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Prediction of ISO 9705 Room/Corner Test Results

Volume I

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16. Abstract

The full-scale International Standards Organization (ISO) 9705 Room/Corner Test is currently used to regulate compartment-lining materials in the High Speed Craft (HSC) Code. This test method involves the use of large amounts of material so that the test method is an impediment in developing new materials. Bench-scale tests like the Cone Calorimeter and the Lateral Ignition Flame Test (LIFT) Apparatus may provide indications of full-scale performance in the ISO 9705. The objective of this work is to assess if correlations and mathematical models based on bench-scale data can predict material performance in the ISO 9705 Test.

The results of this project show that it is possible to learn a great deal about the expected performance of materials in the ISO 9705 Test from bench-scale tests like the Cone Calorimeter and the LIFT Apparatus. Both the simple correlations using the Flammability Parameter deduced from the Cone Calorimeter and the mathematical models using Cone Calorimeter and LIFT data provided clear insights into the burning behavior of materials in the ISO 9705 Test.

The Flammability Parameter deduced from Cone Calorimeter data was able to correlate the heat release rate and time to flashover in the ISO 9705 Test. This provides the opportunity to obtain significant information concerning expected ISO 9705 performance from a few tests of small samples. It is significant that LIFT results are not required to allow correlation of the performance of U.S. Coast Guard (USCG) HSC Materials.

The mathematical models performed well in predicting the heat release rate and time to flashover in the ISO 9705 Test. These more sophisticated methods provide additional confidence in the ability of bench-scale tests to be used to predict the performance of materials in the ISO 9705 Test. Further, these models have the potential to allow prediction of realistic scenarios, which differ from the ISO 9705 Test method.

Neither correlations from the Cone Calorimeter nor the mathematical models adequately predict the smoke generation rates in the ISO 9705 Test. The inability to predict smoke generation is particularly significant for materials that pass the heat release rate criteria in ISO 9705. Significant additional work is needed in this area.

Volume I of this report contains the objectives, approach, test results, and conclusions. Volume II consists of three appendices; a) prediction based on Quintiere's model; b) evaluation of Worcester Polytechnic Institute (WPI) zone model, and c) Hughes Associates/U.S. Navy Corner Flame Spread model and comparison with USCG ISO 9705 Test results.

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EXECUTIVE SUMMARY

The U.S. Coast Guard has responsibility for ensuring adequate safety for passengers and crew onboard commercial vessels. They accomplish this by establishing and enforcing construction and operating regulations both domestically and internationally. The International Code of Safety for High-Speed Craft (HSC Code) is a regulation that addresses safety concerns onboard high-speed craft and was prepared to allow new types of ship construction for fast sea transportation, while maintaining a high degree of safety for passengers and crew.

In accordance with the HSC Code, only materials that pass the International Standard Organization (ISO) 9705 Room/Corner Test may be used as compartment linings. This test generally consists of lining the ceiling and walls of a standard size room, exposing the corner of the room to a fire and evaluating how much heat and smoke are produced over a defined time period. Large quantities of the test material are required, so manufacturers of these materials are reluctant to pursue development of new and improved products. If a test method that did not require such large quantities of material could be used for regulation, manufacturers would potentially be more inclined to develop improved products. Additionally, a simpler (i.e., small-scale) test method would make regulation by the U.S. Coast Guard easier to accomplish.

Reliable and accurate prediction of full-scale performance from small-scale testing is a concern in the area of fire safety. The work documented in this report was conducted to see just how well the ISO 9705 Test results could be predicted from results obtained from small-scale test methods. This was a first step toward the goal of using a small-scale test method as a regulatory tool. Three separate fire research organizations used the Cone Calorimeter and LIFT Apparatus as two small-scale tests to evaluate the degree of predictability of large-scale test results for several materials.

Simple correlations including Flammability Parameters (FP) were deduced from a combination of Cone Calorimeter results and mathematical model results, which used Cone and LIFT data. The correlations provided valuable insight into which materials would easily pass or definitely fail the flammability criteria in the ISO 9705 Test. However, there is a range of FP values that do not provide adequate indications of how the materials would perform in the full-scale test. Additionally, there is a smoke production criteria in the ISO 9705 Test which neither the correlations, nor the mathematical models, adequately predicted. Significant additional research is needed in this area to adequately predict large-scale smoke production results from small-scale tests.

As discussed above, additional research is required to reach the goal of relying on small-scale test results for regulatory purposes. However, the research completed in this study clearly indicate that manufacturers can benefit from evaluating new materials in small-scale tests prior to investing in larger quantities of materials for the large-scale ISO 9705 Tests.

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List of Acronyms, Abbreviations, and/or Symbols

CHF	Critical heat flux for ignition (kW/m^2)
$\dot{E}''$	Heat release rate per unit area (kW/m^2)
FP	Flammability parameter
FR	Fire retardant
FSP	Flame spread parameter
FMRC	Factory Mutual Research Corporation
HAI	Hughes Associates, Inc.
$k\rho c$	Thermal inertia [(kW/m^2-K)^2 sec]
k_f	Flame height parameter (m^2/kW)
$\dot{Q}$	Heat release rate (kW)
$\dot{q}''_{net}$	Net heat flux (kW/m^2)
$\dot{q}''_e$	Eternal heat flux (kW/m^2)
$\dot{m}_f$	Mass loss rate (kg/sec)
SPR	Smoke production rate (m^2/sec)
SwRI	Southwest Research Institute
TRP	Thermal response parameter (kW-sec$^{1/2}$/m^2)
t	Time (sec)
t_b	Burning duration (sec)
t_{bo}	Burning duration (sec)
t_f	Flame spread time (sec)
t_{fo}	Time to flashover (sec)
t_p	Pyrolysis time (sec)
t_{ig}	Time to Ignition (sec)
T_{ig}	Ignition temperature (K or °C)
T_s	Surface temperature (K or °C)
V_p	Pyrolysis velocity (m/sec)
x_b	Burnout height (m)
x_f	Flame height (m)
x_p	Pyrolysis height (m)
V_b	Velocity of burnout (m/sec)
WPI	Worcester Polytechnic Institute
Y_s	Smoke yield
$)H_c$	Heat of combustion (kJ/kg)
λ	Decay coefficient (1/sec)
σ	Specific extinction area (kg/m^2)
Δ	Density (kg/m^3)
EUREFIC	European Reaction to Fire Classification

1.0 INTRODUCTION

Since 1996 compartment linings of high speed craft have been regulated by the High Speed Craft Code (HSC) using the International Standards Organization (ISO) 9705 Room/Corner Test protocol. This test method requires the use of significant amounts of materials in a full-scale room test. The large-scale of the test is an impediment to innovation. Any new material must be produced in relatively large quantities before fire testing can be accomplished. As such, there is interest in using bench-scale tests like the Cone Calorimeter (American Society for Testing and Materials (ASTM) E 1354 or ISO 5660) to provide indications of expected performance in the ISO 9705 Test, and in actual use. If the Cone Calorimeter, with its 10-cm x 10-cm sample size, can provide results which correlate with full-scale performance, the process of developing innovative materials can be made more effective and efficient. Ultimately, if the Cone Calorimeter can fully predict full-scale performance, it may be able to replace the full-scale ISO 9705 as a regulatory test.

Enclosure fire scenarios frequently involve the ignition of furnishings such as wastebaskets, upholstered chairs, curtains, or other easily ignitable objects that can continue to burn in the absence of an external heat flux. Such a fire alone may constitute a threat, depending on the combustion characteristics of the object. For many fire scenarios, however, the significant hazard arises because the incipient furnishings fire exposes a combustible wall or ceiling finish material, which then may ignite and extend the fire causing large property losses and high death tolls due to smoke and toxic gases. Therefore, interior surface lining materials have been subjected to flammability regulations.

In the United States, all model building codes and National Fire Protection Association (NFPA) 101 have traditionally regulated flammability of interior surface finish materials based on ASTM E 84 or NFPA 255. During the 1960s and 1970s due to widespread introduction of synthetic finish materials, an inconsistent flammability rating for many lining materials was observed in the ASTM E 84 tunnel test. Lee and Huggett (1975) reported an inter-laboratory evaluation of the test method. They reported the variation in test performance within and among eleven laboratories. From a fire performance viewpoint, ASTM E 84 is useful only for screening or ranking purposes and is not adequate for hazard quantification because ASTM E 84 does not evaluate the end use fire performance of a product.

New large-scale fire tests (Uniform Building Code (UBC) 42-2, NT Fire 025, ISO 9705) have been developed to determine the fire performance of interior surface lining products in a more elaborate way, under exposure conditions representative of the intended end use. These large-scale tests are much more representative of end use fire performance than the ASTM E 84 tunnel test. Bench-scale testing, however, is usually preferable, as it is less expensive and more conveniently carried out. However, a bench-scale fire test method must be shown to predict real fire performance prior to use as a regulatory tool. Therefore, establishing a relationship between bench-scale performance to large-scale fire performance is essential. The bench-scale results can be judged to be meaningful and accepted only if a predictive relation (a correlation or a mathematical model) exists between product performance in the bench-scale test and in a representative full-scale fire scenario.

The full-scale ISO 9705 Room/Corner Test is widely used for the classification of furnishings and wall linings. Among the small-scale tests, the Cone Calorimeter (ASTM E 1354 or ISO 5660) is considered to be the most useful test to measure the heat release rate, mass loss rate, effective heat of combustion, ignitability, and the generation rate of smoke and toxic gases. The Cone Calorimeter has shown great promise as a bench-scale fire test that is capable of representing the hazards of materials in a full-scale application. The test method achieves this scaling by using an external radiative heat source, which provides radiation to the sample in much the same way that a large flame does. Further, the method utilizes modern methods of measuring heat release rate that are not available in most bench-scale fire test methods. Since the heat release rate is the primary characterization of a fire source, this has obviously some important implications and value.

The dominant hazard parameters in fires are the heat release rate and the smoke production rate. Smoke represents a hazard due to its optical effects. The obscuring effect itself is not considered as a danger, but by reducing the efficiency and speed of escape, the risk to occupants from exposure to lethal toxic gases or heat is increased. Efforts have been made to regulate the hazard associated with loss of visibility and many national building codes have requirements regarding the smoke production of combustible building products. In different countries as well as the ISO, smoke test methods have been developed in order to test combustible products for classification purposes. If bench-scale laboratory tests are to be used to assess and classify combustible products, their relationship to real fire hazard should first be demonstrated.

The production of smoke and its optical properties are often measured simultaneously with other fire properties, such as heat release and flame spread in small-scale or full-scale tests. Normally, these measurements are dynamic, i.e., they are performed in a flow through system (ASTM E 906, ASTM E 1354, ISO 5560, ISO 9705, NT Fire 025, and NT Fire 032). Dedicated, stand-alone smoke measurement techniques are also available. They are mainly performed in small-scale, closed systems and may be called cumulative or static methods (ASTM E 662, ISO 5924, and ISO 5659). The ability of both dynamic and static small-scale tests to predict full-scale behavior is of major interest.

Many factors affect the production of smoke including mode of decomposition, ventilation, burning environment, temperature, and the chemical nature of the burning materials (fuel). The influence(s) of these variables have been studied and detailed reviews are available in Quintiere (1982), Rasbash and Drysdale (1982), Tewarson (1995), and Mulholland (1995).

Prior United States Coast Guard (USCG) work to experimentally evaluate the performance of materials in both bench-scale tests and full-scale tests has been performed. Tests have been conducted on composite materials and one textile wall covering as a part of a program to develop acceptance criteria for qualifying fire-restricting materials for high speed craft linings (Janssens, Garabedian, and Gray, 1998). These tests were conducted at the Southwest Research Institute (SwRI) between August 1997 and July 1998. This testing included the bench-scale Cone Calorimeter Test (ISO 5660), the International Maritime Organization (IMO) Surface Flammability Test (IMO FTPC Part 5, 1998), the Lateral Ignition Flame Test (LIFT) (ASTM E 1321-97a), the IMO Smoke and Toxicity Test (IMO FTPC Part 2, 1998), and full-scale Room/Corner Test (ISO 9705). These test results form the primary basis in this project for evaluating methods to predict full-scale performance from bench-scale test results.

Specimens of the composite materials and the thin textile material were tested in accordance to the standard test methods ISO 5660 Cone Calorimeter in duplicate at 25, 50, and 75 kW/m^2 heat flux levels. Tests were conducted at 100 kW/m^2 on materials that did not ignite at the 25 kW/m^2 heat flux. Complete Cone Calorimeter data were obtained at three heat flux levels for all materials, except Material No. 2 which did not ignite at 50 kW/m^2. Eight composite materials and one textile wall covering were evaluated according to the standard test methods; these materials consisted of the following.

1. FR phenolic;
2. Fire restricting material;
3. FR polyester;
4. FR vinylester;
5. FR epoxy;
6. Coated FR epoxy;
7. Textile wall covering;
8. Polyester; and
9. FR modified acrylic.

2.0 OBJECTIVES AND APPROACH

The objective of this work is to assess the ability of small-scale test results to predict the full-scale fire performance of compartment linings in room/corner configurations. The ultimate goal is to develop the means for specifying the fire performance required in terms of small-scale tests so that material manufacturers/developers can more effectively, and efficiently, develop materials with the required fire performance.

Two means of relating Cone Calorimeter data to full-scale performance will be evaluated; correlations and mathematical models of corner fire flame spread. The ability of existing correlations to predict the fire performance in the ISO 9705 Test based on Cone Calorimeter data will be assessed. Several mathematical models of corner fire growth have been developed and three of these will be evaluated. Both the correlations and the models will be evaluated against the existing USCG ISO 9705 Test data.

The value of correlations is the simplicity of use. The correlations identify how to quantify materials properties in a form that can be directly related to fire performance in the ISO 9705 Test. Mathematical/computer models, while more complex, have the ability to use the Cone Calorimeter results to not only predict ISO 9705 results, but also have the prospect of being useful in assessing fire performance under a wider range of conditions than are inherent in the ISO 9705 Test. Variations in source fires, compartment size, and ventilation can potentially be modeled so that actual fire performance in the end use configuration can be assessed.

3.0 CORRELATION OF BENCH-SCALE FIRE TEST RESULTS WITH FULL-SCALE FIRE TEST RESULTS

There have been a limited number of attempts to develop correlations of small-scale heat release to predict full-scale fire performance, though most do not predict the performance criteria developed for the ISO 9705 Test. Ostman and Tsantaridis (1994) and Ostman and Nussbaum (1987) have correlated time to flashover in ISO 9705 Room/Corner Test, using a simple expression containing time to ignition and peak heat release rate from the Cone Calorimeter. Karlsson (1992) has developed a simple correlation of time to flashover in the ISO 9705 Test based on numerical experiments using a corner flame spread model. Tewarson (1995) has correlated open corner fire peak heat release rates using bench-scale data.

Ostman and Nussbaum (1987) have developed an empirical relationship based on linear regression for predicting the time to flashover in full-scale Room/Corner Tests for the surface lining materials. This relationship is based on the measurements of rate of heat release, time to ignition, and the density of the lining material in Cone Calorimeter Tests. Their correlation includes heat release rate measurements at 50 kW/m^2 Cone Calorimeter heat flux and time to ignition at 25 kW/m^2.

Similar efforts have been made by Karlsson (1992) to find empirical relationships between bench-scale and full-scale fire tests. Karlsson has developed a regression equation by running his mathematical model with 600 combinations of input parameters. The prediction of time to flashover in the regression equation is expressed as a function of the material parameters from bench-scale tests (Cone Calorimeter and LIFT). Time to flashover results from the model have been compared with the time to flashover predicted from the regression equation.

Ostman and Tsantaridis (1994) have modified the earlier empirical approach of Ostman and Nussbaum (1987). The new correlations are slightly better than the previous correlation and can apply to a wider range of surface linings based on heat release rate measurements at 50 kW/m^2 heat flux in the Cone Calorimeter.

Tewarson (1995) has developed a semi-empirical relationship for fire propagation length for a 15 minute test in the Factory Mutual Research Corporation (FMRC) 25 ft Open Corner Test based on the Thermal Response Parameter (TRP) of the material, convective heat release rate measured at 50 kW/m^2 external heat flux in the Flammability Apparatus. The correlation and pass/fail criterion have been adopted in the FMRC Class No. 4880 for insulated wall or wall and ceiling panels, Approval Standard Class No. 4880 (1993).

Mowrer and Williamson (1991) correlated full-scale room/corner peak heat release rates with Cone Calorimeter results for thin lining materials. Their correctional technique is based on a simplified upward flame spread model from which a dimensionless parameter arises that controls whether indefinite flame spread is expected to occur. This dimensionless parameter has been called a Flammability Parameter (FP). The authors successfully correlated the Flammability Parameter deduced from the Cone Calorimeter data of Harkleroad (1989) with the results of full-scale ASTM Room/Corner Test results. However, there are some problems with the method developed by Mowrer and Williams (1991) for determining the Flammability Parameter from Cone Calorimeter data.

Beyler, Iqbal, and Williams (1995) have evaluated flammability characteristics for the U.S. Navy Passive Fire Protection (PFP) test materials (Glass Reinforced Plastic Nomex panel, Manville, thermal insulation, Imi-Tech acoustic insulation, and Waffle-Board acoustic insulation) to evaluate flame spread performance. The correlation developed by Mowrer and Williams (1991) was adopted by the authors and modifications were made based on the analysis of the Cone Calorimeter data. The modified Flammability Parameter successfully correlated both the textile and Navy Cone Calorimeter data with full-scale ASTM Room/Corner Test results. The results are particularly impressive because the correlation was successful in correlating results from a wide range of facing material installed on very different types of substrates. The results of the Beyler, Iqbal, and Williams (1995) work are shown in Figure 1 as an example of the level of correlation that has been found. This figure includes textile wall coverings on gypsum board as well as the U.S. Navy insulation materials with coverings. Based on the prior success of the correlation in the Beyler, Iqbal, and Williams (1995) work, this correlational method is expected to be capable of predicting compartment lining fire performance in the ISO 9705 Test based on Cone Calorimeter data.

3.1 Evaluation of Existing Correlations

Karlsson (1992) described a mathematical model, which uses the rate of heat release and time to ignition results from Cone Calorimeter as input and predicts full-scale fire growth on combustible linings in room/corner configuration. The analytical model calculates the concurrent flow flame spread, gas temperatures, materials surface temperatures, and heat release rate of combustible lining materials mounted under ceiling and wall-ceiling interactions in enclosure. Karlsson developed a single analytical expression for time to flashover by running the model with 600 combinations of input parameters, and fitting the results of these numerical experiments to the following power law expression:

$$t_{fo} = 0.326(\dot{Q}''_{max})^{-1.14}(\lambda)^{0.085}(k\rho c)^{1.07}(T_{ig})^{2.19}$$

where t_{fo} is the predicted time to flashover (sec),

$\dot{Q}''_{max}$ is the peak heat release rate in the Cone Calorimeter at 50 kW/m^2 heat flux (kW/m^2),

λ is the average decay coefficient (1/sec), calculated for each measured value of heat release in the Cone Calorimeter from the following expression:

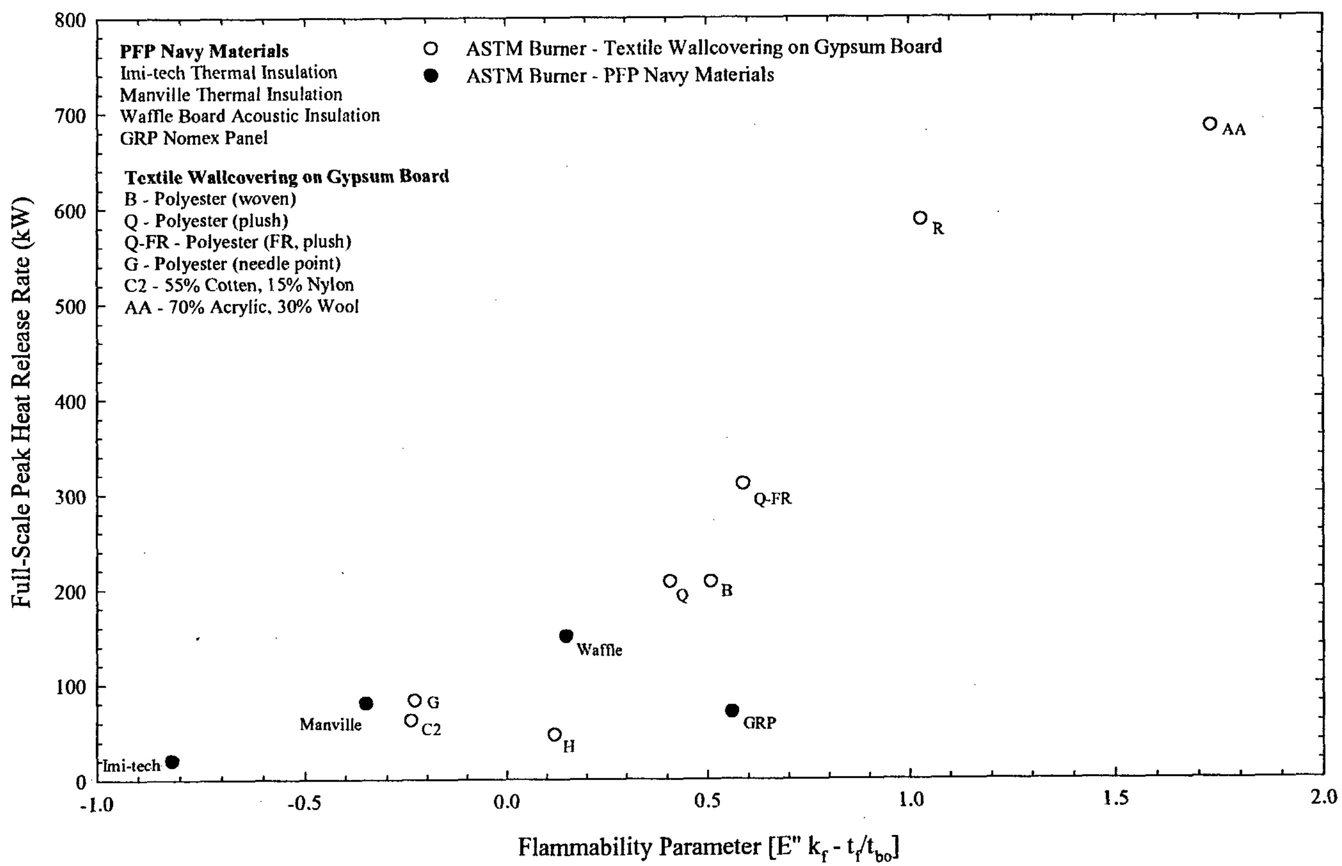

Figure 1. **Previous Correlation of Peak Heat Release Rate for PFP Navy Materials and Textile Wall Covering on Gypsum Board with the Flammability Parameter.**

$$\lambda(t) = \frac{\ln\left(\frac{\dot{Q}''(t)}{\dot{Q}''_{max}}\right)}{t}$$

where $\dot{Q}''_c(t)$ is the time dependent heat release rate in kW/m^2 from the Cone Calorimeter and t is the corresponding time in seconds,

$k\rho c$ is the thermal inertia derived from the LIFT Apparatus (ASTM E 1321) (kW^2-sec/m^4-K), and

T_{ig} is the ignition temperature, measured in the LIFT Apparatus (ASTM E 1321) (°C).

Experimental data and predicted results using the regression equation for time to flashover for nine USCG High Speed Craft Materials are presented in Table 1. As can be seen in Table 1, the Karlsson Correlation for time to flashover does not perform well for the USCG Materials.

Tewarson (1995) has shown that convective heat release rate at 50 kW/m^2 external heat flux and Thermal Response Parameter (TRP) in bench-scale test can be related by the normalized fire propagation length in the full-scale open corner tests configuration by the following empirical expression:

$$\frac{X_p}{X_t} = \frac{\dot{Q}''_{con}}{TRP}$$

where X_p is the average fire propagation length along the eaves of the full-scale corner test measured visually in meters,

X_t is the total available length in the full-scale corner test in meters,

$\dot{Q}''_{con}$ is the convective heat release rate in kW/m^2 as determined at 50 kW/m^2 incident flux in a bench-scale calorimetry test.

Table 1. Summary of Predicted and Measured Full-Scale Room/Corner Tests Time to Flashover Results for the USCG High Speed Craft Bulkhead Lining and Ceiling Materials.

USCG High Speed Craft Materials	Peak Heat Release Rate at 50 kW/m^2 Cone Heat Flux Exposure, $\dot{Q}''_{max}$ (kW/m^2)	Decay Coefficient. At 50 kW/m^2 Cone Heat Flux Exposure, λ (1/sec)	Measured Ignition Temperature from LIFT Apparatus, T_{ig} (°C)	Thermal Inertia from LIFT Apparatus, $k\rho c$ (kW^2-sec/m^4-K)	Predicted Time to Flashover from Regression Equation, t_{fo} (sec)	Time to Flashover from Full-Scale Room/Corner Test t_{fo} (sec)	Error %
1-FR phenolic	33.90	0.0012	Not reported		-	4	-
2- Fire restricting material	Did not ignite at 50 kW/m^2 Cone Calorimeter heat flux				-	4	-
3-FR polyester	116.25	0.0021	375	1.65	633	372	70.20
4-FR vinylester	135.25	0.0017	370	1.89	587	318	84.60
5-FR epoxy	73.00	0.0023	453	1.73	1726	990	74.30
6-Coated FR epoxy	42.40	0.0116	643	8.00	40742	4	-
7-Textile wall covering*	68.60	0.0127	647	0.27	640	4	-
8-Polyester	361.50	0.0046	337	0.74	62	108	42.60
9-FR modified acrylic	129.33	0.0022	385	1.72	623	666	6.50

*Material No. 7 Textile Wall Covering fell off from the wall during the ISO 9705 Room/Corner Test.

TRP is the Thermal Response Parameter, based on the measured bench-scale ignition properties of the material ($kW\text{-}s^{1/2}/m^2$).

The right-hand side of the above equation is defined as the Flame Spread Parameter (FSP):

$$FSP = \frac{\dot{Q}''_{con}}{TRP}$$

Table 2 shows the flame spread parameter results for the USCG High Speed Craft Materials. TRP in Table 2 was calculated by the following equation from Tewarson 1995:

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\sqrt{\frac{4}{\pi}}\left(\dot{q}''_e - CHF\right)}{TRP}$$

where $\dot{q}''_e$ is the external heat flux, 50 kw/m^2,

t_{ig} is the time to ignition (sec), and

CHF critical heat flux for ignition (kW/m^2)

critical heat flux for each USCG Material in Table 2 has been determined from slope of the plot of heat flux us $(1/t_{ig})^{1/2}$ per Tewarson's method.

Figure 2 shows the correlation plot between Flame Spread Parameter (FSP) and ISO 9705 peak heat release rate for the eight USCG High Speed Craft Materials. Figure 3 is the same correlation plot as Figure 2, but with ISO 9705 average heat release rate. Tewarson's correlation does not perform well for the USCG Materials in the ISO 9705 Test. It should be noted that the method was developed for an open corner test configuration and not a room/corner configuration.

Table 2. Summary of FMRC Flame Spread Parameter and Full-Scale Room/Corner Tests Results for the USCG High Speed Craft Bulkhead Lining and Ceiling Materials.

USCG High Speed Craft Materials	Cone Calorimeter Ignition time. Average at all Heat Fluxes $1/(t_{ig})^{1/2}$ $1/(\mathrm{sec})^{1/2}$	Critical Heat Flux for Ignition, *CHF* (kW/m^2)	Thermal Response Parameter at 50 kW/m^2 Cone Calorimeter Heat Flux Exposure, *TRP* ($kW\text{-}sec^{1/2}/m^2$)	Average Heat Release Rate at 50 kW/m^2 Cone Calorimeter Heat Flux Exposure, $\dot{Q}''_{cone}$ (kW/m^2)	Flame Spread Parameter, *FSP* = $\dot{Q}''_{cone}/TRP$	Peak Heat Release Rate from Full-ScaleRoom/ Corner Test (kW)	Average Heat Release Rate from Full-ScaleRoom/ Corner Test (kW)
1-FR phenolic	@50 = 0.0030 @75 = 0.012 @100 = 0.062	42	2924.80	19	0.0064	159	62
2- Fire restricting material	@75 = 0.012 @100 = 0.076	69	Did not ignite at 50 kW/m^2 Cone Calorimeter heat flux			129	31
3-FR polyester	@25 = 0.063 @50 = 0.124 @75 = 0.187	15	318.40	107	0.33	677	191
4-FR vinylester	@25 = 0.056 @50 = 0.115 @75 = 0.172	18	311.66	64	0.20	463	190
5-FR epoxy	@50 = 0.090 @75 = 0.130 @100 = 0.166	42	99.91	90	0.90	421	115
6-Coated FR epoxy	@50 = 0.121 @75 = 0.182 @100 = 0.218	40	93.90	28	0.30	134	28
7-Textile wall covering	@25 = 0.032 @50 = 0.190 @75 = 0.272	19	183.44	34	0.18	131	17
8-Polyester	@25 = 0.090 @50 = 0.184 @75 = 0.254	23	165.48	162	0.97	568	170
9-FR modified acrylic	@25 = 0.046 @50 = 0.103 @75 = 0.127	22	306.32	46	0.15	542	109

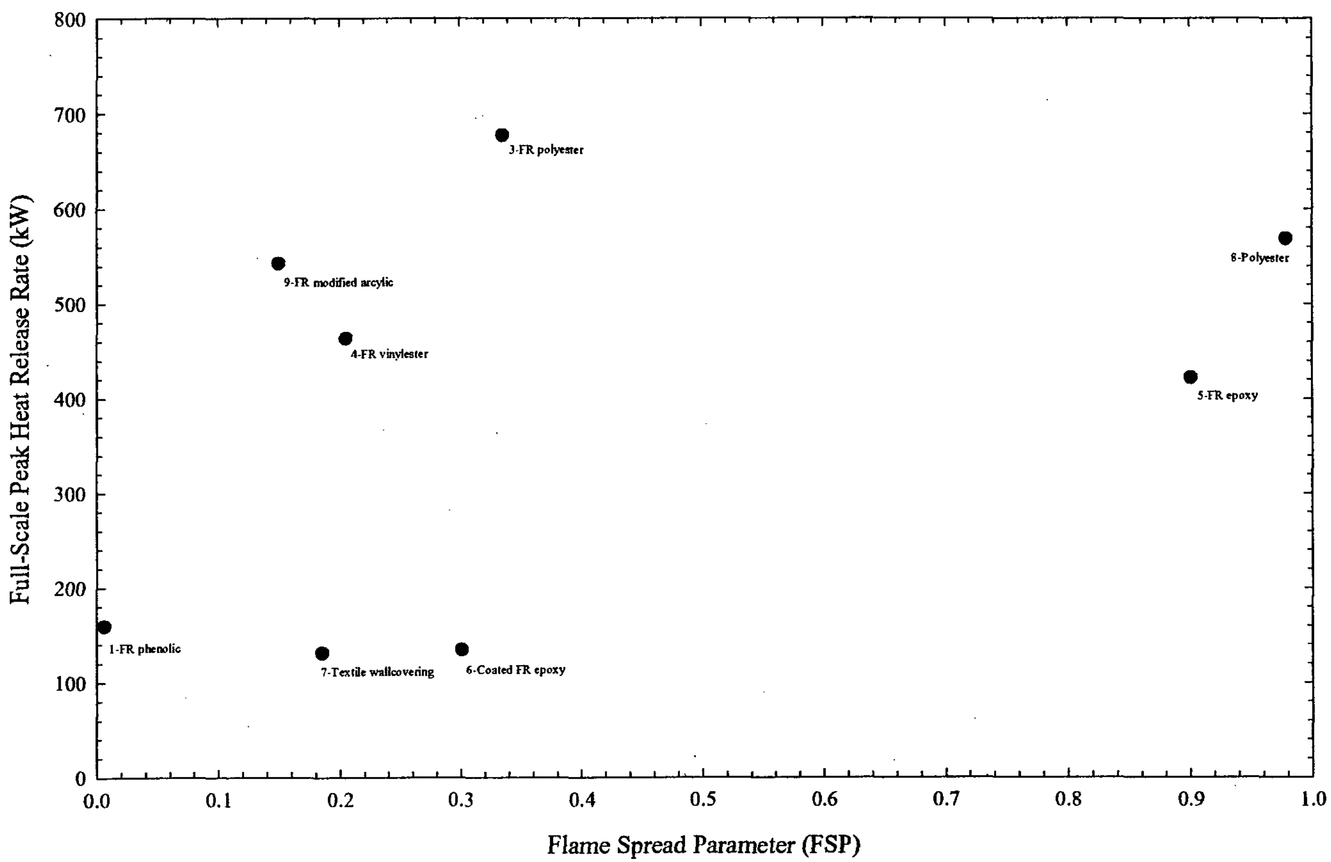

Figure 2. Correlation of the Full-Scale Heat Release Rate with FMRC Flame Spread Parameter for the USCG High Speed Craft Materials. The Flame Spread Parameter was Obtained from the Cone Calorimeter at 50 kW/m^2 Heat Flux, Based on the Method Developed by Tewarson (1995).

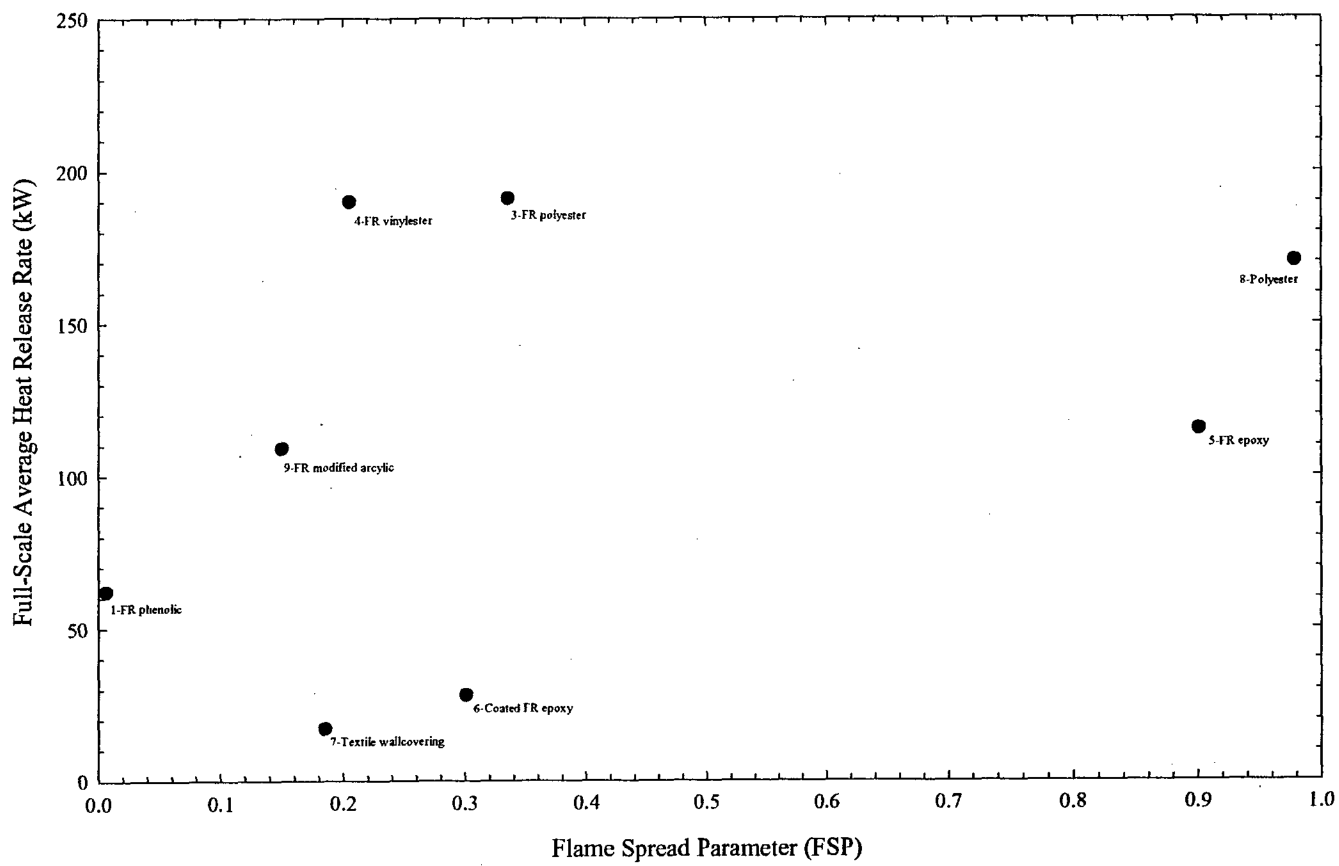

Figure 3. Correlation of the Full-Scale Average Heat Release Rate with the FMRC Flame Spread Parameter for the USCG High Speed Craft Materials. The Flame Spread Parameter was Obtained from the Cone Calorimeter at 50 kW/m^2 Heat Flux, Based on the Method Developed by Tewarson (1995).

3.2 Evaluation of Flammability Parameter Correlations

The correlations investigated in the foregoing section are not directly linked to a flame spread theory and are unable to correlate the USCG test results satisfactorily. The Flammability Parameter (FP) Correlation originated by Mowrer and Williamson (1991) and developed further by Beyler, Iqbal, and Williams (1995) is described and evaluated in this section. The parameter is derived from a simple vertical flame spread model developed by Quintiere, Harkleroad, and Hasemi (1986) and the performance of the parameter in predicting average and peak heat release, average and peak smoke release, and time to flashover in the ISO 9705 test is subsequently reported. The correlation is also tested against other data in the literature.

3.2.1 Flammability Parameter Derivation and Formulation

In this section, the flame spread model is presented to provide the theoretical basis for the Flammability Parameter developed by Mowrer and Williamson (1991). The modifications made by Beyler, Iqbal, and Williams (1995) are also discussed later in this section.

The process of fire development involving interior finish materials is dominated by concurrent flame spread and subsequent burning. Concurrent flame spread is simply flame spread in the same direction as the prevailing fluid flow. Concurrent flame spread occurs when the flame directly contacts the material's surface ahead of the pyrolzing region. This occurs for upward flame spread on walls and flame spread on ceilings. Concurrent flow flame spread rates depend on the flame length, so that it is not a unique function of the material being burned.

The flame spread model developed by Mowrer and Williamson (1991) is based on the approach presented by Quintiere, Harkleroad, and Hasemi (1986). The model includes consideration of the finite burning time, t_b, of thin fuels. The consumption of the all fuel results in burnout of the flame at each location, which is an important aspect of the flame spread on thin fuels.

In this model, the flame-spread rate is defined as the rate of advance of the pyrolysis front:

$$V_p = \frac{dx_p}{dt} \cong \frac{x_p(t + t_{fp}) - x_p(t)}{t_f} = \frac{x_f(t) - x_p(t)}{t_f} \tag{1}$$

The characteristics flame spread (or ignition) time is defined in terms of a simple thermal model of heating a wall with constant thermal properties:

$$t_f \cong k\rho c \left(\frac{T_{ig} - T_s}{\dot{q}''_{net}} \right)^2 \tag{2}$$

Once burnout begins, the velocity of the burnout front can be expected as

$$V_b = \frac{dx_b}{dt} \cong \frac{x_b(t + t_{bo}) - x_b(t)}{t_{bo}} = \frac{x_p(t) - x_b(t)}{t_{bo}} \tag{3}$$

A linearized flame height approximation is used to describe the flame height required in Equation (1), following Quintiere, Harkleroad, and Hasemi (1986), Satio, Quintiere, and Williams (1986), and Cleary and Quintiere (1991).

$$\frac{x_f}{x_p} = k_f \dot{E}'' \tag{4}$$

After burnout begins, the dimensionless flame height is expressed as:

$$\frac{(x_f - x_b)}{x_p - x_b} = k_f \dot{E}'' \tag{5}$$

The parameter, k_f is a correlating factor used to define the flame length. Cleary and Quintiere (1991) suggest a value of approximately 0.01 m^2/kW for k_f. Using Equation (4) for times $t<t_b$ Equation (1) can be rewritten as:

$$\frac{dx_p}{dt} = \left(k_f \dot{E}''-1\right)\frac{x_p}{t_f} \tag{6}$$

Equation (6) can be integrated, with limits $x = x_{po}$ at $t = 0$ and x_p at t:

$$x_p = x_{po} \exp\left(\frac{\left(k_f \dot{E}''-1\right)t}{t_f}\right) \tag{7}$$

Equation (6) and (7) together, with Equation (4) suggest that, before burnout, the flame spread rate will be acceleratory if $x_f > x_p$ and deceleratory if $x_f < x_p$, i.e., if $k_f \dot{E}'' < 1$.

After burnout, at times $t > t_b$, the net rate of flame propagation can be expressed as the difference in pyrolysis front velocity and burnout front velocity:

$$V_p(t) = V_b(t) = \frac{d}{dt}\left(x_p - x_b\right) = \frac{\left(x_f - x_p\right)}{t_f} - \frac{\left(x_p - x_b\right)}{t_{bo}} \tag{8}$$

Using Equation (5), Equation (8) can be rearranged to:

$$\frac{d}{dt}\left(x_p - x_b\right) = \left(x_p - x_b\right)\left(\frac{\left(k_f \dot{E}''-1\right)\left(t_{bo} - t_f\right)}{t_f t_{bo}}\right) \tag{9}$$

Equation (9) can be integrated, with the limit of

$(x_p - x_b) = (x_{p1} - x_{bo})$ at $t = t_b$ and $(x_p - x_b) = (x_p - x_b)$ at time t, to yield the pyrolysis zone height:

$$\left(x_p - x_b\right) = \left(x_{p1} - x_{po}\right) \exp\left(k_f \dot{E}'' - \frac{t_f}{t_{bo}} - 1\right)\left(\frac{t - t_b}{t_f}\right) \tag{10}$$

Equation (10) suggests that, following the onset of fuel burnout, the potential for acceleratory spread depends on a balance among three parameters: the normalized flame height, $(x_f - x_b) / (x_p - x_b)$, which is represented per Equation (5) as a linear function of unit heat release rate, $\dot{E}''$; the flame spread time, t_f given by Equation (2); and the burning duration, t_b. If the parameter, $k_f \dot{E}'' - t_f / t_b > 1$, acceleratory flame spread is predicted.

While this model is based on several idealizations, it is expected that this Flammability Parameter characterizes a material with regard to vertical flame spread. However, attention must be paid to the methods used to evaluate $\dot{E}''$, t_f, and t_b. Mowrer and Williamson (1991) evaluated $\dot{E}''$ as the peak heat release rate of material, t_f, as the ignition time, and t_b as the time from ignition to peak heat release rate. They evaluated these quantities at both Cone Calorimeter heat fluxes of 30 and 50 kW/m^2 (Harkleroad (1989)) and found better performance using the 50 kW/m^2 data.

There are both conceptual and practical problems with the methods proposed by the Mowrer and Williamson (1991) for deducing $\dot{E}''$ and t_b. Conceptually, the role of the burn time is the duration of burning of the ignited material. As such the time required from ignition to peak burning is not directly relevant to upward flame spread. Typically, thick and thin coverings of the same material would have the same burn time as determined by the Mowrer and Williamson method, whereas their observed burning durations would be very different. This fails to resolve a significant difference in behavior. Similarly, the peak heat release rate is less significant than the heat release rate averaged over the burning period. In short, global quantities of burning duration and the average heat release rate during that period are more appropriate definitions of material behavior for the fire spread.

From a practical standpoint, there are serious problems relying upon peak quantities and time to reach peak quantities in a test method. This requires unrealistically rigorous transient response characteristics of the instruments. Beyler, Iqbal, and Williams (1995) have studied this problem and proposed new methods of Cone Calorimeter data reduction, and developed some modified methods to evaluate the Flammability Parameter from Cone Calorimeter test data. These modified methods avoid some of the experimental difficulties with the Cone Calorimeter as applied to thin materials. The authors took burn time, t_b, as the time from ignition until the material stopped flaming. This is best determined visually, but can be determined from the heat release rate verses time output from the Cone Calorimeter. Also they took heat release rate, $\dot{E}''$, as the cumulative heat release, as routinely determined in the Cone Calorimeter, divided by the burn time, t_b. This is an average heat release rate for the material during the active burning period. The cumulative heat release is the area under the heat release rate verses time curve.

The time response characteristics of the Cone Calorimeter are such that the peak measured heat release rate is less than the actual peak for these thin materials due to the small burn time. The effect of various burning durations can be seen from Figure 4 for a methane burner at a heat release rate of 6.80 kW operated for various durations. Of course, if the cone had a zero response time, the measured heat release rates would be square wave pulses with the width equal to the burning duration. For the longer burning duration (Test 1, 120 seconds burn duration), the actual heat release rate is measured after about 20 seconds. For shorter burn durations (Test 5, 10 seconds and Test 6, 5 seconds burn duration), the peak recorded heat release rate occurs at about 5-10 seconds, and the actual burning rate is never recorded. While the response time of the gas analysis system on the Cone Calorimeter does not allow correct measurement of the heat release rate, there is a hope that the cumulative heat release may be measured correctly despite the time response limitations of the system. Table 3 shows the predicted and measured cumulative heat releases for the various burn durations. The result indicates that the Cone Calorimeter can correctly measure the cumulative heat release for short duration burns.

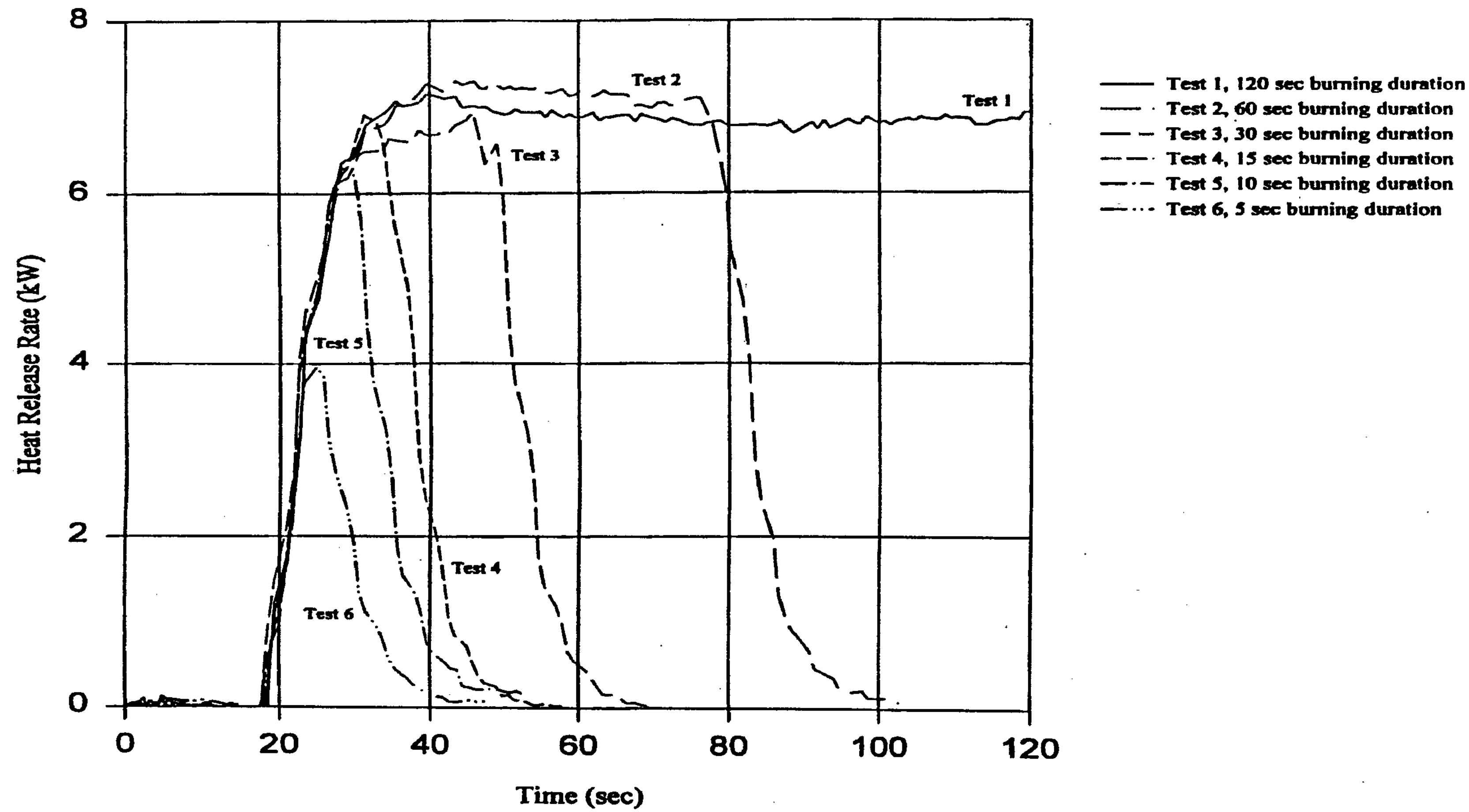

Figure 4. Heat Release Rate for a Methane Burner at 6.80 kW Steady-State.

Table 3. Measured and Predicted Cumulative Rate of Heat Release for a Methane Burner Operated at 6.8 kW.

Test Number	Test Duration (sec)	Measured Cumulative Heat Release Rate (kJ)	Predicted Cumulative Heat Release Rate (kJ)
1	120	830.73	816
2	60	429.81	408
3	30	204.89	204
4	15	109.47	102
5	10	77.75	68
6	5	36.70	34

There is broad agreement in the literature that the performance of materials in the Cone Calorimeter at 50 kW/m^2 incident heat flux gives the best indication of performance (Mowrer & Williamson (1991), Beyler *et al.* (1995), Tewarson (1995), Karlsson (1992)). Measurements of heat fluxes in simple wall fires tend to be in the range of 20-30 kW/m^2 and heat fluxes measured in corner and ceiling configurations range up to about 100 kW/m^2. As such, 50 kW/m^2 is more representative of heat fluxes in the relevant configurations. Correlations developed here are based on data from 50 kW/m^2 incident heat flux tests.

3.2.2 Correlation of Heat Release Rate and Time to Flashover Using the Flammability Parameter

Cone Calorimeter and Room/Corner Fire Tests have been reported by a number of investigators (USCG: Janssens *et al.,* (1998), U.S. Navy PFP: Beyler *et al.*, (1995), Textile Wall Coverings: Mowrer and Williamson (1991) & Harkleroad (1989), Swedish Materials: Sundstrom, B. (1986) & Tsantaridis, L., and Ostman, B., (1989), EUREFIC: Soderbom, J., (1991) & Thureson, P., (1991), and LSF: Dillon *et al.,* (1998)). The Flammability Parameter has been derived from Cone Calorimeter test results for the U.S. Coast Guard, U.S. Navy PFP, and Textile Wall Covering Materials, Swedish Materials, EUREFIC Materials and LSF Materials using a 50 kW/m^2 cone heat flux exposure. The full-scale Room/Corner Tests are ISO 9705 in each of these investigations, except the U.S. Navy and Textile Materials series. These were done using the ASTM 40/160 kW source burner regimen rather than the ISO 100/300 kW regimen.

The Flammability Parameter results for all the materials are tabulated in Table 4a - 4f along with the peak and average heat release rate, peak and average smoke production, and the flashover time measured in the large-scale Room/Corner Tests. Figure 5 shows the correlation of the full-scale peak heat release rate with the Flammability Parameter for the USCG High Speed Craft Materials. Figures 6 shows the results of the USCG, U.S. Navy, and the Textile tests. It should be noted that in Figure 6, the heat release rates for the Textile Wall Coverings are significantly less than the USCG for positive values of the Flammability Parameter. This results from the fact that in the Textile Tests, the corner was not fully lined, but rather had only one foot wide strips of textile up the corner and along the wall/ceiling junction. While this economical configuration is useful in assessing the ability of flames to propagate in the corner configuration, the peak heat release rates are less than would have occurred in a fully lined experiment. In addition, the Navy and Textile Wall Covering Tests used the ASTM burner regimen of 40 kW and 160 kW, rather than the ISO regimen of 100 kW and 300 kW. This difference would tend to shift the ASTM test results to the right of the ISO results in the Flammability Parameter plot.

The correlation of peak full-scale heat release with Flammability Parameter from data at the 50 kW/m^2 exposure level for USCG High Speed Craft Materials, PFP Materials, Textile Wall Covering Materials on gypsum board, Swedish Products, EUREFIC Products, and LSF Materials are shown in Figure 7. While the body of data includes a wide range of material types, the results indicate that a negative Flammability Parameter provides excellent performance, that a Flammability Parameter greater than 0.5 provides poor performance, and that a Flammability Parameter between zero and 0.5 provides marginal or variable results. Figures 8-10 show the correlation of the test average heat release rate as a function of the Flammability Parameter for tests where average heat release rates were reported.

Table 4a. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for USCG High Speed Craft Materials.

USCG High Speed Craft Materials	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure), $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/Corner Test (kW)	Average Heat Release Rate from Full-Scale Room/Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Test t_{fo} (sec)
1-FR phenolic	19	- 0.75	159	62	5.41	1.50	4
2- Fire restricting material	Did not ignite at 50 kW/m^2 Cone Calorimeter heat flux		129	31	0.47	0.15	4
3-FR polyester	107	0.95	677	191	21.7	10.00	372
4-FR vinylester	64	0.57	463	190	32.1	9.08	318
5-FR epoxy	90	0.34	421	115	26.4	6.39	990
6-Coated FR epoxy	28	- 1.85	134	28	3.46	1.45	4
7-Textile wall covering	34	0.18	131	17	0.16	0.10	4
8-Polyester	162	1.5	568	170	4.10	2.28	108
9-FR modified acrylic	46	0.37	542	109	3.81	0.42	666

Table 4b. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for U.S. Navy PFP, Materials.

U.S. Navy PFP Materials	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure), $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/Corner Test (kW)	Average Heat Release Rate from Full-Scale Room/Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Test t_{fo} (sec)
GRP Nomex Panel	68.0	0.65	70	40	-	-	4
Manville Thermal Insulation	5.0	- 0.35	80	30	-	-	4
Imi-Tech Thermal Insulation	7.5	- 0.82	20	12	-	-	4
Waffle Board Acoustic Insulation	60.0	0.15	150	60	-	-	4

Table 4c. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for Textile Wall Coverings on Gypsum Board.

Textile Wall Covering on Gypsum Board	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure), $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/Corner Test (kW)*	Average Heat Release Rate from Full-Scale Room/Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Test t_{fo} (sec)
B-Polyester (woven)	125	0.51	207 (298)	-	-	-	-
Q-Polyester (plush)	130	0.41	207 (497)	-	-	-	-
Q-FR-Polyester (FR, plush)	117	0.59	310	-	-	-	-
G-Polyester (needle point)	37	-0.23	83	-	-	-	-
C2-55% Cotton, 45% Rayon (tight complex wave)	70	-0.24	62 (119)	-	-	-	-
H-85% Wool, 15% Nylon	56.5	0.12	46 (160)	-	-	-	-
AA-70% Acrylic, 30% Wool	185	1.73	684	-	-	-	-
R-Nylon with Backing	145	1.03	587 (590)	-	-	-	-
C1-55% Cotton, 45% Rayon (loose complex wave)	70	0.14	-	-	-	-	-
PP-PF-Polypropylene	131	1.01	(1160)	-	-	-	-

* Parenthetical peak heat release rates are for two foot wide samples while normal values are for one foot wide samples.

Table 4d. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for Swedish Materials.

Swedish Materials	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure), $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/Corner Test (kW)	Average Heat Release Rate from Full-Scale Room/Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Test t_{fo} (sec)
S1-Insulating Fiber Board	90	0.87	1900	-	55	9.3	59
S2-Medium Density Fiber Board	167	1.62	1700	-	58	7.5	131
S3-Particle Board	135	1.28	1900	-	66	11.3	157
S4-Gypsum Board	31	0.21	50	-	1	-	4
S5-Plastic Wall Covering on Gypsum Board	100	0.97	20	-	140	3.6	611
S6-Paper Wall Covering on Gypsum Board	138	1.32	130	-	10	0.5	640
S7-Textile Wall Covering on Gypsum Board	200	1.94	240	-	28	0.3	639
S8-Textile Wall Covering on Rock Wool	400	3.98	1900	-	84	21.8	43
S9-Melamine-Faced Particle Board	132	1.24	1400	-	136	33.3	465
S10-Expanded Polystyrene	163	1.60	1800	-	95	34.1	115
S11-Rigid Polyurethane Foam	125	1.24	1900	-	305	214.0	6
S12-Wood Panel (Spruce)	115	1.11	1400	-	61	7.2	131
S13-Paper Wall Covering on Particle Board	113	1.08	1200	-	67	12.0	143

Table 4e. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for EUREFIC Materials.

EUREFIC Materials (EUREFIC-European Reaction-to-FIre Classification)	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure) $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/Corner Test (kW)	Average Heat Release Rate from Full-Scale Room/Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Testt_{fo} (sec)
E1-Painted Gypsum Paper Plaster Board	113	0.81	300	-	4.1	1.8	4
E2-Ordinary Plywood	201	1.95	1650	-	49.2	9.2	160
E3-Textile Wall Covering on Gypsum Plaster Board	163	1.50	1900	-	11.5	1.9	670
E4-Melamine Faced High Density Non-Combustible Board	95	0.41	300	-	46.4	8.5	4
E5-Plastic Faced Steel Sheet on Mineral Wool	38	0.14	200	-	20.9	6.3	4
E6-FR Particle Board Type B1	75	0.63	1700	-	86.4	6.3	630
E7-Combustible Faced Mineral Wool				-	12.1	2.6	
E8-FR Particle Board	38	0.04	650	-	41.2	14.3	4
E9-Polyurethane Foam Covered with Steel Sheets	211	2.00	1900	-	33.7	9.7	215
E10-PVC Wall Carpet on Gypsum Paper Plaster Board	63	0.59	1400	-	234.0	11.0	650
E11-FR Polystyrene Foam	313	2.70	1900	-	23.3	5.4	80

Table 4f. Summary of Flammability Parameter and ISO Full-Scale Room/Corner Tests Heat Release Rate and Smoke Production Rate Results for LSF Materials.

LSF Materials (LSF.Laboratorio Studi e Ricerche sul Fuoco s.r.l.)	Average Heat Release Rate from Cone Calorimeter Test (50 kW/m^2 Exposure), $\dot{E}''$ (kW/m^2)	Flammability Parameter	Peak Heat Release Rate from Full-Scale Room/ Corner Test (kW)	Average Heat Release Rate from Full-Scale Room/ Corner Test (kW)	Peak Smoke Production Rate from Full-Scale Room/ Corner Test (m^2/sec)	Average Smoke Production Rate from Full-Scale Room/Corner Test (m^2/sec)	Time to Flashover from Full-Scale Room/Corner Test, t_{fo} (sec)
LS1-Paper FACED Gypsum Board	50	0.08	94	50	0.5	-	4
LS2-FR PVC	68	0.37	129	68	2.6	-	4
LS3-Acrylic Glazing (transparent)	700	6.80	1900	700	1.1	-	141
LS4-FR Extruded Polystyrene Board 40 mm	320	2.90	1900	320	39.0	-	96
LS5-PUR Foam Panel with Al Paper	150	0.67	1900	150	21.9	-	41
LS6-mass Timber (pine), Varnished	142	1.38	1900	142	32.8	-	107
LS7-FR Chip Board	92	0.11	423	92	17.4	-	4
LS8-3-Layered FR Polycarbonate Panel	350	3.29	132	70	2.1	-	4
LS9-FR Expanded Polystyrene Board 40 mm	264	2.42	1100	264	14.8	-	87
LS10-FR Expanded Polystyrene Board 30 mm	190	1.66	1900	190	6.2	-	106
LS11-Plywood	55	0.54	1800	55	16.6	-	142
LS12-FR Plywood	50	0.49	2100	50	12.2	-	631

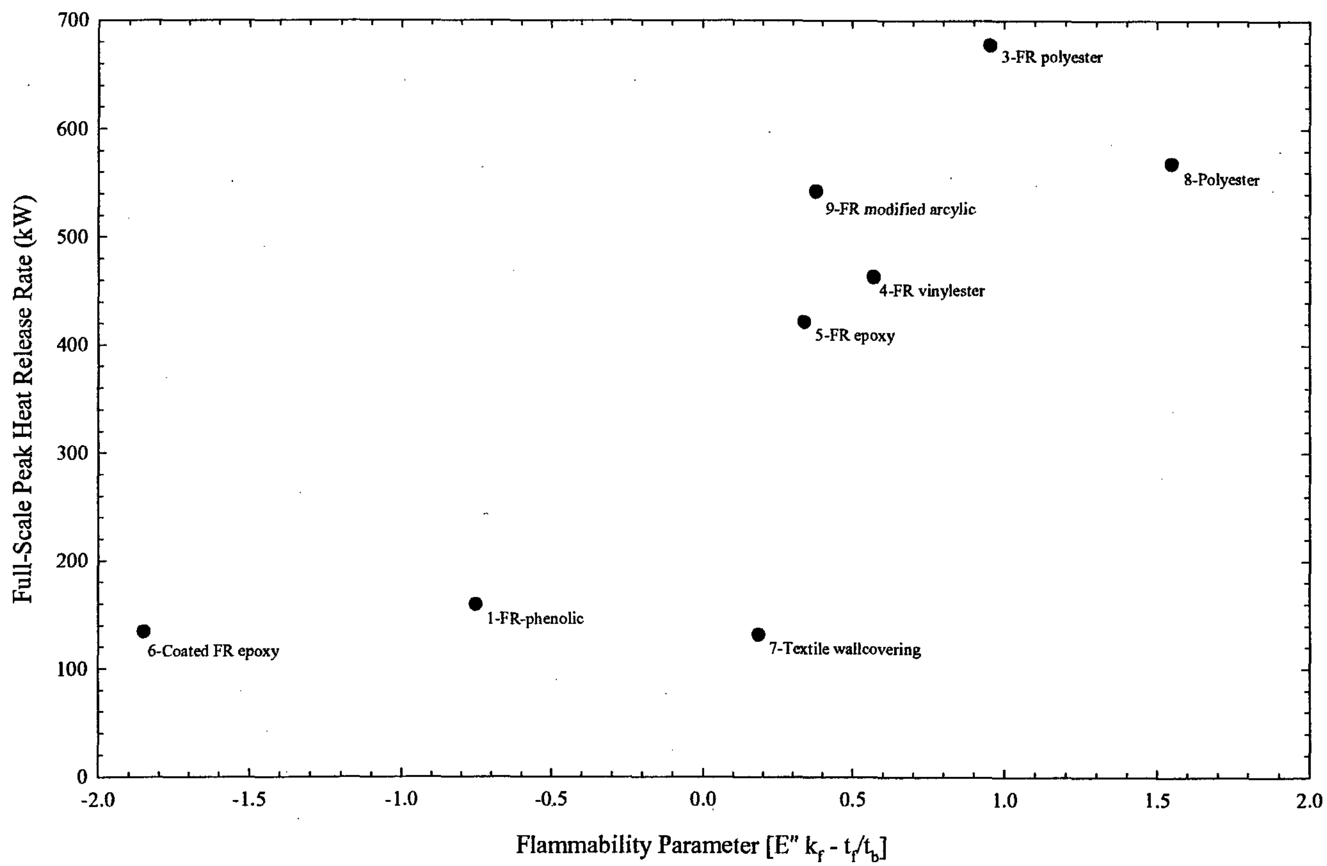

Figure 5. Correlation of the Full-Scale Peak Heat Release Rate with Flammability Parameter for the USCG High Speed Craft Materials.

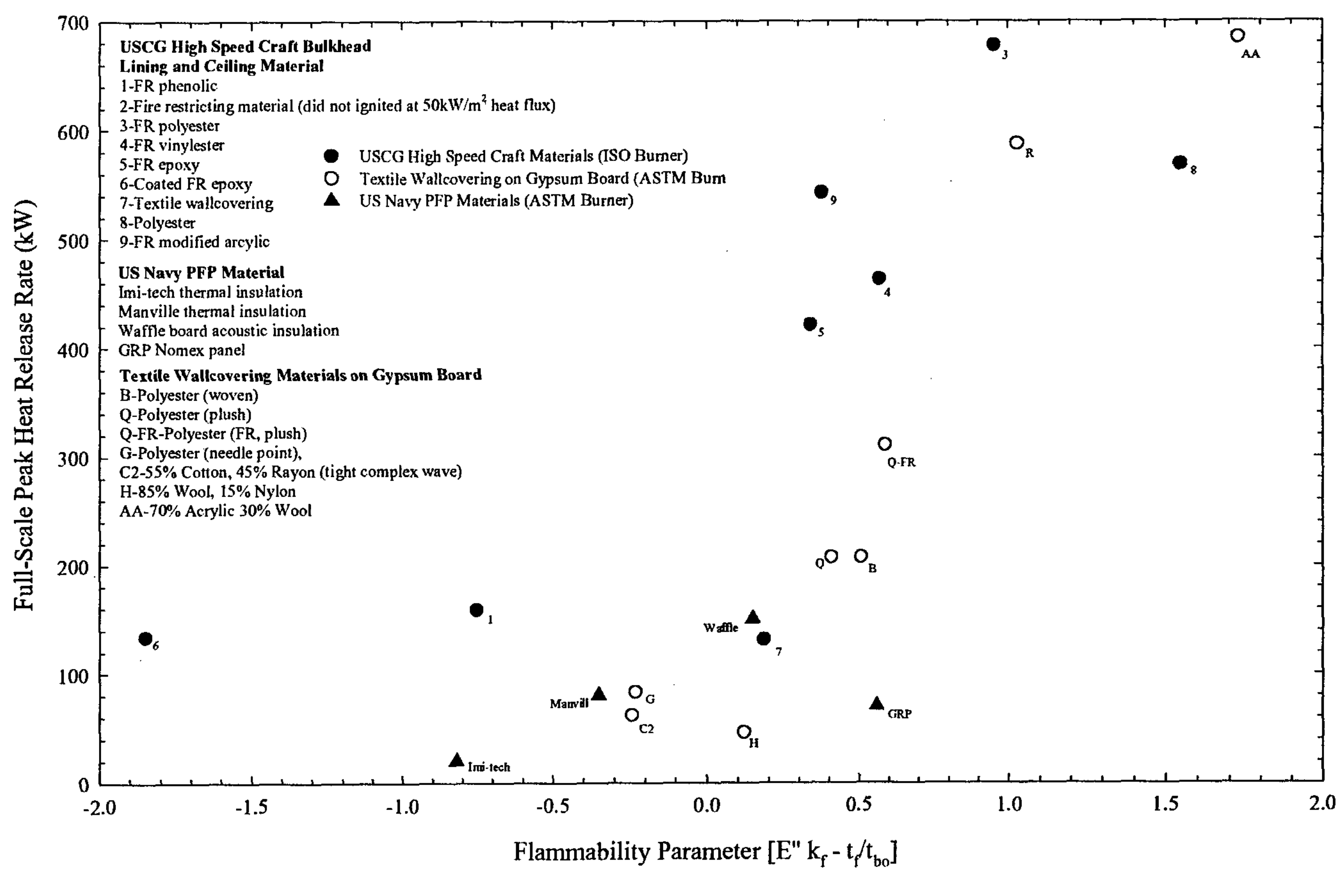

Figure 6. Comparison of USCG High Speed Craft Materials Results with PFP Navy and Textile Wall Covering on Gypsum Board Results.

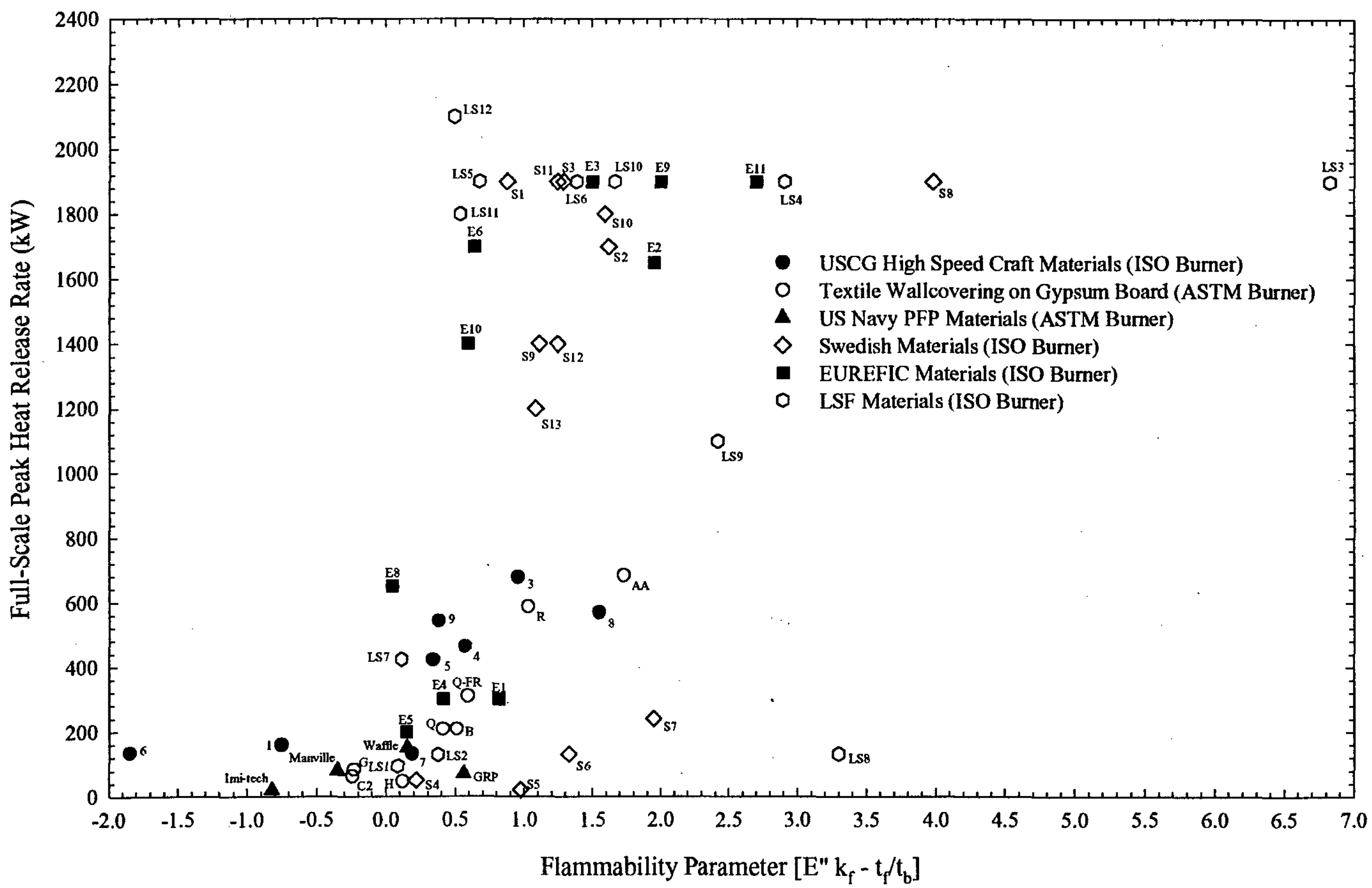

Figure 7. Comparison of USCG High Speed Craft Materials Results with PFP Navy, Textile Wall Covering on Gypsum Board, Swedish, EUREFIC, and LSF Materials Results.

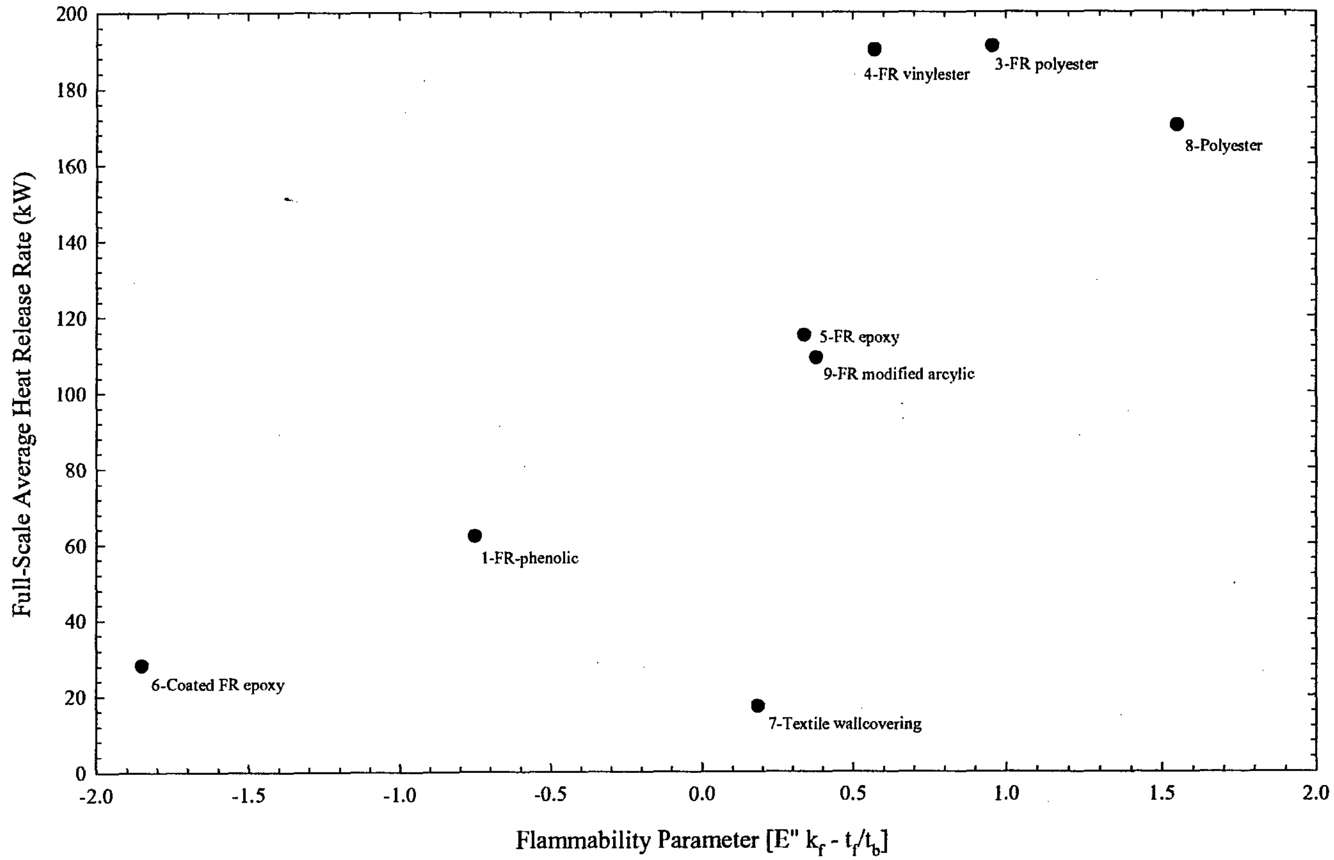

Figure 8. Correlation of Full-Scale Average Heat Release Rate with Flammability Parameter for the USCG High Speed Craft Materials.

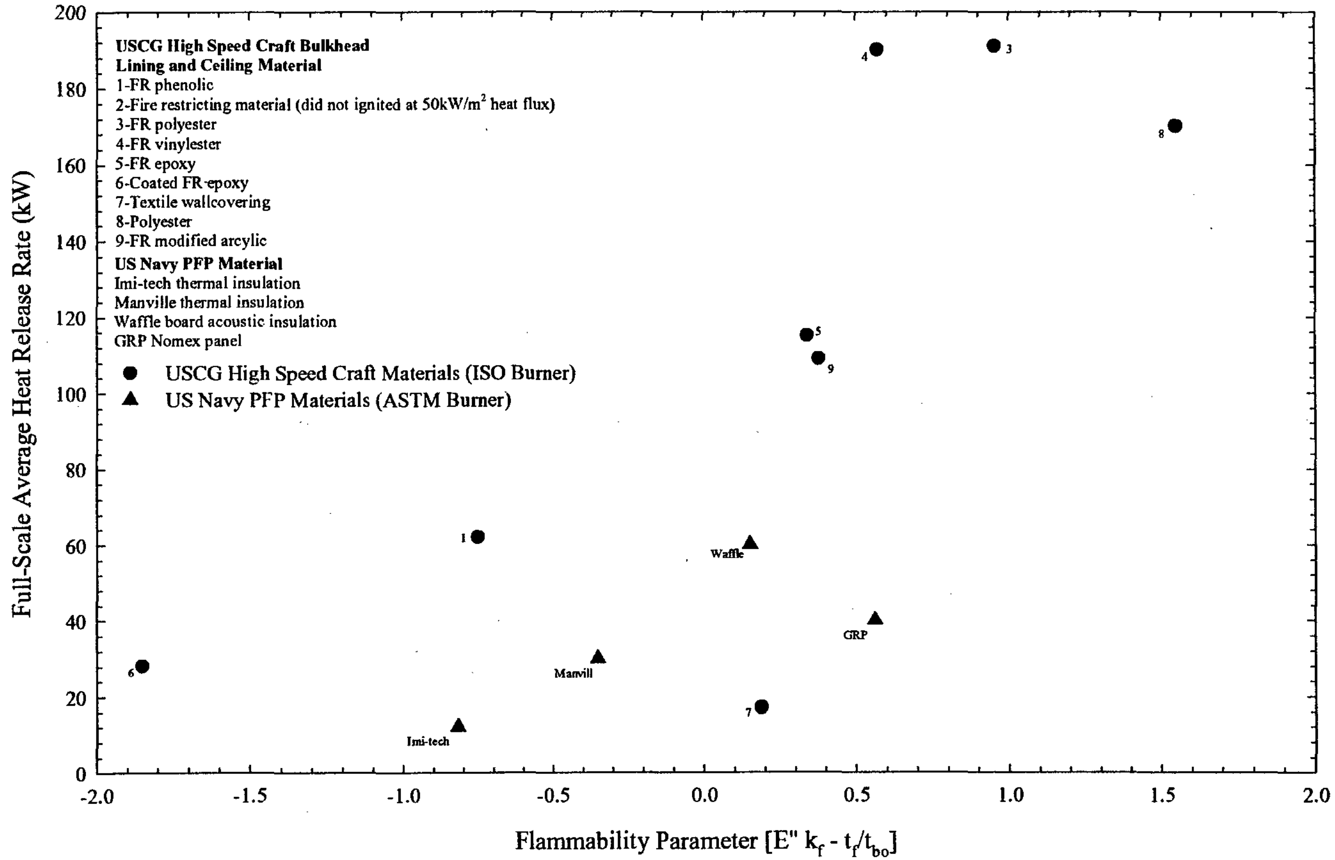

Figure 9. **Comparison of USCG High Speed Craft Materials Results with PFP Navy Results.**

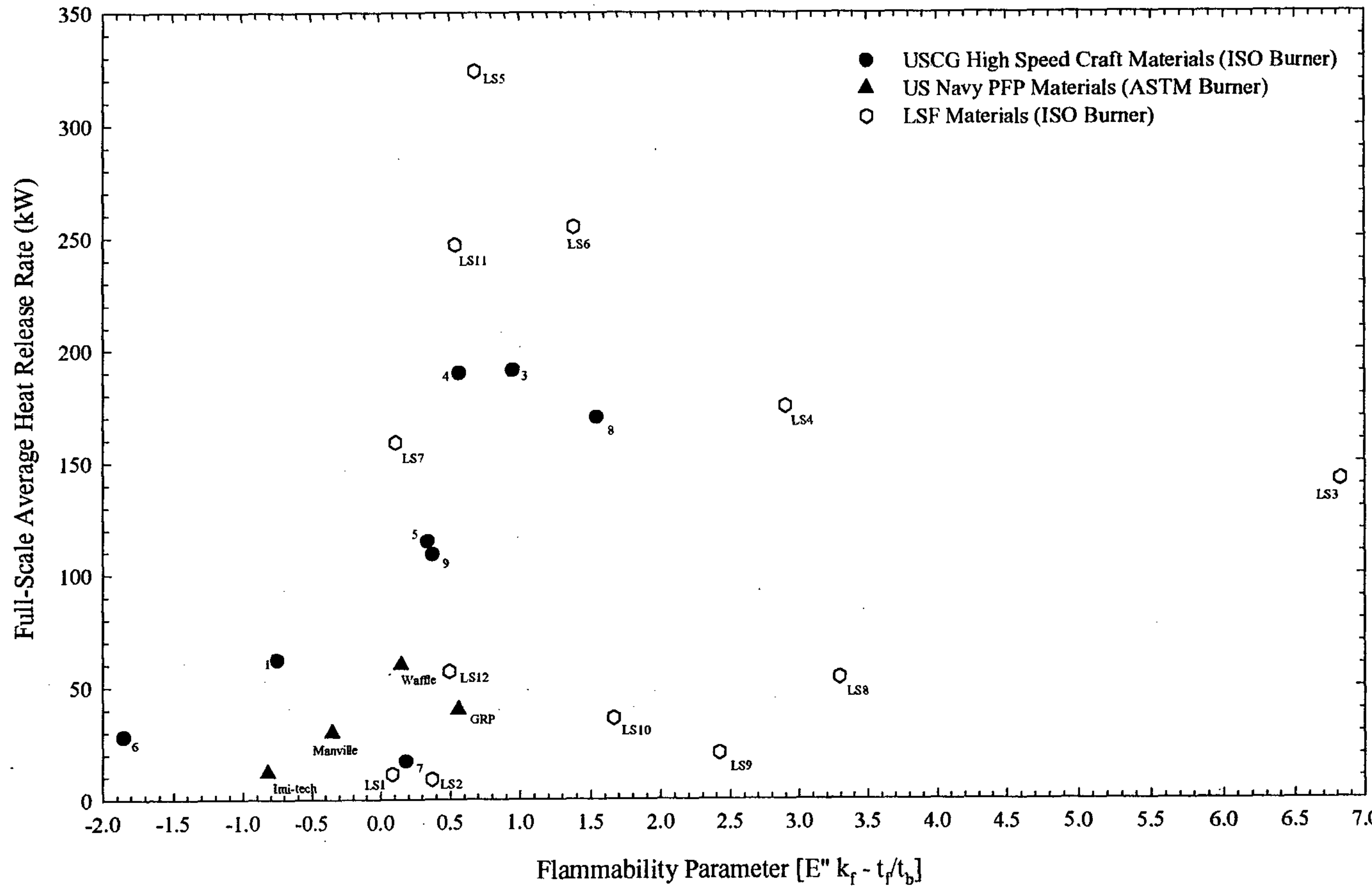

Figure 10. **Comparison of USCG High Speed Craft Materials Results with PFP Navy and LSF Materials Results.**

The correlation of peak and average full-scale heat release with Flammability Parameter from data at the 50 kW/m^2 exposure level for USCG High Speed Craft Materials, PFP Materials, Textile Wall Covering Materials on gypsum board, Swedish Products (only peak available), EUREFIC Products (only peak available) and LSF Materials generally follow the Flammability Parameter correlation. Figures 5 and 8 show the correlation of the full-scale peak and average heat release rates with Flammability Parameter for USCG High Speed Craft Materials only. The correlation of the full-scale results by the Flammability Parameter is quite good. The Flammability Parameter provides a simple means for interpreting Cone Calorimeter data to assess the expected performance in the larger and more costly ISO 9705 Test. The success of the correlation based on Cone tests at 50 kW/m^2 incident heat flux and prior studies (Mowrer & Williamson (1991), Beyler *et al.* (1995), Tewarson (1995), Karlsson (1992)) clearly indicate that 50 kW/m^2 is the preferred test heat flux if only limited Cone Calorimetry is possible. Based on the 53 materials evaluated, five materials had Flammability Parameters less than zero. These materials contributed very little heat to fire development.

In the ISO 9705 Test, USCG Materials 1, 2, 6 and 7 passed the peak and average heat release requirements and all these materials had a flammability parameter less than 0.2. All other tested materials failed by both the ISO 9705 peak/average heat release and Flammability Parameter criterion. Based on the USCG data alone, a Flammability Parameter less than 0.2 would have reproduced the results of the ISO 9705 Testing. However, there are a few materials (E5, E8, and LSF 7) which would have passed by the FP # 0.2 criterion that did not pass the ISO 9705 criterion. Clearly, the behavior of materials changes drastically for modest changes in FP in this region, and this calls for some conservatism in the assessment of the FP pass/fail criterion. Based on all the data available, the recommended FP pass criterion is $FP \leq 0.0$. Note there exists a gap for FP from -0.74 to 0.34 in the USCG data due to material 7's behavior (i.e., textile falling off the wall during testing). However, the $FP \leq 0.0$ criterion is based on all the data reviewed and correlated. It is of note that of the USCG, Navy, and LSF Tests where both peak and average heat release data was available, only one material, LS8, would have passed the heat release criterion in ISO 9705, but with an FP of 3.3 fails by the Flammability Parameter criterion.

Figures 11-13 show the correlation of the time to flashover as a function of the Flammability Parameter. While this is not a criterion in the ISO 9705 Test Method, no flashovers were observed in any of the tests for FP < 0.3. There are a few materials with FPs between 0.3 and 1.0 which do not flashover, as well as two LSF Materials (LS10 and LS8) with higher FPs which do not flashover.

3.2.3 Correlation of Smoke Production Using the Flammability Parameter

There have been numerous efforts to develop correlations between small-scale and large-scale smoke data over the years (e.g. Quintiere (1982), Ostman and Tsantaridis (1991), Ostman and Tsantaridis (1993), Ostman and Tsantaridis (1994), Hirschler (1993), Christian and Waterman (1971), and Heskestad and Hovde, (1994)). Most of the investigations in this area have focused on correlating smoke production rate in bench-scale versus full-scale tests using statistical analysis (linear regression). Often, direct raw data from extinction-beam photometer have been compared. Such comparisons cannot be expected to produce adequate correlations since the effects of different burning rates in the tw.ɔ situations are not considered. The correct variable by which to attempt correlations is specific extinction area (σ_f). For materials where the σ_f does not change much over time, good correlation might be expected on such a basis. For some materials, however, the smoke production may vary greatly over the burning period.

With the specific extinction area (σ_f) from the Cone Calorimeter, smoke production rate (SPR) has be calculated using peak or average heat release rates from full-scale Room/Corner Fire Tests as follows:

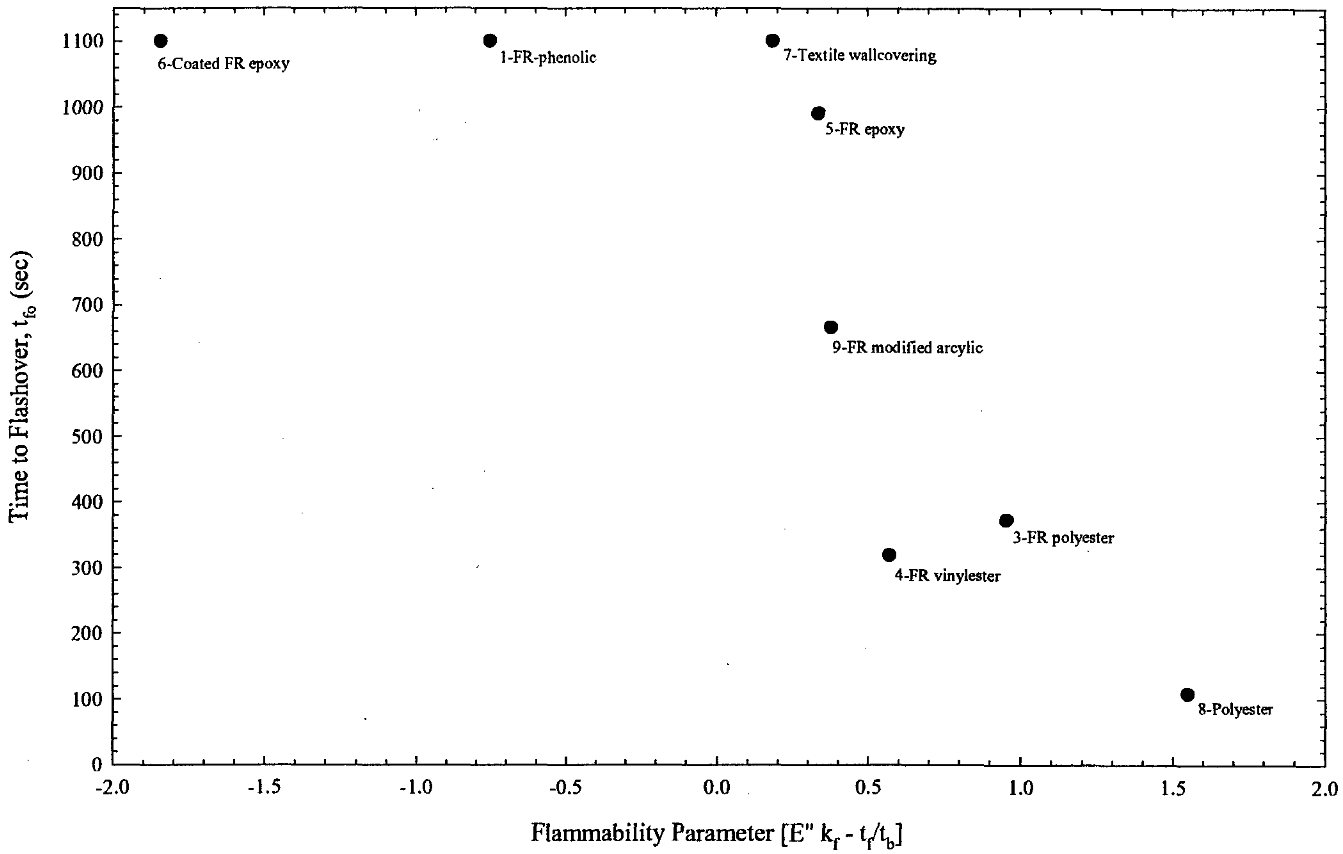

Figure 11. **Correlation of the Time to Flashover with Flammability Parameter for the USCG High Speed Craft Materials.**

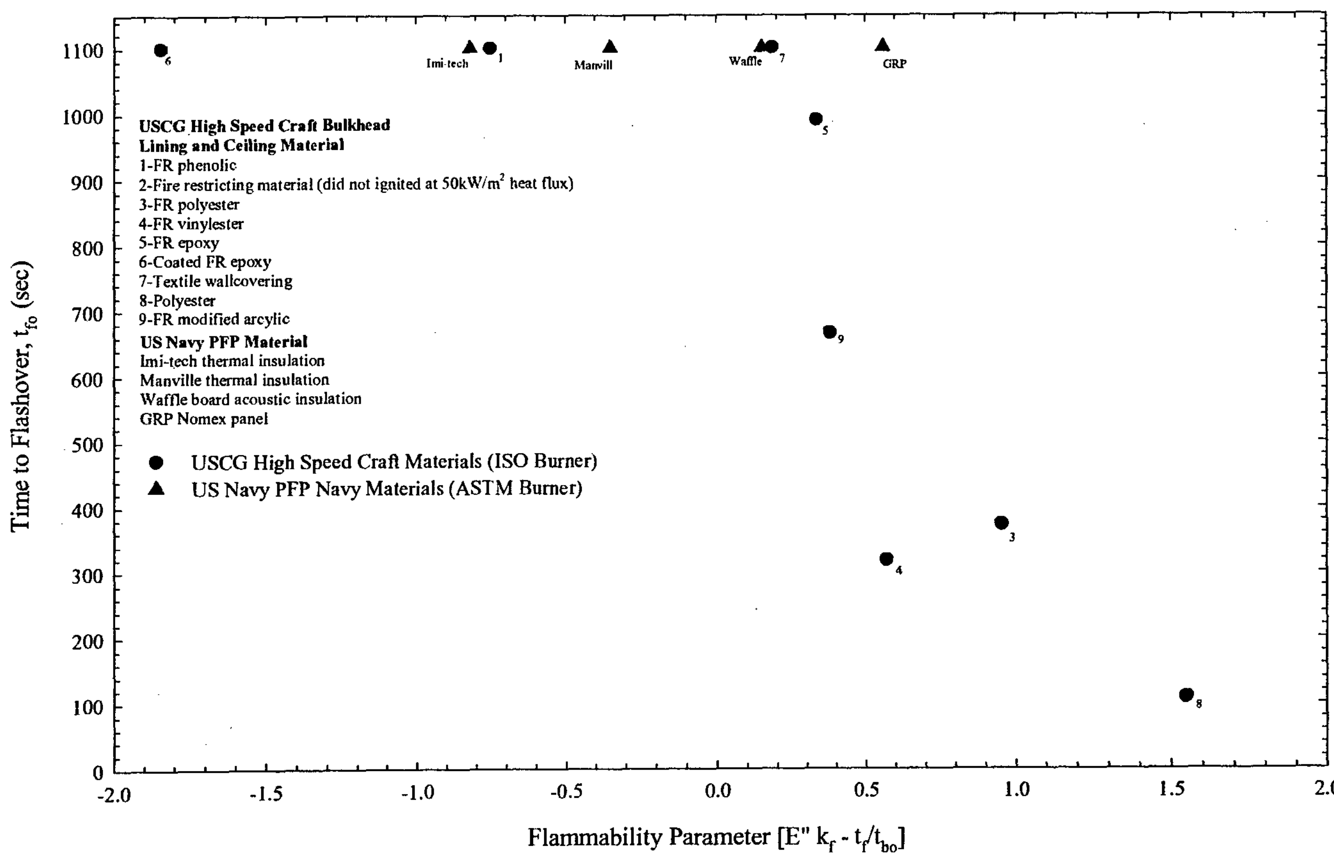

Figure 12. Comparison of USCG High Speed Craft Materials Results with PFP Navy Results.

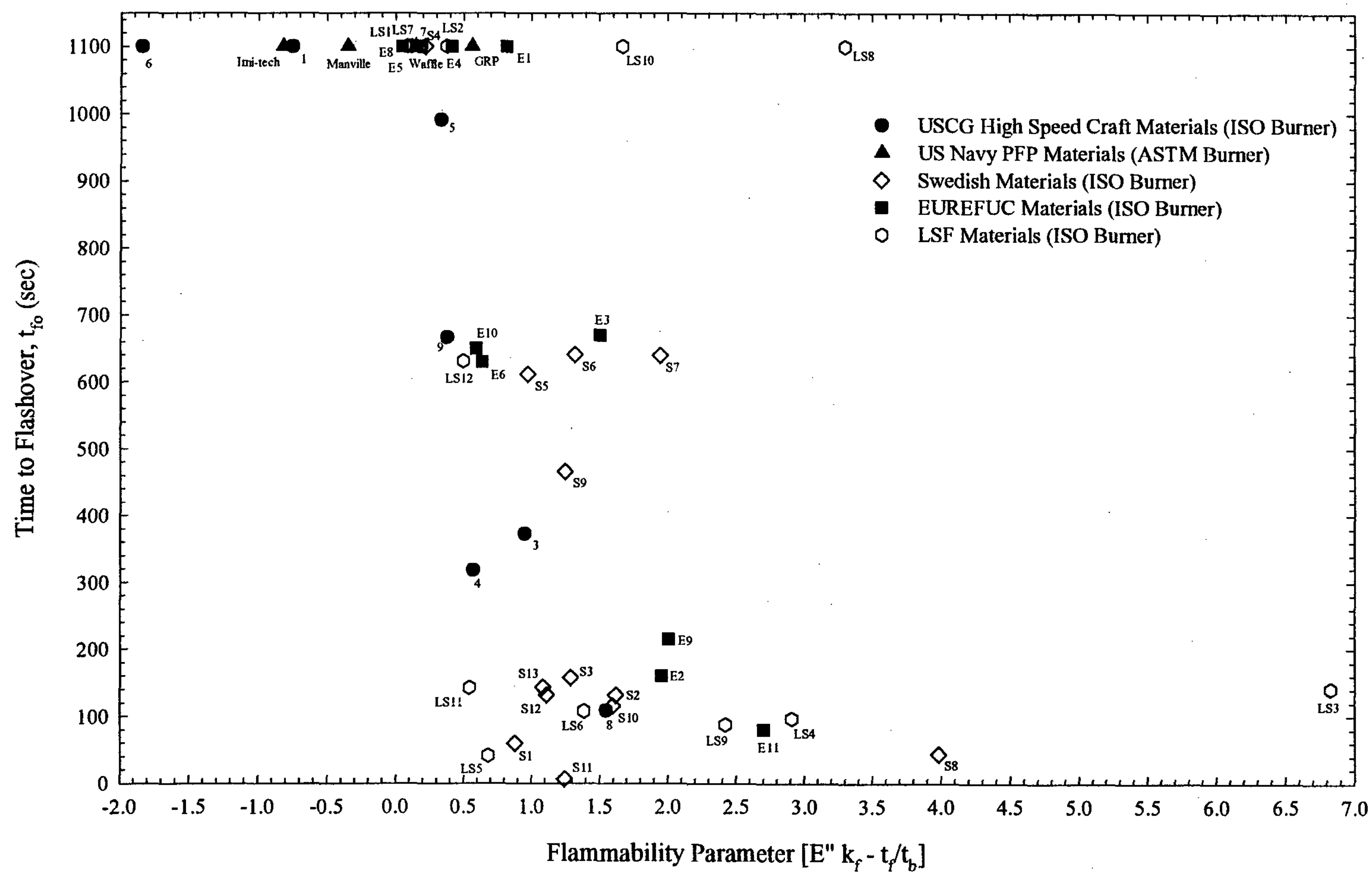

Figure 13. Comparison of USCG High Speed Craft Materials Results with PFP Navy, Swedish, EUREFIC, and LSF Materials Results.

$$\dot{m}_f = \frac{\dot{Q}}{\Delta H_c} \tag{11}$$

where $\dot{m}_f$ is the mass loss rate of the material (kg/sec),

$\dot{Q}$ is the peak or average heat release rate from full-scale Room/Corner Test (kW), and

ΔH_c is the effective heat of combustion from Cone Calorimeter Tests (kJ/kg).

Now the predicted smoke production rate $(SPR)_{pred}$ can be estimated as:

$$(SPR)_{pred} = \dot{m}_f \sigma_f \tag{12}$$

where $(SPR)_{pred}$ is the predicted smoke production rate (m^2/sec), and

σ_f is the specific extinction area from the Cone Calorimeter (m^2/kg).

The smoke production rates for the USCG High Speed Craft Materials are shown in Table 5, based on measured full-scale heat release rate, measured average Cone Calorimeter specific extinction area, σ_f, and Cone Calorimeter average effective heat of combustion. The measured smoke production rates in full-scale Room/Corner Fire Tests are also shown. The effective heats of combustion and specific extinction areas are averaged over all Cone Calorimeter tests where the sample ignited.

Figures 14 and 15 show the correlation between the predicted peak and average smoke production rate based on the specific extinction area of obtained in the Cone Calorimeter (according to Equation 12) and the peak smoke production rate measured in the full-scale ISO 9705 Room/Corner Test. A fairly good correlation can be seen in each figure through agreement is less satisfactory than the prior heat release results, as is most often the case with smoke predictions. It is significant that in the more reliable average SPR results there is no systematic bias in the results, indicating that the small-scale cone results are representative of full-scale performance.

Table 5. **Summary of Predicted and Measured Full-Scale Room/Corner Tests Smoke Production Rate Results for the USCG High Speed Craft Bulkhead Lining and Ceiling Materials.**

USCG High Speed Craft Materials	Effective Heat of Combustion Average at all Cone Heat Fluxes, ΔH_c (kJ/kg)	Average Smoke Extinction Area Based on all Cone Heat Fluxes (m^2/kg)	Average Mass Loss Rate (kg/sec)	Predicted Average Smoke Production Rate (m^2/sec)	Peak Mass Loss Rate (kg/sec)	Predicted Peak Smoke Production Rate (m^2/sec)	ISO Full-Scale Peak Smoke Prod. Rate (m^2/sec)	ISO Full-Scale Average Smoke Prod. Rate (m^2/sec)
1-FR phenolic	8200	100.00	0.0075	0.739	0.019	1.90	5.41	1.50
2- Fire restricting material	9625	16.50	0.0032	0.053	0.013	0.22	0.47	0.15
3-FR polyester	11283	732.00	0.1600	11.750	0.060	41.65	21.7	10
4-FR vinylester	13433	943.00	0.0141	13.340	0.039	32.50	32.1	9.08
5-FR epoxy	8700	249.00	0.0132	3.300	0.048	12.00	26.4	6.39
6-Coated FR epoxy	7725	173.00	0.0036	0.650	0.017	3.00	3.46	1.45
7-Textile wall covering	9083	63.34	0.0018	0.110	0.014	0.92	0.16	0.10
8-Polyester	21600	741.40	0.0078	5.840	0.026	19.50	4.10	2.28
9-FR modified acrylic	12277	74.55	0.0088	0.660	0.066	3.30	3.81	0.62

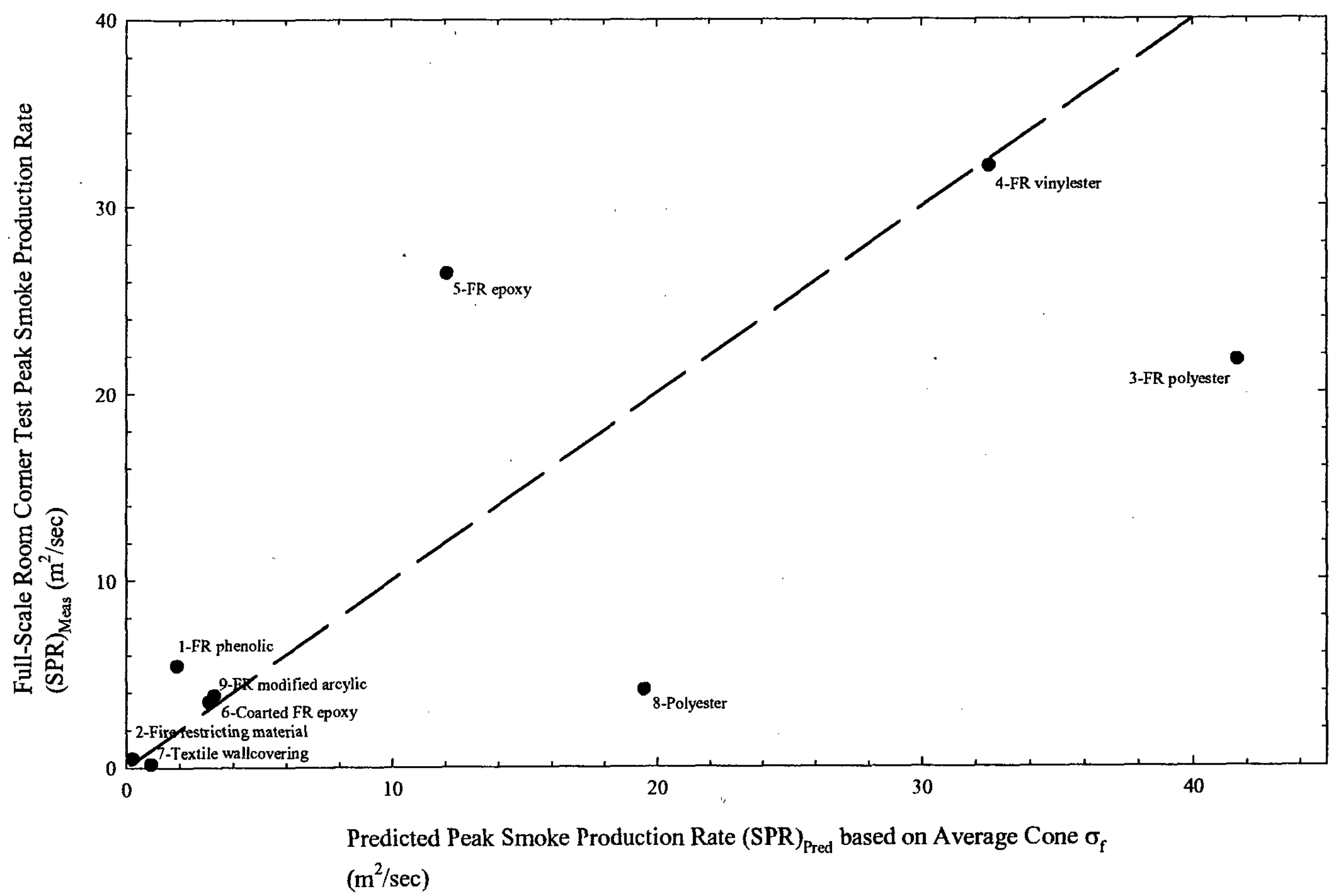

Figure 14. Correlation of the Full-Scale Peak Smoke Production Rate with Predicted Peak Smoke Production Rate for the USCG High Speed Craft Materials.

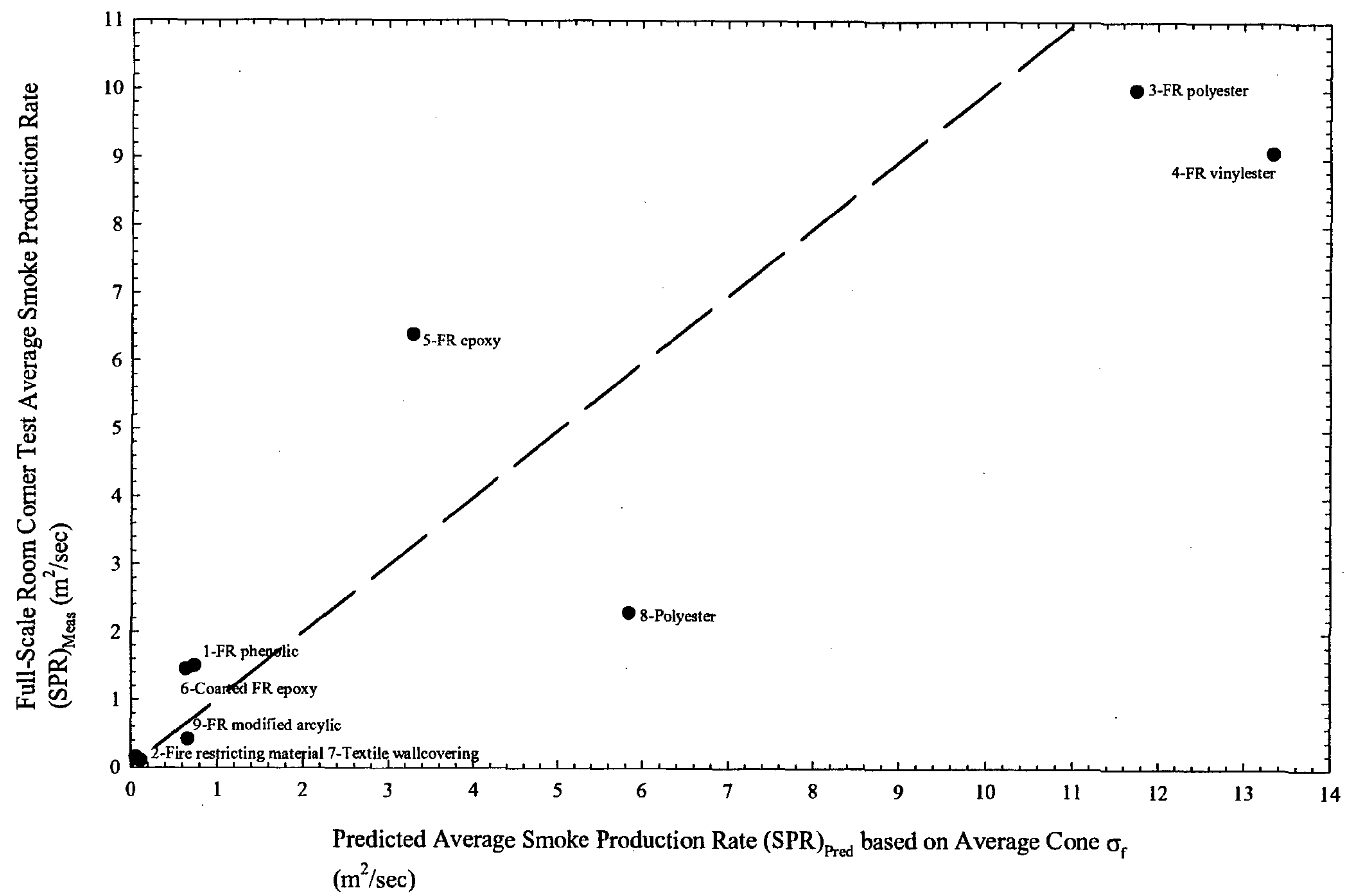

Figure 15. Correlation of the Full-Scale Average Smoke Production Rate with Predicted Average Smoke Production Rate for the USCG High Speed Craft Materials.

Figure 16 shows the peak SPR comparison for USCG, Swedish, and EUREFIC data, the only data sets that include the smoke data required for this comparison. The correlation for all the data is not satisfactory. Unfortunately, there are quite large variation of the Swedish and EUREFIC Products. The predicted smoke production based on the Cone Calorimeter smoke extinction area is probably the best parameter for comparing smoke production rate measured in full-scale Room/Corner Tests.

A potential alternate means of correlating smoke data is through the use of smoke yield. In full-scale Room/Corner Test, the smoke yield is not measured, but by using the full-scale measured smoke production rate, heat release rate, and the effective heat of combustion measured in Cone Calorimeter, the full-scale smoke yield can be estimated as follows:

$$Y_{smoke} = \frac{\sigma_{fuel}}{\sigma_{smoke}} \tag{13}$$

where σ_{fuel} specific extinction area of soot mass of fuel (kg/m^2) and

σ_{smoke} specific extinction area of smoke (kg/m^2) and

$$\sigma_{fuel} = \frac{(SPR)_{full}}{\dot{m}_f} = \frac{(SPR)_{full}\,\Delta H_c}{\dot{Q}_{full}} \tag{14}$$

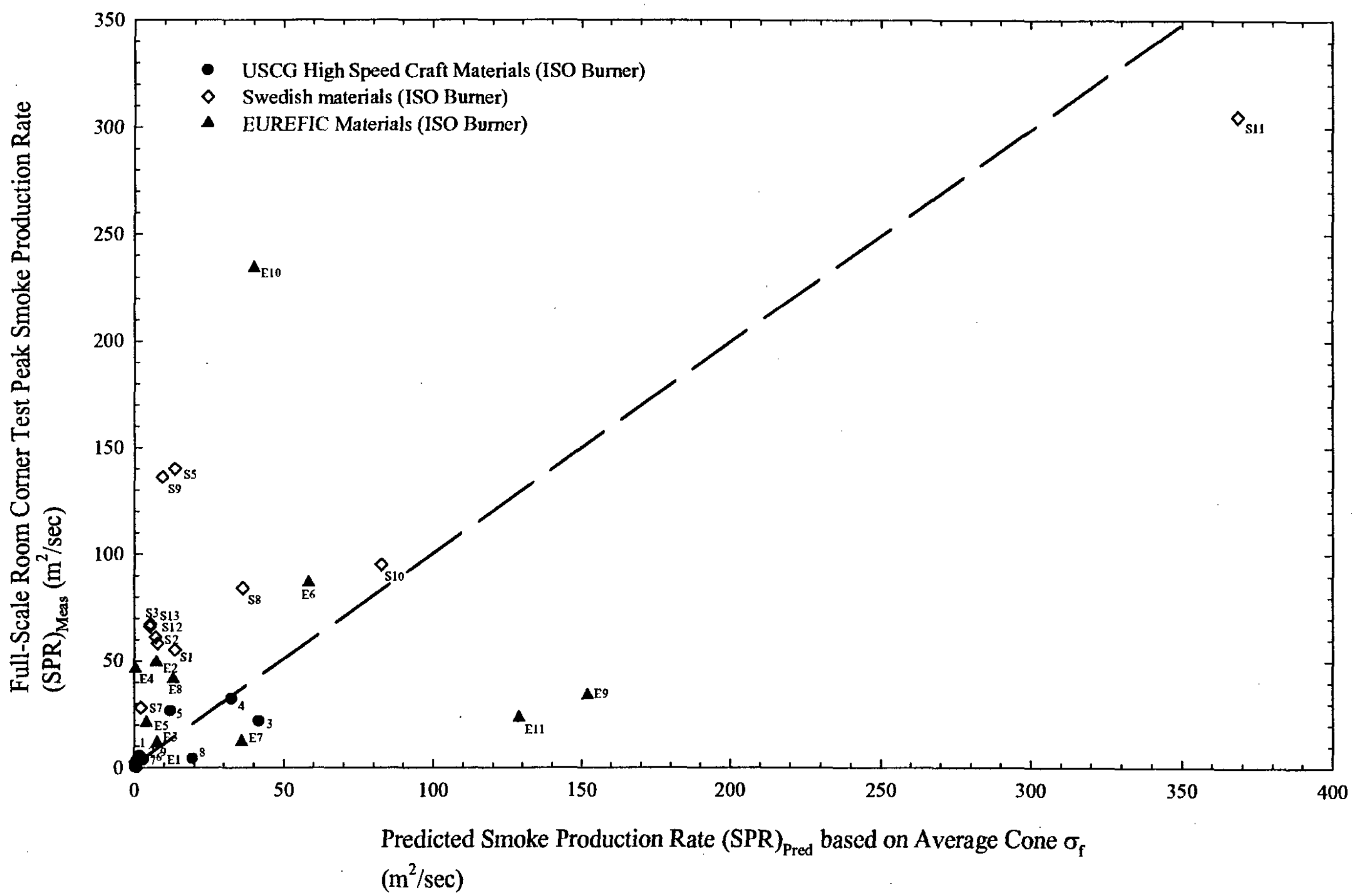

Figure 16. Comparison of USCG High Speed Craft Materials Peak Smoke Production Rate Results with Swedish and EUREFIC Products Results.

The smoke extinction area has been experimental determined by Neuman and Steciak (1987) to be

$$\sigma_{smoke} = 10053 \frac{m^2}{kg} \tag{15}$$

Combining Equations 13, 14, and 15 yields

$$Y_{smoke(full)} = \frac{(SPR)_{full} \Delta H_c}{\dot{Q}_{full} 10053} \tag{16}$$

and using Equation 13 smoke yield, for the Cone Calorimeter is

$$Y_{smoke(cone)} = \frac{\sigma_{f(cone)}}{10053} \tag{17}$$

The yield can be assessed based on peak or average conditions during the room test. The heat of combustion and the specific extinction coefficient determined in the Cone Calorimeter are taken as the average over all tests where ignition was achieved. The smoke yield correlation plot is shown in Figures 17 and 18 and tabulated in Table 6. The qualities of the correlation are similar to the prior smoke production correlation with better performance for the average results as expected. The smoke yield values are in the expected range and again there is not bias in the end results.

Figure 19 shows a comparison of smoke yields using the USCG, Swedish, and EUREFIC data. As before, the overall correlation is not satisfactory, though no Cone Calorimeter bias is objectionable and the smoke yields are realistically on the range 0-0.10.

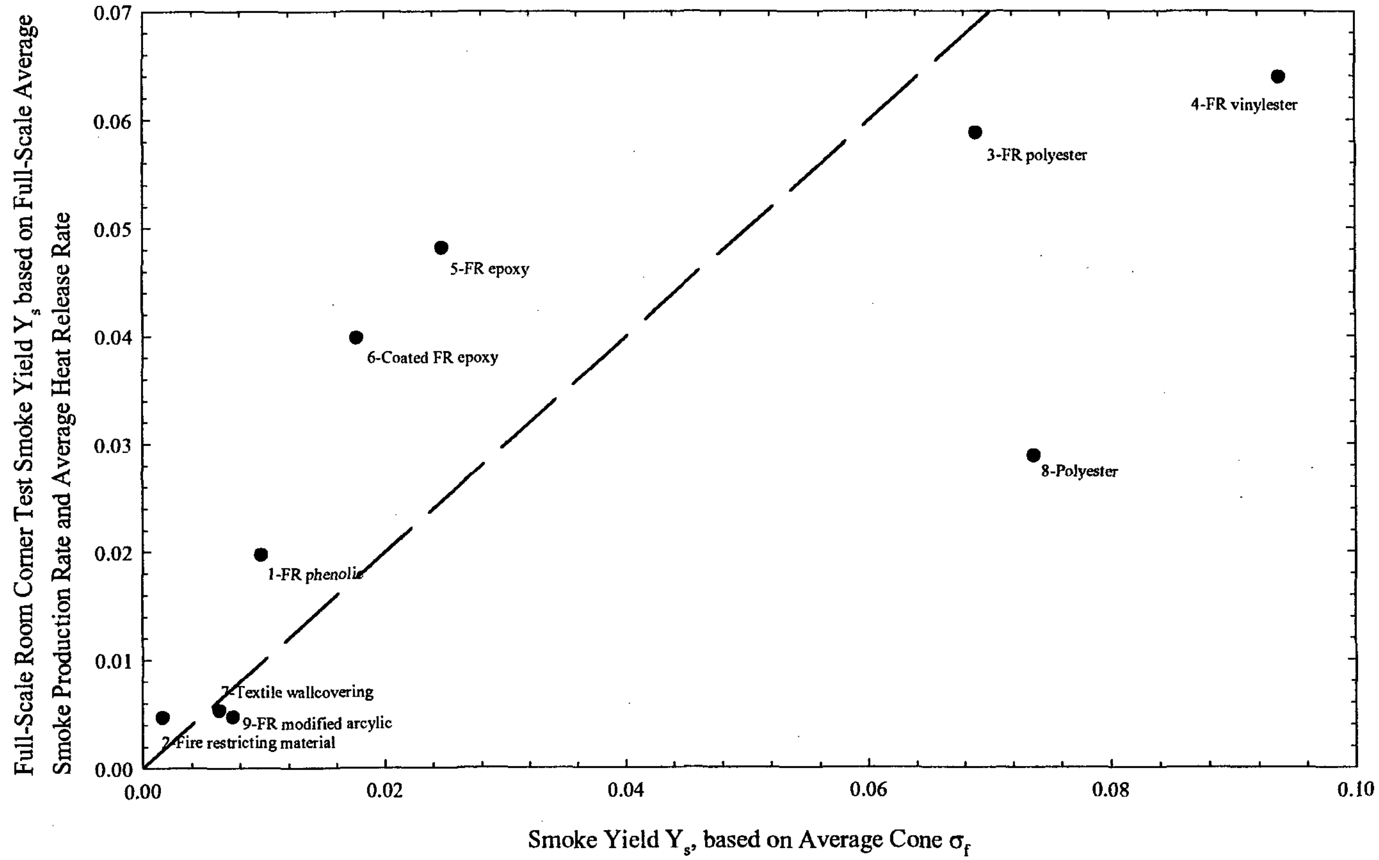

Figure 17. Correlation of the Full-Scale Smoke Yield with Small-Scale Smoke Yield for the USCG High Speed Craft Materials.

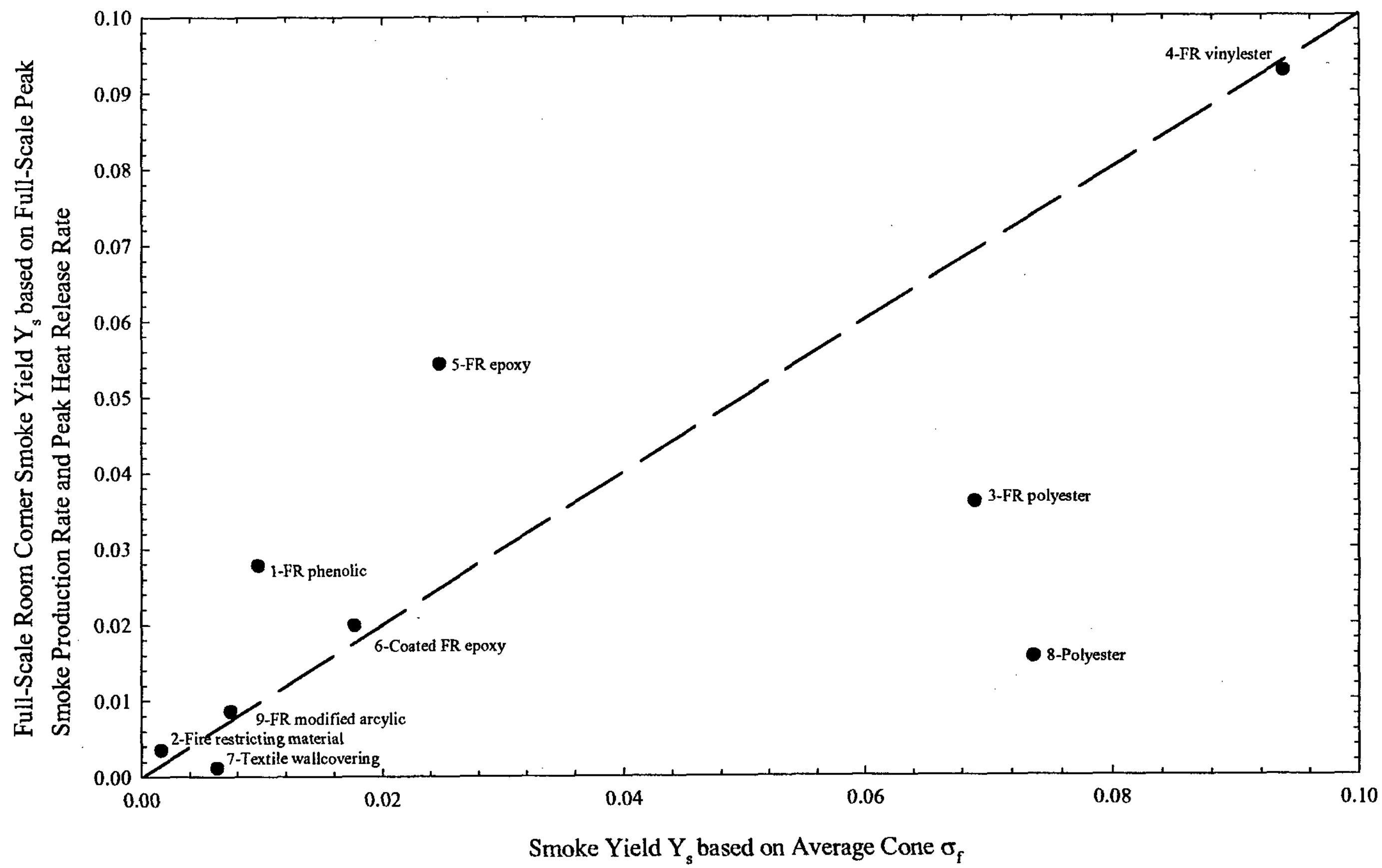

Figure 18. Correlation of the Full-Scale Smoke Yield with Small-Scale Smoke Yield for the USCG High Speed Craft Materials.

Table 6. Summary of Cone Calorimeter and Full-Scale Room/Corner Tests Smoke Yields Results for the USCG High Speed Craft Bulkhead Lining and Ceiling Materials.

USCG High Speed Craft Materials	Average Smoke Extinction Area Based on all Cone Heat Fluxes (m^2/kg)	Optical Parameter	Cone Smoke Yield	Effective Heat of Combustion. Average at all Cone Heat Fluxes, ΔH_c (kJ/kg)	ISO Full-Scale Peak Smoke Yield, $Y_{full\ peak}$	ISO Full-Scale Average Smoke Yield, $Y_{full\ avg}$
1-FR phenolic	100.00	10053	0.0090	8200	0.0270	0.0190
2- Fire restricting material	16.50	10053	0.0016	9625	0.0030	0.0040
3-FR polyester	732.00	10053	0.0690	11283	0.0350	0.0350
4-FR vinylester	943.00	10053	0.0930	13433	0.0920	0.0920
5-FR epoxy	249.00	10053	0.0240	8700	0.0540	0.0540
6-Coated FR epoxy	173.00	10053	0.0170	7725	0.0190	0.0190
7-Textile wall covering	63.34	10053	0.0060	9083	0.0010	0.0001
8-Polyester	741.40	10053	0.0730	21600	0.0155	0.0150
9-FR modified acrylic	74.55	10053	0.0070	12277	0.0080	0.0080

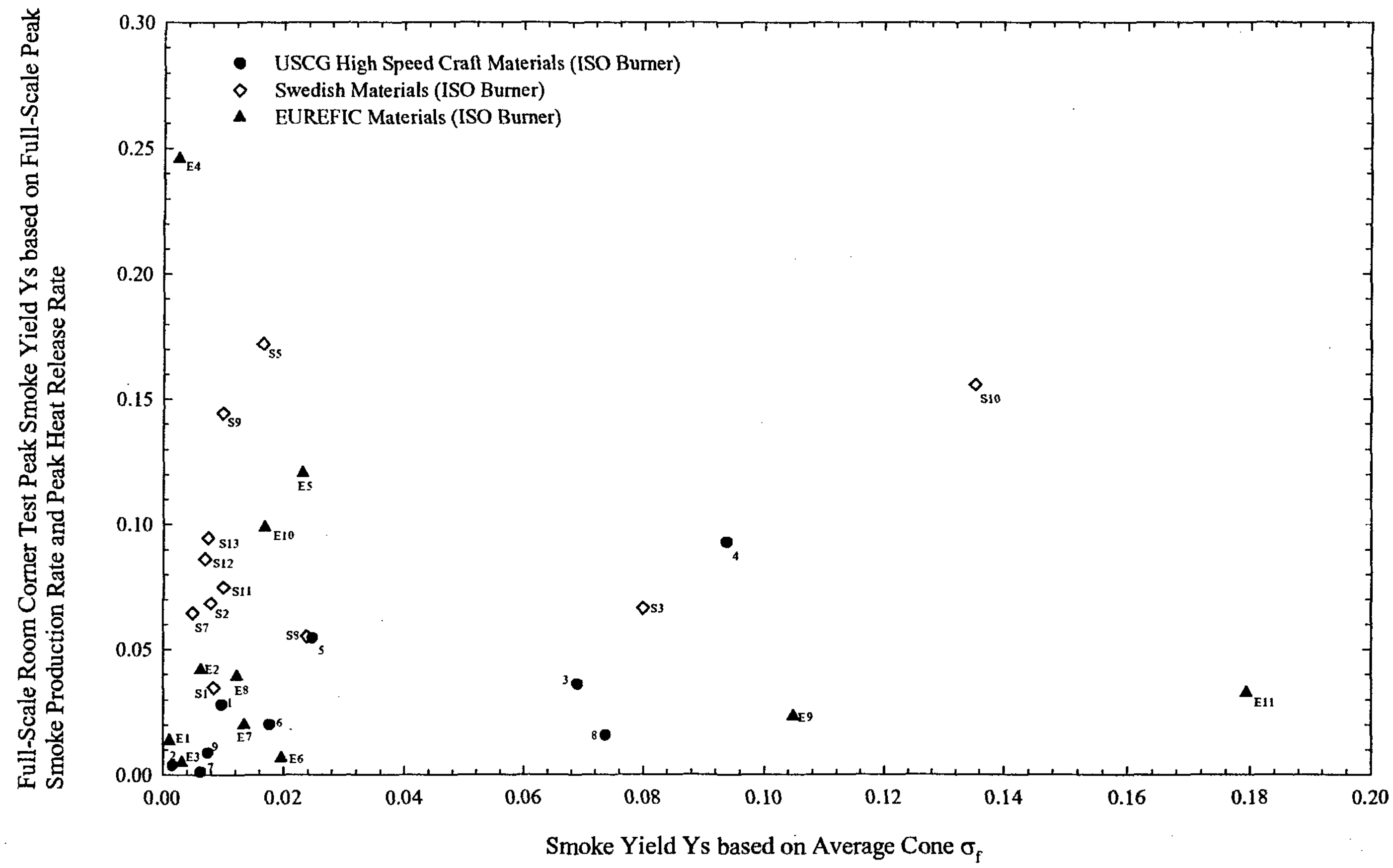

Figure 19. **Comparison of USCG High Speed Craft Materials Smoke Yield Results with Swedish and EUREFIC Products Results.**

4.0 ROOM/CORNER FIRE MODELS

The value of fire models over the simple correlations results from the ability of fire models to include detailed mathematical models of each aspect of fire spread and room fire growth. This enhanced basis allows the fire model to make use of more detailed input information concerning the room and the materials involved. This makes fire models more generally applicable and more robust technically than simple correlations.

Three room/corner fire models were used to predict the results of the USCG ISO 9705 Tests performed by Janssens *et.al.* (1998). These models include the a Modified Quintiere/Dillon Room/Corner Fire Model (Quintiere 1993, Dillon, *et al.*1998), the WPI Room/Corner Fire Model (Wright, 1999), and the HAI/Navy Corner Fire Model (Lattimer *et.al.*, 1999). In this section an overview of each of the models is presented and the results of the predictions of each model are critically reviewed. Detailed model descriptions and complete modeling results are provided in Volume II of this report.

4.1 Overview of the Models

All three of the models are implemented as computer programs. However, the levels of complexity vary significantly, the input data reduction methods vary considerably, and the details of the models for component phenomena differ widely. Generally speaking, the Quintiere/Dillon Model is the simplest model and the HAI/Navy Model is the most complex.

4.1.1 Modified Quintiere/Dillon Room/Corner Model

This is the simplest model of the three evaluated here. This model includes consideration of flame spread on the wall and ceiling portions of a compartment. The heat flux in each of the regions is assumed to be constant. Gridding is effectively not used in this approach, though the burning region is dynamic. The room environment is modeled using a simple correlational approach, which has been successfully used for a wide range of room fire scenarios.

The model as used in this work is modified from the prior Quintiere/Dillon Model based on the shortcomings identified in this project. Changes were made to the methods of determining ignition and flame spread properties. The model was changed to use Cone Calorimeter data directly instead of using the heat of gasification approach previously used, and smoke production prediction was added to the model. These modifications resulted in significant improvements in the performance of the model.

4.1.2 WPI Room/Corner Fire Model

The WPI Model is derived from a wall fire model originally developed by Milter (1994) and Mitler and Steckler (1995). This original model included one-dimensional flame spread and used a one-dimensional grid to predict flame spread. The heating of elements above the fire is predicted and flame spread to the element occurs when the element temperature reaches the material's ignition temperature. The WPI model generalizes this approach to a corner configuration, but retains the one-dimensional gridding of the original Mitler model. Modifications were made to reflect flame height numbers, heat flux correlati ons, and radiation exchange numbers applicable to the corner geometry. In addition, the fire spread model was integrated into CFAST (Peacock *et.al*, 1997), which is a detailed compartment fire model. CFAST is used to predict the compartment environment created by the corner fire.

4.1.3 HAI/Navy Corner Fire Model

The HAI/Navy Corner Fire Model was originally developed as a wall fire spread model (Beyler *et.al.*, 1997), but was always intended to be generalized to the corner configuration. The gridding of the corner configuration is two-dimensional, so that the prediction of heating of the material surface is more spatially refined than the other models. Heat flux mapping experiments were performed to develop heat flux maps for use in the model. Heat of gasification methods are used in this model to determine burning rates. The room gas temperature is predicted using the same sub-model as the Quintiere/Dillon Model.

4.2 Modeling Results

Each of the three models was used to predict the USCG ISO 9705 Test results (Janssens *et.al.*, 1998). The Cone Calorimeter and LIFT test results for each material were available for determination of input parameters (Janssens *et.al.*, 1998).

4.2.1 Quintiere/Dillon Room/Corner Model Results

Model Inputs

The basic Quintiere/Dillon Room/Corner Model uses standard data reduction methods in the Cone Calorimeter and LIFT Test Methods to obtain ignition and flame spread inputs. However, the modified method used in this work uses a different means to determine ignition properties in the Cone Calorimeter. The method used to deduce ignition properties differs from the algorithm used in the model itself. This can lead to inconsistent results. The modified ignition data reduction methods used resulted in critical heat fluxes that were generally less than the measured results. For Materials 3-9, the deduced critical flux was 0-5 kW/m^2 less than measured. For Materials 1 and 2, the critical heat fluxes were about 20 kW/m^2 less than measured. While the 1200 second test duration in the Cone Calorimeter Test may be too short, it is unlikely that the experimental critical heat fluxes would be reduced to the deduced values by longer test durations. The heat release rate model used in the modified Quintiere/Dillon Model uses 50 kW/m^2 incident flux Cone Calorimeter data directly, without regard for the actual heat flux. This input is used in lieu of the heat of gasification normally used in the Quintiere/Dillon Model. This modification was made as a result of initial simulations using the Quintiere/Dillon Model (see Appendix A of Volume II), which generally underestimated the experimental results. It was concluded that the excessively high heats of gasification were responsible for this behavior. This conclusion was reached despite the fact that the heat of gasification is likely underestimated by the Quintiere Method due to the use of the maximum Cone Calorimeter heat release rate in the determination of the heat of gasification.

Model Results

The model results are summarized in Table 7. The full modeling results (heat release rate, room temperature, and smoke production) for each of the nine tested materials are given in Appendix A of Volume II. Table 7 shows comparisons of experimental and model flashover times. The experimental flashover times are based on the time to reach one MW heat release and are generally somewhat less than the time to flames out the door. In the case of Material 5, flames were observed at the door but the heat release rate never reached 1 MW, so the heat release rate criterion used was reduced to 750 kW. This illustrates the somewhat arbitrary nature of the heat release rate criterion. As can be seen in the table, the model does an excellent job in predicting flashover. Only for Material 5 is there a significant difference in the flashover times.

Table 7 also shows the peak and average heat and smoke release results for materials that did not cause flashover in the test. The heat release results are generally quite good and the smoke release predictions tend to be low.

Materials 5 and 9 presented the greatest challenge to the model. While the differences in the modeled versus the predictions are clear in Table 7 for Material 5, the differences are not clearly shown for Material 9. Though the time to flashover is correctly predicted for Material 9, the heat release rate histories are quite different. This can be seen in Appendix A of Volume II.. Overall, this model performed very well, especially in the light of the simplicity of the model.

Model Sensitivity Analysis

No sensitivity analysis was completed for this model. As such, the importance of various inputs to the predicted results is not known at this time.

Table 7. Summary of ISO Room/Corner Test Results and HAI/U.S. Navy Room/Corner Model Results for the Modified Quintiere/Dillon Model.

USCG High Speed Craft Materials	Time to Flashover t_{fo} 1 MW (500 °C)		ISO 9705 Room/Corner Test Full-Scale Heat Release Rate		Predicted Heat Release Rate from Room/Corner Model		ISO 9705 Room/Corner Test Full-Scale Smoke Production Rate		Predicted Smoke Production Rate from Room/Corner Model	
	ISO 9705 Room/ Corner Test (sec)	Room/ Corner Model (sec)	Peak 30 sec Average (kW)	Net Average (kW)	Peak (kW)	Net Average (kW)	Peak 60 sec Average (m^2/sec)	Net Average (m^2/sec)	Peak (m^2/sec)	Net Average (m^2/sec)
1-FR phenolic	∞	∞	159	62	120	36	5.4	1.5	2.0	0.6
2- Fire restricting Material	∞	∞	129	31	134	47	0.5	0.2	0.2	0.1
3-FR polyester	342	345								
4-FR vinylester	306	305								
5-FR epoxy	978	666								
6-Coated FR epoxy	∞	∞	134	28	193	8	3.5	1.5	4.5	0.3
7-Textile wall covering*	∞	∞	131	17	194	48	0.2	0.1	1.5	0.4
8-Polyester	102	56								
9-FR modified acrylic	672	611								
IMO Critera (Resolution MSC.40 (64))			≤500 kW	≤100 kW	≤500 kW	≤100 kW	≤8.3 m^2/s	≤1.4 m^2/s	≤8.3 m^2/s	≤1.4 m^2/s

Shaded regions indicate tests that were terminated due to severe fire conditions. As such, the peak heat release rate and smoke production rate comparisons are invalidated by the test termination. Average heat and smoke release rates are averaged up to the time of predicted flashover to be consistent with the tests.
*Material No. 7 (textile wall covering) fell off the wall during the Room/Corner test.

4.2.2 WPI Room/Corner Fire Model Results

Model Inputs

The most notable issue with model inputs for the WPI Model is the extensive use of literature data sources. The model was not formulated to be driven by Cone Calorimeter and LIFT data alone. This leaves the determination of many input parameters ill-defined. This would confound a material developer who wishes to use the model to assess the performance of a newly developed material. Where is he to go in the literature to find data for the developer's "new" material? This seems to originate from the original Mitler Model and has not been fully addressed by the WPI modelers.

Model Results

The full modeling results (heat release rate, room temperature, and smoke production) for each of the nine tested materials are given in Appendix B of Volume II. The results are summarized in Table 8. Table 8 provides the predicted and measured times to flashover as well as peak and average heat release rates, and peak and average smoke production rates. The experimental peak heat release rates and peak smoke production rates are averaged over 30 seconds and 60 seconds, respectively, to deal with noise in the data.

The model is most seriously challenged in the predictions for Materials 3, 4, 5, and 9. Each of these materials lead to flashover in the experiments, but the predictions do not yield flashover during the test period. For Materials 3 and 4, the time to involvement of the wall material is predicted to not occur until the burner reaches 300 kW, while in the tests the material became involved during the 100 kW burner period. For Materials 5 and 9, the time for material involvement was correctly predicted to occur at the start of the 300 kW burner heat release rate, but the extent of involvement of the material is under-predicted.

Table 8. Summary of ISO Room/Corner Test Results and HAI/U.S. Navy Room/Corner Model Results for the WPI Model.

USCG High Speed Craft Materials	Time to Flashover t_{fo} 1 MW (500 °C)		ISO 9705 Room/Corner Test Full-Scale Heat Release Rate		Predicted Heat Release Rate from Room/Corner Model		ISO 9705 Room/Corner Test Full-Scale Smoke Production Rate		Predicted Smoke Production Rate from Room/Corner Model	
	ISO 9705 Room/ Corner Test (min)	Room/ Corner Model (min)	Peak 30 sec Average (kW)	Net Average (kW)	Peak (kW)	Net Average (kW)	Peak 60 sec Average (m^2/sec)	Net Average (m^2/sec)	Peak (m^2/sec)	Net Average (m^2/sec)
1-FR phenolic	∞	∞	62	159	48	192 (194)	1.50	5.41	2.51	7.45 (7.71)
2- Fire restricting Material	∞	∞	31	129	28	109 (118)	0.15	0.47	1.77	4.33 (4.66)
3-FR polyester	5.8	N/A	191	677	119	366 (388)	10.00	21.70	8.66	23.34 (25.05)
4-FR vinylester	5.1	N/A	190	463	152	660 (693)	9.08	32.10	10.17	38.23 (41.20)
5-FR epoxy	16.4	N/A	115	421	44	218 (223)	6.39	26.40	5.80	22.69 (24.97)
6-Coated FR epoxy	∞	∞	28	134	67	164 (166)	1.45	3.46	8.27	18.91 (19.25)
7-Textile wall covering*	∞	∞	17	131	11	77 (82)	0.10	0.16	0.91	1.41 (1.41)
8-Polyester	1.8	1.4	170	568	131	361 (901)	2.28	4.10	3.86	5.30 (32.23)
9-FR modified acrylic	11.3	N/A	109	542	109	109 (512)	0.42	3.81	1.38	3.30 (3.51)
IMO Criteria (Resolution MSC.40 (64))			≤500 kW	≤100 kW	≤500 kW	≤100 kW	≤8.3 m^2/s	≤1.4 m^2/s	≤8.3 m^2/s	≤1.4 m^2/s

Shaded regions indicate tests that were terminated due to severe fire conditions. As such, the peak heat release rate and smoke production rate comparisons are invalidated by the test termination. Average heat and smoke release rates are averaged up to the time of predicted flashover to be consistent with the tests.
*Material No. 7 (textile wall covering) fell off the wall during the Room/Corner test.

Where the heat release rates are correctly predicted, CFAST generally over-predicts the hot layer temperature as indicated by the door thermocouple. The predicted hot layer temperature tends to follow the experimental ceiling jet temperatures. The smoke production predictions for cases where the heat release histories are well predicted tend to be high. This is significantly different from the other models evaluated in this program. Heat fluxes to the floor are seriously underestimated in all cases. This behavior is surprising in the light of the over-predictions of the hot layer temperature.

Model Sensitivity Analysis

The sensitivity analysis performed on the WPI Model showed some interesting results. As expected the inputs for the ignition and burning rate models had definite effects on the model results. There was very little sensitivity to the lateral flame spread properties. The sensitivity analysis lead the WPI investigators to question the ability of the bench-scale tests and the model to deal with fire retardant materials, a concern not voiced by other investigators on the project and not apparent in other investigators' results. The model results were surprisingly insensitive to the compartment and ventilation. The model was surprisingly sensitive to the ambient temperature differences within the normal range. The sensitivity analysis was most useful in understanding the dynamics of the model and will contribute to future enhancement of the model.

4.2.3 HAI/Navy Corner Fire Model Results

Model Inputs

Model inputs for the HAI/Navy Model are derived from Cone Calorimeter data, LIFT data, and the specifications for the ISO 9705 Test. Procedures for obtaining the input data are consistent with the algorithms in the model. For instance, ignition data required for the model are derived from Cone Calorimeter ignition test results using the ignition model included in the corner fire model. Similarly, the heat of gasification is deduced using the corner model burning rate algorithms in conjunction with Cone Calorimeter data. As noted in Appendix C of Volume II, this process requires assumptions about the flame heat flux to the sample in the Cone Calorimeter, but clear and direct methods have been developed and used. The only current data which needs to be estimated from other sources are the thermal properties used in the McCaffey, Quintiere, Harkleroad (MQH) correlation for room temperature. These are estimated from handbook thermal properties data. As the temperature given by the MQH correlation is dependent upon thermal inertia raised to the $-1/6^{th}$ power, the results are very insensitive to the properties used. The thermal inertia as deduced from the LIFT Test could have been used, though this was not done in the validation studies of the MQH temperature prediction model. The fact that all data required for use in the model is available from the Cone Calorimeter and LIFT, and that definite methods of deducing these inputs from the test methods is very important and useful to the potential user.

Model Results

The full modeling results (heat release rate, room temperature, and smoke production) for each of the nine tested materials are given in Appendix C of Volume II. The results are summarized in Table 9. This table provides the predicted and measured times to flashover, peak and average heat release rates, as well as peak and average smoke production rates. The experimental peak heat release rates and peak smoke production rates are averaged over 30 seconds and 60 seconds, respectively, to deal with noise in the data. No such averaging has been done on the model predictions. The time to flashover in the model results was determined from the time to reach 500 °C in the upper layer of the compartment (Walton and Thomas, 1995) as well as the time to reach 1 MW heat release rate. For both the experiments and the model, the choice of flashover criterion is not critical. The IMO acceptance criteria for the ISO 9705 Test are given at the bottom of the Table 9.

The model performs well in the prediction of the time to flashover. Materials 1,2, 6, and 7 are correctly predicted to not flashover. The predicted times to flashover in all the remaining tests were within 1-2 minutes of the experimental results.

The peak heat release rate predictions cannot really be compared to the test results in those tests that were terminated before the end of the test due to the severity of the fire. The experimental data corresponds to the period just before the test was terminated, while the model results reflect the peak heat release in the absence of any interference in the test. The average heat release rates reported for the model are averaged only up to the time of flashover, so the average heat release rates can be compared. The pre-flashover average heat release rates compare quite well overall. The peak data which cannot be compared in Table 9 are shaded. Predicted peak heat release rates for materials which did not lead to flashover are 25-35 percent of the measured values, and predicted average heat release rates are 50-90 percent of the measured values.

Predictions of smoke production are generally low. Among the non-flashover materials, predicted peak and average smoke production rates are 10-25 percent of the measured values for Materials 1, 2 and 6. For Material 7 predictions are higher than experimentally observed. While this material did fall off the wall during the test, it is unclear if this artificially reduced the experimentally observed smoke production below what would otherwise be expected.

For materials that did flashover, smoke production predictions up to the time of flashover varied widely. The average smoke production rate for Materials 3 and 4 were within about 10 percent of the experimental values. For Material 5, the average smoke production prediction was about 25 percent of the experimental value. For Material 8, the average smoke production prediction was about 25 times the experimental value! For Material 9, the average smoke production prediction was about 50 percent higher than the experimental value.

These results are far worse than the heat release rate predictions. This is to be expected in that the smoke production prediction uses the heat release rate predictions along with the specific extinction area from the Cone Calorimeter testing to produce the smoke production results. As such, there are additional sources of uncertainty in the smoke predictions. Nonetheless, these results are unsatisfactory and are indicative of a lack of insight into smoke generation in these fires. It is possible that for the materials that do not flashover, the smoke generation is dominated by pyrolysis of material that is not ignited. This phenomenon is not included in the model. As these are the materials that are most acceptable with regard to heat release rate, the failure of the smoke production predictions for these materials is a serious issue.

Model Sensitivity Analysis

The sensitivity analysis for the HAI/Navy Model demonstrated that the node spacing and time step used provided a grid independent solution. This is essential to any reliable comparison with experimental data.

The sensitivity of the model to inputs was evaluated for Materials 3 and 9. Material 3 caused flashover during the 100 kW burner period and Material 9 caused flashover during the 300 kW burner period. Ranges in the input values considered were developed from an examination of the uncertainty and variability of the bench-scale test data for Materials 3 and 9, as well as the results of round robin trials for the bench-scale test methods.

The sensitivity analysis showed that the ignition, lateral flame spread, and burning rate inputs had significant effects on model predictions. The significance of individual parameters depends upon the nature of the material. For some materials lateral flame spread played no role and as such the sensitivity to the associated inputs was low. The effects of room size and ventilation rate were found to be significant for both materials evaluated. This is distinctly different from the behavior noted with the WPI Model.

Table 9. Summary of ISO Room/Corner Test Results and HAI/U.S. Navy Room/Corner Model Results for the USCG High Speed Craft Bulkhead Lining and Ceiling Materials.

USCG High Speed Craft Materials	Time to Flashover t_{fo} 1 MW (500 °C)		ISO 9705 Room/Corner Test Full-Scale Heat Release Rate		Predicted Heat Release Rate from Room/Corner Model		ISO 9705 Room/Corner Test Full-Scale Smoke Production Rate		Predicted Smoke Production Rate from Room/Corner Model	
	ISO 9705 Room/ Corner Test (min)	Room/ Corner Model (min)	Peak 30 sec Average (kW)	Net Average (kW)	Peak (kW)	Net Average (kW)	Peak 60 sec Average (m^2/sec)	Net Average (m^2/sec)	Peak (m^2/sec)	Net Average (m^2/sec)
1-FR phenolic	∞	∞	159	62	56	31	5.40	1.5	0.68	0.38
2- Fire restricting Material	∞	∞	129	31	33	18	0.48	0.15	0.05	0.03
3-FR polyester	5.7 (5.5)	7.5 (7.3)	677	191	2300	140	21.7	10	59	9.1
4-FR vinylester	5.1 (5.0)	6.5 (6.2)	463	190	2990	150	32.0	9	13	11
5-FR epoxy	16.5 (15.2)	15.7 (17.7)	421	115	867	54	26.50	6.5	18	1.6
6-Coated FR epoxy	∞	∞	134	28	36	15	3.50	1.5	0.8	0.3
7-Textile wall covering*	∞	∞	131	17	45	23	0.16	0.1	0.31	0.17
8-Polyester	1.7 (1.5) 441 °C	0.8 (0.8)	568	170	10780	130	4.0	2.3	313	57
9-FR modified acrylic	11.2 (11.5)	10.3 (10.0)	542	109	119	102	3.80	0.4	4.4	0.64
IMO Critera (Resolution MSC.40 (64))			≤500 kW	≤100 kW	≤500 kW	≤100 kW	≤8.3 m^2/s	≤1.4 m^2/s	≤8.3 m^2/s	≤1.4 m^2/s

Shaded regions indicate tests that were terminated due to severe fire conditions. As such, the peak heat release rate and smoke production rate comparisons are invalidated by the test termination. Average heat and smoke release rates are averaged up to the time of predicted flashover to be consistent with the tests.
*Material No. 7 (textile wall covering) fell off the wall during the Room/Corner test.

4.3 Evaluation of the Predictive Capabilities of the Models

Overall, the models performed well in the prediction of the ISO 9705 experimental heat release rates and the associated thermal environment. The models poorly predicted the smoke production rates during the ISO 9705 Tests.

During this project, initial predictions of the ISO 9705 Tests were notably less successful than the final results. The WPI results were the best at that time and those results were little changed in the final report. On the other hand, the Modified Quintiere/Dillon Model performed much better than the original Quintiere/Dillon Model results produced initially. These results are included in Appendix A of Volume II for comparison. The modifications to the model and the data reduction methods in the Quintiere/Dillon Model had a significant effect on the performance of the model. The initial HAI/Navy Model results did not include any hot layer effects, as the model was originally developed as an open corner fire model. These open corner model predictions were quite poor in several cases. Adding the hot layer effects to the HAI/Navy Model significantly improved the model's performance.

Clearly, a great deal was learned in the course of this project which improved the models. However, given that the ISO 9705 data was published before this project began and that two of the three models changed in significant ways during the project, the predictions of the performance of the USCG HSC Materials certainly cannot not be classified as blind tests of the models. Blind predictions of test results would be more meaningful evaluations of model performance. This would require that bench-scale tests and model predictions be performed without knowledge of the ISO 9705 Test results.

Throughout the project, there have been significant concerns about the quality of the material response models included in each of the corner fire models, i.e., ignition, flame spread, and burning rate. These concerns relate both to the development of model inputs from the bench-scale tests and the subsequent use of the material response models in the corner fire model. While the Cone Calorimeter is in no sense a new experimental apparatus, the methods for interpreting the results of this test method remain somewhat primitive and, as this report reflects, these methods are in a state of ongoing change and development. In addition to concerns about the material response models, there are concerns about the ability of a bench-scale test to reproduce full-scale fire behavior of material assemblies. The mechanical response of material assemblies cannot be fully understood from small samples of the material. Large scale cracking, loss of mechanical integrity, and dripping are examples of processes that may not be able to be understood in tests like the Cone Calorimeter. While the textile material used in the USCG ISO 9705 Tests fell from the walls during the test, it is unclear if this effected the final results. In any case, it was also a behavior that was not anticipated from the Cone Calorimeter testing.

5.0 CONCLUSIONS

The results of this project show that it is possible to learn a great deal about the expected performance of materials in the ISO 9705 Test from bench-scale tests like the Cone Calorimeter and the LIFT Apparatus. Both the simple correlations using the Flammability Parameter deduced from the Cone Calorimeter and the mathematical models using Cone Calorimeter and LIFT data provided clear insights into the burning behavior of materials in the ISO 9705 Test.

The Flammability Parameter deduced from the Cone Calorimeter was able to correlate the heat release rate and time to flashover in the ISO 9705 Test. The Flammability Parameter is based solely on Cone Calorimeter Tests performed at 50 kW/m^2 incident heat flux. This provides the opportunity to obtain significant information concerning expected ISO 9705 performance from a few tests of 10 cm by 10 cm samples. As such, the Flammability Parameter is a powerful material development tool. It is significant that LIFT results are not required to allow correlation of the material performance.

The mathematical models performed well in predicting the heat release rate and time to flashover in the ISO 9705 Test. These more sophisticated methods provide additional confidence in the ability of bench-scale tests to be used to predict the performance of materials in the ISO 9705 Test. Further, these models have the potential to allow prediction of realistic scenarios, which differ from the ISO 9705 Test. Different initiating sources, different ceiling heights, different room sizes and ventilation rates are among the significant variables that are included in the models that significantly impact fire performance. Blind tests of the models under a wider range of experimental conditions is required to realize this potential.

Neither correlations from the Cone Calorimeter nor the mathematical models adequately predict the smoke generation rates in the ISO 9705 Test. The inability to predict smoke generation is particularly significant for materials that pass the heat release rate criteria in ISO 9705 Test. There are indications in this work that smoke generated by materials which are pyrolyzing but are not ignited during the test contribute significantly to smoke production. This is not considered in any of the existing methods and the Cone Calorimeter Tests needed to support modeling of this effect is not currently performed. Cone Calorimeter Tests at heat fluxes where ignition is not expected are not currently conducted to study thermal degradation of materials and the associated smoke production. Significant additional work is needed in this area.

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