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Development of a Portable Flashover Predictor (Fire-Ground Environment Sensor System)

FEMA AFG 2008 Scientific Report

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An AFG 2008 award supported a science and engineering effort towards development of an integrated Firefighter Locator and Environmental Monitor to provide real-time flashover warning and advanced situational awareness. The goal of the one year effort was evaluation of the feasibility and impact of a new flashover warning technology. The program was designed to balance the tradeoffs between the underlying physics of ideal flashover prediction and the requirements of practical field implementation to ultimately offer firefighters a tool to save lives and enable more efficient firefighting tactics. The project included an integration effort in which the flashover prediction information was fused with a data stream from a system previously developed by WPI under AFG 2006 which provided simultaneous firefighter location and physiological information. This report focuses upon the basic scientific effort to understand the relationship between certain observables on the fireground and the event of flashover, followed by the engineering of a portable device that provides significant warning of the impending event of flashover.

PART 1: Time of Flashover Estimation from Ceiling Temperature Measurements

1. Flashover

Flashover is the term used to describe a phenomenon where a fire burning locally transitions rapidly to a situation where the whole room is burning, causing a rapid increase in the size and intensity of the fire. The occurrence of flashover within a room is of considerable interest as it has been referred to as "the ultimate signal of untenable conditions within the room of fire origin and a sign of greatly increased risk to the occupants of other rooms within the building.[1]" This section looks at various ways to define flashover and the effect of flashover on the safety of both firefighters and civilians. It then presents and analyzes previous data on flashover in order to determine an indicator(s) of flashover that may be useful for predicting flashover to inform situational awareness in the fire service.

1.1 Defining Flashover

Although the occurrence of flashover is of great interest, flashover is not a precise term and several variations in definition can be found in the literature. At least two types of fundamental definitions of flashover have been proposed, one defines flashover as the occurrence of a criticality in a thermal balance sense where at flashover, the heat generation rate exceeds the ability of the system to lose heat at the boundaries. Indicators of flashover previously proposed in the literature include the temperature of the hot upper layer and high heat flux to the floor. The other definition of flashover uses a fluid-mechanical filling process. This definition of flashover is based on observations that experimentally, when flashover is reached in a room, it takes place in a short period of time when the room goes from being mostly filled with cold air to being mostly filled with hot fire gases. When applying the second definition, the flashover indicator is the dropping of the flaming hot gas layer below the half-way height of the room[2]. Other indicators of flashover are the ignition of floor targets, and the ignition of unburnt fuel in the hot upper layer observed as the appearance of flames out the doorway[2].

The development of a fire from ignition to flashover incorporates the phenomena described by both of these definitions. Once a fire ignites, and as it grows, heat is transferred to the surrounding objects in the immediate area of the fire through radiation, conduction, and convection. Over time as the fire gets hotter and as the hot upper layer descends (and thus brings high heat and radiative flux from unburnt fuel in the hot upper layer in closer proximity to all combustibles in the room), the room itself and the surrounding objects also get hotter. Eventually, if the fire is not controlled by some form of suppression, and does not run out of fuel or air, a point is reached where a sufficient amount of heat has been gained by these objects so that their ignition temperature is reached. This point represents the onset of flashover, as a seemingly instantaneous change occurs and suddenly there is full room involvement and the fire has reached a fully involved stage.

1.2 Risk Posed by Flashover

Flashover is an extremely dangerous and life threatening scenario for firefighters and although radiative heat flux is the driving force influencing the heating of the room and contents and determining the time to onset of flashover, the amount of time in which it takes a room to reach this stage is highly variable, dependent on room size and geometry, combustible contents, air supply, the insulation of the room, and the chemistry of the hot upper layer[3].

Flashover is both more prevalent and more dangerous today. Modern comfort furnishing materials and other new materials have caused significant increases in fire growth rates. Highly insulated, energy conserving buildings also promote rapid fire growth. In addition, improvements in protective equipment have greatly reduced the firefighter's ability to "feel" the thermal effects of a rapidly growing fire which significantly lessens the true awareness a firefighter has of his/her surroundings and imminent danger.

While a great deal of research has been done to evaluate structural fires as they relate to building design, materials and contents, very little is known about the thermal environments around fire fighters during normal attack situations. The Building and Fire Research Laboratory at NIST studied Fire Fighter's Protective Clothing and characterized the Thermal Environments typically found in Structural Fire fighting. This study concluded that although structural fire fighter's protective clothing, as currently used by the fire services, is designed to give the fire fighter "limited" protection from heat and flame, "successful fire fighting tactics keep the fire fighter's exposure times to high thermal radiation and temperature environments short."[4] Preventing dangerous exposure of firefighters to flashover conditions will require at least a minute warning to the fire service commander.

In his paper, "Flashover – a firefighter's worst nightmare,"[6] Paul Grimwood documents the experience of Captain Mike Spalding who was experienced a flashover while fighting a fire at the Indianapolis Athletic Club. Captain Spaulding is quoted:

"Then conditions abruptly changed. I'd never seen anything like this. I've fought a lot of fires in different kinds of buildings, in all kinds of weather, with all kinds of combustibles. I thought I'd seen a lot. I thought I'd seen enough that I could deal with whatever happened and I could take care of my crew. But, as I said, this thing abruptly changed. To this day, I'm still amazed that this happened……. The heat from the flashover was like a blast furnace……[3]"

Unfortunately, two of his fellow firefighters died in the fire. And this is not an isolated incident. NFPA statistics recorded from 1985 to 1994 showed that a total of 47 US firefighters died in fires due to flashover events. Of 87 firefighters killed between 1990 and 2003 due to smoke inhalation, the major causes sited were – became lost in the structure and ran out of air (29 deaths) and caught by progress of fire, flashover or backdraft events (23 deaths). During that same time span, of the 31 US firefighters who reportedly died due to excessive burns, 14 were said to be caught in the fire due to flashover or backdraft events[4]**.** A notable increase in fire fighter deaths attributed to flashover has also been documented outside the United States. A 2008 report by the labor Research Department of the Fire Brigades Union in the U.K., *In the Line of Duty*, analyzes fire fighter deaths in the UK since 1978. One of the most alarming findings from this research is that firefighter deaths at fires have risen sharply in the last five years, the worst five-year period in more than 30 years[4].

There have also been a number of specific major events over the years highlighting the dangers of flashover. At the Stardust Disco in Dublin, Ireland in 1981, 48 people were killed in a fire where a flashover occurred. In 1982, a flashover occurred in the Dorothy Mae apartments in

Los Angeles; 24 people were killed. A major fire in St. Petersburg, Russia, in 1991, claimed the lives of 8 firefighters due to a flashover event. Then, in 1996, there were 17 deaths in a Dusseldorf airport as a result of a flashover that took place in the airport terminal. Finally, since 2000 several firefighters have lost their lives in live burn trainings after flashovers took place. What this illustrates is that flashover has been, and continues to be, a major concern with regards to firefighter and civilian lives.

This study seeks a way to predict flashover in order to improve situational awareness of the incident commander and thus reduce the number of injuries and Line of Duty Deaths of fire fighters from traumatic injuries while operating inside structures. To do this, we hoped to provide the incident commander with a tool capable of providing a better awareness of the conditions of the building where his/her firefighters were operating. This tool would come in the form of a deployable sensor that would predict a time to flashover within a particular room or area within a building. Combining this real time countdown with the previously designed WPI Locator Device would enable the incident commander to be fully aware of where his/her firefighters were and what the state of that room was. With this knowledge, he/she would know when to instruct the firefighters to exit the room or building and what path was safe to travel by.

One important step was to determine if flashover could be reliably predicted using a measurement(s) that could be made in the field during a working fire. We began the search for such measurements with a review of the published literature on predicting flashover.

1.3 Previous Flashover Experiments and Determination of Criteria

Establishing one or more measurable quantities that can be used to mark and ultimately to predict a time at which flashover conditions will exist in a compartment fire would be a significant first step towards saving firefighter and civilian lives. Predicting flashover can be a particularly difficult thing to do however, as the definition of a true flashover can vary greatly from scientist to scientist. Questions remain such as, "Which of a number of different physical observations that occur in a fire can act as a point of initiation of a flashover event?" What measurements could be taken to assist in the prediction of flashover? How reliable would these predictions be? These observations include the unpiloted ignition of newspaper at floor level, the lowering of the smoke layer to the halfway point of the room, and flame extension out doorway. Measurements that might be useful include the temperature of the upper layer and the radiative heat flux to the floor.

Experiments that marked flashover using different criteria are documented in papers by Hagglund[8], Babrauskas[13], Fang[5], Lee & Breese[11], and Quintiere and McCaffrey[1]. Hagglund's work involved fire development in residential rooms. He concluded, based on the physical observation of flames exiting out the doorway, that a temperature of 600°C, measured 10 mm below the ceiling, was indicative of the onset of flashover. Babrauskas, with this knowledge in hand, performed a series of full-scale mattress fires. He tested a total of ten mattresses with just two of them displaying the ability to reach full room involvement. In both instances, temperatures exceeded 600°C with flashover occurring at around or just over 600°C.

In Fang's experiments, a full-scale enclosure was used at NBS. Average upper room temperatures ranging from 450°C-650°C were recorded as being sufficient with regards to providing an irradiance capable of igniting crumpled newspaper at floor level. The average upper room gas temperature was recorded as 540 +/- 40°C for tests where the newspaper ignited. Included in these values was the temperature measured at the mid-height of the room, therefore resulting in lower values. Temperatures measured 25 mm below the ceiling generally exceeded 600°C in tests where flashover was noted. Also determined in these tests was that newspaper would ignite over a range of heat fluxes to the floor of 17-25 kW/m^2. Fang and Breese performed 16 full-scale tests in residential basement rooms. The ignition of newspaper at floor level was also used as the indicator of the onset of flashover. They concluded, with a 90% confidence level, that an average upper room gas temperature of 706 +/- 92°C would be sufficient for the ignition of the newspaper. They also found good agreement between a heat flux measurement of 20 kW/m^2 at floor level and the time at which they observed flashover. Finally, Quintiere and McCaffrey performed tests comparing the fire behavior of wood versus plastic materials. In all tests that they classified as "high-temperature fires," or a ceiling gas layer greater than 600°C, flashover behavior in the act of the ignition of newspaper at floor level, occurred. They also state that a heat flux to the floor of 20 kW/m^2 may be used as an indicator of the onset of flashover.

Table 1[18] summarizes the results of all studied experiments pertaining to flashover criteria.

Table 1 - Summary of Previous Flashover Experiments

Source	**Temperature (°C)**	**Heat Flux (kW/m^2)**
Haaglund	600	No data
Fang	450-650	17-33
Budnick and Klein	673-771	15
	634-734	15
Lee and Breese	650	17-30
Babrauskas	600	20
Fang and Breese	705 +/- 92	20
Quintiere and McCaffrey	600	17.7-25
Thomas	520	22
Parker and Lee	No data	20

The discrepancies in values can be attributed to the previously noted differences that exist in the true definition of flashover and at what location in the room and height below the ceiling the measurements were taken at. However, it is clear that for the majority of the tests a temperature range of 600-700°C and a heat flux of approximately 20 kW/m^2 to the floor accurately describe the condition of the room at the time of flashover.

Mathematically, Yuen and Chow, in their paper, “The Effect of Thermal Radiation on the Dynamics of Flashover in a Compartment Fire,” used a three-dimensional non-gray soot radiation model to simulate the radiative exchange between the fuel surface, the hot gas/particulate layer and the surrounding wall. Their results show that the hot layer temperature alone may NOT be an effective indicator for flashover. Other parameters such as particulate volume fraction in the hot layer, venting area and heat transfer to the surrounding wall are also important in determining the occurrence of flashover[4]. However, this paper also notes that in all of the reported flashovers in which both criteria are available, both the gas temperature and the heat flux criteria are meet prior to the onset of flashover.

In conclusion, various definitions of flashover are shown in the literature to be consistent with a broad range of data that shows temperature of the upper layer at flashover to be greater than or equal to 600 ^{O}C and heat flux to be greater than or equal to 20 kW/m2. Thus, for fire engineering and fire fighting purposes, the time at which the upper layer reaches 600 ^{O}C Celsius and/or the heat flux to the floor reaches 20 kW/m^2 are likely to provide a conservative estimate of the time to flashover. As a result, in this project, measurements of upper layer temperature and measurements of heat flux to the floor will be taken with the goal of developing a predictive methodology for the time to flashover in a compartment based on these important parameters.

2. Research Methods

Review of the literature on flashover showed that knowledge of the temperature in the hot upper layer and/or knowledge of the heat flux to the floor as a function of time in the burn room may provide the necessary inputs to an algorithm by which flashover can be predicted. Various team members developed field deployable instrumentation capable of measuring temperature and pressures in the fire room. From here, the four main steps in the research plan involved: 1) Determining the accuracy of these instruments and designing the large scale fire tests, 2) conducting a series of flashover experiments at residential-scale; 3) analyzing the data and development of a flashover prediction algorithm; and 4) Testing of the predictive capability of the algorithm.

Step 1. Intermediate-Scale Testing and Computer Modeling

This phase of the process involves fires and computational modeling to support development and testing of the prototype environmental monitoring devices, characterization of the heat release rate of the proposed fuel, calibration of the field instrumentation against laboratory standards, and design of the fuel package and instrumentation layout for the full-scale tests. All intermediate-scale testing was conducted in the WPI burn chamber in the Fire Protection Engineering Laboratory. Fire modeling was conducted with a computational fluid dynamics model widely used in the fire science community.

Step 2. Full-Scale Residential Burns

Full-scale residential burn experiments were planned for the MA fire academy burn building in Stowe, MA. Three such experiments were conducted in the fire fighter training building there. When this building proved to be non-optimum for flashover testing, a residential-scale stand-alone room, resembling a living room, was built and utilized. The first three tests conducted in the MA fire academy firefighting training building are thus considered part of the Burn Tests Leading to the Final Experimental Design. The series of full-scale residential burns conducted in the Stand-Alone Facility represented real world residential fires and were used for Development of an Algorithm to Predict Flashover.

Step 3. Development of Algorithm to Predict Flashover

Factors considered in the development of a flashover prediction algorithm include the effects of measurement type, measurement location, statistical sample size, and how often the prediction is updated. These parameters are evaluated for a range of fire sizes and fire growth rates which lead to finalization of the algorithm.

Step 4. Evaluation of Predictive Capability of Algorithm

The efficacy of the flashover prediction algorithm is evaluated statistically by use of the results of applying the predictive algorithm to the complete series of full-scale tests. The goal of this research was to develop the instrumentation and software algorithm to provide an incident commander a minimum of one-minute notice of flashover.

3. Burn Tests Leading to Final Experimental Design

Fire testing involves so much more than lighting a match. To get quality data, fire experiments are designed in a multi-step process. First, a fuel is selected to be both representative of a particular application being studied and to achieve repeatability. For our residential application, wood cribs meet both of these criteria. Wood cribs are well characterized in the literature, having been used for many fire tests over several decades. They are easily obtained and outcomes are somewhat repeatable when cribs of a certain dimension and type of wood are used. The National Institute of Standards and Technology have conducted several large scale tests to quantify the heat release rate of burning wood pallets in the open and in an enclosure[17]. Wood cribs are a basic cellulosic fuel, similar to that found in residential applications. Second, the behavior of the fuel within a certain size and geometry space is predicted with a computer fire model. Computer fire models vary in type and complexity and provide an estimate of the amount of fuel (heat release rate) is needed to flash over a given space. When running these models, other factors affecting flashover must be considered such as the wall and floor materials of the enclosure and the leakage rates from the space. The three sections below describe the two facilities where the preliminary tests were conducted, the lab and field instrumentation used in the tests, the number and type of tests conducted and the results.

3.1 Description of Burn Facilities

WPI Burn Room Specs:

Figure 1 - WPI Burn Room

The burn room is designed from ASTM E603. Compartment size is 2.4m (8 ft.) by 3.7 m (12 ft), with a 2.4 m [8-ft] high ceiling. A standard-size doorway (0.80 by 2.0-m high) is located on the front of compartment. In these tests however, the size of the room was reduced to 8ft by 8ft by 8ft to accommodate another experiment and the front side of the room was left open. The outer walls and ceiling are constructed of 5/8” plywood. The inner walls consist of 3 layers of ½” gypsum wall board on the ceiling and walls, 1 layer on the floor.

MFA Firefighter Training Building Specs:

The original location for testing was within the Burn Building located at the Massachusetts Firefighter Academy. This combination 4 story/2 story concrete building was designed to allow live fire training with the use of Class A combustibles. Each room has sources of ventilation provided by window openings and floor vents. Each room is lined with specialized refractory concrete fire tiles which are used to absorb excess heat to allow for safe training practices. The walls and ceilings of the burn building are covered with a 1" insulation board covered by 2" thick refractory concrete tiles that absorb heat and the building leakage rate is significant.

Figure 2 - MFA Burn Building

3.2 Lab and Field Instrumentation

As discussed in earlier sections, the data of interest in all of these tests are the temperatures in the hot upper layer and vertically in the room from floor to ceiling and the heat flux to the floor in the burn room. A focal point for development of practical, deployable field instrumentation is to ensure that field instrumentation provides accurate measurements. Accuracy of field devices was determined through comparisons to calibrated lab instrumentation at WPI

3.2.1 Temperature Measurements

To capture temperature data and create heat profiles for the room a thermocouple tree with multiple thermocouples was created. Thermocouple trees are made up of an array of thermocouples usually aligned one on top of the other at predetermined heights. For this tree the thermocouples started from one inch from the ceiling, down to one inch from the floor at one foot intervals. Each thermocouple recorded data at their respective heights to allow a profile to be generated. The thermocouple tree was placed at a maximum distance from the fire but away from the corner of the room to both minimize radiative heating of the thermocouples from the fire itself, and to avoid corner effects.

Thermocouples are constructed by forming a junction between two different metals. When this junction is exposed to a heat source, a heat gradient is formed due to the difference in temperature between the junction and a reference at the other end of the wires. With this gradient comes a low-level DC voltage. When both wires in the thermocouple assembly begin at the same reference temperature and end at the same junction temperature, the following equation can be used to determine the voltage generated;[12]

$$E = \int_{T_{ref}}^{T_{jct}} (\varepsilon_A - \varepsilon_B) dt$$

Generally, thermocouples are calibrated to determine the relationship between this voltage and a temperature. This relationship is essentially linear over a wide range of operating temperatures which are specific to and well known for the various metal junction types which are employed.[12]

3.2.2 Heat Flux Measurements

Heat Flux measured at the floor was a second important piece of data desired in this project. To obtain this, Thin Skin Calorimeters were used. A thin skin calorimeter is a thin metal plate with a thermocouple welded to it. From this temperature measurement, a one-dimensional heat flux flow analysis can be used, whether it be convective, radiative or both. The overall governing equation for doing this is based on the exposed face of the metal;

$$q = \rho * C_p * \delta * \frac{dT}{d\tau}$$

In this equation ρ is the density of the metal, C_p is the specific heat, δ is the thickness and $dT/d\tau$ is the rate of the temperature rise on the back of the unexposed surface. However, losses need to be accounted for whenever heat transfer is considered. With this the above equation can be represented as the following;

$$q_i = q_c + q_r + q_{sto} - q_{c,st}$$

From left to right this equation expresses the incident heat flux to the thin skin calorimeter as the convective losses from the hot plate to the cool are, plus the heat the metal plate with re-radiate back to the environment, plus the energy stored in the plate, minus the conduction within the plate. Each term can be calculated with the following equations;

$$q_c = h * (T_s - T_\infty)$$

$$q_r = \sigma * \varepsilon * (T_s^4 - T_\infty^4)$$

$$q_{sto} = \rho * \delta * C_p * \frac{dT}{dt}$$

$$q_{c,st} = -k * \frac{DTs}{dt}$$

In these equations T_s represents the temperature measured by the thermocouple welded to the backside of the metal plate, T_∞ is the ambient temperature, σ is the Stefan-Boltzmann constant, h is the convective heat transfer coefficient, and ε is the emissivity.

Thin skin calorimeters deployed in the field were first calibrated against water cooled heat flux gauges manufactured by Medtherm Corporation. Medtherm's devices have NIST traceable calibrations. A more detailed study of think skin calorimeters as detailed by Rangwala.[16]

4 Tests Conducted

4.1 Preliminary WPI Tests


Figure 3 - Photo of WPI Burn Room with QNA deployable sensor and WPI Test Equipment

A total of thirteen preliminary tests were conducted in order to design and refine both the full-scale experiments and the prototype instrumentation being developed. The first ten of these tests were conducted in the WPI burn room.

Tests 1-5 were used to characterize the heat release rate and burn behavior of a single and/or multiple wood pallets stuffed with straw.

Tests 4 and 5 were used as group tests where prototype instrumentation being prepared by the WPI ECE department and QinetiQ North America were tested for their accuracy in environmental monitoring and for their hardiness when exposed to the fire. These tests utilized wooden pallets for a fuel source. Tests 6, 7, and 8 were also conducted as group tests but utilized a gas fire since full characterization of the pallets was completed by then (the gas fire is easier and less messy to run).

During the final test in the WPI burn chamber, all groups conducted a data synchronization to ensure that both their instruments and their individual data collection techniques were accurately collecting information and were recording in the same time frames.

Table 2 - Summary Table of Preliminary Tests performed at WPI Burn Chamber

Tests	Date	Purpose	Fuel	Instrumentation	Data Collected
1 – 2	12/2/2009 12/4/2009	Characterize Fuel	1 -Wood Pallet	Thermocouple Tree, Hood, DAQ System	Time/Temperature, HRR
3,4,5	12/4/2009 12/7/2009 1/21/2010	Characterize Fuel, Group Test	2 - Wood Pallets	Thermocouple Tree, Hood, DAQ System	Time/Temperature, HRR
6, 7, 8	2/10/2010 2/24/2010 3/26/2010	Group Test	Gas	Thermocouple Tree, Hood, DAQ System	Time/Temperature, HRR
9	4/16/2010	Group Test, Data Synch.	Wood Pallets	Thermocouple Tree, Hood, Heat Flux Gauges, DAQ System	Time/Temperature, HRR, Heat Flux
10	5/17/2010	Group Test, Data Synch.	Masonite Board	Thermocouple Tree, Hood, Thin Skins, DAQ System, Williamson Device, Video Recorder, Ceiling Thermocouple	Time/Temperature, Heat Flux, Ceiling Temperature, Video

Satisfied that the heat release rate of the wooden pallets stuffed with straw had been well characterized and that all data systems were reading accurately and in sync., the team moved on to conduct burn testing on a larger scale at the MA fire fighting academy in Stowe, MA. Tests were originally planned for the academy’s burn building where fire department training exercises take place. A room within this enclosure was modeled to determine the number of pallets that would be needed to flashover the room.

The Fire Dynamics Simulator (FDS) is an internationally accepted fire model developed and distributed by NIST. The FDS was used in the research and is fully described in "Fire Dynamics Simulator (Version 5) User's Guide" [6]

Three large-scale flashover tests were conducted in this facility.

Table 3 - Summary Table of Preliminary Tests performed at MFA Burn Building

Test	Date	Purpose	Fuel	Instrumentation	Data Collected
11 - 13	3/3/2010 3/3/2010 3/12/2010	Conduct Flashover Test	Wood Pallets	Thermocouple Tree, Thin Skins	Time/Temperature, Heat Flux

4.2 Results of Preliminary Tests

The heat release rate of the wood cribs stuffed with straw was approximately 0.5 MW per crib. This value is analogous to measurements of wood cribs stuffed with straw made at the National Institute of Standards and Technology.[15]

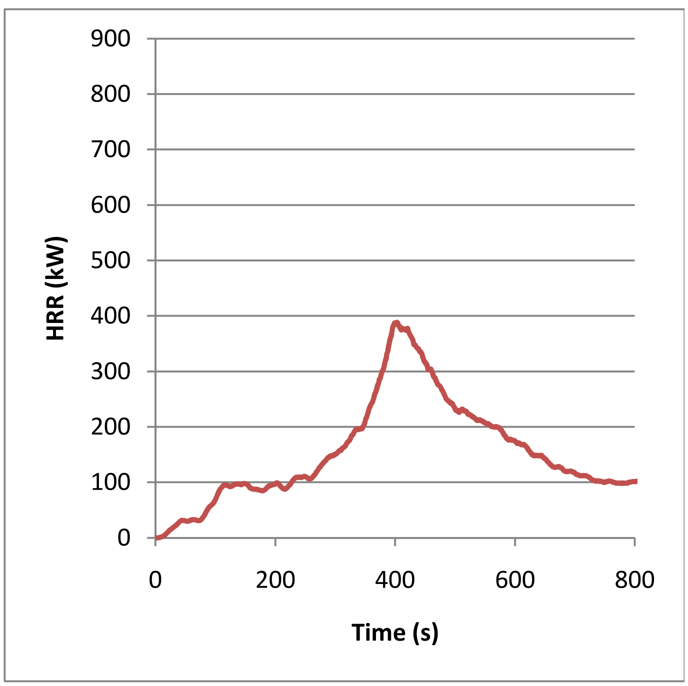

Figure 5 - Heat Release Rate for Single Pallet Burn

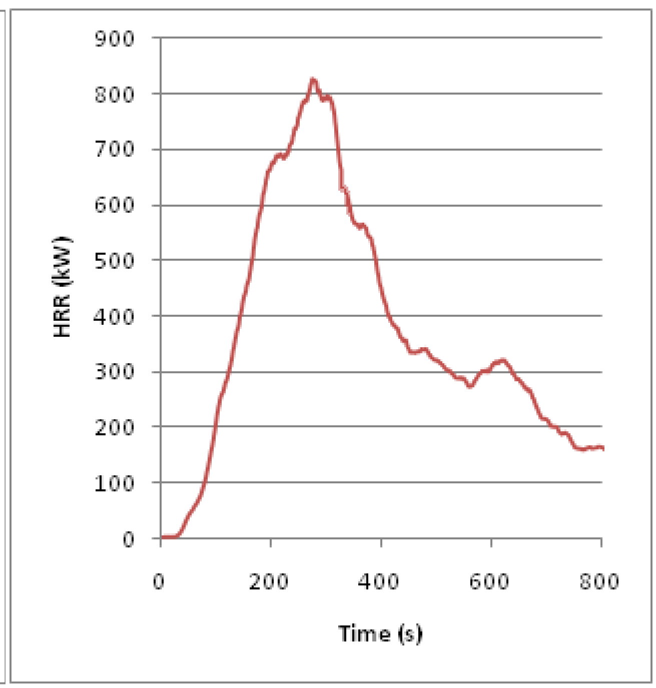

Figure 4 - Heat Release Rate for Two Pallet Burn

Computer modeling of the burn room at the Stowe building training facility showed that 4-5 pallets stuffed with straw should be enough to create a flashover situation in the room.

However the accuracy of computer model predictions is a function of the degree of knowledge of the known leakage rate from the room and the thermodynamic characteristics of the building materials. This facility had specialty building materials with high heat capacity and had large vents cut at floor level for training purposes. These additional features made it difficult to fully simulate fire growth in these rooms.

Three separate burn tests were conducted in the fire-fighter training building. The first test utilized five pallets and read a maximum ceiling temperature of only 472 ◦C. The second test reached a peak ceiling temperature of 640 ^{O} C (fuel was added during the test to compensate for the high leakage rate), but still did not flashover. It was noted that there was very little hot layer development, so in the third test, the walls of the room were lined with masonite in order to achieve some accumulation of of-gassing. However, the masonite could not be secured to the tiles (for fear of damaging them) and the room still did not reach flashover. It was determined that this building was not conducive to flashover testing due to the wall and ceiling materials and the high leakage rates. This non-optimum situation would be repeated in any room in the burn building so an alternative, stand-alone facility was designed and built.

5 Large-Scale Burn Tests in Stand-Alone Facility

5.1 Construction Specifications

To recreate typical residential rooms, the stand-alone structure was built to 12 ft x 16 ft x 8 ft dimensions at the Massachusetts Firefighter Academy grounds. The frame of the room was constructed with 2x6 dimensional lumbers on 16” standards, as per building regulations. The 2x6 standards were spanned by ½” plywood. On top of the plywood, the walls and ceiling were finished with gypsum board while the floor was exposed earth covered in a layer of sand for insulation purposes. The gypsum board was spackled with joint compound between each test for heat retention as to simulate real world constructions. After each test the top layer of gypsum board from the walls and ceiling were taken down as needed and replaced with a new layer of gypsum board. As the room is re-boarded after each trial the room ventilation could be changed. The longer dimensions of the room allowed for a measure of how the temperature of the upper gas layer was changing over time at locations at the opposite side of the room. This provides a more realistic representation of how the conditions within a typical structure change. In the first eight tests conducted in the burn room two vents were cut into the walls to allow for air to feed the fires. For the last two tests full scale windows were cut into the walls. The door installed on the front of the building remained open for all tests.

5.2 Tests performed at Stand-Alone MFA Structure

Figure 7 - Picture of Furnished Standalone Building

Figure 6 - Picture of Standalone Building Fully Engulfed

A series of ten residential scale flashover tests were conducted in the Stand-alone structure previously defined. The ten tests provided data useful for the development and testing of a flashover prediction algorithm. This series of tests were designed to vary the rate of growth of the fire. To vary the fire growth the tests used varied fuel packages as indicated in the following Table 4. Tests 1 through 8 used stacked wood pallets stuffed with straw, and tests 9 and 10 used actual furniture. For each of the tests, flashover was recorded as happening based on a visual indicator that was recognized as the best representation of the event occurring. As previously discussed flashover can be defined by the temperature of the upper gas layer, or by heat flux measured at the floor. Due to the rapid growth of these fires, and the systems used to record data it was determined that a visual indicator would be the best and most accurate was of determining the time at which flashover occurred. The indicator used was a line of crumpled newspapers placed at varying distances from the fire. These crumpled newspapers would spontaneously ignite when the heat flux reached the ignition energy needed, usually in a sequential manner from closet to the fire to furthest.

The time at which the newspaper farthest from the fire ignited was recorded as the time at which flashover occurred. The furthest paper indicator was used to try to eliminate radiant heat directly from the fire causing ignition, as heat flux from the upper gas layer was the measuring indicator. Both the temperature of the room at varying heights as well as heat flux at the floor were recorded using thermocouples and thin skins to have correlating data and time information.

As a final set of tests the stand alone room was fully furnished as shown above in figure 7 The furniture included a full size couch, tables with lights, curtains on the windows, a television set, and a magazine rack filled with magazines and newspapers. The floor was also covered in wall to wall carpeting. These final two tests using furniture provided ultra fast fire growth. While this ultra fast fire growth may astonish many people, the use of real furnishing provides a real world scenario. This allowed for the test equipment and algorithm to be used on real fire data to help prove validity of results.

Table 4 - Table of tests performed at MFA Stand Alone Structure

Test	Date	Purpose	Fuel	Instrumentation	Data Collected
1 – 2, 7	06/29/2010 06/30/2010 AM 07/16/2010 PM	Obtain Data for Algorithm/Test new Room	5 Wood Pallets	TC Tree/Thin Skins	Time/Temperature, Heat Flux
3-6, 8	06/30/2010PM 07/15/2010 AM 07/15/2010 PM 07/16/2010 AM 07/22/2010 AM	Obtain Data for Algorithm/Test new Room	4 Wood Pallets	TC Tree	Time/Temperature
9	07/22/2010 PM	Obtain Data for Algorithm/Test couch fire	3 Seat Sofa	TC Tree/Thin Skins	Time/Temperature, Heat Flux
10	07/23/2010 AM	Final Demo of Testing	3 Seat Sofa	TC Tree/Thin Skins	Time/Temperature, Heat Flux

6 Results from Stand Alone Fire Tests

The tests performed in the Stand Alone structure were designed to provide for different fire growth rates. Varying the fire growth rates was achieved be varying the fuel package from three to five pallets, differing the amount of straw used, moving the location of the masonite board relative to the fuel package, and eventually fully furnishing the room. Collecting data from the different fire growth rates provides a more robust data set from which to delevope and test the flashover prediction algorithm. Table 5 shows the ten tests performed, the resulting peak temperature, peak heat flux, and time to reach peaks and flashover. It also shows the temperate of the hot upper gas layer and heat flux measured at the floor at time of flashover.

Table 5- Summary of MFA Tests conducted in Stand Alone structure

Test	Peak Temp. (°C)	Time to Peak (s)	Peak Heat Flux (kW/m^2)	Time to Peak (s)	Flashover (Y/N)	Time to Flash (s)	Temp. at Flashover (°C)	Flux at Flashover (kW/m^2)
1	728	420	55	414	Y	339	673	23.7
2	617	473	24.1	473	Y	436	567.9	18.1
3	688.5	469	N/A	N/A	Y	431	572	N/A
4	710.7	1009	27.8	1026	Y	954	643.7	14.4
5	693.7	501	23.1	491	Y	475	649.8	18.7
6	692.1	575	23.3	568	Y	550	665.8	19.6
7	702.8	376	21.4	374	Y	341	640.6	16.9
8	685.29	749	N/A	N/A	Y	693	654.6	N/A
9	774.5	349	278	429	Y	320	617.2	19
10	760.7	192	29.5	185	Y	166	629.6	15.6

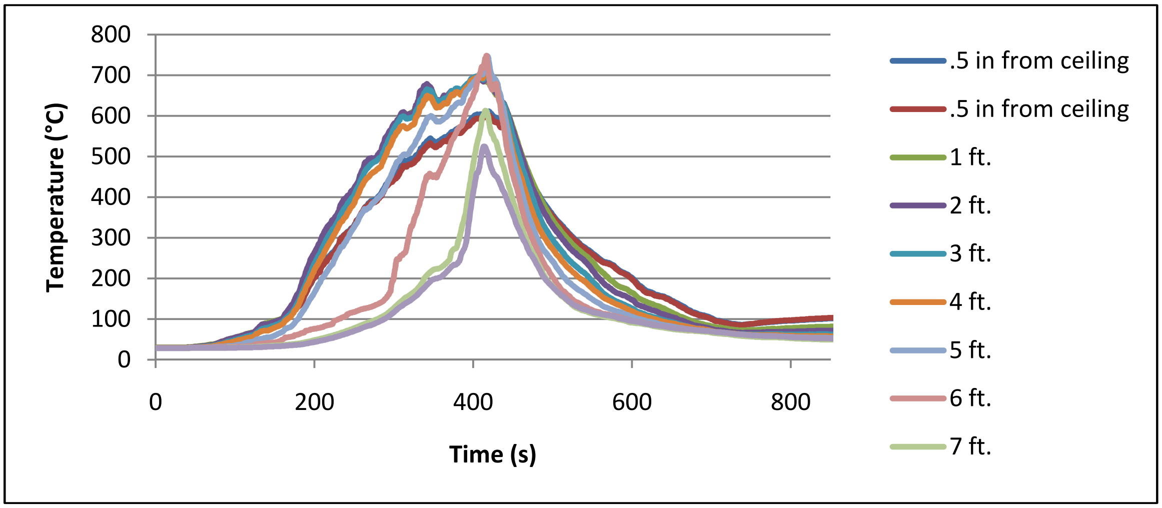

Figure 8 - Time Temperature Graph and Heat Release Rate Graph of typical fast burn, Stow Test 1

The temperatures recorded on the thermocouple tree during the first test conducted in the stand alone structure are shown in Figure 8 as a function of time from ignition. As indicated in previously in Table 5 flashover occurred at approximately 339 seconds (approximately 5.6 minutes). At the time to flashover the temperature in the hot upper gas layer had exceeded 600 degree Celsius. Due to the rapid growth of the fire to flashover Test 1 is characterized as a "fast" growth rate fire. Similar temperature data as a function of time for a "slow" growth rate fire and a "ultra fast" growth rate fire are shown in Figures 9 and 10 respectively. These three tests are representative of each of three different fire growth rates used in this study.

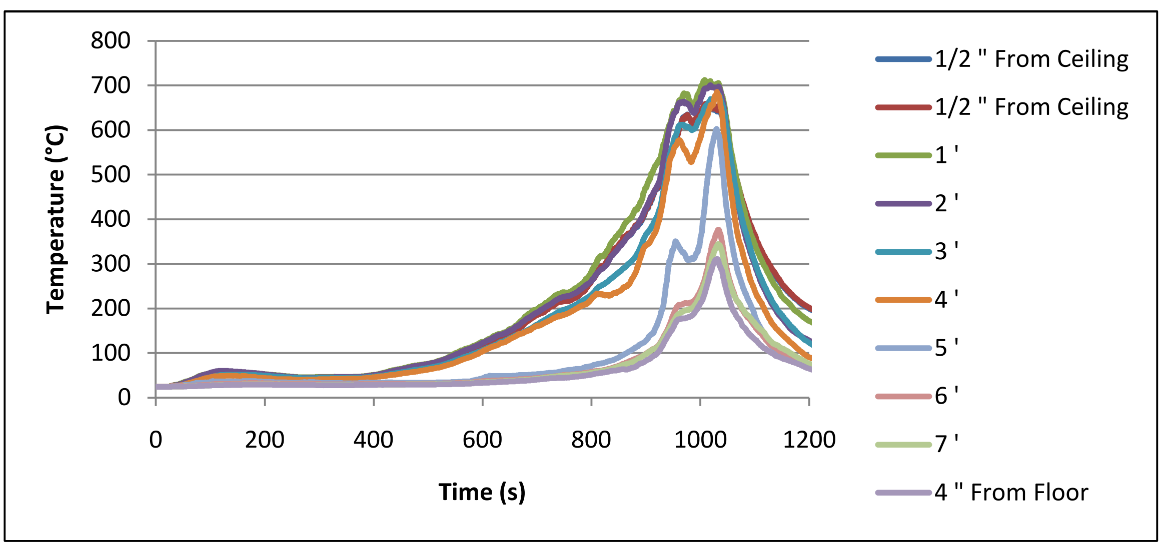

Figure 9 - Time Temperature Graph and Heat Release Graph of typical slow Burn, Stow Test 4

The slow growth rate fire reached flashover at 954 seconds (approximately 15.9 minutes), almost three times slower than the fast growth rate fire. The temperature recorded on the thermocouple tree as a function of time is shown in Figure 9 above. Although the fire grew significantly slower, again at the time of flashover the temperature exceeded 600 degrees Celsius.

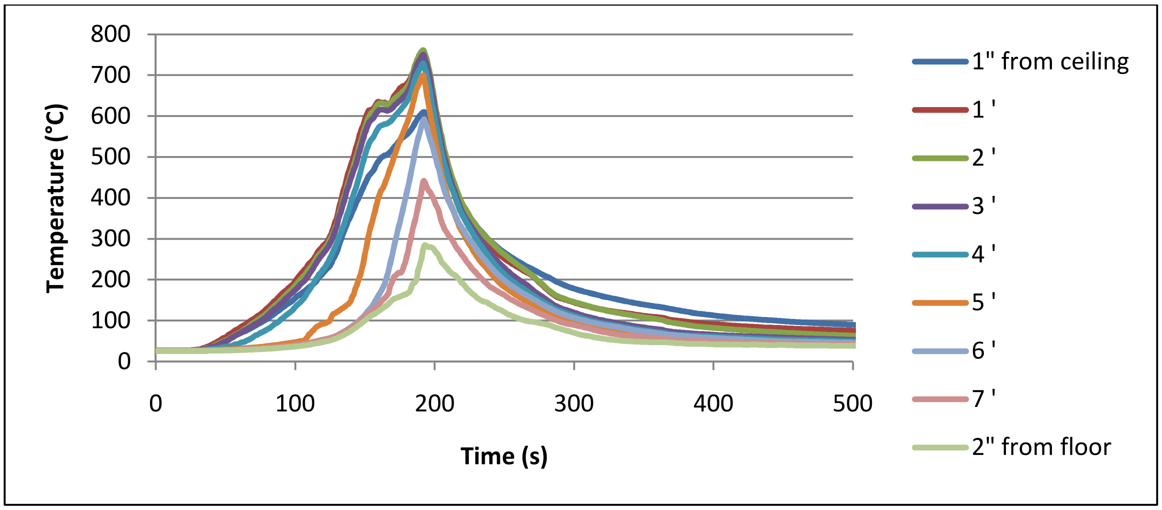

Figure 10 - Time Temperature graph of furnished burn, Stow Test 10

Test 10 was conducted with a fully furnished room, exhibited an ultra fast fire growth rate. Flashover was achieved in only 166 seconds (less than 3 minutes). The temperatures recorded by the thermocouple tree as a function of time is shown in Figure 10. This scenario demonstrates the rapid growth that occurs in modern residential situations, and the resulting danger it poses to firefighters.

Figure 11 shows a comparison of both the time to flashover and the peak temperature at flashover for each of the three fire growth rates. The temperature data shown was recorded from the thermocouple one foot down from the ceiling. This thermocouple location was selected because it consistently recorded the highest temperature.

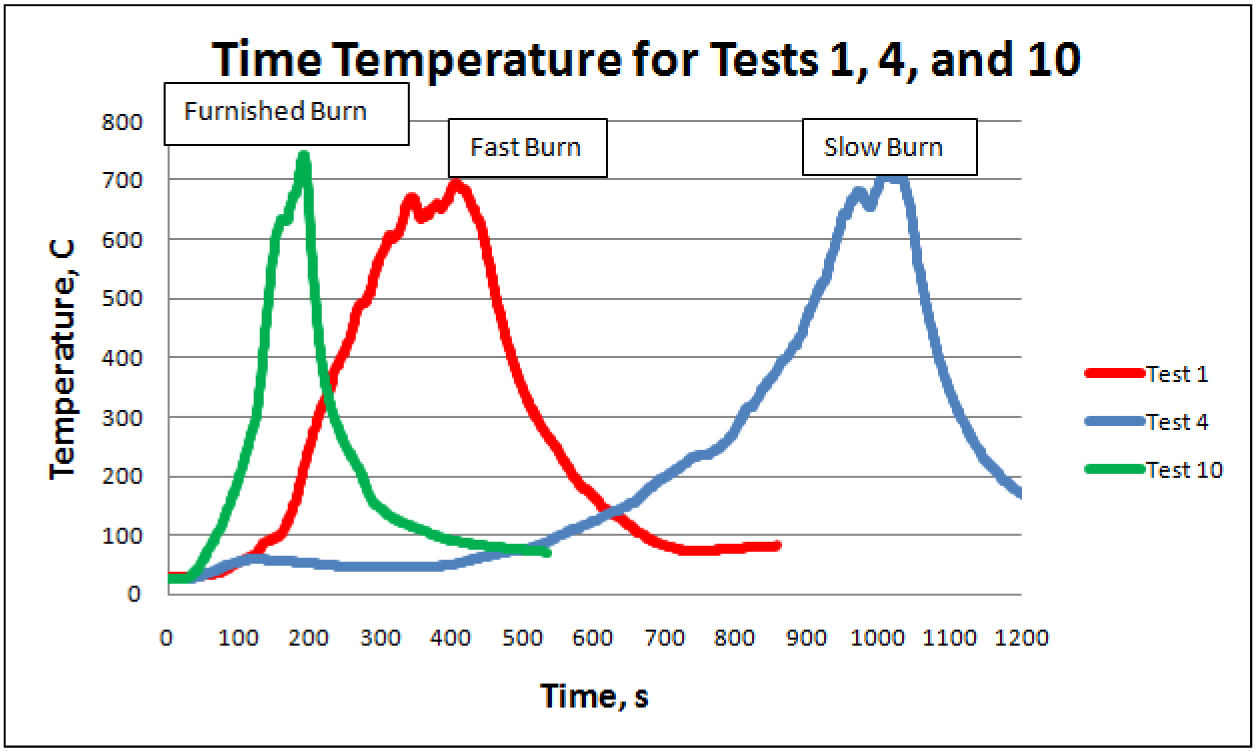

Figure 11 - Time Temperature Graphs for Tests 1, 4 and 10 on a common axis. This graph uses the temperature information from the thermocouple located one foot down from the ceiling

As Figure 11 shows, the fully furnished fire, Test 10, grew at a much faster rate than the other tests, and also peaked at a higher temperature. It can been seen from this graph that although at significantly different rates, all three peaked at about the same temperature. The ultra fast fire peaks at a slightly higher hot layer temperature than the other two slower growth rate fires. The extremely rapid rise of temperature of the hot layer precludes significant heating and thus re-radiation from the walls, leading to a higher hot gas layer temperature at flashover.

Although they performed well in the WPI burn chamber, the thin skin calorimeter did not perform well under the rigorous testing conditions in out stand alone burn structure. During the large full scale testing in the stand alone burn structure, these devices were subject to extreme environmental conditions and were exposed to water when the fire was extinguished. Heat flux data recorded by these devices was unreliable and inconsistent. The data recorded by the thin skin calorimeters was not consistent with the expected range of value for heat flux. Furthermore, although in every test the thin skins were placed within inches of each other they recorded very different values. Thus it was determined that thin skin calorimetry would not be a valid field measurement for prediction of flashover and for situational awareness. Therefore, the development of an algorithm for the prediction of time remaining to flashover is based solely on temperature.

7 Development of Prediction Algorithm

Results of the ten tests presented in Section 6 show that temperature was the most reliably collected data in the field, and that for all ten real scale room flashovers, the temperature in the hot upper gas layer reached a minimum of 600 degrees Celsius. Development of a prediction algorithm that is based on a minimum criteria will provide the fire service with a conservative estimate of time remaining to flashover.

Development of this algorithm followed a four step process; selection of a mathematical curve fitting process, selection of temperature data to be used as an input, determining effects of statistical sample size, and the effect of the prediction update interval.

7.1 Derivation of Linearization Method

The flashover predicting algorithm used is based on a Data Linearization Method for fitting an exponential curve to the data. As a history of data is collected during a real time test, a sub-interval of the data is taken and an exponential curve is then fit to it. As time progresses the curve is altered by new data being added while removing old data. The curve is extrapolated over time and a prediction is made based on what time the curve reaches a certain point. With respect to temperature, this point would be 600°Celcius, representing the demonstrated minimum temperature in the hot upper layer at flashover.

An analysis is then performed based on how accurate the prediction is when compared to the observed flashover time from the test being analyzed. With each time step a predicted time to flashover is recorded, as well as an actual time to flashover. The methodology behind the curve fitting method is as follows;

For a given number of data points, we wish to fit a curve in the form of

$$y = C * e^{A*x}$$

First, the logarithm of both sides must be taken,

$$\ln(y) = A * x + \ln(C)$$

A change of variables in incorporated,

$$Y = \ln(y)$$

$$X = x$$

$$B = \ln(C)$$

There is now a linear relationship in the form of,

Y = A*X + B

The following equations are used in order to determine A and B,

$$(\sum_{k=1}^{N} X_k^2) * A + (\sum_{k=1}^{N} X_k) * B = \sum_{k=1}^{N} X_k * Y_k$$

$$(\sum_{k=1}^{N} X_k) * A + N * B = \sum_{x=1}^{N} Y_k$$

Finally, C can be computed by,

$$C = e^B$$

7.2 Data Selection for Algorithm

The first step in testing and refining the algorithm was determining the best thermocouple location to use as the data indicator of flashover. We decided on three possible locations; the thermocouple nearest the ceiling, the thermocouple that consistently read the highest temperature, and the thermocouple nearest the floor. For the first two thermocouples, a target temperature of 600°C was used by our predictor. A temperature of 190°C was used for the thermocouple nearest the floor as this is the auto-ignition temperature of paper. This was used because the visual indicators of flashover used in the tests were crumpled pieces of newspaper. An analysis of the possible locations were carried out for a total of four tests. In each analysis the time step and the amount of data used in the prediction was held constant, so the only variable changing was the location of the thermocouple. The analysis showed that the thermocouple located one foot from the ceiling, which consistently recorded the highest temperatures in the room, was the best data set to fit the prediction to. The results for two of these tests are provided below.

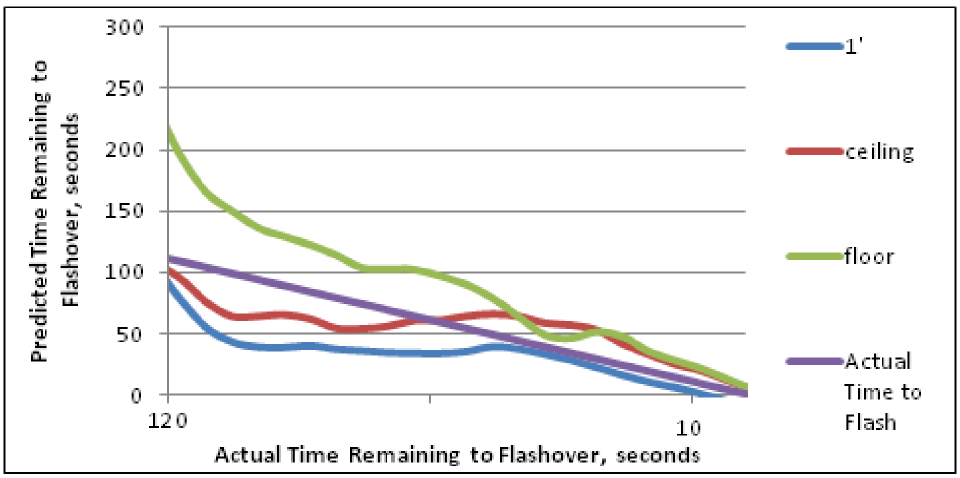

Figure 12 - Results of Location Analysis Fast Test 4

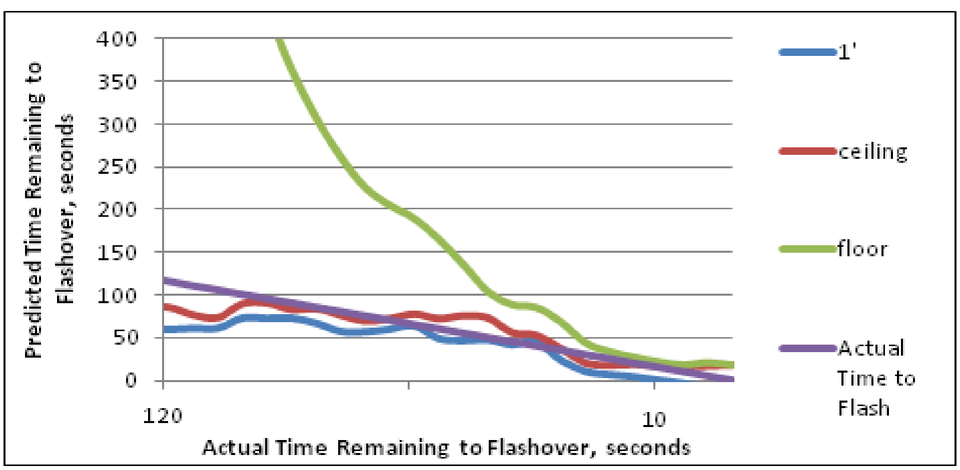

Figure 13 - Results of Location Analysis Slow Test 10

As demonstrated by Figures 12 and 13 the thermocouple located at one foot down from the ceiling when run though the algorithm program, provided results closet to actual time to flashover. Both the ceiling and floor thermocouples deviated too far from the actual time to flash line, and also provided predicted times above actual time, which is an undesired result. The algorithm is preferred for this application, which would show a shorter time to flash rather than a longer time, providing a conservative estimate of time to flashover.

After the optimum thermocouple was selected, the next step was to determine what statistical sample size, and what prediction update interval to use.

7.3 Effect of Statistical Sample Size and Prediction Update Interval

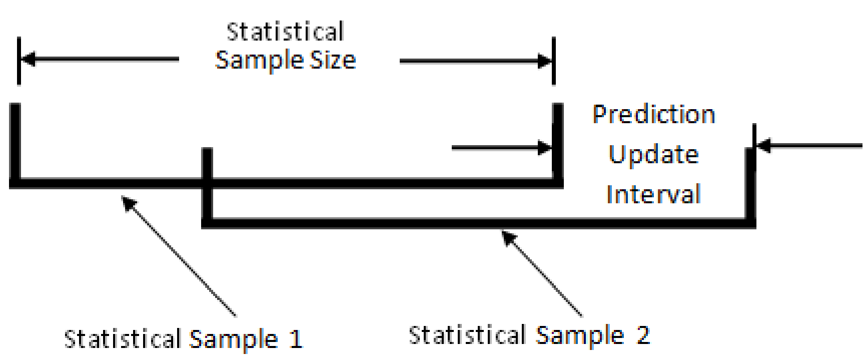

Figure 14 - Visual Representation of Statistical Sample Size and Prediction Update Interval

The statistical sample size is the amount of data being used in the prediction algorithm at any instant, and the prediction update interval is how often a new sample is taken. This concept is demonstrated in Figure 14. For explanation purposes imagine that Sample 1 is taken at time zero. During these tests data is recorded at a rate of one measurement per second. Thus the number of seconds defining a sample size is also reflective of the number of recoded temperatures in the statistical sample. At this instant a sample, i.e. a number of recorded temperature measurements, is taken of size “sample size”. The algorithm uses this data, and creates a prediction of time remaining to flashover. Then at time equal to the “Prediction Update Interval” a new sample of size “Sample Size” is taken. Again the algorithm produces a prediction of time remaining to flashover. This is repeated for as long as data is being taken from a fire. The effects of altering the "Sample Size" and "Prediction Update Interval" will be explored in the following sections.

7.3.1 Effects of Statistical Sample Size

To determine this, three different tests were examined as in correspondence with the tests to find ideal thermocouple locations. For each test, data sample sizes of 10 seconds, 15 seconds, and 20 seconds were used. The time step and the thermocouple location were held constant, making the sample size the only variable. The analysis revealed that there was very little change from one sample size to the next in regard to accuracy of the prediction of time remaining to flashover. Increasing the sample size provides a certain level of additional accuracy, though minimal, at times farther removed from the time to flashover. As time gets closer to the actual time the flashover, sample size played a decreased role. Figures 15 and 16 show the minimal effect of sample size on the prediction capabilities of the algorithm.

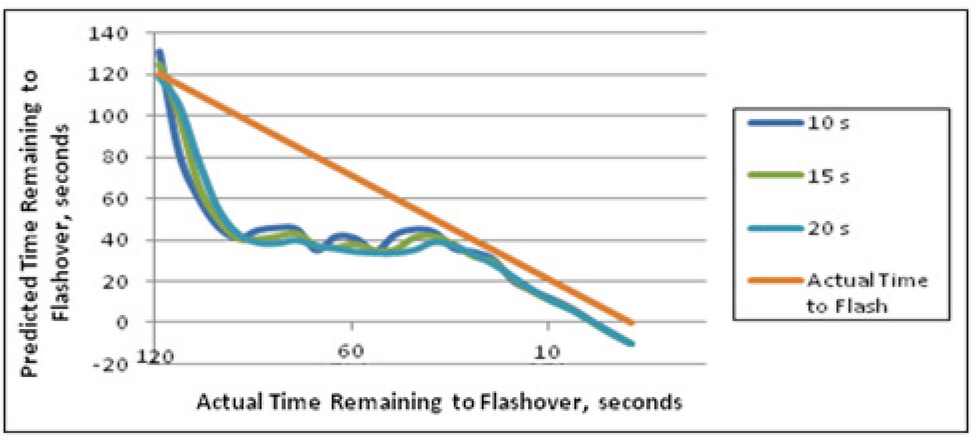

Figure 15 - Results of Sample Size Analysis for Fast Test, Test 1

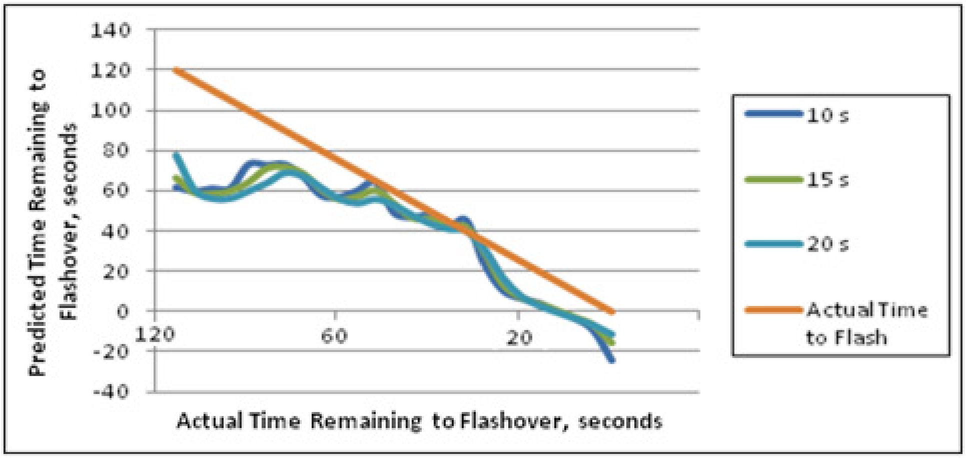

Figure 16 - Results of Sample Size Analysis for Fully Furnished Burn, Test 10

7.3.2 Effect of Prediction Update Interval

With the sample size determined, an update interval had to be examined. The time step signifies how often a new prediction will be made as well as how much of the old data will be included in the new prediction. In order to reach a conclusion on this matter thee different analysis were run. In these analyses the sample size, thermocouple height, and test were kept at a constant while the update interval changed. Update intervals used were 1, 10, and 20 seconds. The analyses showed that the update interval played an insignificant role in how well the prediction faired. Lowering the update interval resulted in a smoother curve but did not have much of an effect on the overall ability of the algorithm to accurately predict time remaining to flashover. Again, figure 5 shows the minimal effect of the varying update interval.

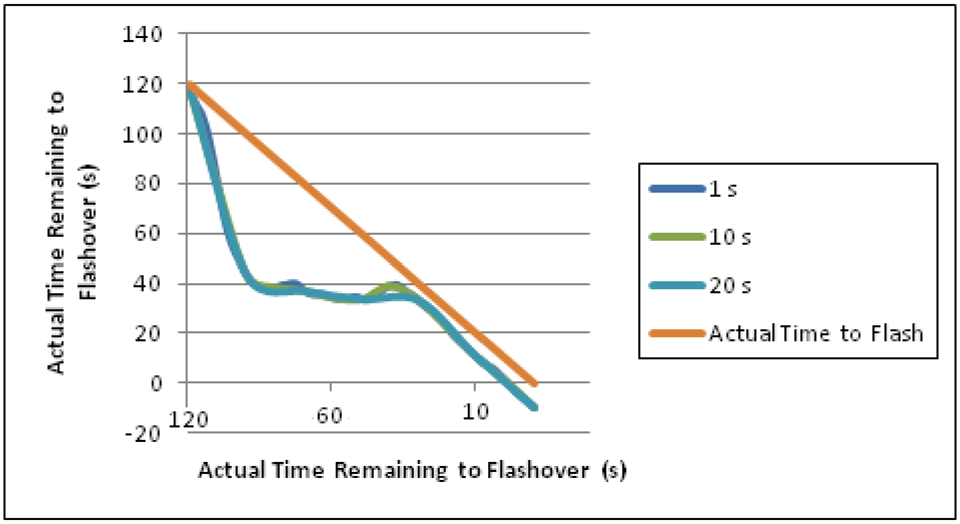

Figure 17 - Results of update interval analysis for Fast Burn, Test 1

8. Flashover Prediction using Algorithm

With these analyses for thermocouple location, sample size and rate of acquisition complete, a data sample size of 15 seconds, a times step of 5 seconds, and a thermocouple height of 1 foot from the ceiling was used to perform an analysis on the remaining tests. The prediction algorithm was applied with each of these specified parameters and graph of the "predicted time remaining to flashover vs. actual time remaining to flashover" graph was produced for each test. The results for each of the three growth rate fires is seen in Figures 18, 19 and 20. Each graph shows the predicted time against the actual time in the last 60 seconds of the fire. To provide the fire service a 60 second warning of impending flashover was the stated goal of this research.

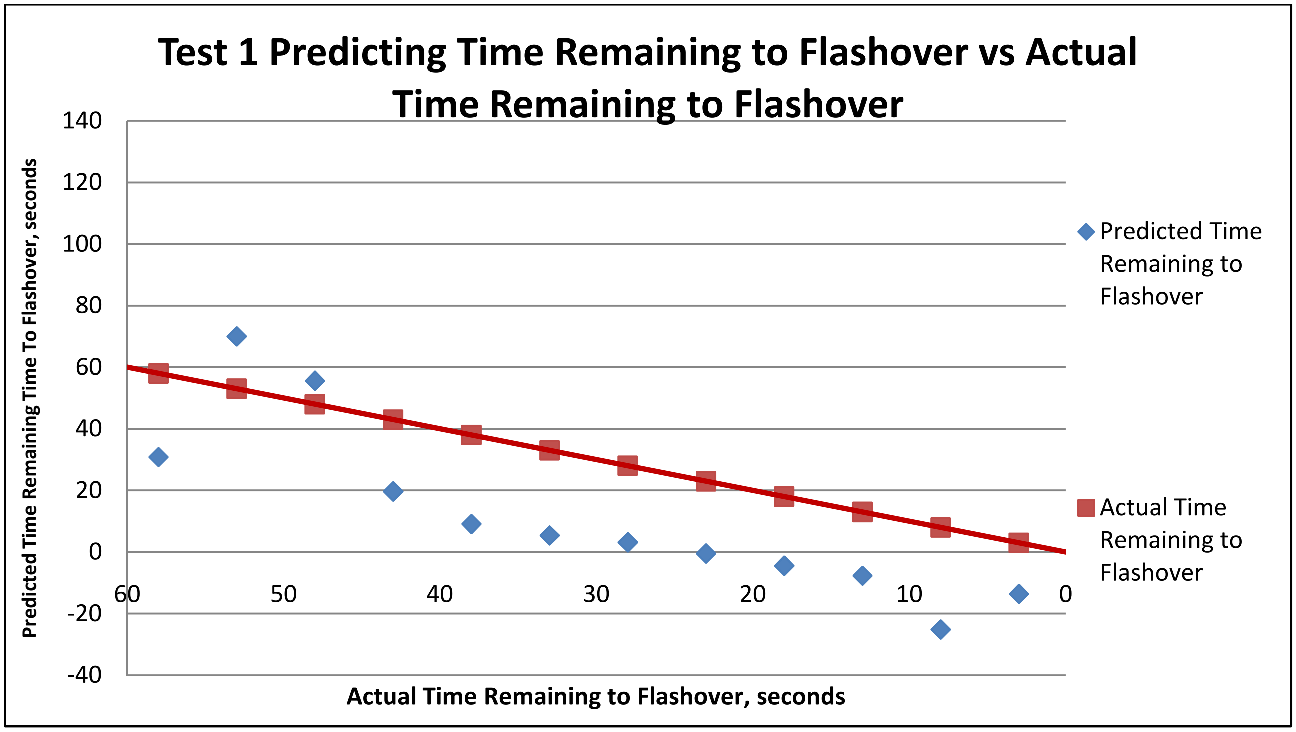

Figure 18 – Testing the algorithm using data collected from Fast Burn, Test 1.

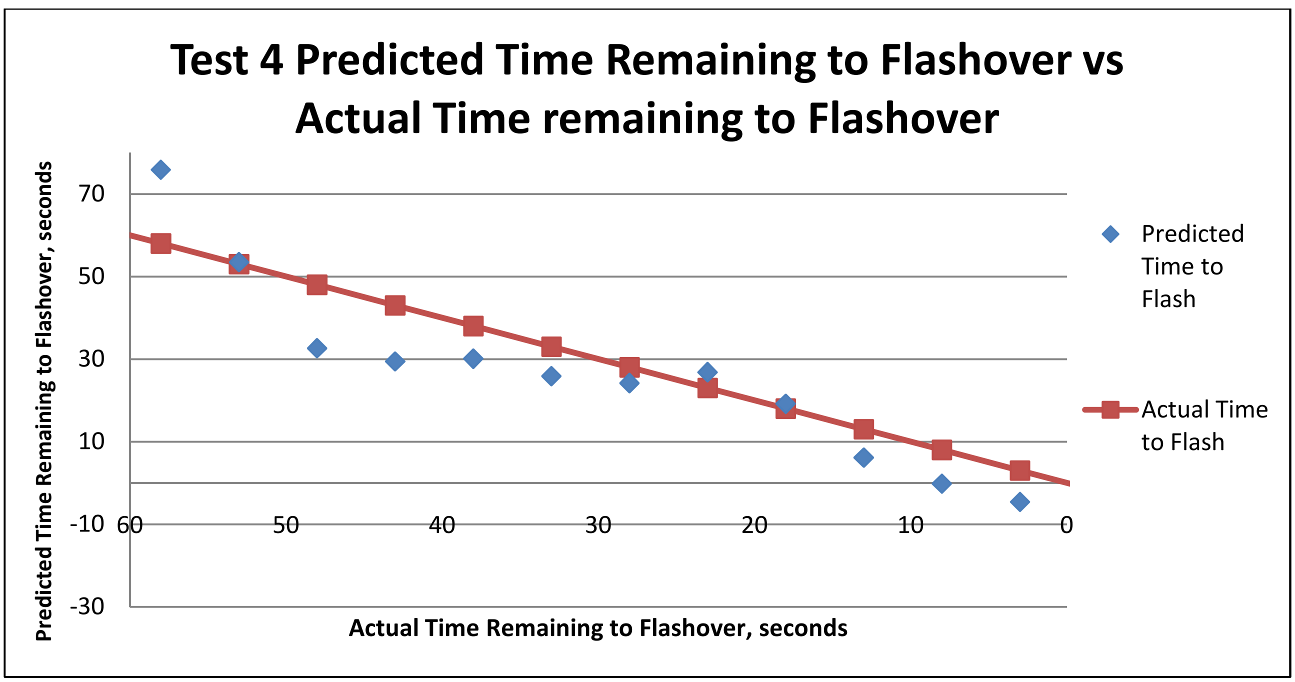

Figure 19– Testing the algorithm using data collected from Slow Burn, Test 4

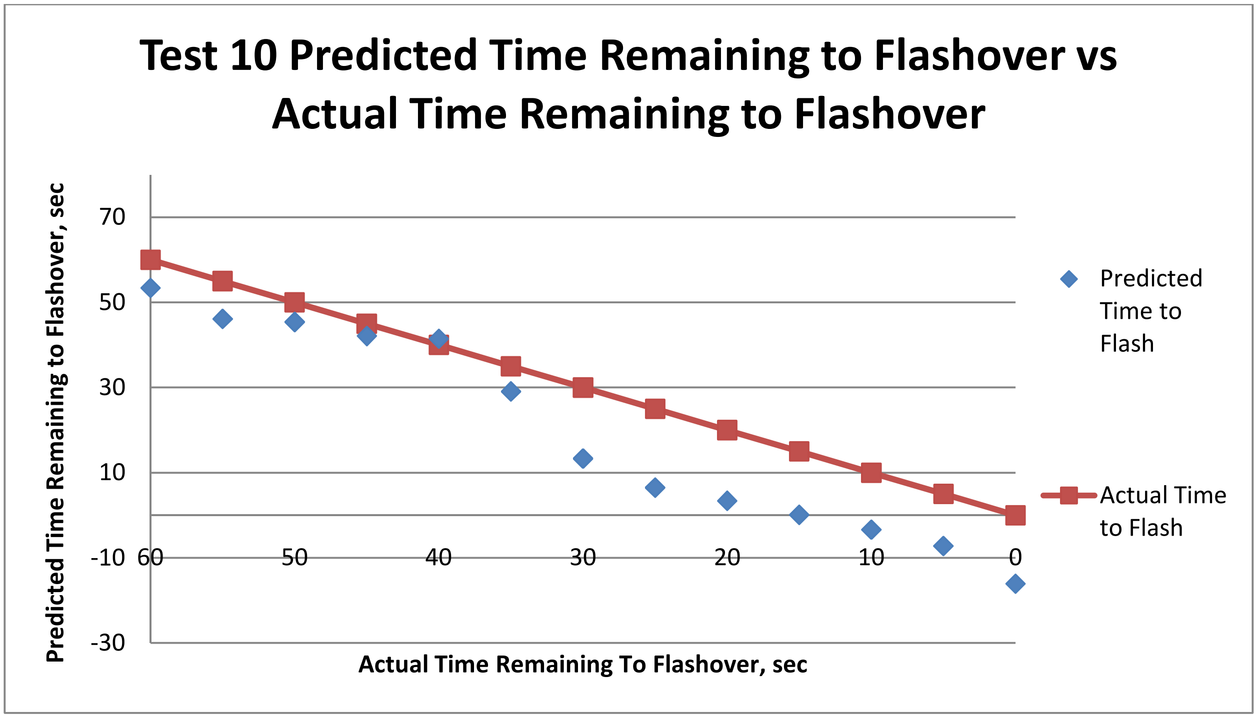

Figure 20 – Testing the algorithm using data collected from Fully Furnished Burn, Test 10

As seen in each of these graphs, the actual time to flashover is a linear function which intersects the x axis at the exact time to flash. The Predicted time to flash data points are the times the algorithm predicts that flashover will occur. Every five seconds, as dictated by the time stamp, the algorithm makes another prediction based on the inputs. For windows of time immediately before flashover the predicted time is very low, which is desirable. This translate to giving the sense that there is less time to flashover than true, which will force firefighters out of occupied space sooner, allowing a larger cushion of time.

To further understand the accuracy of the algorithm, the percent error at each location has been calculated. The formula for percent error used is:

$$\frac{(Predicted\ Time - Actual\ Time)}{Actual\ Time} * 100$$

This calculation will show how accurate the algorithm is as time increases. Negative percent errors show that the algorithm is predicting that flashover will happen sooner than it actually will.

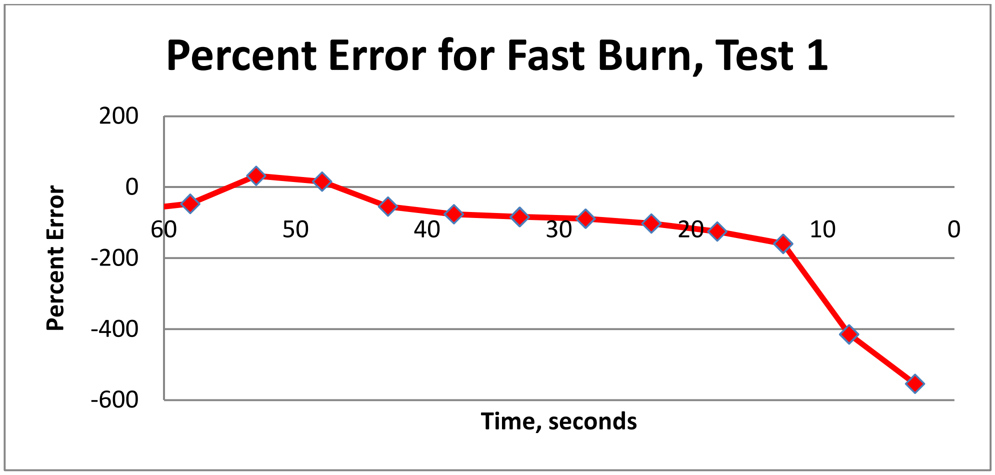

Figure 21 – Percent error calculated from the predicted time to flashover for fast burn, Test 1

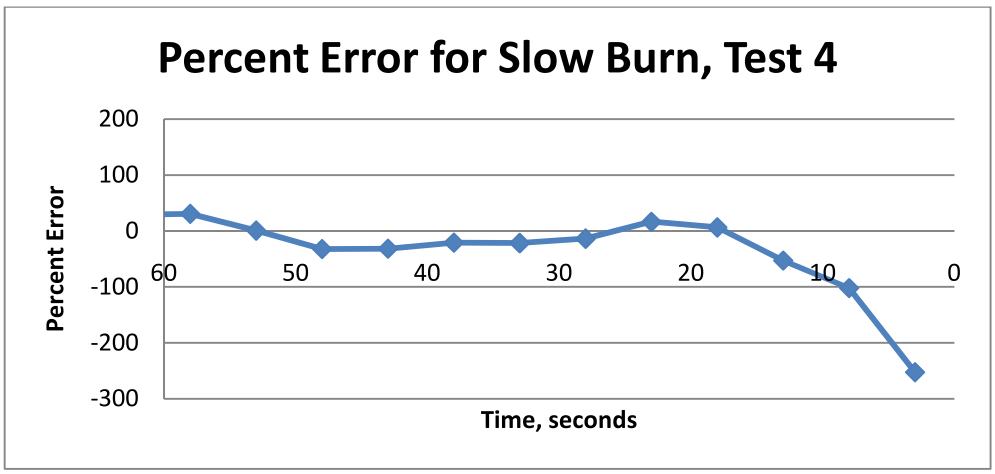

Figure 22– Percent error calculated from the predicted time to flashover for slow burn, Test 4

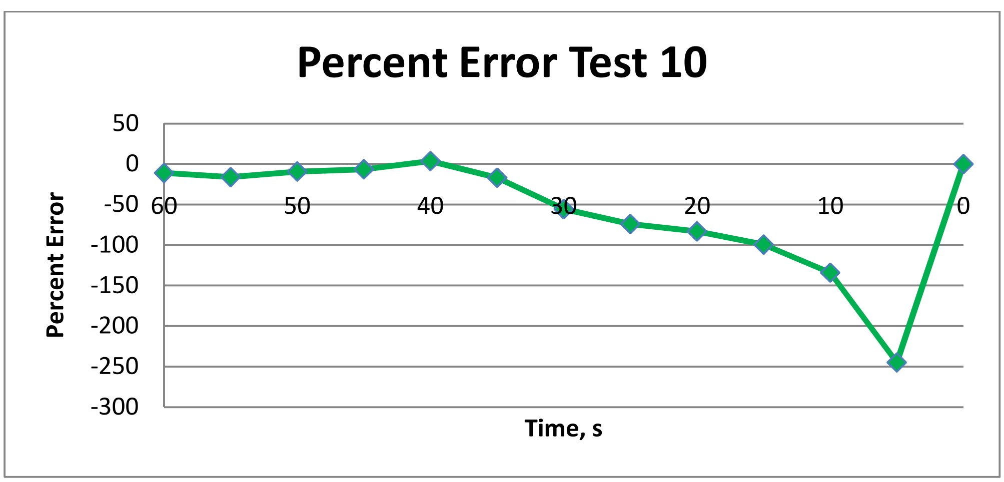

Figure 23– Percent error calculated from the predicted time to flashover for furnished burn, Test 10

As seen in each trial, and accented in Figure 24 each test is relatively accurate until the last 10 to 20 seconds. The accuracy of prediction of actual time remaining time to flashover is less important because it is past the decision time of the incident commander. Providing the commanding officer with a minimum one minute notice prior to flashover allows time for the commanding officer to think, make strategic decisions on the safety of firefighters, communicate this decision, and allow for time of egress of the firefighters.

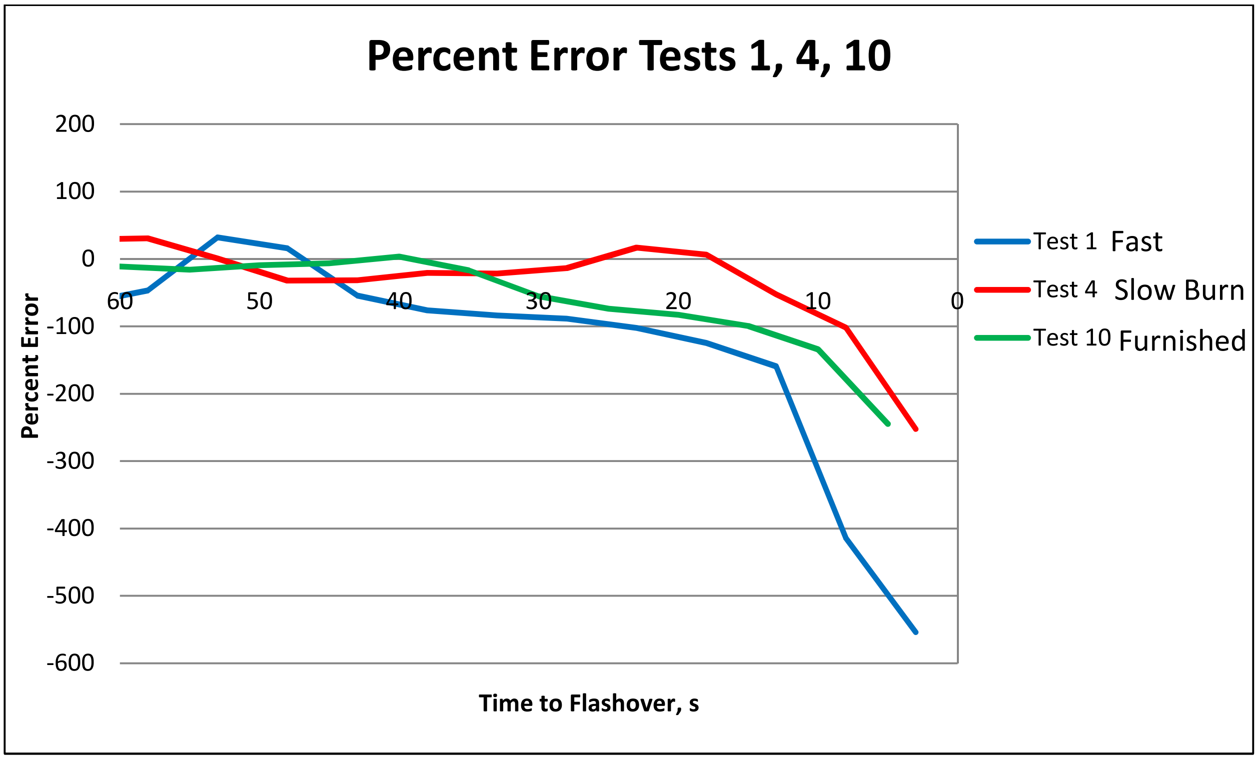

Figure 24 – Percent error calculated from the predicted time to flashover for tests 1, 4, and 10 graphed on a common axis to demonstrate similarities and trends shared by the algorithm's prediction abilities.

8 References

[1] B.J. McCaffrey, J.G. Quintierre and M.F. Harkleroad, Estimating room temperatures and the likelihood of flashover using fire test data correlations, *Fire Technology* **17** (1981), pp. 98–119

[2] Defining Flashover for Fire Hazard Calculations, Peackock, Reneke, Bukowski, and Babrauskas, Fire Safety Journal, Vol 32 (1999), pp. 331-345.

[3] Estimating Temperatures in Compartment Fires, Walton, W.D., and Thomas, P.H., Chapter Six, Section Three in The SFPE Handbook of Fire Protection Engineering, Third Edition, 2002.

[4] Fahy, Rita F. "U.S. Fire Service Fatalities in Structure Fires, 1997 - 2000." *NFPA* (2002).

[5] Fang, J.B., Measurement of the Behavior of Incidental Fires in a Compartment, NBSIR 75-679, (1975), National Bureau of Standards

[6] "Fire Dynamics Simulator (Version 5) User's Guide" National Institute of Standards and Measurements. http://www.fire.nist.gov/fds/documentation.html

[7] Grimwood, Paul, FLASHOVER – a firefighter's worst nightmare!, www.firetactics.com

[8] Hagglund, B., Jannson, R. Onnermark, B., Fire Development in Residential Rooms after Ignition from Nuclear Explosion, FOA C20016-DG (A3), Foresvarets Forskningsanstalt, Stockholm, (1974)

[9] J.N. Breese, J.B.Fang, Fire Development in Residential Basement Rooms. Interim Report., National Bureau of Standards, (Oct 1980) 97p.

[10] Lawson, R.J., Fire Fighter's Protective Clothing and Thermal Environments of Structural Fire Fighting, NISTIR 5804, U.S. Department of Commerce, August, 1996.

[11] Lee, B.T., and Breese, J.N, Submarine Compartment Fire Study-Fire Performance Evaluation of Hull Insulation, NBSIR 78-1548, (1978),National Bureau of Standards, Gaithersburg, Maryland.

[12] Moffat, Robert J. Notes on using thermocouples. www.electronics-cooling.com, 1997.

[13] Peacock, Richard D., Paul A. Reneke, Richard W. Bukowski, and Vytenis Babrauskas. "Defining Flashover for Fire Hazard Calculations." *Fire Safety Journal* 32.4 (1999): 331-45.

[14] Peacock, Richard D., Paul A. Reneke, Richard W. Bukowski, and Vytenis Babrauskas. "Defining Flashover for Fire Hazard Calculations: Part II." *Fire Safety Journal* 38 (2003): 613-622.

[15] Peacock, Richard D., Averill, Jason D., Kerber, Stephen, Madrzykowski, Daniel. “Report of Tests on the Burning Behavior of Wooden Pallets in a Compartment Enclosure”. The National Institute of Standards and Technology. March 2008

[16] Rangwala, Ali, Cecilia, Florit. Internship Report. http://users.wpi.edu/~rangwala/students/report/cecilia1.pdf, 2008.

[17] The Fire Brigades Union, In the Line of Duty, November 2008.

[18] Yuen, W. W., Han, S., and Chow, W. K., The Effect of Thermal Radiation on the Dynamics of Flashover in a Compartment Fire, JSME International Journal, Series B, Vol. 46, No. 4, 2003.

PART 2: Portable Flashover Estimation System and Evaluation

1. Engineering and Design of a mobile flashover predictor

The preceding development demonstrated the possibility of predicting the moment of flashover from measurement of temperature at the ceiling of a room containing an active fire. Conversion of this observation into a device that could enhance the situational awareness and safety of the firefighter would require finding means to make the necessary measurement from a self-contained, pocket sized unit which can be deployed with minimal interaction. In the course of this project five distinct means to accomplish this were evaluated. The first four were based upon the most direct application of the lessons learned from the instrumentation based tests and the notion that ceiling temperature is the fundamental quantity to be measured. The last involved a change in direction imparted in part by the difficulties encountered with the first four and in part from a growing understanding of the phenomenon and modeling of flashover engendered by the experimental outcomes and instrumentation based measurements made available by the various experiments that were undertaken in the course of this project.

This section begins with a short description of the first four sensor concepts, indicating in each case what the challenges and failures of the given approach were.

1.1. Portable self-extending thermocouple tree

The most direct way to measure the temperature at ceiling level is to elevate a thermocouple or other sensor to that level. Less obvious is how such a device can be made portable and deployable without the firefighter having to themselves reach through the hot gas layers to the ceiling or otherwise engage in a complex deployment maneuver. An approach to solving this deployment problem was conceived and prototyped by one of the partnering institutions in this project, QinetiQ North America (QNA).

Figure 25 shows early concept renderings of the sensor concept. In its portable "carrying" configuration, the device is small enough to fit into a firefighter's turnout gear pocket. Once placed on the floor and activated, a built-in motor uses capstan rollers to push a very thin metal strip out the top of the device. This strip is tempered in such a way as to curl on deployment and form a rigid, self-supporting hollow rod able to attain ceiling heights. A cable is attached to the top member of the deploying assembly to which is attached a series of thermocouples at 12 inch intervals. Before deployment this cable is coiled and lies in a deployment bay just below the cap which seals the unit and which acts as the top member of the deployment assembly. The thermocouple leads are connected within the box to an analog to digital conversion system driving an ISM band digital radio for transmission of all information back to the base station.

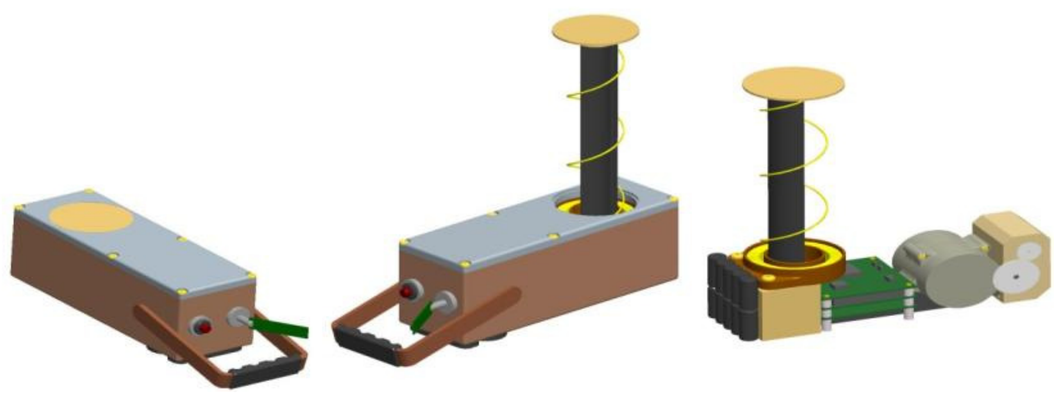

Figure 25: Early CAD renderings of the self-deploying thermocouple tree sensor in carrying configuration, deploying, and with case removed showing the thermocouple deployment bay, capstan and motor.

During development, experiments revealed that it was more favorable to orient the box so that the longest dimension is perpendicular to the floor so that a guidance fixture could be located sufficiently far from the capstan to obtain a fully rolled strip before it left the box as shown in

Figure 26. Figure 27 shows the resulting prototype of the device being tested in the large-scale burn test building.

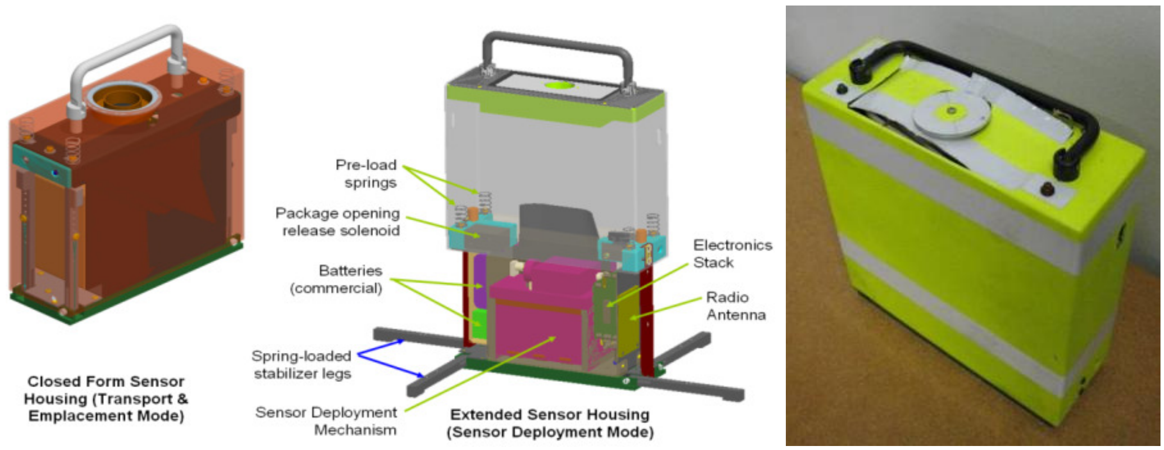

Figure 26: Final Design of the mobile thermocouple tree system.

Figure 27: Mobile thermocouple tree concept prototype shown in pre- and post-deployment.

Tests demonstrated that the tree was capable of capturing thermocouple data on par with that obtained with laboratory instrumentation and thus capable of application in a flashover detection scheme that followed directly from the experiments documented in the preceding section. However, the complexity and delicacy of the physical mechanism proved the undoing of this concept as it suffered from mechanical jamming on both deployment and resetting operations. While the device was used in many of the burn building tests, no data will be presented here as it was decided that mechanical problems remove this concept from immediate practical application as a flashover sensor technology.

1.2. Infra-red optical sensor

In anticipation of possible mechanical deployment problems with the self-extending thermocouple system, the original project proposal called for parallel development of a non-contact temperature or flux measurement system. The notion of a non-contact surface temperature measurement device using the infra-red (IR) emissions, due to the black body radiation of a hot object, is familiar in many applications having spawned commercially available industrial and home use products. However, special problems are introduced with respect to IR based temperature measurements on the fire ground. In a burning room, at floor level the IR emissions from the ceiling are partly shielded by the cooler smoke and soot (and other particulates) layers below the ceiling. Thus a measurement of apparent temperature will be considerably cooled from the true ceiling temperature – and not by a fixed amount, as it depends strongly on the depth of the smoke/particulate layers, their composition and their temperatures.

Some progress has been made in the industry towards obtaining improved IR temperature measurements in some smoky environments by using multispectral measurements. Employing several narrow band IR detectors with spectral sensitivity at IR frequency bands which pass through smoke with a variety of different attenuation factors, it may be possible to find a model for the deviation from direct surface measurements which can be solved for the desired temperature. Such a commercial device has been developed by the Williamson Corporation of Concord, MA. for use in industrial electric furnaces used to liquefy metals where the smoke is a result of impurities in the raw materials. The Williamson Corporation kindly assisted the project team by making one of their advanced devices available and providing application engineer support in applying it and analyzing the data. The multispectral IR sensor can be seen in Figure 28 being used during some of the burn chamber tests.

Figure 28: IR sensor concept test at WPI burn chamber.

Unfortunately tests demonstrated that fires based on burning of wood and other soot producing fuels generated smoke and particulate layers that varied widely from the conditions that would allow solution from multispectral IR measurements. In particular, it seems, the primary problem is that the wide distribution of particulate size yields no window of relative transparency in the IR spectrum. This approach was abandoned early on during the initial burn chamber tests.

1.4. Radiometric sensor

Another solution was explored also based on black body radiation from the hot ceiling. To overcome the problem of attenuation by particulate layers, one has to measure the black body radiation at wavelengths much larger than that of any particulate. Consultation with experimental data regarding fire particulates revealed that to achieve appropriately long wavelengths one has to reach down to frequency bands below 5 GHz and to measure the radio frequency noise generated by the hot surface. WPI designed, constructed and tested a “radiometric” sensor with a narrow reception band centered at 4 GHz which coincided with an FCC restriction of terrestrial emissions for the purpose of protecting certain satellite transmission channels and hence was free from man-made radio emissions which could have impeded radiometric estimation of the thermal noise from black body radiation.

Figure 29 shows both an early and a later prototype of the device. The earlier version demonstrated that a highly directional antenna was needed – otherwise the measured temperature was an average over all surfaces “seen” by the antenna, including the much cooler walls of the burn cavity. A custom high-directionality antenna was designed and deployed as seen in the later prototype’s picture to overcome this problem.

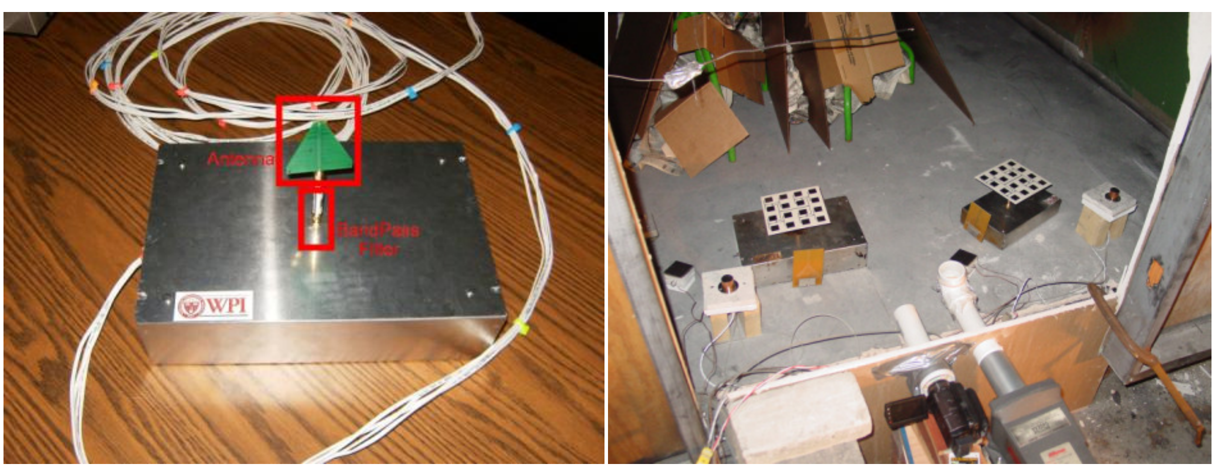

Figure 29: Radiometric thermal emission sensor. On the left an early prototype with low directionality antenna and wired connections to base station is shown. On the right, a later prototype of the sensor is shown with a highly directional array antenna and wireless data link.

Unfortunately, even with the highly directional antenna, the sensor was still found not to accurately describe the temperature at the ceiling, but rather produced greatly depressed values. Ultimately this proved to be caused by the fact that unlike in the case of IR emissions which originate entirely from the hot surface of a given material (such as the ceiling) the radio emissions from a sheetrock ceiling involve a weighted sum over material of several centimeters of depth. Since the outer wall of the building is cooled by air external to the burn cavity, the measured emissions comprise a weighted average of the temperature at the surface and those of much cooler layers. Furthermore, the exact composition of this weighted average will depend strongly on factors such as the thickness, moisture content and outside layer temperature of the ceiling material. Because of these factors, this approach was abandoned after the burn chamber tests and testing in the concrete burn structure.

1.5. Sentinel temperature sensor

Before describing the last concept explored, which was the subject of the tests conducted in the large-scale burn chamber, we will develop some additional background information essential to understanding the underlying theory for this sensor. This will begin in the next section with a treatment of the physics of flashover at a more mesoscopic level than previously undertaken.

2. The physics of flashover

Flashover is usually characterized as the event in which sudden ignition is experienced by most of the combustible materials in the fire compartment. The underlying cause of flashover is the intense thermal radiation emanating directly from the seat of a fire, any subsequently burning materials in the upper zone (hot gas layer) of a fire and radiative or convective heating of the ceiling of a compartment giving rise to further thermal radiation. This intense radiation field nearly uniformly baths materials throughout a compartment including material in the lower (cool gas) zone. The events that follow are well described by the following[1]:

Thus initially unignited objects begin to pyrolyze and eventually to burn. Since all unignited objects heat at about the same rate, all ignite at about the same time and produce an often rapid increase in the rate of gas production, a rapid growth in flame size, and a rapid growth in the fire. Thus occurs what the firefighter calls a "flashover," an ill-defined but sometimes spectacular growth from a "fire in a room" to "full room involvement."

While this description conveys a broad sense of the physics that underlies the sudden beginning of a rapid progression to full room involvement, several of the named factors are somewhat more tenuously connected with the actual physics of the situation in nature than characterized above. Consider for example:

1. All unignited objects in a compartment fire will not heat at quite the same rate. The rate of heating will be determined by such factors as:
    a. Amount of thermal flux illuminating the object's surface as determined by the orientation of object surface normals to the primary radiating surfaces (currently burning fuel, hot ceiling, etc.)
    b. The angular subtend of each thermal radiation source and its associated radiation flux density as a function of wavelength (which depends on its temperature and its grey-body emissivity function)
    c. The flux absorption coefficient of the material surface as a function of wavelength.
    d. The initial temperature of the object, its internal thermal transfer, thermal mass characteristics and moisture content.

e. The temperature of the air and other gases immediately surrounding the object which depend upon position within the compartment and which may either heat or cool the surface.
f. The wavelength dependent radiation attenuation of the particulate content of the surrounding gases an airborne particulates
g. The gas velocity near the object surface (as determined by compartment configuration, air sources, etc.) and the surface texture characteristics which together determine convective heat transfer.

2. All unignited objects at the same temperature do not ignite at the same time owing to such factors as:
   a. The role of external energy (spark, ember, etc.) initiated ignition versus true auto-ignition and the environmental conditions leading to either.
   b. Significant variations across materials of the flash-point or piloted ignition temperature (external energy triggered ignition) and auto-ignition (kindling point) temperatures. For example[2], the flashover temperature of paper is approximately 233 C while that of wood is between 380 and 500 C.

While the factors listed above will greatly affect the micro-analysis necessary to engineer a sensor that can predict the time to flashover, they do not function in diminish the apparent synchronicity of flashover to a significant extent on the fireground. That is, while the above factors seem to imply a prolonged sequence of ignition events, the fact is that flashover does in most cases occupy a very small time interval as described by observation. An understanding of how this comes to pass will also lead to the concept for how consistent prediction of onset may be obtained.

The rapidity of flashover can be attributed to the fact that as each material ignites, it changes the fire environment and promotes ignition of other materials whose time of ignition might have previously been substantially later. As each material body is triggered to ignite, it adds additional radiation flux to the environment of other materials in its line-of-sight, and is a local generator of flames and embers that might trigger a nearby object which has reached its piloted ignition temperature. This progression is thus a higher level and more granular (owing to the participation of different materials with various spacings) parallel of the process of fire spread along a single material surface. In effect, the events that comprise flashover amount to a chain reaction whose onset is due to the material with the smallest auto-ignition temperature.

3. Sentinel based flashover onset prediction

Since the chain-reaction, once initiated, will rapidly progress into the full compartment involvement which constitutes the firefighter's notion of flashover, the predictive sensor would best seek to detect the imminent ignition of the material that will ignite first. With regard to detecting the onset of imminent flashover, and predicting it, this approach eliminates the sensitivity of the model to variation of parameters across various materials and the ignition temperature factors listed under list (2) in the previous section. What appears to be a particularly good "sentinel" material on which to base the prediction of the onset of flashover would be paper (newsprint, book or printer paper) owing to its low flash (233 °C) and auto-ignition (290 °C) temperatures and its prevalence in the typical home and office setting. Notably, the flash and auto-ignition temperature of paper is near and or less than the auto-ignition temperatures of common accelerants such as gasoline (280 °C) , kerosene (295 °C) and butane (420 °C).

However, the factors listed under list (1) in the previous section would appear to still make the task of predicting the ignition time of a single material formidable. Typically, the time of flashover onset has been correlated with two environmental thermal measures[3]:

"Experimentally, studies on flashover were reported both in actual fires and in full-scale burning tests. Two quantitative criteria were consistently observed as conditions for onset of flashover. They are:

a. upper gas layer temperature exceeds 600 °C

b. heat flux at the floor exceeds 20 kW/m^2"

However, a consideration of the factors in list (1) in the previous section discourages the notion that such general measures can capture at a fine level of detail the timing of auto-ignition. For example, as described here:

Results show that the hot layer temperature alone may not be an effective indicator for flashover. Other parameters such as particulate volume fraction in the hot layer, venting area and heat transfer to the surrounding wall are also important in determining the occurrence of flashover. [3]

That such global measures such as ceiling temperature and floor level heat flux do not capture the necessary various factors has been borne out by many other tests that have been conducted and appear in the literature [4-7].

On being confronted by the complex of factors involved, one recourse would be to independently measure and account for each of the factors: radiant flux density as a function of angle and temperature, immediate air temperature, air velocity, paper absorption coefficients as a function of wavelength, etc. However, a much simpler choice would be to simply use a sample of paper as the sensor, as it incorporates by its nature all pertinent thermal input, dissipation and response mechanisms at the physical level. This is in-line with and supports the wisdom of the common practice of firefighters who place a paper ball on the floor of a compartment to observe the moment at which it ignites so as to pinpoint the moment of flashover.

Since the aim here is to predict the onset of flashover well prior (by tens of seconds) to the actual event, however, we cannot simply watch for paper ignition. Rather we must monitor the temperature of the paper itself and use its integration of all relevant thermal factors and inputs to obtain a leading indicator of actualization of the auto-ignition temperature.

4. Measuring the temperature of a paper sentinel

To achieve the goal of measuring of temperature of a paper sample so that its native thermal characteristics lead to a reliable indicator of progress towards auto-ignition, one must measure its temperature without affecting its thermal characteristics. Such a measurement could be achieved by either by a non-contact sensor, or by a contact sensor.

A non-contact strategy would appear favorable as it would introduce no thermal mass or other disturbances to the system. Non-contact temperature measurement by infrared radiation sensing is a well established and commercially applied technology. On investigation for application in this project, involving some laboratory trials, demonstrated some significant problems with this form of measurement. First, the infrared radiation emissivity coefficient of paper is not unity, leading to an under estimate of temperature; and the value of emissivity changes as the material pyrolyses, hence a simple calibration cannot be applied to obtain true surface temperature. Likewise, the reflection coefficient of the surface is not zero, and the measured value is biased by some fraction of the environmental radiation flux leading to over estimation error. Finally, smoke and soot (or steam and smoke from the sample) that intrudes on the space between the sample and the sensor introduces an unknown attenuation and leading to an under estimation error.

A contact measurement scheme must use a sensor which has an exceedingly small thermal mass and low profile so as to not mask the sample from the impinging radiation. Fortunately, temperature sensors which can operate at the necessary temperatures and possess the low mass and profile needed have been developed and are commercially available. The sensor created for this project was based on a commercial K-type thermocouple constructed from a thin (0.0005") foil of

CHROMEGA® and ALOMEGA® alloys elements attached to a polymer/glass laminate which can withstand temperatures of 370 °C for up to 10 hours of exposure. This sensor had a response time of 10-20 ms. The sensor was connected to a “cold junction compensation” circuit which yielded readings commensurate with an ice point reference system without the need for a reference bath. The cold junction compensation circuit used here could operate over a temperature range of 0 to 50 °C which exceeded requirements for the range of temperatures that arose inside the boxed sensor unit from the time of compartment fire ignition until flashover and extinguishment. Typically, for the finished prototype, the internal sensor container temperature reached 30 °C during the critical time interval leading up to the flashover event and reach a maximum of 43 °C only well after the fire was extinguished as the heat propagated slowly through the internal thermal insulation of the boxed unit.

To obtain proof-of-concept data and to allow rapid experimentation with various means of fixturing of the sentinel sample and application of the thin-foil sensor, a multi-sensor unit was constructed as shown in Fig. 1. On the surface of this box, three sensors with at times different and other times same thermocouple-sample coupling strategies were closely co-located. This allowed examination in live-fire tests of the consistency of values obtained by similar sensors for identical conditions and to evaluate the effects of different coupling approaches. The box, though larger than appropriate for carriage by a firefighter in the course of typical firefighting activities, was fully portable. The complete system had dimensions of 22 cm (L) x 14.5 cm (W) x 12.75 cm (H) and a weight of 1422 g.

The unit employed three commercial ISM band wireless transmitters that provided a temperature update once every two seconds for each sensor and a commercial multichannel receiver at the base station to capture data. During initial tests this sample update rate was found inadequate to provided sufficient predictive capability in a rapidly accelerating fire; this issue was addressed in the next build.

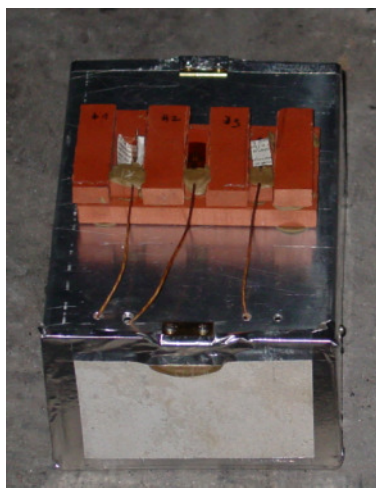

Figure 30: Initial, three sensor research build of the flashover prediction system.

Figure 31: Example of burn chamber testing of the three sensor unit. Paper balls can be seen placed near the sensor as well as the observation camera mounted at floor level which was used to obtain timing information related to paper ball ignition.

To create a portable device that could be easily carried in a turn-out gear pocket and left on the fireground by the firefighter, it was necessary to integrate a wireless transmitter with the sensor. A custom 915 MHz ISM band data transmitter was integrated into the unit with a patch antenna situated inside the containing box. This transmitter, which was capable of higher data rates than the one in the three-sensor system, was set to provide 20 temperature update transmissions per second.

The container comprised an aluminum box with a ceramic cover. The ceramic cover acted both as part of the fixturing of the paper sample and thermocouple system, and as a radio-transparent window below which the patch antenna was mounted. The overall size of the system was 13.3cm (L) x 7.5 cm (W) x 7.5 cm (H) with a weight of 500 g.

The finished pocket-portable prototype unit, which saw service in four of the test fires can be seen in Fig. 3 below. Raw temperature data samples were sent from this sensor to a data collection, processing, display and storage computer at the command post. The sensor in deployment is seen in Fig. 4.

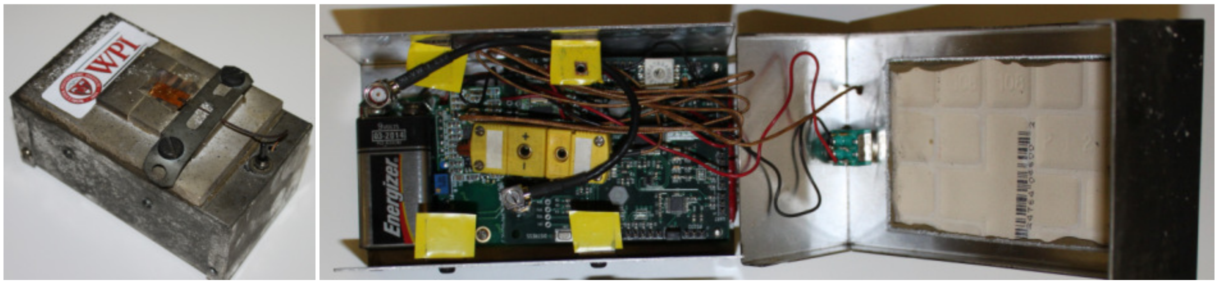

Figure 32: Complete wireless sensor for flashover prediction (patch antenna removed in right image for better internal view).

Figure 33: Pocket-portable sensor placed in view of camera port and paper balls on floor of the burn room constructed for tests at the Stow Firefighting Academy facility.

5. Model based time of ignition estimation

To obtain an estimate of the time until flashover and autoignition temperatures were to be reached, a model based curve fit to the stream must be undertaken. In effect, one must chose a parameterized model for the time function which describes the progression of sentinel temperature that precedes ignition. This parameterized model may be either be derived from the physics of fundamental processes underlying the phenomenon, or by empirical fit to observations from a wide variety of a experimental outcomes. A combination of these approaches were used in determining our model.

A simple analytic model may be obtained by assuming that all heating at floor level far from the seat of the fire is due to thermal radiation from the source re-radiated by the ceiling and smoke layer below the ceiling. Given a very low mass, thin sentinel, the equilibrium temperature of the sentinel is approximately linearly proportional to the thermal radiation exposure over the range of temperatures of concern near ignition temperature (about a 100 K temperature range). Under the assumption of a constant heat release rate per area of fire-involved source, the total thermal radiation is simply proportional to the area of involvement. Thus the rate of thermal radiation growth is fundamentally determined by a flame spread model.

A widely accepted model for flame spread with its roots in the early work by Fons and further elaborated by McAlevy et al. (see reference 8 for essential background) says that in quasi-steady state (source fire established but growing by spreading) the rate of propagation of the fire front is constant. Assuming a deep fuel bed, such that all area of the fuel bed once involved remains involved, this leads to a linear growth of heat release for a linear bed. But a two dimensional fuel bed with give rise in general to a circular (elliptical in the case of air current driven fires) front[9]. Under the same assumption of a deep fuel bed this gives rise to a quadratic growth rate until fuel bed boundaries are reached by the front that allow only linear growth of heat release or a fix rate of release when all boundaries have been reached. If a fuel source is entirely contained within a fixed area and is itself confined to a leaky cavity then upon the fire spread reaching the areal limits of the fuel, growth of cavity ceiling temperature will continue grow at approximately a linear rate (though with a lesser slope) owing to thermal pumping the cavity, until some equilibrium temperature is reached owing to the leakage. This last phenomenon leads again to a period of linear growth in thermal radiation followed by a period of constant radiation output.

Under the above assumptions it can be seen that the progression of thermal radiation at a sentinel may be found to vary from square law, to linear to constant in time. Hence, a general mathematical model for thermal radiation progression, and hence the sentinel temperature according to the assumptions made above, should take the form of a general quadratic with slowly time varying coefficients: $a\ t^2 + b\ t + c$, with the second degree and first degree coefficients possibly being driven to zero as appropriate.

Several mathematical models including linear, exponential and quadratic were evaluated during burn chamber tests of early versions of the sensor and it was determined that the best model fit was indeed obtained with a quadratic model as indicated would be appropriate by the simplified analytic model.

Using the sensor described above, values of the paper sentinel surface temperature were captured at a rate of 20 samples/sec. and subjected to the quadratic fit described above over a moving window of 150 seconds duration. The resulting quadratic fit polynomial was set equal to each of two target temperature values, the flashover temperature and the autoignition temperature (as described above), and solved for its roots. The maximum root of each was chosen as the estimated time for the associated events.

6. Large-Scale Burn Tests in Stand-Alone Facility

As is shown in Figure 34, the flashover sensor was placed on the floor of the standalone building. The location of the sensor was chosen to be at the same distance from the source of the fire as the thermocouple tree and the last paper ball. The sensor design was finalized and ready to deploy for participation in the large-scale burns beginning on the morning of July 15, 2010. The new sensor (initially the 3 sensor prototype and later the smaller single sensor unit) then participated in each subsequent burn for a total of 8 tests.

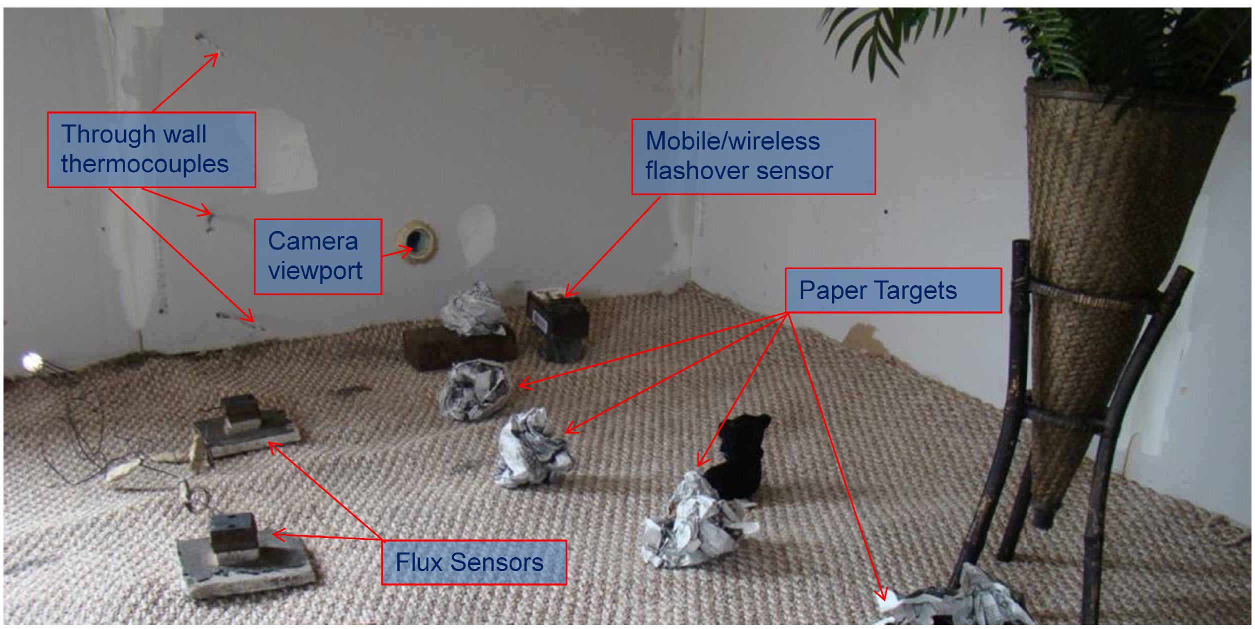

Figure 34: Location of various sensors and paper ball targets in the burn room during Test 10.

In Figure 35 through Figure 37 we show the outcomes for Fast (Test 7) Slow (Test 4) and Furnished Room (Test 10) tests corresponding to the tests reviewed in detail in the preceding section treating the thermocouple tree results. Note: Test 1, which was the subject of the previous treatment took place before the construction of the mobile sensor and hence has been replaced by the similarly fast Test 7.

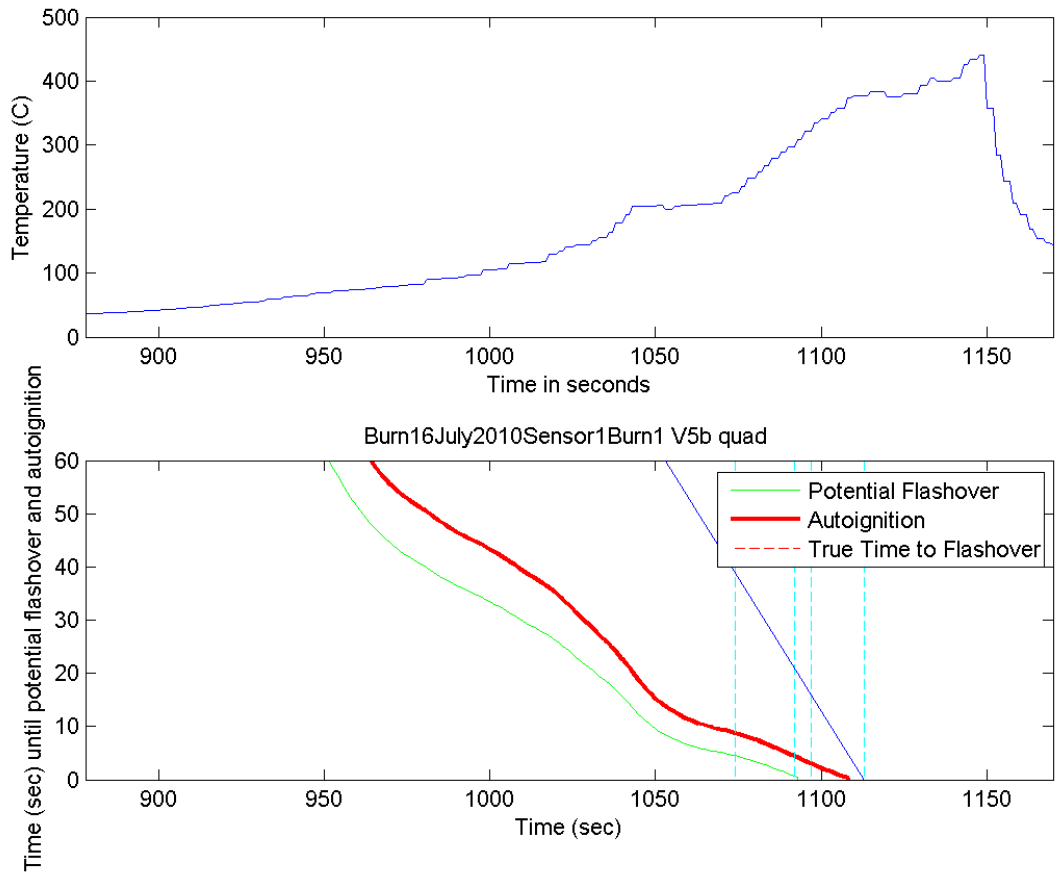

Figure 35: Mobile flashover results for fast burn, Test 7.

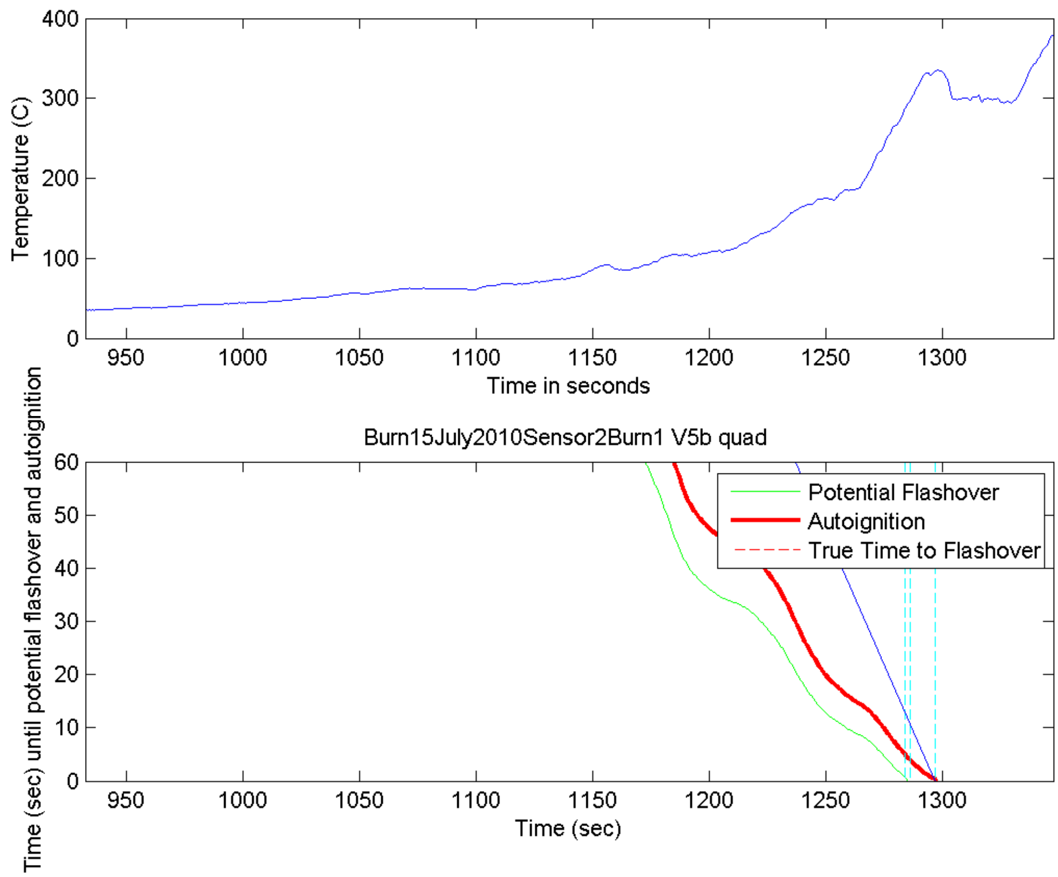

Figure 36: Mobile sensor results for slow burn, Test 4.

Each of figures present in the topmost graph the temperature measured on the sentinel paper target by the mobile sensor and in the bottommost graph:

a) the estimated time remaining to flashover temperature of the sentinel (green curve);

b) the estimated time remaining to autoignition (red curve);

c) vertical cyan lines in the bottom graph indicate the visually observed times of ignition of each of the paper balls in the structure. The last cyan line in each case indicates the ignition of the ball nearest to (i.e. collocated with) the mobile sensor;

d) a slanted blue line shows the true time remaining until the collocated paper target autoignites.

In each case shown we see the final estimated time of autoignition falls quite close to the time of ignition of the nearest paper ball (and in the cases shown here, it happens to fall between the time of ignition of the last paper ball target and the ball that immediately preceded it.)

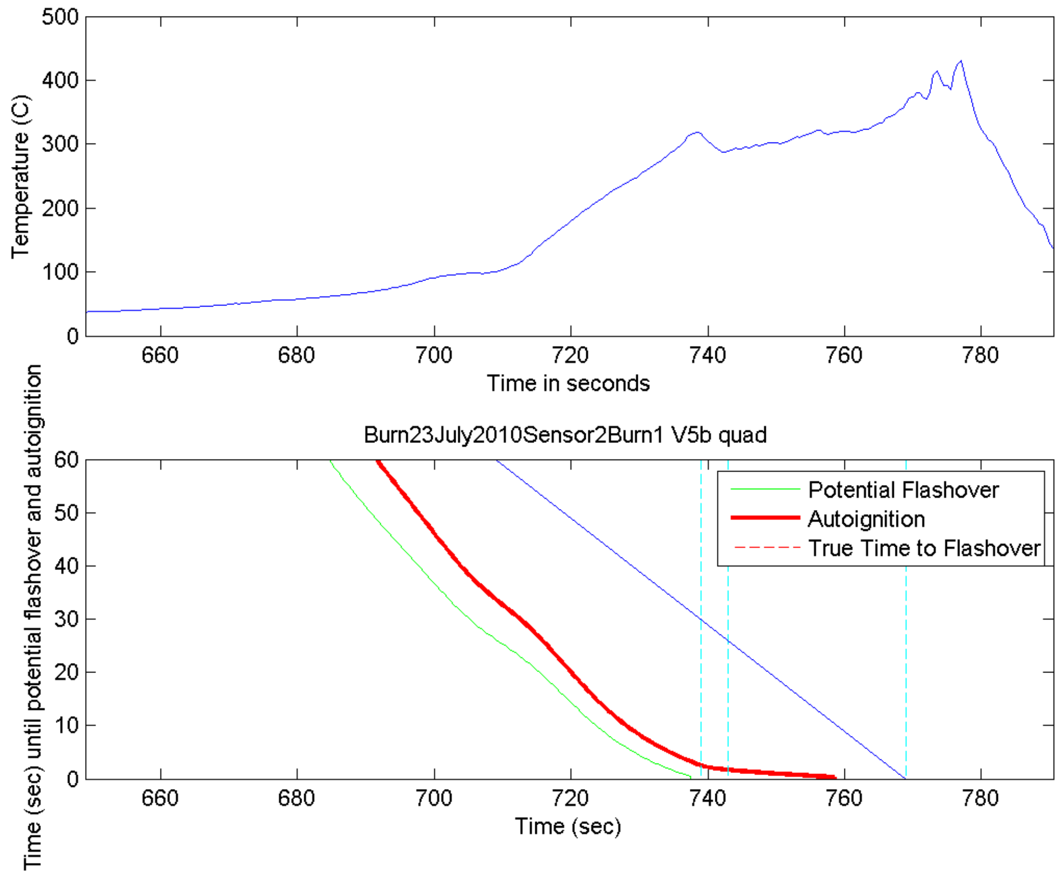

Figure 37: Mobile sensor results for furnished room burn, Test 10.

The most important measure of operational capability is a test of whether the system provides sufficient warning to the firefighter to escape from the threatened area. Table 6 summarizes the following information:

a) The time since start of burn until the paper target collocated with the sensor ignites;

b) the time at which a sixty second warning is issued by the sensor;

c) the time difference between the sixty second warning and the point in time sixty seconds before the ignition of the paper target closest to the source and farthest from sensor;

d) the time difference between the sixty second warning and the point in time sixty seconds before the ignition of the paper target collocated with the sensor.

Examination of the last column of the table reveals that the sensor substantially fulfills the role of a device that provides an appropriate warning of impending flashover in so much as ignition of the collocated target occurred after at no less than 53.5 seconds after the sixty second warning.

The greatest prematurity of the sixty second warning took place in Test 7 in which the sixty second warning was given two minutes prematurely. However, this fact must be interpreted in context of the environments and events that make up the flashover scenario. Consider the information in the fourth column where the difference between the issued warning time and a true sixty second warning preceding the ignition of the paper target farthest from the sensor and nearest the source of the fire. Here we see that the warning from the sensor can be interpreted as only 5 seconds premature and as late as 14.5 seconds (leaving 45 seconds for escape.) To justify this last observation as relevant, one must examine why a comparison of the sensor's estimated warning time to the time of a target ignition of a non-collocated target has practical significance. Such a discussion follows.

Table 6: Times from start of burn of collocated target ignition, the sensor derived sixty second warning and measures of the error corresponding to the warning as determined by the first (farthest) paper target and the colocated target (negative values indicate a premature warning).

Test number	Colocated target ignition time	Sixty second warning time	Leading target ignition prediction error	Colocated target ignition prediction error
3	1297	1185	-39	-52
4	784	671	-25	-53
5	1113	964	-50	-89
6	752	605	-65	-87
7	1276	1101	-5	-115
8	637	583.5	14.5	6.5
9	769	692	13	-17
10	769	690	11	-19

Consider again the combined notions of the fire spreading model and the chain reaction ignition model as the basis for the thermal progression experienced by a target undergoing primarily radiation induced heating. A constant coefficient quadratic rise in target temperature depends upon a sufficiently thick and spatially continuous two-dimensional bed of fuel with a fixed flashover temperature. But the structure of the immediate fire ground is almost certainly less homogeneous, involving multiple fuel beds; e.g. the wood cribs or couch found at one corner of the burn room in the current tests and the islands of other smaller fuel sources such as the paper targets, and the minor furnishing elements that dot the room in those same tests.

As a result of the discontinuous distribution of fuel noted above, the target temperatures may vary from quadratic in nature, during two-dimensional spread across the area of a prominent fuel source, followed by linear growth when the fire spread has reached the limits of the prominent fuel source edges and growth is driven by either linear spread or by thermal pumping of the cavity with heat input. This behavior is particularly clear in Figure 37 where an initially quadratic rise in sentinel temperature transitions to a linear growth between 715 and 736 seconds during which thermal pumping continues to raise the room temperature until the other fuel sources begin to flash over. But because the targets are very small and well separated, the growth returns to linear, as between 740 and 765 seconds. The paper targets are in fact so small, as to not substantially affect the linearity of this growth period despite sequential ignition.

The above model begs the question: what if there had been a more substantial low ignition temperature fuel source at the location of the first paper target? Such a fuel source would have ignited at the same time as that target, but once ignited would have substantially increased the local thermal radiation profile, speeding the progression of subsequent nearby fuel source ignitions in the usual chain reaction fashion. Hence, under slightly different circumstances, the ignition of non-collocated targets can be associated with nearly coincident ignition of a target at the position of the sensor without the benefit of a tell-tale, constant model, sensor temperature progression from which the exact point of autoignition could have been predicted.

From the preceding discussion one sees that the prematurity of the warning given by the sensor as described by the last column of Table 6 must be judged in light of the preceding column that evaluates the sensors warning in relation to what might have happened had a low ignition temperature fuel source been present within a radius of several feet of the sensor.

7. Integration of Location, Physiological and Environment Information

While not a focus of this report, it is noteworthy that another aspect of this project involved integration of the flashover prediction system with a system for firefighter location and physiological monitoring. Figure 38 shows the “mission control” area sited approximately 50 ft. from the burn building erected for these tests at which the real time environmental, physiological and location information was displayed and recorded.

Figure 38: Mission control for the large scale burn tests at the Massachusetts Firefighting Academy in Stow Massachusetts.

Figure 39 shows a demonstration based upon simulated data of the integrated display that was designed and implemented in support of this project. On the left hand side of the screen each firefighter on the fire ground is represented with associated physiological information. In the center of the display a depiction of the floor plan of a building is shown (when available) as well as icons that represent the position of each firefighter and each environmental sensor which has been placed by a firefighter. Each icon contains abbreviated information about the firefighter or in the case of the environmental monitors, the predicted time remaining until flashover. The left had side inset depicts the elevation of each firefighter or monitor.

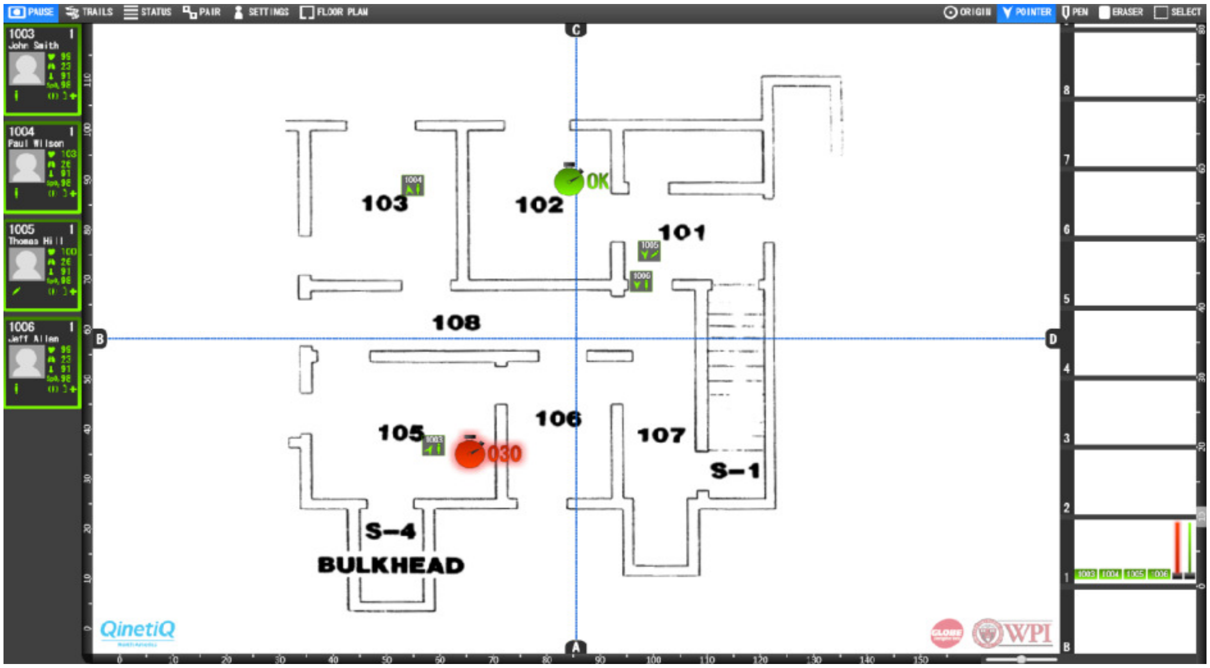

Figure 39: Demonstration of the integrated display designed for this project using simulated information portraying the position and physiological information for several firefighters and of the status of two environment monitors.

Figure 40 shows the actual screens displayed during Test 10 in which the furnished building fire took place. On the left we see an icon representing the single firefighter who has entered the building just after having planted the environmental monitor. The monitor is green indicating conditions at that moment are far from supporting flashover. On the right, minutes later, the firefighter is outside the building, while the monitor's icon is red indicating less than 60 seconds to flashover and a numerical value of 59 seconds gives the current prediction of time remaining until that event.

Figure 40: Screen captures from the integrated display obtained during a burn building test. On left, firefighter inside building has just deposited mobile flashover sensor. On right, the firefighter stands outside the building and flashover warning is indicated.

8. Conclusion

On the basis of theoretical models and experimental outcomes a new sensor concept has been developed, prototyped and tested in large-scale compartment fires. The new concept, based on measurement of the conditions at a low ignition temperature sentinel has been demonstrated as a having excellent potential as a means to obtain an early warning of impending flashover in a compartment fire. A forewarning of approximately 60 seconds was, within the context of these tests, obtainable with good reliability and with variation within acceptable limits wherein the intent is to provide sufficient time to exit the compartment.

The system was successfully integrated with an existing system developed under a previous AFG grant allowing a real time concurrent display of each firefighter's location, physiological information and current fireground environmental condition (flashover prediction). The entire integrated system was demonstrated in a series of tests conducted at the Massachusetts Firefighting Academy.

9 References

[1] "Scientific Progress on fire," Howard W. Emmons, Ann Rev. Fluid Mech. 1980. 12: 223-36.

[2] "Ignition of Wood: A Review of the State of the Art," Babrauskas, V., pp. 71-88, *Interflam 2001*, Interscience Communications Ltd., London (2001).

[3] "The Effect of Thermal Radiation on the Dynamics of Flashover in a Compartment Fire," Walter Wah Yuen, Shousuo Han and Wan Kit Chow, JSME International Journal, Series B, Vol. 46, No. 4, 2003, pp. 528-538.

[4] "Ignitability analysis using the cone calorimeter and lift apparatus," Mark A. Dietenberger, Proc. of the international conference on fire safety, Vol. 22, July 1996, pp. 189-197.

[5] "Flammability characteristics at heat flux levels up to 200 kW/m^2 and the effect of oxygen on flame heat flux," Patricia A. Beaulieu, Ph.D. Dissertation, Fire Protection Engineering, WPI, October 2005.

[6] "The influence of different external heating ways on pyrolysis and spontaneous ignition of some woods," Yang Lizhong, Guo Zaifu, Zhou Yupeng, Fan Weicheng, J. Anal. Appl. Pyrolysis, Vol. 78, 2007, pp.40-45.

[7] Ignition of Cellulosic Paper at Low Radiant Fluxes, K. Alan White, NASA Technical Memorandum 107311, Lewis Research Center, Cleveland, Ohio, August 1996, National Aeronautics and Space Administration.

[8] "A mathematical model for predicting fire spread in wildland fuels", Richard C. Rothermel, USDA Forest Service, Research Paper INT-115, January 1972.

[9]. "An elliptical growth model of forest fire fronts and its numerical solution," G. D. Richards, International Journal for Numerical Methods in Engineering, Volume 30, Issue 6, pages 1163–1179, 20 October 1990.