Development of a Database of Contemporary Material Properties for Fire Investigation Analysis - Materials and Methods

Mark McKinnon
Daniel Madrzykowski
Craig Weinschenk

UL Firefighter Safety Research Institute
Columbia, MD 21045

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Mark McKinnon
Daniel Madrzykowski
Craig Weinschenk

UL Firefighter Safety Research Institute
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To ensure the database is of the most use to the fire investigation, fire protection, and general fire modeling communities, UL FSRI assembled a technical panel comprised of representatives from public, private, academic, and research sectors. The individuals below provided direction for the project.

Project Technical Panel

Name	Affiliation
Vyto Babrauskas	Fire Science and Technology Inc
Ernest Barile	Philadelphia Fire Department
Nicole Brewer	Portland Fire & Rescue
Morgan Bruns	Virginia Military Institute
Steve Carman	Carman & Associates Fire Investigation, Inc
Paul Claflin	Bureau of ATF, Fire Investigation & Arson Enforcement Division
Jason Dress	Bureau of ATF, Fire Research Laboratory
Adam Friedman	Jensen Hughes, Inc., ATF Fire Research Laboratory Contractor
Brian Geraci	Maryland State Fire Marshal
Barry Grimm	International Association of Arson Investigators
Brian Lattimer	Virginia Polytechnic Institute and State University
Kevin McGrattan	National Institute of Standards and Technology
Tom Sabella	Fire Department City of New York
Stanislav Stoliarov	University of Maryland

1 Summary

Meetings with the majority of the Technical Panel were held on June 29 and June 30, 2020. The major subjects of discussion included the list of proposed materials to be tested and characterized, the properties for the database, and the experimental and analytical methods to determine the properties for the database. A list of 101 materials divided into 11 categories were identified for inclusion in the database. The topics of variability in materials and aging of products and furniture items was discussed and it was concluded that investigating these variations is outside the scope of the project in this phase.

The list of properties to be stored in the database for each material as well as proposed experimental methods to determine each property were discussed in the Technical Panel meetings. The discussion emphasized that the priorities for the properties represented in the database are dependent on the expected users for the database. Three potential user groups and the sets of properties that each group would likely require were identified. To ensure that the data contained in the database is useful for modeling, it was determined that prioritization would be given to complete sets of properties to be measured and stored in the database.

Over the course of the two meetings, several tools were proposed to make the database easier for model practitioners to use. Once such tool included functionality to output lines of code for the models or entire model input files to simplify the process of inserting the properties into computational fire models. Another tool that was discussed would involve automatically extracting derived properties from data sets or translating between complex and simple representations of burning.

The next phase of the project includes conducting research to finalize the structure of the database and finalizing experimental procedures and protocols to populate the database.

2 Materials and Methods

The list of materials and products to be characterized for the database is provided as Table 2.1. This list includes the materials and products that were proposed prior to the meeting as well as additional materials that were suggested during the Technical Panel meetings. During the meetings, the importance of the properties of non-combustible materials was discussed and it was determined that knowledge of these properties may be important to fire models, and that they should be included in the list. The final list of materials to be characterized includes several non-combustible materials that were mentioned in the Technical Panel discussions.

All of the 11 material categories were deemed important, and several methods were proposed to identify the materials that should be characterized during the initial period of performance for this project. It was proposed that to prioritize the materials, all of the materials should be ranked in order of fire load within the built environment. Determination of the fire load would require knowledge of the total mass of the material or item in the built environment as well as the total mass of pyrolyzate produced during burning. Because of the extensive effort required to determine the fire load and the relative lack of available data about the majority of these materials and products, the fire load was not calculated for the materials and products. Furthermore, the consensus among the Technical Panel was that all of the materials and products were important and specific priorities could not be identified.

Table 2.1: Initial Proposed Materials for the Database

Number	Category	Material/Product
1	Roofing	EPDM Membrane on XPS Rigid Foam
2	Roofing	Roof Felt Underlayment
3	Roofing	Cedar Shake
4	Roofing	Asphalt
5	Roofing	Fiberglass Asphalt
6	Exterior Siding	Composite Decking
7	Exterior Siding	Exterior Insulation and Finish Systems
8	Exterior Siding	Tent Systems
9	Exterior Siding	Vinyl Siding with EPS Foam
10	Exterior Siding	Vinyl siding
11	Exterior Siding	Window Systems
12	Exterior Siding	Pine lap siding (Painted)
13	Exterior Siding	Window Screen Material (Vinyl-Laminated)
14	Exterior Siding	Fiber Cement siding
15	Exterior Siding	Stucco
16	Structural	Exterior Plywood/CLT
17	Structural	Oriented Strand Board
18	Structural	SPF Wood Joist/Stud

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Number	Category	Material/Product
19	Structural	Particle Board
20	Structural	Medium Density Fiberboard
21	Structural	Cinder Block
22	Structural	Concrete
23	Insulation	Extruded Polystyrene Rigid Foam (XPS)
24	Insulation	House Wrap
25	Insulation	Polyisocyanurate Rigid Foam
26	Insulation	Polyurethane Spray Foam
27	Insulation	Wool
28	Insulation	Cellulose
29	Insulation	Fiberglass
30	Interior Finish	Rebond foam carpet padding
31	Interior Finish	Memory foam padding with moisture barrier
32	Interior Finish	Nylon carpeting high pile
33	Interior Finish	Nylon carpeting (low pile)
34	Interior Finish	Wool
35	Interior Finish	Fiber Reinforced plastic panel
36	Interior Finish	Laminate flooring
37	Interior Finish	Polyester carpet (high pile)
38	Interior Finish	Polyester (low pile)
39	Interior Finish	Triexta
40	Interior Finish	Vinyl plank flooring
41	Interior Finish	Vinyl tile
42	Interior Finish	Rayon (Rug)
43	Interior Finish	Cotton (Rug)
44	Interior Finish	Pine board paneling
45	Interior Finish	Rubber carpet padding
46	Interior Finish	Luan Paneling
47	Interior Finish	Solid Oak Hardwood flooring
48	Interior Finish	Basswood bead board
49	Interior Finish	Engineered hardwood flooring
50	Interior Finish	Eucalyptus Hardboard paneling
51	Interior Finish	Ultralite Gypsum Board (2 Coats of Latex Paint)
52	Interior Finish	Standard Gypsum
53	Interior Finish	Plaster
54	Plumbing	Foam insulation
55	Plumbing	Heat-tape Materials
56	Plumbing	Cross linked polyethylene (PEX)
57	Plumbing	Polyvinyl chloride (PVC)
58	Plumbing	Chlorinated Polyvinyl chloride (CPVC)

Continued on next page

Table 2.1 – continued from previous page

Number	Category	Material/Product
59	Cable	Solid Romex NM-B (PVC jacket)
60	Cable	Coaxial Cable (PVC Conduit)
61	Engineered Wood	Counter top, Solid acrylic polymer
62	Engineered Wood	Engineered wood cabinets/furniture vinyl over particle board
63	Engineered Wood	Counter top, Plastic Laminate over particle board
64	Engineered Wood	Engineered wood cabinets/furniture vinyl over MDF
65	Upholstered Furniture	Bean Bag Furniture
66-68	Upholstered Furniture	Polyester Microfiber/PUF/ Polystyrene
69-71	Upholstered Furniture	Vinyl/Polyester batting/PUF
72	Upholstered Furniture	Cotton Upholstery
73	Upholstered Furniture	Hemp
74-76	Upholstered Furniture	Polyester Microfiber/Polyester batting/PUF
77	Sleeping Products	Mattress Topper, Latex Foam
78	Sleeping Products	Polyester Sheets
79	Sleeping Products	Microfiber Sheets
80	Sleeping Products	Mattress Topper, Polyurethane Foam
81	Sleeping Products	Mattress Topper, High Density Polyurethane Foam
82-84	Sleeping Products	Innerspring Mattress
85-87	Sleeping Products	High Density Polyurethane Foam Mattress
88	Sleeping Products	Cotton sheets
89	Sleeping Products	Feather Pillow
90	Sleeping Products	Bamboo Sheets
91	General Polymers	High-Density Polyethylene (HDPE)
92	General Polymers	Low-Density Polyethylene (LDPE)
93	General Polymers	Polypropylene (PP)
94	General Polymers	Polystyrene (PS)
95	General Polymers	Polyethylene Terephthalate (PET)
96	General Polymers	Polycarbonate (PC)
97	General Polymers	Polyamide (PA) (Nylon)
98	General Polymers	Acrylonitrile butadiene styrene (ABS)
99	General Polymers	Acrylic (PMMA)
100	General Polymers	Polylactic Acid (PLA)
101	General Polymers	Polyvinyl chloride (PVC)

The history of materials, and particularly aging of upholstered furniture items, was acknowledged as a potentially important factor. Aging or contamination of furniture items may affect the thermo-physical properties and flammability characteristics of the component materials. Because there is a plan to support development and hosting of this database in perpetuity, the sensitivity of properties and the fire response of the materials to these factors is an important consideration to study, but it is outside the scope of the initial period of performance.

There may be significant differences in the components, properties, and reaction-to-fire between materials that are sold under the same trade name due to variations in manufacturing processes, standards, and intended end use. A detailed investigation into all of the scatter in properties and reaction-to-fire or variation in composition for all of the proposed materials is unfeasible for this period of performance. Material from a single manufacturer/production method will be investigated during this period of performance with a structure in place to update the entry in the future with data collected from different manufacturers/production methods. Descriptions of the materials and products that appear in the database will provide as much detail as possible to specify the material or product that was characterized.

One specific variation in preparation that may be investigated during this period of performance is gypsum wallboard with the surface painted and unpainted. Additionally, many of the pure materials from the General Polymers category have been characterized in previous studies and the properties and test data measured during this project may provide a representation of the variability in the properties due to different formulations, manufacturers, and processes. The list of materials presented here should be considered a baseline and starting point, with a structure in place to expand the number of materials and variables investigated after the initial period of performance.

A discussion was held in each Technical Panel meeting to determine the relative importance of each property in order to rank the priority of each. These discussion were intended to allow UL FSRI to focus on the high priority proposed properties in the event that all of the proposed properties could not be determined during this period of performance. It was noted that the most important experimental data and properties for each material and product in the database will vary with the various stakeholder groups. Representation of all groups that may use the database and incorporation of their data needs into planning will be essential to maximize the utility of the database.

The discussions during the Technical Panel meetings identified three major groups that are expected to use the database: fire investigators, fire protection engineers, and fire researchers. It is important to identify how these groups will use the data in the database to ensure a full set of data is provided to fulfill the needs of each of these groups. Table 2.2 identifies the sets of properties that must be complete to ensure each user group can effectively use the database. The property denoted as 'HRR' in Table 2.2 includes all heat release related properties, including HRR, total heat released, and heat release rate per unit area (HRRPUA). In the table, an 'X' symbol denotes a property that is expected to be required by that user group as an input to a model, a 'V' symbol indicates data that is expected to be useful for validation of a modeling methodology or modeling results, and no symbol indicates a property that is not expected to be heavily used by that user group.

The Fire Investigators user group is expected to use the database as a reference for ignition temperatures and melting temperatures as well as for inputs to models used to test hypotheses about potential fire scenarios. The models that fire investigators use are generally related to fire spread, ignition, and burning rates. To model these phenomena, investigators may require HRRPUA, HRR, total heat released, time to ignition, ignition temperature, heat of combustion, and the thermophysical properties.

The Fire Protection Engineers user group is expected to use the database for inputs to fire protection analyses and models that predict fire growth and spread and smoke movement in the built environment. These methods generally require the same inputs as those used by the Fire Investigators user group, with the addition of product yields and the radiative fraction of the fuel.

The Fire Researchers user group are expected to use the properties in the database for model development and modeling fire phenomena from first principles. The Fire Researchers user group is expected to use all of the properties in the database because of the breadth of inputs required to describe burning using the most complex model representations. This means that Fire Researchers user group is expected to need the pyrolysis reaction kinetics, heats of reaction/gasification, and the optical properties in addition to the expected requirements for the Fire Protection Engineers user group. The HRRPUA, time to ignition, ignition temperature, and full scale HRR data are expected to be used by Fire Researchers to validate models and modeling methodologies.

Table 2.2: Expected Property Requirements for Each User Group

User Group	HRR	Ignition Temperature	Time to Ignition	Soot Yield	CO Yield	Reaction Kinetics	Heat of Reaction	Heat of Combustion	Density	Thermal Conductivity	Specific Heat Capacity	Emissivity	Absorption Coefficient	Radiative Fraction
Fire Investigators	X	X	X					X	X	X	X			
Fire Protection Engineers	X	X	X	X	X			X	X	X	X			X
Fire Researchers	V	V	V	X	X	X	X	X	X	X	X	X	X	X

Although this database has been conceptualized to serve many sectors of the fire protection community, the initial funding for the database comes from the National Institute of Justice (NIJ), which has a vested interest in fire investigations. To ensure the database is effective for the fire investigation community, the properties that correspond to the Fire Investigators user group in Table 2.2 will hold the highest priority.

Some of the properties that are listed in Table 2.2 must be determined from raw data through an analytical method, and the resulting property may be dependent on the method used to determine the property value. Compounding this issue is the fact that several of the properties lack a consensus on the definition of the property or the accepted methods to determine the property. To combat confusion and misuse of the derived properties provided in the database, the definitions of the properties and the equations used to derive the properties will be clearly indicated in the database.

The experimental methods and standard tests that were proposed to measure each of the properties were discussed in the meetings. The proposed experimental methods are presented in Table 2.3 in order of descending priority. The property denoted as 'HRR' in Table 2.3 includes all heat release related properties, including HRR, total heat released, and HRRPUA. The proposed methods were generally accepted by the Technical Panel with a few points of conversation.

The use of the Controlled Atmosphere Pyrolysis Apparatus (CAPA) to measure thermal conductivity was initially proposed. Determination of the thermal conductivity using the CAPA is dependent on a pyrolysis model to conduct an inverse analysis, which also makes the measured thermal conductivity dependent on the assumptions and inputs to the model. Because of the model-dependent nature of determination of thermal conductivity using the CAPA, the other well-established methods for measuring thermal conductivity that are also listed, and the relatively recent emergence of the CAPA to the fire protection community, the CAPA was identified as a lower priority measurement method and was removed for the initial period of performance for this project.

A discussion about the typical range of emissivity values for the proposed materials raised the question of the importance of measuring emissivity and the sensitivity of the model results to the definition of emissivity. The prediction of the time to ignition is particularly sensitive to the emissivity, but it is true that most practical materials have average emissivity values in the range of approximately 0.7 to 0.95. Additionally, there is currently no computational fire model in which the spectral emissivity of a material may be defined. For these reasons, the measurement of emissivity using an integrating sphere was deemed a low priority measurement relative to the other listed measurement methods.

Table 2.3: Initial Proposed Properties and Methods for Database

Property	**Method**
HRR	Oxygen Consumption Calorimetry
Heat of Combustion	Oxygen Consumption Calorimetry
Ignition Temperature	Cone Calorimeter
Density	Balance and Direct Volume Measurement
Thermal Conductivity	Heat Flow Meter
Specific Heat Capacity/Heat of Reaction	DSC
Thermal Diffusivity	Transient Plane Source
Radiative Fraction	Calorimeter
Emissivity/Absorption Coefficient	Integrating Sphere
Reaction Kinetics	TGA

3 Tools for Analysis of Collected Data

The data that will be stored in the proposed database will include comma-separated values (CSV) files of experimental data, as well as photographic and video data of the specimens and pertinent tests. The database will provide as much information as possible to identify the material or product to minimize misuse of the data. Uncertainty is an important consideration in fire protection and predictive modeling, and the uncertainty in the experimental method and in each measured quantity for each material will be clearly presented. As the database becomes populated with data collected on high priority materials and products and the ability to test material samples produced with different formulations and through different processes becomes available, the uncertainty of each property for a material with a specific trade name will also be quantified.

The raw data that will be stored in the database is expected to be useful to a subset of the potential users and various tools that interface with the database will be essential to ensure the entire set of potential users is able to benefit from the data. Ideas for tools and functionality were mentioned throughout the Technical Panel meetings.

As previously mentioned, it is expected that there will be several user groups that will require different data and properties from the database. One of the tools that was suggested is a method to translate between more complex representations of burning to less complex representations of burning to ensure all user groups extract their specific required properties from the same set of data. Such a method should guarantee that the same general results and conclusions are achieved regardless of the complexity of the model. This type of tool may also help to minimize the effort required to extract derived properties from the raw experimental data. As an example, an automated tool may be capable of extracting the melting temperature from TGA data according to the definition of the melting temperature, and automatically populate that property to the database.

Because computational fire modeling requires many property values as inputs and the intention is to make this database easy for fire model practitioners to use, a tool was recommended that will output the lines of code required for common fire models using the selected properties from the database. Such a tool will bring the database closer to a state where it is seamlessly integrated with common publicly-available computational fire models. To validate this type of tool and the set of properties that are stored in the database, it will also be important to demonstrate that common fire models parameterized with the collected properties adequately describe realistic fire scenarios. Through these validation exercises, the most accurate representation of burning that uses the measured properties will be explored to improve the utility of the tool that generates input lines for the fire model.

4 Future Work

The meetings with the Technical Panel and the valuable suggestions provided in the discussions have helped develop a roadmap for future work on this project. The next major phase of this project involves conducting additional research to finalize the structure and type of database as well as the format of the experimental data to be stored in the database. It is expected that the tools and functionality that have been proposed will factor into the structure of the database, and that ideas for additional tools and functions will result from the database research. Concurrently, the experimental procedures and protocols proposed to measure each property will be finalized to ensure consistency between experiments conducted on different materials. The procedures for securing and storing data and the format of the raw data will also be finalized to facilitate transfer of the data and properties from the laboratory to the database.