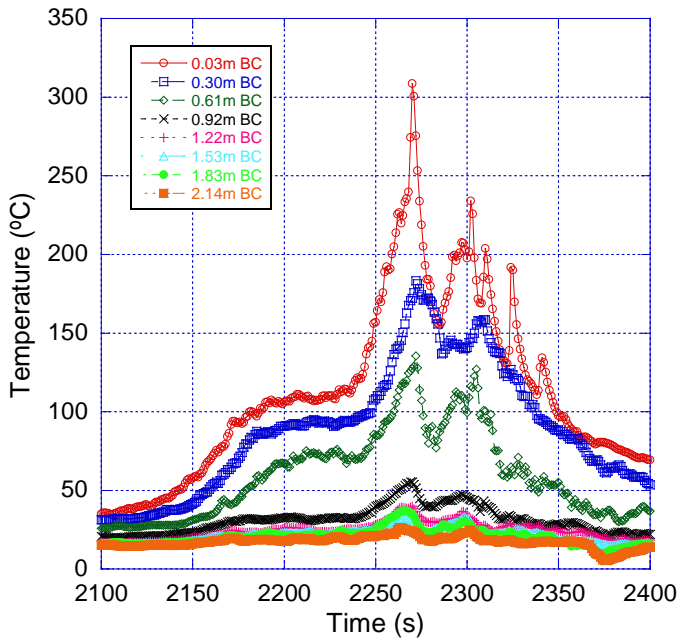
**KSG 18 Timeline  
Automatic Wet Chemical 3**

Time	Event
0	Burner On
2103	Auto Ignition
2263	Auto Suppression
	Fire Not Extinguished
2295	Manual Suppression
	Fire Extinguished (Several Tries)

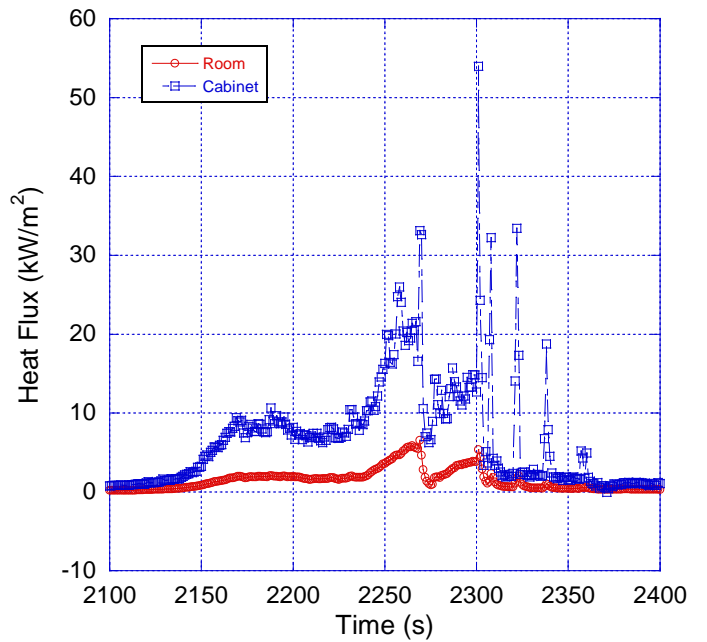
**Oil Temperature**



**Room Temperature**



**Heat Flux**



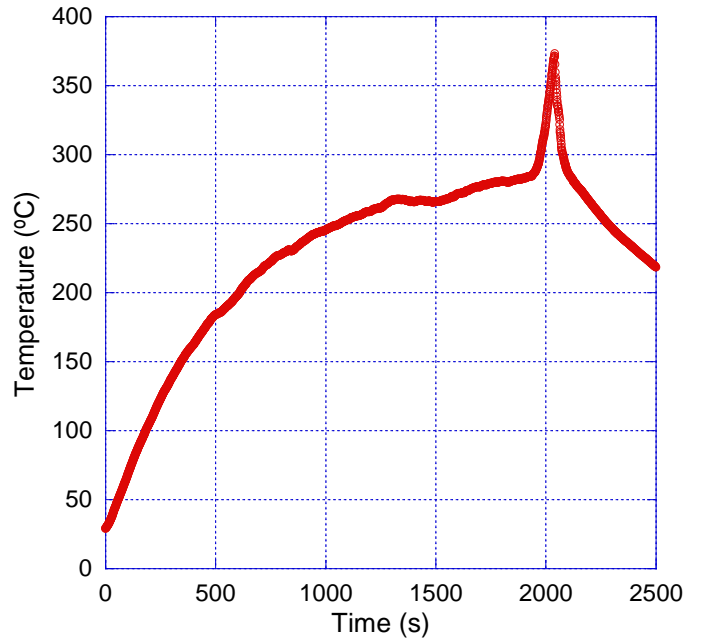
**Figure A1-40. Experiment KSG 18 timeline and data**



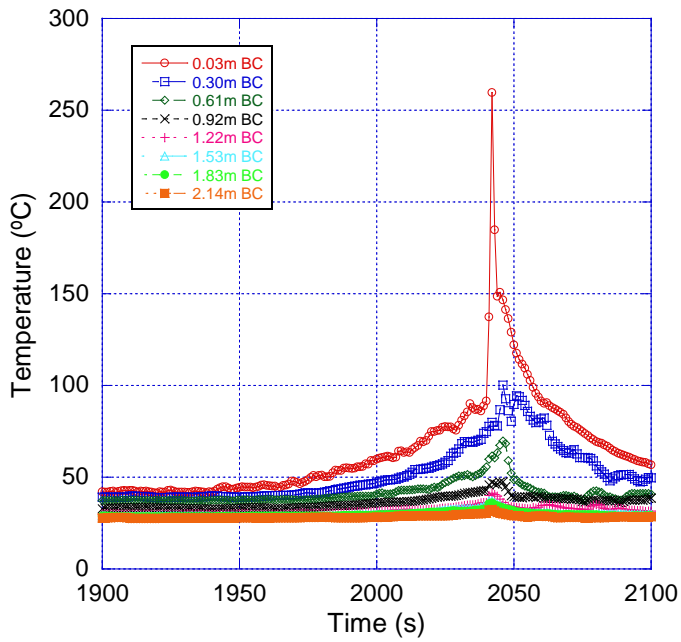
**KSG 19 Timeline  
Automatic Wet Chemical 1**

Time	Event
0	Burner On
1946	Auto Ignition
2038	Auto Suppression
	Fire Extinguished

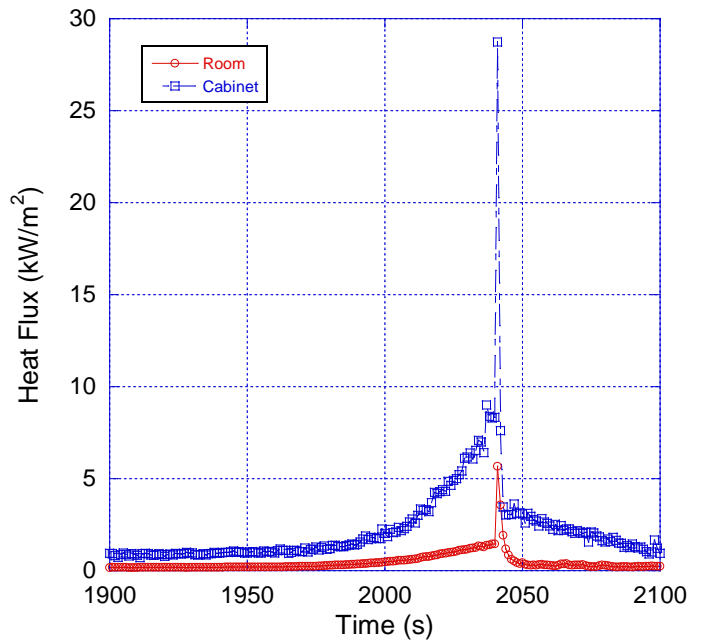
**Oil Temperature**



**Room Temperature**



**Heat Flux**

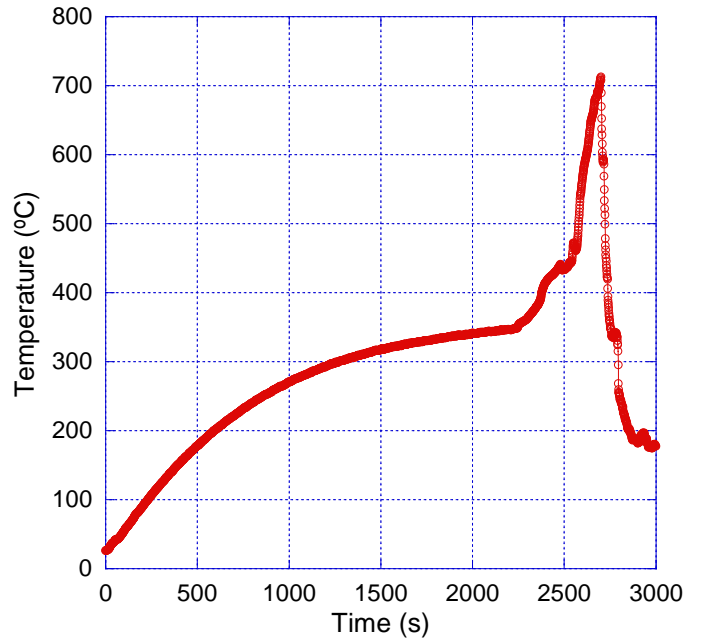


**Figure A1-41. Experiment KSG 19 timeline and data**

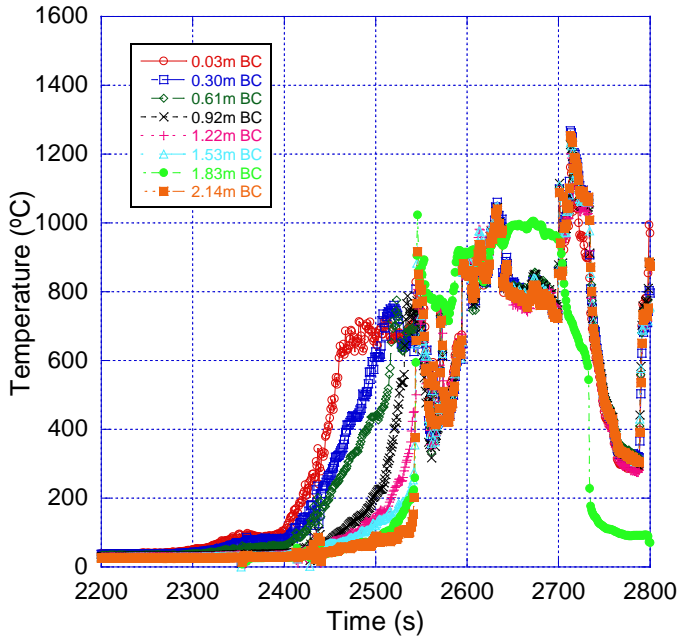
### KSG 20 Timeline Free Burn

Time	Event
0	Burner On
2280	Auto Ignition
2722	Manual Suppression Start
2758	Manual Suppression Complete
	Fire Extinguished

### Oil Temperature



### Room Temperature



No Data

Figure A1-42. Experiment KSG 20 timeline and data

## Appendix 2: Experimental Environmental Conditions

The table below indicates the ambient temperature and relative humidity during each of the suppression experiments in the full-scale kitchen fire series. The estimated expanded uncertainty is  $\pm 1$  °C for temperature and 5 % for relative humidity.

Table A2-1. Environmental conditions during the experiments.

Test	Temperature (°C)	Relative Humidity	Test	Temperature (°C)	Relative Humidity
KSE 01	31.1	52	KSG 01	28.9	68
KSE 02	29.6	63	KSG 02	30.6	63
KSE 03	30.7	56	KSG 03	31.0	58
KSE 04	28.6	57	KSG 04	29.4	64
KSE 05	31.8	53	KSG 05	30.6	51
KSE 06	29.4	64	KSG 06	27.3	66
KSE 07	30.6	51	KSG 07	30.0	56
KSE 08	27.3	66	KSG 08	21.0	46
KSE 09	30.0	56	KSG 09	22.6	61
KSE 10	No Data	No Data	KSG 10	23.9	60
KSE 11	21.0	46	KSG 11	18.8	55
KSE 12	21.9	62	KSG 12	18.5	55
KSE 13	23.9	60	KSG 13	20.6	67
KSE 14	18.8	55	KSG 14	20.1	53
KSE 15	18.5	55	KSG 15	16.2	27
KSE 16	20.6	48	KSG 16	14.8	21
KSE 17	16.4	26	KSG 17	13.4	19
KSE 18	12.5	20	KSG 18	19.7	13
KSE 19	26.1	44	KSG 19	26.4	56
KSE 20	28.0	35	KSG 20	25.2	56
KSE 21	27.7	59			
KSE 22	28.6	52			