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Railcar Interior Finish Flammability Requirement Based on Heat Release Rate



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14. ABSTRACT The Federal Railroad Administration issued a contract to American Public Transportation Association (APTA) to conduct this study to develop a material flammability requirement based on heat release rate that would prevent accelerated surface flame spread leading to flashover. Jensen Hughes, Inc. conducted the research on behalf of APTA and created a database of over 320 rail car materials and flammability data to support development of a requirement and a comparison of flammability requirements in NFPA 130 and EN 45545-2. The team determined that the average heat release rate per unit area (HRRPUA) from a cone calorimeter test is the single most important variable in classifying the occurrence of flashover. At an exposure of 50 kW/m ² , the requirement is to limit the average HRRPUA to less than 85 kW/m ² for large spaces; for small spaces, an average HRRPUA less than 70 kW/m ² is needed. The team found the average HRRPUA to be more accurate at predicting flashover compared with EN 45545-2 maximum average rate of heat emission (MARHE). The NFPA 130 ASTM E162 requirement could not be used to accurately predict flashover. The EN45545-2 MARHE was found to be a stricter requirement compared with NFPA 130 ASTM E162.						
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Executive Summary

The Federal Railroad Administration (FRA) contracted with American Public Transportation Association to conduct a research study on flammability of materials used in passenger rail car interior. Jensen Hughes, Inc. (JH) conducted this research study on behalf of APTA. JH developed recommendations for a material flammability requirement based on heat release rate that would prevent accelerated surface flame spread which could result in flashover conditions. The research was performed between September 2022 and December 2023.

Rail car interiors are manufactured with advanced materials to improve energy efficiency, aesthetics, and passenger comfort. Many of these materials are combustible and thus are required to meet flammability and smoke requirements. For most of the interior finish surfaces, the current flammability requirement in 49 CFR Part 238.103 and NFPA 130 is based on an ASTM E162 flame spread test. Though ASTM E162 does screen out poor performing materials, the results have been shown to not correlate with fire behavior for plausible rail car fire scenarios [1]. As a result, a requirement based on heat release rate is needed so that the requirement is related to the desired performance in a rail car. There are material flammability requirements in EN 45545-2, including some heat release rate based requirements; however, it is not clear whether these requirements correlate with NFPA 130 requirements or which standard is more conservative.

The study focused on materials on the interior of the rail car that represent large surface areas, except cables, floors, cushioning, fabrics, elastomers, structural components, and adhesives since these materials have unique requirements. JH created a database of 320 rail car materials to support the research effort. This included data from the ASTM E1354 / ISO 5660-1 cone calorimeter including ignition time, heat release rate, total heat release, effective heat of combustion, burning duration, heat release rate curves, and maximum average rate of heat emission (MARHE). Smoke data from the cone calorimeter as well as ASTM E662 is included. The database also contains ASTM E162 radiant panel index data and whether the material passes or fails NFPA 130 and EN 45545-2 flammability and smoke requirements.

The research team conducted statistical analysis to determine the correlation between different variables and how well these variables correlate with the prediction of flashover. They predicted flashover using the flammability parameter with a threshold value to classify the occurrence of flashover (1) or no flashover (0). Based on previous analysis, the threshold value for large spaces, for example passenger seating area is $F=0.75$, while the threshold for small spaces, such as toilet area is $F=0.6$. As determined through statistical analysis, three independent variables correlate to the prediction of flashover: the ignition time, burning duration, and average heat release rate per unit area (HRRPUA). Using machine learning tree-based classifiers (random forest and decision tree), the research team found that the average HRRPUA is the most important variable and it alone is sufficient to accurately predict the occurrence of flashover.

The team used the decision tree classifiers based on average HRRPUA alone to develop heat release based requirements. They determined that materials in large spaces should have an average HRRPUA $<85 \text{ kW/m}^2$, while small spaces should have a requirement of $<70 \text{ kW/m}^2$. The team found the MARHE to be statistically related to the occurrence of flashover; however, the average HRRPUA more accurately predicted flashover. ASTM E162 radiant panel index was not statistically correlated to the occurrence of flashover, and the radiant panel index had low

accuracy in predicting flashover using a decision tree classifier. A comparison of the NFPA 130 and EN 45545-2 requirements was inconclusive since there were limited data. The research team determined that the EN 45545-2 MARHE requirements are stricter compared with the NFPA 130 ASTM E162 radiant panel index flammability requirement.

1. Introduction

The design of passenger rail cars continues to evolve in order to decrease cost while increasing energy efficiency, aesthetics, and passenger comfort. To accomplish this, light-weight materials (aluminum, plastics, fiber-reinforced plastics, etc.) are increasingly used to achieve these design advances. The flammability and smoke performance of these materials are an important consideration in this design process. To ensure the safety of passengers and personnel in passenger rail cars in the U.S., the Federal Railroad Administration (FRA) published fire safety requirements in 1999 and 2002 to provide a requisite level of safety for passenger rail cars. The requirements apply to rail cars ordered on or after September 8, 2000 or placed in service on September 9, 2002 or later; rail cars refurbished or overhauled on November 9, 1999 or later in which new materials were introduced in the rail car were required to meet the standards. Since this rule making, advances in fire science have shown that heat release rate (HRR) based requirements are a better indicator of material performance in the end-use condition compared with historic flame spread tests that may not account for heat exposures or conditions in the final scenario. The primary focus of this study was to create a publicly available material flammability database and use this database to establish an HRR-based flammability requirement for rail car interior finish materials.

1.1 Background

The FRA has long recognized the importance of maintaining and improving the level of passenger train fire safety and emergency preparedness. In 1999, as part of the passenger rail equipment safety standards rulemaking process required by Congress, FRA issued regulations in 49 CFR, Part 238 that include fire safety requirements for new and existing passenger rail cars and locomotives. FRA issued an update to these requirements in 2002 [2], which included clarification of certain fire performance requirements, as well as responses to comments to the 1999 final rule.

Following the release of the rule in 2002, FRA, the Volpe National Transportation Center, the National Institute of Standards and Technology (NIST), and industry partners identified several technical issues related to the fire performance of certain component materials as warranting further study. One of these issues is material acceptance considering HRR-based performance criteria. In 49 CFR 238.103—Appendix B [3], material smoke and flammability approvals are primarily based on American Society of Testing Materials (ASTM) E662 Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials [4] and the ASTM E162 Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source [5].

During the last rulemaking process, FRA considered whether the HRR of materials was a more practical and valuable performance test to evaluate the fire safety of materials to be used in a passenger rail car design. The HRR-based performance requirements would provide designers, engineers, scientists, and testing and acceptance personnel a better understanding of the fire hazard threat, flashover HRR, and time-temperature curve resulting from burning materials. This would allow for improvements in the fire hazard analysis, emergency egress analysis and threats analysis of an enclosed space of a station or tunnel for heat and smoke control, and a better understanding of the performance of various construction materials.

The American Public Transportation Association (APTA) Passenger Rail Equipment Safety Standards, Construction and Structural Working Group identified an industry need to compare material flammability and smoke production performance in NFPA 130 [6] and EN 45545-2 [7]. The NFPA 130 flammability and smoke requirements are equivalent to those in the 49 CFR 238.103—Appendix B, with the majority of interior surface finish materials evaluated based on ASTM E162 [5] and ASTM E662 [4]. Due to the low exposure and type of flame spread in the ASTM E162 test, materials passing ASTM E162 may not have good fire performance when exposed to more realistic fire conditions (i.e., could spread flame and cause flashover) [1]. EN 45545-2 includes flammability requirements based on HRR using the ISO 5660-1 cone calorimeter test [8] well as a lateral flame spread requirement in addition to smoke and toxicity requirements. Supply chains for materials are complicated by having materials typically only tested to a single standard. It is uncertain whether the NFPA or CFR flammability and smoke testing requirements are more or less challenging compared with the EN 45545-2 testing.

Previous work by Luo, et al. [1] on developing an HRR-based flammability requirement explored identifying a material heat release rate per unit area (HRRPUA) threshold that would prevent an individual material to accelerate the fire growth causing flashover. Through this analysis, HRR-based requirements were developed based on an ASTM E1354 cone calorimeter [9] test, average HRRPUA, and an EN 45545-2 Maximum Average Rate of Heat Emission (MARHE). However, the thresholds were based on a limited number of rail car interior finish materials. The authors recommended that the HRR requirements be reconsidered with a larger database of rail car materials to better demonstrate HRR threshold.

1.2 Objectives

The overall objective of this research was to collect data from available sources and use this data to assess HRR-based requirements. The following are the specific research objectives for this effort:

- Create a publicly available database that contains material flammability and smoke data. This will include cone calorimeter data, data for NFPA 130 requirements, and data for EN 45545-2 requirements.
- Develop an HRR-based requirement using database information.
- Compare materials that have been tested in both NFPA 130 and EN 45545-2 to determine which standard is more restrictive.

1.3 Overall Approach

The approach to achieving the research objectives are as follows:

- Create a cross-correlation table of materials/function between NFPA 130 and EN 45545-2 standards along with required testing and criteria. This will provide a road map to identify the needed data to collect along with the corresponding material requirements for each standard.
- Collect existing data where materials have been tested per NFPA 130/49 CFR Part 238.103 Appendix B and tested in the cone calorimeter, including materials that meet the EN 45545-2. Data collection will focus on flammability but will also include smoke data when available.

- Analyze the data to determine an HRR-based flammability requirement using the larger data set. This will include a statistical analysis to determine the measurements required for the HRR-based requirement as well as machine learning to determine the requirement threshold. Analysis will be conducted to determine the accuracy of the new requirement in predicting the occurrence of flashover compared with other existing standards.
- Compare the performance of materials between the two standards to determine which standard is more challenging.

1.4 Scope

The requirements provided in this research were taken from NFPA 130 – 2023 Edition [6] and EN 45545-2 from 2016 [7]. The research effort focused on the large surface area materials on the rail car interior. Thus, no material data were included from NFPA 130 categories such as Cushioning, Fabrics, Floor Coverings, Adhesives and Sealants, Elastomers, Wire and Cable, and Structural Components. The data used in the analysis were publicly available through reports, scientific articles, material data sheets, and websites. Some data were also contributed by material manufacturers.

1.5 Organization of the Report

The report is organized into three sections. The first section focuses on the database created in this effort. The second section of the report includes the statistical analysis of the data to determine the correlation between variables and relative importance. The final section focuses on the development of the HRR-based requirement as well as the comparison of the EN45545-2 and NFPA 130 data.

2. Material Database

The research team created a railcar material database from data available in open scientific literature, data sheets, and contributions from APTA members. This section outlines the types of materials considered in the database and correlation of the requirements between NFPA 130 and EN 45545-2 for these materials. The section then summarizes the database and outlines some statistics that can be used for requirement analysis and comparison. [The database](#) is available through the APTA website and can be downloaded in a spreadsheet format along with heat release rate curves.

2.1 Material Categories

The research effort focused on the majority of large surface area materials on the rail car interior. This was based on the material categories given in NFPA 130, shown in [Figure 1](#). The red boxes include the materials considered in this study. The other materials were excluded because they typically have other function-specific tests to evaluate their performance (e.g., seating cushion and fabric materials are typically tested in a seating assembly fire test, floor coverings have a horizontal flame spread test, etc.).

Category	Function of Material	Test Method	Performance Criteria
Cushioning	All individual flexible cushioning materials used in seat cushions, mattresses, mattress pads, armrests, crash pads, and grab rail padding ^{a-e}	ASTM D9675 _≤	$I_f \leq 25$
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 175$
Fabrics	Seat upholstery, mattress ticking and covers, curtains, draperies, window shades, and woven seat cushion suspensions ^{a-c,f-h}	14 CFR 25, Appendix F, Part I (vertical test)	Flame time ≤ 10 sec Burn length ≤ 6 in.
		ASTM E662	$D_i (4.0) \leq 200$
Other vehicle components	Seat and mattress frames, wall and ceiling lining and panels, seat and toilet shrouds, toilet seats, trays and other tables, partitions, shelves, opaque windscreens, combustible signage, end caps, roof housings, articulation bellows, exterior shells, nonmetallic skirts, battery case material, and component boxes and covers ^{a,b,j-k}	ASTM E162	$I_f \leq 35$
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 200$
	Thermal and acoustical insulation ^{a,b}	ASTM E162	$I_f \leq 25$
		ASTM E662	$D_i (4.0) \leq 100$
	HVAC ducting ^{a,b}	ASTM E162	$I_f \leq 25$
		ASTM E662	$D_i (4.0) \leq 100$
	Floor covering ^{b,h,l}	ASTM E648	CRF ≥ 5 kW/m ²
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 200$
	Light diffusers, windows, and transparent plastic windscreens ^{a,h,i}	ASTM E162	$I_f \leq 100$
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 200$
	Adhesives and sealants ^{a,b,p}	ASTM E162	$I_f \leq 35$
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 200$
Elastomers ^{a,b,l,j}	Window gaskets, door nosings, intercar diaphragms, seat cushion suspension diaphragms, and roof mats	ASTM C1166	Flame propagation ≤ 100 mm (4 in.)
		ASTM E662	$D_i (1.5) \leq 100$ $D_i (4.0) \leq 200$
Wire and cable	All	See 8.6.7.1.1.1 through 8.6.7.1.3.	See 8.6.7.1.1.1 through 8.6.7.1.3.
Structural components ^m	Flooring, ⁿ other ^p	ASTM E119	Pass

Figure 1. The material fire test procedures and performance criteria table in NFPA 130 [6] with the red boxes highlighting the material categories considered in this research

2.2 Cross-Correlation Table

Table 1 outlines the correlations between NFPA 130 and EN 45545-2 requirements for large surface area materials on the interior of the rail car considered in this study. The table provides the requirements for the NFPA 130 materials by different categories, along with the corresponding EN 45545-2 requirements. **Appendix A** provides details of the EN 45545-2 flammability and smoke requirements and an expanded list of materials (by function) and their NFPA 130 and EN 45545-2 requirements. Note that the EN 45545-2 requirement in **Table 1** is “R1”, “R2”, etc.; these identifiers pertain to a specific set of performance criteria (heat release rate, flame spread, smoke density, etc.) depending on the categorization of the railcar’s hazard level. The researchers used these cross-correlation tables to label materials by specific NFPA 130 material categories and EN 45545-2 requirements. In addition, the tables allowed the team to screen out materials whose function was not consistent with these types of materials. This labeling was also used to determine if a material passed or failed different requirements.

Table 1. Relating NFPA 130 material category requirements to EN 45545-2 requirements

NFPA 130 Ed.2023 TESTS AND PASS CRITERIA			NFPA 130 MATERIAL CATEGORY	EN 45545-2 REQUIREMENT
Radiant Panel	Smoke Chamber – Vertical			
ASTM E162	ASTM E662 ^b			
I _s ^a <=	Ds (1.5min)<=	Ds(4min)<=		
(--)	(--)	(--)		
25	--	100	Thermal/acoustic insulation, HVAC ducting	R1
100	100	200	Windows, Transparent windscreens	R1
35	100	200	Toilet shroud/seat, Tables – upper surface	R2
100	100	200	Light diffusers	R4
35	100	200	Seat frame/shroud	R6
35	100	200	Articulating bellows	R7
35	100	200	Shelves, Component Boxes, Covers – upward facing	R10

^a No flaming running or dripping

^b Both flaming and nonflaming modes (with and without pilot flame)

I_s : radiant panel index

Ds(1.5min) : smoke specific optical density at 1.5 min. into test

Ds(4min) : smoke specific optical density at 4 min. into test

2.3 Database Description

The database developed in this research includes information on material flammability and smoke production. Specifically, the database includes the columns to describe the material, specify its NFPA 130 and EN 45545-2 requirements, whether the material passes or fails the requirement, ASTM E1354 and ISO 5660-1 cone calorimeter data, MARHE, HRRPUA curves, ASTM E162 radiant panel index, and ASTM E662 smoke data. The only EN 45545-2 numeric data available is for the MARHE. No smoke data were identified for ISO 5659-2, which is used to assess material smoke production in EN 45545-2. **Appendix B** provides a list of all column labels.

The database includes a total of 320 material entries, which the team obtained from proprietary sources of railcar operators and manufacturers, as well as publicly available data from data sheets and literature [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. Of these entries,

269 materials have numeric data describing their fire performance while 51 materials only have a Pass/Fail description for performance. All 269 materials with numeric data have cone calorimeter data; however, only 88 of them have HRRPUA curves and 91 have MARHE values. The HRRPUA curves have been digitized and are part of the database. There are 213 entries that have ASTM E162 radiant panel index data and 203 entries have ASTM E662 smoke data. The 51 materials with only Pass/Fail entries are data which were taken from websites or technical data sheets.

The database is publicly available through the APTA website. It is organized in three views: Summary Data, Cone Calorimeter Data, and NFPA 130 & EN 45545-2. These views are available directly on the APTA website with searching and sorting ability. In addition, the database is available for download in spreadsheet format.

3. Data Statistical Analysis

The research team conducted statistical analysis on the data to determine the parameters that should be considered in developing a material flammability requirement based on heat release rate. The goal of the new requirement is to screen out materials that exhibit an accelerated surface flame spread that can cause flashover. This section provides an overview of the metric used to quantify accelerated surface flame spread. Following this, a description is given on the data preparation required to create a dataset for analysis based on the database. The team then performed statistical analysis to identify the appropriate cone calorimeter data to consider for developing a heat release rate based requirement. All data preparation and statistical analysis was conducted using Python 3.

3.1 Flammability Parameter

The flammability parameter was derived based on flame spread theory developed by Quintiere, Harkleroad, and Hasemi [21], Mowrer and Williamson [22], and Beyler, et al. [23]. Beyler's work contains a full derivation and explanation of the theoretical approach. Based on this work, the dimensionless flammability parameter is defined as

$$F = 0.01\dot{Q}'' - t_{ig}/t_b \quad (1)$$

where $\dot{Q}''$ is the HRRPUA (kW/m^2), t_{ig} is the ignition time, and t_b is the burning duration. All of these quantities can be measured in the cone calorimeter. Theoretically, an $F > 1$ will result in accelerated surface flame spread which is an indicator that the material would contribute significantly to a fire causing the space to reach flashover. A $F < 1$ indicates the material will not readily spread flames over the surface.

Studies have been conducted to assess whether the flammability parameter described above could be used to predict the potential for an interior finish material to cause a room to reach flashover. These studies compared large-scale room corner fire test data with the flammability parameter calculated using Eqn. (1) and data from the small-scale cone calorimeter test. Large-scale room corner fire tests use a standard size room, which is 2.4 m wide, 3.6 m long, 2.4 m high room with a 2.0 m high, 0.8 m wide door. The side walls, back wall, and ceiling are lined with a combustible material and a propane gas burner is placed in the back corner. The primary difference between test methods is the initiating fire. The ISO 9705 [24] test specifies that the initiating fire should be generated from a 0.17 m square burner with a heat release rate of 100 kW for 600 s followed by 300 kW for 600 s. Conversely, the NFPA 286 [25] test requires an initiating fire produced using a 0.3 m square burner with a heat release rate of 40 kW for 300 s followed by 160 kW for 600 s. Due to the higher heat release rate and longer test duration, the ISO 9705 test is generally regarded as a more severe test compared with NFPA 286.

Beyer, et al. [23] conducted the analysis to calibrate the analytical model described above against ISO 9705 standard room/corner fire test data. Through this analysis, the research team determined that the data used in Eqn. (1) above should be from a cone calorimeter test conducted at an exposure heat flux level of 50 kW/m^2 . In addition, the best results were achieved with the $\dot{Q}''$ value was the average HRRPUA over the material burning duration in the cone calorimeter test. Through this analysis, a flammability parameter of $F > 0.5$ indicated that a material would cause flashover in an ISO 9705 room/corner fire test.

Luo, et al. [1] performed analysis to calibrate the analytical model based on flammability parameter against NFPA 286 room/corner fire test results. NFPA 286 was the preferred room-corner fire test because the initiating fire used in this standard was most representative of plausible initiating fires in a rail car [1]. Similarly to the case outlined above, the flammability parameter was calculated using cone calorimeter data at 50 kW/m^2 , with $\dot{Q}''$ being the average HRRPUA during the burning duration.

Through the analysis in [1], the team determined that materials with $F < 0.6$ would not cause flashover while materials with $F > 0.75$ would be expected to cause flashover (Figure 2). For materials which have a flammability parameter between 0.6 and 0.75 ($0.6 < F < 0.75$), the results were mixed; some materials resulted in flashover and some did not. For the materials in this range of flammability parameter that caused flashover, this typically occurred when the initiating fire had been increased to the higher heat release rate level of 160 kW. Note that there were a few materials that had better or worse behavior than expected based on the flammability parameter. Materials with $F > 1$ and no flashover were non-reinforced thermoplastics that melted away from the initiating fire resulting in less flame spread than expected. Materials with $F < 0.6$ that resulted in flashover were due to either facesheet fall off for a sandwich material or foam materials where flames propagated into the sample. The majority of materials were well characterized using a single value for the flammability parameter.

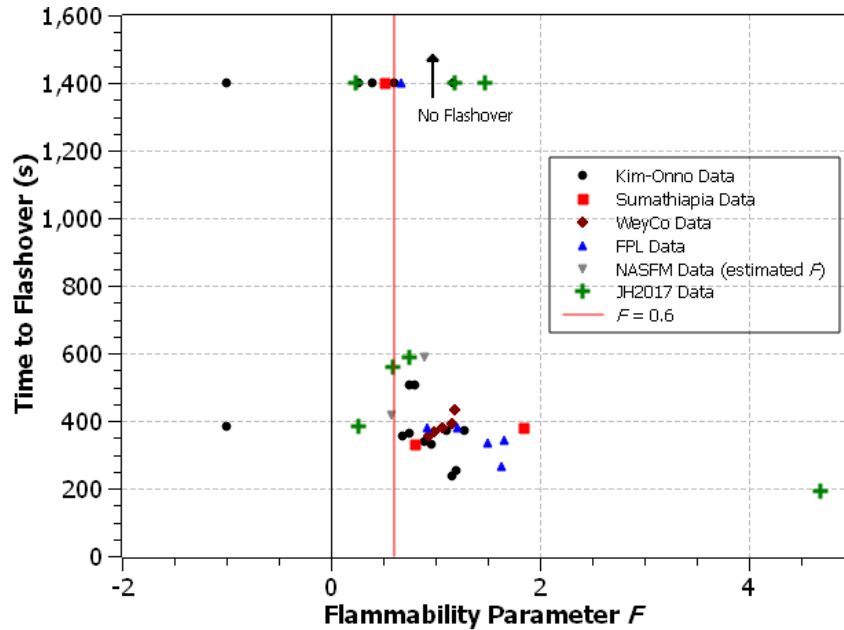


Figure 2. Flammability parameter compared with time to flashover in a NFPA 286 room-corner test [1]

The flammability parameter threshold value is also sensitive to the room size and ventilation (number of doors). To evaluate this, particularly for the cases with $0.6 < F < 0.75$, Luo, et al. [1] performed simulations to compare material flame spread behavior in the standard room versus a larger space such as the passenger area of a rail car. All simulations were with the NFPA 286 initiating fire in a corner. In this analysis, materials with a flammability parameter of $F > 0.75$ were expected to cause flashover inside of the passenger area of a rail car, while a flammability parameter less than $F < 0.75$ did not cause flashover. Luo, et al. [1] concluded that for rail applications, a threshold of $F = 0.75$ can be used for materials in the larger spaces (e.g., passenger

seating area) but for smaller spaces (e.g., toilets, sleeping areas, etc.), a threshold of $F=0.6$ may be more appropriate. The analysis in this research provides an HRR-based requirement for both flammability parameter threshold values.

3.2 Data Preparation

The research team used the materials database described in [Section 2](#) to create an analysis dataset for development of the HRR-based flammability requirement. This involved removal of materials without sufficient data, cleaning the data, populating missing values if possible, cross-checking data, and generating new features. The team removed materials from the dataset if there were not sufficient numeric cone calorimeter data or if it was unknown whether the material met NFPA 130 requirements. They then cleaned the dataset to remove unwanted characters (e.g., NaN, quotes, dashes, etc.) and converted the values from string to float so data could be used in calculations and plotting.

Existing data were also used to determine if the material passed or failed the NFPA 130 requirement if it was not listed in the database. The researchers then reviewed the data to determine if there were values missing that could be inserted based on other data or requirements. There were several materials that did not have ASTM E162 radiant panel index values, but they were noted as meeting NFPA 130 requirements. In these instances, the maximum radiant panel index value based on the material category was inserted into the dataset. The final dataset used for analysis included a total of 180 materials.

The researchers also cross-checked the data to ensure that it was internally consistent. This ensured that the total heat released per unit area (THRPUA) was consistent with the burning duration and average HRRPUA over the burning duration. These data were of particular interest since the burning duration and average HRRPUA are used to calculate the flammability parameter. Burning duration can sometimes be difficult to assess due to the occurrence of edge burning, so this cross-check ensured that the data were internally consistent. The burning duration was calculated for 10 materials based on the THRPUA and average HRRPUA:

$$t_b = Q''/\dot{Q}'' \quad (2)$$

where Q'' is the THRPUA (kJ/m^2) and $\dot{Q}''$ is the average HRRPUA (kW/m^2). [Figure 3](#) shows a plot of the measured THRPUA and the calculated THRPUA based on HRRPUA and burning duration by Eqn. (2). The data in the plot follow the perfect correlation line to within 10 percent, indicating the data are internally consistent. Lastly, the research team created the flammability parameter using the provided data; it was the only new variable created from the data. The flammability parameter was calculated using Eqn. (1).

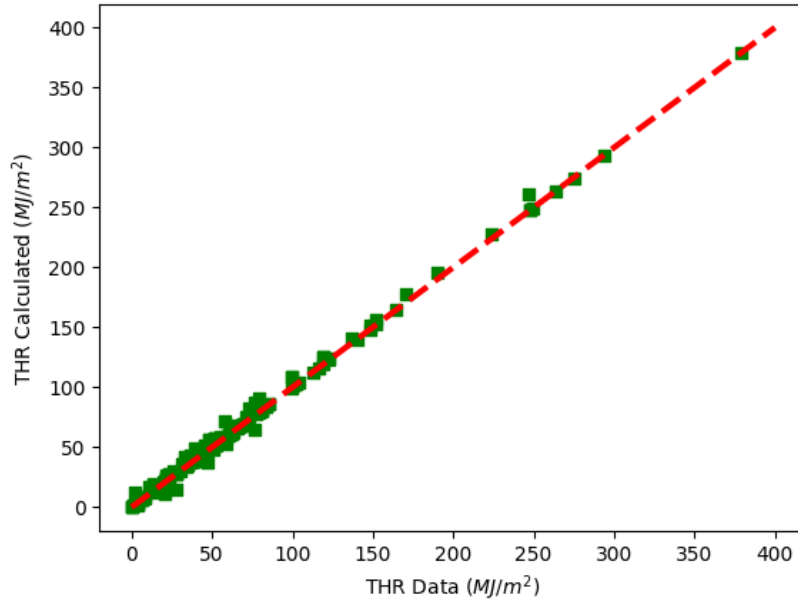


Figure 3. A plot of the measured and calculated THRPUA for materials in the dataset.

3.3 Statistical Analysis

The research team performed a statistical analysis to determine which parameters (features) were highly correlated with different target variables (e.g., radiant panel index, flammability parameter, etc.). As seen in [Appendix B](#), there are eight different features that come out of the cone calorimeter test related to flammability. However, for statistical analysis, features must be independent. For material flammability related cone calorimeter data, there are four independent features: ignition time, HRRPUA, burning duration, and char fraction. In the dataset, only ignition time, HRRPUA, and burning duration were reported. Interestingly, these are the same three parameters that are in the flammability parameter. The team conducted the analysis using both the average HRRPUA over the burning duration and average over the initial 300 s of burning. The 300 s average HRRPUA was included in the analysis since it is a standard output from ASTM E1354. In addition to these three features, the team kept the MARHE as a feature since it is used as a flammability related requirement. The two target variables included were the radiant panel index and flammability parameter.

The research team generated a pair grid plot of the data to visualize and quantify the relationship between the variables ([Figure 4](#)). Since the MARHE was considered in this plot, data without MARHE values were removed from the dataset so that more accurate statistical correlation values could be obtained. In [Figure 4](#), the diagonal provides the distribution for each variable, the upper tridiagonal of the plot contains a pair plot of each variable relative to all other variables, and the lower tridiagonal includes contour plots of each variable relative to all other variables. The Pearson Coefficient is also included for the two variables in the plot. The Pearson Coefficient (r) varies from -1 to 1 with values close to -1 or 1 meaning that the data are strongly correlated. A coefficient of $r = -1$ means a negative linear correlation (as one variable increases the other decreases) while a coefficient of $r = 1$ indicates a positive linear correlation (as one variable increases the other one also increases). In general, features should be independent of each other, so their Pearson Coefficient relative to each other should be close to $r = 0$. However,

features and targets should be strongly correlated so their Pearson Coefficient should be close to -1 or 1.

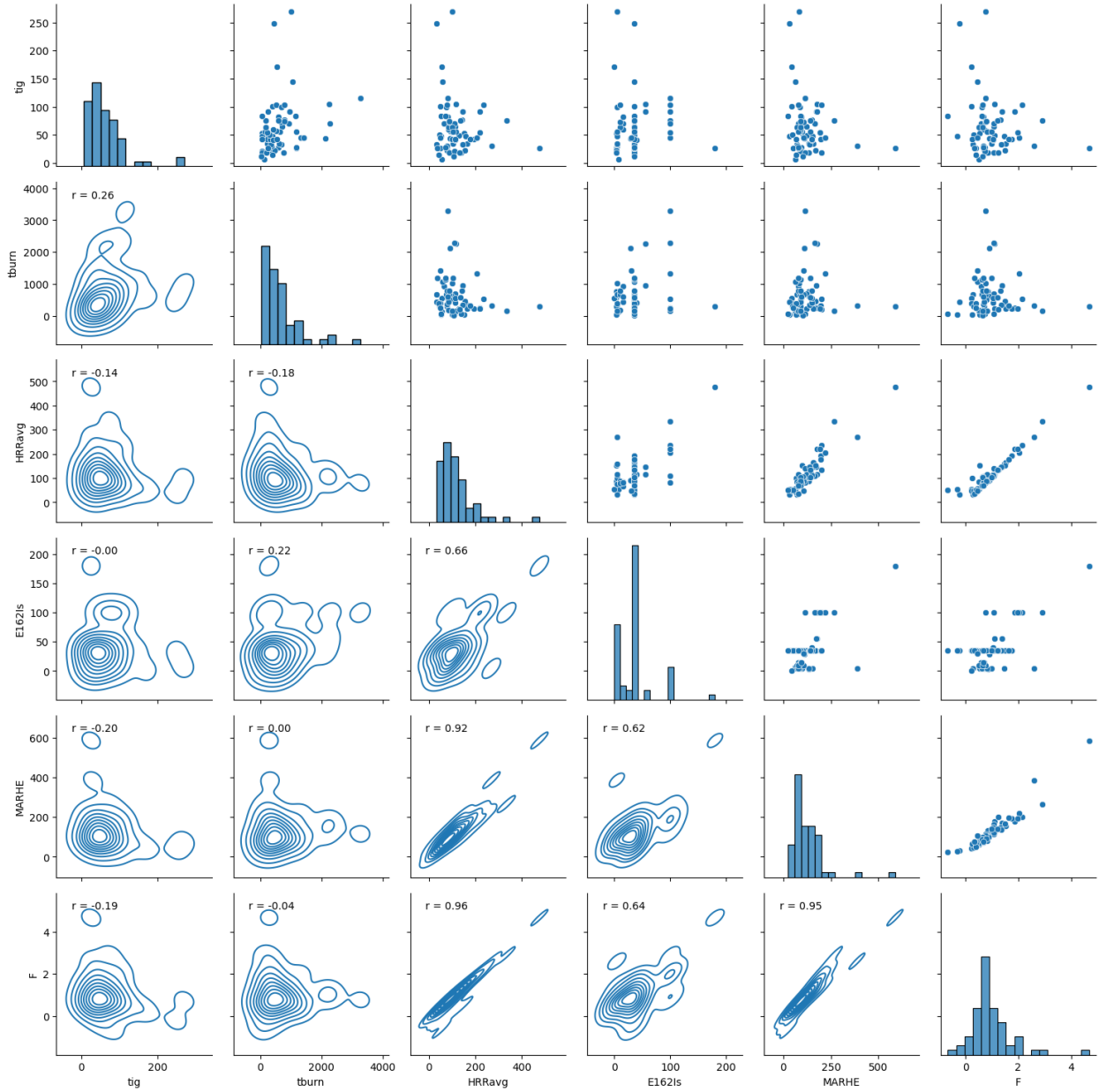


Figure 4. Pair grid plot of feature and target variables

These data indicate that the three features from the cone calorimeter (ignition time [*tig*], burning duration [*tburn*], and average HRRPUA over the burning duration [*HRRavg*]) have a Pearson Coefficient close to $r = 0$ relative to each other, indicating they are not correlated, which is expected. The MARHE and average HRRPUA have a Pearson Coefficient close to $r = 1$ relative to each other, indicating that these are highly correlated, which is expected since the MARHE is calculated based on the HRRPUA curve. The MARHE is not strongly correlated with the time to ignition even though a delayed time to ignition would affect the MARHE value. The radiant panel index (EI62Is) target variable is weakly correlated with the average HRRPUA and

MARHE. The flammability parameter (F) is strongly correlated with the average HRRPUA and MARHE but only weakly correlated with ignition time and burning duration despite being part of the equation to calculate F . This lack of correlation may be due to the fact that these variables are divided by one another resulting in some cancelation of their effect on F . The conclusion from this statistical analysis is that an average HRRPUA alone should be sufficient to predict F (i.e., whether a material may contribute significantly in causing flashover), and that average HRRPUA and MARHE are equally good indicators of predicting F .

The research team also conducted analysis to explore whether the 300 s average HRRPUA could also be used to predict F . The Pearson Coefficient between the 300 s average HRRPUA and F was found to be $r=0.65$ indicating only weak correlation. Since the average HRRPUA over the burning duration had strong correlation with F ($r=0.95$), the average HRRPUA over the burning duration was used in all future analysis.

3.4 Feature Importance

Another way to quantify how strongly a feature affects a target variable is through feature importance. In this analysis, the research team quantified feature importance using a random forest classifier, which is a tree-based machine learning technique used to predict a target class based on a given number of features. A class is an integer that represents a group of labeled data. The team created a classifier to label the data as either a material that would result in the occurrence of flashover (1) or no flashover (0). They set the classes based on the flammability parameter. An $F \geq 0.75$ is expected to cause flashover (1) while $F < 0.75$ is no flashover (0).

The researchers created a random forest classifier in Python 3 using Scikit-Learn libraries. The features included were the ignition time, burning duration, and average HRRPUA. The target classifier was whether or not flashover would occur, which was determined based on the flammability parameter as described above. The classifier was trained on 75 percent of the dataset while the other 25 percent of the dataset was reserved to test the classifier performance. The classifier had a prediction accuracy of 0.985 on the training set and 0.91 on the test set. The lower accuracy on the test set indicates the classifier is slightly overtrained, but overall the classifier performance is excellent. [Appendix C](#) details the machine learning model used in this analysis.

[Figure 5](#) shows the relative importance of the three features (an output of the tree-based classifier). As seen in this figure, the average HRRPUA is significantly more important in the prediction of the occurrence of flashover than ignition time or burning duration. This result confirms the results from the statistical analysis, which also showed that the average HRRPUA was more strongly correlated to the flammability parameter. From this, the researchers concluded that only the average HRRPUA needs to be considered when developing the HRR-based requirement.

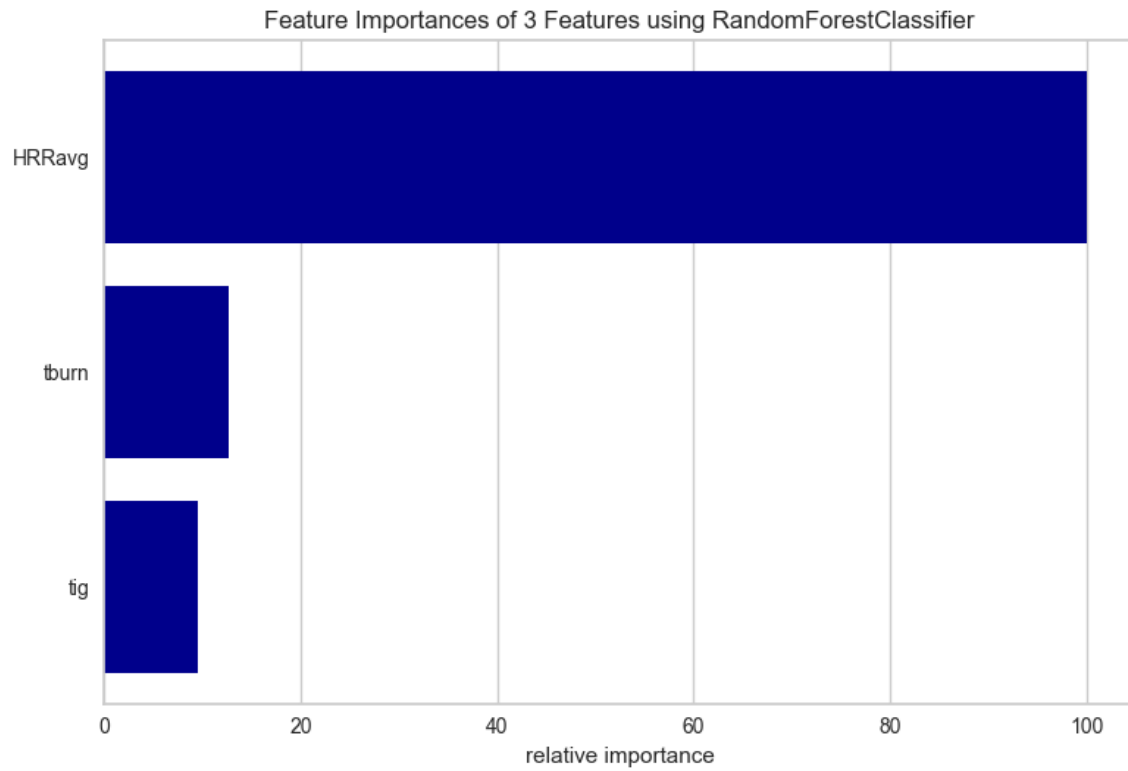


Figure 5. Relative importance of features on the prediction of flashover

4. HRR-Based Flammability Requirement

The team developed the HRR-based flammability requirement using a decision tree classifier. This type of classifier was used because the model is transparent, so the split in the dataset can be clearly seen through a plot of the trained decision tree. The split values become the requirement levels. The classifier was developed using Python 3 with Scikit-Learn libraries.

4.1 Decision Tree Classifier

The team developed a decision tree classifier to predict the occurrence of flashover due to the combustible material lining (1 is flashover and 0 is no flashover). The classifier was trained using 75 percent of the dataset with 25 percent of the dataset reserved to test the classifier. The team accomplished this by considering ignition time (tig), burning duration (tburn), and average HRRPUA (HRRavg), as well as only the average HRRPUA (HRRavg) feature. The classification used two different threshold values for the flammability parameter: $F = 0.6$ and $F = 0.75$. As previously mentioned, the 0.75 threshold would be for larger spaces for example, general seating area while a 0.6 threshold is more conservative and may be more appropriate for smaller spaces, such as sleeping compartment, restroom. [Appendix D](#) provides details on the implementation of the classifiers.

[Table 2](#) shows the results for the different classifiers. The split value listed is the average HRRPUA that best divides the dataset between flashover and no flashover. The accuracy is the fraction of predicted classifiers that agree with the actual labeled classifiers. If the classifier perfectly predicted all cases, the accuracy would be 1. [Appendix D](#) contains the trees and confusion matrices for these classifiers. As seen in [Table 2](#), there is not a significant difference in classifier accuracy when only the average HRRPUA is used versus the three features. As a result, the team adopted the HRRPUA split values for the simpler model as the requirement to determine whether a material would cause flashover.

Table 2. Results for different classifiers

F Threshold for Flashover	Features	HRRPUA Split (kW/m ²)	Accuracy	
			Train	Test
0.6	tig, tburn, HRRavg	65-68*	0.92	0.87
0.6	HRRavg	68	0.90	0.87
0.75	tig, tburn, HRRavg	85**	0.94	0.89
0.75	HRRavg	85	0.93	0.82

*Two splits for HRRavg and one split for tig

**One split for HRRavg, tig, and tburn

[Figure 6](#) illustrates the confusion matrices for the two different F threshold levels for the decision tree classifiers with only average HRRPUA as a feature. The confusion matrix provides a visualization of the classification performance. Along the diagonal are the cases that are predicted correctly. In the top right are cases where the classifier incorrectly predicts flashover (false positive), while in the bottom left are cases where the classifier incorrectly predicts no flashover (false negative). These would ideally be zero, which would indicate the classifier correctly predicts all instances.

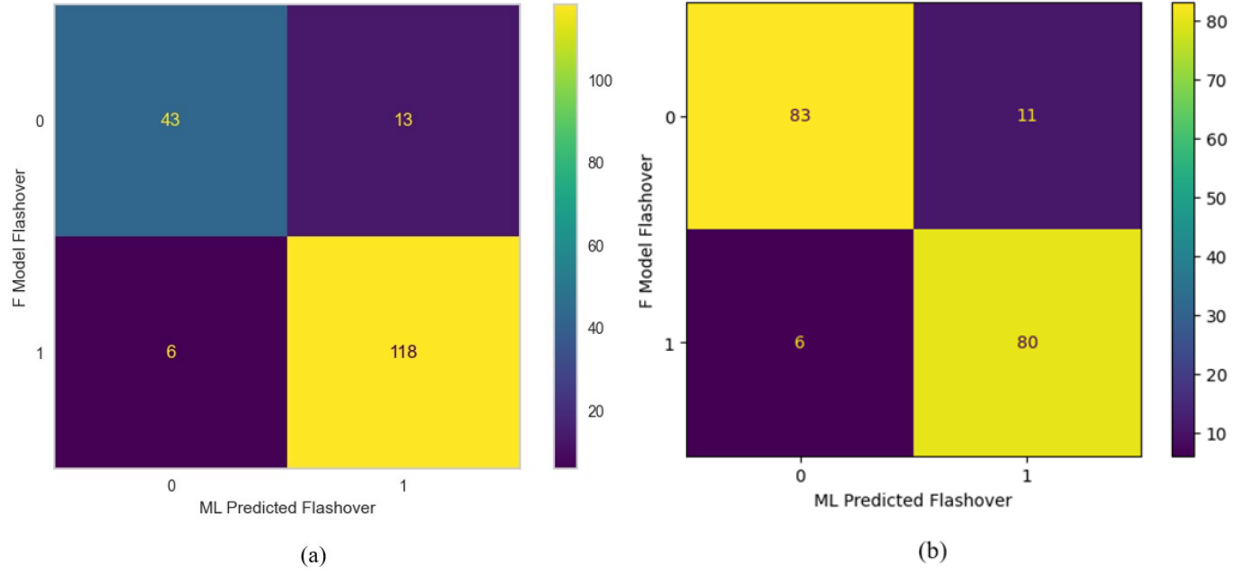


Figure 6. Confusion matrix with (a) $F=0.6$ flashover threshold and (b) $F=0.75$ flashover threshold with classifiers using only average HRRPUA as a feature

For both F thresholds, the majority of the instances are along the diagonal which is expected based on the high accuracies of the classifiers. Both classifiers tend to incorrectly predict no flashover cases, indicating the classifiers are slightly conservative (predicting more flashover cases than actually occur). As expected, the lower F threshold results in more predicted cases of flashover: 124 cases for $F=0.6$ and 86 cases for $F=0.75$. Overall, the confusion matrix confirms that the classifiers have good performance as indicated by the accuracy in Table 2. Note that for the confusion matrices in this report, a category 1 (either axis in the figure) corresponds to the flashover condition, and category 0 to the no flashover condition.

The research team generated the confusion matrices in Figure 7 using an average HRRPUA requirement, which was determined by rounding the split value from the classifiers. This resulted in an HRRPUA requirement of 70 kW/m² for the more conservative $F=0.6$ flashover threshold and 85 kW/m² for the $F=0.75$ flashover threshold shown to be a good predictor for larger spaces such as passenger seating area. The confusion matrices are quite similar to those from the actual classifiers.

From the confusion matrices above, the team concluded that these simple average HRRPUA accurately capture the classifier prediction as well as the expected occurrence of flashover based on the flammability parameter. In the same manner as for the F categories, the HRRPUA requirement yields a 1 for flashover predicted, and a 0 for no flashover predicted.

The confusion matrices in Figure 8 contain the average HRRPUA requirement predictions of materials expected to cause flashover (1) and those with no expected flashover (0) with the materials that fail (1) or pass (0) the NFPA 130 ASTM E162 radiant panel index requirements. The majority of materials not expected to cause flashover pass the NFPA 130 requirements. However, most materials expected to cause flashover also pass the requirements. This supports the statistical analysis results in Section 3, and the previous findings that the ASTM E162 radiant panel index test is insufficient to screen out materials that may cause flashover when exposed to plausible initiating fires inside a rail car [1].

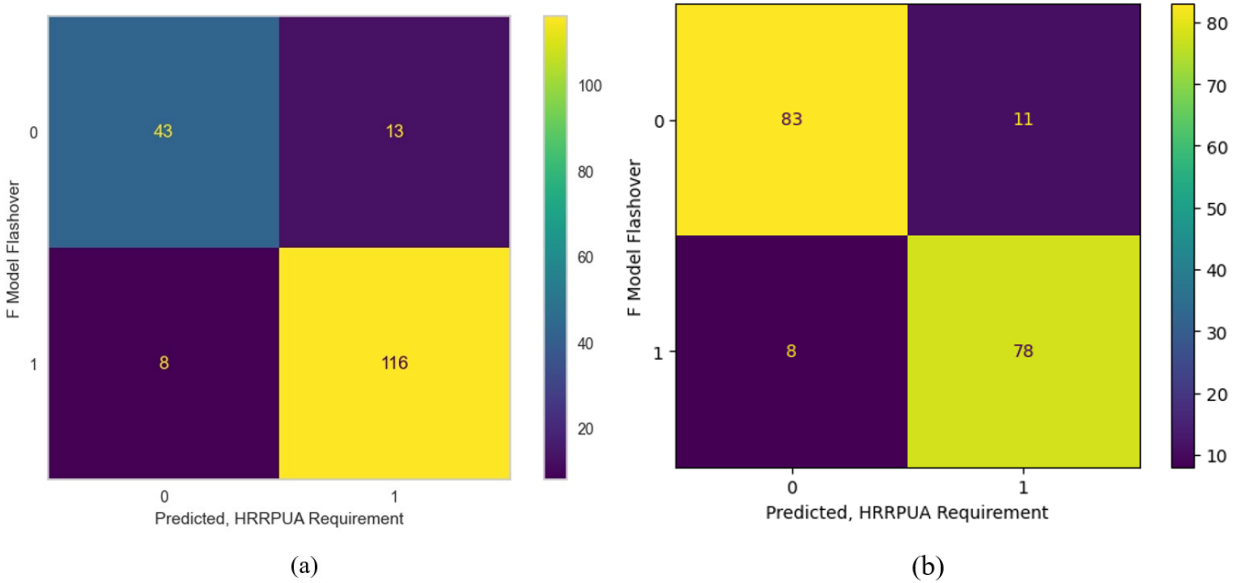


Figure 7. Confusion matrix with (a) $F=0.6$ flashover threshold and average HRRPUA requirement of 70 kW/m^2 and (b) $F=0.75$ flashover threshold and average HRRPUA requirement of 85 kW/m^2

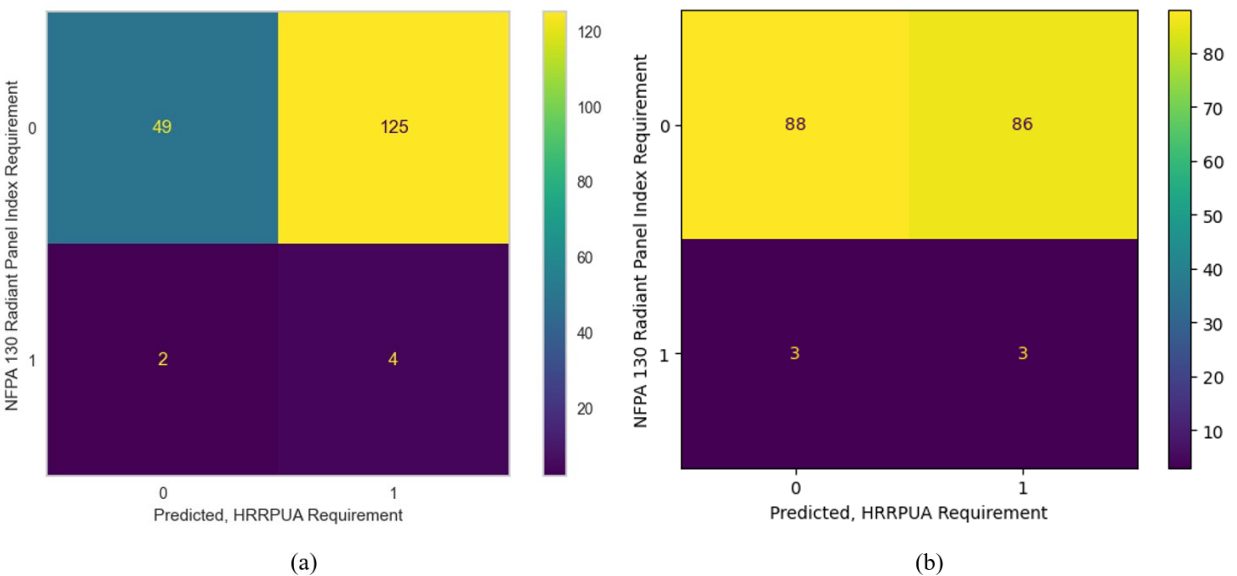


Figure 8. Confusion matrix with NFPA 130 ASTM E162 radiant panel index Pass (0) / Fail (1) compared with average HRRPUA requirement of a) 70 kW/m^2 and b) 85 kW/m^2

4.2 Comparison of Flammability Requirements

The team used the database to compare the flammability requirements from NFPA 130, EN 45545-2, and the new average HRRPUA. They also compared the potential for flashover based on the flammability parameter with these different requirements.

There were no materials in the database that had numeric values for both NFPA 130 and EN 45545-2 for all flammability tests. The database included statements that select materials passed either NFPA 130, EN 45545-2, or both, but it did not specify that any value did not pass the

other standard. Thus, there was no conclusive evidence available to compare the NFPA 130 and EN 45545-2 material performance. There were 43 materials listed as passing the EN 45545-2 test, but no result was provided for NFPA 130. In order to make this comparison, the team recommends that these materials be procured and tested per the NFPA 130 requirements so a comparison of performance can be made.

There was a significant amount of data available for ASTM E162 radiant panel index and the EN 45545-2 MARHE. Though the MARHE is only one of potentially three tests that must be performed as part of EN 45545-2 to assess flammability, the researchers conducted analyses to compare the current NFPA 130 requirement (ASTM E162) versus the EN 45545-2 MARHE requirement. In addition, they compared the new HRRPUA requirements of 70 kW/m² and 85 kW/m² were with the EN 45545-2 MARHE requirements.

Table 3 and Table 4 contain comparisons of how similarly two flammability requirements predict material performance. Table 3 contains requirements based on a $F=0.75$, while Table 4 includes requirements based on $F=0.60$. The pass/fail threshold for each requirement is given in the table. The accuracy is how similarly both requirements pass or fail a material. An accuracy of 1.0 would indicate that both requirements predicted pass/fail the same for all materials. In both tables, the average HRRPUA has the highest accuracy in predicting flashover (defined by F).

Table 3. Comparison of accuracy for different requirements to predict pass/fail for a material

Requirement 1	Requirement 2	Accuracy
Flashover, $F<0.75$	HRRPUA<85	0.89
Flashover, $F<0.75$	NFPA 130 Radiant Panel Index*	0.51
Flashover, $F<0.75$	MARHE<90	0.86
Flashover, $F<0.75$	MARHE<60	0.66
HRRPUA<85	NFPA 130 Radiant Panel Index*	0.51
HRRPUA<85	MARHE<90	0.81
HRRPUA<85	MARHE<60	0.73
MARHE<90	NFPA 130 Radiant Panel Index*	0.38
MARHE<60	NFPA 130 Radiant Panel Index*	0.17

*Varies based on material category.

Room flashover and HRRPUA requirements are based on an $F=0.75$ threshold. Requirements given are for passing (0).

Table 4. Comparison of accuracy for different requirements to predict pass/fail for a material

Requirement 1	Requirement 2	Accuracy
Flashover, $F<0.60$	HRRPUA<70	0.88
Flashover, $F<0.60$	NFPA 130 Radiant Panel Index*	0.31
Flashover, $F<0.60$	MARHE<90	0.80
Flashover, $F<0.60$	MARHE<60	0.84
HRRPUA<70	NFPA 130 Radiant Panel Index*	0.29
HRRPUA<70	MARHE<90	0.78
HRRPUA<70	MARHE<60	0.89

*Varies based on material category.

Room flashover and HRRPUA requirements are based on an $F=0.60$ threshold. Requirements given are for passing (0).

The MARHE accurately predicted flashover; however, it was not as accurate as the average HRRPUA in predicting flashover. The MARHE and average HRRPUA have similar predictions of material performance. In all cases, the NFPA 130 radiant panel index from an ASTM E162 test did not have good accuracy relative to any other requirements. This includes the ability of

the ASTM E162 test to determine whether a material would be expected to cause flashover. This further supports previous findings that NFPA 130 flammability compliant materials may have the potential to cause flashover in a railcar end-use condition.

Figure 9 shows a more detailed look at the pass/fail prediction of NFPA 130 and EN 45545-2 for different materials (pass is 0 and fail is 1). As expected from the poor accuracies shown in Table 3, the off-diagonal numbers are high. This indicates there are numerous materials for which the two requirements did not predict the same pass/fail condition. Nearly all materials pass the NFPA 130 requirement; however, 60–90 percent of materials fail using the EN 45545-2 standard. This indicates the EN 45545-2 requirements are generally stricter compared with the NFPA 130 flammability requirements.

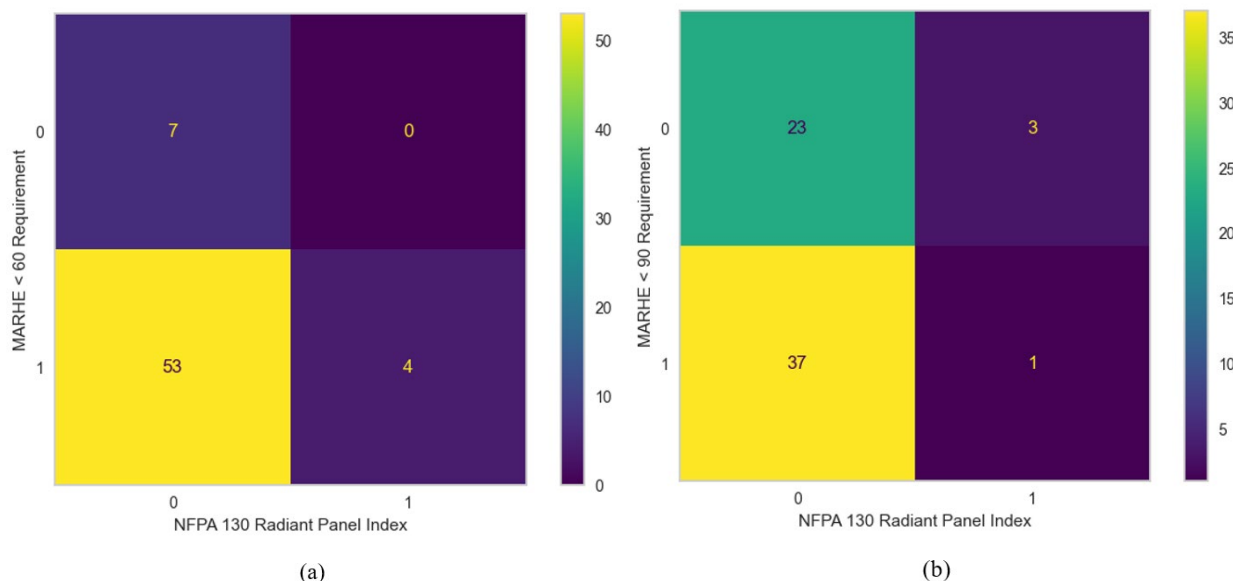


Figure 9. Confusion matrices comparing pass (0) / fail (1) using NFPA 130 Radiant Panel Index with the EN 45545-2 MARHE requirement for a) MARHE < 60 (pass 0) and b) MARHE < 90 (pass 0)

5. Conclusion

This research effort developed a database of flammability and smoke data for materials used on the interior of rail cars. Using this data, the research team developed an HRR-based requirement to screen out materials that would cause a plausible initiating fire inside a rail car by growing to flashover. They also compared the NFPA 130 and EN 45545-2 flammability data to determine if the requirements in one standard were more challenging to meet.

Flashover in a room can be related to the flammability parameter, which includes three independent outputs from the cone calorimeter: ignition time, burnout time, and average HRRPUA over the burning duration. Statistical analysis and machine learning models demonstrated that the average HRRPUA was the most important parameter to consider for predicting the occurrence of flashover. Material ignition time and burning duration were of secondary importance; therefore, they were not needed as part of a flammability requirement.

The team determined the HRR requirements from the split value of a machine learning decision tree classifier based on average HRRPUA from a cone calorimeter test at an exposure heat flux of 50 kW/m^2 . To prevent flashover in larger spaces (e.g., railcar passenger seating area), the material average HRRPUA would need to be less than 85 kW/m^2 . For smaller spaces (e.g., toilet area), a material average HRRPUA would need to be less than 70 kW/m^2 . Materials that do not meet these requirements could be tested in a NFPA 286 room-corner test to demonstrate they do not cause flashover.

Based on analysis of the available data, the researchers could not conclude whether the flammability requirements in NFPA 130 or EN 45545-2 were more challenging. The only data that could be broadly compared were cases meeting the NFPA 130 radiant panel index (ASTM E162) requirement versus the EN 45545-2 MARHE requirement based on cone calorimeter data. The team determined that the EN 45545-2 MARHE requirements were more challenging than the NFPA 130 radiant panel index requirements. Both the MARHE and average HRRPUA requirements are good predictors of the occurrence of flashover; however, the average HRRPUA provided slightly higher accuracy in the prediction of flashover.

This work could be further enhanced through additional testing and analysis. Smoke data for the cone calorimeter and ASTM E662 are available in the database. The ASTM E662 test method is limited in the exposure level and configuration that can be tested. Cone calorimeter testing can be conducted in the vertical or horizontal configurations as well as various heat flux exposure levels. In addition, the smoke data from the cone calorimeter can be used to predict smoke levels at the end-use condition. The research team recommends a study to explore the use of the cone calorimeter smoke data as a requirement instead of the ASTM E662 requirement.

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Appendix A.

Cross-correlation Between NFPA 130 and EN 45545-2

The tables in this appendix provide additional information on the cross-correlation between NFPA 130 and EN 45545-2. [Table 5](#) provides the material flammability and smoke requirements for the requirement levels in EN 45545-2 relevant to the materials considered in this study. Note that EN 45545-2 also has a material smoke toxicity requirement, which is not shown in this table since the most recent version NFPA 130 does not have a material smoke toxicity requirement. As seen in this table, the material requirements vary based on the Hazard Level for the rail car. [Table 6](#) includes the Hazard Level (HL) classification definitions from EN 45545-1 [26], which is dependent on the Operational Category descriptions (also given in [Table 6](#)) as well as the type of rail car. In general, HL1 has the least restrictive requirements while HL3 has the most restrictive. [Table 7](#) provides an expanded list of materials (by function) and their requirements in NFPA 130 and EN 45545-2.

Table 5. EN 45545-2 requirements for materials considered in this study

EN 45545-2 REQUIREMENT	EN 45545-2:2020 TESTS AND PASS CRITERIA															
	LIFT			Horizontal Spread			Verical FS	Cone Calorimeter			Smoke Chamber - Horizontal					
	ISO 5658-2			ISO 9239-1			ISO 11925-2	ISO 5660-1 @ 50kW/m ²			ISO 5659-2					
	CFE ^c >=			CHF>=			FS (60s) <=	MARHE<=			Ds ^d <=			VOF(4min) ^e <=		
	(kW/m ²)			(kW/m ²)			(mm)	(kW/m ²)			(- -)			(min)		
	HL1	HL2	HL3	HL1	HL2	HL3	All HL	HL1	HL2	HL3	HL1	HL2	HL3	HL1	HL2	HL3
R1	20	20	20	--	--	--	*	--	90	60	600	300	150	1200	600	300
R2	13	13	13	--	--	--	*	--	--	90	600	300	150	1200	600	300
R4	13	13	13	--	--	--	150	--	--	--	--	--	--	--	--	--
R6	--	--	--	--	--	--	--	90	90	60	600	300	150	1200	600	300
R7	20	20	20	--	--	--	*	--	90	60	--	600	300	--	--	--
R10	--	--	--	4.5	6	8	--	--	--	--	600	300	150	--	--	--

^c For R1, R2, R7 if flaming droplets/particles in ISO 5658-2 or did not ignite in ISO 5658-2, test in ISO 11925-2 with 30 s application (flame spread < 150mm after 60s, no burning droplets/particles); R10 test in ISO 11925-2 with 30 s application (flame spread < 150mm after 60s, no burning droplets/particles)

^d R1, R2, R6 tests conducted at 50 kW/m² without pilot flame and smoke specific optical density at 4 min into test (Ds(4)); R7 tests conducted at 50 kW/m² with pilot flame and max smoke specific optical density over 10 min. test duration (Ds,max); R10 tests conducted at 25 kW/m² with pilot flame and max smoke specific

^e R1, R2, R6 tests conducted at 50 kW/m² without pilot flame

CFE : critical flux at extinguishment (lateral spread)

CHF: critical heat flux at extinguishment (horizontal spread)

FS (60s) : maximum flame spread after 60 seconds, no flaming droplets/particles

MARHE : maximum average rate of heat emission

Ds : smoke specific optical density in test chamber

VOF(4min) : cumulative value of smoke specific optical density in the first 4 minutes of test

HL1: Hazard Level 1 from EN 45545-2

HL2: Hazard Level 2 from EN 45545-2

HL3: Hazard Level 3 from EN 45545-2

Table 6. Hazard Level and Operational Category for trains from EN 45525-1 [26]

Operational Category	Hazard Level (HL) Classification, EN 45545-2			
	Design Category			
	N All Other (Standard)	A Automatic*	D Double Deck	S Sleeping / Couchette
1	HL1	HL1	HL1	HL2
2	HL2	HL2	HL2	HL2
3	HL2	HL2	HL2	HL3
4	HL3	HL3	HL3	HL3

*Vehicles forming part of an automatic train having no emergency trained staff on board

Operational Category Descriptions, EN 45545-1					
Operational Category	Running Time	Minimum Average Speed*	Operation Area	Safe Area Location	Time to Reach Safe Area
1	May stop with minimum delay	Not Applicable	Infrastructure where vehicle may be stopped with minimum delay	Can always be reached	Immediately
2	4 min.	80 km/h	Underground sections, tunnels and/or elevated structures; side evacuation available	Stations or rescue stations that offer a place of passenger safety	Short running distance
3	15 min.	80 km/h	Underground sections, tunnels and/or elevated structures; side evacuation available	Stations or rescue stations that offer a place of passenger safety	Long running distance
4	4 min.	No requirement	Underground sections, tunnels and/or elevated structures; without side evacuation	Stations or rescue stations that offer a place of passenger safety	Short running distance

Note: Vehicles may be allocated to more than one Operational Category, which would then require them to meet requirements for all categories they are in.

*Per Directive 2008/57/EC, vehicles operating in SRT TSI Category A are covered by Operational Category 2 and SRT TSI Category B are covered by Operational Category 3, subject to minimum average speed requirement being met.

Table 7. Detailed list of materials by function and their NFPA 130 and EN 45545-2 requirements

	NFPA 130, Ed. 2023			EN45545-2:2020		
	Flammability	Smoke				
Material	ASTM E162	ASTM E662				
Function	I _s <=	Ds(1.5)<=	Ds(4.0)<=	Name	Product No.	Requirement
mattress frame	35	100	200	Underside surface of couch	F5	R1
wall lining	35	100	200	Interior vertical surfaces	IN1A	R1
wall panel	35	100	200	Interior vertical surfaces	IN1A	R1
ceiling lining	35	100	200	Interior horizontal downwards	IN1B	R1
ceiling panel	35	100	200	Interior horizontal downwards	IN1B	R1
trays	35	100	200	Tables, folding tables downwards	IN9B	R1
tables	35	100	200	Tables, folding tables downwards	IN9B	R1
partitions	35	100	200	Interior vertical surfaces	IN1A	R1
shelves	35	100	200	Luggage storage areas	IN4	R1
shelves	35	100	200	Interior horizontal downwards	IN1B	R1
opaque windscreen	35	100	200	Interior vertical surfaces	IN1A	R1
combustible signage	35	100	200	Devices for passenger information	IN14	R1
articulation bellows	35	100	200	Interior surfaces of gangways	IN6A	R1
component boxes	35	100	200	Interior vertical surfaces	IN1A	R1
component boxes	35	100	200	Interior horizontal downwards	IN1B	R1
component covers	35	100	200	Interior vertical surfaces	IN1A	R1
component covers	35	100	200	Interior horizontal downwards	IN1B	R1
thermal insulation	25		100	Interior horizontal upwards	IN1C	R1
acoustic insulation	25		100	Interior horizontal upwards	IN1C	R1
HVAC ducting	25		100	Air duct-interior surfaces	IN12A	R1
HVAC ducting	25		100	Air duct-exterior surfaces	IN12B	R1
windows	100	100	200	Interior vertical surfaces	IN1A	R1
transparent windscreens	100	100	200	Interior vertical surfaces	IN1A	R1
shelves	35	100	200	Interior horizontal upwards	IN1C	R10
component boxes	35	100	200	Interior horizontal upwards	IN1C	R10
component covers	35	100	200	Interior horizontal upwards	IN1C	R10
toilet shroud	35	100	200	Tables, folding table tops, and	IN9A	R2
toilet seat	35	100	200	Tables, folding table tops, and	IN9A	R2
tables	35	100	200	Tables, folding table tops, and	IN9A	R2
light diffusers	100	100	200	Light diffusers	IN3B	R4
seat frame	35	100	200	Passenger seat shell-base	F1C	R6
seat shroud	35	100	200	Passenger seat shell-back	F1D	R6
articulation bellows	35	100	200	Interior surfaces of gangways	IN6B	R7

Appendix B.

Database Structure

The database is organized into three different views: Summary Data, NFPA 130 & EN 45545-2, and Cone Calorimeter Data. The column headings and their meanings are provided in [Table 8–Table 10](#).

Table 8. Columns in all views and the Summary Data view

Column Name	Description	View
ID #	Identification number for material	All
Detailed Description	Detailed material description	All
Type	Type of material construction	All
NFPA 130 Category	Category of material based on NFPA 130	Summary
EN 45545-2 Requirement	Material EN 45545-2 requirement label	Summary
NFPA 130 (Pass/Fail)	Whether material passes or fails NFPA 130 smoke and flammability requirement	Summary
EN 45545-2 (Pass/Fail)	Whether material passes or fails EN 45545-2 fire performance requirements	Summary
Pass Both (Yes/No)	Whether a material passes both NFPA 130 and EN 45545-2 fire performance requirements	Summary
Testing at Certified Lab	Whether material testing performed at a certified lab	Summary

Table 9. Columns specific to the NFPA 130 & EN 45545-2 view

Column Name	Description
NFPA 130 – ASTM E162 Is (- -)	Radiant panel index from ASTM E162 flame spread tests
NFPA 130 – ASTM E662 Ds (1.5) (- -)	Maximum specific optical density during initial 1.5 minutes of test (value is the highest from testing in flaming and non-flaming modes)
NFPA 130 – ASTM E662 Ds (4.0) (- -)	Maximum specific optical density during initial 4.0 minutes of test (value is the highest from testing in flaming and non-flaming modes)
EN 45545-2 – ISO 5660-1 MARHE (kW/m ²)	Maximum average rate of heat emission

Table 10. Columns specific to the Cone Calorimeter Data view.

Column Name	Description
ASTM E1354 or ISO 5660-1	Cone calorimeter standard followed to produce data
Thickness (mm)	Material thickness tested
Flux (kW/m ²)	Exposure heat flux used in cone calorimeter test
t _{ig} (s)	Time to ignition from start of exposure
t _{burn} (s)	Burning duration of material
THR (MJ/m ²)	Total heat released per unit area
HOC (MJ/kg)	Effective heat of combustion
HRR _{pk} (kW/m ²)	Peak heat release rate per unit area
t _{HRRpk} (s)	Time of peak heat release rate per unit area
HRR _{300s} (kW/m ²)	Average heat release rate per unit area over the initial 300 s of burning
HRR _{avg} (kW/m ²)	Average heat release rate per unit area over the burning duration
SEA (m ² /kg) or SPR (m ² /m ²)	Average smoke specific extinction area or smoke production rate over the burning duration
HRR curve	Whether there is a heat release rate per unit area curve, if there is an image of the curve is given

Appendix C.

Random Forest Classifier for Predicting Flashover

Below is the random forest classifier used to predict the occurrence of flashover due to the presence of a combustible material lining.

```
from sklearn.model_selection import train_test_split

features = df_Fclass[['tig', 'tburn', 'HRRavg']].copy()
targets = df_Fclass['F']

x_train, x_test, y_train, y_test = train_test_split(features,
                                                    targets,
                                                    stratify=targets,
                                                    random_state=42)

from sklearn.ensemble import RandomForestClassifier

rfc = RandomForestClassifier(n_estimators= 100, max_depth=5, n_jobs=-1, random_state=42)
rfc.fit(x_train, y_train)
print(rfc.score(x_train, y_train))
print(rfc.score(x_test, y_test))

0.9851851851851852
0.9111111111111111
```

Figure 10. Random forest classifier used to predict the occurrence of flashover due to the presence of a combustible material lining

Appendix D.

Decision Tree Classifier to Determine Heat Release Rate Requirement

D.1 Classifiers with $F=0.60$

Using a classification of $F=0.60$, below is the decision tree classifier using all three features along with a plot of the tree created based on the trained classifier.

```
from sklearn.model_selection import train_test_split

treefeat = df_Fdt[['tig', 'tburn', 'HRRavg']].copy()
treetar = df_Fdt['F']

xtr_train, xtr_test, ytr_train, ytr_test = train_test_split(treefeat,
                                                            treetar,
                                                            stratify=treetar,
                                                            random_state=42)
```

```
from sklearn.tree import DecisionTreeClassifier

small_dt = DecisionTreeClassifier(max_depth=2, max_features=None)
small_dt.fit(xtr_train, ytr_train)
print(f'Train accuracy: {small_dt.score(xtr_train, ytr_train)}')
print(f'Test accuracy: {small_dt.score(xtr_test, ytr_test)}')
```

Train accuracy: 0.9185185185185185
Test accuracy: 0.8666666666666667

Figure 11. Decision tree classifier using all three features using a classification of $F=0.60$

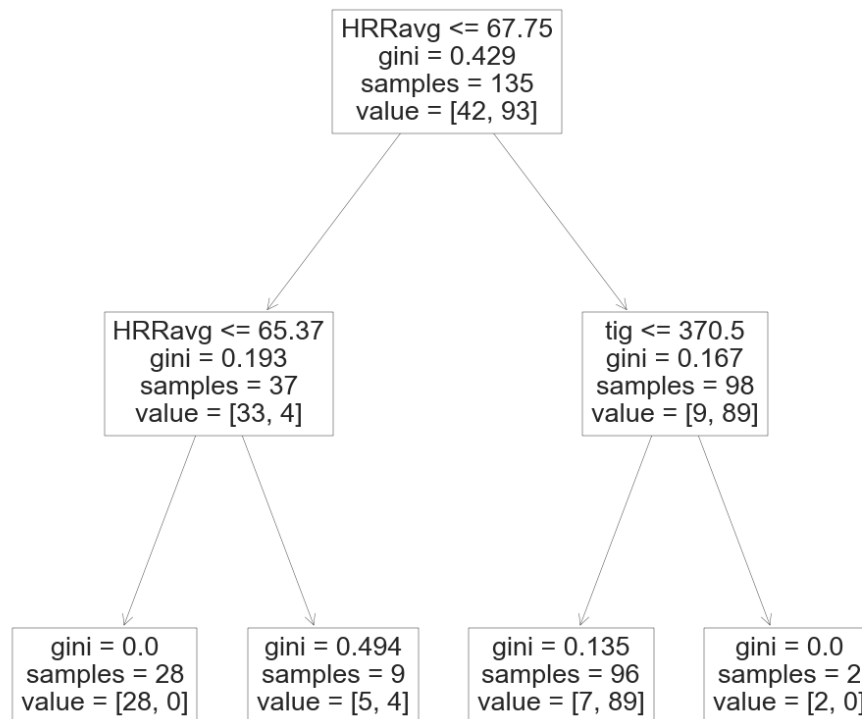


Figure 12. Decision tree using all three features using a classification of $F=0.60$

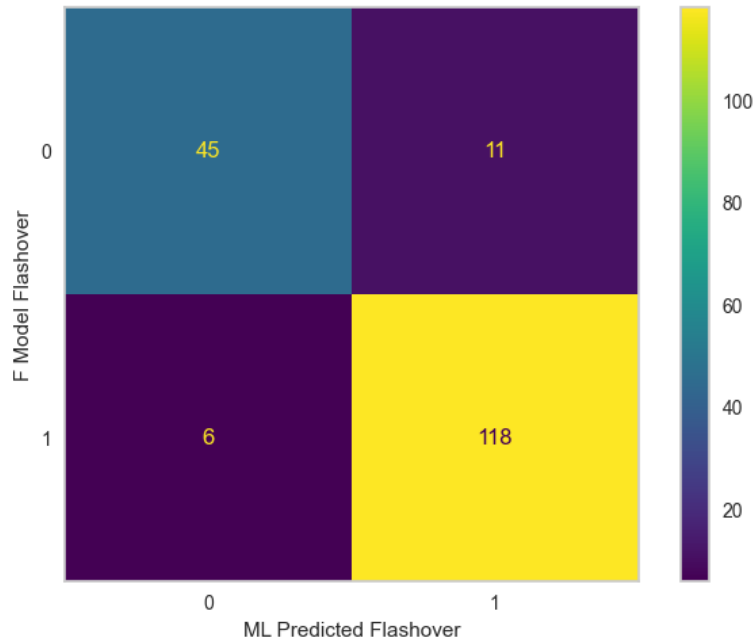


Figure 13. Plot of the tree created based on the trained classifier using all three features and a classification of $F=0.60$

Using a classification of $F=0.60$, below is the decision tree classifier to predict the occurrence of flashover with only the average HRRPUA over the burning duration feature. The tree created from the trained classifier is also shown.

```
from sklearn.model_selection import train_test_split

treefeat1 = df_Fdt[['HRRavg']].copy()
treetar1 = df_Fdt['F']

xtr_train, xtr_test, ytr_train, ytr_test = train_test_split(treefeat1,
                                                             treetar1,
                                                             stratify=treetar1,
                                                             random_state=42)

from sklearn.tree import DecisionTreeClassifier

small_dt1 = DecisionTreeClassifier(max_depth=1, max_features=None)
small_dt1.fit(xtr_train, ytr_train)
print(f'Train accuracy: {small_dt1.score(xtr_train, ytr_train)}')
print(f'Test accuracy: {small_dt1.score(xtr_test, ytr_test)}')
print(f'Overall accuracy: {small_dt1.score(treefeat1, treetar1)}')

Train accuracy: 0.9037037037037037
Test accuracy: 0.8666666666666667
Overall accuracy: 0.8944444444444445
```

Figure 14. Decision tree classifier to predict the occurrence of flashover with only the average HRRPUA over the burning duration feature, using a classification of $F=0.60$

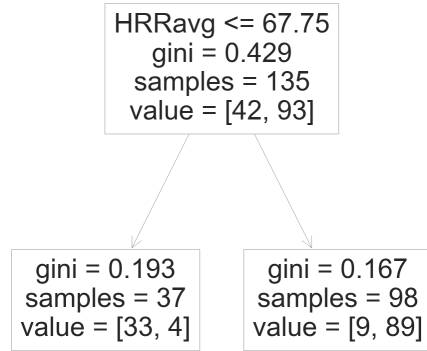


Figure 15. Decision tree predicting the occurrence of flashover with only the average HRRPUA over the burning duration feature, using a classification of $F=0.60$

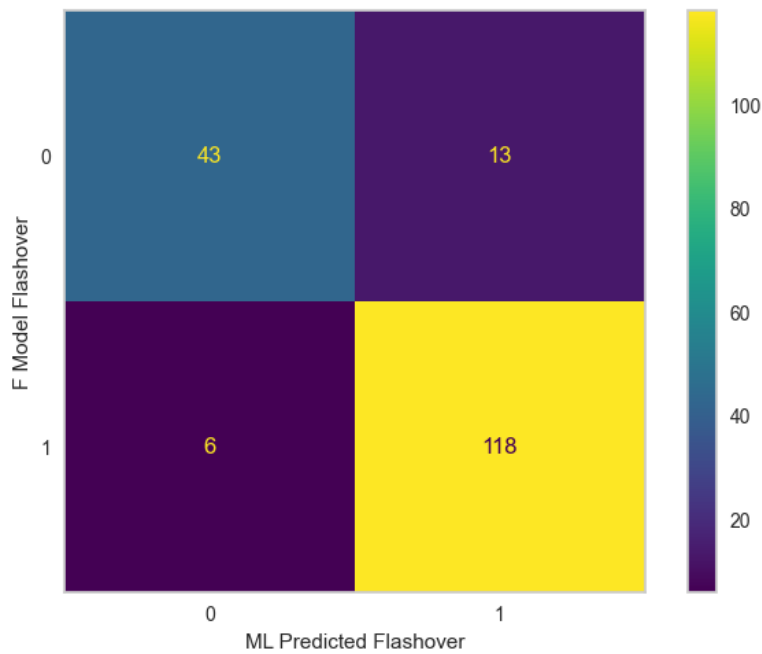


Figure 16. Plot of the tree created based on the trained classifier predicting the occurrence of flashover with only the average HRRPUA over the burning duration feature, using a classification of $F=0.60$

D.2 Classifiers with $F=0.75$

Using a classification of $F=0.75$, below is the decision tree classifier using all three features along with a plot of the tree created based on the trained classifier.

```

from sklearn.model_selection import train_test_split

treefeat = df_Fdt[['tig', 'tburn', 'HRRavg']].copy()
treetar = df_Fdt['F']

xtr_train, xtr_test, ytr_train, ytr_test = train_test_split(treefeat,
                                                            treetar,
                                                            stratify=treetar,
                                                            random_state=42)

from sklearn.tree import DecisionTreeClassifier

small_dt = DecisionTreeClassifier(max_depth=2, max_features=None)
small_dt.fit(xtr_train, ytr_train)
print(f'Train accuracy: {small_dt.score(xtr_train, ytr_train)}')
print(f'Test accuracy: {small_dt.score(xtr_test, ytr_test)}')

Train accuracy: 0.9407407407407408
Test accuracy: 0.8888888888888888

```

Figure 17. Decision tree classifier using all three features with a classification of $F=0.75$

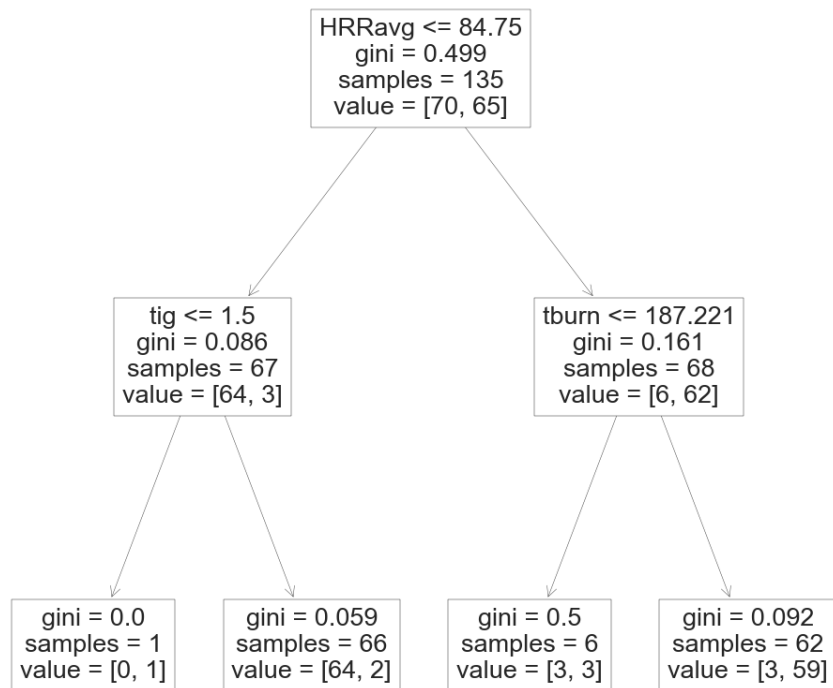


Figure 18. Decision tree using all three features with a classification of $F=0.75$

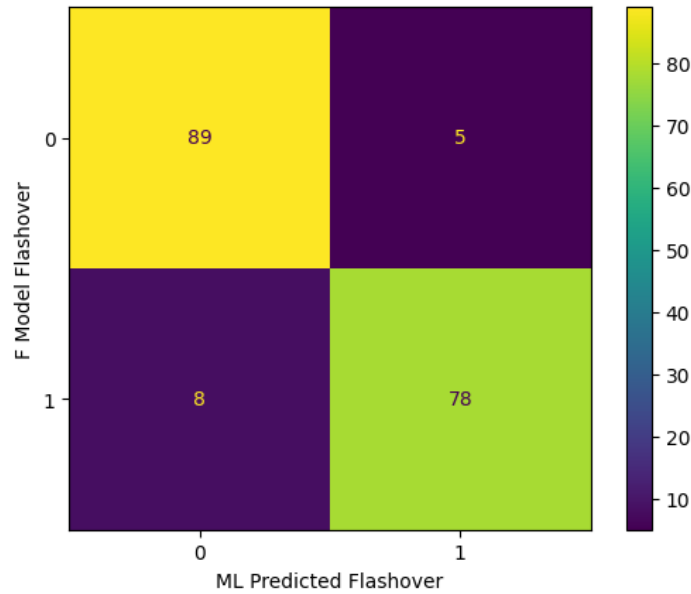


Figure 19. Plot of the tree created based on the trained classifier using all three features with a classification of $F=0.75$

Using a classification of $F=0.75$, below is the decision tree classifier to predict the occurrence of flashover with only the average HRRPUA over the burning duration feature. The tree created from the trained classifier is also shown.

```
from sklearn.model_selection import train_test_split

treefeat1 = df_Fdt[['HRRavg']].copy()
treetar1 = df_Fdt['F']

xtr_train, xtr_test, ytr_train, ytr_test = train_test_split(treefeat1,
                                                            treetar1,
                                                            stratify=treetar1,
                                                            random_state=42)

from sklearn.tree import DecisionTreeClassifier

small_dt1 = DecisionTreeClassifier(max_depth=1, max_features=None)
small_dt1.fit(xtr_train, ytr_train)
print(f'Train accuracy: {small_dt1.score(xtr_train, ytr_train)}')
print(f'Test accuracy: {small_dt1.score(xtr_test, ytr_test)}')
print(f'Overall accuracy: {small_dt1.score(treefeat1, treetar1)}')
```

Train accuracy: 0.9333333333333333
 Test accuracy: 0.8222222222222222
 Overall accuracy: 0.9055555555555556

Figure 20. Decision tree classifier to predict the occurrence of flashover with only the average HRRPUA over the burning duration feature, using a classification of $F=0.75$

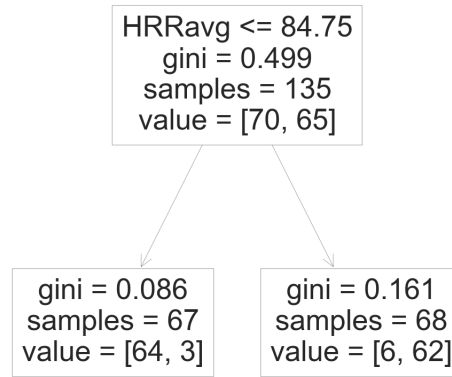


Figure 21. Decision tree predicting the occurrence of flashover with only the average HRRPUA over the burning duration feature, using a classification of $F=0.75$

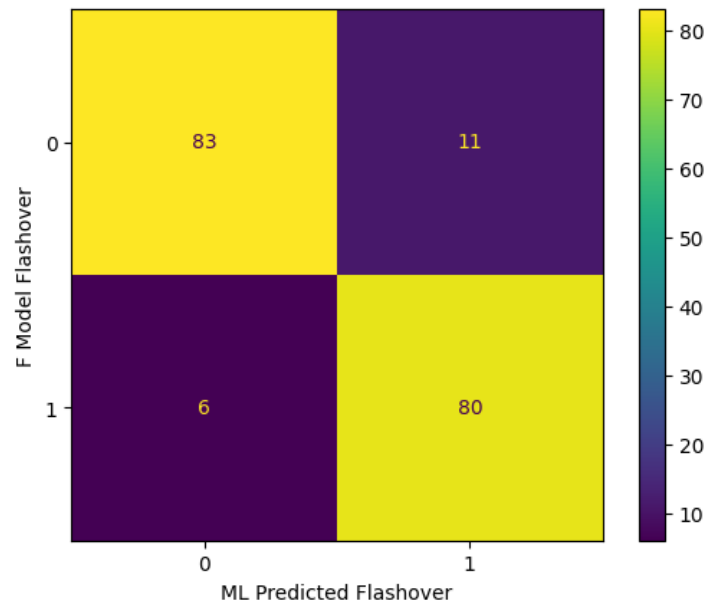


Figure 22. Plot of the tree created based on the trained classifier with only the average HRRPUA over the burning duration feature, using a classification of $F=0.75$

Abbreviations and Acronyms

ACRONYM	DEFINITION
APTA	American Public Transportation Association
ASTM	American Society of Testing and Materials
CFR	Code of Federal Regulation
E162Is	Radiant Panel Index from ASTM E162
EN	European Norm
F	Flammability Parameter
FRA	Federal Railroad Administration
ISO	International Standards Organization
HRR	Heat Release Rate
HRRavg	Heat Release Rate Per Unit Area averaged over burning duration
HRRPUA	Heat Release Rate Per Unit Area
MARHE	Maximum Average Rate of Heat Emission
ML	Machine Learning
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
t _{burn}	Burning Duration
THRPUA	Total Heat Released Per Unit Area
t _{ig}	Ignition Time