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Microscale Fire Test for Component Substitutions in Aircraft Cabin Materials

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Final Report

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16. Abstract

A physically based microscale combustion parameter for early stage fire growth, called the fire growth capacity (FGC) (J/g-K), is derived from a simple burning model. The FGC combines the ignitability and heat release of the material into a single parameter that can be measured in a microscale combustion calorimeter (MCC) using the standard ASTM D7309 method. The FGC measured at microscale (10^{-6} kg) in the MCC successfully ranks commercial materials according to their behavior in bench (kg) scale flame (UL 94 V) and fire (14 CFR 25) tests. For this reason, FGC is being evaluated by an aviation industry working group as an alternate means of complying with Federal Aviation Administration fire performance requirements of cabin materials in transport category aircraft when a small component of a certified cabin material must be changed due to cost, availability, performance or environmental concerns. The intent of this report is to validate the proposed methodology and criteria for comparing the components of aircraft cabin materials with respect to flammability. Results for twelve industry case studies were collected and analyzed. In 95% of the cases, the proposed similarity criteria successfully detects a significant change in 14 CFR 25 fire test performance of two materials.

17. Key Words Microscale combustion calorimeter, fire growth capacity, fire performance, similarity, component, aircraft materials.	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

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Contents

Figures

Tables

Acronyms

Acronym	Definition
ABS	Acrylonitrile Butadiene Styrene
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
FAATC	Federal Aviation Administration Technical Center
FEP	Fluorinated Ethylene Propylene
FGC	Fire Growth Capacity
HIPS	High Impact Polystyrene
HR	Heat Release
HRR	Heat Release Rate
JAA	Joint Aviation Authority
MCC	Microscale Combustion Calorimetry
OSU	Ohio State University
PA66	Polyhexamethyleneadipamide
PAI	Polyamideimide
PBI	Polybenzimidazole
PC	Polycarbonate of Bisphenol-A
PE	Polyethylene
PEEK	Polyetheretherketone
PEI	Polyetherimide
PEKK	Polyetherketoneketone
PHRR	Peak Heat Release Rate
PI	Polyimide
POM	Polyoxymethylene
PP	Polypropylene
PPS	Polyphenylene sulfide
PPSU	Polyphenylsulfone
PSU	Polysulfone
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
THR	Total Heat Released
UL	Underwriters Laboratory

VBB	Vertical Bunsen Burner
WJHTC	William J. Hughes Technical Center

Executive summary

A physically-based microscale combustion parameter for early stage fire growth, called the fire growth capacity (FGC) (J/g-K), is derived from a simple model of fire growth in compartments such as aircraft cabins. The FGC includes the ignitability and heat release that drive the fire growth of a material in a single parameter that can be measured in a microscale combustion calorimeter (MCC) using the standard American Society for Testing and Materials (ASTM) D7309 method. The FGC measured at microscale (10^{-6} kg) in the MCC successfully ranks commercial materials according to their behavior in bench (kg) scale flame (UL 94 V [1]) and fire (14 CFR 25 [2]) tests. For this reason, the MCC is being evaluated by a Federal Aviation Administration (FAA)-industry working group as an alternate means of complying with FAA fire performance requirements of cabin materials in transport category aircraft when a component of a certified cabin material must be changed due to cost, availability, or environmental concerns. The Material Change Similarity Task Group within the International Aircraft Materials Fire Test Forum has developed a method and criteria to compare the intrinsic flammability of materials measured in ASTM D7309 to the fire performance of these materials in 14 CFR 25 flammability tests. Results for twelve industry case studies were collected and analyzed by the William J. Hughes Technical Center's (WJHTC) Fire Research Laboratory. Bench-scale tests included in the study are the Ohio State University (OSU) Rate of Heat Release Apparatus, the Radiant Panel test for thermal acoustic insulation, and the Vertical Bunsen Burner. Samples for MCC testing at WJHTC were obtained from industry participants, who conducted bench-scale tests of coupons or constructions containing certified and substitute components. Statistical criteria to compare ASTM D7309 and 14 CFR 25 flammability test results were developed and applied to twelve case studies. In 95% of the cases, the ASTM D7309 methodology and similarity criteria were able to detect a significant difference in 14 CFR 25 fire test performance of two materials.

1 Background

Small changes in the composition of certified aircraft cabin materials are often necessitated by the unavailability or environmental regulation of the original constituents, requiring costly recertification of entire constructions and assemblies containing these components. Aircraft manufacturers and suppliers have asked the Federal Aviation Administration (FAA) to explore alternate means of complying with flammability regulations when a component of a certified cabin material, which may contain many components, is changed. The FAA responded by initiating a Material Change Similarity Task Group under the auspices of the International Aircraft Materials Fire Test Forum to develop a method and criterion for comparing the intrinsic flammability of component materials measured in ASTM D7309 Standard Test Method for Determining Flammability Characteristics of Plastics and Other Combustible Solid Materials Using Microscale Combustion Calorimetry (MCC) [3] to the fire performance of these materials in 14 CFR 25 flammability tests of aircraft cabin interior materials.

A component of a cabin material is defined to be a substance that can be represented at the 5-20 mg scale of an MCC sample, e.g., a panel adhesive, potting compound, thermoplastic, thermosetting resin, fabric, coating, or decorative film. The repeatability and reproducibility of MCC have been documented [3, 4], and several intrinsic combustion properties have been defined, including the heat release capacity η_c (J/g-K), the heat of complete combustion Q_∞ (J/g), the burning temperature, T_p, the char yield μ (g/g), and more recently, the ignition temperature, T_{ign} [5, 6, 7, 8]. With the exception of the intrinsic/intensive/mass-based properties Q_∞ and η_c, some of the MCC combustion properties are not particularly reliable predictors of bench-scale fire test results [8, 9, 10, 11] because they fail to include the ignitability/thermal stability of the material and cannot account for the extrinsic/extensive/mass-dependent processes in bench scale testing, such as melting/dripping, swelling, intumescence, sagging, sample thickness, and gas phase flame inhibition. Consequently, a reliable method to demonstrate equivalent flammability of substitute component materials in bench scale fire tests using MCC will require a combustion property that captures the three main processes of fire growth as they occur in bench- and full-scale fire tests: ignition, flame spread, and heat release, as well as an MCC criterion for equivalent fire test performance (similarity) that allows for the uncertainty in bench-scale flame and fire tests.

The goal of the Material Change Similarity Task Group validation study was to explore the possibility of using a standard, small-scale test (ASTM D7309) to measure combustion parameters of two components and correlate any differences in the intrinsic combustibility with changes in the flammability of constructions or coupons containing these components as measured in 14 CFR 25 fire tests. Success in this effort would be formalized as a method to demonstrate similarity of substitute components. In the context of this study, a component of a cabin material is defined to be a substance that can be represented by a milligram size MCC sample—such as an adhesive, thermosetting resin, thermoplastic, film, fiber, coating, etc.—while a construction is a fabricated part—such as a sidewall panel, stowage bin, bulkhead, partition, etc.—that may contain one or more components. A coupon is a simplified construction that is fabricated for the sole purpose of fire testing in accordance with 14 CFR 25.

This validation study was conducted to determine if the ASTM D7309 microscale test and criteria for equivalent flammability of a substitute component of a certified construction were consistent with the results of 14 CFR 25 tests of coupons containing both certified and substitute components. To this end, coupons containing certified components that had been changed or substituted were tested in accordance with 14 CFR 25, while the components themselves were tested in accordance ASTM D7309 to obtain FGC.

The fire size—in Watts as a function of time, $\dot{q}(t)$, for a characteristic time τ and initial condition, $\dot{q}(0) = \dot{q}_0$ at $t = 0$—can be expressed as follows [12]:

$$\dot{q}(t) = \dot{q}_0 \exp\left(\frac{t}{\tau}\right) \qquad 1$$

Equation 1 describes exponential fire growth with time at a rate that depends on the material properties, sample thickness, and initial fire size, $\dot{q}_0$. At the earliest stages of fire growth, when $t \ll \tau$ (e.g., at the initiation of post-crash fire), Equation 2 gives the fire size when the heat released is

$$\dot{q} = \dot{q_0}\left(1 + \frac{t}{\tau}\right) = \dot{q_0} + \frac{q}{\Delta T_{ign}/\beta} \qquad 2$$

According to Equation 2, the early fire size depends on the rate of heat release of the material and its propensity for flame spread, $q\beta/\Delta T_{ign}$. When Equation 2 is normalized for the mass of the cabin material ($m = \rho b A$) and the thermal insult from the fire or flame (β), the capacity for fire growth, or fire growth capacity (FGC), can be expressed in terms of parameters that are measured in the MCC:

$$\text{FGC} = \frac{\dot{q}}{m\,\beta} = \frac{\dot{q}_0/m}{\beta} + \frac{q/m}{\Delta T_{ign}} = \frac{Q'_{max}}{\beta} + \frac{Q_\infty}{\Delta T_{ign}} = \frac{Q_\infty}{\Delta T_{burn}} + \frac{Q_\infty}{\Delta T_{ign}} \qquad 3$$

In Equation 3, Q'_{max} (W/g) is the maximum specific heat release rate measured in the MCC, Q_∞ (J/g) is the total heat of complete combustion, and $Q'_{max}/\beta = Q_\infty/\Delta T_{burn} = \eta_c$ (J/g-K) is called the heat release capacity, where ΔT_{burn} is the temperature range over which pyrolysis occurs at a constant rate of temperature rise, β (K/s), in a thermal analysis experiment. For a material initially at ambient temperature T_0, whose temperature is raised to the ignition temperature T_{ign}, at a constant rate of temperature rise β, the temperature interval for ignition is, $\Delta T_{ign} = T_{ign} - T_0$ [5, 6].

2 Microscale flammability parameters and bench scale fire tests

The motivation for this work was to identify a microscale fire parameter that captures the processes of early fire growth and to use this parameter to compare the flammability of materials used in aircraft cabins. To this end, a probabilistic analysis of pass/fail fire test results [9, 10, 11] was performed to determine which MCC fire properties reported in the standard test [3], $P = Q_\infty$, η_c, T_p, μ (char yield), were the most discriminating with regard to the performance of materials in bench scale fire tests [8, 9, 10, 11]. In those analyses, Q_∞ was found to be the single best indicator of fire test performance when the continuous likelihood, $p(x)$, of a pass/fail (1/0) outcome in a fire test of a material having microscale fire property P was obtained from a fit of Equation 4 to the discreet binary (1/0) results using P^* and n as fitting parameters,

$$p(x) = \frac{1}{1 + x^n} = \frac{1}{1 + (P/P^*)^n} \qquad 4$$

In Equation 4, n is the slope (steepness) of the transition region at $P/P^* = x = 1$ [9]. **Error! Reference source not found.** is a probabilistic analysis of the effect of Q_∞ on the peak heat release rate results of 14 CFR 25 in the OSU heat release apparatus, where the binary data are coded:

$$p = \begin{cases} 1, & PHRR \le 65\ kW^2 \\ 0, & PHRR > 65\ kW^2 \end{cases} \qquad 5$$

The points in **Error! Reference source not found.** are the discrete binary data for the 19 polymers in Figure 2 and the solid line is the cumulative distribution of likelihoods, i.e., Equation 4 evaluated for best-fit parameters, $P^* = Q_\infty^* = 14.7$ kJ/g and $n = 14.8$. The transition from passing to failing Peak Heat Release Rate (PHRR) results is centered at $Q_\infty = 14.7$ and occurs over a narrow range, $\Delta Q_\infty = \pm 1.3$ kJ/g, indicated by the shaded area. The relative uncertainty of Q_∞^* as a threshold for pass/fail results in the OSU is therefore, $\delta Q_\infty / Q_\infty^* = (1.3$ kJ/g)/ (14.7 kJ/g) = 0.09. This sharpness of the transition from passing to failing results indicates that Q_∞ is highly correlated with PHRR in the OSU [8] heat release test, as has been demonstrated for Vertical Bunsen Burner tests [10, 11].

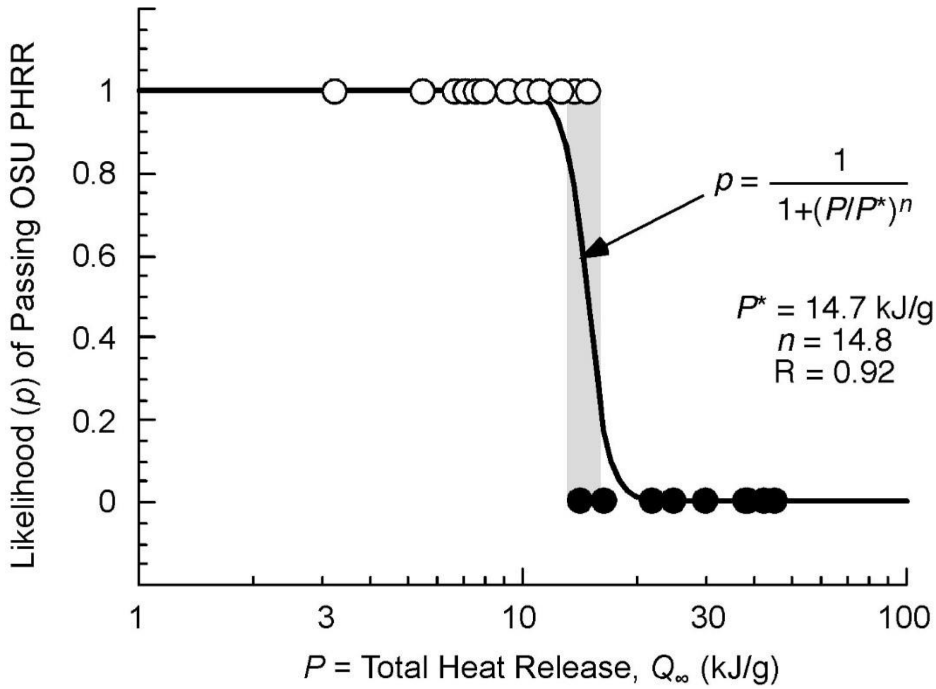

Figure 1. Likelihood of Passing *PHRR* versus Q_∞ of the 19 Polymers in Figure 2.

Equation 3 defines a new MCC flammability parameter called the fire growth capacity (FGC) that includes Q_∞ in the sum of an ignitability term ($Q_\infty/\Delta T_{ign}$) and a heat release rate term ($Q_\infty/\Delta T_p$) [13]. Fire growth capacities (FGC) of 19 polymers were computed from Equation 3 using baseline corrected MCC data for Q′(T) obtained by the standard method [3]. Figure 2 is a bar graph of these FGC, and the number in parentheses at the end of each bar in Figure 2 is the likelihood—where 1.00 equals 100% likely—that each polymer will pass the 14 CFR 25 requirement for peak heat release rate in the OSU heat release apparatus [14, 15], *PHRR* < 65 kW/m^2, computed using a statistical analysis of pass/fail fire test results [8, 9, 10, 11] (see Figure 3). The magnitudes of FGC, and the likelihoods of the OSU heat release apparatus outcomes, are in general agreement with the expected fire performance of the polymers in bench scale fire and flame tests.

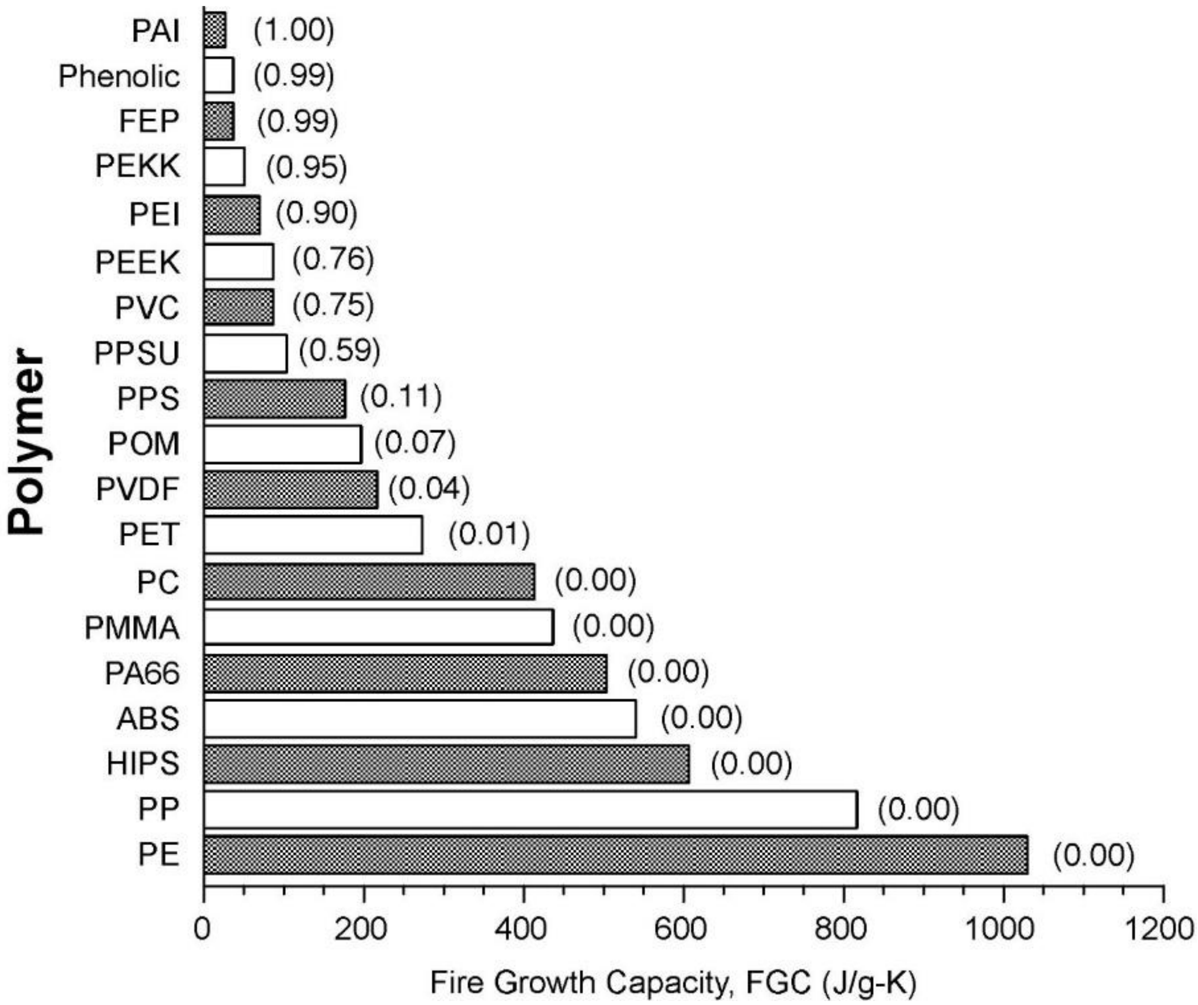

Figure 2. Fire Growth Capacities (FGC) of 19 commercial polymers

Figure 3 is a plot of the cumulative likelihood of passing PHRR versus $P = FGC$. A fit of the discreet pass/fail (1/0) data for the 19 polymers in Figure 2 using Equation 4 gives best fit parameters, $P^* = FGC^* = 111$ J/g-K and $n = 4.6$. The width of the transition region is δFGC = 21 J/g-K and the relative uncertainty in FGC^* at the pass/fail transition is, $\delta FGC / FGC^* = (21$ J/g-K$)/(111$ J/g-K$) = 0.19$. This uncertainty is twice as large as the uncertainty, $\delta Q_\infty / Q_\infty^* = 0.09$ in **Error! Reference source not found.** due to the uncertainty introduced by including the polymer thermal stability terms (ΔT_{burn}, ΔT_{ign}) in the fire growth capacity (Equation 3).

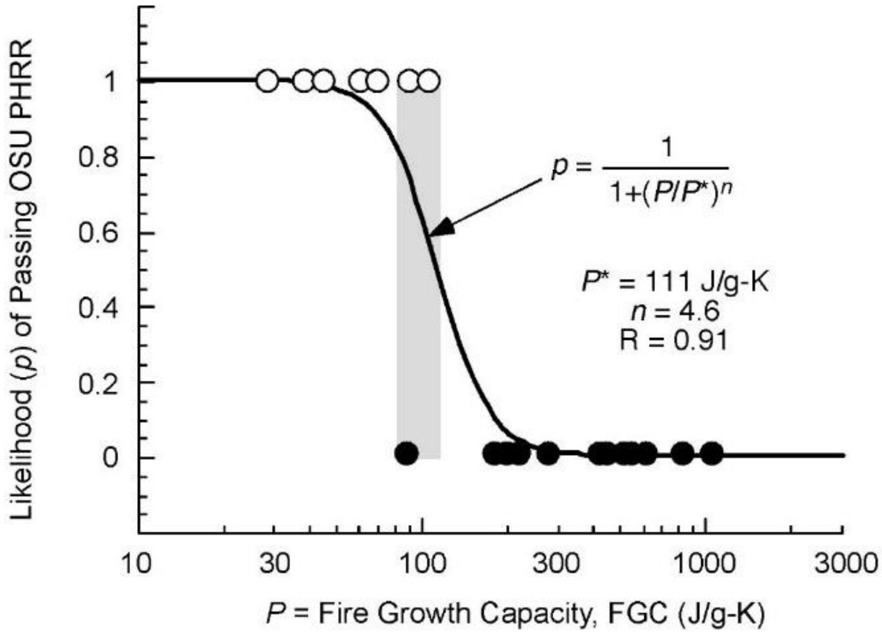

Figure 3. Likelihood of passing the *PHRR* versus *FGC* of the 19 polymers in Figure 2

A widely used voluntary standard for flame propagation of plastics is the Underwriters Laboratories UL 94 test [16]. The vertical test, UL 94 V [1, 17], with three ten-second exposures to a small flame, is roughly equivalent to the 12-second Vertical Bunsen Burner (VBB) exposure test for vertical flame propagation [14] in 14 CFR 25. The advantage of the UL 94 V test is that different classes of flame propagation can be achieved—V-0, V-1, V-2, or NR (no rating)—based on material performance, instead of the simple pass/fail rating in the 14 CFR 25 VBB test. The V-0 classification is the most stringent, and we obtained these V ratings for 1/8-inch (3-mm) specimens of the 19 polymers of Figure 2 from commercial data sheets. Binary pass/fail ratings in the UL 94 V test were assigned according to

$$p = \begin{cases} 1, & V-0 \\ 0, V-1, V-2, HB, NR & \end{cases} \qquad 6$$

Figure 4 is a plot of these binary pass/fail (1/0) data versus the fire growth capacities FGC of the 19 polymers in Figure 2. The solid line in Figure 4 is Equation 4 evaluated for the best-fit parameters $P^* = 213$ J/g-K and $n = 6.4$. The uncertainty of FGC^* at the pass/fail transition for UL 94 fire test results is $\delta FGC = 33$ J/g-K, and the relative uncertainty of the FGC^* threshold is $\delta FGC/FGC^* = (33 \text{ J/g-K})/(213 \text{ J/g-K}) = 0.16$. This relatively sharp transition from passing (V-

0) to failing (V-1, V-2, HB) fire test results suggests that FGC is a reasonably good predictor of self-extinguishing behavior in Bunsen burner tests of vertical flame propagation.

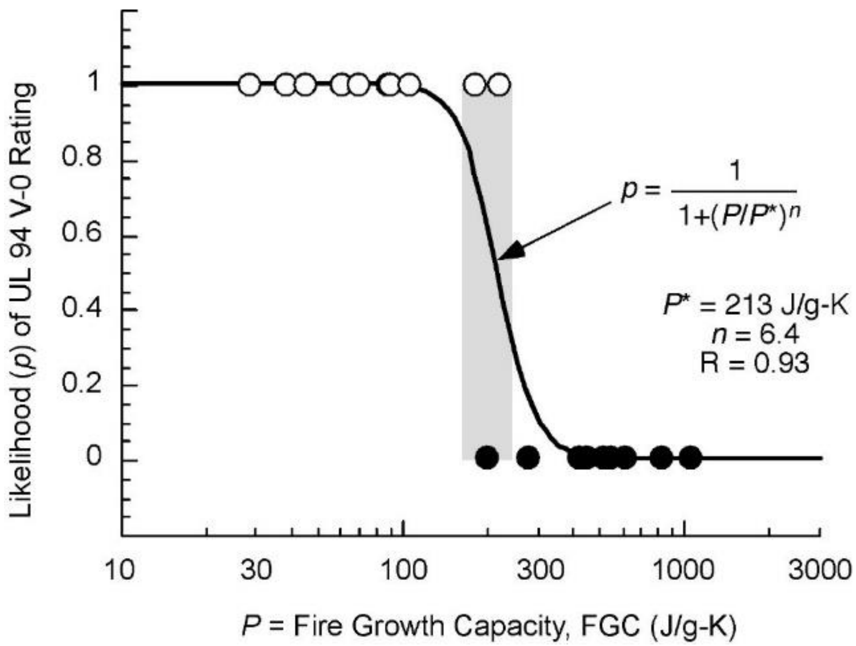

Figure 4. Likelihood of a UL 94 V-0 rating versus *FGC* for the 19 polymers in Figure 2

3 Microscale criteria for equivalent flammability

Ranking the performance *X* of two or more materials in a single fire test for research and development purposes is common practice using correlation or a statistical comparison of the means [18]. However, comparing the fire test performance of different materials in different fire tests is notoriously problematic, as demonstrated by the eponymous Emmons scatter plot [18]. **Error! Reference source not found.**, Figure 3, and Figure 4 show that the relationship between a microscale combustion property ($P = Q_\infty$, *FGC)* and a bench-scale flame/fire test result ($X =$ *PHRR*, UL 94 V-0), is probabilistic rather than deterministic, as would be required (at a minimum) for regulatory purposes. However, if the bench-scale fire test result *X* is the product of an intensive, mass-based (specific) combustion property *P*; the mass of the component in the cabin material *M*; and a parameter *V* that accounts for variations in processing, fabrication, and fire testing as they affect the test results, i.e., $X = X(P,M,V) \equiv PMV$; then the variation in the fire test result *X* due to variations in these factors can be written as the sum of intensive (*P*) and extensive (*M*,*V*) terms [19]:

$$\Delta X = \left(\frac{\partial X}{\partial P}\right)_{M,V} \Delta P + \left(\frac{\partial X}{\partial M}\right)_{P,V} \Delta M + \left(\frac{\partial X}{\partial V}\right)_{P,M} \Delta V \qquad 7$$

The partial derivatives are: $(\partial X/\partial P)_{M,V} = MV$, $(\partial X/\partial M)_{P,V} = PV$ and $(\partial X/\partial V)_{P,M} = PM$, so the relative variation in X is

$$\frac{\Delta X}{X} = \frac{\Delta P}{P} + \frac{\Delta M}{M} + \frac{\Delta V}{V} \qquad 8$$

Although M and V are independent of material composition, they depend on the mass and arrangement of the components in the test specimen, the repeatability of the manufacturing processes, the physical and chemical behavior of the test specimen during flaming combustion in the bench scale fire test, and the variability of the test itself. The effects of these variations on test results are difficult to quantify, so Equation 8 becomes an inequality with respect to variations in the intensive combustion property P:

$$\frac{\Delta X}{X} \geq \frac{\Delta P}{P} \qquad 9$$

For a substitute component A and certified component B performing the same function in a cabin material (e.g., an adhesive) and having MCC combustion properties P_A and P_B, respectively, Inequality 9 show that the maximum allowable difference between P_A and P_B in the MCC is bounded by the relative difference between X_A and X_B in 14 CFR 25 fire tests of the cabin materials containing A and B:

$$\frac{|P_A - P_B|}{P_B} \leq \frac{|X_A - X_B|}{X_B} \qquad 10$$

Inequality 10 contains a parameter, X, that can be any fire test result in 14 CFR 25, i.e., X = peak heat release rate in first 5-minute (PHRR), total heat released at 2-minute (THR), burn length in a Bunsen burner test, after-flame time, etc. Direct comparison of the relative fire performance of A and B in microscale and bench scale fire tests of both A and B is called an A/B Basis for similarity [12].

If $Y_P = |P_A - P_B|/P_B$ and $Y_X = |X_A - X_B|/X_B$, the similarity criterion can be written as

$$Y_P \leq Y_X \qquad 11$$

Both Y_P and Y_X are positive-valued, relative differences, and each will have a variance σ^2 associated with the measurement of P and X. Using Z to represent either P or X:

$$\left(\frac{\sigma_Y}{1+Y}\right)^2 = \left(\frac{\sigma_{Z_A}}{Z_A}\right)^2 + \left(\frac{\sigma_{Z_B}}{Z_B}\right)^2 \qquad 12$$

The uncertainty in *Y* on both sides of Equation 11 is therefore,

$$\sigma_Y = \sqrt{\left(\frac{\sigma_{Z_A}}{Z_A}\right)^2 + \left(\frac{\sigma_{Z_B}}{Z_B}\right)^2}\ (1 + Y) \tag{13}$$

By way of example, the A/B criterion (Equation 10) is used to compare the results in Table 1 for two decorative laminates tested as self-supporting films in ASTM D7309-19A (MCC) and 14 CFR 25 (OSU peak and total heat release, and 60 second vertical Bunsen burner test).

Table 1. ASTM D7309 and 14 CFR 25 Test Results for Two Decorative Laminates

Symbol	Test/Result	Units	Decorative Laminate A	Decorative Laminate B
P	Fire Growth Capacity (FGC)	J/g-K	38.7 ± 1.0	41.8 ± 1.4
X	OSU Peak Heat Release Rate (PHRR)	kW/m^2	31.4 ± 1.2	35.8 ± 1.8
X	OSU 2-minute Total Heat Release (THR)	kW-min/m^2	26.3 ± 2.4	27.8 ± 3.0
X	60s Vertical Bunsen Burner (Burn Length/BL)	Inches	3.97 ± 0.06	3.70 ± 0.26

The mean relative difference in the Fire Growth Capacity (FGC) of Decorative Laminate A and Decorative Laminate B measured in the MCC is computed by using the average values of FGC in the second row of Table 1,

$$Y_P = \frac{|FGC_A - FGC_B|}{FGC_B} = \frac{|38.7 - 41.8|}{41.8} = 0.07$$

The uncertainty in Y_P is computed from the average value and standard deviation of FGC_A and FGC_B in Table 1 using Equation 13,

$$\sigma_P = \left(\sqrt{\left(\frac{\sigma_{Z_A}}{Z_A}\right)^2 + \left(\frac{\sigma_{Z_B}}{Z_B}\right)^2}\right)(1 + Y_p) = \left(\sqrt{\left(\frac{1}{38.7}\right)^2 + \left(\frac{1.4}{41.8}\right)^2}\right)(1 + 0.07) = 0.05$$

The mean value and range of Y_P for Decorative Laminates A and B, is

$$Y_P = 0.07 \pm 0.05$$

The relative change in the fire test results for the decorative laminates in the requisite 14 CFR 25 fire tests are computed as per the above example.

$$Y_X = Y_{PHRR} = \frac{|PHRR_A - PHRR_B|}{PHRR_B} = \frac{|31.4 - 35.8|}{35.8} = 0.12 \pm 0.07$$

$$Y_X = Y_{THR} = \frac{|THR_A - THR_B|}{THR_B} = \frac{|26.3 - 27.8|}{27.8} = 0.06 \pm 0.15$$

$$Y_X = Y_{BL} = \frac{|BL_A - BL_B|}{BL_B} = \frac{|3.97 - 3.70|}{3.70} = 0.07 \pm 0.08$$

The magnitude of the uncertainties for Y_P and Y_X limit the precision of these relative changes to one significant figure, in this case, $Y_P = Y_X = 0.1$ (all Y_X), so the inequality is satisfied for all of the 14 CFR 25 fire tests of Decorative Laminate A and Decorative Laminate B on an A/B basis using FGC as the MCC combustion property. In other words, the two decorative laminates are statistically indistinguishable (similar) at the microscale level with respect to flammability.

An MCC similarity criterion, based on 14 CFR 25 fire test performance of the certified component alone (B-Basis), can be derived as follows. If X_A is the fire test result of a cabin material containing substitute component A with variance $\sigma^2_{X_A}$, and X_B is the fire test result of the reference component B in the certified cabin material with variance $\sigma^2_{X_B}$, and if $[(P_A - P_B)/P_B]^2 \ll 1$, it is expected that the fire test result X_A in 14 CFR 25 will be in the range

$$\left(X_B - 2\sigma_{X_B}\right) \leq X_A \leq \left(X_B + 2\sigma_{X_B}\right) \qquad 14$$

Substituting, $X_A = X_B \pm 2\sigma_{X_B}$ from Equation 14 into Equation 10, allows Y_X for a substitute material to be determined based solely on test results X_B for the certified component B:

$$\frac{|P_A - P_B|}{P_B} \leq \frac{\left|\left(X_B \pm 2\sigma_{X_B}\right) - X_B\right|}{X_B} \approx \frac{2\sigma_{X_B}}{X_B} \qquad 15$$

Equation 15 is based on the assumption that 14 CFR 25 bench scale fire test results X_A of substitute component A would fall within two standard deviations of X_B, the fire test results of certified component B, if $P_A \approx P_B$ in ASTM D7309 microscale test. In this case, the determination of equivalent fire performance of a substitute component A using the MCC is based solely on the fire performance X_B and its variability σ_{X_B} for a certified component B in the 14 CFR 25 fire test. This is the B-Basis for similarity.

4 Experimental

4.1 ASTM D7309

All experiments in the MCC were conducted in accordance with ASTM D7309-19 Method A on samples of components received from industry participants in the study. Figure 5 is a plot of the specific heat release rate history in the MCC for a PC/ABS blend on the left ordinate and its time integral Q on the right ordinate versus temperature at a constant heating rate, $\beta = 1$ K/s. The abscissa value of the lowest temperature point T_1 in Figure 5 is the temperature at which 5% of the total heat Q_∞ has been released, which approximates the ignition temperature, i.e., $T_{5\%} = T_{ign}$ [7]. The abscissa value, T_2, is the temperature at which 95% of Q_∞ has been released, and this approximates the burning temperature, i.e., $T_{burn} = T_{95\%}$. The reference temperature is taken to be the standard room temperature, $T_0 = 298\text{K} = 25°\text{C}$, regardless of the actual starting temperature of the MCC test. Using these definitions, $\Delta T_{burn} = T_2 - T_1 = T_{95\%} - T_{5\%}$, and $\Delta T_{ign} = T_1 - T_0 = T_{5\%} - T_0$. Substituting these terms into the early fire growth equation, Equation 3, gives the capacity for early stage fire growth [12, 13] in terms of parameters that can be measured in the MCC using a standard ASTM method:

$$\text{Fire Growth Capacity (FGC)} = \frac{\dot{q}}{m\,\beta} = \left(\frac{Q_\infty}{T_2 - T_1}\right)\left(\frac{T_2 - T_0}{T_1 - T_0}\right) \qquad 16$$

Note that as the ambient temperature T_0 approaches the ignition temperature of the cabin materials T_1, as would occur at flashover of an aircraft cabin, the fire growth capacity of the material becomes infinite. Fire growth capacities for all the components obtained from industry were obtained in triplicate and are listed along with the 14 CFR 25 test results for each case study in the Appendix.

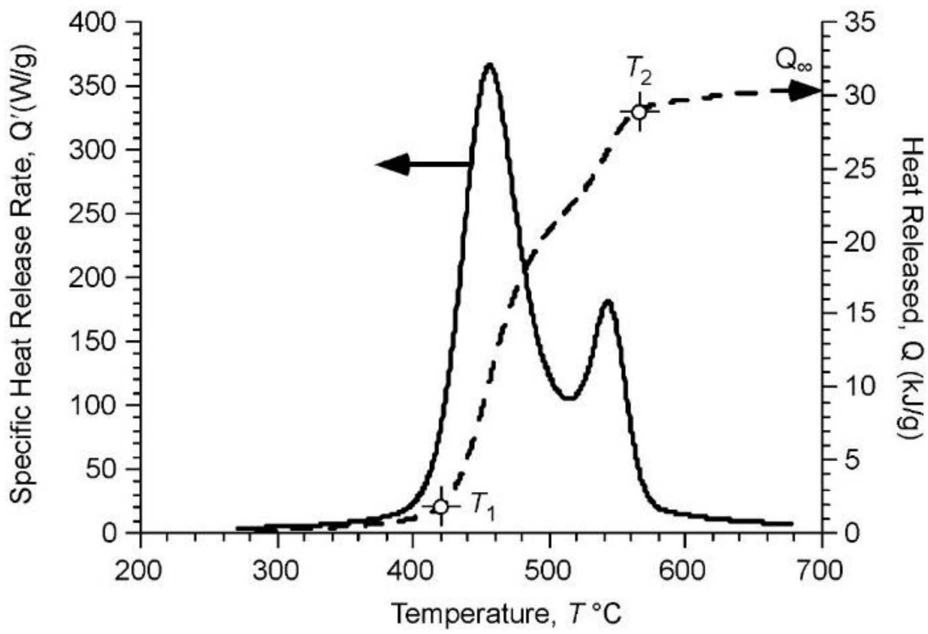

Figure 5. Specific Heat Release Rate and its Time Integral versus Temperature in the MCC Showing location of T_1, T_2, and Q_∞ for Calculation of *FGC*.

4.2 14 CFR 25 Fire tests

Bench-scale flammability tests were conducted by industry participants in accordance with 14 CFR 25 [2] as described in the FAA Fire Test Handbook [14]. Results of these fire tests were submitted to this validation study from industry participants and included OSU Heat Release Rate apparatus (large surface area materials), Radiant Panel (thermal-acoustic insulation), and Vertical Bunsen Burner (all other materials) tests. Industry members also submitted samples of certified and substitute components for ASTM D7309 testing at WJHTC. These data are listed in the Appendix.

Some cases included test results for samples in different forms, for example, 2-ply and 6-ply laminate for phenolic resin. If the case study included more than two materials, pair-wise comparison was applied to changed component-certified component pair. A few case studies contained 14 CFR 25 results from more than one laboratory. Below is a summary of the twelve case studies.

Table 2. Overview of the Case Studies and Test Coupon Description

Case #	Change	Coupon
1	Decorative laminate (declam) color	1.1 Declam alone 1.2 Declam on standard panel
2	Declam adhesive FR film	2.1 Declam adhesive on fiberglass panel 2.2 2 adhesive on phenolic panel 2.3 Declam adhesive on carbon fiber panel 2.4 Declam adhesive on stow bin panel
3	Adhesive film FR components 3.1 Sample B vs. Sample A1 3.2 Sample B vs. Sample A2	Adhesive + décor laminate + 2-ply phenolic
4	Resin system	Resin + 2-ply aramid fiber laminate
5	Polymer supplier	Thermoplastic part
6	Phenolic resin 6.1 Pure resin 6.2 2-ply system in MCC	 6.1.1 2-ply laminates 6.1.2 6-ply laminates 6.2.1 2-ply laminates 6.2.2 6-ply laminates
7	Phenolic system	2-ply phenolic laminates
8	Adhesive minor formulation change	Kydex + adhesive + Al
9	Processing conditions Lab A	Thermoplastic specimen

Case #	Change	Coupon
	Sample B vs. Sample A1 Sample B vs. Sample A2 Sample B vs. Sample A3 Lab B Sample B vs. Sample A1 Sample B vs. Sample A2 Sample B vs. Sample A3	
10	Phenolic with added top coat Lab A Sample B vs. Sample A Lab B Sample B vs. Sample A	Laminate with and without varnish
11	Insulation blankets dye color Sample B vs. Sample A1 Sample B vs. Sample A2	Insulation blankets
12	Grade and color of polymer Lab A Sample B vs. Sample A1 Sample B vs. Sample A2 Lab B Sample B vs. Sample A1 Sample B vs. Sample A2 Lab C	Thermoplastic part

Case #	Change	Coupon
12	Sample B vs. Sample A1 Sample B vs. Sample A2	

Table 3, Table 4, and Table 5 contain acceptance criteria for 14 CFR 25 tests.

Table 3. Acceptance (Passing) Criteria for 14 CFR 25 VBB Test

Test	Flame Extinguish Time (seconds)	Burn Length (inches)	Drip Extinguish Time (seconds)
60 s VBB	≤ 15	≤ 6	≤ 3
12 s VBB	≤ 15	≤ 8	≤ 5

Table 4. Acceptance (Passing) Criteria for 14 CFR 25 Heat Release Rate Test

Peak HRR (kW/m^2)	2-minute THR (kW-min/m^2)
≤ 65	≤ 65

Table 5. Acceptance (Passing) Criteria for 14 CFR 25 Radiant Panel Test

Flame propagation distance (inches)	After flame time (seconds)
< 2	< 3

5 Results

Experimental results for the materials in the 12 case studies listed in Appendix A were collected and analyzed for similarity in the WJHTC Fire Research laboratory. The goal of this validation phase was to apply the microscale criteria for equivalent flammability, Equations 10 and 15, to the results of the ASTM D7309 and 14 CFR 25 tests in the Appendix A. Equation 10 is the A/B basis for the similarity when both components (substitute component A and certified component B) undergo 14 CFR 25 fire tests and ASTM D7309 microscale tests. Equation 15 is the B basis for similarity, requiring only ASTM D7309 tests of components A and B, and certification or quality control data for component B in 14 CFR 25 fire tests.

The objective of this study was to validate the microscale criterion for equivalent flammability of substitute components at the coupon level. In particular, if component A (changed) and component B (certified) have outcomes FGC_A and FGC_B in MCC testing, and outcomes X_A and X_B in 14 CFR 25 coupon testing (X = PHRR, 2-minute HR, burn length, etc.), then the A and B will have equivalent fire performance if the relative change in FGC is less than or equal to the relative change in 14 CFR 25 test results (Equation 10):

$$\frac{|FGC_A - FGC_B|}{FGC_B} \le \frac{|X_A - X_B|}{X_B}$$

This method and criterion for demonstrating equivalent fire performance of substitute components requires both ASTM D7309 component testing and 14 CFR 25 testing of coupons or constructions containing components A or B, and is called an A/B basis for similarity. In most cases, 14 CFR 25 fire test data for X_B and its standard deviation σ_{X_B} will be available for the certified construction or quality control samples. In this case, equivalent fire performance can be demonstrated at microscale (Equation 15):

$$\frac{|FGC_A - FGC_B|}{FGC_B} \le \frac{2\sigma_{X_B}}{X_B}$$

In this validation study, both A/B and B basis criteria are applied to the experimental results from all twelve submitted case studies.

For example, for case study #1, A/B and B basis criteria were applied to both OSU and VBB test results in the following manner:

- Generate $\frac{|FGC_A - FGC_B|}{FGC_B}$ values : $\frac{|38.7-41.8|}{41.8} = 0.1$
- Generate $\frac{|X_A - X_B|}{X_B}$ values for X= Burn length (in) subset 1.1 : $\frac{|4.0-3.7|}{3.7}$ = 0.1
- Generate $\frac{|X_A - X_B|}{X_B}$ values for X= Burn length (in) subset 1.2 : $\frac{|3.2-3.4|}{3.4}$ =0.1
- Generate $\frac{|X_A - X_B|}{X_B}$ values for X=Peak HRR, (kW/m^2) subset 1.1: $\frac{|31.4-35.8|}{35.8}$ = 0.1
- Generate $\frac{|X_A - X_B|}{X_B}$ values for X=Peak HRR, (kW/m^2) subset 1.2: $\frac{|31.4-34.8|}{34.8}$ = 0.1
- Generate $\frac{|X_A - X_B|}{X_B}$ values for X= 2-minute THR, (kW-min/m^2) subset 1.1: $\frac{|26.1-27.8|}{27.8}$ = 0.1

- Generate $\frac{|X_A - X_B|}{X_B}$ values for X= 2-minute THR, (kW-min/m^2) subset 1.2: $\frac{|37.1-39.3|}{39.3}$ = 0.1
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= Burn length (in) subset 1.1 : $\frac{2*0.3}{3.7}$ = 0.2
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= Burn length (in) subset 1.2 : $\frac{2*0.1}{3.4}$ = 0.1
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= Peak HRR, (kW/m^2) subset 1.1 : $\frac{2*1.8}{35.8}$ = 0.1
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= Peak HRR, (kW/m^2) subset 1.2 : $\frac{2*3.5}{34.8}$ = 0.2
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= 2-minute THR, (kW-min/m^2) subset 1.1 : $\frac{2*3.0}{27.8}$ = 0.2
- Generate $\frac{2\sigma_{X_B}}{X_B}$ values for X= 2-minute THR, (kW-min/m^2) subset 1.2 : $\frac{2*4.5}{39.3}$ = 0.2
- Compare $\frac{|FGC_A - FGC_B|}{FGC_B}$ =0.1 to all scenarios for X = Burn length (in), Peak HRR, (kW/m^2), 2-minute THR, (kW-min/m^2) for A/B and B basis criteria for two subsets.

The results of the last step for case study #1 example are presented in both Table 7 and Table 8.

Raw data for each case study is summarized in Appendix A.

Table 6 through 8 summarize the results of applying A/B and B basis criteria to the samples in twelve case studies grouped by the 14 CFR 25 tests. Table 6 contains results for the radiant panel test of three thermal acoustic insulation materials (constructions). Table 7 contains results for the 60-second Vertical Bunsen Burner tests from three case studies, two of which also have OSU heat release rate results (Table 8). The majority of the 14 CFR 25 tests in this validation study are the ten sets of OSU Heat Release Rate results summarized in Table 8, three of which contain results from multiple laboratories for a single component.

Table 6. Similarity criteria applied to Radiant Panel test results.

Case #/ Samples	$\frac{\lvert FGC_A - FGC_B\rvert}{FGC_B} \leq \frac{\lvert X_A - X_B\rvert}{X_B}$		$\frac{\lvert FGC_A - FGC_B\rvert}{FGC_B} \leq \frac{2\sigma_{X_B}}{X_B}$	
	X = After flame time, (seconds)	X = Flame propagation distance, (inches)	X =After flame time, (seconds)	X = Flame propagation distance, (inches)
Case # 11 B-A1	0 ≤ 0	0 ≤ 0.3	0 ≤ 0	0 ≤ 0
Case # 11 B-A2	0 ≤ 0	0 ≤ 0	0 ≤ 0	0 ≤ 0

As shown in Table 6, relative change in materials observed in ASTM D7309 is always equal or less to the relative change in materials observed in radiant panel tests. This subset of the validation study has a success rate of 6/6 (100%).

Table 7. Similarity criteria applied to Vertical Bunsen Burner. Negative results in bold. Anomalous results marked with *.

Case #/ Samples	$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{\lvert X_A - X_B \rvert}{X_B}$ X = Burn length (in)	$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{2\sigma_{X_B}}{X_B}$ X = Burn length (in)
Case #1		
1.1	0.1 ≤ 0.1	0.1 ≤ 0.2
1.2	0.1 ≤ 0.1	0.1 ≤ 0.1
Case #2		
2.1	0.1 ≤ 0.1	0.1 ≤ 0.3
2.2	0.1 ≤ 0.1	0.1 ≤ 0.1
2.3	0.1 ≤ 0.1	0.1 ≤ 0.2
2.4	0.1 ≤ 0.1	***0.1 > 0 ****
Case #5	0.1 ≤ 0.5	0.1 ≤ 0.2

Acceptance criteria for the 14 CFR 25 VBB test, as shown in Table 3, includes three parameters: flame extinguish time (seconds), burn length (inches), and drip extinguish time (seconds). The similarity criteria were applied to the only reported parameter for these case studies, which was X = burn length (inches). The B basis criterion is not satisfied for one subset, case 2.4, due to the fact that reported variability for that particular certified sample was $\sigma = 0$ because the burn lengths were all listed as zero inches. The success rate for B-basis criterion is 6/7 (86%). The success rate for the A/B basis is 7/7 (100%).

Table 8. Similarity criteria applied to OSU data. Negative results in bold. Anomalous results marked with *.

Case #/ Samples	$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{\lvert X_A - X_B \rvert}{X_B}$		$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{2\sigma_{X_B}}{X_B}$	
	X = Peak HRR, (kW/m^2)	X = 2-minute THR, ($kW\text{-}min/m^2$)	X = Peak HRR, (kW/m^2)	X = 2-minute THR, ($kW\text{-}min/m^2$)
Case #1				
1.1	0.1 ≤ 0.1	0.1 ≤ 0.1	0.1 ≤ 0.1	0.1 ≤ 0.2
1.2	0.1 ≤ 0.1	0.1 ≤ 0.1	0.1 ≤ 0.2	0.1 ≤ 0.2
Case #2				
2.1	**0.1 > 0***	**0.1 > 0***	0.1 ≤ 0.1	0.1 ≤ 0.2
2.2	0.1 ≤ 0.1	0.1 ≤ 0.1	0.1 ≤ 0.1	0.1 ≤ 0.1
2.3	**0.1 > 0***	**0.1 > 0***	0.1 ≤ 0.1	0.1 ≤ 0.1
2.4	**0.1 > 0***	**0.1 > 0***	0.1 ≤ 0.3	0.1 ≤ 0.1
Case #3				
3.1	0 ≤ 0	0 ≤ 0.1	0 ≤ 0.2	0 ≤ 0
3.2	0 ≤ 0.1	0 ≤ 0	0 ≤ 0.2	0 ≤ 0
Case #4	0 ≤ 0	0 ≤ 0	0 ≤ 0.1	0 ≤ 0.2
Case #6				
6.1.1	0.1 ≤ 0.3	0.1 ≤ 0.3	0.1 ≤ 0.5	0.1 ≤ 0.4
6.1.2	**0.1 > 0***	0.1 ≤ 0.6	0.1 ≤ 0.3	0.1 ≤ 0.6
6.2.1	0.3 ≤ 0.3	0.3 ≤ 0.3	0.3 ≤ 0.5	0.3 ≤ 0.4
6.2.2	**0.3 > 0***	0.3 ≤ 0.6	0.3 ≤ 0.3	0.3 ≤ 0.6
Case #7	0.1 ≤ 0.1	0.1 ≤ 0.4	0.1 ≤ 0.1	0.1 ≤ 0.3
Case #8	0 ≤ 0	0 ≤ 0.1	0 ≤ 0.1	0 ≤ 0.1
Case #9				
Lab A				
9.1.a	0 ≤ 0.2	0 ≤ 0.6	0 ≤ 0.5	0 ≤ 2.5

Case #/ Samples	$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{\lvert X_A - X_B \rvert}{X_B}$		$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{2\sigma_{X_B}}{X_B}$	
	X = Peak HRR, (kW/m^2)	X = 2-minute THR, (kW-min/m^2)	X = Peak HRR, (kW/m^2)	X = 2-minute THR, (kW-min/m^2)
9.2.a	0.2 ≤ 0.2	0.2 ≤ 1.8	0.2 ≤ 0.5	0.2 ≤ 2.5
9.3.a	**0.3 > 0***	0.3 ≤ 0.8	0.3 ≤ 0.5	0.3 ≤ 2.5
Lab B				
9.1.b	0 ≤ 0.3	0 ≤ 0	0 ≤ 0.2	0 ≤ 1
9.2.b	0.2 ≤ 0.2	0.2 ≤ 1.2	0.2 ≤ 0.2	0.2 ≤ 1
9.3.b	0.3 ≤ 0.4	0.3 ≤ 0.8	**0.3 > 0.2**	0.3 ≤ 1
Case #10				
Lab A	0.1 ≤ 0.4	0.1 ≤ 0.7	0.1 ≤ 0.6	0.1 ≤ 0.4
Lab B	0.1 ≤ 0.1	0.1 ≤ 0.4	0.1 ≤ 0.2	0.1 ≤ 0.3
Case #12				
Lab A				
12.1.a	**0.2 > 0.1**	**0.2 > 0.1**	0.2 ≤ 0.2	0.2 ≤ 0.3
12.2.a	0.2 ≤ 0.2	0.2 ≤ 0.7	0.2 ≤ 0.2	0.2 ≤ 0.3
Lab B				
12.1.b	0.2 ≤ 0.3	0.2 ≤ 0.2	0.2 ≤ 0.2	**0.2 > 0.1**
12.2.b	0.2 ≤ 0.2	0.2 ≤ 0.6	0.2 ≤ 0.2	**0.2 > 0.1**
Lab c				
12.1.c	0.2 ≤ 0.3	0.2 ≤ 0.4	0.2 ≤ 0.3	0.2 ≤ 0.2
12.2.c	**0.2 > 0.1**	0.2 ≤ 0.6	0.2 ≤ 0.3	0.2 ≤ 0.2

Table 8 shows that there are a few instances when neither the A/B nor B basis similarity criteria are satisfied for X = PHRR or X = 2-minute HR. The success rate for A/B basis OSU parameter Peak HRR (kW/m^2) is equal to 21/29 subsets (72%). The success rate for A/B basis OSU parameter 2-minute THR (kW-min/m^2) is 25/29 (86%). The success rate for B-basis OSU Peak

HRR (kW/m^2) is 28/29 (97%). The success rate for B-basis OSU 2-minute THR (kW-min/m^2) is 27/29 (93%). However, if all 69 individual results are pooled and anomalies resulting from the poor sensitivity of 14 CFR 25 tests to small changes in chemical composition in the range of passing results (as evidenced by zeros in Tables 6-8, marked by asterisks) are removed from consideration, the success rate of the A/B criterion for the pooled data is 57/60 (95%), while the success rate of the B-basis criterion for the pooled data is 65/68 (96%).

Case study #12 has test results from three different labs. According to lab A, sample pair "beige sample grade Y versus navy sample grade Y" has relative change in MCC larger than relative change of both OSU parameters Peak HRR and 2-minute THR. According to lab B, both sample pairs—"beige sample grade Y versus navy sample grade Y" and "beige sample grade Y versus beige sample grade X"—do not satisfy B basis for OSU parameter 2-minute THR since the relative changes in MCC results are larger than $2\sigma_{X_B}$. According to lab C, sample pair "beige sample grade Y versus beige sample grade X" has relative change in MCC larger than relative change in OSU peak HRR. If the OSU test results from the three labs in Table 8 are averaged, with σ_{X_B} now the reproducibility (as opposed to repeatability) standard deviation, the anomalous (*) values for case #12 in Table 8 disappear, because the relative uncertainty in X_{OSU} is correspondingly larger, as evidenced by the data in Table 9.

Table 9. Similarity criteria for case #12 OSU Lab Averages. Negative results in bold. Anomalous results marked with *.

Case #/ Samples	$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{\lvert X_A - X_B \rvert}{X_B}$		$\frac{\lvert FGC_A - FGC_B \rvert}{FGC_B} \leq \frac{2\sigma_{X_B}}{X_B}$	
	X = *Average* Peak HRR, (kW/m^2)	X = *Average* 2-minute THR, (kW-min/m^2)	X = *Average* Peak HRR, (kW/m^2)	X = *Average* 2-minute THR, (kW-min/m^2)
Case #12				
12.1	0.2 ≤ 0.3	0.2 ≤ 0.3	0.2 ≤ 0.3	0.2 ≤ 0.2
12.2	0.2 ≤ 0.2	0.2 ≤ 0.6	0.2 ≤ 0.3	0.2 ≤ 0.2

As see in Table 9, the relative change in MCC results for both sample pairs are always less or equal to relative change in OSU test results from three laboratories.

6 Conclusions

A physically-based fire parameter called the fire growth capacity (FGC) (J/g-K) is derived from flame-spread theory, calibrated against fire tests, and measured in MCC using the standard ASTM D7309 method. FGC was selected and evaluated as the metric to demonstrate equivalent fire performance of substitute components of aircraft cabin materials. A validation study was initiated and conducted to demonstrate the use of two similarity criteria:

- an A/B-basis that involves MCC component and 14 CFR 25 coupon testing of both certified (B) and substitute (A) components of cabin materials,
- and a B-basis that involves the MCC testing of both A and B but only 14 CFR 25 certification or quality control data for construction containing the certified component B.

Both the A/B and B criteria were able to detect significant differences in 14 CFR 25 test results of coupons containing substitute components using ASTM D7309 and FGC in 95% of valid cases. Therefore, the ASTM D7309/FGC methodology and the proposed similarity criteria would be a reliable procedure for demonstrating equivalent fire performance of substitute components of cabin materials at the milligram scale when certified components must be changed for environmental, availability, or economic reasons.

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A Appendices

CASE STUDY #1

Two colors of decorative laminate were used for this study. Sample A is the grey wood grain decorative laminate and Sample B (reference material) is the dark brown bamboo decorative laminate. Data was generated for two colors of decorative laminates intended for use in interior cabin panels. The following samples have been tested:

MCC – decorative laminate alone

OSU – decorative laminate alone

OSU – decorative laminate attached to standard panel with heat-activated adhesive

60s VBB – decorative laminate alone

60s VBB – decorative laminate attached to standard panel with heat-activated adhesive

Table A1. Case study #1 MCC, OSU and VBB Test Results.

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m^2)	2-minute THR ($kW\text{-}min/m^2$)	Burn length (in)
Sample B alone	41.8 ± 1.4	35.8 ± 1.8	27.8 ± 3.0	3.7 ± 0.3
Sample B on standard panel	-	34.8 ± 3.5	39.3 ± 4.5	3.4 ± 0.1
Sample A alone	38.7 ± 1.0	31.4 ± 1.2	26.1 ± 2.4	4.0 ± 0.1
Sample A on standard panel	-	31.4 ± 1.2	37.1 ± 4.2	3.2 ± 0.3

CASE STUDY #2

ASTM D7309 MCC testing was conducted on the embossing resin alone. 3″x 3″ samples of the embossing resin film for use in MCC testing were cured in an oven at 320 ± 10 F for 15 ± 1 minutes.

Four different panel configurations were tested in 14 CFR 25 bench scale fire tests. These configurations were chosen to be representative of the types of surfaces found in airplane interiors.

Fiberglass sidewall panel: 2-ply phenolic resin impregnated glass fabric +1 ply crushed honeycomb core +1 ply phenolic resin impregnated glass fabric. Thickness: 0.080” ± 0.02

Glass fabric laminate panel: 5-ply phenolic resin impregnated glass fabric

Carbon fiber sidewall panel: 1-ply phenolic resin impregnated glass fabric + 1 ply carbon fiber prepreg +1 ply honeycomb core +1 ply carbon fiber prepreg. Thickness: 0.100” ± 0.03

Stow bin panel: 2 ply phenolic resin impregnated glass fabric +1 ply honeycomb core +2 ply phenolic resin impregnated glass fabric +1 ply Tedlar. Thickness: 0.375” ± 0.03

Table A2. Case study #2 MCC, OSU and VBB Test Results

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m^2)	2-minute THR ($kW\text{-}min/m^2$)	Burn length (in)
Sample B alone	60.5 ± 2.0	-	-	-
Sample B on Fiberglass Panel	-	41.8 ± 3.1	45.4 ± 5.6	1.2 ± .2
Sample B on Glass Fabric Laminate Panel	-	51.7 ± 2.4	55.0 ± 2.9	1.6 ± .1
Sample B on Carbon Fiber Panel	-	49.0 ± 3.0	58.5 ± 3.5	1.1 ± .1
Sample B on Stow Bin Panel	-	59.5 ± 8.1	70.9 ± 3.9	1.0 ± 0
Sample A alone	69.1 ± 2.8	-	-	-
Sample A on Fiberglass Panel	-	43.6 ± 4.8	45.4 ± 4.0	1.3 ± .1
Sample A on Glass Fabric Laminate Panel	-	56.0 ± 4.5	58.9 ± 4.2	1.5 ± .2

Sample A on Carbon Fiber Panel	-	50.8 ± 3.4	57.8 ± 4.1	1.2 ± .1
Sample A on Stow Bin Panel	-	58.0 ± 4.2	68.4 ± 3.5	1.1 ± .1

CASE STUDY #3

Pure adhesive samples were tested in ASTM D7309 MCC test. OSU Heat Release Rate tests were completed on a 2-ply phenolic laminate.

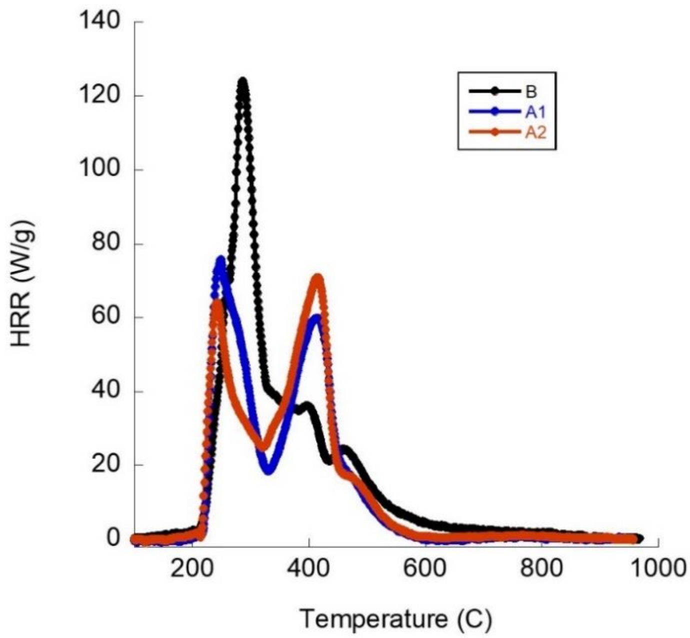

Figure A1. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #3

Table A3. Case Study #3 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m^2)	2-minute THR ($kW\text{-}min/m^2$)
Sample B	104 ± 2	45.5 ± 3.7	44.1 ± 1.1
Sample A1	102 ± 3	44.4 ± 1.6	39.7 ± 1.1
Sample A2	101 ± 7	41.3 ± 1.6	42.4 ± 1.0

CASE STUDY #4

ASTM D7309 MCC testing was completed on the cured resin. 14 CFR 25 OSU tests were performed on a 2-ply aramid fiber laminate.

Table A4. Case Study #4 MCC and OSU Test Results

Sample/Test	FGC, (J/g-K)	Peak HRR, (kW/m^2)	2-minute THR, ($kW\text{-}min/m^2$)
Sample B	80 ± 2	50.3 ± 3.2	34.5 ± 3.5
Sample A	82 ± 2	47.9 ± 1.6	35.6 ± 1.3

CASE STUDY #5

ASTM D7309 MCC tests were completed on the pure resin. 14 CFR 25 VBB 12-second tests were completed using 3mm thickness samples.

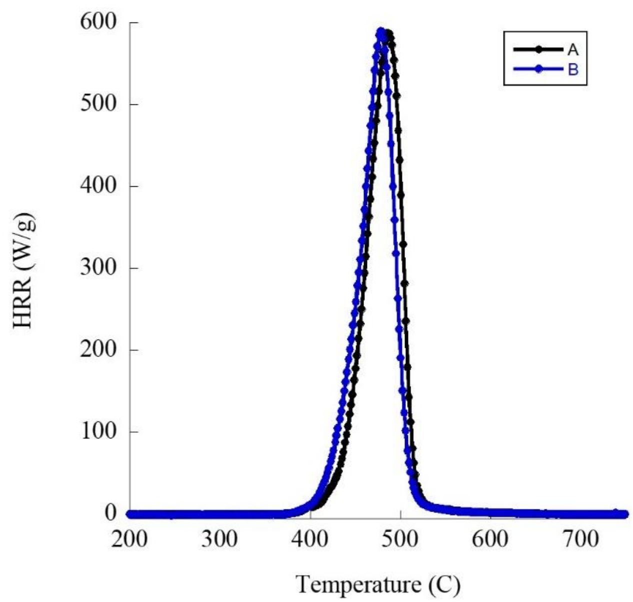

Figure A2. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #5

Table A5. Case Study #5 MCC and VBB Test Results

Sample/Test	FGC (J/g-K)	Burn length (in)
Sample B	499 ± 8	0.2 ± 0.02
Sample A	464 ± 3	0.1 ± 0.02

CASE STUDY #6

Change in the phenolic resin chemistry is the objective of this case study. Sample B is currently qualified to a material specification and used to fabricate interior panels such as sidewall panels, stow bins, and ceiling panels. Sample A is changed phenolic chemistry being evaluated for qualification to the material specification. ASTM D7309 MCC tests were completed for pure resin squeeze-out and 2-ply fiberglass. 14 CFR 25 OSU tests were performed on 2-ply and 6-ply samples. The comparison matrix was the following:

6.1.1 MCC Pure resin/ OSU 2-ply

6.1.2 MCC Pure resin/ OSU 6-ply

6.2.1 MCC 2-ply/ OSU 2-ply

6.2.2 MCC 2-ply/ OSU 6-ply

Table A6. Case Study #6 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m2)	2-minute THR (kW-min/m2)
Sample B Resin only	40.6 ± 0.6	-	-
Sample B 2-ply	24.0 ± 0.6	39.3 ± 10.2	30.7 ± 5.7
Sample B 6-ply	-	32.5 ± 4.7	24.3 ± 6.8
Sample A Resin only	43.6 ± 0.6	-	-
Sample A 2-ply	17.4 ± 0.9	28.0 ± 10.6	20.0 ± 7.2

Sample A 6-ply	-	33.5 ± 6.3	9.9 ± 4.9

CASE STUDY #7

Phenolic system was tested in ASTM D 3309 and in 14 CFR 25 OSU.

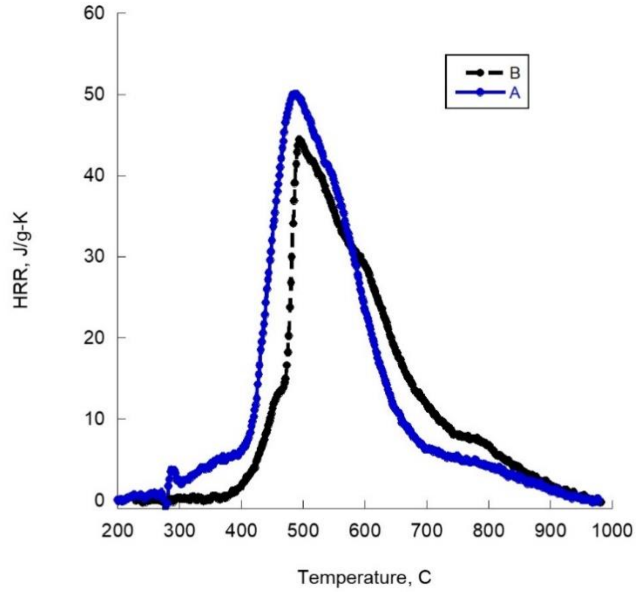

Figure A3. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #7

Table A7. Case Study #7 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m^2)	2-minute THR (kW-min/m^2)
Sample B	44 ± 1	12.8 ± 0.5	15.1 ± 2.6
Sample A	49 ± 1	14.3 ± 8.7	8.4 ± 4.7

CASE STUDY #8

Adhesive samples with minor formulation change were tested in MCC and OSU.

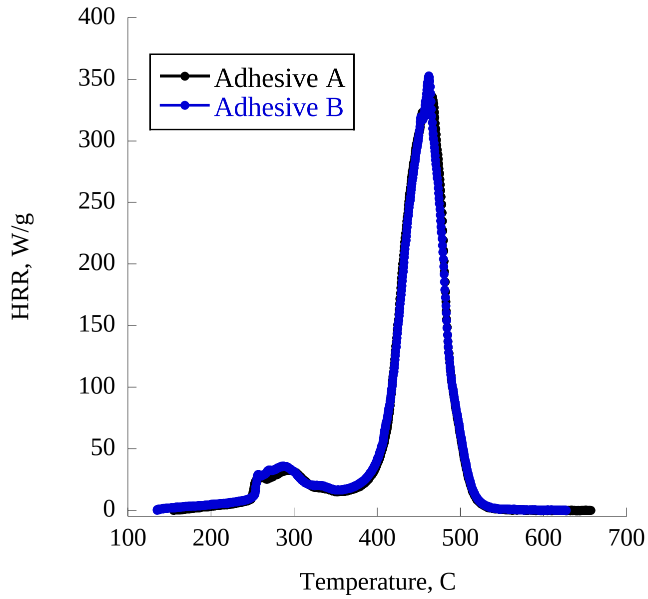

Figure A4. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #8

Table A8. Case Study #8 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Peak HRR (kW/m^2)	2-minute THR ($kW\text{-}min/m^2$)
Sample B	113 ± 1	52 ± 2	64 ± 4
Sample A	109 ± 1	54 ± 2	72 ± 3

CASE STUDY # 9

The minor change for the following data set is the processing conditions for thermoplastic specimens. Set of 4 materials consisting of reference material, along with recyclate and 2 additional samples with different pigment concentrations, was tested in MCC and OSU. OSU testing was performed in 2 laboratories, which are represented and Lab A and Lab B in the results table.

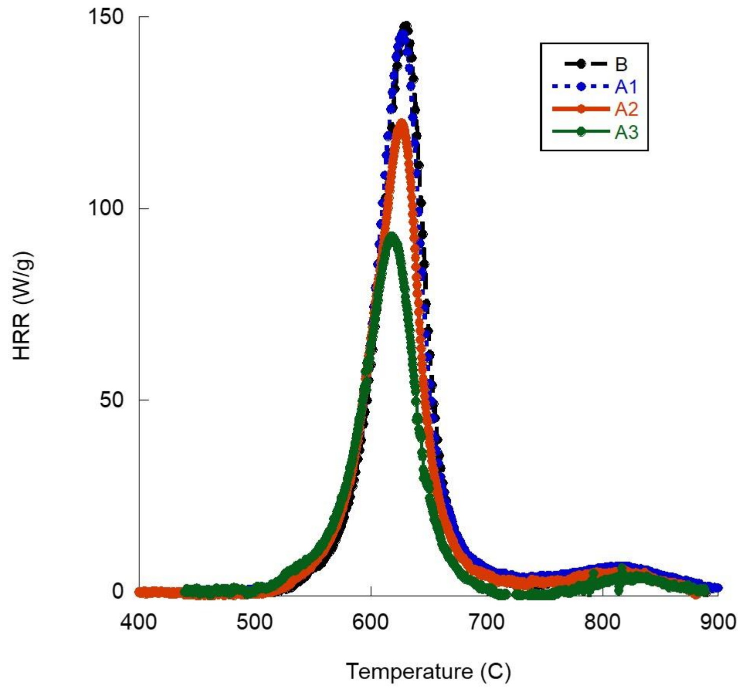

Figure A5. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #9

Table A9. Case Study #9 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Lab A Peak HRR (kW/m^2)	Lab A 2-minute THR (kW-min/m^2)	Lab B Peak HRR (kW/m^2)	Lab B 2-minute THR (kW-min/m^2)
Sample B	59 ± 2	23 ± 6	2 ± 2	34 ± 3	4 ± 2
Sample A1	57 ± 1	28 ± 8	3 ± 2	43 ± 14	4 ± 1
Sample A2	50 ± 1	28 ± 6	5 ± 2	40 ± 6	9 ± 5
Sample A2	44 ± 1	23 ± 9	3 ± 3	48 ± 9	7 ± 3

CASE STUDY #10

Phenolic samples with and without varnish were tested in MCC and OSU. OSU testing was performed in two laboratories, which are represented as Lab A and Lab B in the results table.

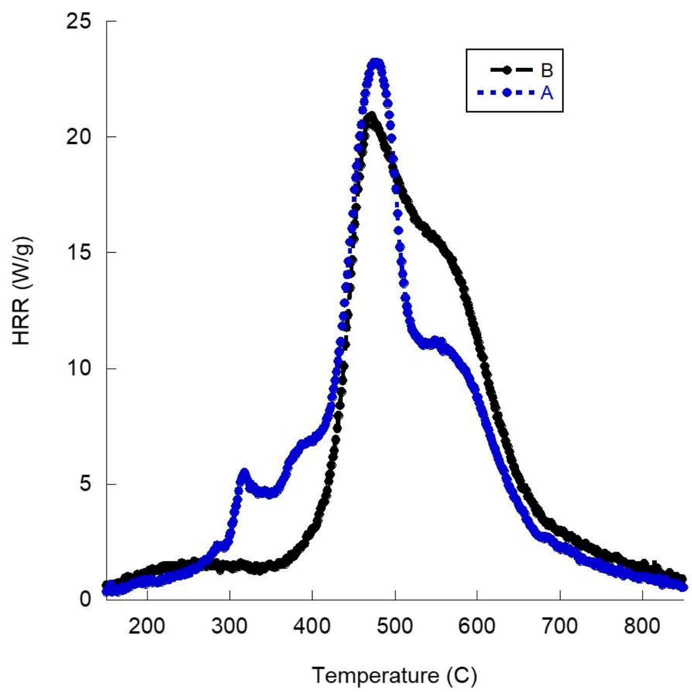

Figure A6. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #10

Table A10. Case Study #10 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Lab A Peak HRR (kW/m^2)	Lab A 2-minute THR ($kW\text{-}min/m^2$)	Lab B Peak HRR (kW/m^2)	Lab B 2-minute THR ($kW\text{-}min/m^2$)
Sample B	23 ± 3	53 ± 15	32 ± 7	68 ± 6	44 ± 6
Sample A	26 ± 2	75 ± 6	53 ± 6	72 ± 3	60 ± 3

CASE STUDY #11

0.34pcf Microlite AA fiberglass blankets with different dye added to the binder were tested in MCC and radiant panel tests.

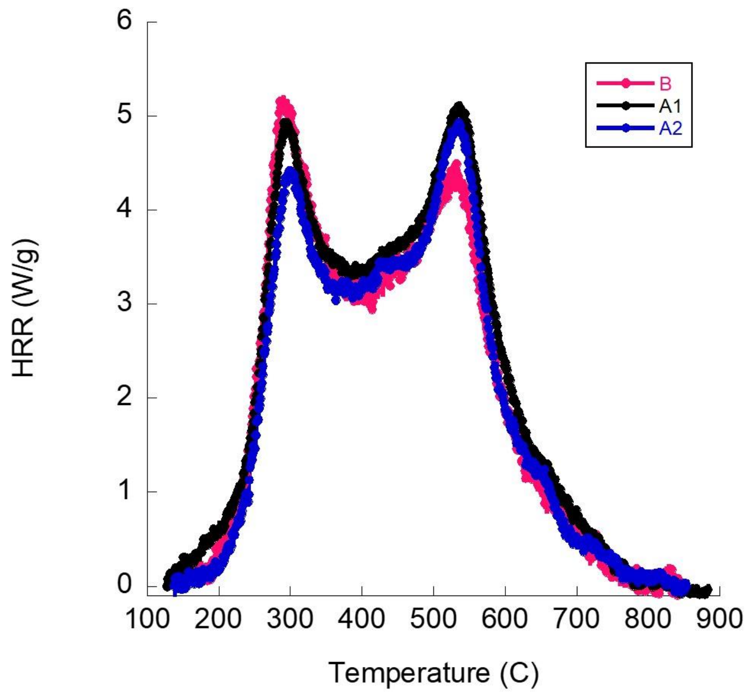

Figure A7. Specific Heat Release Rate Curves versus Temperature in MCC for Case Study #11

Table A11. Case Study #11 MCC and Radiant Panel Test Results

Sample/Test	FGC (J/g-K)	After flame time (seconds)	Flame propagation distance (inches)
Sample B	10 ± 1	0 ± 0	0.8 ± 0.0
Sample A1	10 ± 1	0 ± 0	1.0 ± 0.1
Sample A2	10 ± 1	0 ± 0	0.8 ± 0.2

CASE STUDY #12

The set contains samples of thermoplastic resin of two grades and different colors. Two complete 3-sample OSU tests results (six points each) were provided from three labs across the world (US and Europe). Sample B (certified) is beige color sample of grade Y. Sample A1 is the navy color sample from the same grade Y. Therefore, the pair B-A1 will provide the effect of color for samples within the same grade. Sample A2 is the beige color sample from grade X. Therefore, the pair B-A2 will provide the comparison on effect of grade for the same beige color.

Table A12. Case study #12 MCC and OSU Test Results

Sample/Test	FGC (J/g-K)	Lab A Peak HRR (kW/m^2)	Lab A 2-minute THR (kW-min/m^2)	Lab B Peak HRR (kW/m^2)	Lab B 2-minute THR (kW-min/m^2)	Lab C Peak HRR (kW/m^2)	Lab C 2-minute THR (kW-min/m^2)
Sample B	64 ± 1	39.5 ± 3.6	38.7 ± 5.0	48.2 ± 3.6	38.6 ± 1.8	50.4 ± 8.6	37.9 ± 4.3
Sample A1	76 ± 1	44.7 ± 3.0	34.2 ± 3.1	64.5 ± 3.9	48.2 ± 1.7	65.2 ± 4.0	52.1 ± 4.4
Sample A2	79 ± 3	30.7 ± 2.5	11.9 ± 3.2	37.7 ± 3.9	16.9 ± 1.6	46.3 ± 5.7	14.8 ± 2.3

Table A13. Case study #12 OSU results from 3 labs combined into *average* value

Sample/Test	FGC (J/g-K)	*Average* Peak HRR (kW/m^2)	*Average* 2-minute THR (kW-min/m^2)
Sample B	64 ± 1	46.3 ± 7.4	38.4 ± 3.8
Sample A1	76 ± 1	61.9 ± 10.1	47.9 ± 8.4
Sample A2	79 ± 3	38.3 ± 7.0	14.5 ± 3.2