NIST Technical Note 1709

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Sponsored in part by
Department of Homeland Security
Federal Emergency Management Agency
United States Fire Administration

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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July 2011

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National Institute of Standards and Technology Technical Note 1709
Natl. Inst. Stand. Technol. Tech. Note 1709, 80 Pages (July 2011)
CODEN: NTNOEF

Abstract

Four real-scale experiments were conducted by the National Institute of Standards and Technology to measure the temperatures above and below a wood floor assembly exposed to fire conditions from below. The objectives of the experiments were: 1) to examine the heat transfer through a wood floor assembly and 2) to examine the ability of a thermal imager to determine the potential severity of the fire beneath the floor assembly and the ability to provide a sense of the structural integrity of the floor assembly in order to provide improved situational awareness.

Each experiment was conducted in a wood framed two story structure. Each story consisted of a single compartment with interior dimensions of approximately 4.7 m (15.3 ft) x 4.8 m (15.9 ft) x 2.4 m (8.0 ft) high. The initial fuel in each experiment consisted of six wood pallets and hay in the center of the lower level compartment. Three different floor assemblies were used in the experiments: 18.3 mm (0.72 in) thick oriented strand board (OSB) supported by engineered wood I-joists, 18.3 mm (0.72 in) thick OSB supported by solid wood joists, and 18.3 mm (0.72 in) thick OSB supported by engineered wood I-joists with 12.7 mm (0.50 in) thick gypsum board attached to the bottom face of the joists.

Gas temperatures of the upper and lower compartments as well as the surface temperatures of the floor assembly were measured with thermocouples (TCs). Three commercially available thermal imagers (TIs), each with a different type of sensor were used to view and record the thermal conditions of the top of the floor assembly from the open doorway in the upper compartment. Times to collapse of each floor were also noted. Given the insulating effects of the OSB and the floor coverings, the temperature increase or thermal signatures viewed by the TIs were small given the fact that the ceiling temperatures below the OSB were in excess of 600 ºC (1112 ºF).

These experiments demonstrated that TIs alone cannot be relied upon to determine the structural integrity of a wood floor system. Therefore, it is critical for the fire service to review their practice of size-up and other fire ground tactics needed to enable the location of the fire prior to conducting fire operations inside a building. The United States Fire Administration (USFA) provided support for this project.

Keywords: engineered wood, fire fighters, oriented strand board, real-scale fire experiment, structural, thermal imager, wood

Disclaimer

Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

Regarding Non-Metric Units: The policy of the National Institute of Standards and Technology is to use metric units in all its published materials. To aid the understanding of this report, in most cases, measurements are reported in both metric and U.S. customary units.

Acknowledgements

The authors would like to thank Roy McLane, Steve Kerber, Doug Walton, Jay McElroy and David Stroup for their significant contributions during the preparation, construction, instrumentation and conduct of these experiments. We wish to thank Dave Stacy and Francine Amon for their contributions to this report. Appreciation is extended to the staff of the Delaware County Emergency Services Training Center, especially Kerby Kerber and Mike Gura for providing the infrastructure and construction support. We wish to thank the firefighters from City of Chester, Parkside and Sharon Hill Fire Departments for providing fire control during the experiments.

We would also like to thank Steve Austin, State Farm Insurance Co. as well as Deputy Chief Billy Goldfeder from Loveland-Symmes Fire department and G. Crawford Wiestling, Fire Chief Emeritus from West End Fire & Rescue, Shippensburg, PA., James Dalton from the Chicago Fire Department for their contributions to the project.

Finally we would like to thank Bill Troup from the U.S. Fire Administration for his support of this research program.

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1 Introduction

Every year firefighters are killed or injured as a result of some form of structural collapse in residential structures. Techniques for improving the situational awareness to prevent these incidents are being sought by fire departments. NIOSH recommends to "Use a thermal imaging camera to help locate fires burning below or within floor systems, but recognize that the camera cannot be relied upon to assess the strength or safety of the floor. Fire fighters should be trained on the use of thermal imaging cameras, including limitations and difficulties in detecting fire burning below floor systems." [**1**]

Currently there are no standards for training fire fighters in the use of thermal imagers. In order to develop data on the type of situation that fire fighters might face before entering a structure above the fire, four real-scale experiments were conducted by the National Institute of Standards and Technology (NIST) to measure the temperatures above and below a wood floor assembly. A fire was started in the lower level compartment, below the floor assembly, to simulate a basement fire. The experiments were conducted at the Delaware County (PA) Emergency Services Training Center. The objectives of the experiments were: 1) to examine the heat transfer through a wood floor assembly and 2) to examine the ability of a thermal imager to determine the potential severity of the fire beneath the floor assembly and the ability to provide a sense of the structural integrity of the floor assembly in order to provide improved situational awareness.

Three different commercially available thermal imagers designed for fire service use were tested in the experiments. Each imager employed a different type of infrared sensor technology: Barium Strontium Titanate (BST), Vanadium Oxide (VOx), and Amorphous Silicon (aSi). This report documents the experiments, presents the results in graphical and photographic form, and discusses implications for the fire department response. This provides data for future guidelines on the training and use of the thermal imagers, and should ultimately improve fire ground safety. The United States Fire Administration (USFA) provided support for this project.

1.1 Background

When a fire occurs in a wood framed residential structure, enough energy may be transferred to the structural members and connecting hardware to degrade and impact their structural integrity. In addition, the combustible elements of the structural members and other components of the flooring system add to the fuel load, resulting in increase production of fire gases. Floor loads from furnishings, equipment, or from the movement of people may result in a partial structural (failure) collapse. Floor collapse represents one of the hazards to firefighters, who enter a structure without precise knowledge of the fire's location. Several research studies examining "lightweight" construction have shown it to collapse in a shorter timeframe after fire exposure when compared to solid wood joists [**2, 3, 5**, **6**]. A review of reports published by USFA indicated that 17 fatalities resulted from structural collapse incidents at residential fires between 2005 and March 2011 [**7**]. All of these fatalities involved the collapse or partial collapse of a floor or roof assembly. The most common scenario was the firefighter falling through the floor and into a burning basement.

Between 2004 and 2008, the National Fire Protection Association (NFPA) reported that 1719 fire fighters have incurred collapse related or "hole burned through" related injuries at single family dwelling fires [**8**]. A breakdown of the injuries is provided in Table 1-1. The NFPA's complete list of the 16,350 fire ground injuries at single-family dwellings, during the period from 2004 through 2008, is presented in Appendix A.

Table 1-1. Number of firefighter injuries due to collapse at single family dwellings [8]

Injury Factor	No. of Injuries
Collapse or falling object, other	246
Roof Collapse	153
Wall Collapse	51
Floor Collapse	328
Ceiling Collapse	557
Stair Collapse	64
hole burned through roof	24
hole burned through floor	296
Total	1719

While the fatalities have been investigated and reported by the National Institute of Occupational Safety and Health (NIOSH), the injuries have typically not been given wide publication or exposure so it is difficult to understand the detailed causation factors. [**9**]

In 2005, the International Association of Fire Chiefs (IAFC) with the sponsorship of a Department of Homeland Security, Federal Emergency Management Agency (DHS/FEMA) Assistance to Firefighters Grant (AFG), began a web-based firefighter near-miss reporting system. The system relies on voluntary, anonymous reports. The date of the incident is provided as a means of determining if an incident is unique. This is especially useful when comparing several databases. Another web site, www.closecalls.com has been set up to describe near-miss incidents. This site identifies the injured firefighters and fire departments.

NIST conducted a review of data from both websites for the period from January 2005 to March 2011. There were 118 incidents reported that involved residential structural collapse. Seventy-six of the incidents resulted in 128 firefighters being injured. A spreadsheet summarizing the incidents in which a LODD, injury or near-miss was reported is provided in Appendix B.

Comparing the number of self-reported injuries to the number of injuries reported to NFPA would indicate under reporting. USFA also reports that the lack of consistency in reporting injury events and their details makes an accurate representation of injuries caused by floor collapse difficult. Similarly, near-miss incidents are typically unreported [**10**].

2 Technical Approach

To examine the thermal conditions above the floor assembly, a fire was started in the lower level of a two level structure. Two steel drums of water were centered on the floor of the upper level to load the structure. Degradation of structural integrity of the floor was observed as the fire progressed. Thermal imagers were mounted to a frame, positioned in the upper level doorway, and aimed at the top surface of the floor assembly. The cameras recorded the view a firefighter would have of the floor surface at the entrance to the structure on the upper level. They were removed when conditions that would damage them were reached.

The fire growth and environmental conditions on both floors of the structure were measured with thermocouples (TCs). Four TC arrays measured gas temperatures between the floor and ceiling on both levels. In addition, four floor system TC arrays measured gas and surface temperatures on and around the floor joist, sub-floor, and floor covering. Visible-spectrum cameras mounted in and around the structure document the fire development as well as key events in ventilation and structural failure.

Each structure was built using a different floor support assembly to represent a range of possible real-world scenarios. Fuel loading and instrumentation was similar for all four tests, however the both the structural loading and the amount of fuel loading in the lower level were less than expected in a typical residence. During each test, ventilation to the lower level was increased in stages by removing large gypsum board obstructions from the door.

2.1 Structures

Figure 2-1. The four structures prior to any of the experiments

2.1.1 Framework

The structures were built outside on a paved surface at the Delaware County Emergency Services Training Center (see Figure 2-1). Each structure was built on a base composed of two layers of 12.7 mm (0.50 in) thick gypsum board. Additional gypsum board was positioned around the perimeter of each structure to protect the paved surface. The walls of the structure were constructed from kiln dried fir, dimensional lumber nominally "2 x 4." The actual cross section measured 38 mm (1.5 in) by 89 mm (3.5 inches). The walls were framed with the vertical members 0.41 m (16 in) on center. Nominal "2 x 8" lumber was attached to the base of each wall in order to level the tops of the walls. A framed lower level can be seen in Figure 2-2. The interior dimensions of the lower level were 4.7 m (15.3 ft) in the north-south (front to back) direction and 4.8 m (15.9 ft) in the east west direction (see Figure 2-3).

Figure 2-2. Lower level frame structure prior to the construction of the floor

After the lower level was erected, the floor assembly was built on top of the lower level walls. The floor assemblies for each experiment were different and will be described in the following sections. One of the common materials for each experiment was the sub-flooring, which was 18.3 mm (0.72 in) thick, tongue and groove oriented strand board (OSB). OSB is an engineered wood structural panel made of compressed wood strands arranged in layers and bonded with phenolic resin. In each case, the OSB was nailed to the joists with 8d nails spaced in accordance with the manufacturer's installation guidelines [**11**].

Once the floor assembly was in place atop the lower level, 0.15mm (0.006 in.) thick plastic sheeting was stapled to the inside of the framework. Then, two layers of 12.7 mm (0.50 in) thick gypsum board were installed on the walls. The seams were offset in order to maintain a tight

seal and improved wall integrity under fire conditions. The distance between the floor and the bottom of the joist on the lower level was approximately 2.4 m (8.0 ft).

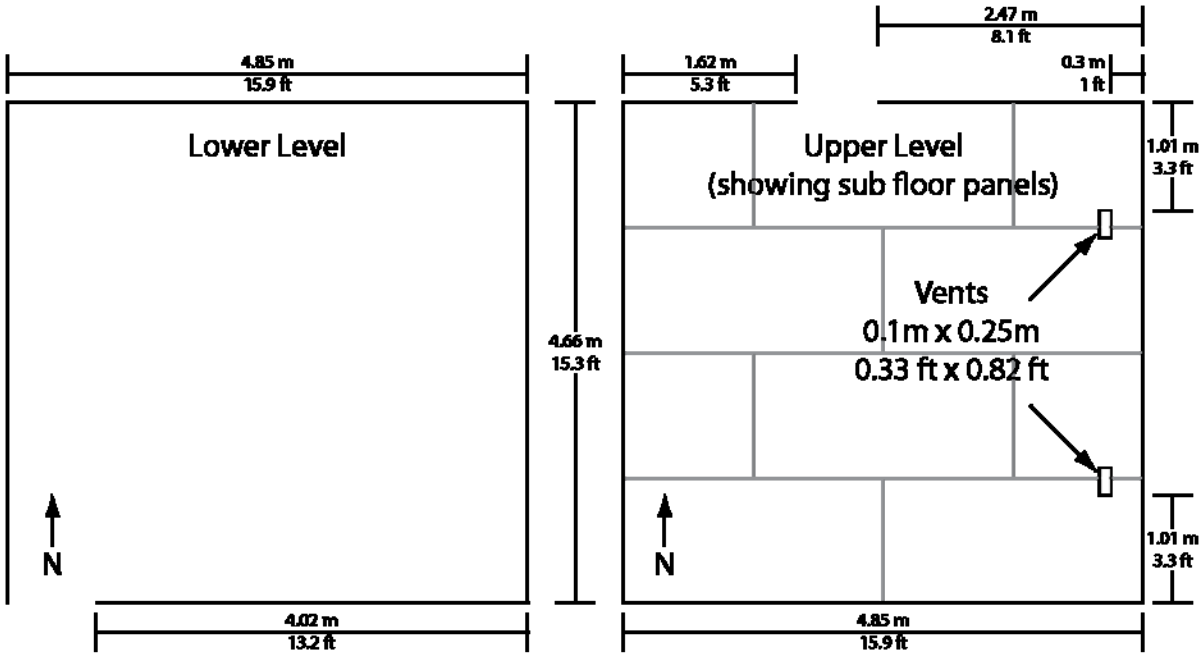

Figure 2-3. Floor plan of the upper and lower levels of the structures with dimensions

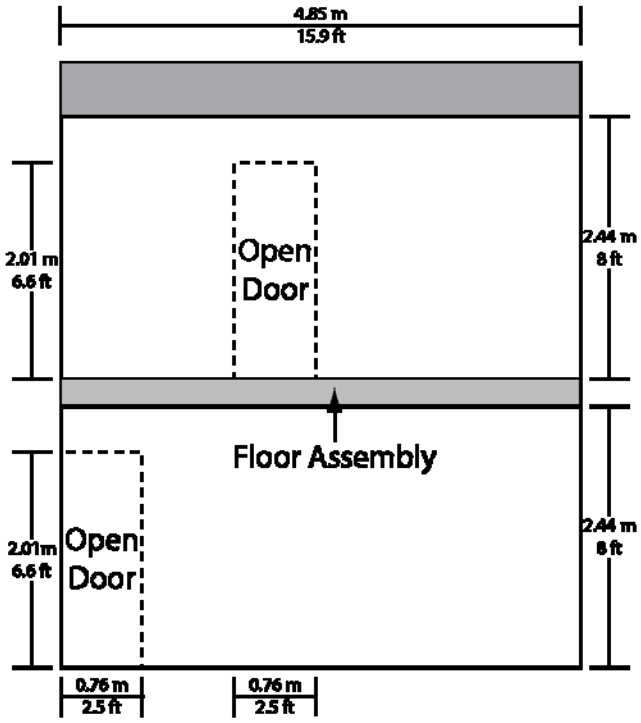

Figure 2-4. Elevation view of the structure, looking North, with dimensions

The walls for the upper level were constructed in the same manner as those for the lower level and lifted into place on top of the floor assembly. The support for the upper level ceiling was

composed of wooden I-joists, 241 mm (9.5 in) tall with a laminated veneer lumber flange width of 59 mm (2.3 in.) and a height of 36 mm (1.4 in). The web of the joist was made from OSB that was 11 mm (0.43 in) thick. These joists conformed to the APA standard PRI 40 series specifications [**11**]. The upper level walls were lined with 0.15mm (0.006 in.) plastic sheeting and then covered with one layer of 12.7 mm (0.50 in) gypsum wall board. The ceiling of the upper level consisted of a layer of 18.3 mm (0.72 in) thick OSB which was covered with one layer of 12.7 mm (0.50 in) thick gypsum board. The seams were filled and sealed with paper tape and spackled as required. The height of the ceiling above the exposed OSB on the floor was 2.4 m (8.0 ft). The floor plan of the upper level is summarized in Figure 2-3. The vertical dimensions of the structures are in Figure 2-3.

Two penetrations in the sub floor included typical residential air vents, which were 0.10 m (0.33 ft) wide by 0.25 m (0.82 ft) long. This allowed combustion products and hot gases to move up to the upper level. The vents were positioned in the east corners of every structure, one 1.1 m (3.3 ft) from the north wall of the structure and one 1.1 m (3.3 ft) from the south wall of the structure. Both vents were placed 0.33 m (1.0 ft) from the east wall. An example of a floor vent is shown in Figure 2-5.

Figure 2-5. Vent installed on the upper floor through to the lower as it was installed in all experiments

2.1.2 Doorways

Each structure had two doorways, one on the lower level and one the upper level. The doorway on the lower level was located on the south side (rear) of the structure, adjacent to the southwest corner. The doorway on the upper level was positioned with the east edge of the opening centered on the north side of the structure. Each doorway opening was 0.76 m (2.5 ft) wide by 2.0 m (6.6 ft) high. The dimensions and positioning for both doorways are given in Figure 2-3. The doorway on the lower level was initially 2/3 covered by gypsum board sections; these sections were removed to increase ventilation during the experiments.

In an effort to reduce leakage around the perimeter of the flooring assembly, pieces of 12.7 mm (0.50 in) thick plywood, approximately 0.61 m (2.0 ft) wide were attached over the intersection of the walls and the floor assembly.

2.1.3 Experiment 1 Structure

The support for the floor in this experiment was composed of wooden I-joists, 302 mm (11.9 in) tall with a laminated veneer lumber flange width of 59 mm (2.3 in) and a height of 36 mm (1.4 in). The web of the joist was made from OSB that is 11 mm (0.43 in) thick. These joists conformed to the APA standard PRI 40 series specifications. The joists were spaced 610 mm (24 in) apart on center. The maximum recommended spacing by the manufacturer [**11**]. An example of the floor joist structure is shown in Figure 2-6.

Figure 2-6. Composite wood I-joists spaced 610 mm (24 in) on center, as used in experiment 1 and 2

The OSB sub-floor in this experiment was partially covered by wood grain surface laminate flooring. The laminate flooring was, as installed, 10 mm (0.4 in) thick. The upper 8 mm of the flooring was composed of a particle board material with a melamine top surface. A 2 mm (0.08 in) thick plastic foam underlayment was attached to the bottom of the particle board. The overall density of the laminate flooring was (761 kg/m^3 (47.7 lb/ft^3). The objective was to examine the affect of laminate flooring on the transmission of heat through the floor. It was not intended to simulate the effect of the flooring material on floor collapse time and was not used to cover the entire floor surface. The flooring extended from the upper level doorway, where the thermal imagers were located, past the load in the center of the floor. A photograph of the flooring in this experiment is shown in Figure 2-7.

Figure 2-7. Laminate flooring covering a portion of the upper level floor; this flooring was used in experiment 1 only

2.1.4 Experiment 2 Structure

As in experiment 1, the support for the floor in this experiment was composed of wooden I-joists, 302 mm (11.9 in) tall with a laminated veneer lumber flange width of 59 mm (2.3 in) and a height of 36 mm (1.4 in). The web of the joist was made from OSB that is 11 mm (0.43 in) thick. These joists conformed to the APA standard PRI 40 series specifications.

Figure 2-8. Composite wood I-joists spaced 406 mm (16 in) on center, as used in experiment 2

Unlike experiment 1, the joists were spaced 0.41m (16 in) apart on center. This is typically the minimum recommended spacing and is similar to the typical spacing used with the dimensional lumber joists [**11**]. An example of the floor joist structure is shown in Figure 2-8.

Figure 2-9. Carpet and padding covering a portion of the upper level floor, as it was in experiments 2, 3, and 4

Carpeting and padding partially covered the OSB sub-flooring in this experiment. The objective was to simulate haw the insulation of typical carpet flooring could affect the transmission of heat through the floor as viewed through the thermal imager. It was not intended to simulate the effect of the flooring material on floor collapse time and was not used to cover the entire floor surface. The flooring extended from the upper level doorway, where the thermal imagers were located, past the load in the center of the floor. A photograph of the flooring in this experiment is shown in Figure 2-9.

Figure 2-10. Nominal "2 x 12" solid wood joists used in experiment 3

The carpeting was 100% nylon with a polyolefin backing. The 3.66 m x 3.66 m carpeting had a mass of 24 kg (53 lbs). The padding was 12 mm (0.5 in) thick polyurethane foam. The padding was installed under the carpeting and had a mass of 22 kg (48 lbs). The same carpeting and padding with the same area of coverage was installed in experiments 2, 3 and 4.

2.1.5 Experiment 3 Structure

The floor support in this experiment was composed of solid wood joists. The joists had a nominal "2 x 12" cross-section which measured 32 mm (1.25 in) by 286 mm (11.25 in). The joists were spaced 0.41 m (16 in) apart on center. They spanned the entire 4.8 m (16 ft) width of the structure. Solid wood bridging was installed between the joists. Each bridging member was aligned on alternating sides of the centerline of each joist. A photograph of the floor joists and bridging arrangement for this experiment is shown in Figure 2-10.

As with experiment 2, carpet and padding partially covered the OSB sub-flooring in this experiment. The objective was to examine how the carpet and padding could affect the transmission of heat through the floor. It was not intended to simulate the effect of the flooring material on floor collapse time and was not used to cover the entire floor surface. The carpeting extended from the upper level doorway, where the thermal imagers were located, past the load in the center of the floor. A photograph of the typical carpeting used in this experiment is shown in Figure 2-9.

2.1.6 Experiment 4 Structure

The joist structure in this experiment was similar to experiment 1. The floor structure was composed of wooden I-joists, 302 mm (11.9 in) tall with a laminated veneer lumber flange width of 59 mm (2.3 in) and a height of 36 mm (1.4 in). The web of the joist is made from OSB that is 11 mm (0.43 in) thick. These joists conformed to the APA standard PRI 40 series specifications. The joists were spaced 0.61 m (24 in) apart on center. An example of the floor joist structure is shown in Figure 2-6.

For this experiment a ceiling comprised of 12.7 mm (0.5 in) thick gypsum board was attached to the bottom of the joist to protect the floor assembly. It was left finished but unpainted as was the wall structure. The joints between each 1.2 m (4 ft) by 2.4 m (8 ft) sheet of gypsum board were filled with spackling compound. The screw heads were also spackled over. A photograph of the ceiling as it appeared before the experiment is shown in Figure 2-11. Two penetrations in the ceiling were cut just below the floor vents and, similar to the floor vents; typical residential air vents were used, having dimensions of 0.10 m (0.33 ft) wide by 0.25 m (0.82 ft) long. No ducts were used and gases passing through the vents could contact the joist structure. An example of these vents from the lower level is shown in Figure 2-12.

Figure 2-11. Gypsum board covering an OSB joist structure, as was used in experiment 4

Figure 2-12. Vent installed in the Gypsum board which covered the joist structure in experiment 4

As with experiment 2 and 3, carpeting partially covered the OSB sub-flooring in this experiment. The objective was to examine the impact that carpet flooring and a 12 mm (0.5 in.) layer of gypsum board could have on the transmission of heat through the floor. It was not intended to simulate the effect of the flooring material on floor collapse time and was not used to cover the entire floor surface. The carpeting extended from the upper level doorway, where the thermal imagers were located, past the load in the center of the floor.

2.2 Instrumentation

The instrumentation in each test consisted of 8 vertical thermocouple (TC) arrays. Three different types of arrays were used: a floor system array, a floor to ceiling array and a doorway array. Each was installed and positioned to quantify a specific element of each test. All of the arrays used bare-bead, Chromel-Alumel (type K) TCs, with a 0.5 mm (0.02 in) nominal

diameter. The descriptions of the TC arrays are given in the paragraphs below. The locations and numerical dimensions for the lower level instrumentation are given in Figure 2-17. Locations and numerical dimensions for the upper level instrumentation are given in Figure 2-18.

In addition, 8 video cameras were positioned around and inside the structures to document the experiment and to assess potential warning signs for collapse.

Floor system TC arrays at locations 2 and 5 measured surface temperatures of the joist and sub-floor elements in order to assess their heat exposure. TCs were held in contact with the surfaces using staples as shown in Figure 2-15. Floor system TC arrays at locations 7 and 3 utilized thermocouples in contact with the upper and lower surfaces of the OSB sub-floor to assess the heat conduction through that layer. The floor system TC array at location 7 also incorporated a thermocouple in contact with the floor covering for each test.

Figure 2-13. TC arrangement measuring surface temperature of the top flange, bottom flange, and web sections of an OSB floor joist, as was used in experiments 1, 2, and 4

Figure 2-14. TC arrangement measuring the surface temperature of a "2 x 12" joist where the structural elements of top flange, bottom flange, and web from an OSB joist would otherwise be located; such an arrangement was used in experiment 3

Joist-surface TCs, used in the floor system TC arrays at locations 2 and 5, were mounted at the center of each joist element, bottom flange, top flange, and web as shown in Figure 2-13. Experiment 3 was an exception, as composite wood I-joists were not used. The TCs were instead placed at approximately the same vertical heights of the joist components in other experiments. An example of this placement is shown in Figure 2-14.

Figure 2-15. TC measuring the surface temperature of the OSB sub-floor

The sub-floor-surface TCs, used in all floor system TC arrays, were mounted vertically above the rest of the array, but in a similar horizontal position. In all cases, the floor system TC arrays were wired through a small hole in the sub floor and mechanically fastened to the material surface. The bead of the TC was bent to press against the surface. An example of the sub-floor-surface TCs is shown in Figure 2-15.

TC arrays at locations 4 and 8 measured the ceiling to floor gas temperatures for the areas in which they were located. The vertical arrays had TCs located 0.03 m (1 in), 0.3 m (1.0 ft), 0.61 m (2.0 ft), 0.91 m (3 ft), 1.22 m (4 ft), 1.52 m (5ft), 1.83 m (6 ft), and 2.13 m (7 ft) below the ceiling (BC). In positions with exposed joists, locations were measured below the sub-floor of the upper level. An example of a gas temperature TC array is shown in Figure 2-16.

Figure 2-16. Gas temperature TC array as used in all experiments, each band of tape above the floor shows the approximate location of a junction

TC arrays at locations 1 and 6 measured the gas temperatures from the soffit to the base of the lower and upper level doors respectively. These arrays had TCs located 0.03 m (1 in), 0.3 m (1.0 ft), 0.61 m (2.0 ft), 0.91 m (3 ft), 1.22 m (4 ft), 1.52 m (5ft), and 1.83 m (6 ft) below the soffit (BS).

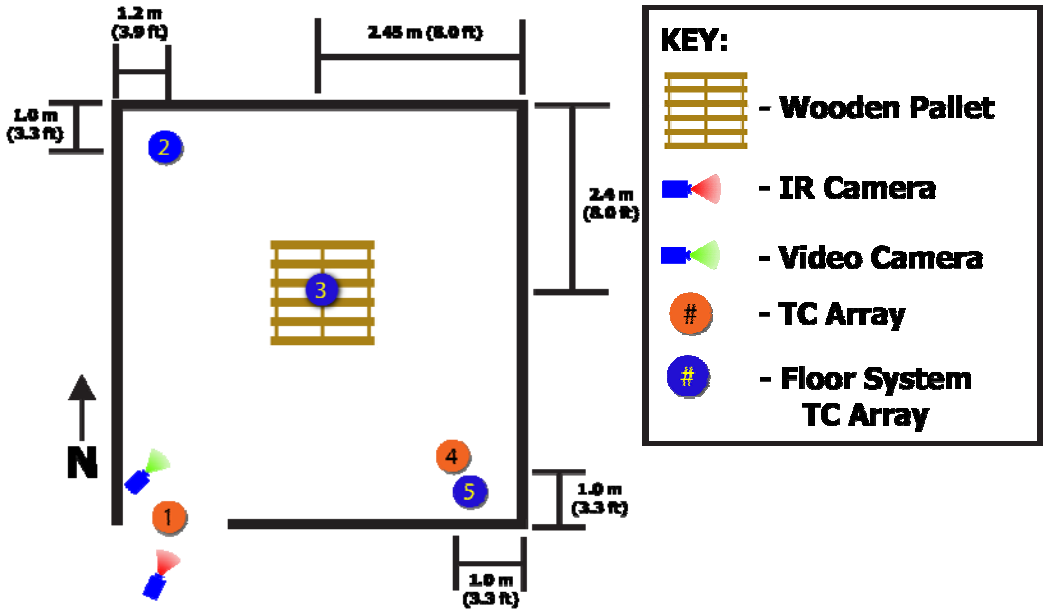

Figure 2-17. Floor plan of the lower floor with instrumentation positions noted

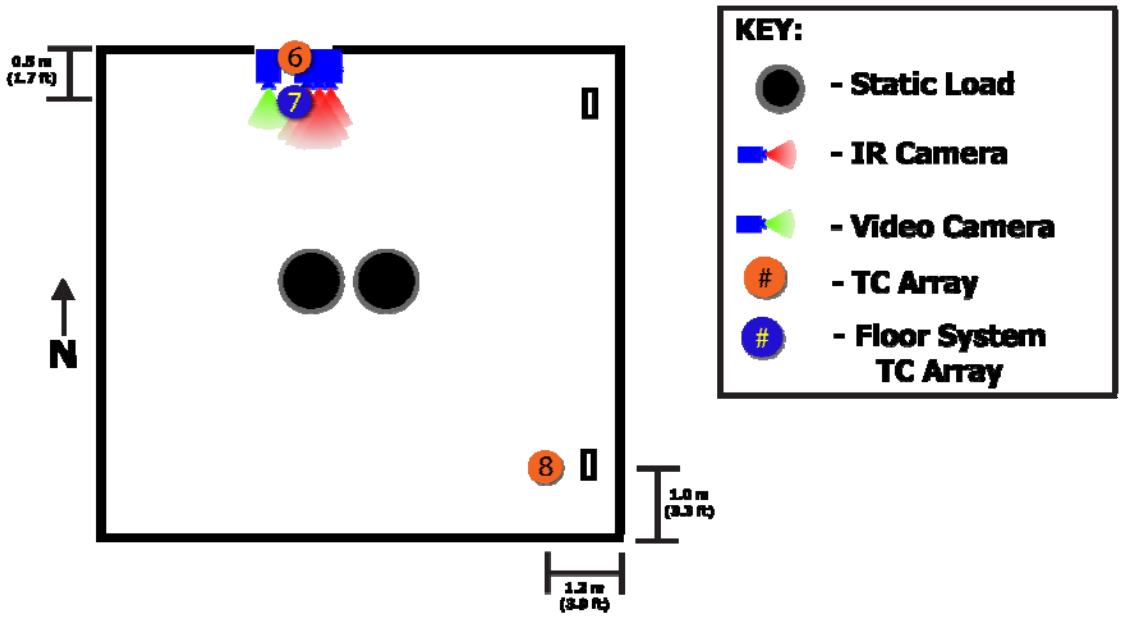

Figure 2-18. Floor plan of the upper floor with instrumentation positions noted

Four thermal imagers and up to five visible-spectrum video cameras were used in each test. The locations of most of the cameras used are noted in Figure 2-17 and Figure 2-18. Three of the four thermal imagers were used to record the conditions that a fire fighter preparing to enter the structure through the doorway on the upper level might see to identify potential warning signs

for thermal hazards or structural collapse. One video camera was installed just above the three thermal imagers to provide a view of what a firefighter without a thermal imager would see (or not see). An aluminum frame held them in place with the upper level floor in view. The lenses of the thermal imagers were located approximately 0.45 m (18 in) above the floor and tilted downward at approximately a 45° angle. A photograph of the mounting apparatus is shown in Figure 2-19 and a photograph of the lift used to position the cameras in the doorway is shown in Figure 2-20.

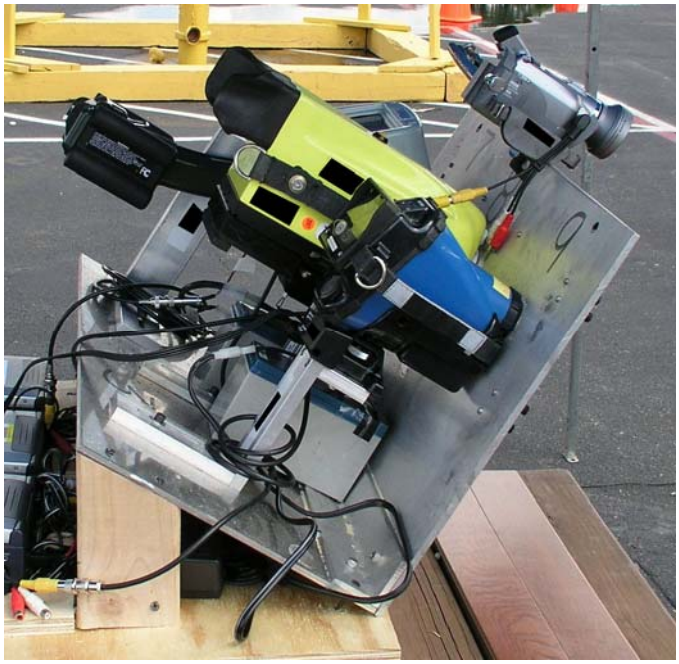

Figure 2-19. Apparatus used to lift the thermal imagers to and from the upper floor doorway

Figure 2-20. Lift used to remove the thermal imagers as used in all four experiments

Each of the three thermal imagers mounted on the lift apparatus were commercially available models and each used a different detector technology. At the time of these experiments three well-established detector technologies were commercially available to the fire service, Barium Strontium Titanate (BST), Vanadium Oxide (VO_X), and Amorphous Silicon (aSi) [**12**]. Each of the thermal imagers was used in each experiment. Since these experiments were conducted, thermal imagers using BST detectors have been withdrawn from the fire service market.

Most detectors used for first responder applications are un-cooled focal plane arrays (FPA), utilizing an array of sensors located at the focal plane of the optics. Each specific detector technology is capable of generating different levels of information in the displayed image, as seen in the thermal images presented in Section 3. The differences seen in these sets of images are the result not only of different detector technologies, but also of different optical and electronic systems, which can contribute significantly to overall image quality. These three thermal imagers also are of different sizes, weights, and cost [**12**].

VOx and ASi cameras are called microbolometers, which means that the detector pixels are essentially very small heat flux gauges, changing their electrical resistance based on how much heat is absorbed by the pixel. The size of the FPA for the microbolmeters used in this project is 160 pixels x 120 pixels. BST detectors are solid-state ceramic devices with an embedded array of sensors (or nodes) that convert changes in electrical polarization to voltage differences. A thermoelectric cooler provides thermal stability. These are AC-coupled detectors that measure relative levels of infrared radiation, thus the detector output requires a correction based on reference points provided by a chopper. A chopper is a bladed wheel that rotates directly in front of the detector such that it sees the chopper blades alternately with the thermal scene. The chopper blades are assumed to have a constant temperature and the detector nodes are continuously reset to a uniform value corresponding to that constant temperature every time a chopper blade passes in front of the detector array. The oscillation between the thermal scene and the chopper blades provide the AC component to the detector signal. The size of the FPA for the BST detector is 320 pixels x 240 pixels [12].

The radiating surfaces and gases visible to thermal imagers have a property known as emissivity (ε) that affects how the thermal radiation intensity relates to the actual temperature of the surface or gas. A surface or gas having an emissivity of 1 is said to be a "blackbody", meaning that it absorbs and re-emits all energy incident upon it. A surface or gas having an emissivity of 0 reflects all energy, making the surface or gas appear to be the temperature of reflected objects [**14**]. In general, surfaces that are flat black in color and somewhat rough in texture tend to have high emissivities and surfaces that are shiny and smooth tend to have low emissivities. Most thermal imagers are designed to use a constant emissivity value of 0.95 for its surface temperature calculations; the further away an object's emissivity is from 0.95, the less accurate that object's surface temperature will be. The term "apparent temperature" is used to account for temperature deviations caused by differences in emissivity.

Several visible-spectrum cameras were also included to document the events of each test. A camera was placed at ground level on the south side of the structure with the lower level doorway in view to document changes in ventilation. A camera was also placed just inside the west side of the lower level doorway to document the fire development. A photo of this camera is shown in Figure 2-21. A camera which documented the ventilation of the structure from the upper floor doorway was mounted on a tower on the north side of the structures. A thermal imager was placed at the lower level doorway to assist in documenting the fire development, but it required regular movement to remain protected from thermal damage. All camera locations were similar for all 4 experiments with the exception of an additional camera in experiment 3. This additional camera was included to monitor the upper level floor for flame penetrations. It was thermally protected and located near the upper level doorway; it was independently mounted and not removed with the lift apparatus.

Figure 2-21. Camera looking into the burn room from the corner nearest the lower level doorway

2.3 Uncertainty Analysis

There are different components of uncertainty in the length and temperature. Uncertainties are grouped into two categories according to the method used to estimate them. Type A uncertainties are those which are evaluated by statistical methods and Type B are those which are evaluated by other means **[15]**. Type B analysis of systematic uncertainties involves estimating the upper (+ a) and lower (- a) limits for the quantity in question such that the probability that the value would be in the interval (± a) is essentially 100 %. After estimating uncertainties by either Type A or B analysis, the uncertainties are combined in quadrature to yield the combined standard uncertainty. Multiplying the combined standard uncertainty by a coverage factor of 2 results in the expanded uncertainty, which corresponds to a 95 % confidence interval (2σ). For some of these components, such as the zero and calibration elements, uncertainties are derived from instrument specifications.

Each length measurement was taken carefully. Length measurements such as the room dimensions, instrumentation array locations and furniture placement were made with steel tape measures with a resolution of ± 0.5 mm (0.02 in). However, conditions affecting the measurement, such as levelness or tautness of the device, yield an estimated uncertainty of ± 0.5 % for measurements in the 2.0 m (6.6 ft) to 10.0 m (32.8 ft) range. The standard uncertainty in temperature of the TC wire itself is ± 2.2 °C at 277 °C and increases to ± 9.5 °C at 871 °C as determined by the wire manufacturer [**16**]. The variation of the temperature in the environment surrounding the TC is known to be much greater than that of the wire uncertainty [**17, 18**]. Small diameter TCs were used to limit the impact of radiative heating and cooling. The estimated total expanded uncertainty for temperature in these experiments is ± 15 %.

In the following sections, the measurements will be presented in graphic and tabular form. In the graphs an error bar will represent the estimated uncertainty of the measurement.

2.4 Experimental Procedure

In each test, a stack of wood pallets surrounded and filled with field cut, dry hay which were ignited by two electrically activated match ignition sources. The lower floor doorway opening was the primary vent for the fire compartment. At the start of the experiment, the lower half of the doorway was open. As the fire grew, the area of the doorway vent was increased by removing sections of gypsum board which blocked the upper portion of the doorway. The fire was allowed to burn freely until floor collapse occurred or until the pallets burned out, whichever came first. After the experiment, the fire was suppressed by firefighters using fire hoses.

Figure 2-22. Fuel package used in experiment 3, comprised of wooden pallets and hay; a similar fuel package was used in all other experiments

2.4.1 Fuel Load

The fuel load in each experiment consisted of 6 wood pallets and 7.5 kg (16.5 lbs) of hay. The mass of each pile of pallets ranged from 100 kg (220 lbs) to 114 kg (250 lbs). The pallets were 1.22 m (48 in) in length, 1.02 m (40 in) wide and 0.13 m (5 in) high, as shown in Figure 2-21.

Four replicate experiments with similar stacks of pallets were burned in the NIST Large Fire Facility under the 6 m (20 ft) by 6 m (20 ft) oxygen consumption calorimetry hood. The mass of the pallet stacks with hay burned in the laboratory ranged from 103 kg (227 lbs) to 112 kg (247 lbs). The average peak heat release rate from each stack of six pallets with hay was approximately 2.3 MW ± 0.2 MW. The total energy released during the laboratory experiments ranged from approximately 1500 MJ to 1900 MJ.

The fuel load was ignited by two electrically activated match sources located at floor level approximately at the midpoint of the east and west sides of the pallet stack in each experiment. The stack of pallets was fully involved with fire in less than 2 minutes for every experiment.

Figure 2-23. Two "55 gallon" drums filled with water comprising the 272 kg (600 lb) static load used in all four experiments

2.4.2 Structural Loading

The upper level floor was loaded with two "55 gallon" drums of water which had a total mass of 272 kg (600 lb). This mass was intended to simulate the weight of two stationary firefighters mid span. This is a minimal loading and it was not intended to replicate the structural loading expected in a

furnished residential structure. Each barrel was supported by two 0.304 m (1 ft) long "2x4" boards which were oriented parallel to the joists. The load and its positioning are shown in Figure 2-23.

Figure 2-24. Lower level vent with 3 configurations of gypsum board obstructions; from left to right, approximately 2/3 covered, approximately 1/3 covered, and fully open

2.4.3 Ventilation

In order to represent a realistic "basement" fire scenario the ventilation was limited. The vent was increased in size when the fire was determined to be sufficiently ventilation limited. The initial vent between the lower level room with the fire and the exterior was the lower portion of the doorway. The initial vent size was 0.76 m (2.5 ft) wide and 0.67 m (2.2 ft) high. Ventilation to the lower level was increased in stages by removing the gypsum board obstructions from the lower level doorway. At the beginning of each experiment, the lower third of the doorway was open. Two pieces of gypsum board, each covering approximately 1/3 of the doorway's upper area, were removed from the bottom up, opening the top of the doorway last. In each experiment, the gypsum board was removed in two stages, with one piece being removed in each stage. Photographs showing each stage are shown in Figure 2-24.

3 Results

The results of the experiments include timelines based on observations, temperature measurements, photographs and videos. Graphical representations of the TC data gathered in each experiment, as well as the timeline of events for each experiment, are presented in the following sections. Each experiment differed primarily in the floor system configuration used.

Changes in ventilation were made to facilitate the progression to flashover in the lower level. A similar ventilation strategy was used for each of the experiments. The first ventilation change occurred approximately

10 minutes after ignition and the second ventilation change occurred at least five minutes later (see section 2.4.3). The timeline lists the ventilation times for each experiment.

Ignition of wood and wood composites are a function of wood species, density, incident heat flux, area of exposure, moisture content, and specimen thickness. Consequently, a complete study of the building materials would be required to accurately predict ignition. Studies have shown ignition temperatures of plywood and OSB under specific conditions to be 368 ºC (694 ºF) and 364 ºC (687 ºF), respectively [**19**]. For these experiments, a surface temperature over 350 ºC (660 ºF) was assumed to indicate that the integrity of the floor system was beginning to be compromised through pyrolysis, where the material decomposed due to heat alone.

3.1 Experiment 1

The floor system installed for this experiment was laminate flooring over OSB with composite wood I-joists spaced 0.61 m (24 in) apart. The structure examined in this test was instrumented as described in Section 2.2; the instrumentation locations are shown in Figure 2-17 and Figure 2-18. The timeline for this experiment is presented in Table 3-1.

Table 3-1. Timeline of events for experiment 1, given by approximate start and end times for each event.

Event	Start Time sec (min:sec)	End Time sec (min:sec)
Ignition	0 (00:00)	0 (00:00)
First gypsum board removed	610 (10:10)	615 (10:15)
Second gypsum board removed	935 (15:35)	940 (15:40)
Localized flashover	935 (15:35)	1090 (18:10)
Flames out first floor door	1085 (18:05)	continuous
Complete flashover	1065 (17:45)	1090 (18:10)
Thermal imagers removed	1405 (23:25)	1405 (23:25)
Floor collapse	1470 (24:30)	1470 (24:30)
Begin extinguishment	1490 (24:50)	

3.1.1 Thermal images

In this experiment, the web element of the joist to which the floor system TC array at location 5 was attached reached 350 ºC (660 ºF) prior to any other measured floor element. This exposure occurred at approximately 615 s after ignition and was used to indicate degradation of the structural integrity of the floor structure.

In this section, the view captured by the thermal imagers located in the upper level doorway are compared at various times. The initial set is given prior to any exposure, the next is given at 615 s after ignition, and the remaining sets are given at 180 s intervals subsequent to 615 s.

As energy from the fire and its combustion products was transferred into the flooring system, areas of contrast began to show in the images. Lighter shades indicated areas of higher temperature relative to the darker areas

of the image. In Figure 3-1, the flooring area was nearly uniform in color, indicating a similar temperature over the floor. The relatively low emissivity of the polished laminate flooring ($0.68 < \varepsilon < 0.73$), compared with that of the carpet flooring ($0.85 < \varepsilon < 1.00$) used in the following tests, allowed the reflection of the steel drums filled with colder water to appear in these images [**20**, **21**]. In these images, as well as all of the following thermal images, the relative lightness/darkness of the images was due to each thermal imager's internal algorithms for assigning a grayscale value to each pixel in the scene. These algorithms are proprietary and may be unique for each model of thermal imager. The most useful information derived from these images is the distribution of apparent heat within each image produced by a particular thermal imager during the course of the experiment, rather than comparing results across thermal imager types.

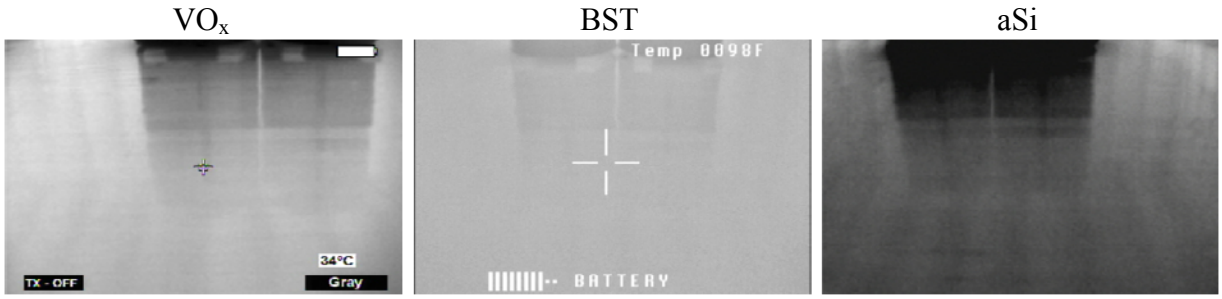

Figure 3-1. Thermal images representative of three technology types, at the time of ignition and prior to heating of the floor system elements

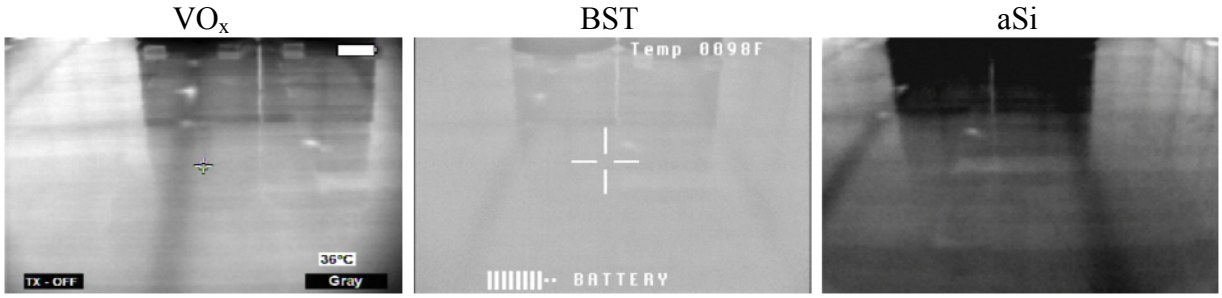

Figure 3-2. Thermal images at 615 s after ignition. The joist structure as well as the sub-floor joints are faintly visible in all three technologies, as are several bright spots

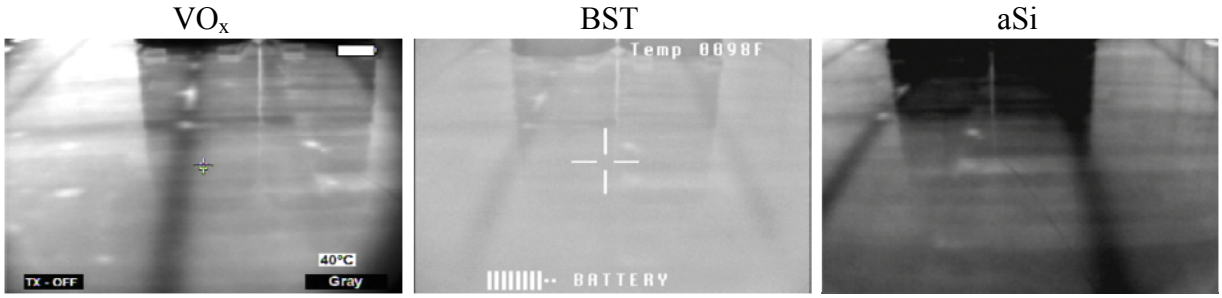

Figure 3-3. Thermal images at 795 s after ignition. The contrast had increased.

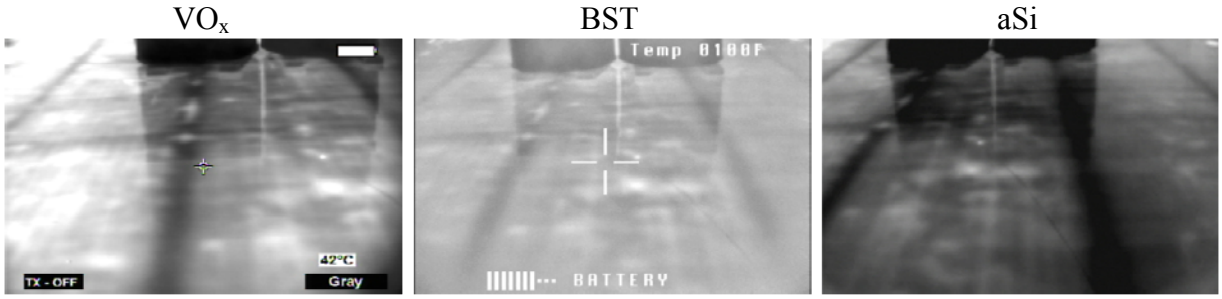

Figure 3-4. Thermal images at 975 s after ignition. Inconsistencies in the thermal conductivity of the sub-floor and floor surface are clearly visible.

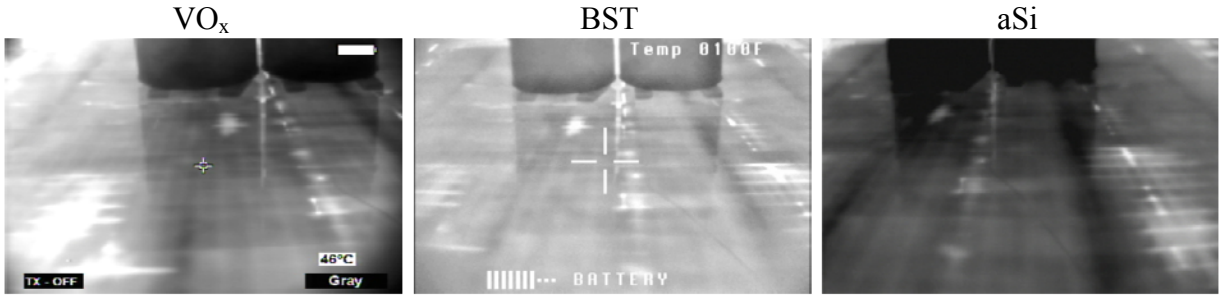

Figure 3-5. Thermal images at 1155 s after ignition. The contrast of the joist structure has decreased.

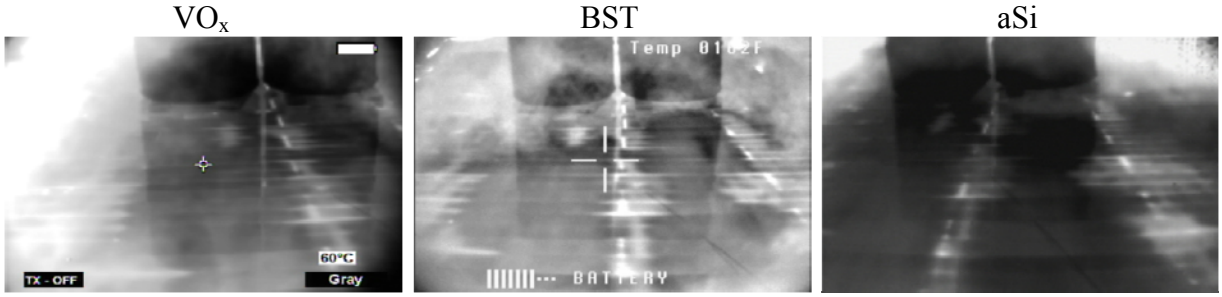

Figure 3-6. Thermal images at 1335 s after ignition. By this point hot gases were flowing through the upper level compartment. The temperature of the gases one inch below the upper level doorway soffit was 265 ºC (509 ºF) at this time.

3.1.2 Gas Temperature TC Arrays

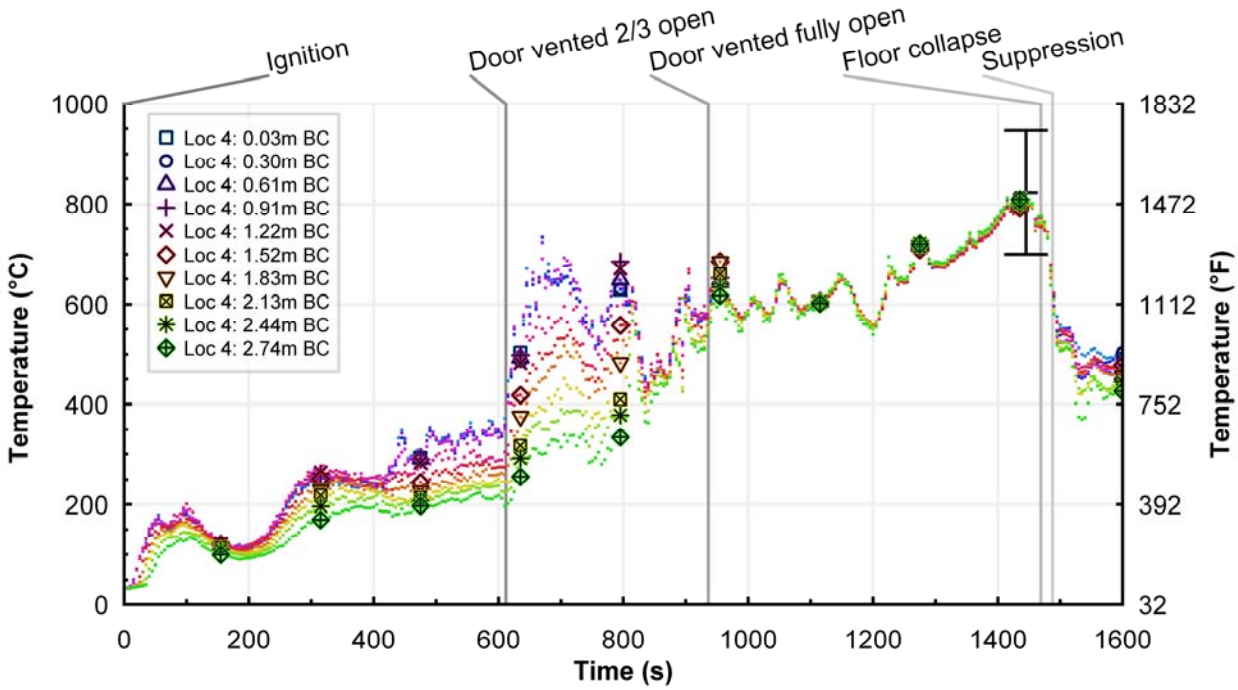

Figure 3-7. Experiment 1, lower level southeastern corner (TC array at location 4), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.7 m (9 ft) below the ceiling versus time.

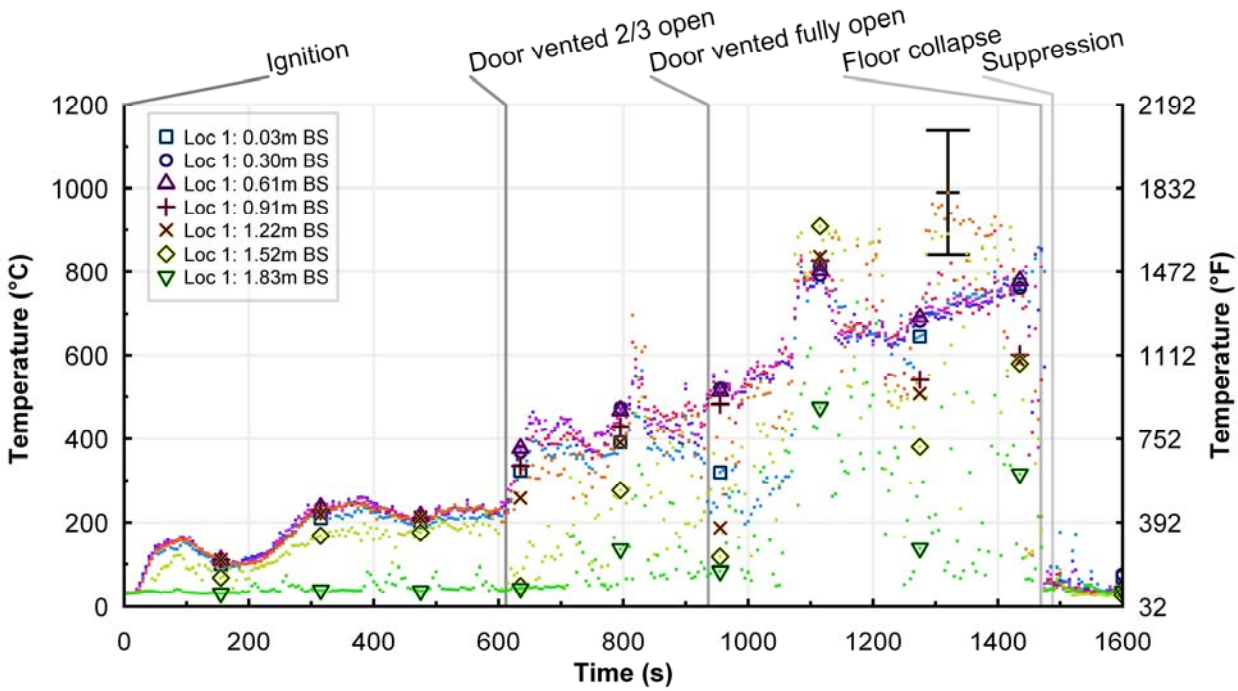

Figure 3-8. Experiment 1, lower floor doorway (TC array at location 1), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit, given versus time

Figure 3-9. Frame captures from the video camera just to the west of the lower level door showing combustion and flow patterns at various times, from left to right 14 s, 827 s, and 909 s after ignition. The TC array at location 4 is just out of view to the right.

Figure 3-7 shows the temperature at Location 4, located on the southeast corner of the structure (as shown in Figure 2-17). The measurements indicated a high-temperature, thermally-mixed environment. This is attributable to the ventilation through the doorway on the lower level which resulted in a circular flow path through the lower level of the structure. This leads to a thermally mixed condition on the east side of the structure which supports the combustion of gases at the floor level prior to well mixed burning throughout the lower level compartment. Figure 3-9 demonstrates the effect of ventilation on the flame movement toward the east side of the structure. As presented in Section 2.3, the estimated total expanded uncertainty for temperature in these experiments is ± 15 %. This uncertainty estimate is represented by a range bar placed at the peak value on each of the temperature graphs in this report.

There was a two-way flow in the lower doorway for most of the experiment. Figure 3-8 documents the temperature of gases flowing through the lower level doorway. The spike in temperatures just before 1100 s corresponds to combustion outside the doorway and a post-flashover condition within the structure.

Gas temperatures in the upper level, location 8, and out of the upper level doorway, location 6, remained below 100 ºC until approximately 1200 s when temperatures in the upper level began to rise rapidly, indicating fire penetration through the floor on the east side. The gas temperatures at location 8 and 6 are shown in Figure 3-10 and Figure 3-11, respectively.

Gas temperatures in the upper level doorway are shown in Figure 3-11. The temperature of gases moving through the upper level doorway, measured by this TC array, reflected a rise in temperatures prior to 1300 s, which is approximately 100 s sooner than the room temperature TC array, location 8, indicating a rise in temperature.

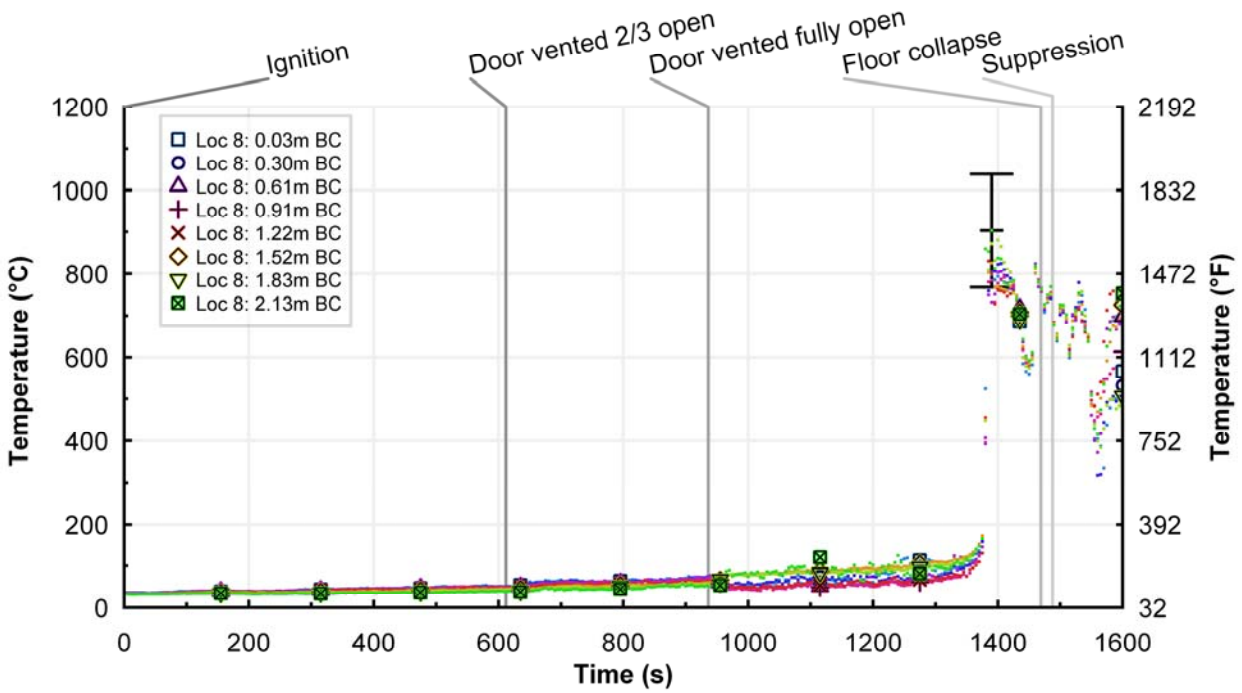

Figure 3-10. Experiment 1, upper level southeast (TC array at location 8), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.1 m (7 ft) below the ceiling versus time

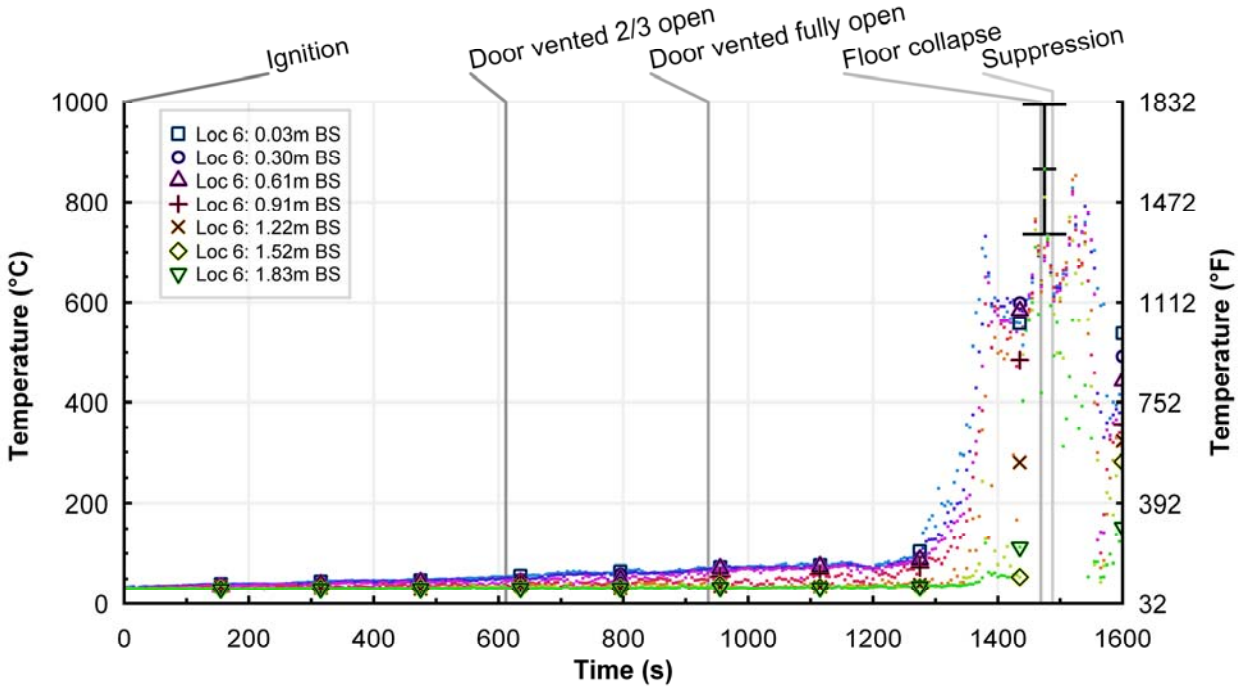

Figure 3-11. Experiment 1, upper level door opening (TC array at location 6), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time

3.1.3 Floor System TC Arrays

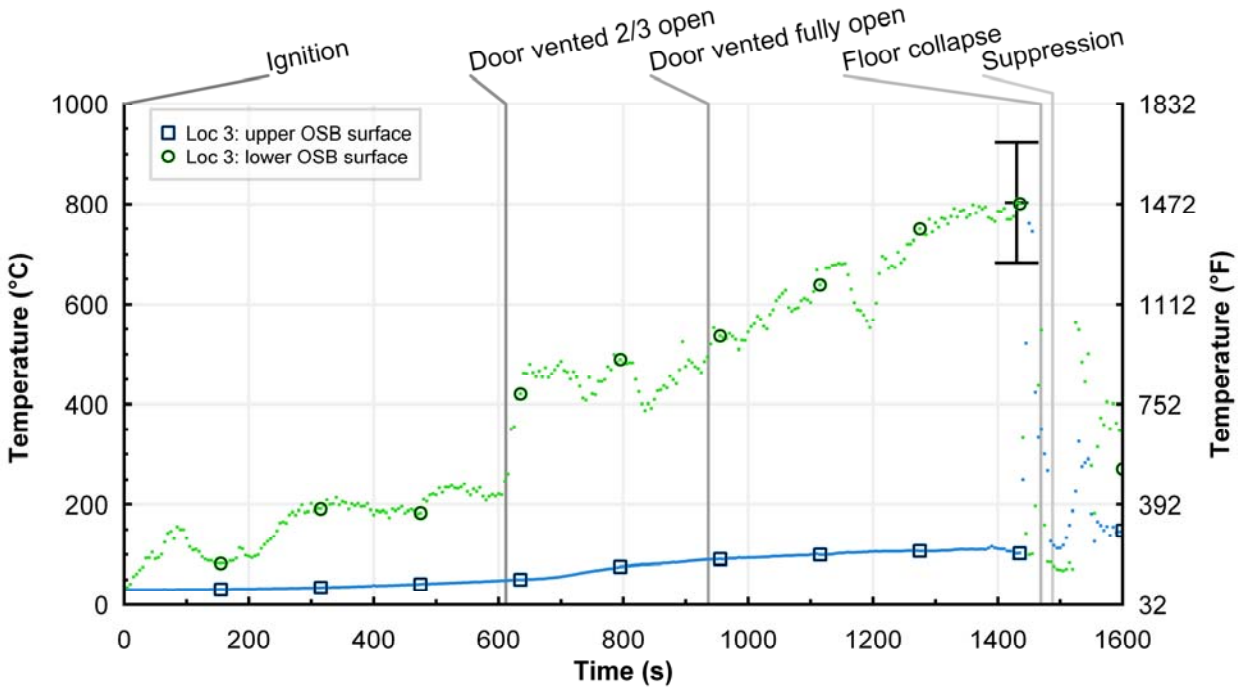

Figure 3-12. Experiment 1 center of fire (floor system TC array at location 3), floor OSB surface temperatures versus time.

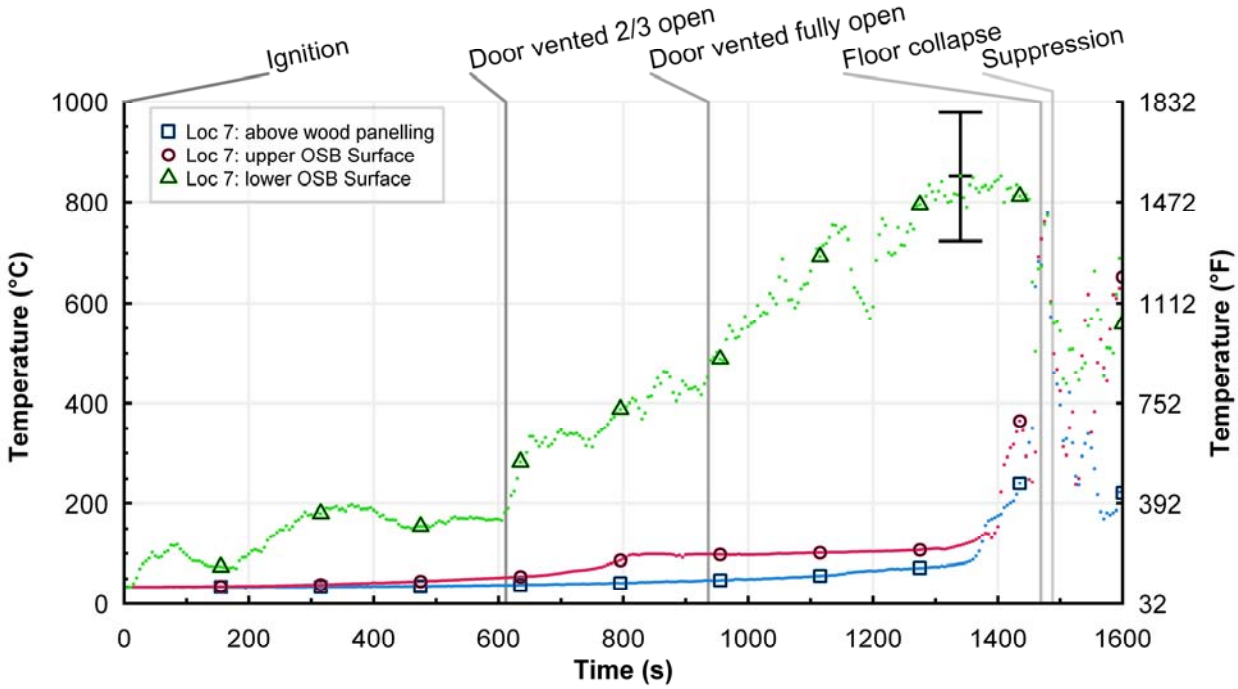

Figure 3-13. Experiment 1, upper level door opening (floor system TC array at location 7), temperatures below OSB, below the floor covering, and above the floor covering versus time.

The temperatures of the sub-floor surfaces just below the water –filled barrels were measured by a floor system TC array at location 3. The temperatures measured by that array are shown in Figure 3-12. The demonstrated the insulation the OSB provided in a full scale fire environment; the peak temperature of the upper surface was approximately 116 ºC (241 ºF) at 1390 s. The lower surface temperature at this time was approximately 770 ºC (1418 ºF).

The floor system TC array at location 7 was located directly in front of the upper level opening so as to measure the temperature of the area immediately visible to a firefighter entering the structure. The temperatures measured by this array are shown in Figure 2-14. This data represents the thermal exposure of the sub floor from below, the temperature conducted through it, and the temperature above the laminate flooring material. Only the flooring material surface would be visible to a thermal imager; the flooring surface deviates noticeably from ambient only when the lower OSB temperature significantly exceeds 600 ºC (1110 ºF)

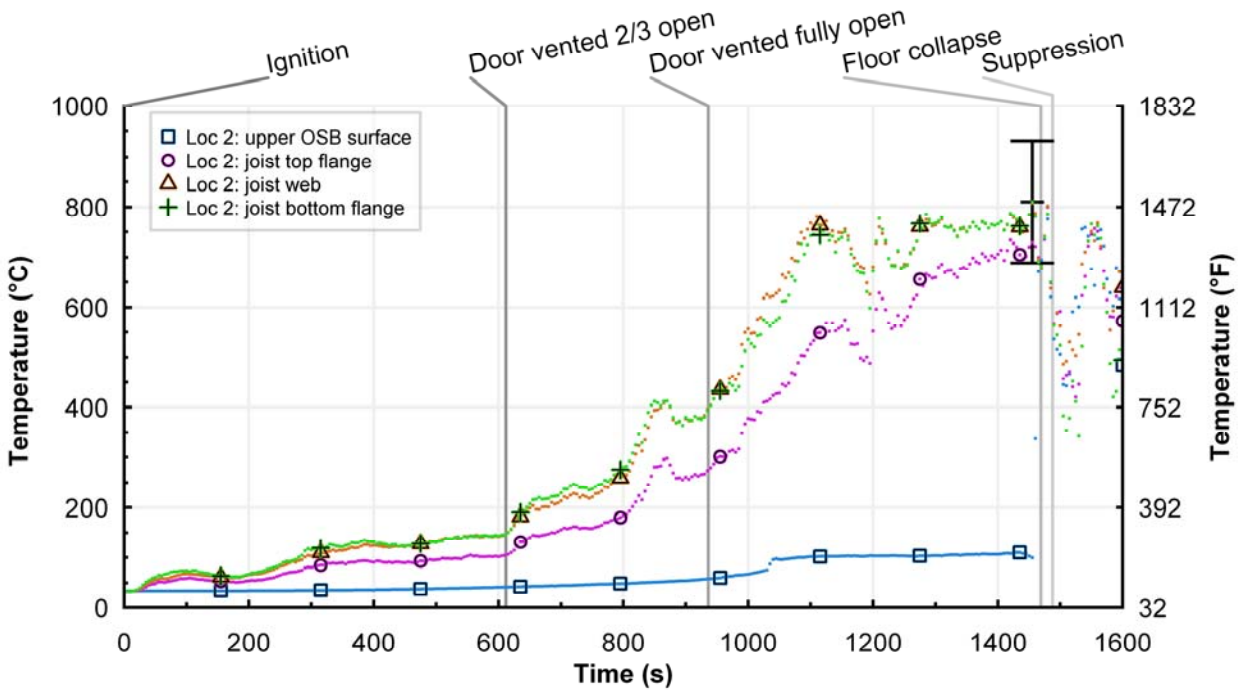

Figure 3-14. Experiment 1, northwestern corner (floor system TC array at location 2), joist through floor temperatures versus time.

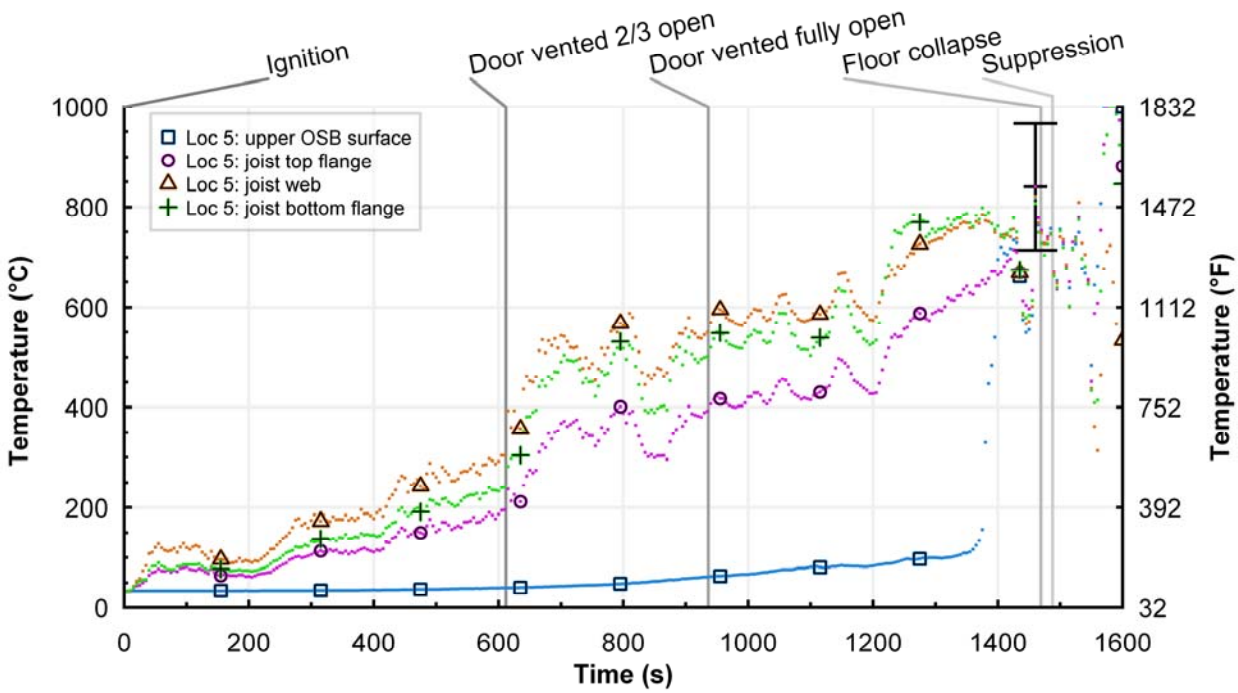

Figure 3-15. Experiment 1, southeastern corner (floor system TC array at location 5), joist through floor temperatures versus time.

Location 5, located in the southeastern corner of the floor system, differed from the other floor system TC arrays in that the sub-floor in this area was not covered by flooring material. Consequently the OSB surface was not insulated from the hot gases in the upper level. The temperatures of this floor system TC array are given in Figure 3-15.

Location 2 was located in the northwestern corner of the floor system, approximately opposite to location 5 in the southeastern corner. The data collected by the array at location 2 is given in Figure 3-14. The temperatures at locations 2 and 5 differed due to the nature of the flow into the compartment. The flow near location 5 was more mixed and less uniform than the flow at location 2. This resulted in greater temperature variations at location 5.

3.2 Experiment 2

The floor cover examined was a carpet surfaced floor with composite wood I-joists spaced 406 mm (16 in) apart, as described in Section 2.1.4. The structure examined in this test was instrumented as described in Section 2.2; the instrumentation locations are shown in Figure 2-17 and Figure 2-18. The timeline for this experiment is presented in Table 3-2.

Table 3-2. Timeline of events for experiment 2, given by approximate start and end times for each event in seconds

Event	Start Time sec (min:sec)	End Time sec (min:sec)
Ignition	0 (00:00)	0 (00:00)
First gypsum board removed	600 (10:00)	605 (10:05)
Second gypsum board removed	1025 (17:05)	1030 (17:10)
Localized flashover	1040 (17:20)	1110 (18:30)
Thermal imagers removed	1090 (18:10)	1090 (18:10)
Complete flashover	1110 (18:30)	-
Floor collapse	1675 (27:55)	1680 (28:00)
Begin extinguishment	1695 (28:15)	

3.2.1 Thermal images

In this experiment, the bottom flange element of the joist to which floor system TC array at location 5 was attached reached 350 ºC (660 ºF) prior to any other measured floor element. This occurred at approximately 935 s after ignition and was used to indicate degradation of the structural integrity of the floor structure.

In this section, the view captured by the thermal imagers located in the upper level doorway are compared at various times. The initial set is given prior to any exposure, the next is given at 935 s after ignition, and the remaining sets are given at 180 s intervals subsequent to 935 s. In this and the following experiments, the reflected coolness of the drums of water is not apparent in the carpet flooring material, although a relatively cold splatter pattern appears in the VO_x images due to cold water, spilled prior to the experiment.

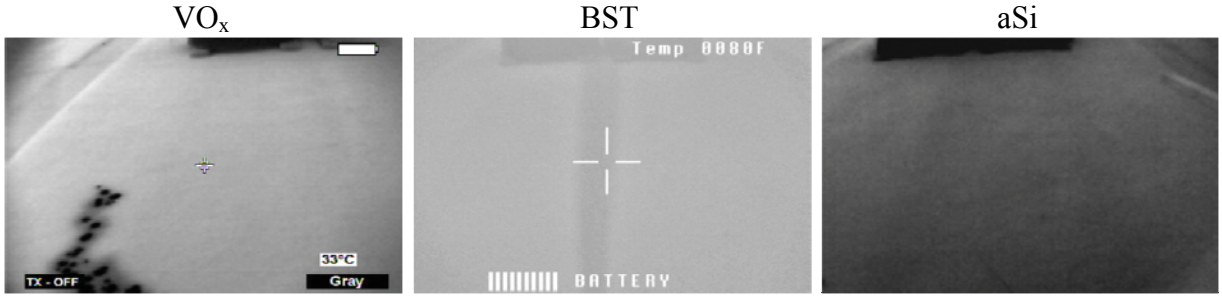

Figure 3-16. Thermal images at the time of ignition, and prior to heating of the floor system elements.

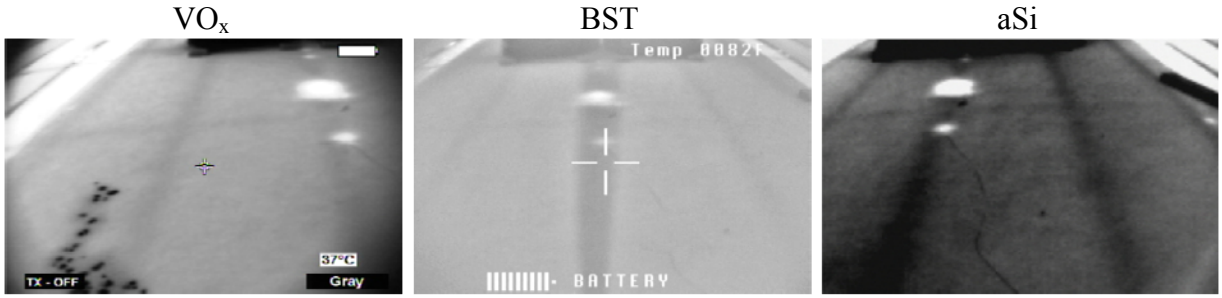

Figure 3-17. Thermal images 935 s after ignition. The joist structure as well as the sub-floor joints are faintly visible in all three viewers, as are several bright spots, due to holes in the sub-floor.

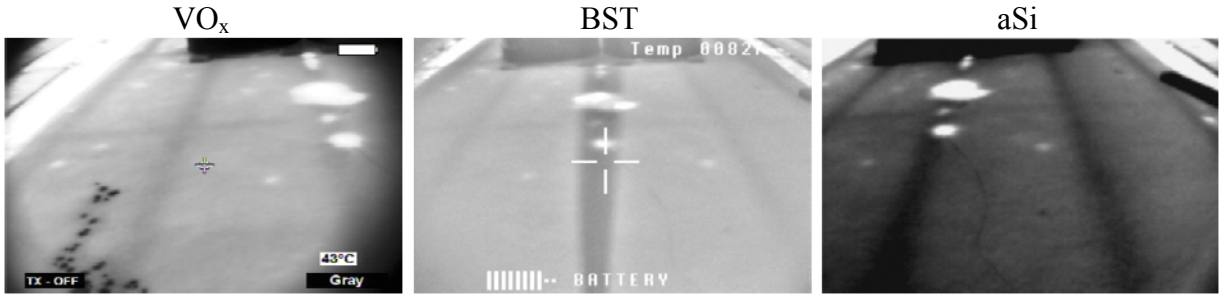

Figure 3-18. Thermal images 1115 s after ignition.

3.2.2 Gas Temperature TC Arrays

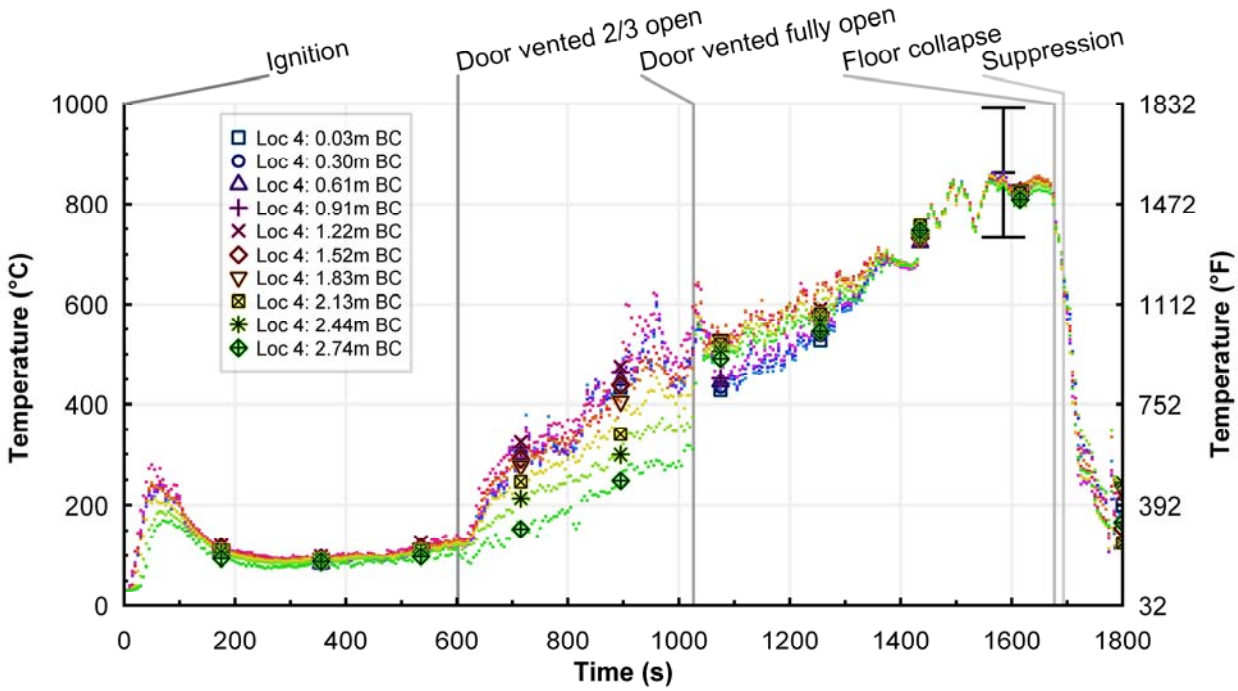

Figure 3-19. Experiment 2, lower level southeastern corner (TC array at location 4), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.7 m (9 ft) below the ceiling versus time.

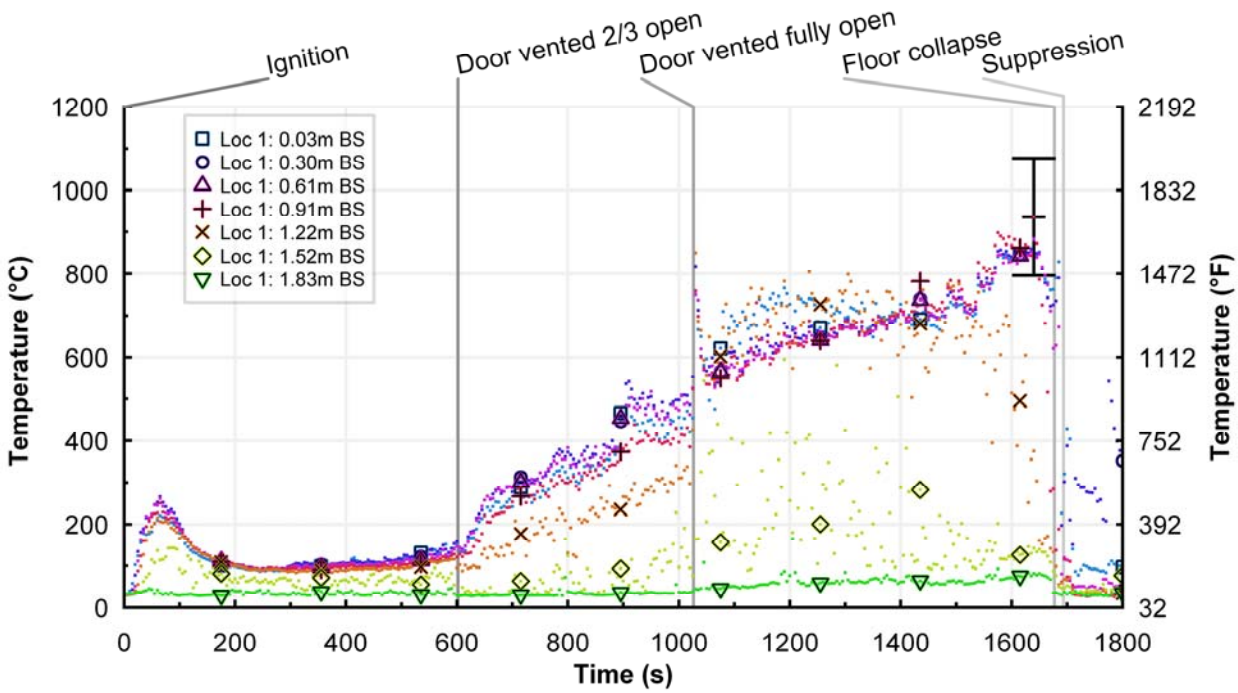

Figure 3-20. Experiment 2, lower floor doorway (TC array at location 1), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

There was a two way flow in the lower level doorway for most of the experiment. Figure 3-20 documents the temperature of gases flowing through the lower level doorway. Combustion outside the lower level entrance was observed approximately 1040 s after ignition. However, unlike experiment 1, a flow of ambient temperature air entering 1.83 m (6 ft) below the soffit level was maintained throughout the experiment.

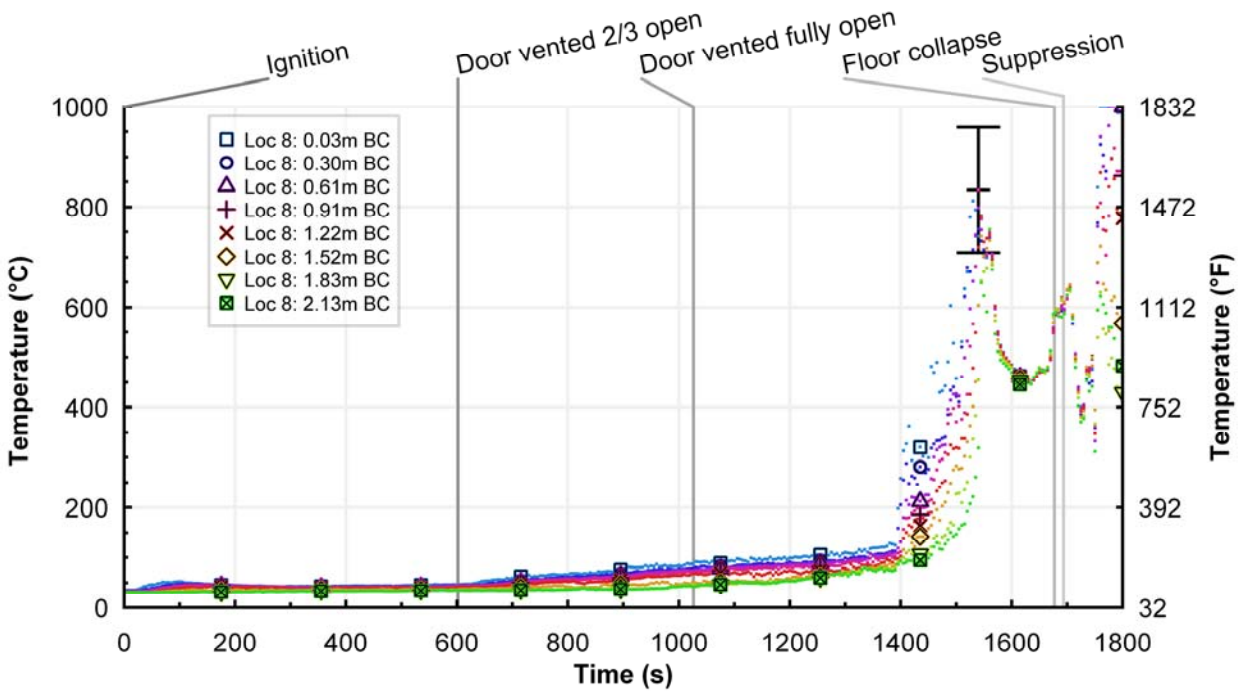

Figure 3-21. Experiment 2, upper level southeast (TC array at location 8), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.1 m (7 ft) below the ceiling versus time.

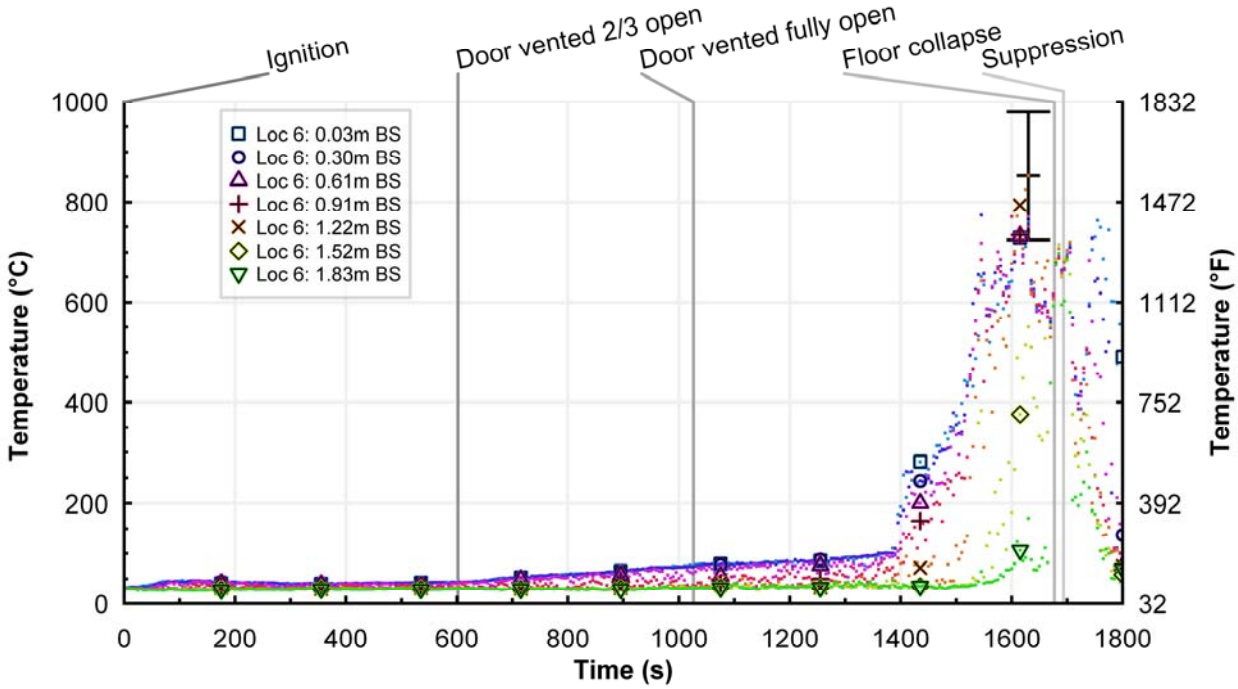

Figure 3-22. Experiment 2, upper level door opening (TC array at location 6), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

Gas temperatures from the southeast corner of the upper level are given in Figure 3-21. Temperatures in this area rose slowly and uniformly, never exceeding 125 ºC (257 ºF), until approximately 1395 s after ignition. At

this point temperatures in the upper level began to rise culminating in a post flashover environment by approximately 1560 s after ignition. Gas temperatures in the upper level doorway are shown in Figure 3-22.

3.2.3 Floor System TC Arrays

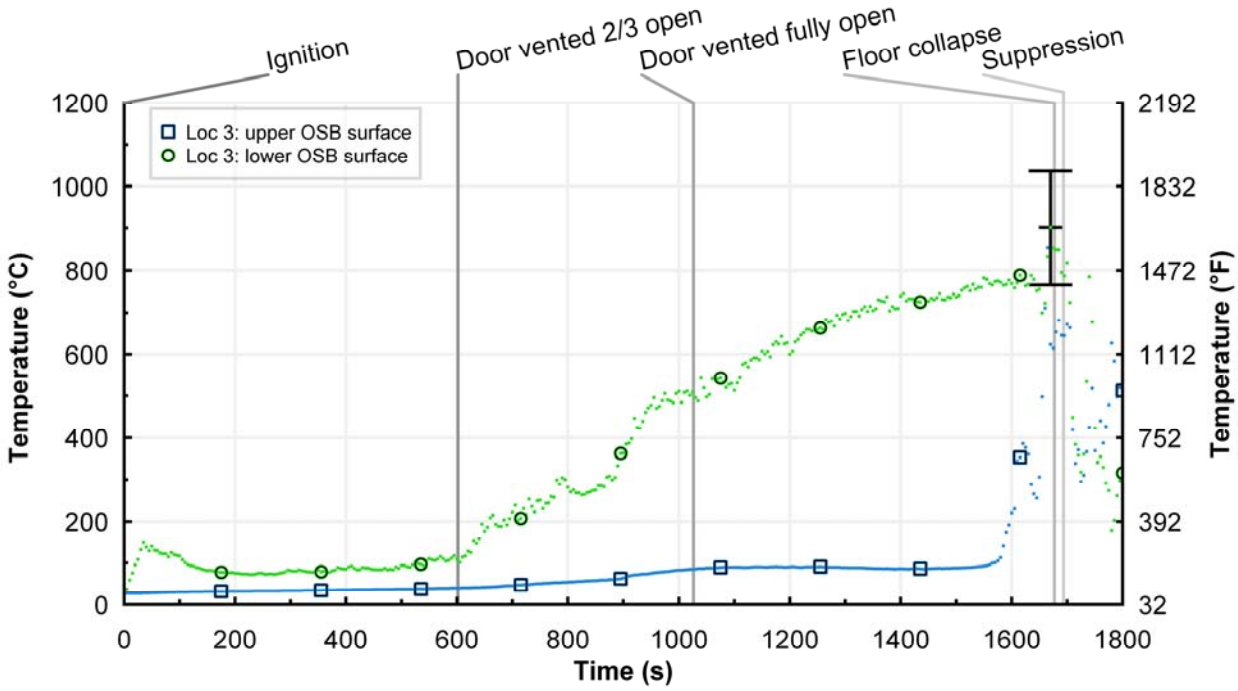

Figure 3-23. Experiment 2 center of fire (floor system TC array at location 3), floor OSB surface temperatures versus time.

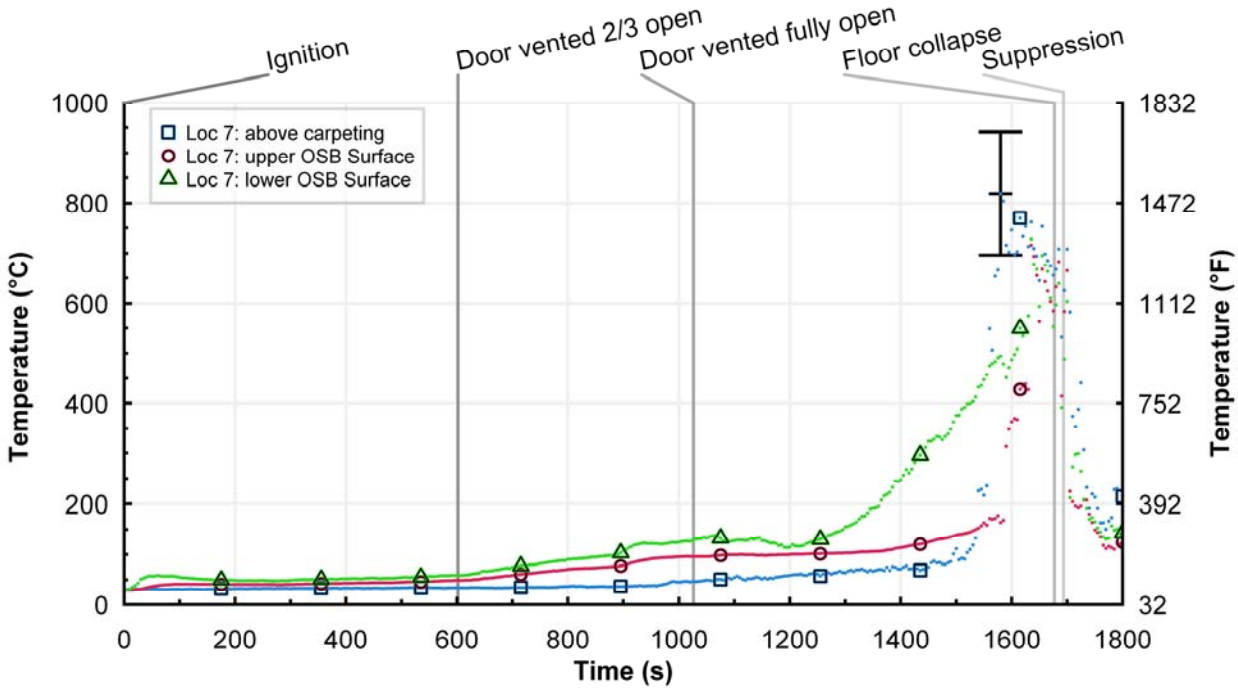

Figure 3-24. Experiment 2, upper level door opening (floor system TC array at location 7), temperatures below OSB, below the floor covering, and above the floor covering versus time.

The temperatures of the sub-floor surfaces just below the water-filled barrels were measured by a floor system TC array at location 3. The temperatures measured by that array are shown in Figure 3-23. This roughly demonstrated the insulation the OSB board provides in a full scale fire environment; upper OSB surface temperature remained below 100 ºC (212 ºF) until approximately 1555 s when the temperature began to increase dramatically. At this point the upper level is transitioned to flashover.

The floor system TC array at location 7 was located 0.5 m (1.7 ft) in front of the upper level doorway so as to measure the temperature of the area immediately visible to a firefighter entering the structure. The temperatures measured by this array are shown in Figure 3-24. The lower OSB surface temperature in this location was distinctly lower than in location 3. The lower surface temperature in location 7 exceeded 400 ºC (752 ºF) only by approximately 1530 s after ignition. Location 3, which was directly above the fuel load, exceeded this lower level OSB temperature by approximately 915 s after ignition. The upper OSB surface temperature began to increase rapidly after approximately 1585 s.

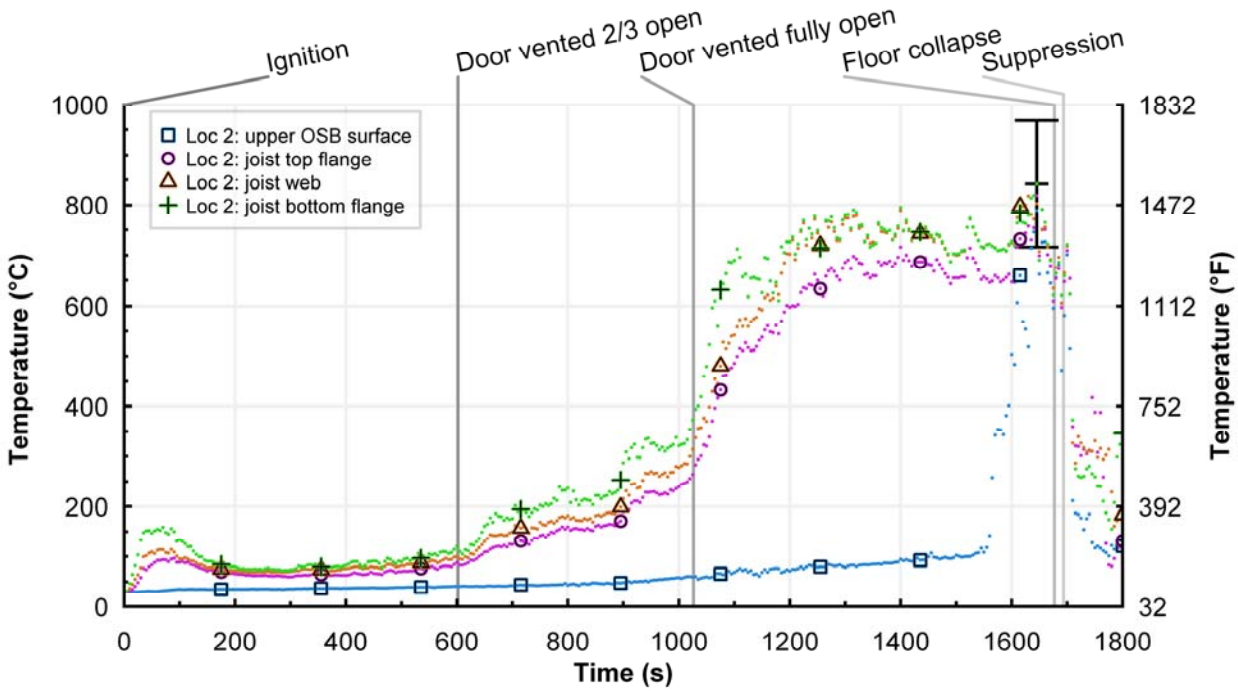

Figure 3-25. Experiment 2, northwestern corner (floor system TC array at location 2), joist through floor temperatures versus time.

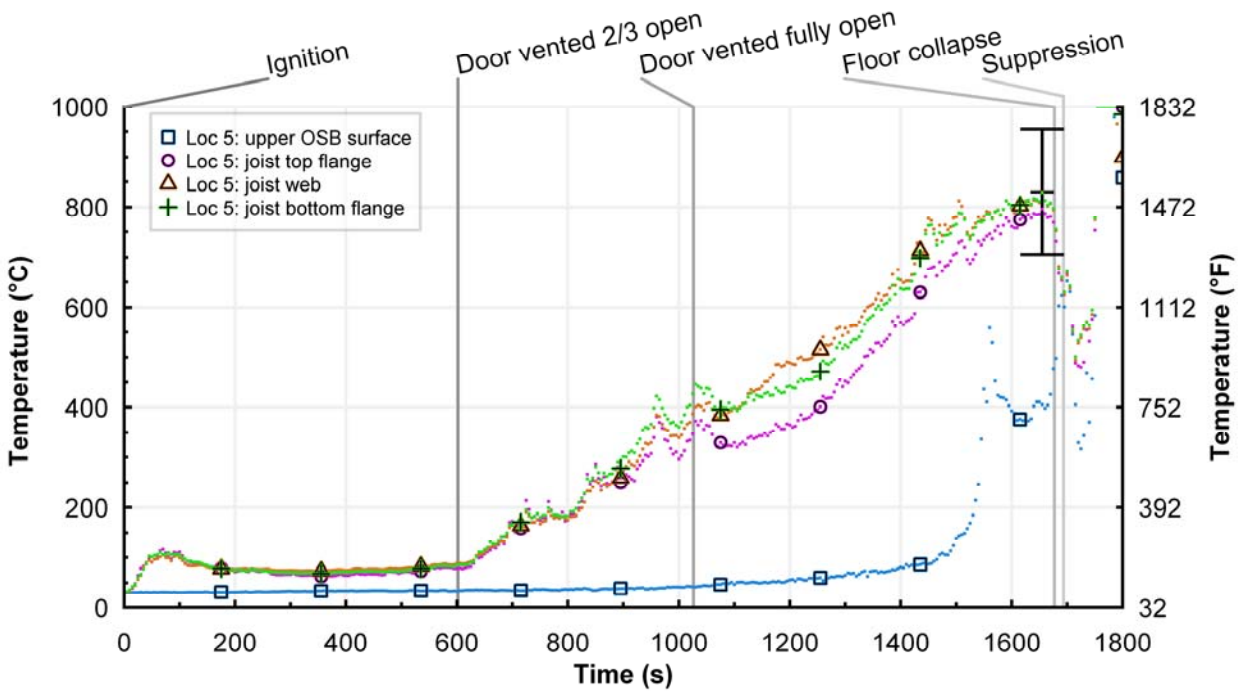

Figure 3-26. Experiment 2, southeastern corner (floor system TC array at location 5), joist through floor temperatures versus time.

Temperatures of the northeast corner floor system array are given in Figure 3-25. The floor surface temperature at this location did not exceed 110 ºC (230 ºF) until approximately 1545 s at which point the floor surface temperature rose rapidly.

Location 5, located in the southeastern corner of the floor system, differed from the other floor system TC arrays in that the sub-floor in this area was not covered by carpet padding. Consequently the OSB surface was not insulated from the hot gases in the upper level. The temperatures of this floor system TC array are given in Figure 3-26.

The progression of exposure of this location was slightly faster than location 2, with the bottom flange element experiencing the most significant exposure throughout most of the test.

3.3 Experiment 3

The floor examined was a carpet surfaced floor with solid wood joists spaced 406 mm (16 in) apart, as described in Section 2.1.5.

The structure examined in this test was instrumented as described in Section 2.2; the instrumentation locations are shown in Figure 2-17 and Figure 2-18. The timeline for this experiment is presented in Table 3-3.

Table 3-3. Timeline of events for experiment 3, given by approximate start and end times for each event in seconds.

Event	Start Time sec (min:sec)	End Time sec (min:sec)
Ignition	0 (00:00)	0 (00:00)
First gypsum board removed	600 (10:00)	600 (10:00)
Second gypsum board removed	930 (15:30)	930 (15:30)
Localized flashover	930 (15:30)	965 (16:05)
Complete flashover	965 (16:05)	-
Thermal imagers removed	1200 (20:00)	1200 (20:00)
Floor collapse	1485 (24:45)	1485 (24:45)
Begin extinguishment	1505 (25:05)	

3.3.1 Thermal images

In this experiment the vertical center of the joist to which the floor system TC array at location 2 was attached reached 350 ºC (660 ºF) prior to any other measured floor element. This occurred at approximately 640 s after ignition and was used to indicate degradation of the structural integrity of the floor structure.

In this section the view captured by the thermal imagers located in the upper level doorway are compared at various times. The initial set is given prior to any exposure, the next is given at 640 s after ignition, and the remaining sets are given at 180 s intervals subsequent to 640 s.

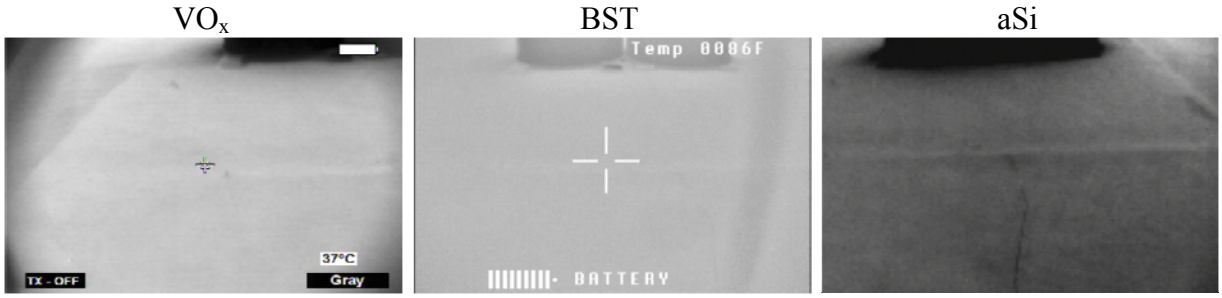

Figure 3-27. Thermal images at the time of ignition and prior to heating of the floor system elements; a TC array is visible to the right of the center view and appears as a dark line

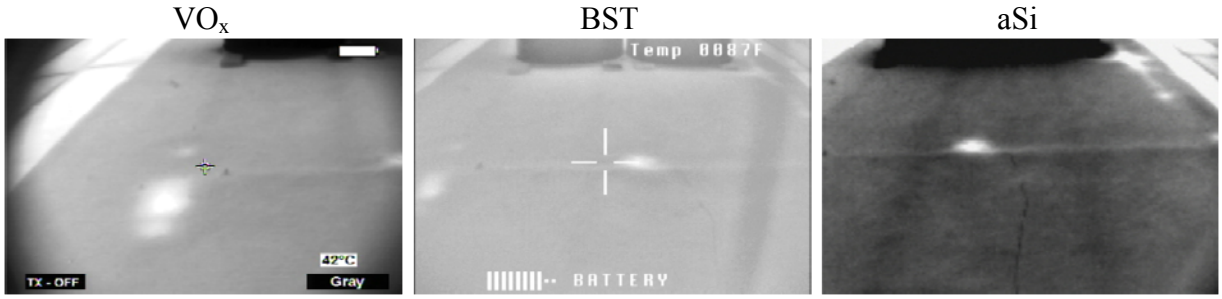

Figure 3-28. Thermal images at 640 s after ignition, the joist structure as well as the sub-floor joints are faintly visible in two of the three views, several bright spots from holes or gaps in the sub-floor are visible in all views.

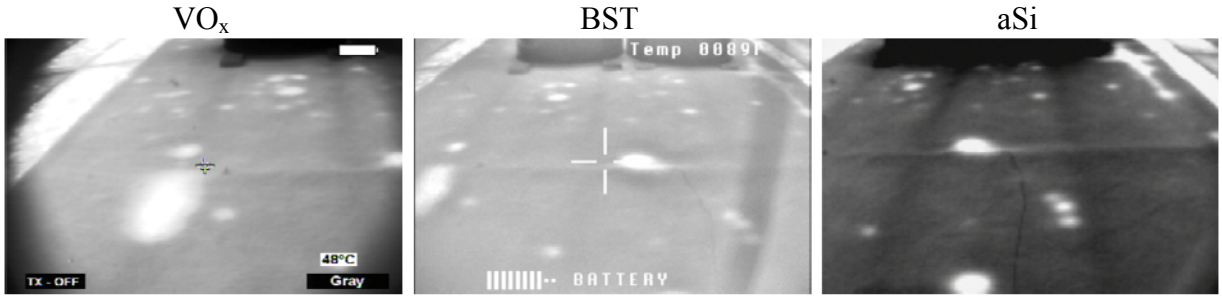

Figure 3-29. Thermal images 820 s after ignition

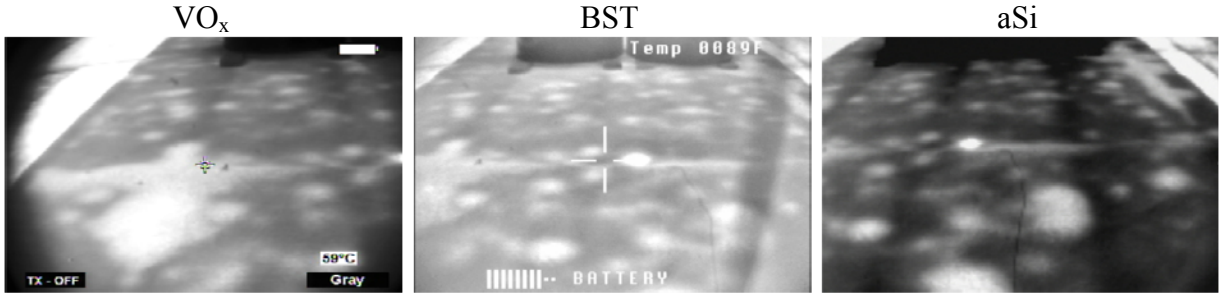

Figure 3-30. Thermal images 1000 s after ignition

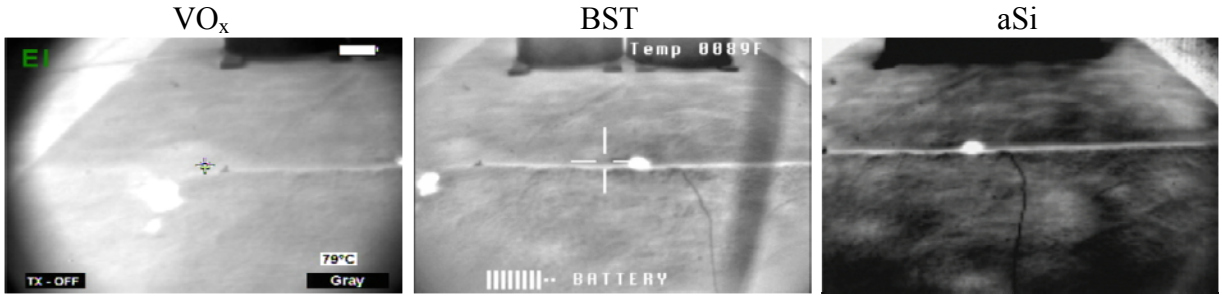

Figure 3-31. Thermal images 1180 s after ignition

3.3.2 Gas Temperature TC Arrays

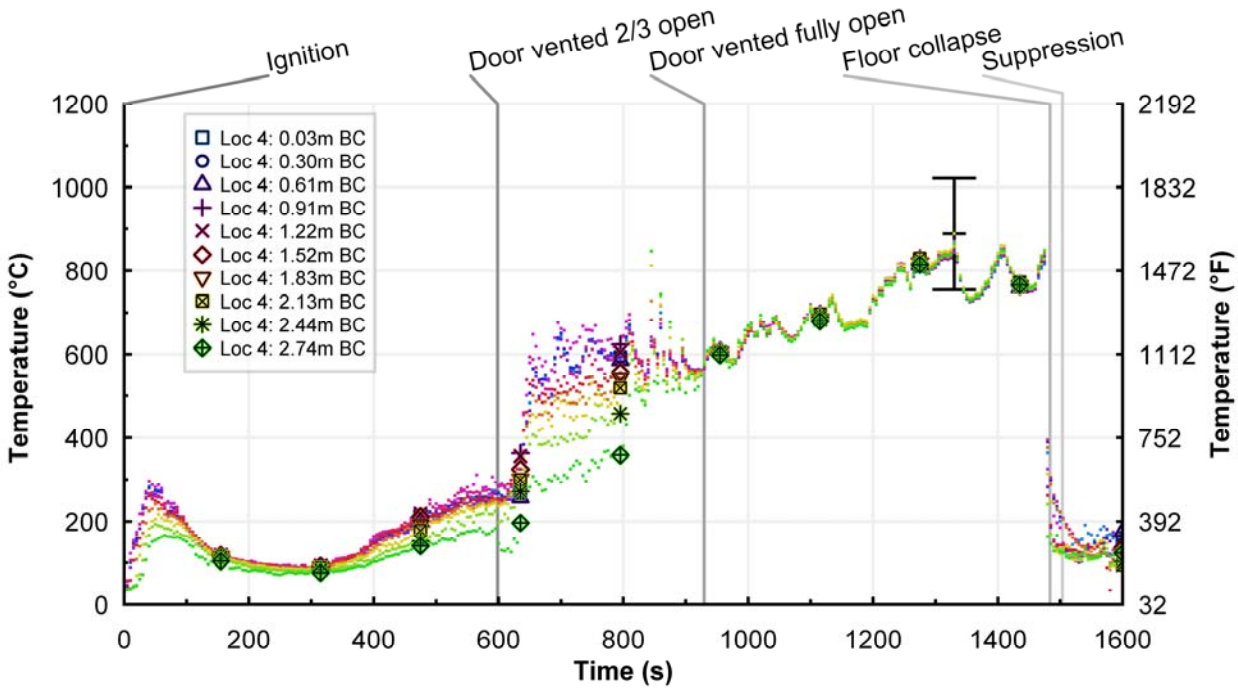

Figure 3-32. Experiment 3, lower level southeastern corner (TC array at location 4), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.7 m (9 ft) below the ceiling versus time.

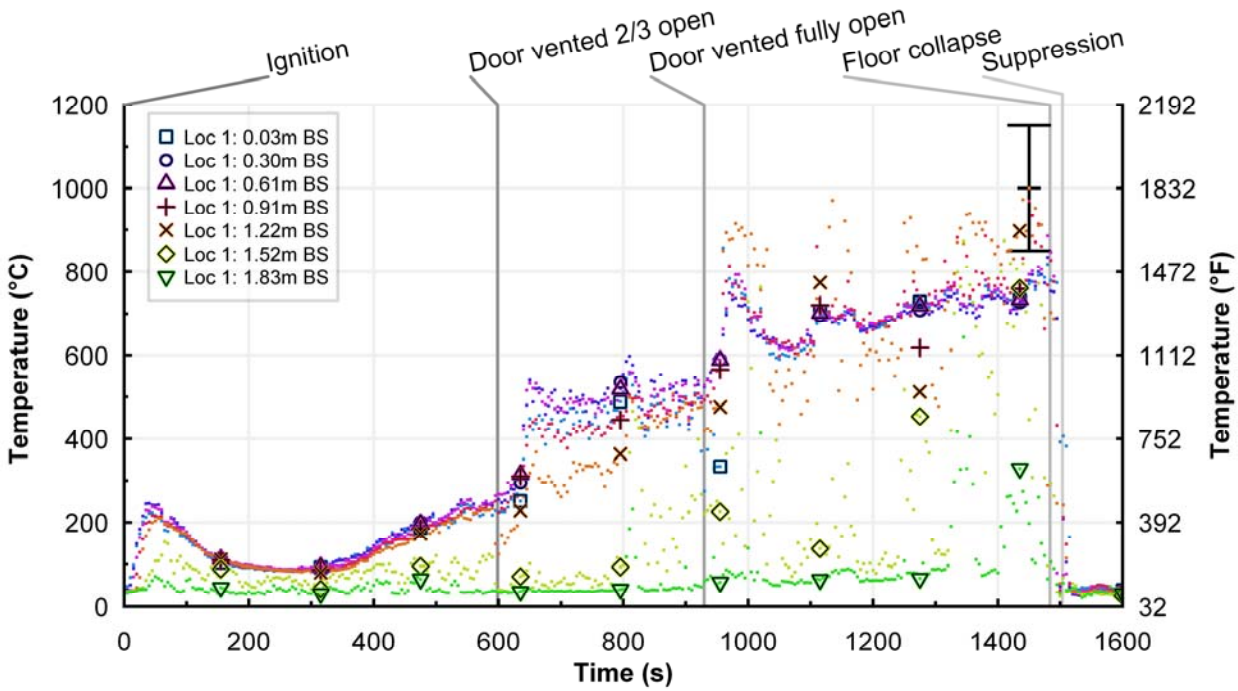

Figure 3-33. Experiment 3, lower floor doorway (TC array at location 1), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

Figure 3-32 shows the temperatures measured by the TC array, Location 4, positioned in the southeastern corner of the lower level. As observed in experiment 1, this array does not provide an accurate representation of the gas temperatures across the entire lower level, but it does provide an approximation of the fire intensity as well as response to changes in ventilation.

There was a two-way flow in the lower level doorway for most of the experiment. Figure 3-33 shows the temperature of gases flowing through the lower level doorway. Combustion outside the lower level entrance was observed approximately 965 s after ignition. The temperature peaks measured at the 1.83 below the soffit level at approximately 1325 s and 1405 s was due to pulsing and turbulence in the flow through the lower level door.

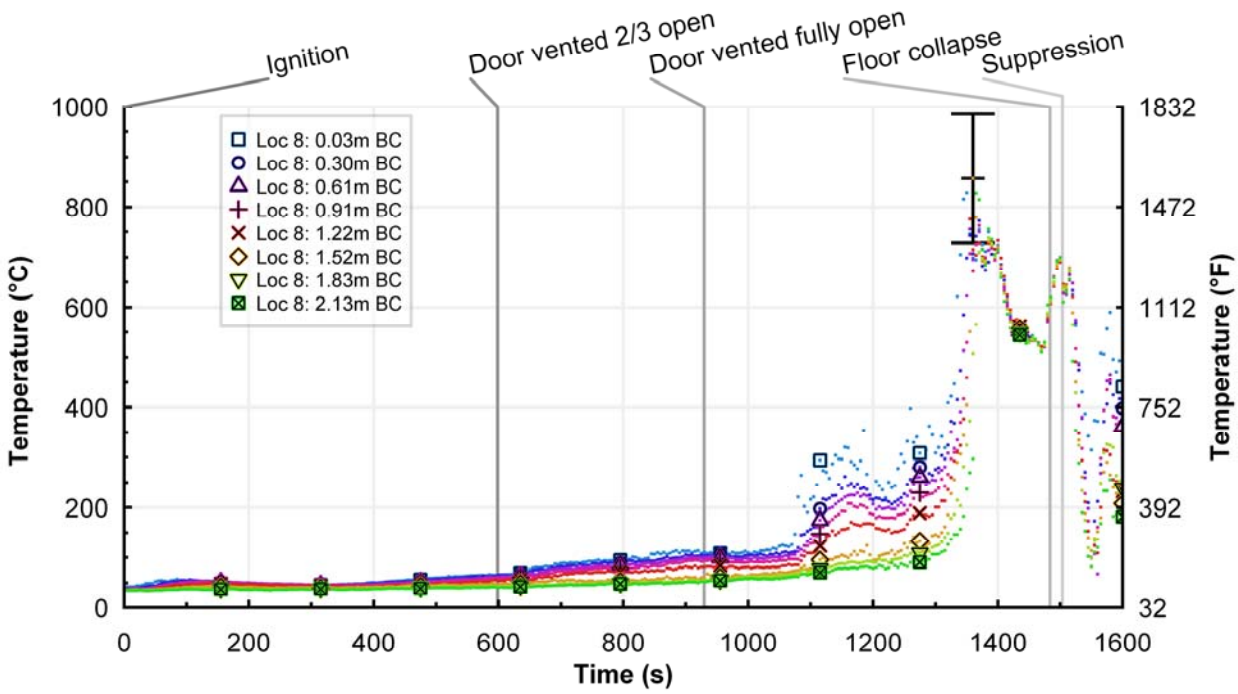

Figure 3-34. Experiment 3, upper level southeast (TC array at location 8), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.1 m (7 ft) below the ceiling versus time.

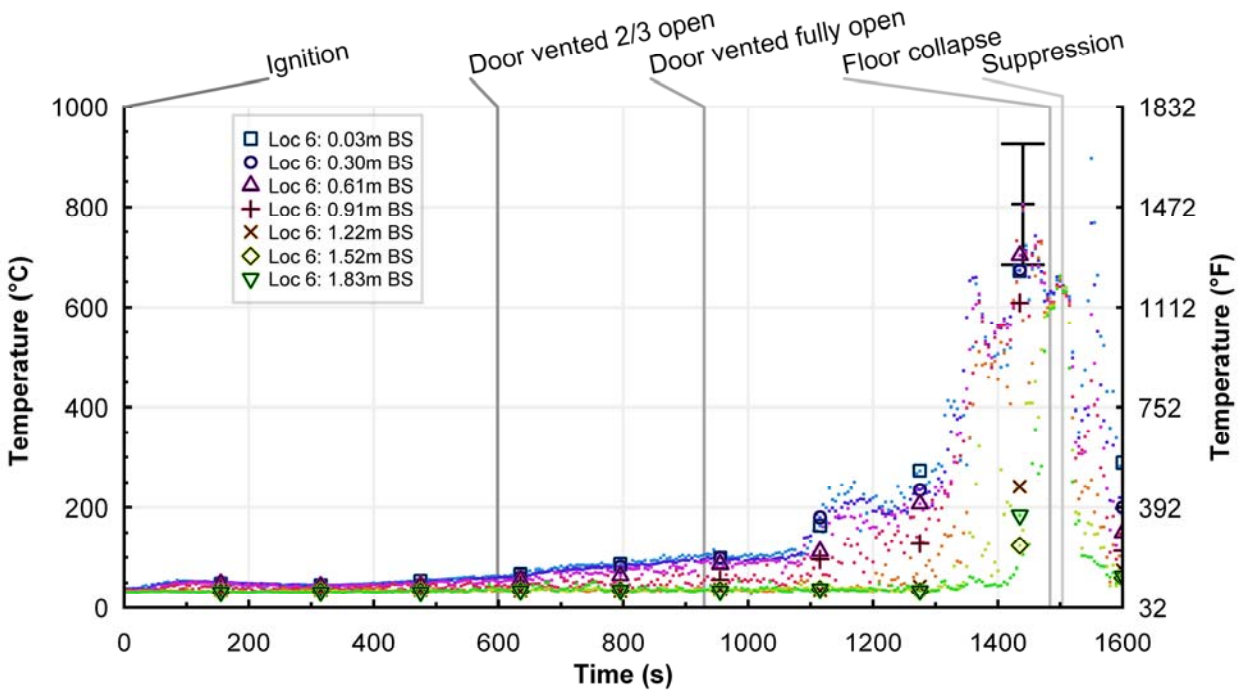

Figure 3-35. Experiment 3, upper level door opening (TC array at location 6), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

Gas temperatures from the southeast corner of the upper level are given in Figure 3-34. Temperatures in this area rose slowly and uniformly, never exceeding 130 ºC (266 ºF), until approximately 1075 s after ignition. At this point temperatures in the upper level began to rise, culminating in a post flashover environment by approximately 1365 s after ignition. Gas temperatures in the upper level doorway are shown in Figure 3-35.

3.3.3 Floor System TC Arrays

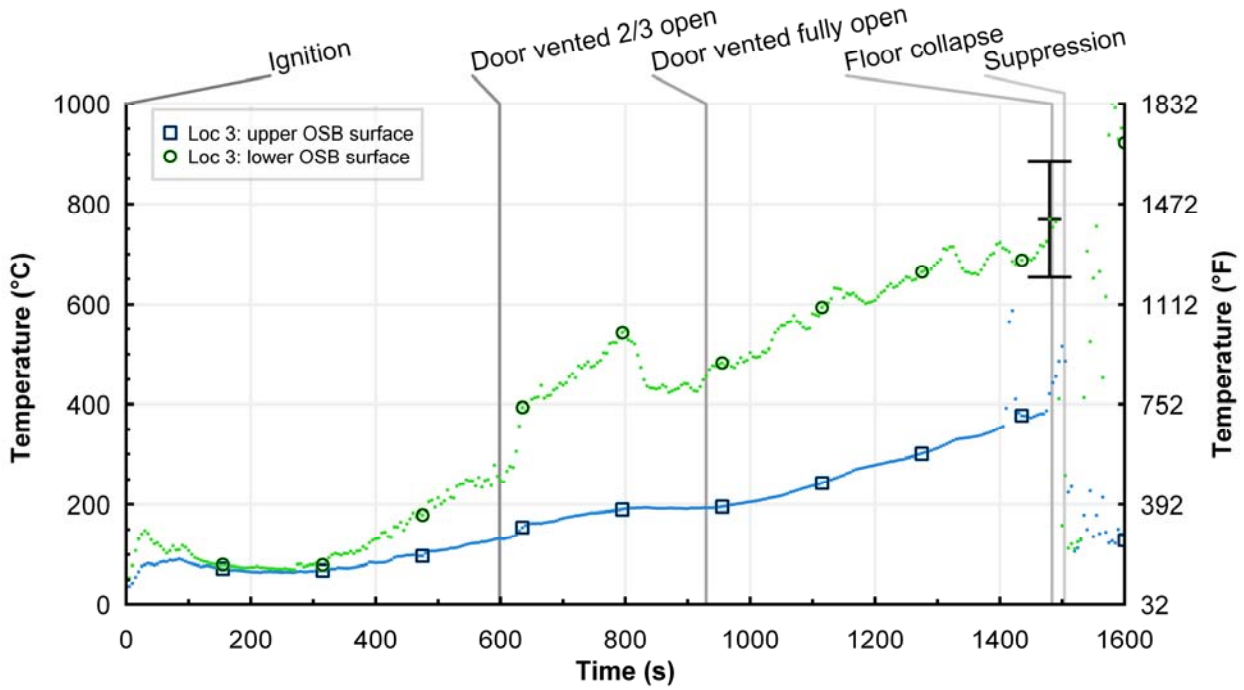

Figure 3-36. Experiment 3, center of fire (floor system TC array at location 3), floor OSB surface temperatures versus time.

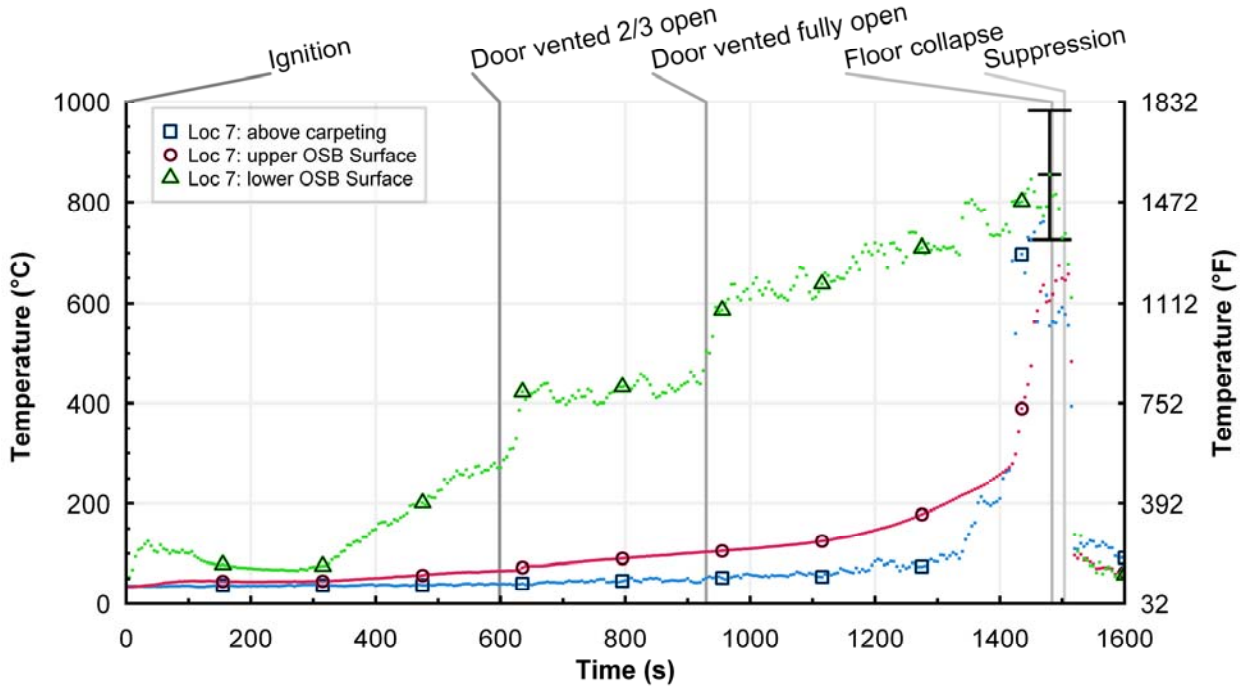

Figure 3-37. Experiment 3, upper level door opening (floor system TC array at location 7), temperatures below OSB, below the floor covering, and above the floor covering versus time

The floor temperature at the floor system TC array at location 3 reflected temperatures significantly above what is to be expected by conduction alone. The likely explanation was small leakage around the OSB sub floor members. This likely caused sub-floor surface TCs at locations 2 and 7 to be heated, as those TCs were also under the carpeting material.

The floor system TC array at location 7 was located directly in front of the upper level opening so as to measure the temperature in the area immediately visible to a firefighter entering the structure. The temperatures measured by this array are shown in Figure 3-24.

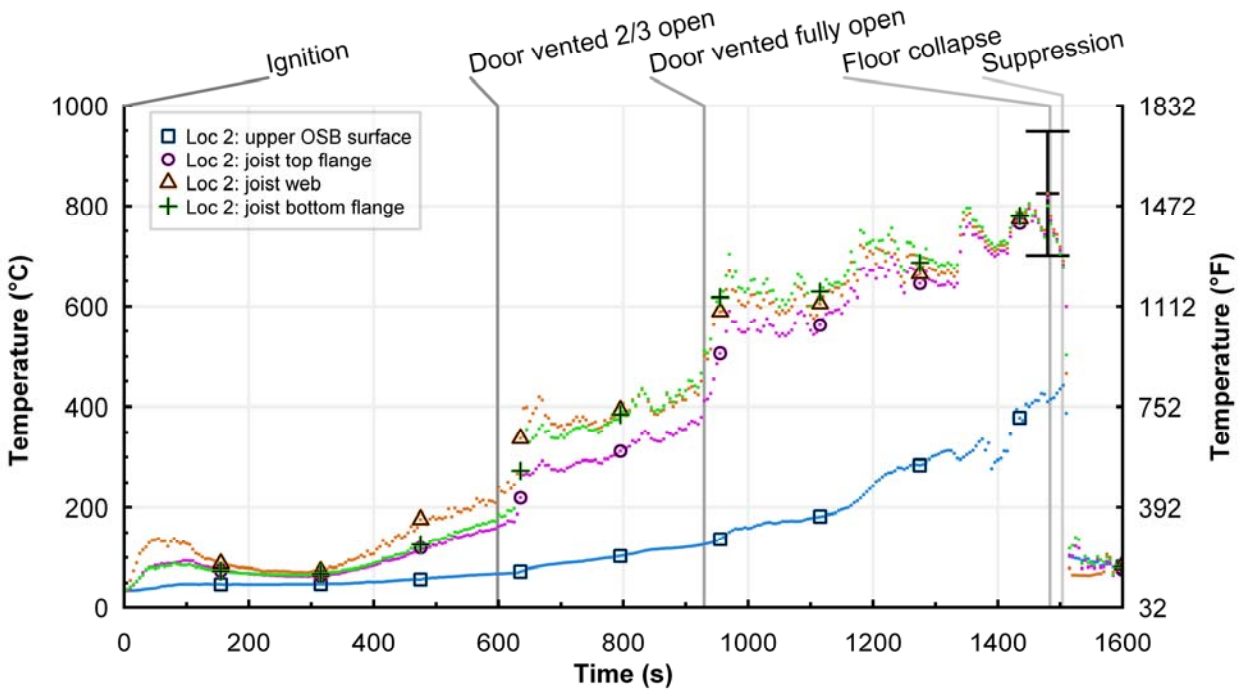

Figure 3-38. Experiment 3, northwestern corner (floor system TC array at location 2), joist through floor temperatures versus time.

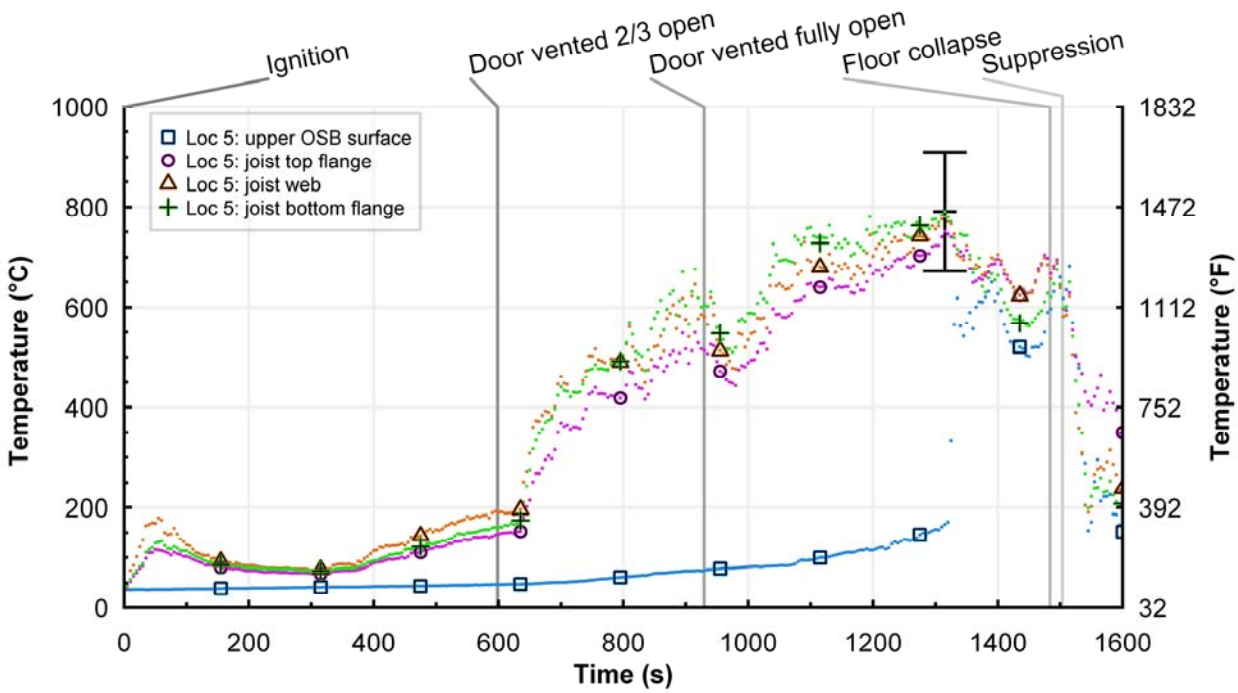

Figure 3-39. Experiment 3, southeastern corner (floor system TC array at location 5), joist through floor temperatures versus time.

Location 5, located in the southeastern corner of the floor system, differed from the other floor system TC arrays in that the sub-floor in this area was not covered by flooring material. Consequently the OSB surface was not insulated from the hot gases in the upper level. The temperatures of this floor system TC array are given in Figure 3-39. The floor surface temperature starts to increase rapidly by 1325 s after ignition.

Location 2 was in the northwestern corner of the floor system, approximately symmetric to location 5. The data collected by the array at location 2 is given in Figure 3-38. The arrays at locations 2 and 5 measured temperatures on the same components and consequently are a valuable comparison of the exposure at different locations but the same time. The temperatures at these locations responded very differently to the ventilation events.

3.4 Experiment 4

The floor system installed for this experiment had carpet and padding over OSB sub-floor supported with composite wood I-joists spaced 610 mm (24 in) apart. A more detailed description of the structure used in experiment 4 is discussed in Section 2.1.6. The structure examined in this test was instrumented as described in Section 2.2; the instrumentation locations are noted in Figure 2-17 and Figure 2-18. Experiment 4 differed from the other experiments in that a layer of 12.7 mm (0.5 in) gypsum board was installed on the bottom of the floor assembly. Therefore most of the flooring assembly was protected from the pallet fueled fire and did not contribute to the fuel load. As a result flashover conditions were not achieved in the lower level and there was no structural collapse event. The timeline for this experiment is presented in Table 3-4.

Table 3-4. Timeline of events for experiment 4, given by approximate start and end times for each event in seconds.

Event	Start Time sec (min:sec)	End Time sec (min:sec)
Ignition	0 (00:00)	0 (00:00)
First gypsum board removed	600 (10:00)	600 (10:00)
Second gypsum board removed	930 (15:30)	930 (15:30)
Gap in gypsum above fire	1235 (20:35)	1235 (20:35)
Section of gypsum above fire falls	1345 (22:25)	1345 (22:25)
Flames visible on upper level	1460 (24:20)	1460 (24:20)
Thermal imagers removed	1685 (28:05)	1685 (28:05)
Flashover in upper level	2190 (36:30)	2195 (36:35)
Begin extinguishment	2265 (37:45)	

3.4.1 Thermal images

The joist structure in this experiment was protected by a 12.7 mm (0.5 in) thick gypsum board ceiling in the lower level which was screwed to the bottom edge of the joist. The insulation provided caused sporadic heating of the joist structure as the gypsum board ceiling failed and exposed the joists. Prior to any failure, no element of the floor structure measured approached 350 ºC (660 ºF). The gypsum ceiling failed in many small increments, but the first significant single failure occurred at approximately1410 s when a full sheet of gypsum board fell from the ceiling above the fuel load. This failure is used as the compromising event for this experiment.

In this section the view captured by the thermal imagers located in the upper level doorway are compared at various times. The initial set is given prior to any exposure, the next is given at 1410 s after ignition, and the remaining sets are given at 180 s intervals subsequent to 1410 s.

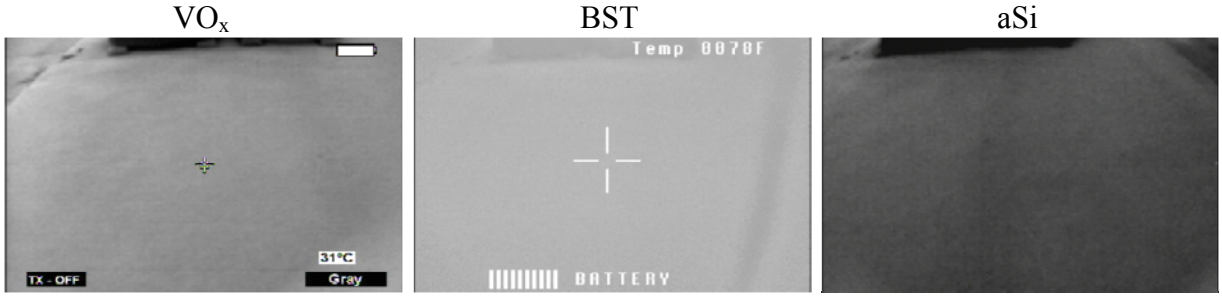

Figure 3-40. Thermal images at the time of ignition; this is prior to heating of the floor system elements.

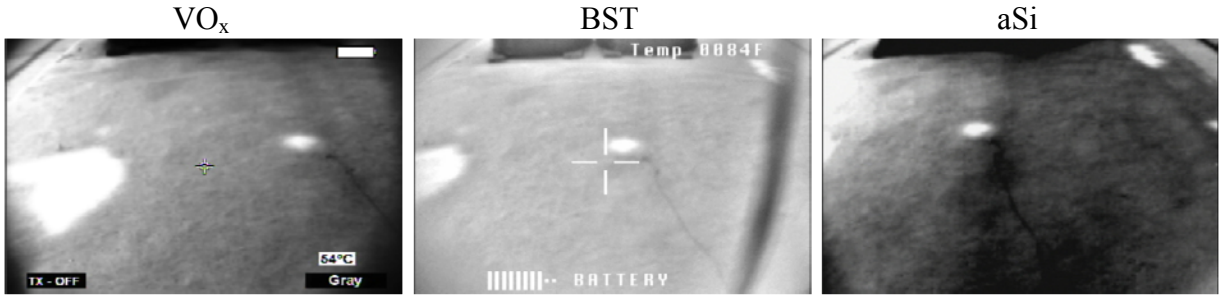

Figure 3-41. Thermal images 1410 s after ignition.

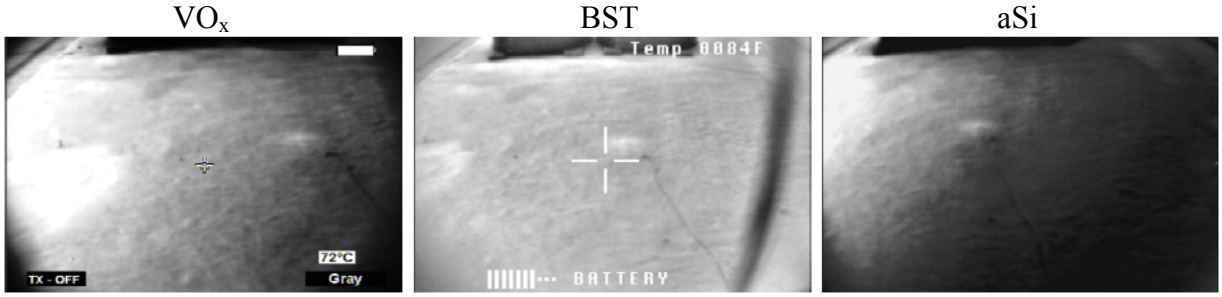

Figure 3-42. Thermal images 1590 s after ignition.

3.4.2 Gas Temperature TC Arrays

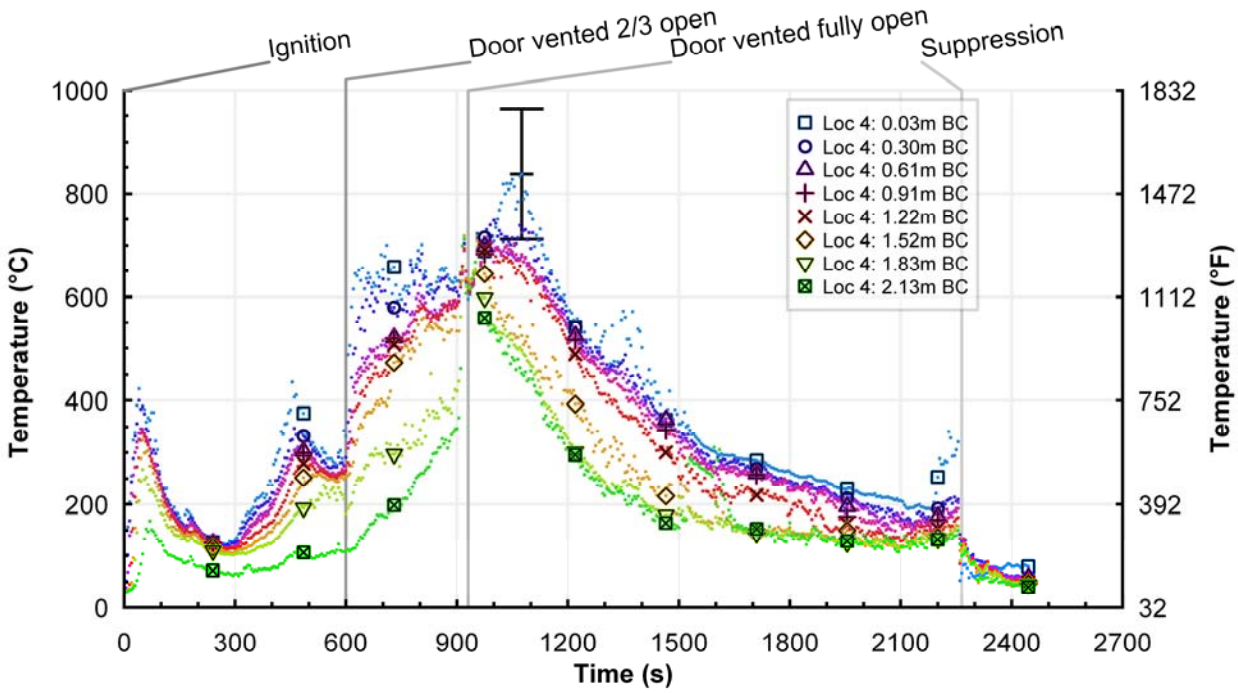

Figure 3-43. Experiment 4, lower level southeastern corner (TC array at location 4), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.1 m (7 ft) below the ceiling versus time.

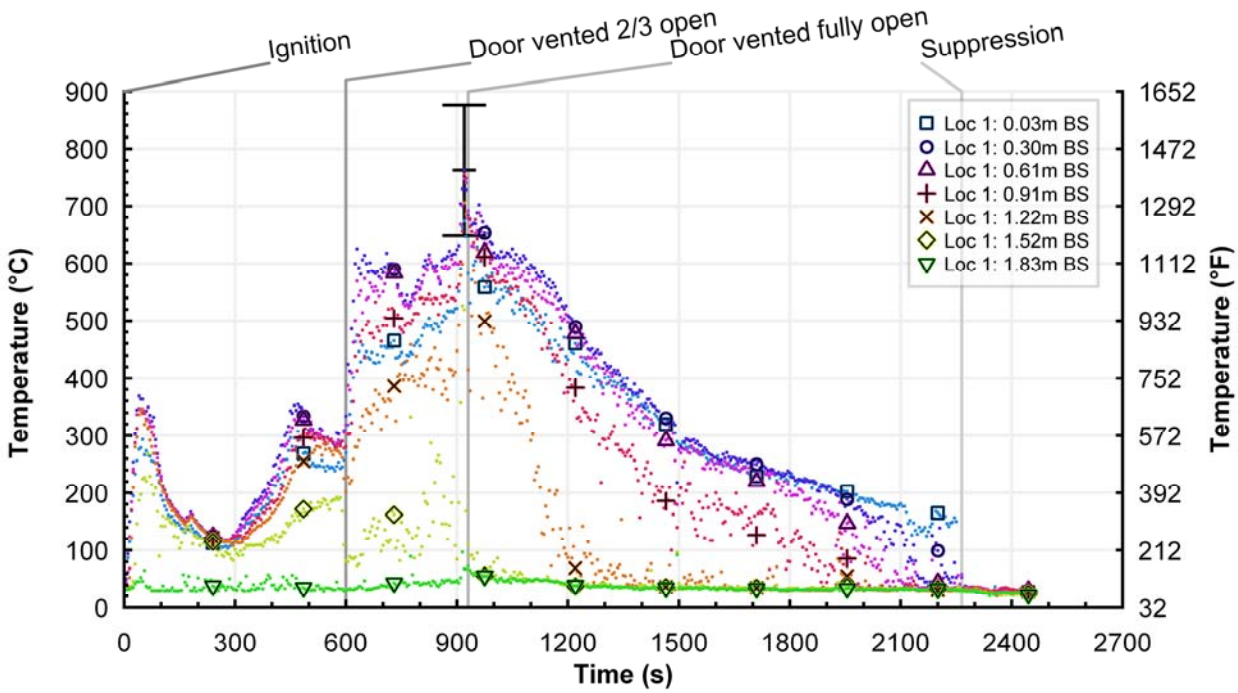

Figure 3-44. Experiment 4, lower floor doorway (TC array at location 1), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

Figure 3-43 shows the temperatures measured by the TC array positioned in the southeastern corner of the lower level. As observed in experiment 1, this array is not an accurate measure of the gas temperatures in the entire lower level, but it does provide an approximation of the fire intensity as well as response to changes in ventilation.

There was a two-way flow in the lower level doorway for most of the experiment. Figure 3-44 shows the temperature of gases flowing through the lower level doorway. Temperature inside the structure was never sufficient to support combustion outside the doorway as in the other experiments.

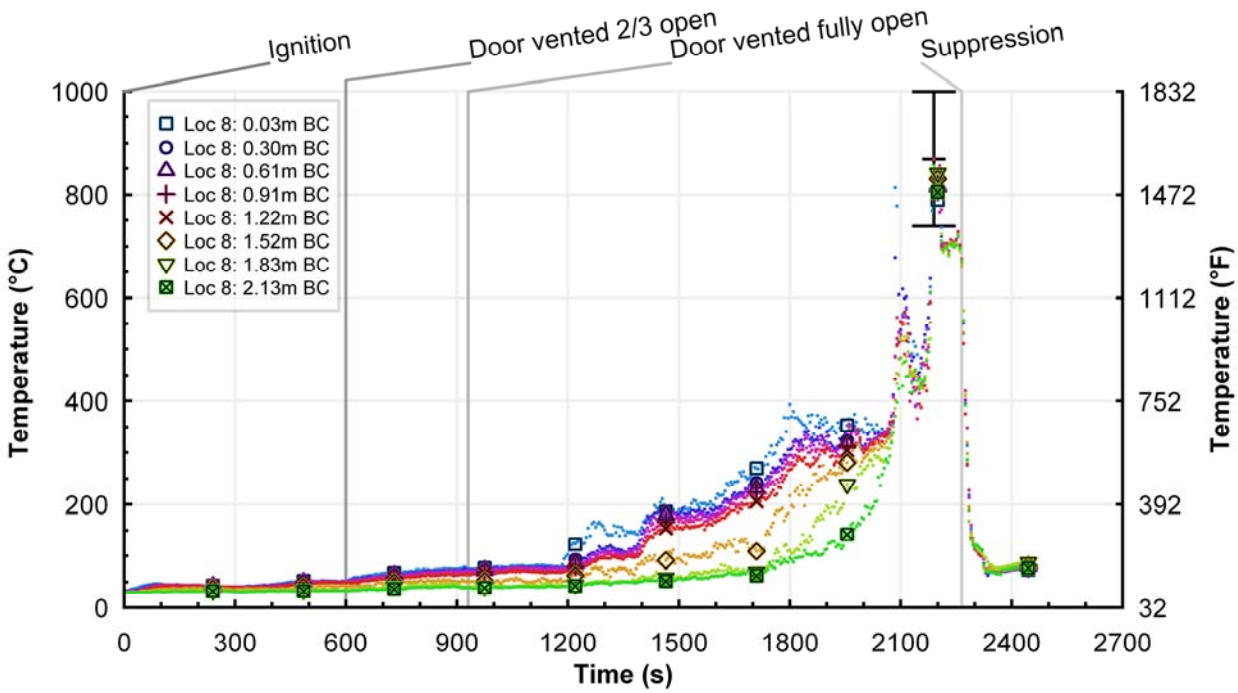

Figure 3-45. Experiment 4, upper level southeast (TC array at location 8), gas temperatures from 0.03 m (1 in) below the ceiling (BC) to 2.1 m (7 ft) below the ceiling versus time.

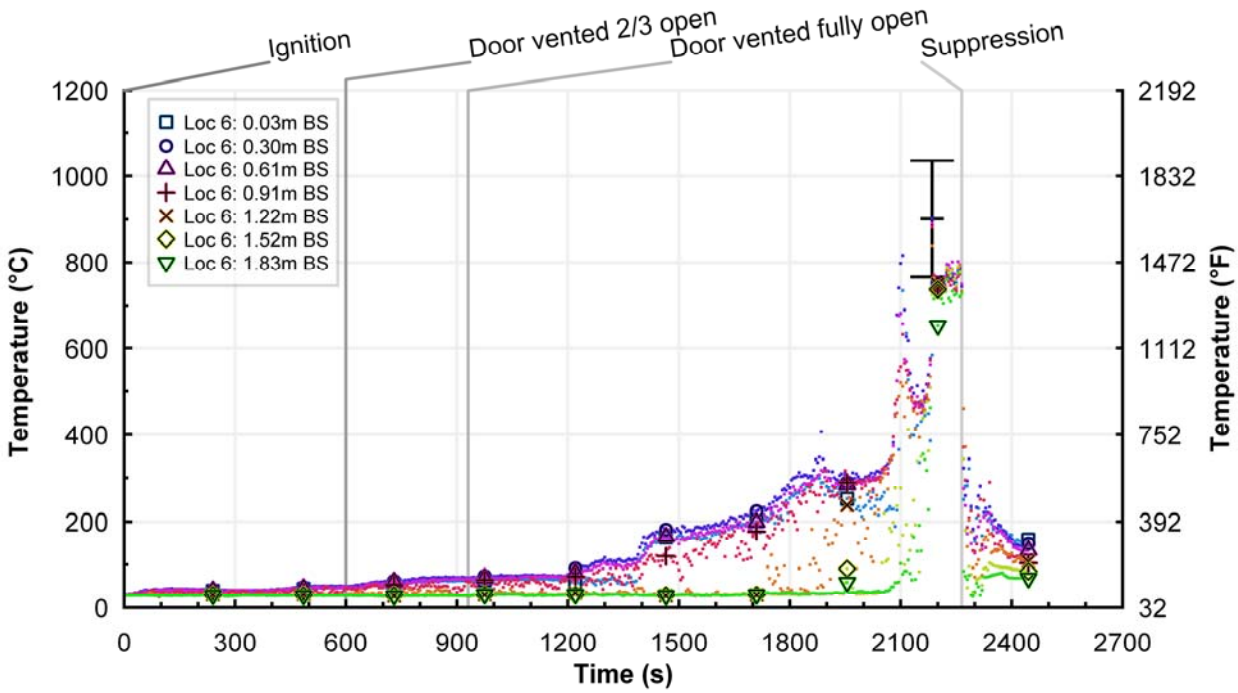

Figure 3-46. Experiment 4, upper level door opening (TC array at location 6), gas temperatures from 0.03 m (1 in) below the soffit (BS) to 1.8 m (6 ft) below the soffit versus time.

Gas temperatures from the southeast corner of the upper level are given in Figure 3-45. Temperatures in this area rose slowly and uniformly, never exceeding 90 ºC (194 ºF), until approximately 1185 s after ignition. At that time, temperatures in the upper level began to rise culminating in a post flashover environment by approximately 2185 s after ignition. Gas temperatures in the upper level doorway are shown in Figure 3-46.

3.4.3 Floor System TC Arrays

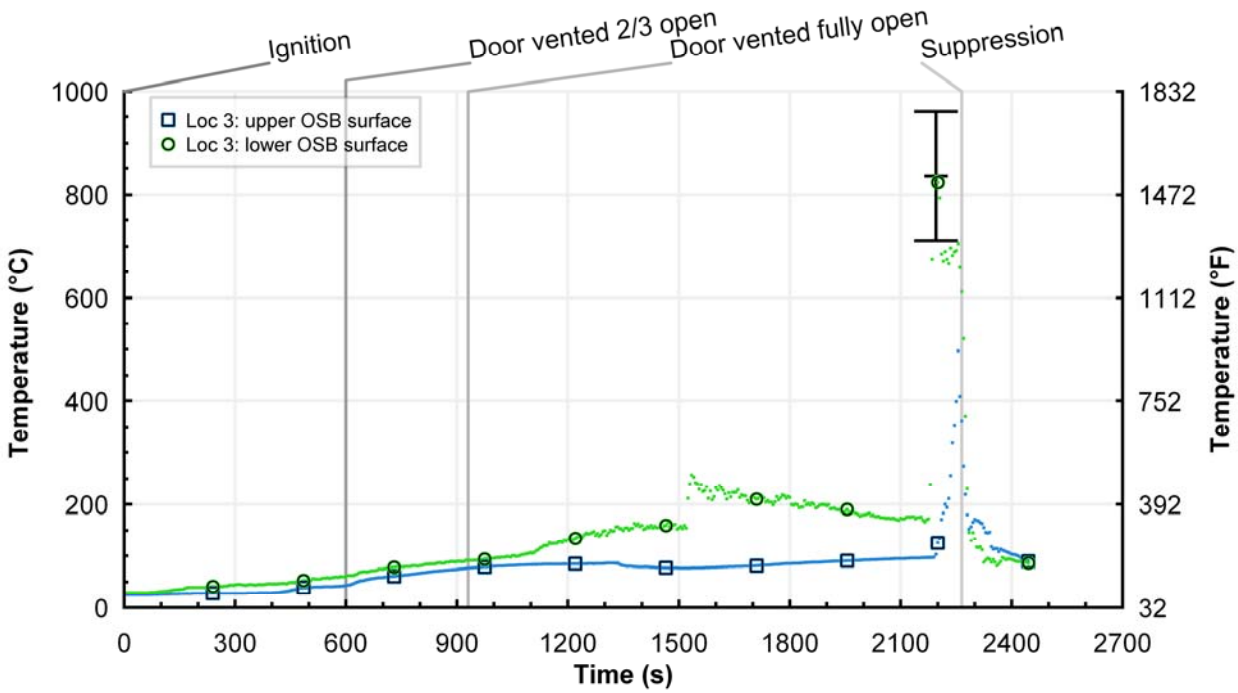

Figure 3-47. Experiment 4 center of fire (floor system TC array at location 3), floor OSB surface temperatures versus time

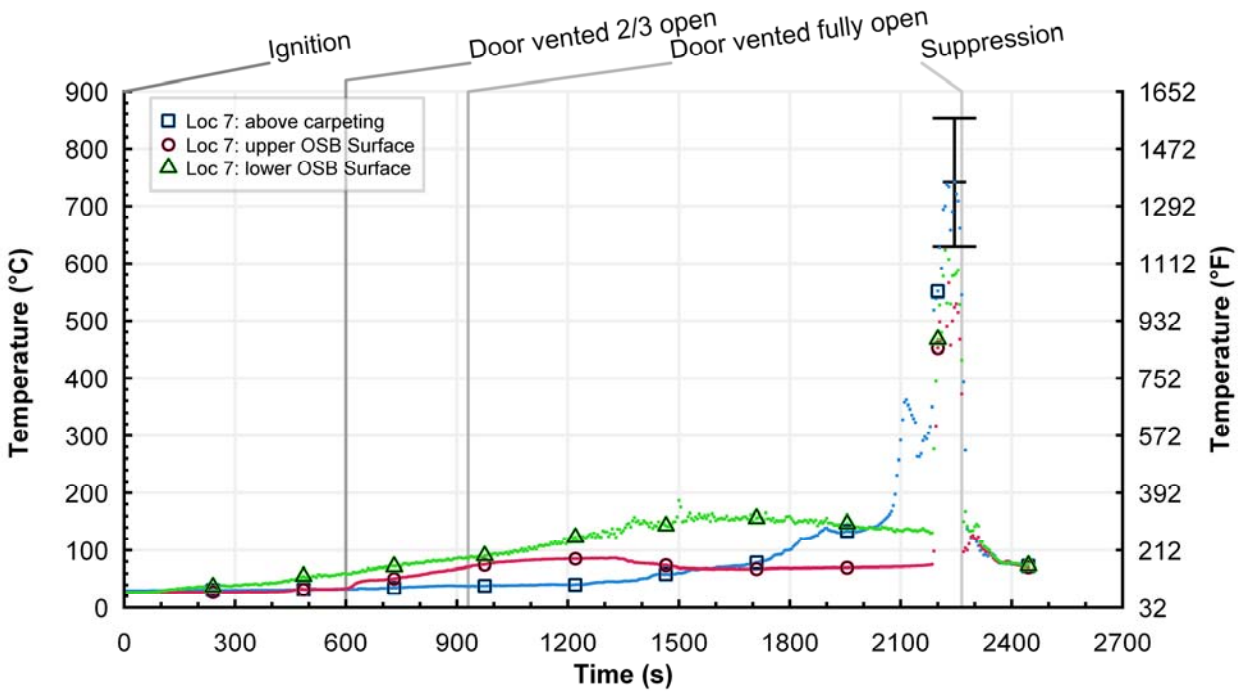

Figure 3-48. Experiment 4, upper level door opening (floor system TC array at location 7), temperatures below OSB, below the floor covering, and above the floor covering versus time

The temperatures of the sub-floor surfaces just below the water-filled barrels were measured with a floor system TC array at location 3. The temperatures measured by that array are shown in Figure 3-47. The spike in lower OSB temperature occurring soon after 1500 s corresponded to a failure of the ceiling structure in the lower level, which occurred at approximately 1510 s. The rise in temperatures at around 2200 s roughly corresponded to flashover in the upper level; at approximately that time, flaming gases exited the upper level doorway through its full height.

The floor system TC array at location 7 was located directly in front of the upper level opening so as to measure the temperature of the area immediately visible to a firefighter entering the structure. The temperatures measured by this array are shown in Figure 3-48.

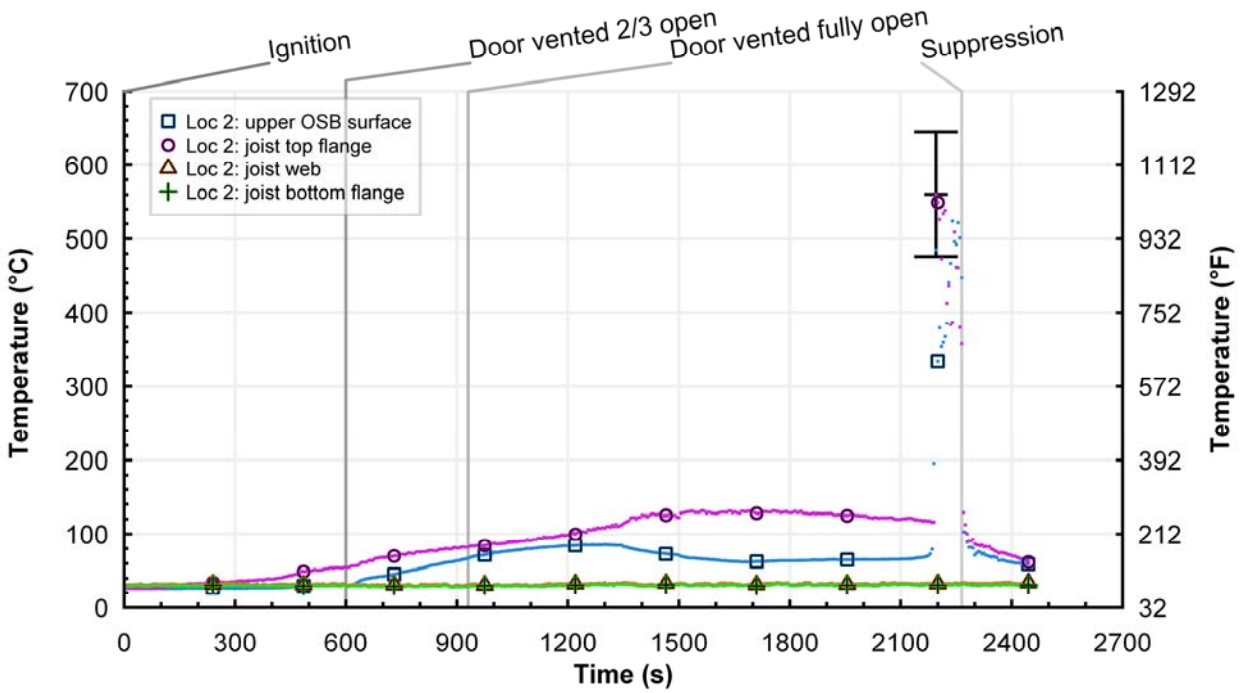

Figure 3-49. Experiment 4, northwestern corner (floor system TC array at location 2), joist through floor temperatures versus time

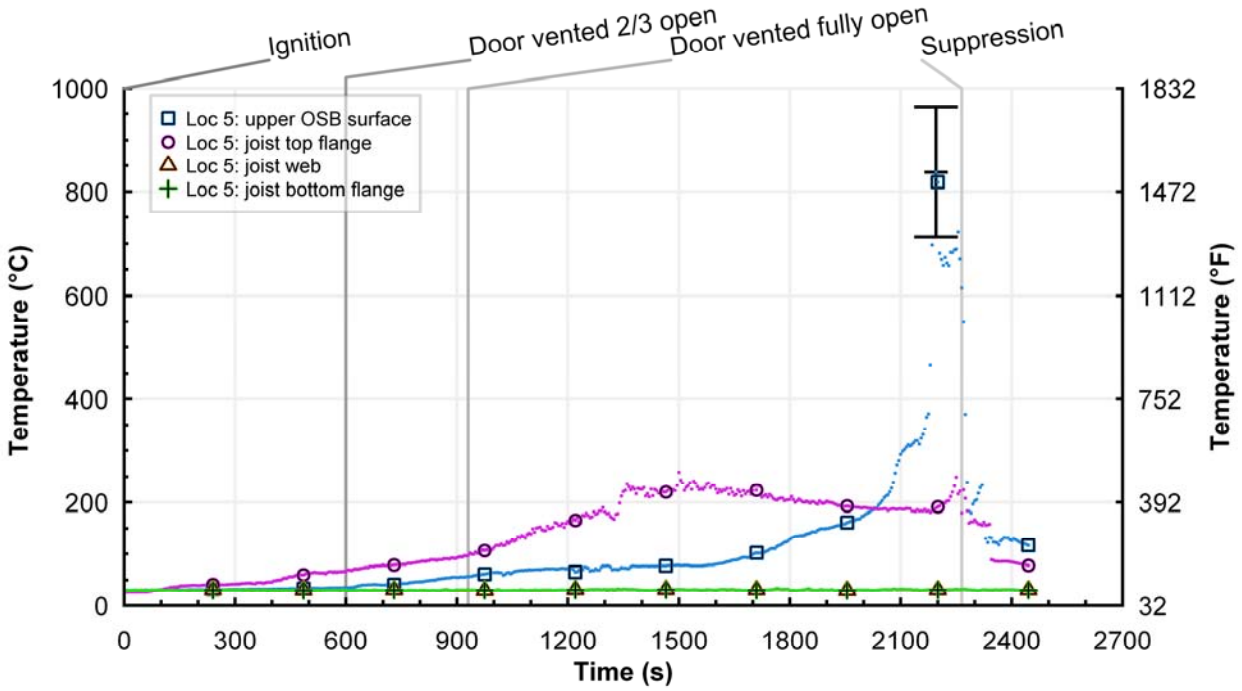

Figure 3-50. Experiment 4, southeastern corner (floor system TC array at location 5), joist through floor temperatures versus time

Figure 3-49 and Figure 3-50 show the temperatures measured at locations 2 and 5 respectively. These figures show the approximate exposure of the floor joists as protected by the gypsum board. The large temperature peaks at approximately 2200 s are due to flashover of the upper level compartment.

4 Discussion

All four experiments show that the combination of surface temperature and contrast of the joists past the flooring material as viewed with a thermal imager could be used as a reasonable indication of the existence of a fire, but very little could be determined qualitatively about the potential for floor collapse. The information available from a thermal imager, namely the variations and magnitude of infrared radiation from the flooring surface, is complicated by many factors. Consequently, it provides no straightforward indication of either severity of the fire below or its duration, which are better characterized indicators of potential collapse hazard. This set of experiments provides evidence of many of these complicating factors, and the effect they have on qualitative analysis using thermal imagers.

Although these tests do not conclusively disprove the possibility of an accurate qualitative analysis using thermal imagers in combination with other information gained through an external size up, knowledge of the structure and fuel load, and or other instrumentation. However, knowledge of these other factors would probably remove the necessity of an assessment using thermal imagers.

The structures used in all four experiments were very similar in exterior dimensions, as described in Section 2.1. Comparison of floor system TC arrays at locations 2 and 5 for experiments 1, 2, and 3 (unprotected floor joist experiments) reveals variations in exposure within each structure. Table 4-1 compares location 2 and 5, TC by TC to one another and presents the maximum duration a given difference in temperature between the two locations was maintained. The first row represents a difference in temperature greater than 100 ºC, greater than 200 ºC for row two, and greater than 300 ºC for row three. For experiments 1 and 3 the nature of the difference in temperature was that the thermocouples at location 5 maintained a higher temperature, and in both cases the maximum difference in temperature occurred after the initial ventilation event and before the final ventilation event; during this time the gas temperature in the lower level is escalating. For experiment 2 the difference in temperature was reversed, with the thermocouples at location 2 maintaining a higher temperature; this period was subsequent to the final ventilation event, up until the point of flashover in the lower level.

Table 4-1. Temperature differential between the elements of floor system TC arrays at locations 2 and 5; presented as maximum duration over the temperatures 100 ºC, 200 ºC, and 300 ºC

Difference in Temperature (ºC)	Experiment 1 (s)	Experiment 2 (s)	Experiment 3 (s)
>100	410	345	190
>200	205	265	N/A
>300	40	N/A	N/A

Location 2, despite being roughly the same distance from the fuel load as location 5, experienced differences in thermal exposure greater 100 ºC (212 ºF) for several minutes in every test. This variability means that an assessment of a single area of the affected floor structure would not provide an accurate picture of the thermal exposure of the entire floor structure. In this series of experiments, the opening in the upper level was on the north side, closest to location 2. The area immediately around this opening would be visible to a firefighter entering the structure, meaning that conditions in experiment 1 and 3 would lead to an under estimation of the thermal conditions below, where as the conditions in experiment 2 would lead to an over estimation. Again ventilation was the cause the circular thermal flows in the lower level that resulted in the temperature differences.

One dimensional heat transfer rate through a material is a function of the temperature difference between its boundaries. Assuming steady-state 1-dimensional conduction, the heat flux rate through the sub floor can be given by a simple equation.

where and are the hot(exposed to the lower level compartment) and cooler (exposed to upper level compartment) surfaces of the OSB sub-floor, respectively, is the thickness of the sub-floor, is the thermal conductivity of OSB, and is the heat flux through the sub-floor. Using a value of [**22**], approximate values for the heat flux through the sub-floor can be calculated using the experimental data for upper and lower OSB temperature. The maximum heat transfer through the floor is given in Table 4-2.

Table 4-2. Approximate maximum heat transfer rate through the OSB sub-floor in each experiment. The temperature measurements were taken at location 3 (just above the fuel). The temperature on the fire side of the sub-floor is also given.

Experiment	Heat Flux (kW/m²)	Lower OSB Temperature (°C)
1	5.8	803
2	5.7	779
3	3.3	715
4	1.9	232

Comparing the surface temperatures from the upper and lower levels from each test reveals that the upper level was thermally insulated relatively well from the lower level. This has two implications with respect to thermal imagers. The first is that the ambient side surface temperature of the sub-floor and flooring materials will radiate only a fraction of the energy of the exposed side. This is demonstrated by arrays at location 3 and 7 for every experiment. The second implication is that heating due to the fire, i.e., heat conduction through the sub-floor and flooring material, is relatively small compared to the convective heating from the air space above. These convective heating effects are functions of flow patterns and ambient temperature as well as fire conditions. This means that any measurement of the temperature below the sub-floor using the surface temperature of flooring material or sub-floor will have an error associated with it which grows in significance when the measured temperature which can be seen is small.

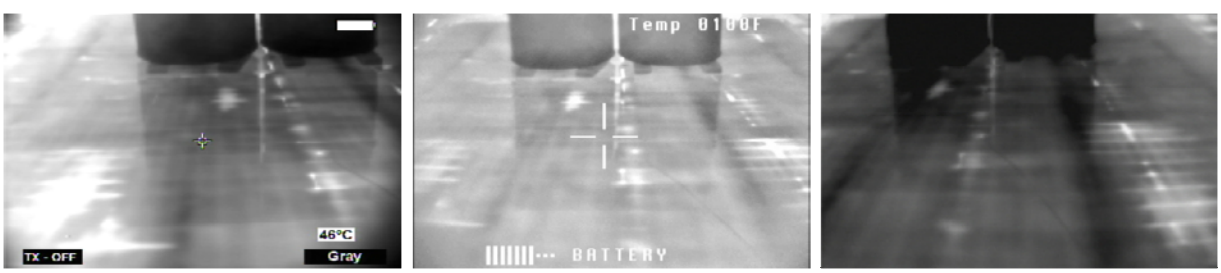

Figure 4-1. Experiment 1, thermal images at 1155 s after ignition.

Figure 4-1 shows the thermal images in experiment 1 1155 s after ignition. The difference in temperature between the top and bottom of the OSB sub floor at location 7 at 1155 s after ignition for experiment 1 is 648 ºC (1200 °F). The temperature below the sub-floor is 750 ºC (1400 °F), the temperature above the OSB is 102 ºC (216 °F), and the temperature above the laminate flooring is 60 ºC (140 °F). It is important to note that the thermal imagers measure surface temperatures which are significantly lower than the TC measurements for all the imagers used, which may be in part due to differences in surface emissivity.

Figure 4-2. Post experiment photo of the sub floor in experiment 1.

Figure 4-2 shows a portion of the collapsed sub-floor in experiment 1 after the experiment. Much of the sub-floor which was covered by flooring material is not charred on the upper level side.

The difference in insulating properties between the two floor covering materials used in this experiment could not be determined conclusively. It is clear that both provide significant insulation, as is demonstrated by the array at location 7 in every experiment, but the degree of difference between the two was too small to be evident considering other variations in the experiments. The sub-floor alone provided adequate insulation leading to little discernable correlation between surface temperature and basement conditions. The two flooring types used in these experiments do not represent the array of possible flooring materials as well, nor do they represent all of the possible configurations. For instance, it is common to install carpet on top of an older flooring material.

The collapse times for these experiments is given in Table 4-3, no floor collapse occurred on the fourth experiment. In a real world scenario, differences in structural loading and fuel load could affect collapse time. In these experiments, the fuel loading was small compared to a furnished structure, and the loading on the upper level consisted only of the water-filled barrels in the center. In a more realistic scenario, fuel loading in the lower level could vary greatly from densely furnished to almost empty, and the structural loading would likely include, at a minimum, a full set of furniture. Firefighters inside the structure would likely be moving as well, providing significantly greater stress on the floor than the static load used in these experiments. Although collapse times are reported here, it should be noted that wood flooring systems can become weakened prior to complete structural collapse.

Table 4-3. Floor collapse times in each of the four experiments

Experiment	Collapse time after ignition sec (min:sec)
1	1470 (24:30)
2	1675 (27:55)
3	1485 (24:45)
4	No Collapse

Gypsum board shielding of the floor system in experiment 4 resulted in little or no damage to the joists in areas where the gypsum board was not damaged by heat to the point of falling off of the joists. Figure 4-3 shows a post-fire comparison of the protected joist structure in experiment 4 to the exposed structure in experiment 3. It was for this reason that no collapse occurred in experiment 4. The finding that gypsum board provides additional thermal protection can be extended to other floor systems and is consistent with previous studies. [**3**, **23**]

Figure 4-3. Post-fire photographs of the joist structure in an experiment where the joists were protected (left) and an experiment where the joists were exposed (right).

5 Summary

NIST conducted a series of experiments in order to assess the feasibility of using commercially available thermal imagers as a tool for assessing the structural integrity of a floor during a structure fire. Arrays of TCs were used to measure the thermal exposure at various points throughout the structure. The goal was to analyze the correlation between the measured thermal exposure and the video output of the thermal imagers. Visible contrast and surface temperature measurements provided by the thermal imagers could only be loosely correlated to thermal conditions in the lower level, the limiting factor in this correlation being the complexity of heating and conduction effects observed and surface emissivity. Several complicating factors for fire fighters using TIs are identified in these experiments.

Despite the structure being small and open, thermal exposure of the floor system was highly non-uniform in these experiments. The fuel distribution as well as the flow path of the fire and hot gasses drastically affected exposure. The area of sub-floor, which represents the highest exposure may or may not be visible from the entry point in a real structure fire.

OSB and floor covering materials, such as carpeting and laminate flooring, are relatively poor conductors of heat and the surface temperature on the cooler side represents only a fraction of the temperature of the warmer side. Additionally, as the warmer side is heated by a growing fire, the temperature distribution within the OSB sub-floor is not steady. Under conditions of long duration medium exposure, the cooler side surface temperature may be as high as during a short duration intense exposure.

In a real structure fire, exhaust gases from a lower level fire may make their way into the upper levels through stairwells and penetrations in the sub-floor, ducts, and walls. These gases may also heat the floor surface resulting in a higher surface temperature than would be possible with lower level heating alone. Additionally, thermal imagers that have visible flame within the field of view may cause the thermal imagers to auto-range thereby displaying the other heated, but cooler, surfaces in the field of view as cool in comparison.

Thermal imagers cannot be used to determine if the temperature the floor system has been exposed from below without also considering other factors, and these experiments indicated that such an analysis could be very complicated. Consequently, an accurate assessment of structural integrity with a TI alone would be impossible in nearly all cases. The hazard of a floor collapse in a lower level fire scenario is significant, particularly with an exposed wood floor assembly.

A basement with an exposed, or unprotected wood flooring assembly at the ceiling level can contribute a significant fuel load to a basement fire while simultaneously being weakened and consumed by the fire. Previous research and fire incident data has shown that wood flooring systems, when exposed to a fire environment, have the potential to collapse within the timeframe of fire ground operations. Since the time of ignition on an actual fire is unknown to the fire service, the extent of structural damage by the fire is unknown, and thermal imagers cannot provide a reliable indicator of the hazard, other technologies need to be considered to address this problem. In the mean time, it is critical for the fire service to review their practice of size-up and other fire ground tactics to enable the location of the fire prior to conducting fire operations inside a building [24].

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Appendices

A. NFPA List of Fire Ground Injuries 2004-2008

2004-2008

version 5.0

fire ground injuries at single-family dwellings

Injury Factor	Fire-fighter Injuries	PCT
00 - Other factor contributed to injury	2,396	14.7%
10 - Collapse or falling object, other	246	1.5%
11 - Roof collapse	153	0.9%
12 - Wall collapse	51	0.3%
13 - Floor collapse	328	2.0%
14 - Ceiling collapse	557	3.4%
15 - Stair collapse	64	0.4%
16 - Falling objects	675	4.1%
20 - Fire development, other	905	5.5%
21 - Fire progress, including smoky conditions	2,806	17.2%
22 - Backdraft	12	0.1%
23 - Flashover	186	1.1%
24 - Explosion	96	0.6%
30 - Lost, caught, trapped, or confined, other	34	0.2%
31 - Person physically caught or trapped	43	0.3%
32 - Lost in building	10	0.1%
33 - Operating in confined structural areas	326	2.0%
34 - Operating under water or ice	20	0.1%
40 - Holes, other	193	1.2%
41 - Unguarded hole in structure	96	0.6%
42 - Hole burned through roof	24	0.1%
43 - Hole burned through floor	296	1.8%
50 - Slippery or uneven surfaces, other	640	3.9%
51 - Icy surface	807	4.9%
52 - Wet surface, included are water/soap/foam, etc.	370	2.3%
53 - Loose material on surface	336	2.1%

54 - Uneven surface, included are holes in the ground	863	5.3%
60 - Vehicle or apparatus, other	100	0.6%
61 - Vehicle left road or overturned	2	0.0%
62 - Vehicle collided with another vehicle	4	0.0%
63 - Vehicle collided with non-vehicular object	6	0.0%
64 - Vehicle stopped too fast	4	0.0%
65 - Seat belt not fastened	2	0.0%
66 - Firefighter standing on apparatus	43	0.3%
91 - Civil unrest, including riots/civil disturbances	6	0.0%
92 - Hostile acts	79	0.5%
NN - None	3,566	21.8%
TOTALS	16,350	100.0%

Source: National Fire Protection Association, Fire Analysis and Research Division, Quincy MA, May 2010

B. Review of Near-miss and Fatality Incidents, 2005 to 2011

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
1	02/19/05	Capt.	Death	Residential	Capt. died after being trapped under debris from roof collapse	Grady Don Burke 2005 Firefighter Fatality Notices
1	02/21/05	Off.	Injury	Residential	Officer fell through floor into heavily involved basement	FF Near-Miss Report 09-0000663
1	04/06/05	FF	Near-miss	Residential	Firefighter fell through floor of single wide trailer	FF Near-Miss Report 05-0000152
1	06/16/05	Capt.	Near-miss	Residential	Capt. fell through floor during fire attack; no injury due to being stopped by a box spring	FF Near-Miss Report 05-0000306
3	09/25/05	2 FF 1 Off.	Injury	Residential	During search firefighters fell into basement due to fire in floor joists	FF Near-Miss Report 05-0000552
1	11/27/05	FF	Near-miss	Residential	Firefighter notices hole in floor during search	FF Near-Miss Report 05-0000638
1	12/11/05	LT	Near-miss	Residential	Firefights resort to defensive operations after a floor held by only 3 beams began to collapse	FF Near-Miss Report 06-0000454
1	01/01/06	FF	Near-miss	Residential	Firefighter fell through first floor	FF Near-Miss Report 06-0000007
1	01/06/06	LT	Near-miss	Residential	Firefighter fell through floor	FF Near-Miss Report 06-0000037
1	02/10/06	Capt.	Injury	Residential	Captain fell through floor of trailer	FF Near-Miss Report 09-0000181
1	02/14/06	Capt.	Near-miss	Residential	While hooking ceiling, firefighter took a step forward and fell through floor to floor below	FF Near-Miss Report 06-0000101
1	03/02/06	FF	Injury	Residential	Firefighter fell through 2nd story floor	FF Near-Miss Report 06-0000165
1	04/11/06	FF	Death	Residential	1st floor collapsed into basement during rescue	Kevin Anthony Apuzzio 2006 Firefighter Fatality Notices
1	04/15/06	FF	Near-miss	Residential	Floor collapse found during overhaul after incident; collapse prevented by carpeting	FF Near-Miss Report 06-0000263
1	04/16/06	FF	Near-miss	Residential	Firefighter falls through floor of trailer	FF Near-Miss Report 09-0000381

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
1	06/01/06	LT	Near-miss	Residential	Firefighter in room when floor collapse due to unknown basement fire	FF Near-Miss Report 09-0000628
1	06/04/06	FF	Near-miss	Residential	Probie stopped from falling through ceiling during attic operations	Probie Almost Falls Through Ceiling www.firefighterclosecalls.com
1	06/13/06	FF	Near-miss	Residential	Firefighter fell through floor of mobile home into involved fire area	FF Near-Miss Report 09-0000511
1	06/25/06	Deputy Chief	Death	Residential	Firefighter stretching handline fell through floor after entering	Steven A. Smith 2006 Firefighter Fatality Notices
1	08/13/06	LT	Death	Residential	Collapse of 1st floor into involved basement	Arnold W. Wolff 2006 Firefighter Fatality Notices
1	08/20/06	FF	Near-miss	Residential	Firefighters leg falls through floor with unnoticed fire beneath	FF Near-Miss Report 06-0000170
1	08/27/06	FF	Death	Commercial	Fell through 1st floor into basement	Michael C. Reilly 2006 Firefighter Fatality Notices
1	08/27/06	LT	Death	Commercial	Fell through 1st floor into basement	Howard John Carpluk, Jr. 2006 Firefighter Fatality Notices
1	10/02/06	FF	Near-miss	Residential	Firefighter notices hole in floor while advancing to extinguish fire	FF Near-Miss Report 06-0000512
1	12/24/06	FF	Near-miss	Residential	Firefighter fell through 1st floor into basement upon entering structure	FF Near-Miss Report 09-0000509
1	12/24/06	N/A	Near-miss	Residential	Floor completely burned through; did not collapse due to carpet being held up by debris	FF Near-Miss Report 07-0001110
1	12/29/06	FF	Near-miss	Residential	Firefighter's leg goes through floor after not sounding floor	FF Near-Miss Report 07-0000694
1	01/03/07	FF	Death	Residential	Firefighter died from injuries after partially falling through 1st floor then being struck by object overhead and pushed through hole	Sidney Alan Hall 2007 Firefighter Fatality Notices
1	01/23/07	FF	Near-miss	Residential	Firefighter partially falls through floor into involved basement	FF Near-Miss Report 07-0000698
1	01/26/07	FF	Death	Residential	Firefighter died after falling through first floor into fully involved basement	Shane Michael Daughetee 2007 Firefighter Fatality Notices

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
2	02/04/07	FF	1 Death 1 Injury	Residential	Firefighters trapped after awning collapse; 1 FF died from asphyxiation due to entrapment	Jeremy Charles LaBella 2007 Firefighter Fatality Notices
1	02/09/07	FF	Near-miss	Residential	Firefighter falls through 2nd floor onto first during fire attack	FF Near-Miss Report 07-0000730
2	02/14/07	FF	Injury	Residential	Firefighters fell through floor into basement during attack	FF Near-Miss Report 07-0000814
1	03/07/07	FF	Injury	Residential	Firefighter fell through floor into involved basement	FF Near-Miss Report 07-0000789
1	03/12/07	FF	Injury	Residential	Firefighter fell through floor during fire attack	FF Near-Miss Report 07-0000803
3	03/23/07	LT	Injury	Residential	Firefighter partially fell through floor into basement	FF Near-Miss Report 07-0000942
1	03/23/07	LT	Injury	Residential	Officer fell through 1st floor up to chest level during fire attack; no fire in basement	FF Near-Miss Report 07-0000883
1	04/20/07	FF	Injury	Residential	Firefighter fell through floor during overhaul	FF Near-Miss Report 07-0000879
1	06/06/07	FF	Near-miss	Residential	Firefighter struck by falling ceiling during overhaul	Near-miss During Overhaul www.firefighterclosecalls.com
1	06/13/07	1 LT 1 FF	Near-miss	Residential	2 firefighters momentarily trapped after floor collapse	Floor Collapse Traps Firefighters www.firefighterclosecalls.com
1	06/19/07	FF	Near-miss	Residential	Firefighter fell into basement after stairs collapsed	Be Ready for Any Type of Fire www.firefighterclosecalls.com
1	06/26/07	Off.	Injury	Residential	Officer fell ~15 feet through attic floor	Firefighter Falls Through Ceiling www.firefighterclosecalls.com
1	08/03/07	Capt.	Death	Residential	Roof collapsed during interior attack	Kevin Glenn Williams 2007 Firefighter Fatality Notices
1	08/03/07	FF	Death	Residential	Roof collapsed during interior attack	Austin Hague Cheek 2007 Firefighter Fatality Notices
3	09/26/07	FF	1 Death 2 Injuries	Residential	Firefighters became trapped when attached garage collapsed during overhaul	Mike D. Reagan 2007 Firefighter Fatality Notices
1	11/05/07	FF	Death	Residential	Firefighter became trapped when roof and ceiling collapsed during interior ops	Jeremy W. Wach 2007 Firefighter Fatality Notices
1	12/04/07	FF	Near-miss	Residential	Firefighter momentarily trapped after 8' fall into basement	FF Near-Miss Report 07-0001146

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
1	12/17/07	FF	Injury	Residential	Firefighter fell through floor during search of vacant house	FF Near-Miss Report 09-0000252
1	12/25/07	LT	Near-miss	Residential	First floor became "spongy" while operating, collapsed after exiting	FF Near-Miss Report 08-0000333
1	01/11/08	FF	Near-miss	Residential	Firefighter fell through second floor, self extricated by hose line	FF Near-Miss Report 08-0000036
1	01/24/08	FF	Near-miss	Residential	Firefighter falls through floor up to shoulders	FF Near-Miss Report 08-0000048
1	02/12/08	FF	Injury	Residential	Fell through first floor into basement while advancing line	Successful Rescue of Mayday Firefighter Through Floor www.firefighterclosecalls.com
1	02/18/08	FF	Injury	Residential	Firefighter burned as flashover causes floor collapse while crews evacuate	Situational Awareness Leads to Safe Exit www.firefighterclosecalls.com
2	02/20/08	2 Off. 1 FF	Injury	Residential	Ceiling collapsed on 3 firefighters during overhaul, injuring 1	Firefighter Injured in Ceiling Collapse www.firefighterclosecalls.com
4	02/21/08	FF	Near-miss	Residential	Flashover causes ceiling collapse; trapped FFs forced to call mayday	Mayday at House Fire www.firefighterclosecalls.com
1	02/29/08	N/A	Injury	Residential	Fell through floor after collapse while trying to find crew	Complacency Almost Hurts Firefighters www.firefighterclosecalls.com
4	03/01/08	FF	Injury	Residential	Front concrete slab porch collapsed into basement	Kansas City Firefighters Caught in Collapse www.firefighterclosecalls.com
1	03/01/08	FF	Near-miss	Residential	Firefighter partially falls through 3rd floor due to unlocated fire on 1st floor.	Firefighter Near-Miss Report 10-0000024
1	03/07/08	FF	Death	Commercial	Interior wall collapsed after prolonged interior operations, trapping and killing 2 firefighters	Victor Anthony Isler 2008 Firefighter Fatality Notices
1	03/07/08	FF	Death	Commercial	Interior wall collapsed after prolonged interior operations, trapping and killing 2 firefighters	Justin Edward Monroe 2008 Firefighter Fatality Notices
1	03/08/08	N/A	Near-miss	Residential	Partial first floor collapse	FF Near-Miss Report 08-0000169
1	03/08/08	FF	Injury	Residential	Firefighter partially falls through floor	FF Near-Miss Report 08-0000138

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
1	03/12/08	LT	Injury	Residential	Fell through floor while performing RIT ops for a reported missing firefighter who was outside	Mayday Firefighter Out Safe but No One Knows www.firefighterclosecalls.com
1	03/24/08	FF	Injury	Residential	Firefighter falls through floor during fire attack into non involved basement	FF Near-Miss Report 08-0000375
1	03/25/08	FF	Injury	Residential	Second floor collapse, fell through to first floor	Tennessee Firefighter Injured in Abandoned Building Fire www.firefighterclosecalls.com
1	04/04/08	FF	Death	Residential	1st floor collapsed into basement while they fire attack was occurring in the basement	Brian Schira 2008 Firefighter Fatality Notices
1	04/04/08	FF	Death	Residential	1st floor collapsed into basement while fire attack was occurring in the basement	Robin Broxterman 2008 Firefighter Fatality Notices
1	04/04/08	FF	Injury	Residential	Fell through steps while descending	www.firefighterclosecalls.com Downloaded: January 7, 2009.
1	04/28/08	FF	Near-miss	Residential	Firefighters nearly fall through floor after basement fire burns through	FF Near-Miss Report 08-0000471
3	05/03/08	FF	Injury	Residential	Floor collapse during fire attack	www.firefighterclosecalls.com Downloaded: January 7, 2009.
1	05/04/08	FF	Near-miss	Residential	Partial floor collapse during fire attack	FF Near-Miss Report 09-0000047
2	05/22/08	FF	Injury	Residential	First floor collapse into basement during fire extinguishment	www.firefighterclosecalls.com Downloaded: January 7, 2009.
1	06/14/08	FF	Injury	Residential	Second floor collapse onto first floor	www.firefighterclosecalls.com Downloaded January 7, 2009.
1	07/05/08	Chief	Death	Commercial	Brick façade collapsed outward toward crews operating outside	Robert Leland Knight 2008 Firefighter Fatality Notices
1	07/10/08	FF	Injury	Residential	Partially fell through floor but caught himself	"Firefighters Hurt Battling House Blaze"
6	07/17/08	FF	Injury	Residential	First floor collapse into the basement	www.firefighterclosecalls.com Downloaded: January 8, 2009
1	07/22/08	FF	Death	Residential	First floor collapse, fell into basement	Brian J. Munz 2008 Firefighter Fatality Notices
3	08/15/08	FF	Injury	Commercial	Division 2 floor collapse	www.firefighterclosecalls.com Downloaded: January 8, 2009

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
1	09/10/08	FF	Injury	Residential	Running a line up the stairs to the second floor, stairs collapsed into the basement	www.firefighterclosecalls.com Downloaded: January 8, 2009
3	09/23/08	FF	Injury	Residential	Fell through floor while advancing line, able to catch himself	www.firefighterclosecalls.com Downloaded: January 7, 2009.
1	10/03/08	FF	Injury	Residential	Fell through first floor after collapse due to basement fire	www.firefighterclosecalls.com Downloaded: January 8, 2009
1	10/03/08	LT	Near-miss	Residential	Fell through front stone patio, pulled out by crew	FF Near-Miss Report 08-0000497
1	10/10/08	LT	Injury	Residential	Ceiling collapse onto firefighter after he fell through floor	www.firefighterclosecalls.com Downloaded: January 8, 2009
1	10/19/08	FF	Injury	Residential	Fell through 3rd floor to 2nd floor	FF Near-Miss Report 08-0000532
1	10/22/08	FF	Injury	Residential	Division 3 partial floor collapse after flashover	www.firefighterclosecalls.com Downloaded: January 8, 2009
1	11/04/08	FF	Injury	Residential	Firefighter fell through second floor, able to catch himself	"New York Firefighter Falls Through Floor, Calls Mayday" www.firehouse.com Downloaded: January 13, 2010.
2	11/05/08	1 LT 1 FF	Near-miss	Residential	Firefighter fell through bathroom floor, able to catch himself	FF Near-Miss Report 08-0000577
2	11/09/08	FF	Injury	Residential	Firefighter fell into basement after partial collapse	www.firefighterclosecalls.com Downloaded: January 8, 2009
1	11/15/08	FF	1 Death, 4 Injuries	Residential	Firefighters became trapped after roof collapse during overhaul	Walter Patrick Harris,Sr. 2008 Firefighter Fatality Notices
1	11/18/08	FF	Injury	Residential	Partial Floor Collapse	"Floor Collapse Leaves Firefighter Injured" www.boston.com Downloaded: January 8, 2009
1	11/23/08	LT	Death	Residential	Collapse while crews were operating in attic	Robert J. Ryan, Jr. 2008 Firefighter Fatality Notices
1	11/23/08	Capt.	Near-miss	Residential	Porch roof collapses on officer while walking to entrance	FF Near-Miss Report 08-0000615
1	12/17/08	FF	Injury	Residential	Partial first floor collapse	www.firefighterclosecalls.com Downloaded January 7, 2009
2	12/25/08	FF	Injury	Residential	First floor collapsed into basement, followed by second floor collapse through first floor, into basement	Story Number 123008129 www.1rbn.com Downloaded: January 7, 2009.

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
3	12/29/08	FF	Injury	Residential	Partial floor collapse	www.firefighterclosecalls.com Downloaded: January 7, 2009
1	01/16/09	FF	Near-miss	Residential	Firefighter partially falls through floor upon entering front door	FF Near-Miss Report 09-0000200
2	02/05/09	FF	Near-miss	Residential	During fire attack, floor caved in and flames extended up from basement	FF Near-Miss Report 09-0000164
1	02/29/09	FF	Near-miss	Commercial	Floor collapsed as firefighters were exiting due to unnoticed fire in basement; no injuries	FF Near-Miss Report 09-0000215
1	03/02/09	FF	Injury	Residential	Firefighter falls through floor into flooded basement after master stream use	FF Near-Miss Report 09-0000239
1	04/30/09	Asst. Chief	Near-miss	Residential	Floor collapse 3 min into arrival on scene; no injuries	FF Near-Miss Report 09-0000461
1	05/01/09	FF	Injury	Residential	Firefighter fell through floor	"Ohio firefighter injured in floor collapse" www.firerescue1.com/firefighter-safety/articles/
1	08/24/09	LT	Death	Commercial	Fell into basement after floor collapse	Charles W. McCarthy, Jr. 2009 Firefighter Fatality Notices
1	08/24/09	FF	Death	Commercial	Fell into basement while searching for Lt. McCarthy	Jonathan S. Croom 2009 Firefighter Fatality Notices
1	10/30/09	FF	Injury	Residential	Firefighter fell through floor after fire burned in crawl space	"Ohio Firefighter Falls Through Floor" www.firehouse.com
1	11/14/09	Deputy Chief	Near-miss	Residential	Front wall of structure fell forward toward crews	FF Near-Miss Report 10-0000070
5	11/16/09	1 LT 4 FF	Injury	Residential	Building collapses when crews resume interior attack after going to defensive ops	FF Near-Miss Report 10-0000345
1	11/22/09	FF	Injury	Residential	Firefighter fell through floor into basement	"Firefighter falls through floor while battling suspected arson" www.wthr.com
1	11/29/09	FF	Injury	Residential	Firefighter fell through floor	"Ohio Firefighter Falls Thru Floor at Working House Fire" www.firelink.monster.com/news
3	12/09/09	FF	Injury	Residential	Roof collapsed onto interior crews	FF Near-Miss Report 10-0000163
1	12/18/09	FF	Near-miss	Residential	Firefighter's foot falls through roof after failure to sound	FF Near-Miss Report 10-0000183

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
2	01/01/10	FF	Injury	Residential	Firefighters trapped when ceiling fell on top of them	www.firefighterclosecalls.com
2	01/02/10	FF	Injury	Residential	Firefighter fell through roof due to collapse	www.firefighterclosecalls.com
3	01/20/10	FF	Injury	Residential	Firefighters injured after falling through floor	www.firefighterclosecalls.com
1	01/26/10	FF	Injury	Residential	Firefighter injured after falling through a hole in the floor	www.firefighterclosecalls.com
13	01/30/10	FF	Injury	Commercial	Firefighters were injured when multiple floors above a restaurant collapsed	www.firefighterclosecalls.com
1	02/06/10	FF	Injury	Residential	Firefighter fell through first floor into working fire in basement	www.firefighterclosecalls.com
2	03/16/10	FF	Injury	Residential	Two firefighters fell through first floor into basement while operating	www.firefighterclosecalls.com
1	03/23/10	FF	Injury	Residential	Firefighter fell through roof after collapse	www.firefighterclosecalls.com
3	04/08/10	FF	Injury	Residential	Firefighters injured after deck collapse	www.firefighterclosecalls.com
1	04/17/10	FF	Near-miss	Residential	Unknown attic fire caused chimney and roof to collapse as crew advanced attack line	FF Near-Miss Report 10-0000719
1	04/20/10	FF	Injury	Residential	Firefighter fell through first floor of home into basement during operations	www.firefighterclosecalls.com
1	04/25/10	FF	Injury	Residential	Firefighter fell through floor while operating at a house fire	www.firefighterclosecalls.com
1	05/17/10	FF	Injury	Residential	Firefighter fell through floor in a single story house fire	www.firefighterclosecalls.com
1	06/24/10	Capt.	Injury	Residential	Firefighter operating on 1st floor fell into basement after floor collapse	www.firefighterclosecalls.com
3	06/25/10	FF	Injury	Residential	Firefighters injured after floor tilted, collapsed	www.firefighterclosecalls.com
1	07/25/10	FF	Injury	Residential	Firefighter fell through 1st floor into working basement fire	"Firefighter recovering after burning floor collapses" www.whas11.com
1	08/05/10	FF	Injury	Residential	Firefighter fell through 1st floor into basement while operating at a house fire	www.firefighterclosecalls.com

# FF	Date	Rank	Type	Property Type	Description of Collapse	Source
2	08/06/10	FF	Injury	Residential	Firefighters injured when floor collapsed into basement while operating in the kitchen area	www.firefighterclosecalls.com
3	08/09/10	FF	Injury	Residential	Firefighters injured when ceiling beams collapse	www.firefighterclosecalls.com
1	08/16/10	LT	Injury	Residential	Firefighter injured when entering a house fire and first floor gave way to fire conditions in basement	Michigan FF Critical After Fall Through Floor www.firehouse.com
1	08/30/10	Capt.	Injury	Residential	Firefighter injured after first floor collapse from basement fire	FF Near-Miss Report 10-0001072
1	12/16/10	FF	Injury	Residential	Firefighter trapped after ceiling collapse	Ohio Firefighter Trapped in Fire/Collapse www.firefighterclosecalls.com
1	12/24/10	Capt.	Near-miss	Residential	Firefighter calls through floor, catches himself on wires	www.firetruckblog.com Downloaded: 03/18/11
2	02/14/11	FF	Injury	Residential	Firefighters fall into basement after floor collapse	Firefighters Fall Through the Floor in NY www.firefighterclosecalls.com
1	02/15/11	FF	Injury	Residential	Firefighter injured after falling into basement due to floor collapse	Utah Firefighter Falls Through Floor of Working House Fire www.firefighterclosecalls.com
1	02/21/11	FF	Injury	Residential	Firefighter injured after ceiling collapsed during interior ops	Georgia Firefighter Injured in Collapse www.firefighterclosecalls.com
6	02/22/11	FF	1 Death 5 Injuries	Residential	1 firefighter died and 5 others injured after roof collapse	L.A. Firefighters Down – Critical www.firefighterclosecalls.com
2	02/22/11	FF	Injury	Residential	Firefighters injured after chimney collapsed into house during interior ops	Virginia Chimney Collapse Close Call www.firefighterclosecalls.com
2	03/07/11	FF	Injury	Residential	Firefighter fell through floor after unlocated fire in basement caused collapse	Peoria, IL Firefighters Injured in Fall Through Floor
1	03/07/11	Capt.	Injury	Residential	Capt. fell through floor while searching for victims	North Carolina Fire Captain Falls Through Floor www.firefighterclosecalls.com
1	03/10/11	FF	Near-miss	Residential	FF fell through floor while searching for reported victims	Off-Duty Detroit Firefighter Falls Through Floor at Southfield House – No Injury www.firefighterclosecalls.com