

Effect of Airflow and Measurement Method on the Heat Release Rate of Aircraft Cabin Materials in the Ohio State University Apparatus

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| 16. Abstract <p>Materials for aircraft cabin interiors must meet the flammability requirements of Title 14 Code of Federal Regulations (CFR) Part 25.853. The 14 CFR 25.853 requirement includes a test for large-area materials that measures the heat release rate (HRR) during burning using a fire calorimeter originally developed at Ohio State University (OSU). In the standard 14 CFR 25 procedure, a sample is inserted into the combustion chamber of the OSU apparatus and subjected to a calibrated radiant heat flux of 35 kW/m² and an impinging pilot flame. Room temperature air is forced through the combustion chamber and exits through the exhaust duct at the top of the apparatus where a thermopile senses the temperature of the exhaust gases. The HRR during the test is deduced from the sensible enthalpy rise of the air flowing through the combustion chamber using the temperature difference between the exhaust gases and the ambient incoming air to calculate the amount of heat released by burning after suitable calibration using a metered methane diffusion flame. Limits of 65 kW/m² and 65 kW/m²-min for the maximum (peak HRR) and the total heat release (HR) up to 2 minutes into the test (2-min HR), respectively, are placed on large-area materials used in passenger cabins of transport category airplanes carrying more than 19 passengers.</p> <p>Results from multi-laboratory studies of the same materials tested for HR and HRR according to 14 CFR 25.853 indicated that the laboratory-to-laboratory variation of the test results was relatively high. There are many factors that can contribute to poor agreement between OSU fire calorimeter results obtained in different laboratories (i.e., reproducibility), including the accuracy of the heat flux calibration, contaminated temperature sensors, thermal inertia of the apparatus and its components, and changes in the convective environment in the combustion and bypass chambers caused by airflow and airflow distribution. This study focused on the effect of the airflow through the 14 CFR 25.853 fire calorimeter on the repeatability and reproducibility of the HR and HRR by the sensible enthalpy (temperature rise) of the standard method, compared to HR and HRR measured simultaneously by the oxygen consumption method.</p> | | | | | |
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LIST OF ACRONYMS

| | |
|-----|-----------------------------|
| CFR | Code of Federal Regulations |
| HR | Heat release |
| HRR | Heat release rate |
| OSU | Ohio State University |
| PEI | Polyetherimide |
| TP | Thermopile |

EXECUTIVE SUMMARY

Materials for aircraft cabin interior materials must meet the flammability requirements of Title 14 Code of Federal Regulations (CFR) Part 25.853. The 14 CFR 25.853 requirement includes a test for large-area materials that measures the heat release rate (HRR) during burning by using a fire calorimeter that measures the temperature rise of the combustion gases from the burning sample. The values of heat release (HR) and HRR depend not only on the temperature rise of the combustion gases, but also on the flow rate of air through the calorimeter, which is presumed to be a constant in 14 CFR 25.853. Multi-laboratory studies indicated that the laboratory-to-laboratory variation (reproducibility) of HR and HRR in the 14 CFR 25.853 test was relatively high, so this study focused on whether differences in the airflow through three 14 CFR 25.853 fire calorimeters at the Federal Aviation Administration William J. Hughes Technical Center could account for the poor reproducibility of the HR and HRR. It was found that the test-to-test variation on a single fire calorimeter by a single operator (repeatability) of HR and HRR was independent of airflow through the combustion chambers of the different calorimeters, but the absolute values of HR and HRR from the different calorimeters (reproducibility) were highly sensitive to airflow. When HR and HRR were measured by the oxygen consumption method, repeatability was comparable to the temperature rise (14 CFR 25.853) method, but reproducibility was two to three times better.

INTRODUCTION

Materials for new aircraft cabin interiors must meet the flammability requirements of Title 14 Code of Federal Regulations (CFR) Part 25.853. The 14 CFR 25.853 requirement includes a test for the heat release rate (HRR) of large-area materials using a fire calorimeter originally developed at Ohio State University (OSU) [1]. In the standard 14 CFR 25 procedure [2], a sample is inserted into the combustion chamber of the OSU apparatus and subjected to a calibrated radiant heat flux of 35 kW/m^2 and an impinging pilot flame. Room temperature air is forced through the combustion chamber and exits through the exhaust duct at the top of the apparatus where a thermopile (TP) senses the temperature of the exhaust gases. The HRR during the test is deduced from the sensible enthalpy rise of the air flowing through the combustion chamber using the temperature difference between the exhaust gases and the ambient incoming air to calculate the amount of heat released by burning after suitable calibration using a metered methane diffusion flame [2]. Limits of 65 kW/m^2 and 65 kW-min/m^2 for the peak HRR and the total heat release (HR) up to 2 minutes into the test (2-min HR), respectively, are placed on large-area materials used in passenger cabins of transport category airplanes carrying more than 19 passengers [3].

Results from a multi-laboratory study, in which the same materials were tested according to 14 CFR 25.853 in several OSU fire calorimeters at different locations, indicated that the reproducibility could be improved [4]. There are many factors that can contribute to poor agreement between the OSU fire calorimeter results obtained in different laboratories (i.e., reproducibility), including the accuracy of the heat flux calibration, contaminated temperature sensors, thermal inertia of the apparatus and its components, and changes in the convective environment in the combustion and bypass chambers caused by airflow and airflow distribution. This study focused on the effect of airflow through the combustion chamber on the repeatability and reproducibility of the HRR measured by the sensible enthalpy (i.e., temperature) rise of the combustion stream and the oxygen consumption method for comparison. Previous studies examined the effect of the thermal inertia of the OSU apparatus on the accuracy of the measured HRR [5].

METHODS

MODIFICATION OF THE OSU FIRE CALORIMETERS FOR OXYGEN CONSUMPTION MEASUREMENTS

All tests were conducted in OSU fire calorimeters conforming to the 14 CFR 25.853 HRR test for cabin materials as described in the Federal Aviation Administration's Aircraft Materials Fire Test Handbook [2], except that a removable gas sampling system that could be inserted down through the exhaust gas stack into the combustion chamber was constructed to make oxygen consumption measurements. The removable sampling system was adopted to avoid permanently modifying the three OSU fire calorimeters used in the study to make oxygen consumption measurements. The oxygen measuring system consisted of a sampling ring 7.6 cm (3 in.) in diameter made of 6.4 mm (1/4 in.) stainless steel tubing into which 12 holes were drilled, each 1.6 mm in diameter (see figure 1). The standoff on the right side of the sampling ring ensures that it is centered in the pyramidal section above the combustion chamber of the OSU fire calorimeter during use. Sampling the combustion gases in the pyramidal section of the

combustion chamber before they are diluted with bypass air entering the chimney section increases the sensitivity of the oxygen consumption measurements, but makes direct measurement of the chamber airflow impossible without changes in the air distribution system to accommodate external flow meters (see Combustion Chamber Airflow Measurements section). A thermocouple was attached to the sampling ring to measure the temperature of the gases at the sampling point in the combustion chamber. Figure 2 is a schematic diagram of the oxygen consumption system. Stainless steel tubing connects the sample ring inside the OSU fire calorimeter to Teflon[®] tubing outside the calorimeter. An inline fiberglass soot filter removed particulates before the combustion gases were drawn into a commercial combustion gas conditioning system with a corrosion-resistant cold trap and a sample pump at 8–10 L/min. The particulate-free, relatively dry combustion gas stream from the conditioning system was split into a sample stream of 0.150 L/min (150 cm³/min) and passed over calcium sulfate (Drierite) to remove any residual moisture before entering a paramagnetic oxygen analyzer. The remainder of the gas stream was exhausted into the hood.



Figure 1. Exhaust gas sampling ring

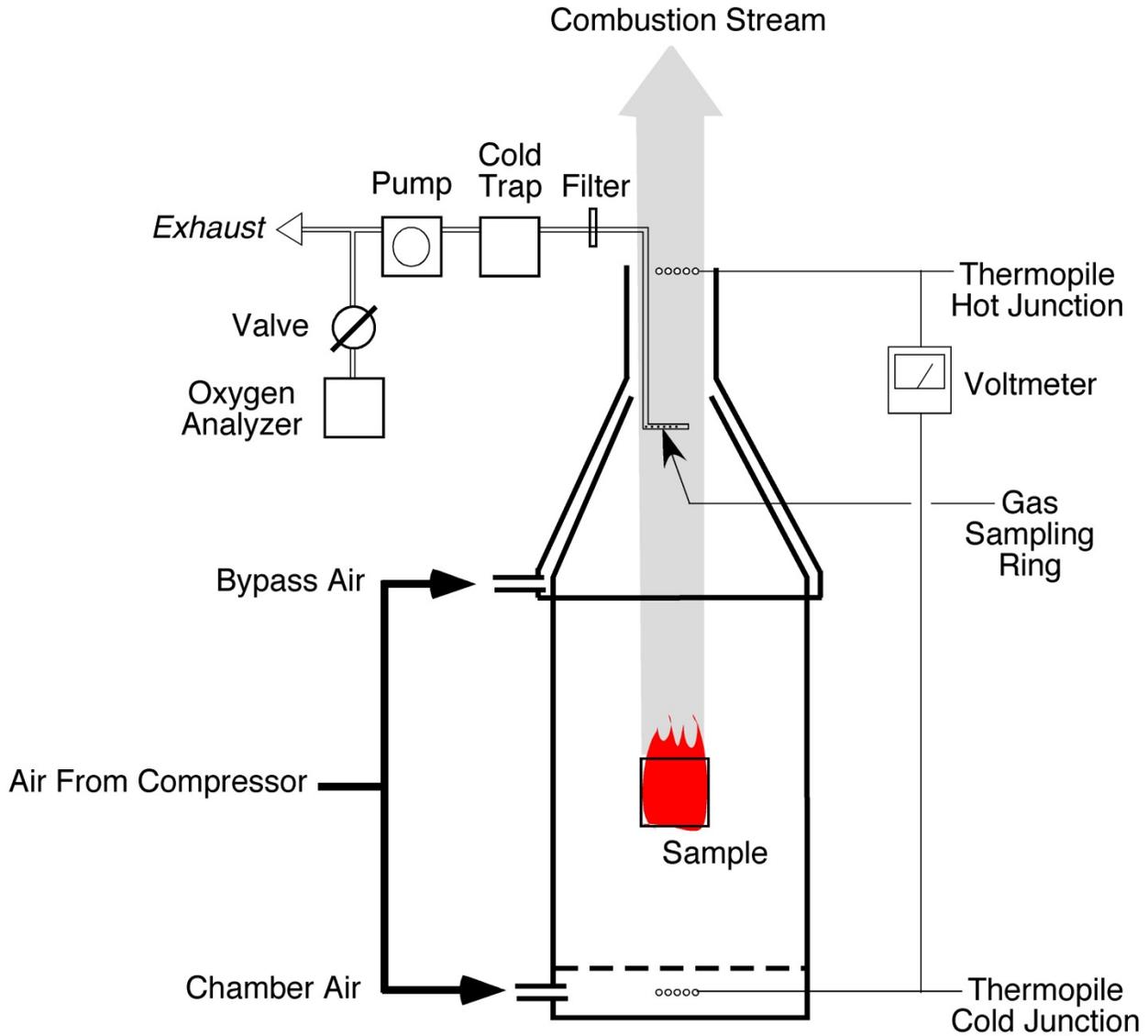


Figure 2. Oxygen consumption modification to the OSU apparatus

COMBUSTION CHAMBER AIRFLOW MEASUREMENTS

The flow rate of air entering the upper and lower manifolds of the OSU fire calorimeter is traditionally set using a mercury manometer to measure the pressure difference across an inline orifice plate (see figure 3). A pressure transducer was added to the inlet air stream across the orifice plate so the differential pressure could be monitored and logged during the experiments. This allows the stability of the airflow to be monitored during a series of tests. The ASTM standard [1] and the Aircraft Materials Fire Test Handbook [2] state that the total flow of air into the OSU apparatus should be 2400 L/min. This flow is split by the backpressure of the orifices in the floor of the sample chamber such that 25% of the flow (600 L/min, nominally) enters the combustion chamber and 75% of the flow (1800 L/min, nominally) bypasses the combustion chamber and recombines with the exhaust gases in the upper duct.

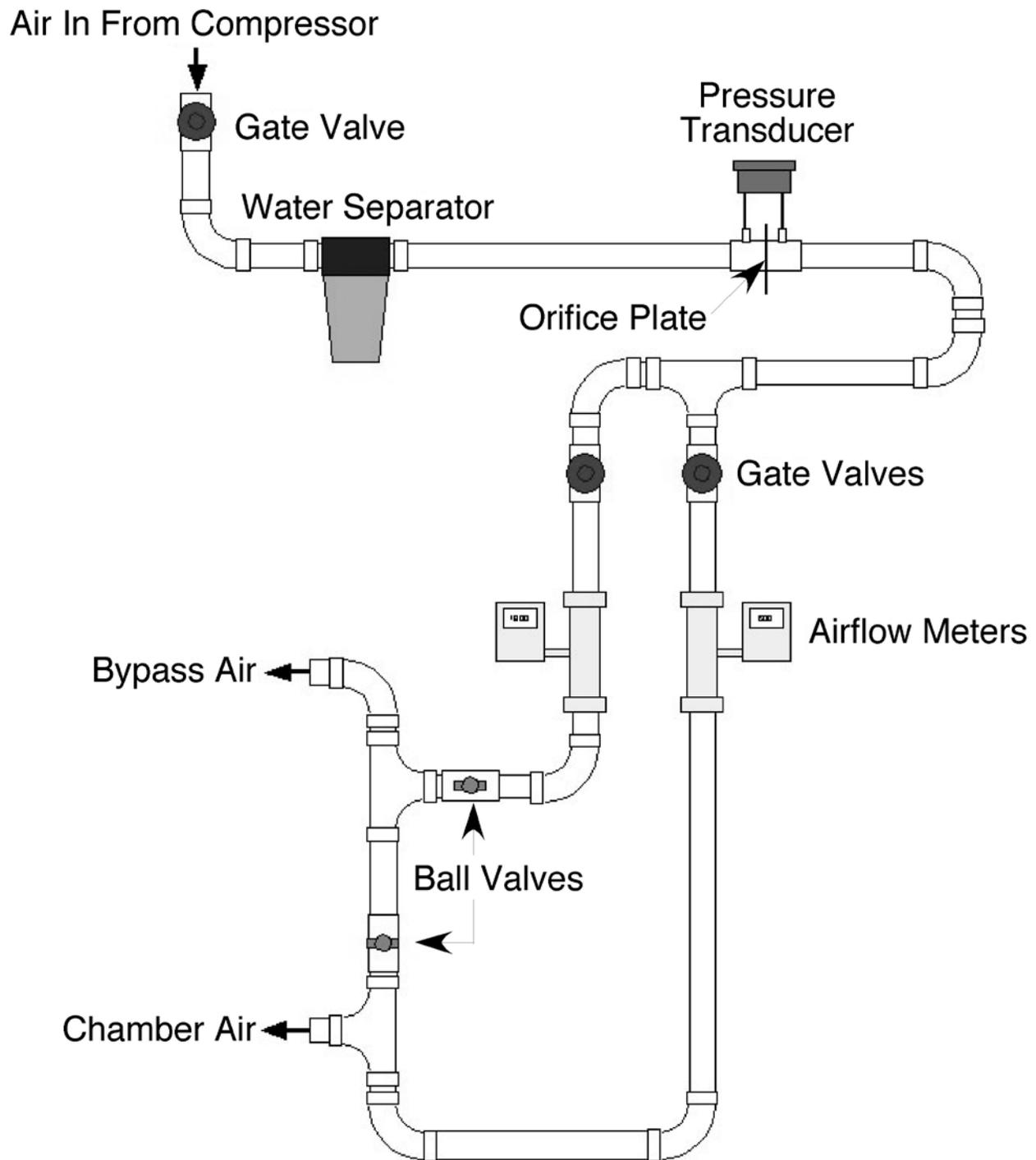


Figure 3. Modified plumbing showing valves and instrumentation for controlling and monitoring the airflows

In the 14 CFR 25 procedure, the flow rate of air into the combustion chamber is not measured. What is measured is the TP response to a methane calibration procedure, which yields a calibration (k_h) factor that relates the TP voltage to the methane heat release rate, Q . The calibration routine listed in the Aircraft Materials Fire Test Handbook [2] states that methane

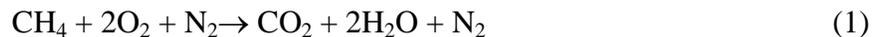
should be metered in as a sequence of square waves lasting 2 minutes each with 2-minute intervals between waves. The 14 CFR 25 sequence is: 8 - 1 - 4 - 1 - 6 - 1 - 8 - 1 - 6 - 1 - 4 L/min. The value of the TP calibration constant k_h is not specified in the 14 CFR 25 procedure, though it does state that its relative error for the sequence of methane flows should be less than 5% [2]. Consequently, changes in the convective environment in the combustion chamber because of differences in airflow are empirically accounted for by the magnitude of k_h . In these experiments, the methane calibration procedure was automated using software and a methane mass flow controller. The methane output from the mass flow controller was measured using a wet test meter every time the calibration was performed to get the exact flow of methane at each set point.

Direct Measurements Using External Flow Meters

Mass flow meters (Fox Thermal Instruments, Inc. Model FT2) were used to measure the flow rates of the air going to the upper and lower manifolds in the nominal (i.e., 14 CFR 25) and controlled configurations. The valves, plumbing, and instrumentation of the air distribution system are shown in figure 3. In the nominal configuration, only the total flow rate is measured using the pressure difference across an orifice plate in the air supply line. The airflow through the combustion chamber is assumed to be 600 L/min based on the nominal 3-to-1 split of bypass-to-chamber airflows. In the modified plumbing of figure 3, airflows of precisely 1800 L/min and 600 L/min were sent to the upper manifolds and combustion chamber, respectively, using gate valves to control the flow. In this method, the flow rate of air into the combustion chamber can be measured directly, and an accurate calculation of the HRR by oxygen consumption can be obtained.

Indirect Measurement Using Oxygen Consumption

In addition to the TP k_h factor, an oxygen consumption c -factor was determined before each day of testing. Measuring Q by the oxygen consumption method requires the airflow rate and the oxygen depletion by combustion. In this and previous studies [5 and 6], the exhaust gases are sampled inside the pyramidal section of the combustion chamber, rather than in the upper section, so that they are not diluted with the fresh bypass air, and maximum sensitivity is obtained. The combustion chamber airflow for the nominal 14 CFR 25 testing was calculated from the methane calibration using the stoichiometric reaction of methane with air,



Because 3 moles of reactants (i.e., methane and air) generate 3 moles of combustion products, the combustion reaction is constant volume. This means that the volume of the combustion gases exiting the OSU fire calorimeter is the same as the volume of the incoming gases when both are at the same temperature and pressure. In practice, the temperature of the combustion gases exiting the OSU fire calorimeter is higher than the temperature of the incoming gases because heat is generated by the combustion reaction. The molar ratio of O_2 to CH_4 in the combustion reaction (see equation 1) is 2, so $2n$ moles of O_2 are consumed for each mole of CH_4 combusted. The rate of HR, Q , is related to mass flow rate of incoming air m'_{air} (kg/s) at flow rate F_{air} (m^3/s),

density ρ_{air} (kg/m³), molar mass M_{air} (kg/mole), and having oxygen volume fraction $X_{O_2}^0$ (m³-O₂/m³-air) [7 and 8],

$$Q' = E \frac{X_{O_2}^0 - X_{O_2}^A}{1 - X_{O_2}^A} \frac{M_{O_2}}{M_{air}} m'_{air} \quad (2)$$

In equation 2, $X_{O_2}^A$ is the oxygen concentration measured at the analyzer after soot, CO₂, and H₂O have been removed. In this case, the mole (i.e., volume) fraction of oxygen is,

$$X_{O_2}^A = \frac{n_{O_2}}{n_{O_2} + n_{N_2}} \quad (3)$$

In these experiments, only the soot (which is negligible for methane calibrations) and H₂O are removed from the gas stream going to the oxygen analyzer; the oxygen concentration measured in the OSU fire calorimeter for well-ventilated combustion ($n_{CO_2} \gg n_{CO}$) is,

$$X_{O_2} = \frac{n_{O_2}}{n_{N_2} + n_{O_2} + n_{CO_2}} \quad (4)$$

From equations 3 and 4 and the stoichiometry of the methane calibration (equation 1), the oxygen concentrations for over-ventilated combustion, where $X_{O_2} \approx X_{O_2}^0$, are related by,

$$\frac{X_{O_2}^A}{X_{O_2}} = \left\{ \frac{1 - \frac{1}{2} X_{O_2}^0}{1 - X_{O_2}^0 + \frac{1}{2} X_{O_2}} \right\} \approx 1 \quad (5)$$

For fresh air at $X_{O_2}^0 = 0.2095$ (20.95% v/v), the error associated with neglecting CO₂ in the analyzer stream is less than 1%, as long as the oxygen concentration in the exhaust gases is $X_{O_2} > 0.18$. This error is considered negligible in the following analysis. The mass flow rate of ambient air having density ρ_{air}^a entering the combustion chamber is,

$$m'_{air} = \rho_{air}^a F_{air} \quad (6)$$

Substituting equations 5 and 6 into equation 2,

$$Q(W) = F_{air} \left\{ E \rho_{air}^a \frac{M_{O_2}}{M_{air}} \frac{X_{O_2}^0 - X_{O_2}}{1 - X_{O_2}} \right\} = F_{air} \left\{ E \rho_{air}^a \frac{M_{O_2}}{M_{air}} f(X_{O_2}) \right\} \quad (7)$$

During the flow rate calibrations, methane is metered into the combustion chamber at $F_{CH_4} = 1, 4, 6,$ and 8 L/min at $T_a = 298K$ ($77^\circ F$) and burned in a diffusion flame, producing rate of HR $Q = (F_{CH_4})(800 \text{ kJ/mole})/(0.0409 \text{ mole/L})(1 \text{ min}/60s) = 545(\text{W}\cdot\text{min}/\text{L}) \times F_{CH_4}$. The constants are $E_{CH_4} = 12.51 \text{ MJ/kg}\cdot\text{O}_2$ for methane, $\rho_{air}^a = 1.18 \text{ kg/m}^3$, and $M_{O_2}/M_{air} = (32 \text{ g/mole})/(28.9 \text{ g/mole}) = 1.1$. Figure 4 is a plot of Q versus the bracketed term on the right side of equation 7. The slope of the line forced through the origin is $F_{air} = 768 \text{ L/min}$, which agrees with the inline flow meter values of approximately $F_{air} = 720 \text{ L/min}$ but is considerably higher than the nominal 14 CFR 25 value of $F_{air} = 600 \text{ L/min}$ based on a 1-to-3 (25%) split of the incoming 2400 L/min of air.

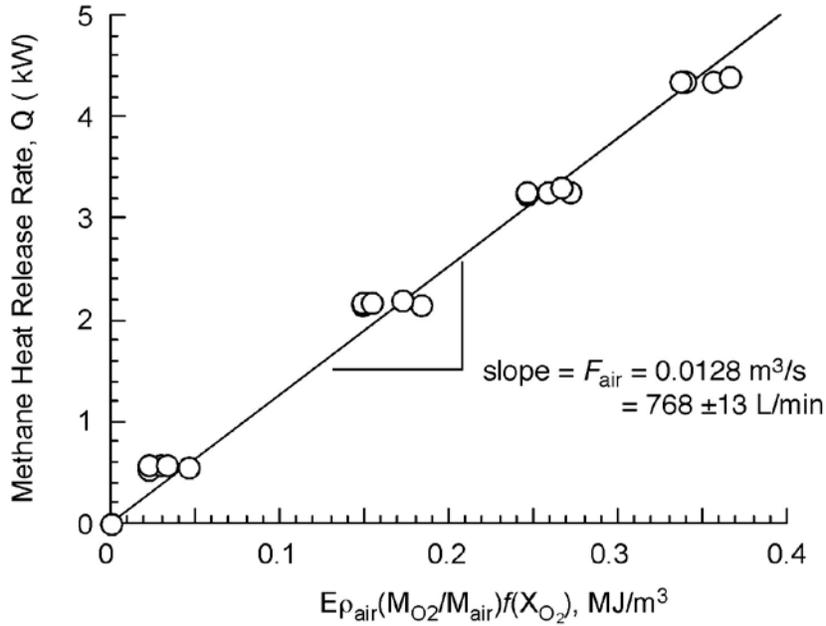


Figure 4. The Q of methane versus the bracketed term on the right side of equation 7 (slope is $F_{air} = 768 \pm 13 \text{ L/min}$)

The TP (mV) and oxygen (X_{O_2}) histories during a typical methane calibration are shown in figure 5. Note that the TP signal does not reach steady state (i.e., equilibrium) at any time during the methane calibration sequence because of the sluggish thermal response (i.e., thermal inertia) of the apparatus. These dynamics are highly dependent on airflow, which determines the rate of convective heat exchange with the apparatus walls. In contrast to the TP signal, the oxygen signal is in equilibrium with the methane flow rate at all times during the test, so differences in apparatus construction and airflow rate are unimportant. The first column in table 1 for each OSU fire calorimeter contains data for methane flow rate, and the second column is the change in the volume fraction of oxygen measured by the analyzer. The last row is the slope of the best-fit line forced through the origin of a plot of Q versus the bracketed term in equation 7 for each of the three OSU fire calorimeters. These values were used to calculate the HRR of the cabin materials by oxygen consumption.

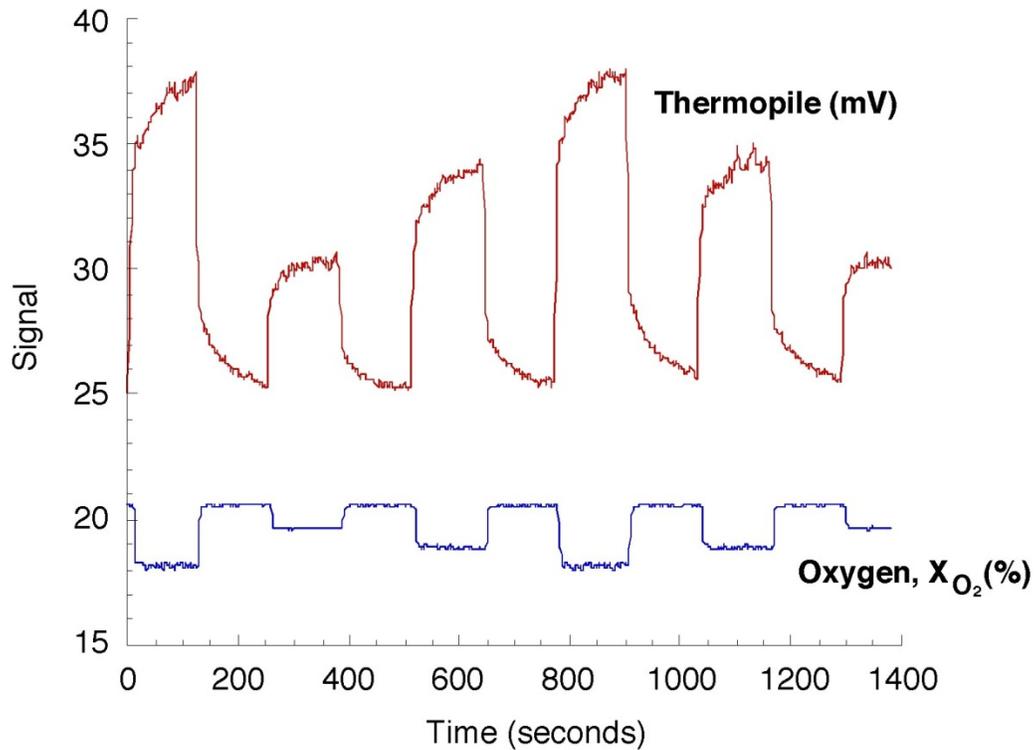


Figure 5. The TP and oxygen signals during methane calibration

Table 1. Combustion chamber airflows calculated from methane flow and oxygen depletion

| OSU-1 | | OSU-2 | | OSU-3 | |
|--------------------------------------|-------------------------|--------------------------------------|-------------------------|--------------------------------------|-------------------------|
| CH ₄ Flow Rate (L/min) | ΔX_{O_2} (%) | CH ₄ Flow Rate (L/min) | ΔX_{O_2} (%) | CH ₄ Flow Rate (L/min) | ΔX_{O_2} (%) |
| 1.04 | 0.23 | 0.99 | 0.34 | 0.93 | 0.29 |
| 3.96 | 0.91 | 3.93 | 1.43 | 3.73 | 1.29 |
| 5.97 | 1.43 | 5.90 | 2.21 | 5.59 | 2.05 |
| 7.98 | 2.00 | 8.14 | 3.10 | 7.45 | 2.79 |
| Air Flow = 768 L/min | | Air Flow = 495 L/min | | Air Flow = 520 L/min | |

THE HRR TESTS OF AIRCRAFT MATERIALS

Ten tests were conducted for each of two commonly used aircraft interior materials (thermoset composite and thermoplastic sheet) in three different OSU fire calorimeters for a total of 2 materials x 3 OSU calorimeters x 10 replicates = 60 experiments. The thermoset composite panels were 150 mm x 150 mm squares, 3.2 mm thick, made of fiberglass reinforced phenolic resin skins bonded to a NOMEX[®] honeycomb core supplied by Schneller, Inc. Thermoplastic samples were 1.6 mm thick polyetherimide (PEI) sheets (ULTEM 1668 PEI, GE Plastics). When preparing the thermoplastic samples, two thin-gauge wires were attached to the sample holder and passed over the front face of the sample to stop it from melting and falling out of the sample holder. Also, a sample tray was attached to the bottom front face of the holder to catch any

molten drips during the test. External heat flux was calibrated to 35 kW/m² using the same heat flux transducer for all tests.

The instantaneous HRR per unit area of irradiated sample surface (A) was calculated by the oxygen consumption method using equation 7,

$$HRR_{O_2} = \frac{Q}{A} = \left(\frac{E F_{air} \rho_{air}^a M_{O_2}}{A M_{air}} \right) \left(\frac{X_{O_2}^0 - X_{O_2}}{1 - X_{O_2}^0} \right) \approx \left(\frac{E F_{air} \rho_{air}^a M_{O_2}}{A M_{air} (1 - X_{O_2}^0)} \right) \Delta X_{O_2} = c \Delta X_{O_2} \quad (8)$$

In equation 8, $E = 13.1$ kJ/g-O₂ is the (average) heat of combustion of oxygen with common fuels, ρ_{air} is the density of oxygen at standard temperature (298K) and pressure (1 ATM), ΔX_{O_2} is the change in the oxygen volume fraction at time t during the test, and the burning sample area A is 0.023 m². Equation 8 allows for quantitative HRR for any airflow rate F_{air} if c is determined from a plot of Q versus ΔX_{O_2} from the methane calibration.

The instantaneous HRR was also calculated using the TP method as per 14 CFR 25.853 with $k_h = (\Delta Q/\Delta V)/A$ (kW/m²-mV) as the methane calibration factor measured at the beginning of each day of testing, for a change in the TP potential ΔV (mV) during the test,

$$HRR_{TP} = \frac{1}{A} \left(\frac{\Delta Q}{\Delta V} \right)_{CH_4} = k_h \Delta V \quad (9)$$

RESULTS AND DISCUSSION

Figure 6 shows representative data for the HRR of the composite panel computed by the oxygen consumption method (HRR_{O_2}) and the TP method HRR_{TP} , with the typically higher HRR for the oxygen consumption method [5, 6, and 9]. Figure 7 shows representative data for the thermoplastic sheet for the oxygen consumption and TP methods.

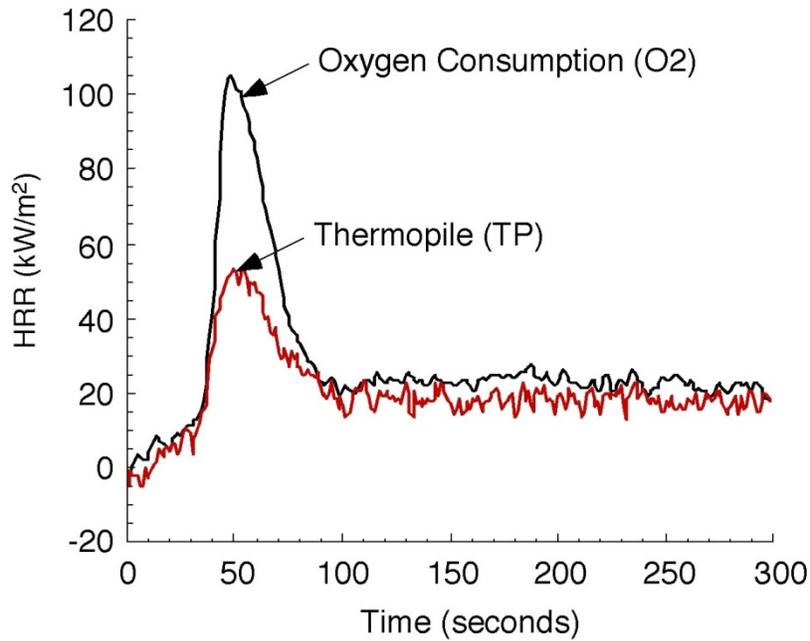


Figure 6. The HRRs for thermoset panel by oxygen consumption and TP methods

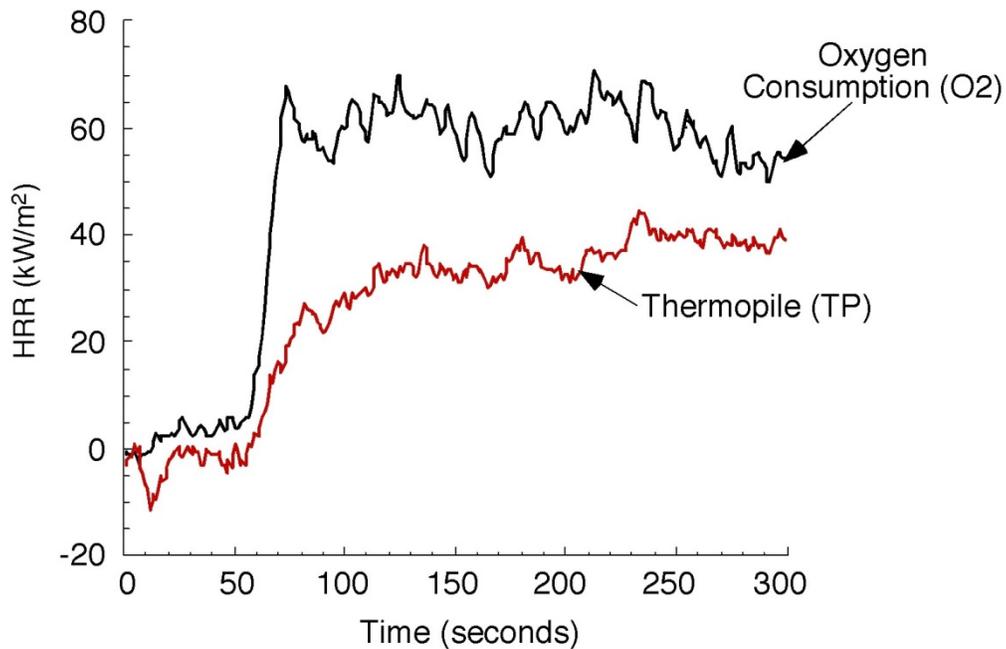


Figure 7. The HRRs for thermoplastic sheet by oxygen consumption and TP methods

The test results summarized in table 2 show that the peak HRR and total HR by oxygen consumption (O_2) is higher than the TP method. This well-known effect [4 and 5], which is shown in figures 6 and 7, occurs because the radiant heat absorbed by the apparatus during the test does not contribute to the enthalpy rise of the gases in the TP method, and the fraction of

radiant heat varies by material: approximately 50% for the thermoset panel and 33% for the thermoplastic sheet based on the ratio of peak HRR in table 2 by the two methods.

Table 2. Average values of peak HRR, 2-min HR, and 5-min HR for 10 tests \pm one standard deviation (also listed is the average coefficient of variation for a single OSU fire calorimeter [repeatability] and different OSU fire calorimeters [reproducibility])

| | | OSU-1 | OSU-2 | OSU-3 | AVG | COV (repeat.) (%) | COV (reprod.) (%) |
|-----------------------------------|-----------------------------------|--------------|--------------|--------------|---------------|-------------------------|-------------------------|
| Test Chamber Airflow (L/min) | | 768 | 495 | 520 | 594 \pm 151 | | |
| Thermopile Method | Thermoset (phenolic) Panel | | | | | | |
| | Peak HRR (kW/m ²) | 56 \pm 3 | 50 \pm 2 | 57 \pm 4 | 54 \pm 4 | 5.5 | 7.4 |
| | 2-min HR (kW-min/m ²) | 38 \pm 4 | 44 \pm 3 | 48 \pm 4 | 43 \pm 5 | 8.6 | 11.6 |
| | 5-min HR (kW-min/m ²) | 90 \pm 8 | 92 \pm 7 | 101 \pm 8 | 94 \pm 6 | 8.1 | 6.4 |
| | Thermoplastic (PEI) Sheet | | | | | | |
| | Peak HRR (kW/m ²) | 50 \pm 5 | 42 \pm 2 | 53 \pm 5 | 48 \pm 3 | 8.1 | 6.3 |
| | 2-min HR (kW-min/m ²) | 20 \pm 4 | 22 \pm 4 | 37 \pm 5 | 26 \pm 9 | 17.2 | 34.6 |
| | 5-min HR (kW-min/m ²) | 144 \pm 18 | 130 \pm 10 | 171 \pm 18 | 148 \pm 21 | 10.2 | 14.2 |
| AVERAGE COEFFICIENT OF VARIATION: | | | | | | 10 | 13 |
| Oxygen Consumption | Thermoset (phenolic) Panel | | | | | | |
| | Peak HRR (kW/m ²) | 125 \pm 4 | 119 \pm 7 | 109 \pm 5 | 118 \pm 8 | 4.6 | 6.9 |
| | 2-min HR (kW-min/m ²) | 70 \pm 4 | 76 \pm 4 | 68 \pm 4 | 71 \pm 4 | 5.6 | 5.6 |
| | 5-min HR (kW-min/m ²) | 143 \pm 10 | 155 \pm 9 | 139 \pm 8 | 146 \pm 8 | 6.2 | 5.5 |
| | Thermoplastic (PEI) Sheet | | | | | | |
| | Peak HRR (kW/m ²) | 75 \pm 6 | 75 \pm 5 | 72 \pm 8 | 74 \pm 2 | 8.6 | 2.7 |
| | 2-min HR (kW-min/m ²) | 46 \pm 6 | 43 \pm 2 | 49 \pm 4 | 46 \pm 3 | 8.6 | 6.5 |
| | 5-min HR (kW-min/m ²) | 237 \pm 17 | 236 \pm 10 | 214 \pm 25 | 229 \pm 13 | 7.7 | 5.7 |
| AVERAGE COEFFICIENT OF VARIATION: | | | | | | 7 | 5 |

Note: COV = Coefficient of variation; PEI = polyetherimide

CONCLUSIONS

The test chamber airflows varied from 495–768 L/min for the three Ohio State University (OSU) fire calorimeters in this study compared to the nominal 600 L/min of Title 14 Code of Federal Regulations (CFR) Part 25.853. However, despite the 25% difference in the combustion chamber flow rates, all three OSU calorimeters calibrated to within the error limits of k_h by 14 CFR 25.853. These widely different chamber airflows did not significantly affect the repeatability of any individual OSU calorimeter by either the O₂ or thermopile (TP) methods. However, the different airflow rates in the OSU calorimeters did affect the average value of the heat release rate (HRR) and heat release (HR) measured by the TP method in the different apparatuses, though these differences could not be explained by airflow alone. Consequently, the variability in the TP results is probably because of differences in the thermal response dynamics of the individual apparatus [10]. The reproducibility of the O₂ method, which is not susceptible to apparatus thermal dynamics, was two to three times better than the TP method based on the overall coefficient of variation of 5% and 13% for O₂ and TP, respectively. These results are consistent with previous studies by Tsuchiya indicating 40% better reproducibility of HRR and

HR in the OSU calorimeter when HRR is calculated from oxygen consumption (O₂) rather than the TP method.

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