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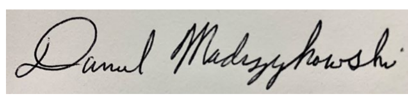

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Printed Name	Signature	Date

Summary of the Project:

Purpose:

Predictive models are employed by fire investigators, and it is critical that exposure conditions and physical phenomena such as material degradation are properly represented to ensure accurate predictions. The purpose of this study is to develop a novel experimental dataset to address three distinct fire model validation spaces that are relevant to fire investigation: spatially and temporally varying fire exposures to walls, heat transfer within and thermal degradation of fire-exposed walls, and fire damage patterns arising on fire-exposed walls. This was achieved by the conduct of a series of experiments in which free-standing walls were exposed to several types of well-controlled fires, including: a gas burner, liquid fuels, wood cribs, and furnishings. The results of this work will be used in future validation studies to advance the state of the art in the use of fire modelling to support fire investigation.

Motivation:

The proposed work is motivated by the present lack of understanding of the significance of the simplifying assumptions made by fire investigators in their application of fire dynamics models, specifically pertaining to representation of heat transfer through compartment walls. This lack of knowledge is attributed to a lack of validation data in this space. A novel dataset is needed to understand if, and when, those simplifying assumptions are appropriate. Additionally, while more complex representations of boundary heat transfer have been developed, they have not yet been extensively tested or validated. A novel dataset is required to support this validation and provide a technical basis for future adoption.

Major Goals and Objectives:

The objectives of this work include:

- Develop a novel dataset that may be used to validate predictions of thermal exposures and heat transfer in present and future fire. The primary measurements to support this objective include surface temperature of walls, gas temperature near walls, and heat flux to walls subjected to fire exposures.
- Develop a novel dataset that may be used to validate predictions of fire damage patterns, specifically pertaining to discoloration and mass loss fire effects arising on gypsum wallboard from non-impinging fires. The primary measurements to support this objective include: photographs of walls, mass loss of walls, surface temperature of walls, and heat flux to walls subjected to fire exposures.
- Produce a set of thermophysical properties for the materials that were used in this study (lightweight gypsum wallboard, calcium silicate board, and stainless steel). This property data will be directly used in validation of fire models of these experiments, as well as in future work involving these materials.

This work directly addresses one of the Fire & Arson Investigation research issues identified by the Forensic Science Technology Working Group Operational Requirements (November 2019): "the evaluation of incident heat flux profiles to walls and neighboring items in support of fire model validation". Additionally, the following issues are indirectly addressed: "adequate materials property data inputs for accurate computer fire models" and "repeatability and reproducibility of test measurements of large-scale structure fires".

Research Design, Methods, Analytical, and Data Analysis Techniques:

This study was designed and conducted as 8 major tasks:

- Task 1 – Technical Panel
- Task 2 – Development of an Inverse Heat Transfer Model for Heat Flux Field Measurements
- Task 3 – Design Experiments
- Task 4 – Procurement and Fabrication of Apparatus
- Task 5 – Conduct Experiments
- Task 6 – Data Compilation and Analysis
- Task 7 – Develop Final Project Report
- Task 8 – Dissemination of Results

Task 1 – Technical Panel

FSRI brought together panel of technical experts from the public fire investigator community, the fire research field, and private fire investigators. The panel worked to ensure that fire investigators' needs and concerns were addressed and that the results will be technically sound and useful to the fire investigation community. The members of the technical panel were:

- Michael Browne, City of Philadelphia Fire Department
- Donald A. Brucker, Allegheny County Fire Marshal's Office
- Barry Burnside, Mississippi State Fire Academy
- Kevin Connelly, Bureau of Alcohol, Tobacco, Firearms and Explosives
- Andrew Cox, Bureau of Alcohol, Tobacco, Firearms and Explosives
- Jason Fedoriw, City of Winnipeg Fire Paramedic Service
- Jason Floyd, Underwriters Laboratories Inc., Fire Safety Research Institute
- Timothy Gammage, II, City of Phoenix Fire Department
- Shijin Kozhumal, Eastern Kentucky University
- Robert Mcloud, City of Los Angeles Fire Department
- Randy Watson, S-E-A Limited
- Marcos Vanella, National Institute of Standards and Technology

Task 2 – Development of Inverse Heat Transfer Model for Heat Flux Field Measurements

An inverse heat transfer model was developed for the measurement of field heat flux to a flat planar surface (a wall was considered in the present study, but the model is applicable to any flat surface). The model is based on a finite element numerical approximation of the partial differential equation developed from conservation of energy about discretized elements of the wall. The primary inputs to the model are the surface temperature of the wall, the gas temperatures adjacent to the wall, and the thermophysical properties of the wall. An optional procedure was also implemented to refine estimates of the convection heat transfer occurring at the wall surface based on discrete radiometer measurements. Experiments (Task 3) were designed to capture these measurements, and the model was employed to calculated heat flux over the surface of fire-exposed walls in those experiments.

Task 3 – Design Experiments

Experiments were conducted in which a fire source was positioned under an exhaust hood instrumented for the measurement of heat release rate by oxygen consumption calorimetry. A freestanding wall was placed adjacent to the fire source, and the experiments were designed to characterize the impact of the fire on the wall. The fire sources used are summarized in Table 1. The peak heat release rate (HRR) and peak flame height (H_f) are also reported in Table 1, and these were consistent with the design values selected to achieve peak heat flux values (q'') ranging from 15 kW/m^2 to 30 kW/m^2 to the wall, based on the given spacing between the fire and the wall (L). This range of heat flux was selected to produce validation data that is relevant to the validation space, and would produce fire damage patterns consistent with the objectives.

Table 1. Fire sources and size characteristics.

ID	Description	$W \times D \times H$ (in.)	L (in.)	L/D	Peak HRR (kW)	Peak H_f (in.)	Peak q'' (kW/m^2)
BURN	Natural gas burner	24 × 24 × 12	12	0.5	500	76	20
CRIB	Wood crib	24 × 24 × 12	12	0.5	370	70	28
CRIF	Wood crib with PU foam	24 × 24 × 15	12	0.5	410	90	28
GASA	Gasoline pool	20 × 20 × 3.5	25	1.25	415	82	16
GASB	Gasoline pool	20 × 20 × 3.5	20	1.0	430	82	22
HEPT	Heptane pool	20 × 20 × 3.5	20	1.0	610	94	28
UPCH	Upholstered chair	27 × 24 × 31	24	1.0	625	60	25

The wall types used in the experiments are summarized in Table 2. Each wall type was selected to address a specific validation objective. The wall size measured 48 in. wide by 96 in. tall. Panels were mounted in insulated steel frames prior to each experiment, which were then mounted in front of the fire source, perpendicular to grade. Experiments were performed in triplicate for each combination of wall and fire type to characterize variability.

Table 2. Wall types and measurements to address the study objectives.

ID	Description	*Objective*	*Measurements to Address Objective*
CSB	Non-combustible calcium silicate board	Heat transfer	Surface temperature, gauge heat flux, fire size (HRR & H_f).
GWB	Gypsum wallboard painted on the exposed side	Fire damage patterns	Surface temperature, gauge heat flux, mass, fire damage patterns, fire size.
STL	Stainless steel (plate heat flux sensor)	Fire exposures	Surface temperature, gas temperature, field heat flux (IHT model), fire size.

In each experiment, the back-side temperature of the wall was measured using infrared thermography. In the case of the steel wall (plate heat flux sensor), which was thermally thin, the exposed-side temperature was equal to the measured back-side temperature. The gas temperatures on the exposed and unexposed sides of the wall were measured with a grid of thermocouples. These measurements, in combination with the IHT model, were used to deduce the field heat flux over the surface of the wall in the STL experiments. For CSB and GWB experiments, combination total heat flux and radiometer gauges were installed at five locations on the walls, along with a thermocouple to measure the gas temperature local to the gauge.

In addition to these experiments, small scale tests were conducted to determine the optical and thermophysical properties of the three wall types. These data are critical to future validation efforts utilizing the measurements from these experiments.

Task 4 – Procurement and Fabrication of Apparatus

The three wall materials, fuels, insulation, and framing were procured from local vendors. GWB and CSB panels were stored in a conditioning chamber (20 °C and 50 % relative humidity) prior to the conduct of experiments to ensure consistent properties. The apparatus was designed and constructed prior to the conduct of experiments. The wall framing was fabricated from galvanized steel strut channel and fixtures; this is depicted in Figure 1.

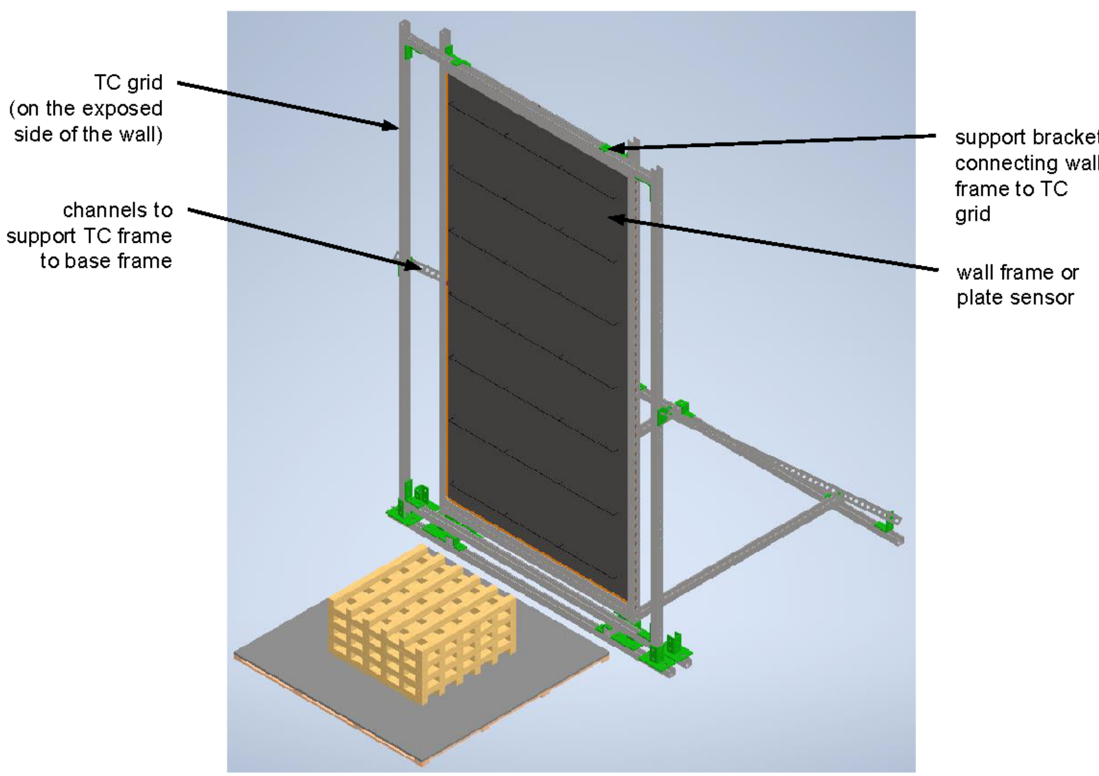
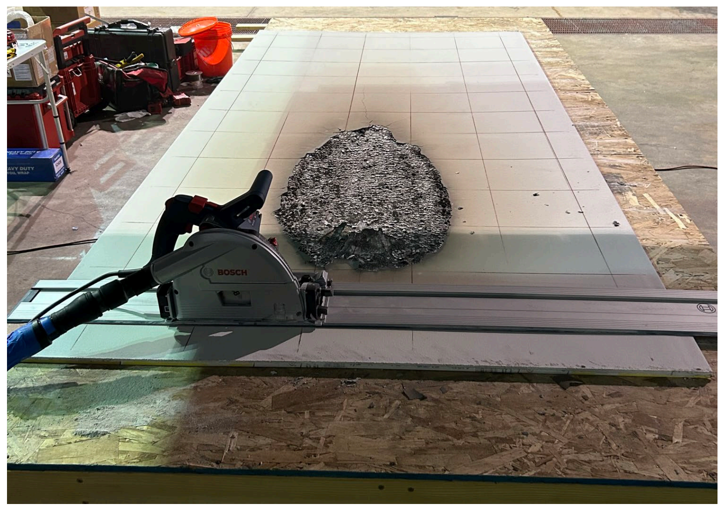


Figure 1: Rendering of the apparatus showing the fire source (wood crib is depicted), wall (steel plate heat flux sensor), framing, and gas thermocouple grid.

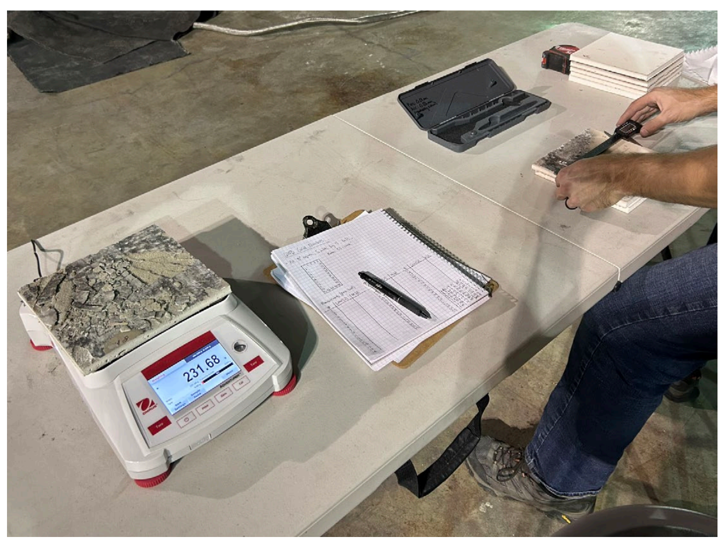
Task 5 – Conduct Experiments

Experiments were conducted at the Bureau of Alcohol, Tobacco, Firearms and Explosives Fire Research Laboratory (ATF-FRL) from December, 2022 through January, 2023. A total of 63 experiments (7 fire types, 3 wall types, each in triplicate) were conducted. Duplicate backups of all measurements were made after each experiment. In addition to timeseries measurements, after each GWB test the walls were grid-marked and photographed. The panels were then removed from the framing, cut into 55 square samples (side length of 8 in.), and the mass and dimensions of each sample were measured. In this manner both discoloration and mass loss fire effects of the GWB were documented. This procedure is shown in Figure 2 for the exposure of a GWB wall to the gas burner fire source.

a) Marking grid for mass analysis.



b) Cutting of GWB samples.



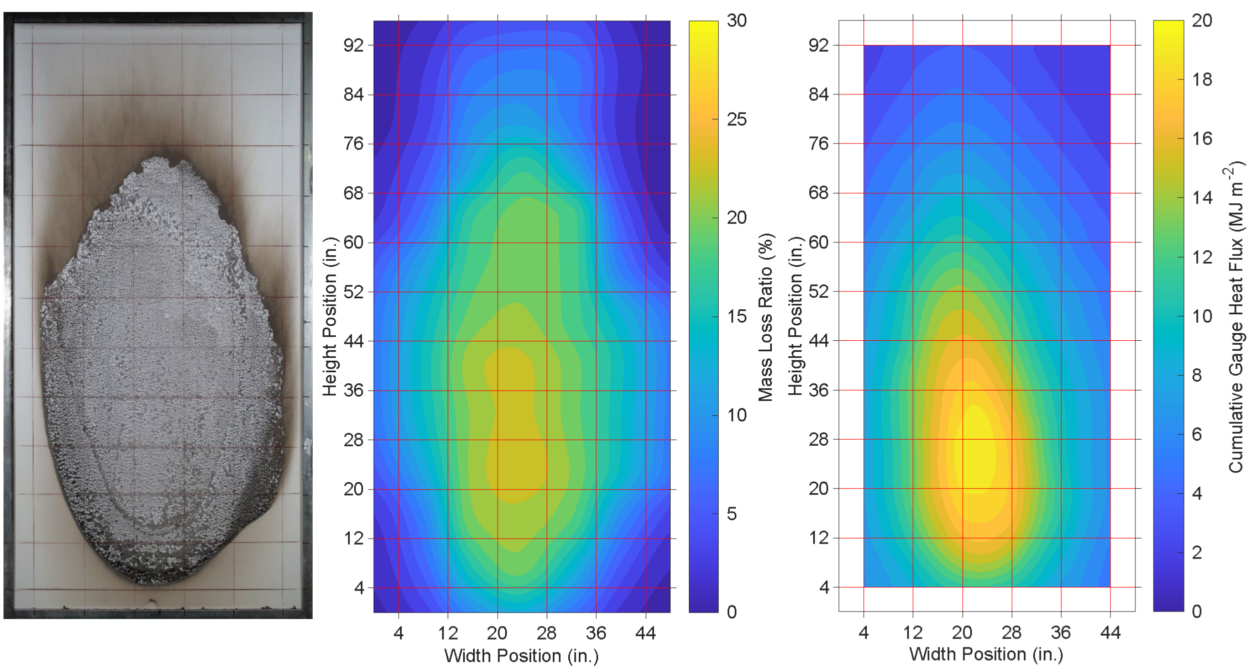
c) Measuring mass and dimensions of GWB samples.

Figure 2: Procedure for measuring fire effects on gypsum wallboard.

Task 6 – Data Compilation and Analysis

The IHT code developed in Task 2 was used in conjunction with measurements obtained from the plate heat flux experiments to calculate the heat flux field over the surface of the wall. It was shown that this same heat flux field was applied to CSB and GWB walls for a given fire type. Field heat flux estimates were compared to gauge heat flux measurements for those experiments, and it was shown that those two independent measurements of heat flux were consistent. This demonstrates the utility of the field heat flux data for fire model validation.

For each experiment, contours of the mass loss ratio and cumulative heat flux were generated. These are shown in Figure 3 for a heptane pool fire experiment. These parameters were then compared to the discoloration fire effects to investigate the viability of these measurements as predictive damage metrics. A fire investigator identifies a fire pattern from discoloration fire effects by establishing lines of demarcation between those effects. In this study, charring of the painted paper facing was used to distinguish lines of demarcation from photographs of the fire damage patterns, since it was hypothesized that charring would only occur when certain exposure conditions were achieved, and that the mass loss occurring in those locations would be related to those exposure conditions. It was found that the lines of demarcation in fire-exposed GWB samples corresponded to a mass loss ratio of 14.9 ± 2.1 % and a cumulative heat flux of 10.4 ± 1.5 MJ/m^2, averaged over all experiments. Of the two, mass loss ratio was found to be a more consistent predictor of the line of demarcation over all fire types, with cumulative heat flux overpredicting the line of demarcation for the gas burner fire and underpredicting the line of demarcation for the heptane pool fire.



a) Damage pattern. b) Mass loss ratio. c) Cumulative heat flux.

Figure 3: Fire damage patterns and damage metrics for a heptane pool fire exposure.

The finding that lines of demarcation established for discoloration fire effects are related to mass loss fire effects is useful as it provides a technical basis for the prediction of fire damage patterns using a fire model. A fire model can be used to predict the mass loss occurring in a wall for a given exposure scenario, and these findings can be used to translate those predictions into a discoloration fire pattern. In this manner, a fire investigator can use a fire model as a tool to test hypotheses related to origin and cause by comparing model predictions of discoloration fire effects to fire patterns on walls that were documented with photography.

Task 7 – Develop Final Project Report

A final project report was developed to document the measurement and analysis procedures as well as the results of this study. This project report is publicly hosted on FSRI.org, and contains a persistent link (Digital Object Identifier) to a public data repository that contains both the measurements and analysis results.

Task 8 – Dissemination of Results

The final project report and data repository have been made publicly available, and future work on this topic will directly refer to these resources. The following publications are in review or in the final stages of development, and publication is expected in 2024:

- Measurement of Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation
    - Submitted to: Data in Brief: https://www.sciencedirect.com/journal/data-in-brief
- Heat Flux Measurements using Steel Panels and Infrared Thermography (HFSPIR)
    - Submitted to: SoftwareX: https://www.sciencedirect.com/journal/softwarex
- Measuring Heat Flux from a Fire using Steel Panels and Infrared Thermography
    - Submitted to: MethodsX: https://www.sciencedirect.com/journal/methodsx
- Relationship between Discoloration and Mass Loss Fire Effects on Gypsum Wallboard
    - Submitted to: Fire Technology: https://link.springer.com/journal/10694

Expected Applicability of the Research

This study provides a robust dataset to the fire modeling and fire investigation community to support the development and validation of fire models. This includes timeseries measurements of temperature, heat flux, heat release rate, flame height, and other important parameters for fire model validation. Additionally, measurements of mass loss ratio may be used to validate predictions of the calcination of gypsum wallboard in these fire models, which will facilitate model predictions of fire damage patterns based on discoloration fire effects. A procedure for hypothesis testing utilizing fire models based on this approach has been documented in the final project report; fire investigators and fire model practitioners can use this reference as guidance for applying this methodology. Furthermore, the material property data that was measured in this work may be directly leveraged in fire models utilizing these materials. The data repository also includes spatially calibrated videos of the fire profiles. Recent research has found that analysis of such videos, supplemented by machine learning and artificial intelligence, can develop estimates of heat release rate based on projected flame volumes. These videos will be a valuable training dataset for future developments in this research area.

Participants and Other Collaborating Organizations

The Fire Safety Research Institute conducted this study in collaboration with the Bureau of Alcohol, Tobacco, Firearms and Explosives – Fire Research Laboratory. Future collaborations with Worchester Polytechnical Institute (heat flux measurement procedure) and Imperial College London (heat release rate from flame volume estimates) are planned.

Outcomes:

Results and Findings

The data repository that was developed in this work will serve as an invaluable resource to the fire modelling community to validate model predictions of field heat flux from fires to surfaces, heat transfer within fire-exposed surfaces, and the formation of fire damage patterns on gypsum wallboard from fire exposures.

A novel code for measurement of field heat flux was developed, termed “HFSPIR”. The code is presently in a beta phase, and upon final release both the source code and compiled binaries will be made available to the public. HFSPIR will facilitate fire researchers and experimentalist in related fields to characterize the field heat flux to surfaces. FSRI will continue to host, maintain, and develop this code base in perpetuity.

This research resulted in the identification and quantification of a direct relationship between mass loss and discoloration fire effects. It is envisioned that this finding may be incorporated into future guidance for the use of fire models to support fire investigation.

Limitations

There are no limitations to access of the data by the public. The entire repository amounts to almost a terabyte of data, and may pose a storage limitation in some applications. To make the data repository more manageable for individual downloads, the repository has been divided into five individual datasets (identified in the Artifacts section, below).

This research focused on the acquisition and development of a large dataset for fire model validation, but no validation was performed within this scope. Future research will address this next logical step in the development of fire models to support fire investigation.

The thermophysical properties developed for the materials in this study were limited to the virgin state. For materials that undergo thermal decomposition, the kinetics and energetics of reaction must also be accounted for in a fire model. Future work will address this need by developing a thermal decomposition model for gypsum wallboard; these associated properties will be published and made publicly available on FSRI.org.

One limitation of this study is that only a single material type was selected that is suitable for validation of fire damage patterns. It is envisioned that the relationship between mass loss and discoloration fire effects is dependent on the material; for example, the mass loss ratio for fire-rated "Type-X" gypsum wallboard may differ from that of the lightweight gypsum wallboard used in this study. Future work should investigate the robustness of this relationship over several material types that are relevant to fire investigators.

Artifacts:

List of Products

Final Project Report:

- *Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation*. Matthew DiDomizio, Fire Safety Research Institute, 6200 Old Dobbin Lane, Columbia, MD, USA and Jon Butta, ATF Fire Research Laboratory, 6000 Ammendale Rd., Beltsville, MD USA (Currently In review with ATF)

Data Repository:

- *Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation*. Matthew DiDomizio and Daniel Madrzykowski. https://doi.org/10.5281/zenodo.10543089.
- *Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation – IR_CSB*. Matthew DiDomizio and Daniel Madrzykowski. https://doi.org/10.5281/zenodo.10542739.
- *Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation – IR_GWB*. Matthew DiDomizio and Daniel Madrzykowski. https://doi.org/10.5281/zenodo.10542974.
- *Heat Transfer and Fire Damage Patterns on Walls for Fire Model Validation – IR_STL*. Matthew DiDomizio and Daniel Madrzykowski. https://doi.org/10.5281/zenodo.10543028.

Additional:

- Links to journal articles as they are published will be found at https://fsri.org/.
- Links to the IHT software that was developed from this project, HFSPIR, will be found at https://fsri.org/ upon release of version 1.0.0.

Dissemination Activities:

Standards and Guides

Information from this study will be shared with NFPA Technical Committee on Fire Investigations. The data repository will be shared with the fire modelling community, and particularly the developers of Fire Dynamics Simulator (the most prevalent code for simulation of fire dynamics used by researchers and fire safety professionals in the fire science field).