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Monitoring Smoke Emissions Using the Heat Release Rate Test Apparatus (HR2)

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Technical Note

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16. Abstract

A study was conducted to determine the feasibility of adding the capability of measuring material smoke emissions to the Federal Aviation Administration (FAA) rate of heat release test method, which is performed in a specially developed test device that is commonly referred to as the Heat Release Rate 2 Apparatus (HR2). A laser/sensor means of measuring cumulative smoke release, analogous to specific optical density D_s as measured in the FAA smoke emission test, was devised by using a continuous wave 670-nanometer wavelength laser and a thermopile power sensor. Tests performed in the FAA smoke emission chamber compared the output obtained from the legacy smoke chamber photometric system and the newly devised laser/sensor assembly measurement system. Neutral density light filters with varying percentage of light transmission were placed in the light paths, and specific optical density was determined for each value of percentage light transmission, which found both measurement systems to be in good agreement over the entire range of filters tested. Material smoke tests using both measurement systems were performed to compare the material smoke emission. In general, peak smoke-density measurements obtained with the laser/sensor system were lower than those obtained with the photometric system, though test-to-test repeatability was similar for both measurement methods. Material smoke emission tests were performed in the HR2 apparatus with the laser/sensor assembly attached horizontally such that the laser light path spanned the width of the vertical exhaust gas stream. Cumulative smoke release data obtained during the HR2 tests were affected by the conditions at the exhaust stack of the HR2. The elevated temperature at the exhaust opening was found to increase the thermopile sensor output reading; though this was compensated for by setting the sensor baseline after the HR2 has reached a stable operating temperature. In materials that produce large flames from the HR2 exhaust, thermopile sensor readings were observed to be significantly impacted, as the luminosity of the flames resulted in increased thermopile sensor output. Overall, this study demonstrated the feasibility of measuring smoke density during a heat release test in the HR2 apparatus, with mitigations employed to compensate for the elevated temperatures and possibility of visible flames at the HR2 exhaust opening.

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Acronyms

Acronym	**Definition**
ASTM	American Society of Testing and Materials
CSR	Cumulative smoke release
FAA	Federal Aviation Administration
HR2	Heat Release Rate Apparatus 2
NBS	National Bureau of Standards
ND	Neutral Density
NPRM	Notice of proposed rule making
SRR	Smoke release rate

Executive Summary

A study was conducted to determine the feasibility of adding the capability of measuring material smoke emissions to the Federal Aviation Administration (FAA) rate of heat release test method, which is performed in a specially developed test device that is commonly referred to as the Heat Release Rate 2 Apparatus (HR2). A laser/sensor means of measuring cumulative smoke release, analogous to specific optical density D_s as measured in the FAA smoke emission test, was devised by using a continuous wave 670-nanometer wavelength laser and a thermopile power sensor.

Tests performed in the FAA smoke emission chamber compared the output obtained from the legacy smoke chamber photometric system and the newly devised laser/sensor assembly measurement system. Neutral density light filters with varying percentage of light transmission were placed in the light paths, and specific optical density was determined for each value of percentage light transmission, which found both measurement systems to be in good agreement over the entire range of filters tested. Material smoke tests using both measurement systems were performed on three different materials to compare the material smoke emission. In general, peak smoke-density measurements obtained with the laser/sensor system were lower than those obtained with the photometric system, though test-to-test repeatability was similar for both measurement methods. The vertically oriented laser/sensor system light path was unable to span the entire height of the chamber, unlike the photometric system, thereby excluding any smoke near the ceiling that may be denser due to the nature of smoke to stratify within the test chamber.

The same material sample set was then evaluated in the HR2 apparatus with the laser/sensor assembly attached horizontally such that the laser light path spanned the width of the vertical exhaust gas stream. Smoke density measurements obtained during the HR2 tests were affected by the conditions at the exhaust stack of the HR2. The elevated temperature at the exhaust opening was found to increase the thermopile sensor output reading; though this was compensated for by setting the sensor baseline after the HR2 has reached a stable operating temperature. In materials that produce large flames from the HR2 exhaust, thermopile sensor readings were observed to be significantly impacted, as the luminosity of the flames resulted in increased thermopile sensor output.

Overall, this study demonstrated the feasibility of measuring smoke density during a heat release test in the HR2 apparatus, with mitigations employed to compensate for the elevated temperatures and possibility of visible flames at the HR2 exhaust opening.

1 Introduction

1.1 Objective

The objective of this study was to determine the feasibility of adding the capability of measuring smoke density to the Federal Aviation Administration's (FAA) modified rate of heat release test device, commonly referred to as the HR2 apparatus.

1.2 Background

Federal Aviation Administration regulations require that for airplanes with capacity exceeding 20 passengers, specific cabin interior components with large surface areas must meet the requirements of a heat release rate fire test and a smoke emission test intended to improve survivability in the event of a post-crash fire. A notice of proposed rulemaking (NPRM) issued in 2019 proposed to remove the requirement for testing of smoke emissions, as FAA research data has demonstrated that heat release rate of cabin materials is the primary impact factor affecting occupant survivability rather than smoke emission (Interior parts and components fire protection for transport category airplanes, 2019). The data do not correlate smoke emission test results with post-crash survivability as they do with heat release test results, and therefore the FAA concluded that the smoke emission test requirement does not add to post-crash fire safety and therefore would be removed from the routine method of compliance. However, in theory there may exist a material with a low heat release rate but high smoke output, so the FAA included provisions in the NPRM to establish general performance standards for interior components which influence occupant survivability during a post-crash fire. Continual monitoring of material smoke output is recommended, either by the existing FAA smoke emission test, or another means of demonstrating that smoke emission does not impact post-crash survivability.

2 Experimental setup

This study was conducted in the Fire Safety laboratories at the William J. Hughes Technical Center in Atlantic City, NJ. The following apparatuses, equipment, and calculations were used to obtain data for this study.

2.1 FAA smoke emission test

The FAA National Bureau of Standards smoke emission test apparatus (NBS), is displayed in Figure 1. The test apparatus and method are described in detail in the FAA Aircraft Materials Fire Test Handbook (Federal Aviation Administration, 2000).

Figure 1. FAA NBS smoke emission test apparatus

2.2 Specific optical density

Specific optical density, D_s, is the metric used in NBS smoke tests to assess a material's smoke production. It is a dimensionless measure of the amount of smoke produced per unit area by a material when it is burned. D_s is calculated with knowledge of the percentage of light transmittance as shown in Equation 1.

$$D_s = 132 \log_{10}\left(\frac{100}{\%LT}\right) \quad (1)$$

Federal Aviation Regulations (14 C.F.R. 25.853(d), Amdt. 25–116, 69 FR 62788, Oct. 27, 2004) require that the D_s during a 4-minute test not exceed 200.

2.3 FAA rate of heat release test

The modified rate of heat release test is conducted on the HR2 apparatus and is based on the currently required FAA rate of heat release test. Figure 2 displays a photograph of the HR2 test apparatus. The test apparatus and method are described in detail in the Aircraft Materials Fire Test Handbook Revision 3 (Federal Aviation Administration, 2019).

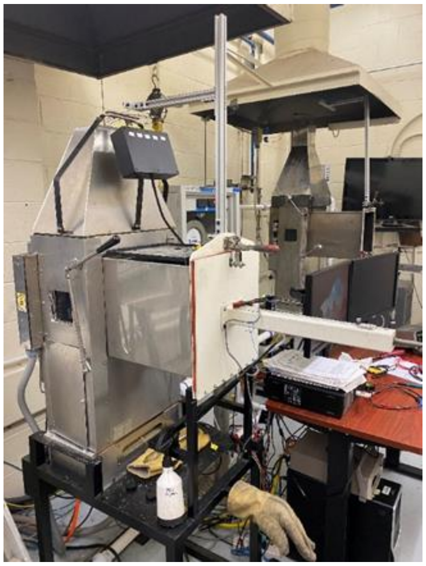

Figure 2. FAA rate of heat release test apparatus (HR2)

2.4 Smoke release rate

The smoke release rate (SRR) is the metric used in the heat release test for assessing a material's smoke output when burning as described in ASTM E906/E906M (ASTM International, 2017). It is expressed in smoke units per minute per square meter of exposed material surface and can be calculated as shown in Equation 2.

$$Smoke\ Release\ Rate = SRR = \frac{D}{kLA} \cdot \left(\frac{V_O}{t}\right) \qquad 2$$

Where:

k = Absorption coefficient = 1.0 m^2/smoke

D = Optical density (absorbance) = $\log_{10}\left(\frac{100}{\%LT}\right)$

L = Light path = 0.134m (stack width)

A = Exposed surface area of specimen, m^2

$\frac{V_0}{t}$ = Flow rate of air leaving apparatus, *m^3/min*

$\frac{V_O}{t}$ = $\frac{V_i}{t} \times \frac{T_O}{T_i}$

$\frac{V_i}{t}$ = Flow rate of air entering apparatus, *m^3/min*

T_i, T_O = Absolute temperature of air in and out of apparatus, respectively

The cumulative smoke release (CSR) over a specified time interval can be calculated by determining the area under the curve of SRR plotted against time. This metric is analogous to the D_s calculated in the NBS smoke test, which considers the accumulation of smoke over time inside the smoke chamber.

2.5 Laser and thermopile power sensor assembly

A continuous wave 670-nanometer wavelength laser and a thermopile power sensor were paired together as an alternative means of measuring smoke emission. The laser/sensor assembly is shown in Figure 3. The thermopile sensor operates by absorbing and converting incident laser radiation into heat, which then flows into a heat sink. The temperature difference between the absorber and heat sink is converted into an electrical signal by a thermocouple junction. The output of the sensor, in watts, is proportional to the amount of laser light received by the sensor. As smoke or other media enter the laser light path, the light is reflected, refracted, or absorbed, reducing the amount of light received by the sensor and thus the wattage output. The percent light transmittance was determined as the difference between the sensor baseline, with only clear air between the laser and sensor, and the test measurement, when an obscuration may be present in the light path, reducing the sensor output signal below the baseline.

Figure 3. Continuous wave laser (left) and thermopile sensor (right)

2.6 Neutral density filters

Neutral density (ND) filters were used as a means of calibration among the differing smoke measurement systems and apparatuses. The filters attenuate the light signal between the light source and the sensor by a fixed and known amount when placed in the light path. Three filters, ND2, ND4, and ND8, corresponding to percent light transmittance values of 50.1, 25.1, and 12.6, respectively, were used individually and stacked together to provide percent light transmittance values from 100% down to 0%. D_s is calculated in the same manner as the smoke emission test, as shown in Table 1.

Table 1. Neutral density filter % light transmittance and corresponding D_s

Filters	**% Light Transmittance**	$\boldsymbol{D_s}$
NONE	100	0.0
ND2	50.1	39.6
ND4	25.1	79.2
ND8	12.6	118.8
ND2 + ND8	6.3	158.4
ND4 + ND8	3.2	198.0

2.7 Modifications to NBS test

The NBS test apparatus was slightly modified in this study to accommodate the addition of the laser/sensor assembly to ensure simultaneous comparative measurement with the NBS photometric system. Figure 4 displays the laser/sensor assembly mounted in the NBS chamber. It is significant to note that the light path between the laser and sensor is unable to span the entire height of the chamber due to the physical dimensions of the equipment, whereas the NBS photometric system does span the entire height. This is displayed in the schematic in Figure 5. This difference in span could affect the amount of smoke that is quantified by the laser/sensor assembly, as smoke tends to stratify within the chamber resulting in non-uniform smoke density from floor to ceiling, and smoke near the top of the chamber may not be captured in the light path.

Figure 4. Laser/sensor assembly mounted in the NBS chamber adjacent to the photometric system

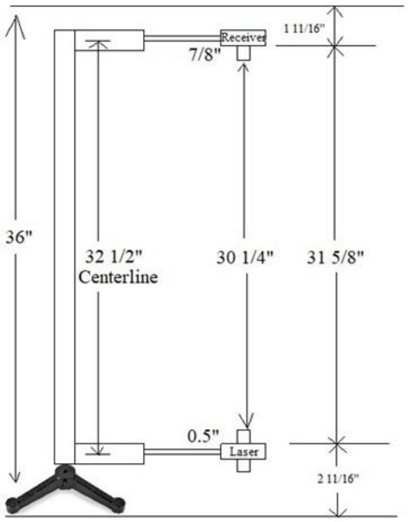

Figure 5. Laser/sensor light path distance as compared to the overall height of the NBS chamber and the photometric system

2.8 Modifications to HR2 test

The HR2 test was slightly modified to allow for the measurement of smoke output at the exhaust opening. The laser/sensor assembly was mounted above the HR2 apparatus as displayed in Figure 6. The distance between the laser and sensor was 5.25 inches and the assembly was 2 inches above the HR2 exhaust opening.

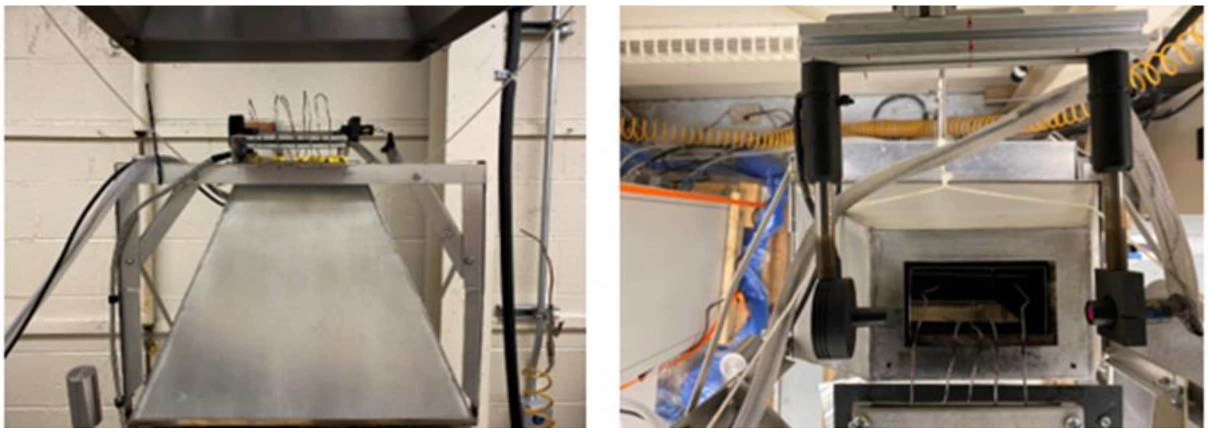

Figure 6. Laser/sensor assembly mounted above the exhaust opening of the HR2 – front view (left) and top view (right)

Initial testing revealed sensitivity of the thermopile sensor to the elevated temperature at the exhaust opening of the HR2. Figure 7 shows the thermopile sensor output as a function of time during a sixty-minute HR2 warmup period. During this time, the HR2 exhaust temperature ranges from room temperature to approximately 572°F. It is evident that the thermopile sensor is sensitive to the surrounding temperature, as a 15% increase in power output was found during this time. Therefore, the thermopile sensor baseline was determined after the HR2 reached a stable operating temperature.

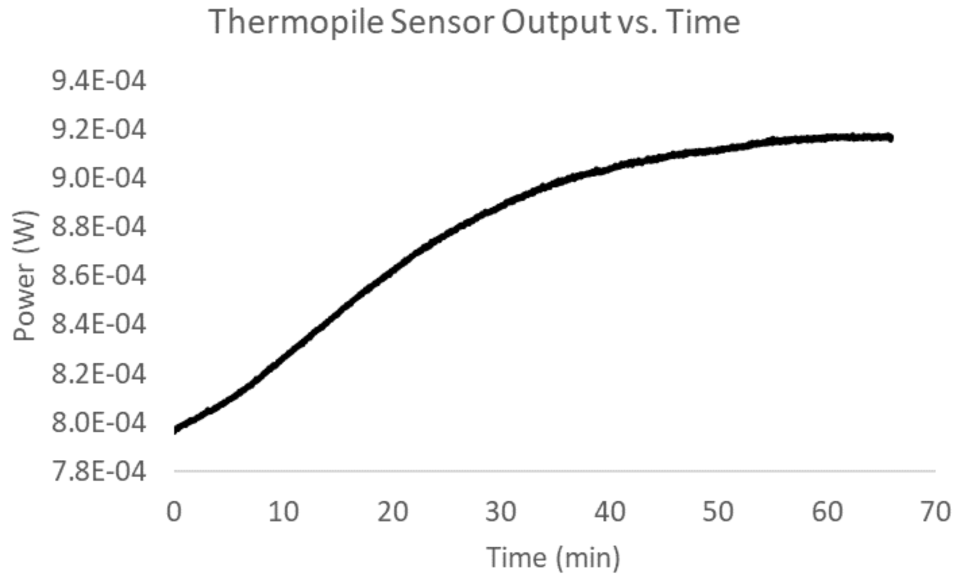

Figure 7. Thermopile sensor output (watts) vs. time (min) during HR2 Warmup period

2.9 Test materials

Three materials were chosen for this study based on prior knowledge of D_s values obtained in the NBS smoke test. Information about the materials is provided in Table 2. The D_s values were chosen to bracket the pass/fail criteria of $D_s < 200$.

Table 2. Test materials

Material	**Material Description**	**Material Thickness**	**Approximate D_s**
Material 1	Honeycomb Panel with Decorative	0.25 inch	50
Material 2	Double-sided Tape (6 layers of Tape A) on Aluminum	0.030 inch	215
Material 3	Double-sided Tape (6 layers of Tape B) on Aluminum	0.030 inch	190

Material 1 was a honeycomb panel with a decorative face, 0.25-inch-thick with an approximate D_s of 50. Material 2 was a 0.030-inch-thick aluminum substrate with six layers of double-sided tape (Tape A) and an approximate D_s of 215. Material 3 was also a 0.030-inch-thick aluminum substrate with six layers of a different type of double-sided tape (Tape B) and an approximate D_s of 190. Five test coupons of each material system were tested in each apparatus to determine repeatability of the smoke measurements.

3 Experimental results

3.1 Neutral density filter calibrations

A series of measurements were obtained by placing the neutral density filters in the light path of the NBS photometric system, the laser/sensor assembly in the NBS chamber, and the laser/sensor assembly above the HR2 apparatus. D_s was calculated from the percent light transmittance from the NBS photometric system and the thermopile sensor output. The measurements are displayed in Table 3. Good agreement was found for each neutral density filter combination across the three different scenarios. This indicated that for a known amount of light signal attenuation, both measurement systems provided a similar signal reduction and D_s.

Table 3. D_s for neutral density filters in the NBS and HR2 tests

Neutral Density Filters	**NBS Photometric**	**NBS Laser/Sensor**	**HR2 Laser/Sensor**
ND2	38.2	37.7	38.1
ND4	80.9	79.4	78.8
ND8	103.1	98.9	99.5
ND4 + ND2	118.9	116.9	117.0
ND8 + ND2	142.5	139.9	137.9
ND8 + ND4	182.3	181.5	179.3
ND8 + ND4 + ND2	223.6	227.5	220.1

3.2 Material smoke tests in the NBS

The D_s from five different tests of materials 1, 2, and 3 in the NBS test chamber are displayed in Figure 8, Figure 9, and Figure 10, respectively. The blue bars represent the D_s as measured with the NBS photometric system, while the orange bars represent the D_s as measured with the laser/sensor assembly. Across all three materials, the NBS photometric system provided a higher D_s than the laser/sensor assembly. This may be due to the difference in light path distance, as the laser/sensor system is unable to capture the smoke across the entire height of the test chamber.

Table 4 provides the average, standard deviation, and relative standard deviation for both methodologies inside the NBS chamber for all three materials. The NBS photometric system provided a relative standard deviation ranging from 9.1% - 10.9%, indicating good repeatability from test to test. The laser/sensor system in the NBS provided a relative standard deviation of

10.0% - 12.1%, only slightly higher than the NBS photometric system. This indicates that the laser/sensor system is nearly as repeatable as the NBS photometric system.

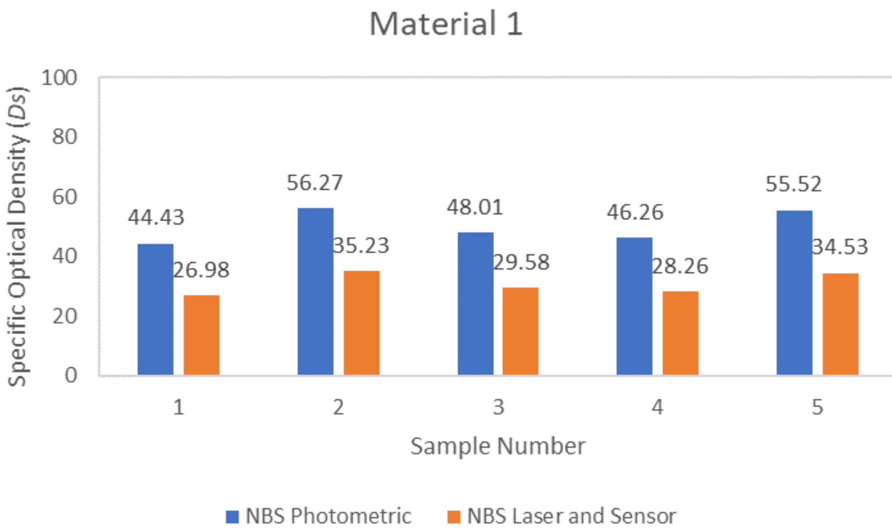

Figure 8. D_s for material 1 in the NBS test

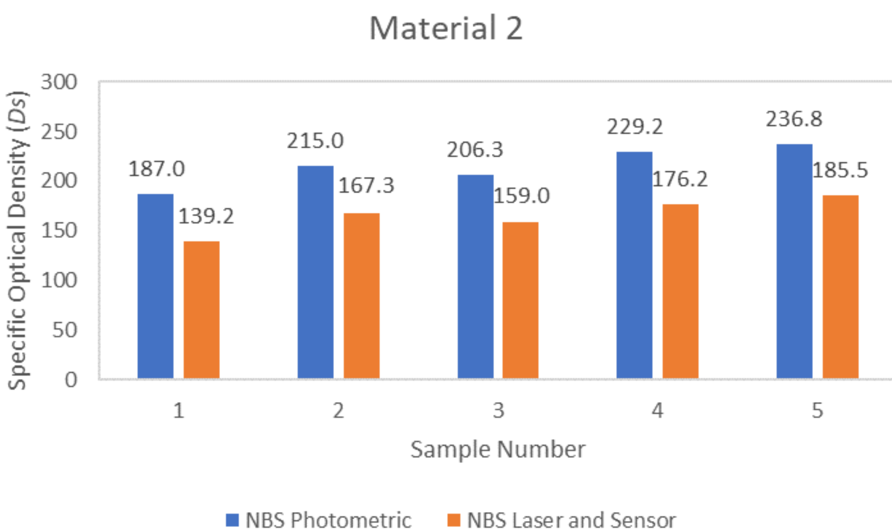

Figure 9. D_s for material 2 in the NBS test

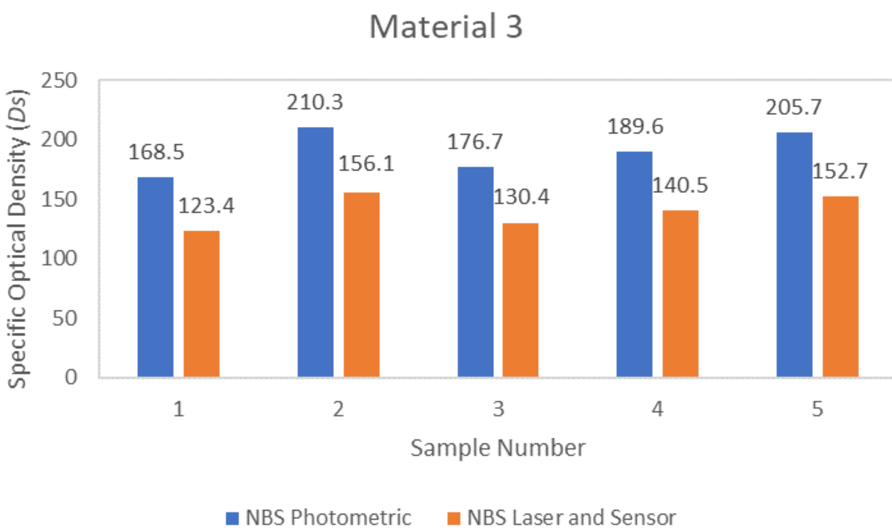

Figure 10. D_s for material 3 in the NBS test

Table 4. Average D_s for NBS tests

Material	NBS Photometric			NBS Laser/Sensor		
	Average	**Standard Deviation**	**Relative Standard Deviation**	**Average**	**Standard Deviation**	**Relative Standard Deviation**
1	50.1	5.45	10.9%	30.92	3.74	12.1%
2	214.86	19.60	9.1%	165.44	17.71	10.7%
3	190.16	18.03	9.5%	140.61	14.02	10.0%

3.3 Material tests in the HR2

Heat release rate and SRR measurements from one test of material 1 in the HR2 are displayed in Figure 11. The CSR for five different tests of material 1 in the HR2 are shown in Figure 12. The heat release rate is represented by the purple line and the SRR is represented by the green line. As the material burns, both the heat release rate and the SRR increase, which indicates smoke emitted by the sample is obscuring the light path between the laser and thermopile sensor. The CSR is calculated by integrating the SRR over the five-minute test interval. The average CSR across all five tests was 6.7 with a standard deviation of 1.5. The relative standard deviation, or the standard deviation divided by the mean, was 22.9%.

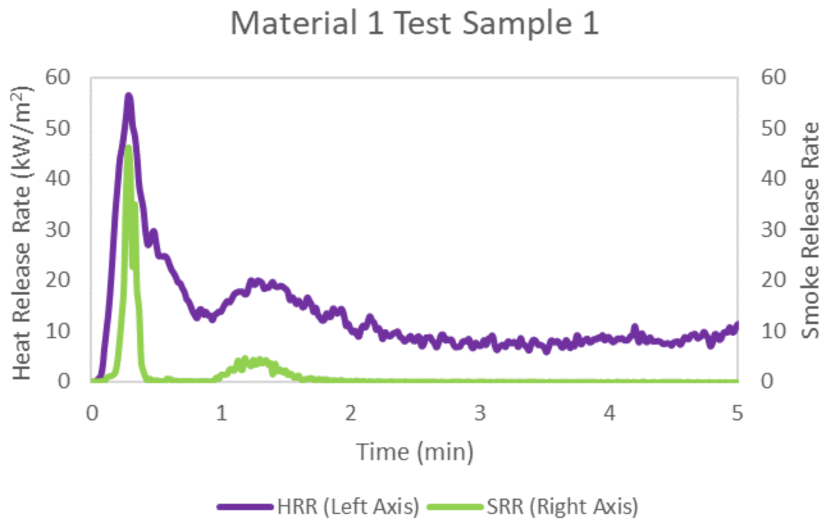

Figure 11. Heat release rate and SRR vs. time for material 1 test sample 1

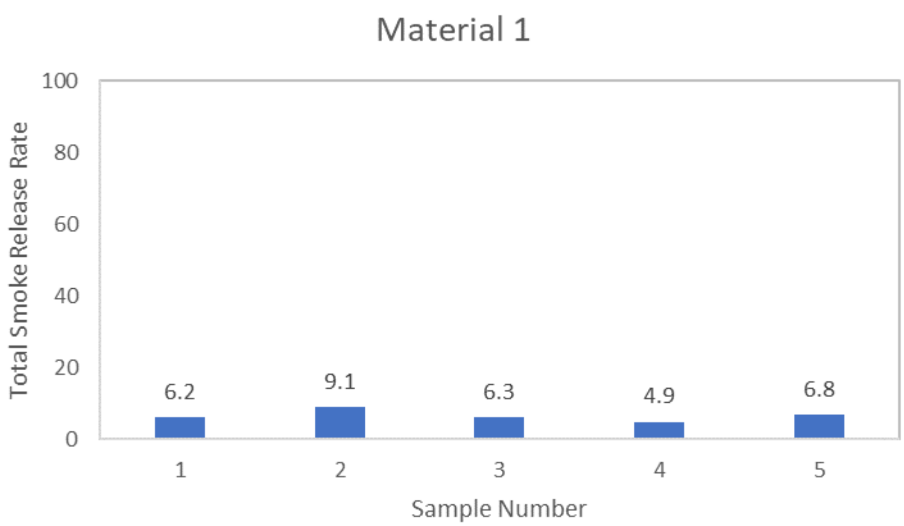

Figure 12. CSR for material 1 in the HR2 test

Heat release rate and SRR measurements from one test of material 2 in the HR2 are displayed in Figure 13. The CSR is calculated by integrating the SRR over the five-minute test interval. The CSR for five different tests of material 2 in the HR2 are shown in Figure 14. The average CSR across all five tests was 68.8 with a standard deviation of 2.8. The relative standard deviation was 4.0%.

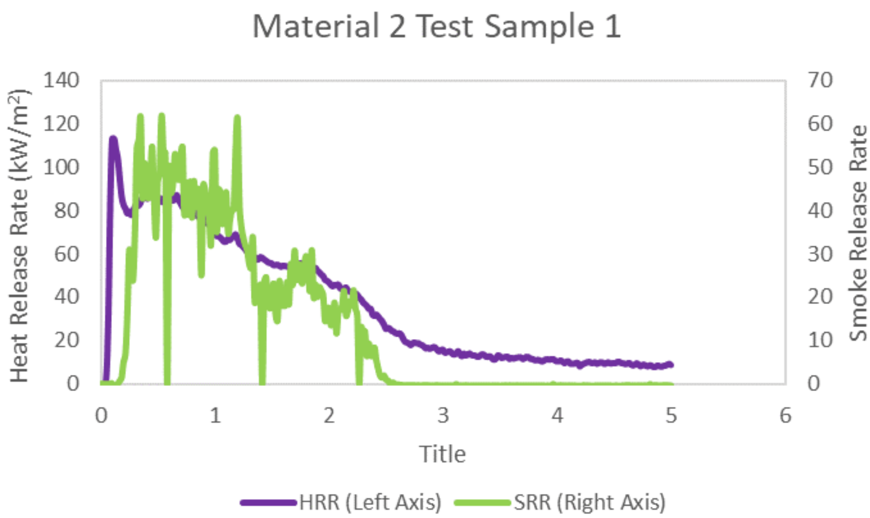

Figure 13. Heat release rate and SRR vs. time for material 2 test sample 1

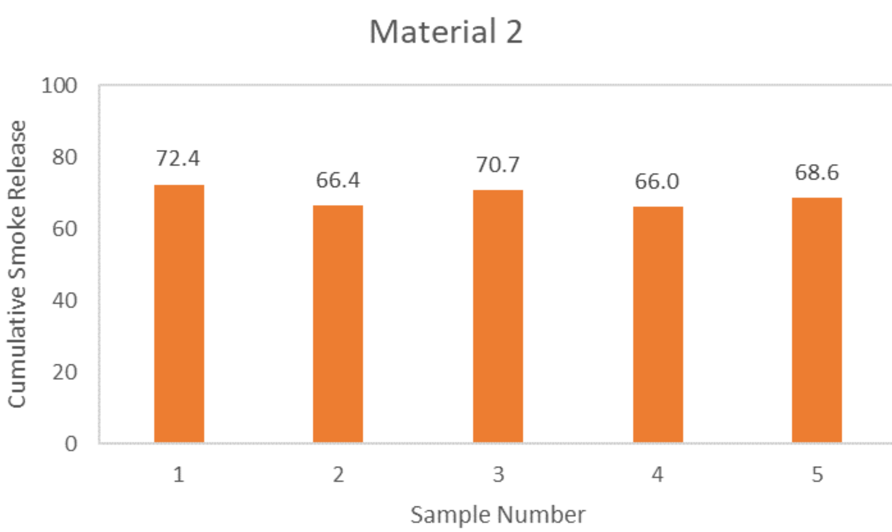

Figure 14. CSR for material 2 in the HR2 test

Material 3 presented a challenge to the laser/sensor measurement technique. Heat release rate and SRR measurements from one test of material 3 in the HR2 are displayed in Figure 15. During HR2 tests, material 3 burned with very tall flames that could be seen exiting the HR2 exhaust opening. This heat and light passed through the light path of the laser/sensor assembly, amplifying the power output of the thermopile sensor, resulting in an increase rather than a decrease in the sensor output as the test progressed. This resulted in erroneous calculations for the SRR and CSR rate for these tests. Though this affects the measurement of smoke emission, it is likely that any material producing visible flames from the exhaust opening will also exceed the acceptance criteria for the rate of heat release test.

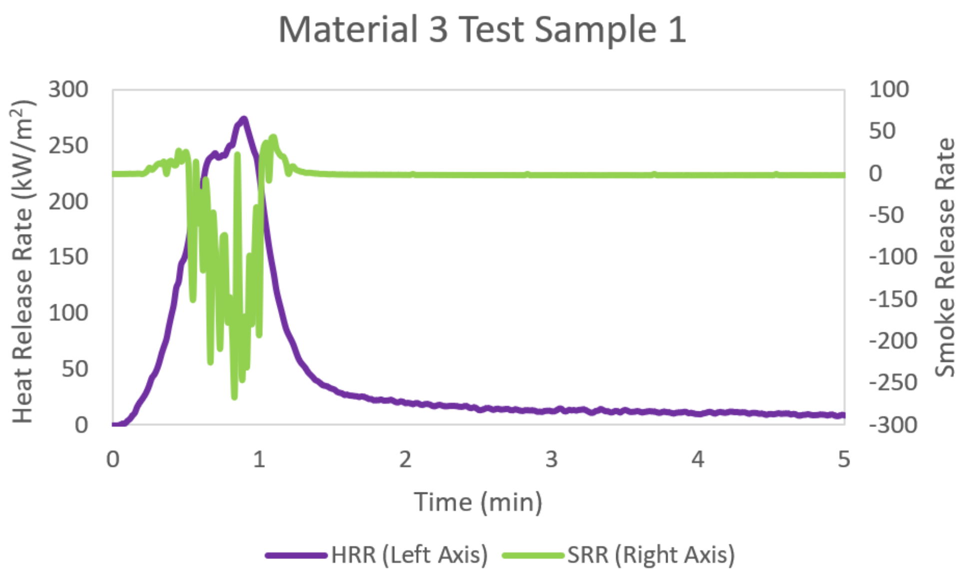

Figure 15. Heat release rate and SRR vs. time for material 3 test sample 1

The overall results for the HR2 Laser/Sensor system are displayed in Table 5, including the average CSR, standard deviation, and relative standard deviation.

Table 5. Average CSR for the HR2 tests

	HR2 Laser/Sensor		
Material	**Average**	**Standard Deviation**	**Relative Standard Deviation**
1	6.7	1.5	22.9%
2	68.8	2.8	4.0%
3	N/A	N/A	N/A

3.4 Comparison of results

An overall comparison of results is displayed in Table 6. Although the CSR for material 3 was unable to be determined, it can be seen that based on materials 1 and 2, the CSR as measured in the HR2 trends in the same manner as the NBS photometric D_s and the NBS laser/sensor D_s. This gives confidence that the laser/sensor measurement system in the HR2 can provide a quantitative assessment of the smoke output of a material and can be used to monitor material performance over time to verify that a material smoke output is consistent with those traditionally used.

Table 6. Comparison of D_s and cumulative smoke release (CSR)

Material	NBS Photometric D_s	NBS Laser/Sensor D_s	HR2 Laser/Sensor CSR
1	50.1	30.92	6.7
2	214.86	165.44	68.8
3	190.16	140.61	N/A

4 Summary

Test results indicate that it is possible to obtain useful smoke density measurements from the FAA rate of heat release HR2 apparatus test. A laser and thermopile sensor system was found to provide smoke density measurements similar to the FAA smoke density (NBS) chamber with a similar level of test-to-test repeatability. When installed above the HR2 apparatus, the laser/sensor was affected by the elevated temperatures at the HR2 exhaust opening, providing an increase in sensor output. This was compensated for by allowing the HR2 to reach a stable operating temperature prior to setting the sensor baseline power-output. Visible flames exiting the HR2 exhaust opening were found to significantly amplify the sensor output signal, resulting in erroneous smoke release rate calculations. This may be mitigated by the use of narrow band filters between the laser and sensor, filtering out all other wavelengths but the 670-nanometer laser light. Additional testing is necessary to confirm this.

5 References

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