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Project Title: Examination of the Use of Fire Dynamics Analysis Techniques With Furniture Fueled Fires

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Summary of the Project:

Motivation:

Fire investigations provide a means to identify the cause of a fire as well as collect data that may provide insight about the development and spread of a fire. By determining the cause of a fire and identifying products and phenomena that contributed to fire spread, investigators may be able to prove guilt or innocence in criminal proceedings, assign blame in civil proceedings, or contribute to the knowledge base that informs the fire protection community for future designs. Data such as the thermal conditions in area of fire origin, the time to flashover of a compartment, and the influence of ventilation on the fire are critical to understanding the cause of the fire.

Computational models are increasingly relied upon in fire investigations, as part of the scientific method, to analyze data or to test hypotheses. The models can be used to qualitatively gain insight on fire phenomena or fire-induced fluid flows. The models can also be used for quantitative analysis if an appropriate range of uncertainty is included. Model results, much like measurements, have varying degrees of uncertainty that can be affected as much by limitations of the model as well as unknowns in the model input parameters.

Current computational models range in complexity from algebraic-based specialized fire dynamics routines derived from fundamental physical concepts and empirical data to generalized, physics-based computational fluid dynamics codes that require a wide range of property values as inputs. The latter may also require specialized knowledge and significant computational resources.

The understanding of the limitations, accuracy, and inherent uncertainties in each model is primarily based on fire measurements generated with well-characterized and, in many cases, steady-state heat sources, such as natural gas-fueled burners or liquid hydrocarbon pool fires. However encountered in fire investigations are often fueled by natural and synthetic solid materials. These fuels are three-dimensional (as opposed to a two-dimensional burner surface), and the foam plastics used in furnishings tend to drip and flow during burning. Fires with these fuels are characterized by non-steady burning where rapid transitions in energy and fuel output are possible.

The Fire and Arson Investigation Technology Working Group Operational Requirements, published in December 2016, addressed several issues regarding input data and fire model validation: (1) repeatability and reproducibility of test measurements of large-scale structure fires, (2) materials property data inputs for accurate computer models, and (3) evaluation of incident heat flux profiles to walls and neighboring items in support of fire model validation.

Major Goals and Objectives:

With the Fire and Arson Investigation Technology Working Group Operational Requirements in mind, the goal was to improve the reconstruction and modeling capabilities of the fire investigation community by adding to the knowledge base in the following areas:

- Improve the understanding of the repeatability of key test measures associated with fire dynamics analysis such as heat release rate (HRR), heat flux, gas velocity, and temperature.
- Add fire test data on several samples of commercially available furnishings for use with fire models.
- Add heat flux profiles to walls of a compartment close to and remote from the fire origin.
- Assess the accuracy of a range of predictive fire algorithms and models when provided with HRR data from residential furniture and compared to replicate fire test results.
- Provide guidance toward standard best practices for the use of fire dynamics analysis techniques with furniture fueled, compartment fires based on research results.

Research Questions:

What is the repeatability and reproducibility of large-scale fire calorimeters?

What is the repeatability and reproducibility of the HRR from upholstered chairs?

What is the repeatability of thermal environment measurements in a compartment based on steady-state natural gas fueled burner fires?

What is the repeatability of thermal environment measurements in a compartment based solely on the burning of a single upholstered furniture item?

In terms of end-user application, input data provided, and the known limitations of the numerical methods used, how do the fire model outputs compare with the compartment thermal environment measurements?

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

This study was designed and conducted in three parts: HRR experiments, compartment experiments, and assessment of three types of models used for fire dynamics analysis. The HRR experiments were conducted in large laboratory spaces so that any impact of compartment effects on the burning rate of the fuels would be reduced. Some of this HRR data was used as input data for the assessment of fire models. Replicate compartment experiments were conducted to generate the fire environment data that the models would be compared against.

Examination of Fire Dynamics Analysis Techniques: Heat Release Rate Experiments

HRR is one of the most important input variables for use in numerically simulating a fire. However, when analyzing a fire, care must be taken to assure that the analytical tool or model is being used with the appropriate input data and a corresponding understanding of the uncertainty of that input data as well as limitations, assumptions, and validation of the model itself.

Underwriters Laboratories Firefighter Safety Research Institute (UL FSRI) partnered with the Bureau of Alcohol, Tobacco and Firearms (ATF), the National Institute of Standards and Technology (NIST) and UL LLC to conduct an interlaboratory study with large-scale fire calorimeters . Each of the laboratories has a range of oxygen consumption calorimetry hood sizes. The size is typically designated by a peak steady state heat release rate, based on and the dimensions of the hood and the exhaust mass flowrate. In this study, the large scale oxygen consumption calorimeters ranged from 3 MW to 10 MW, with hood areas of 36 m^2 to 45 m^2 and exhaust gas flow rates of 16 kg/s to 26 kg/s . Each of the calorimeters operated using the same basic principle of collecting all gaseous combustion products from the burning fuel, determining the mass flow rate, and measuring the oxygen concentration of the gases through the collection duct work .
The first measurement series conducted with each calorimeter used natural gas fueled burners with HRRs ranging from 50 kW to 1 MW. These natural gas fueled burner fires provided a comparison of the capabilities of the three full-scale fire calorimeters used to measure HRR. The second measurement series consisted of replicates of three types of upholstered chairs. Replicate HRR measurements with the upholstered chairs provided a means to examine the repeatability of the burning chairs as well as means to examine the reproducibility of the HRR measurements between the calorimeters.

Examination of Fire Dynamics Analysis Techniques: Repeatability of Compartment Fire Experiments

Experiments were conducted in two similar compartments with interior dimensions of 3.7 m long by 3.7 m wide by 2.4 m high. The compartments were lined with non-combustible panels. The compartments had one doorway, which measured 2.0 m high by 0.9 m wide. Experiments were conducted with either the door opened or closed.
Instrumentation was installed throughout the compartment to measure gas temperature, oxygen concentration, gas velocity, total and radiative heat flux, and pressure. The fixed instrumentation arrangement is shown in Figure 1. Additional heat flux gauges and bi-directional probes were installed above

and adjacent to the fuel package to measure fire plume conditions. The position of these plume measurement instruments changed based on the location of the fuel package within the compartment.

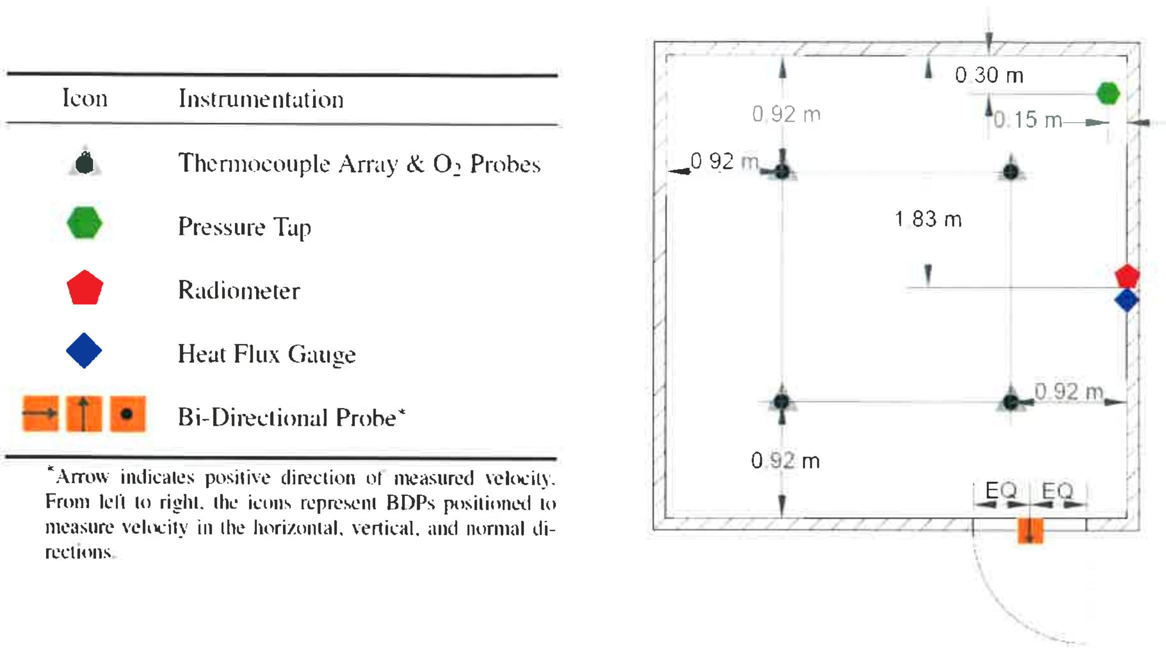

Figure 1. Schematic of the compartment floor plan with location of fixed instrumentation arrays identified.

Experiments were conducted with a natural gas fueled burner with HRRs ranging from 100 kW to 500 kW to provide a best case in terms of repeatability. Subsequent experiments were conducted with two types of upholstered furniture items, an upholstered chair and an upholstered sofa. The furnishings were chosen based on the peak HRR and total energy released under free-burn conditions. Based on calculations, the HRR from the sofa was sufficient to generate a flashover in the compartment when the door was opened. The HRR from the chair was not sufficient to generate a flashover in the compartment. All of these compartment experiments were conducted in the UL large scale calorimetry laboratory in Northbrook, IL. The data was analyzed for repeatability and then used to provide values to assess the fire model results.

Examination of Fire Dynamics Analysis Techniques: Assessment of Predictive Fire Algorithms and Models

This research focused on evaluating the ability of three types of models commonly used in fire investigations to predict characteristics of the fire environment generated from gas burners and a single upholstered furniture items. In other words, these configurations could be considered simple as the experiments did not consider fuel to fuel spread or lack of spread between fuels. Conditions that are common to many fire investigations. The models used represented the three categories of models identified in NFPA 921, Guide for Fire and Explosion Investigations:

1) Fire Dynamics Tools (FDT) is a collection of specialized fire dynamics routines
2) Consolidated Model of Fire and Smoke Transport (CFAST) is a zone model
3) Fire Dynamics Simulator (FDS) is a computational fluid dynamics model

The three models utilized in this study are maintained with on-going verification and validation conducted by the National Institute of Standards and Technology with the support of the Nuclear Regulatory Commission. A quantitative analysis of the accuracy of predicting plume and compartment temperatures, flow velocities, flame heights, heat fluxes, oxygen concentrations, and additional measurands was provided for each model.

Expected Applicability of the Research

This study will provide guidance and insight into the uncertainty bounds that should be considered when using HRR and fire environment data as input for a fire dynamics analysis that is part of a fire investigation. In addition to providing HRR and fire environment data sets, the modeling results show how uncertainties in the data propagate through the models.

Participants and Other Collaborating Organizations

National Institute of Standards and Technology (NIST), Fire Research Division, National Fire Research Laboratory

Bureau of Alcohol, Tobacco, Firearms and Explosives, Fire Research Laboratory

Outcomes:

The reports, the time histories of the data, and the analysis of the data from this study provide foundational documentation for an improved understanding of the repeatability of HRR data and thermal environment measurements both a free-burn and compartment setting. This information can provide guidance to enable better choices for using the data in the analysis of a fire event.

Results and Findings

Examination of Fire Dynamics Analysis Techniques: Heat Release Rate Experiments

The results from the interlaboratory HRR experiments demonstrated that the repeatability and reproducibility of HRR measurements have improved considerably in the past twenty years. Even with uncertainties introduced by a different flaming ignition source, the expanded uncertainty intervals (95 % confidence level) for peak HRRs across the three calorimeters for all of the chair tests were 19% to 22%. The range of expanded uncertainties for the total heat release was 6% to 16%. This is a major improvement from a similar study conducted 20 years ago that showed the mean standard deviation of the peak HRR was 40 %. This provides a guideline for the uncertainty bounds to use when the HRR for upholstered furniture is needed for use in a fire dynamics analysis. This study also provided HRR data which will be included in the NIST Fire Calorimetry Database available at https://www.nist.gov/el/fcd.

Examination of Fire Dynamics Analysis Techniques: Repeatability of Compartment Fire Experiments

A total of 117 fire experiments were conducted inside a compartment with a single door that was either opened or closed for the entirety of each experiment. Natural gas burners set to different HRRs and two upholstered furniture items were used as fuel sources and were placed at four different locations within the compartment over the course of the experimental series. Multiple iterations of the different experimental configurations were conducted to evaluate the repeatability of the thermal measurements.

Comparisons of measurements between replicate experiments revealed that fire conditions generated by gas burner fuels were generally more repeatable than those generated by furniture fuels. For both the open- and closed-door configurations, temperature and flame height were typically the most repeatable measurements, while the wall heat flux measure was the least repeatable. For the gas burner experiments, the mean values of experimental data collected during the period of steady thermal conditions (final three minutes of the experiment) were used for the repeatability assessment of the experiments with an open door. Table 1 displays the ± 2σ values computed over the normalized steady mean values from the various measurement groups for open door replicate experiments with each gas burner fuel source. The total number of normalized steady mean values, N, over which each ± 2σ value was computed is also included in the table.

Table 1. Repeatability Results from Open Door Experiments with Gas Burners

	0.3 m Burner at 100 kW		0.6 m Burner at 100 kW		0.6 m Burner at 250 kW		0.6 m Burner at 500 kW	
Measurement Group	N	$\pm 2\sigma$	N	$\pm 2\sigma$	N	$\pm 2\sigma$	N	$\pm 2\sigma$
Quadrant TCs	192	± 5 %	192	± 3 %	240	± 5 %	252	± 6 %
Doorway TCs	24	± 14 %	24	± 10 %	24	± 3 %	27	± 10 %
Plume TCs	18	± 19 %	18	± 13 %	18	± 7 %	12	± 2 %
Doorway BDPs	12	± 5 %	24	± 21 %	24	± 6 %	27	± 23 %
Plume BDPs	18	± 27 %	18	± 46 %	17	± 25 %	12	± 8 %
Wall HF	24	± 17 %	24	± 19 %	36	± 11 %	36	± 28 %
Plume HF	18	± 12 %	18	± 19 %	18	± 21 %	12	± 21 %
Quadrant O_2	48	± 7 %	48	± 3 %	48	± 8 %	36	± 8 %
Pressure	12	± 9 %	12	± 8 %	12	± 7 %	9	± 7 %
Flame Height	12	± 5 %	9	± 9 %	9	± 6 %	5	± 4 %
Heat Release Rate	0	—	0	—	9	± 17 %	8	± 11 %

Shading	Range
	$\leq \pm \sigma_M$
	$> \pm \sigma_M$ and $\leq \pm 2\sigma_M$
	$> \pm 2\sigma_M$ and $\leq \pm 3\sigma_M$
	$> \pm 3\sigma_M$

Table 2, similar to Table 1, was developed for the open door furniture fire experiments. For the experiments with furniture, peak values from experimental data were utilized for the repeatability analysis of all measurement groups except the quadrant O2 concentration data, which utilized minimum values instead. These tables are an example of the repeatability results from the compartment experiments.

Table 2. Repeatability Results from Open Door Experiments with Furniture

	Red Accent Chair		Overstuffed Sofa	
Measurement Group	N	$\pm 2\sigma$	N	$\pm 2\sigma$
Quadrant TCs	192	± 27 %	192	± 12 %
Doorway TCs	30	± 27 %	42	± 23 %
Plume TCs	6	± 1 %	12	± 3 %
Doorway BDPs	24	± 23 %	24	± 8 %
Plume BDPs	6	± 5 %	12	± 9 %
Wall HF	24	± 25 %	24	± 44 %
Plume HF	6	± 20 %	12	± 23 %
Quadrant O_2	24	± 33 %	24	± 14 %
Pressure	12	± 18 %	12	± 3 %
Flame Height	3	± 8 %	5	± 22 %
Heat Release Rate	5	± 15 %	6	± 28 %

Shading	Range
	$\leq \pm \sigma_M$
	$> \pm \sigma_M$ and $\leq \pm 2\sigma_M$
	$> \pm 2\sigma_M$ and $\leq \pm 3\sigma_M$
	$> \pm 3\sigma_M$

Examination of Fire Dynamics Analysis Techniques: Assessment of Predictive Fire Algorithms and Models

The accuracy of the predictions from all the models was found to be better in the gas burner experiments than in the furniture experiments. All the models were sensitive to the definition of the heat release rate and the geometry of the burning item. Figure 2. Provides examples of results, in this case, the layer temperature predictions for the gas burner and the furniture fire experiments.

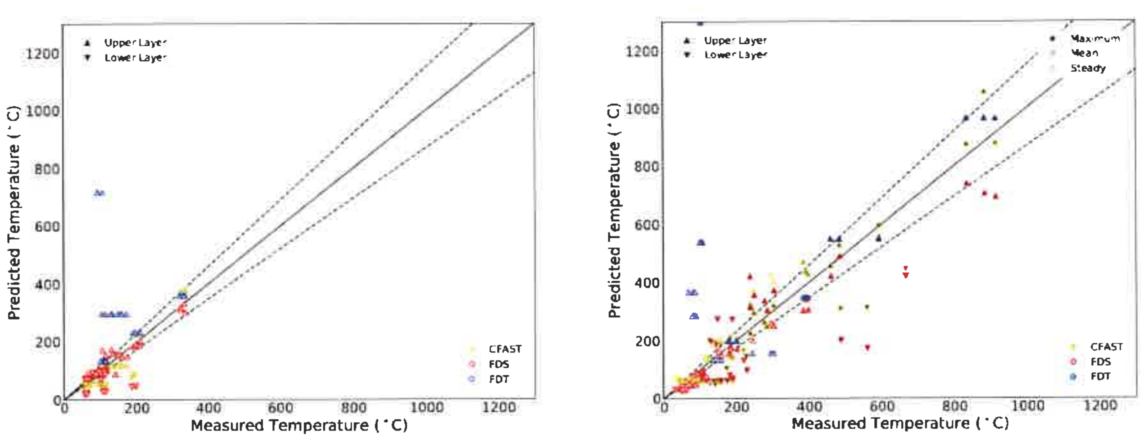

Figure 2. Comparison of Layer Temperature Predictions to Experimental Data Collected in Compartment Experiments with Steady State Gas Burner Fires (left) and Furniture Fires (right).

Because fire investigators are expected to almost exclusively encounter compartment fires fueled by materials and products that are common to residential and commercial occupancies, the recommendations presented in this work focus on the furniture experiments conducted in the compartment. The FDT methods for predicting flame height are the only FDT methods investigated in this work that yielded accurate predictions. The FDT methods for flame height were generally accurate when the observed flame heights were below the ceiling height and also correctly indicated when the flame impinged on the ceiling. The FDT predictions of plume temperature and layer temperature, for the compartment size and fire HRRs examined were overly conservative and cannot be recommended to investigators.

CFAST is recommended for predicting the layer interface height with the understanding that the maximum depth of descent was typically underpredicted when the door was open and overpredicted when the door was closed. If CFAST is used for layer temperature prediction, practitioners should understand that all predicted temperatures were typically lower than the measurements. CFAST was able to accurately predict that flames impinged on the ceiling in the furniture compartment experiments and is expected to slightly overestimate flame heights below the ceiling when the door to the compartment is open. Temperature and flame height predictions in CFAST are most sensitive to the uncertainty in the HRR, so it is recommended that uncertainty in the defined HRR be reduced and that a sensitivity analysis be conducted to define the uncertainty in the predictions and declare a level of confidence for the conclusions drawn from the analysis.

FDS is capable of predicting realistic temperatures throughout the computational domain. It is the recommended method for predicting layer temperatures because it generally yielded accurate predictions for the maximum layer temperatures. If FDS is used to predict the depth of descent of the layer interface, the mean and steady layer interface heights are more reliable than the predicted maximum depth of descent of the interface. FDS is capable of conservative plume velocity and ceiling jet velocity predictions as well as accurate prediction of the flow velocity through the open compartment door. Model practitioners should understand the relatively high uncertainty when using FDS for velocity predictions. FDS was capable of predicting flame impingement on the ceiling for the furniture-fueled fires and is a recommended method to predict flame heights when the compartment door is open and flames are not expected to impinge on the ceiling.

Both FDS and CFAST are recommended for oxygen concentration predictions. In general, CFAST and FDS are capable of accurate predictions of the mean oxygen concentration but model practitioners should be cognizant of the uncertainties when using either model to predict the minimum oxygen concentration in a compartment. Both models have shown issues simulating under-ventilated fires and those concerns have been confirmed in this work.

The scatter exhibited in all the modeling methods for heat flux predictions make recommendation of a method for predicting heat flux from a furniture-fueled fire in a compartment impossible. Because of the uncertainty in the results in each case, none of the methods can reliably be considered to provide a conservative estimate. This is an area that requires further research and development.

Limitations

Examination of Fire Dynamics Analysis Techniques: Heat Release Rate Experiments

The study only examined three types of upholstered chairs. While the construction of the three types of chairs represented different construction materials and configuration design factors, additional research is needed to examine other types of furnishings to broaden the findings of this study.

Examination of Fire Dynamics Analysis Techniques: Repeatability of Compartment Fire Experiments

The results from this study represent a small compartment with a single fuel package. A wider breadth of upholstered furniture items should be utilized as fuel sources. Compartment fires fueled by multiple upholstered furniture items as well as fires in fully furnished compartments need to be examined. Fires in compartments with larger volumes and different ventilation openings should also be considered. Lastly, to continue the examination of the effect of burner size on fire conditions, experiments with burners of different shapes and sizes should be performed for a variety of fire sizes.

Examination of Fire Dynamics Analysis Techniques: Assessment of Predictive Fire Algorithms and Models

More research is necessary to develop recommendations for fire investigators on how to model burning furniture. This research constitutes a starting point to understanding the limitations of the application of fire models with real world fuels to ensure a given model is appropriate and physical phenomena are accurately represented. Radiant heat transfer measurement and modeling in compartment fires needs

Artifacts:

List of products

Willi, J., Madrzykowski, D., McKinnon, M., Examination of Fire Dynamics Analysis Techniques: Repeatability of Compartment Fire Experiments, UL FSRI, Columbia, MD March, 2021.

McKinnon, M., Willi, J., Madrzykowski, D., Examination of Fire Dynamics Analysis Techniques: Assessment of Predictive Fire Algorithms and Models, UL FSRI, Columbia, MD March, 2021.

Madrzykowski, D., Willi, J., Bundy, M, Fuss, S.P., Repeatability and Reproducibility of the Heat Release Rate Measurements of Upholstered Chairs. Prepared for Journal of Forensic Sciences

Willi, J., Application and Validation of Object Detection Model to Measure Flame Height from Video. Prepared for Fire and Materials.

McKinnon, M., and Madrzykowski, D., Considerations for Furniture Input for Fire Analysis Reconstructions, In preparation for Journal of Fire Sciences.

McKinnon, M and Willi, J., Flame Height Correlations for Upholstered Furniture, In preparation for Fire Safety Journal.

Reports and links to journal articles as they are published will be found at https://ulfirefightersafety.org/

Dissemination activities

Standards and Guides

Information from this study will be shared with the NFPA Technical Committee on Fire Investigations.

The results of the study have been presented at:

Presentation: Madrzykowski, D., *Examining the Repeatability & Reproducibility of the Heat Release Rate (HRR) From Upholstered Furniture*, American Academy of Forensic Sciences, Annual Scientific Meeting, February 2021.

Presentation: Willi, J., *Using Object Detection to Measure Flame Height & Evaluate Predictive Models*, American Academy of Forensic Sciences, Annual Scientific Meeting, February 2021.

Poster: McKinnon, M., Willi, J., Madrzykowski, D., *The Use of Computational Models for Fire Investigation Analysis*, NIJ R&D Symposium, February 2021.

Poster to be presented: McKinnon, M., Willi, J., and Madrzykowski, D., *An Assessment of Computational Fire Models for Upholstered Furniture Fires*, International Symposium on Fire Safety Science, April 26 to 30, 2021.

Poster to be presented: Madrzykowski, D., and Willi, J., *Examining the Repeatability and Reproducibility of Heat Release Rate Measurements Using Upholstered Chairs*, International Symposium on Fire Safety Science, April 26 to 30, 2021.