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Project Title: Study of the Impact of Ventilation on Fire Patterns and Electrical System Damage in Single Family Homes Incorporating Modern Construction Practices

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Purpose of the Research:

Improve the capabilities of the fire investigation community by adding to the knowledge base in the following areas:

(1) understand the effects of ventilation on fire damage and patterns

(2) characterize electrical system response as a means to study fire progression

(3) assess repeatability and reproducibility of test measurements of large-scale structure fires

(4) develop materials property data inputs for accurate computer models

Each of these areas were listed as needing research on the Fire and Arson Investigation Technology Working Group Operational Requirement list published in the Fall of 2014.

Specific project objectives relative to the operational requirements 1 and 3 listed above included:

a) Examine how differences in ventilation to full-scale structure fires result in changes to the fire damage and fire patterns within the structure.

b) Measure the fire environment within the structures and compare the data with the fire damage in the structures.

c) Document the repeatability or lack thereof of the fire conditions and fire patterns within a structure based on the available ventilation.

Specific project objectives relative to the operational requirement 2 listed above included:

a) Determine if there are critical thermal exposure conditions to exposed cables.

b) Determine if the cable type affected the trip type when exposed to fire conditions.

c) Determine if the remote circuit protection type affected trip type when cables were exposed to fire conditions.

d) Determine if a correlation can be made between the cable damage and the trip type.

Operational requirement 4 was addressed by conducting heat release rate experiments on the furnishings used in the structure fire experiments.

Project Design and Methods

All experiments described in this report were conducted at full scale in purpose-built structures. The design of the structures, fuel loads, and types of experiments were planned during a workshop with the project technical panel. The intent was to optimize the project resources and provide foundational information for fire investigators. Technical panel members were selected based on their experience related to fire investigation.

Three test structures were used. A single compartment structure measuring 3.6 m on each side and 2.4 m tall with a single opening in one wall 2.4 m wide and 2.0 m high was used for the electrical cable fire exposure experiments. The fire pattern experiments were conducted in two different test structures with variable ventilation configurations. A single-story (ranch) structure and a two-story (colonial) structure with approximate floor areas of approximately 111 m^2 and 297 m^2 respectively were constructed (Figure 1). The colonial had an open floor plan design with a two-story tall family room and open foyer.

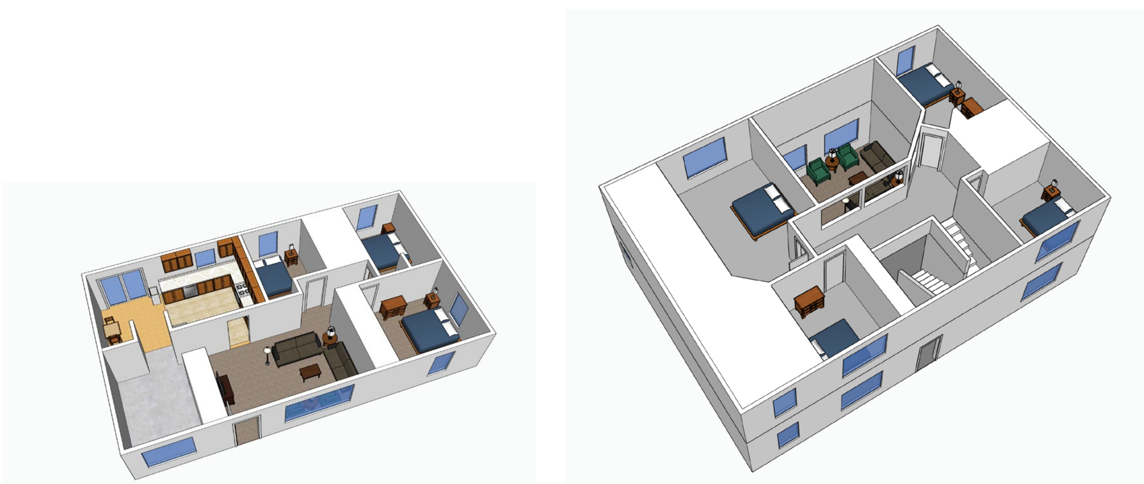


Figure 1. Drawings of the furnished ranch (left) and colonial (right) fire experiment structures.

Heat release rate experiments were conducted on the sofas, chairs, and beds used as fuel load within the structures to ensure that flashover conditions could be attained within the structures planned for use.

The project was divided in to two major components: 1) the Impact of Flashover Fire Conditions on Exposed Energized Cables, and 2) the Impact of Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures.

Impact of Flashover Fire Conditions on Exposed Energized Cables

The electrical cable fire exposure experiment compartment was instrumented to measure the thermal gradient within the compartment. Heat flux measurements were made adjacent to the 18 cable samples which were installed on the floor of the compartment between the sofa(s) and the opening to the compartment. Each electrical circuit was monitored for conductivity, voltage, current and differential current.

Every experiment began with the ignition of the sofa against the back wall of the compartment. The cables were exposed to thermal radiation from the hot gases and flames that flowed across the ceiling of the fire compartment and out of the opening in the front wall of the compartment. Once all of the circuits had stopped conducting electricity, the experiment was over and the fire was extinguished. The cable samples were photographed and examined for beads, wire breaks, and other signs of fire damage.

Six cable types (18-2 SPT1, 16-3 SJTW, 12-2 NM-B, 12-3 NM-B, 18-3 SVT, 18-2 NISPT-2) and three types of circuit protection (Molded case circuit breaker (MCCB), combination Arc-fault circuit interrupter (AFCI), Ground-fault circuit interrupter (GFCI)) were exposed to six room-scale fire exposures. Three replicate experiments were conducted using two sofas and a carpeted floor as the fuel load, two replicate experiments were conducted with only one sofa and a carpeted floor as the fuel load and the last experiment had two sofas, walls covered with MDF paneling on the three full walls of the room and a carpeted floor. Heat release rates were measured for each of the compartment experiments.

Impact of Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures

The test scenarios ranged from fires in the structures with no exterior ventilation to room fires with flow paths that connected the fires with remote intake and exhaust vents. In the ranch, two replicate fires were conducted for each room of origin and each ventilation condition. Rooms of fire origin included the living room, bed room, and kitchen. In the colonial, the focus was on varying the flow paths to examine the change in fire behavior and the resulting damage. No replicates were conducted in the colonial. After each fire scene was documented, the interior finish and furnishings were replaced in affected areas of the structure.

Instrumentation was installed to measure gas temperature, gas pressure, and gas movement within the structures. In addition, oxygen sensors were installed to determine when a sufficient level of oxygen was available for flaming combustion. Standard video and firefighting IR cameras were also installed inside of the structures to capture information about the fire dynamics of the experiments. Video cameras were also positioned outside of the structures to monitor the flow of smoke, flames, and air at the exterior vents.

Each of the fires were started from a small flaming source. The fires were allowed to develop until they self-extinguished due to a lack of oxygen or until the fire had transitioned through flashover. The times that fires burned post-flashover varied based on the damage occurring within the structure. The goal was have patterns remaining on the ceiling, walls, and floors post-test. In total, thirteen experiments were conducted in the ranch structure and eight experiments were conducted in the colonial structure. All experiments were conducted at UL's Large Fire Laboratory in Northbrook, IL.

Data Analysis

Impact of Flashover Fire Conditions on Exposed Energized Cables

The cable samples were photographed and examined for broken strands, beads, notches and other fire damage. The time to the circuit fault (open) and the signal response (trip type) were also examined.

Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures

After the experiments, the fire scenes were documented, the data was plotted, and videos were reviewed. The numerical and visual field data were compared between the experiments to examine the repeatability of replicate fire experiments and to examine the correlation of the change in fire damage relative to the change in ventilation.

Project Findings

Flashover Fire Conditions on Exposed Energized Cables

Assessments of both the thermal exposure and physical damage to the cables did not reveal any correlation between the total integrated heat flux exposure or the type/magnitude of damage (broken strands, beads, notches) and the signal response (trip type). There were three different groups of cables that had statistically similar thermal exposure protection, however no group included more than three of the cable types.

The results from this study are consistent with bench-scale, steady-state thermal exposure studies that indicated a heat flux of more than 20 kW/m^2 was needed to fault the cables. While heat fluxes in excess of

20 kW/m^2 are required to ignite or thermally damage the cable insulation, the heat flux at the time of the circuit faults due to the growing room fire occurred at much higher values and total heat exposures.

Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures

The replicate ranch experiments demonstrated repeatability in fire behavior, numerical data trends, and damage observations. Examples are shown in the figures below (Figure 2 - 6). One of the fundamental concepts demonstrated by these is experiments is the relationship between oxygen consumption and the generation of heat.

Ranch Living Room After Experiment 1

Ranch Living Room After Experiment 2

Ranch Living Room After Experiment 3

Ranch Living Room After Experiment 4

Figure 2. Photographs of the living room for Experiments 1 through 4. In each case the fire was started on a sofa positioned against the back wall. Experiments 1 and 2 were replicates with all of the exterior openings closed. Experiments 3 and 4 were replicates with the front door to the structure open.

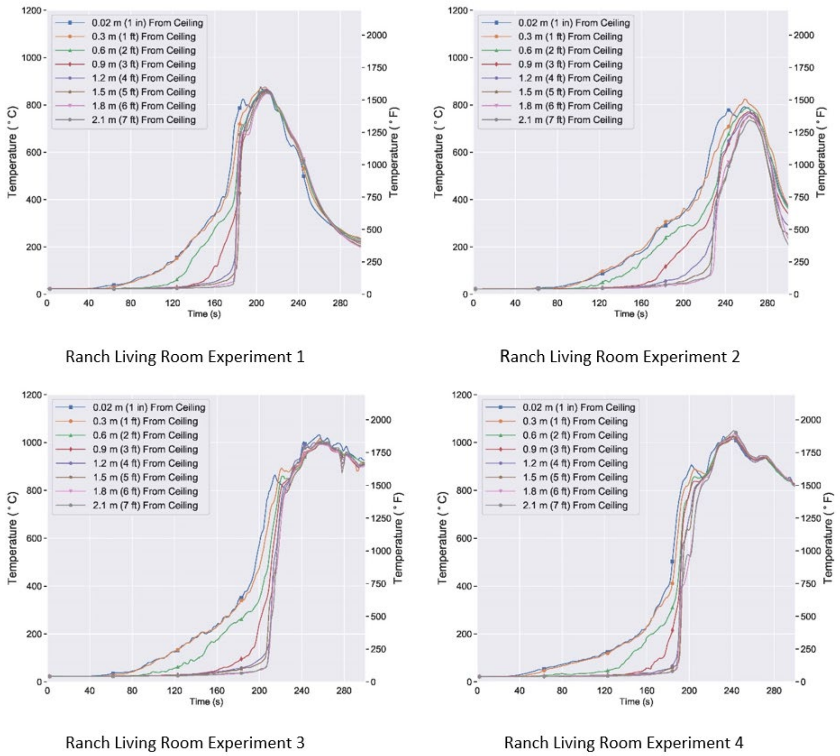


Figure 3. Temperature time histories of the living room for Experiments 1 through 4.

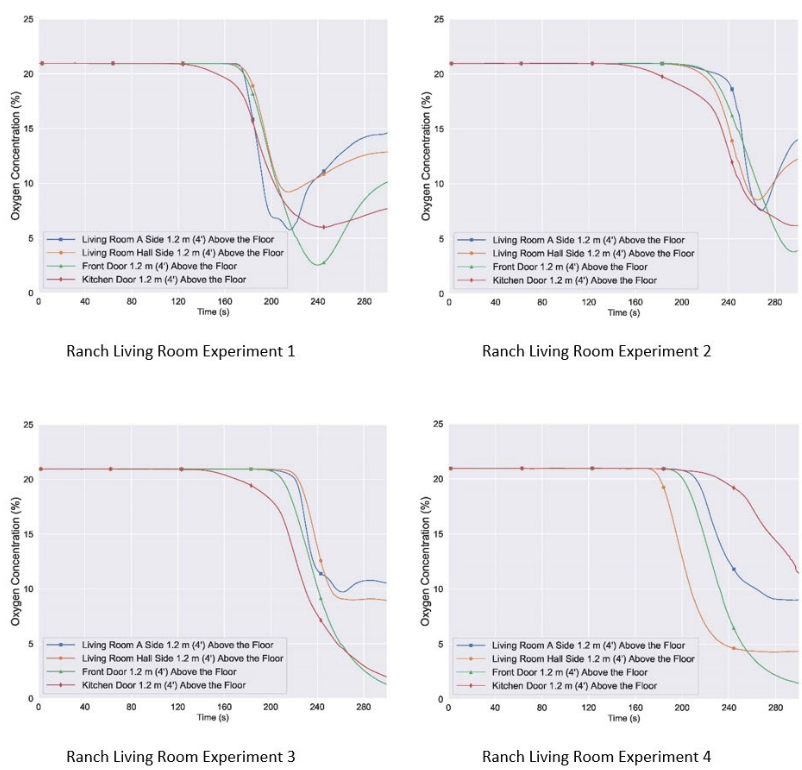
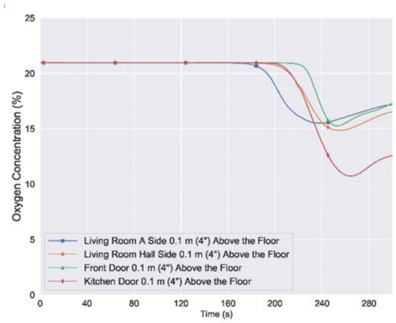
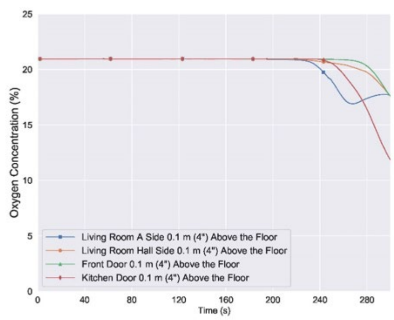


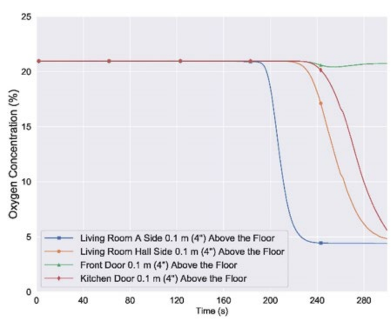
Figure 4. Oxygen concentration time histories at 1.2 m above the floor for experiments 1 through 4.



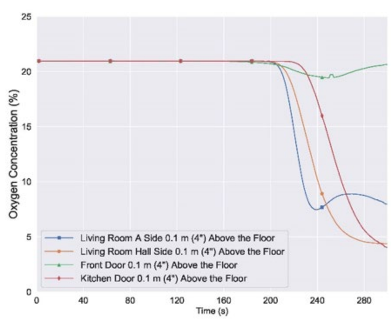
Ranch Living Room Experiment 1



Ranch Living Room Experiment 2



Ranch Living Room Experiment 3

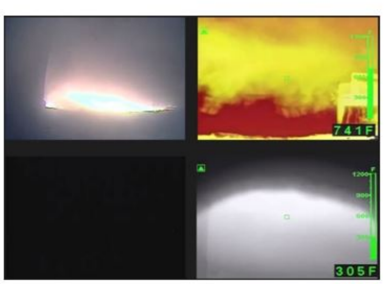


Ranch Living Room Experiment 4

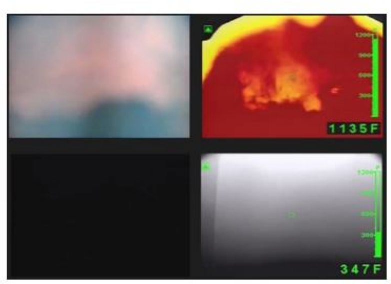
Figure 5. Oxygen concentration time histories at 0.1 m above the floor for experiments 1 through 4.

Ranch Living Room Experiment 1

Ranch Living Room Experiment 2



Ranch Living Room Experiment 3



Ranch Living Room Experiment 4

Figure 6. Pairs of video and infrared images from two views of the living room for Experiments 1 through 4 at 300 seconds after ignition. The two upper views in each set of images are from cameras near the front door and looking toward the area of origin. The lower two views in each set of images are from cameras in the dining room, with the center of the image view approximately 1 m to the left of the area of origin.

The images in Figure 6 show that in Experiments 1 and 2, (exterior vents closed), the fire had depleted the oxygen levels within the structure such that the flames self-extinguished shortly after flashover. Experiments 3 and 4 had the front door open. The air flow through the open door enabled the fire to continue to burn post-flashover. However the fire only burned near the open front door where the hot fuel gases could mix with oxygen entering the door (upper images). At the same time, the gas-phase combustion near the area of origin had stopped due to a lack of oxygen (lower images).

Ranch Living Room Experiment 1

Ranch Living Room Experiment 2

Ranch Living Room Experiment 3

Ranch Living Room Experiment 4

Figure 7. Pairs of video images from Experiments 1 through 4 at 300 seconds after ignition showing the front and rear sides of the ranch test structure.

Increasing the ventilation available to the fire, in both the ranch and the colonial, resulted in additional burn time, additional fire growth, and a larger area of fire damage within the structures. These changes are consistent with fire dynamics based assessments and were repeatable. Fire patterns within the room of origin led to the area of origin when the ventilation of the structure was considered. Fire patterns generated pre-flashover, persisted post-flashover if the ventilation points were remote from the area of origin.

Implications for Criminal Justice Policy and Practice in the United States.

The report, the time histories of the data, and the videos from this study provide foundational documentation for the understanding of ventilation-controlled fires and the resulting fire patterns. Lack of knowledge of post-flashover and ventilation-controlled fire damage by fire investigators has resulted in unwarranted prosecutions and incarcerations for arson. This study supports the understanding of separate and distinct fire patterns that are generated by ventilation-controlled burning conditions in a structure. In past criminal cases, fire investigators have mis-understood ventilation generated patterns and incorrectly identified them as evidence of arson.

Further, the experiments on exposing electrical cabling to a fire environment document that when the energized cables insulation burns away to the point that a short circuit or ground fault occurs the physical damage was similar among the different cable types regardless of the type of electrical circuit protection.

Standards and Guides

Information from this study is being provided to the NFPA Technical Committee on Fire Investigations and the NFPA Technical Committee on Fire Investigator Professional Qualifications.

Fire Investigator Training

The findings from this study, along with videos and supporting data, are being incorporated into the Fire Investigator Training Courses that are given at FEMA's National Fire Academy. The new courses are scheduled to be piloted in the Fall of 2019.

Information from this study is being incorporated into the International Fire Service Training Association's *Fire Investigator 3rd edition* training manual. This document is planned for release in 2020.

Elements of this study are being included into a new IAAI CFITrainer.net® On-line Module, *Fire Flow Analysis,* which will be completed and issued in 2019.

The results of the study have been presented at:

Madrzykowski, D., *The Evolution of Fire Investigation from the Perspective of Science: Why Science Matters in the Search for Justice: Current Research to Support the Science of Fire Patterns and Their Interpretation.* Workshop #19, American Academy of Forensic Sciences, 2018 Annual Scientific Meeting, Seattle WA, February 20, 2018.

Madrzykowski, D., Weinschenk, C.G., *The Impact of Ventilation on Fire Damage Patterns From Room Fires in Full-Scale Structures.* D5, American Academy of Forensic Sciences, 2018 Annual Scientific Meeting, Seattle, Washington, February 22, 2018.

Madrzykowski, D., *The Impact of Ventilation on Room Fires in Full Scale Structures*, IAAI International Training Conference, Las Vegas, NV, April 10, 2017.

The report, videos of the experiment, and interactive floor plans for the experiments will be available from the UL FSRI website, ulfirefightersafety.org.