DEVELOPMENTS NEEDED TO EXPAND THE ROLE OF FIRE MODELING IN MATERIAL FIRE HAZARD ASSESSMENT

Andrew J. Fowell

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

To assess the fire hazards associated with aircraft interior materials, prediction of how the materials perform under different fire scenarios is needed. This requires information on a variety of fire characteristics including thermal inertia, ease of ignition, rate of heat release, flame spread, products of combustion and the response to suppressants. Exposure conditions such as location, orientation, ventilation and proximity to other materials can influence some of those characteristics. Pass/fail test methods of the past cannot provide the information to assure fire safety under a variety of circumstances. Fire modeling in combination with new bench scale material flammability test methods can meet the need. National and international developments in model validation, documentation and acceptance are presented. The transition to aircraft cabin fire hazard assessment using fire models requires a data base on material fire properties. The case is made for greater use of improved bench scale test methods which can provide data suitable for use in the fire models.

INTRODUCTION

Aircraft fire safety has improved dramatically over the last twenty five years mainly because of the emphasis placed on the development of improved fire test methods for cabin interior materials, primarily for seats and wall linings. More than twenty years ago, Marcy and Johnson (1968) used available test methods for material flammability, a 1 1/2 inch bunsen burner, flame vertical test method, and ASTM E 162 as screening devices to study the burning characteristics of many different materials, and recommended allowable flammability limits for tightening the fire protection requirements of interior materials. In the early 1980's the FAA used full-scale fire tests to determine the effectiveness of the seat cushion fire blocking layer concept (Sarkos, 1982a, and Sarkos 1982b). Subsequently a new test method was developed by FAA that simulated the end use seat configuration and allowed for the burning interaction of cover fabric, blocking layer and foam cushion (FAA, 1984). The entire US airline fleet is now protected by seat fire blocking layers which give 40-60 seconds additional time for escape during a post crash fire (Sarkos, 1989). Further full-scale fire tests conducted by the FAA illustrated quite dramatically the effect of different honeycomb panel constructions on the rate of fire development within a fuselage with an open door and a large external fuel fire (Hill, 1985). The Ohio State University (OSU) rate of heat release apparatus, an American Standard of Testing and Materials standard test (ASTM, 1984), appeared to agree with full-scale cabin flammability tests and was adopted by the FAA. The full-scale tests were used to confirm the pass/fail criterion for aircraft cabin interior panels, namely a peak heat release rate of 65 kW/m2 and total heat release of 65 kW min/m2.

These examples serve to illustrate the way in which a specific full-scale fire test scenario considered important to post crash aircraft fires has led to the selection of test criteria for the flammability of aircraft cabin materials. To further improve cabin fire safety, materials with better flammability properties will be needed, but the benefits of material changes will depend on the location and orientation of the material and on the fire scenarios of concern. Of course, other factors including weight, strength, wear, acoustic

International Conference for the Promotion of Advanced Fire Resistant Aircraft Interior Materials. February 9-11, 1993, Atlantic City, NJ, 255-262 pp, 1993.

absorption, and cost must also be considered in selecting cabin interior materials. Quantifying and evaluating the needed changes will be a challenge.

Real accidents involving post crash fuel fires entail different scenarios. Variations in factors such as wind speed and direction, fuselage integrity, fire location and fuselage door openings, can all affect the growth of a fire. To run full-scale tests on all scenarios and parameter variations will be impossible. Advanced aircraft fire computer models supported by selected full-scale verification tests will provide information on the best use of available materials and where improved fire characteristics will be of greatest benefit. The selection of fire scenarios and parameter variations will require aircraft fire risk and vulnerability analysis. The use of computer models to predict the spread of fire in the cabin requires that information on material flammability be expressed quantitatively. Rank ordering of materials based on a single fire test is not sufficient.

MATERIAL FIRE CHARACTERISTICS

Material fire and thermal characteristics that can influence the development of fire in a cabin include:

- ignition temperature,
- rate of heat release,
- flame spread rate,
- mass loss rate,
- thermal conductivity,
- specific heat,
- density,
- emissivity,
- optical properties of the smoke,
- toxicity of combustion products,
- response to suppressants, and
- fire endurance.

Many of the above characteristics depend on the conditions of exposure. Therefor, to be able to predict fire development, measurements are usually needed at more than one exposure condition.

Some input data for compartment fire models and submodels can be obtained from currently available measurement methods. A useful guide providing a compilation of material properties and other data needed as input to computer models will be published soon by ASTM. This guide lists the apparatus, procedures and in some cases reference texts to obtain necessary data. Although emphasis is on zone models of compartment fires, much of the same input data is used in field models.

Three ASTM test methods provide much of the data for fire models. They are: the OSU apparatus, ASTM E 906 (ASTM, 1984); the LIFT apparatus, ASTM E 1321 (ASTM, 1990); and the Cone, ASTM E 1354 (ASTM, 1992a). The oldest of these, the OSU apparatus, is used widely in the aircraft industry for testing interior panels because it is required by the FAA who documented interlaboratory comparisons of heat release data from aircraft panels (Hill, 1986). The LIFT apparatus, designed to measure flame spread on materials, has been used to test many aircraft panels and building materials but has yet to gain widespread acceptance. The Cone calorimeter, of which there are more than eighty in use around the world, measures time to ignition and release rates of mass, heat, smoke and gaseous products of combustion at various levels of external radiant flux. The use of the Cone is now an international standard, ISO (International Organization for Standards) 5660 (ISO, 1992). In Europe there is effort underway to use the cone for building materials, plastics, electrical products, and building furnishings and contents. A recent report on fire safety and ASTM standards suggested that the Cone calorimeter is likely to be the principle fire testing instrument of the future (Hirschler, 1992). By now, testing techniques and protocols have been suitably worked out for well behaved materials. However, improvements are needed in the apparatus or the procedures for materials that intumesce or melt and for laminated composites that display unusual degradation mechanisms. Each of the above tests requires a flux calibration using a calibrated heat flux gauge. An improved high flux calibration source is needed to improve the high end calibration of flux gauges.

STATUS OF MODELING

Although improvements in measurement methods will produce better data and thereby enhance the accuracy of computer model assessment of the influence of material fire properties on fire in aircraft cabins, the major advances in fire assessment will result from advances in models themselves. It is not possible here to present a complete review of fire models, but it is important to mention some of those that address the effects of material flammability on fire in compartments. An excellent review of room fire models is contained in a new publication on heat release in fires (Babrauskas, 1992). A recent survey by Friedman (1992) identified 62 operational computer programs relevant to fire protection. Of these one addresses aircraft cabin fires (MacArthur, 1982), one addresses fire spread on furniture (Dietenberger, 1989), and two submodels address flame spread on walls (Mitler, 1990) and (Delichatsios, 1991).

MacArthur's Dayton Aircraft Cabin Fire Model (DACFIR3), a zone model, was developed specifically to obtain a better understanding of the relationship of small-scale fire test data on individual cabin materials to the behavior of those materials when involved in an actual full scale fire. The model assumes all interior surfaces are vertical or horizontal and divides each surface within the cabin into square elements 0.154m (0.5ft.) on the side. Each element can contribute heat and combustion products to the compartment fire while smoldering or burning. No specific test methods are identified to obtain the nineteen material flammability characteristics listed as input to DACFIR3. Among the list are horizontal and vertical flame spread rates, release rates of heat and smoke, various time intervals for such events as transition to flaming, and properties of the pyrolyzate. Flame spread is addressed by making an element ignite at a time interval when the flame would have spread from the center of an adjacent burning element to the center of the element under consideration. The Cone Calorimeter and the LIFT apparatus could be used to obtain much of the needed input, but before special protocols are developed to provide this data, improved flame spread models need to be developed.

Dietenberger's furniture fire spread model addresses fire spread across the seat, the back cushion and the side arms of furniture but it can be applied to fire spread on walls. The flame spread submodels of Mitler and Delichatsios mentioned above address flame spread, burn out, and the associated release of heat and combustion products on vertical surfaces when exposed to external radiation and radiation from the wall flame itself. As yet these submodels have not been fully tested against full-scale tests or incorporated into compartment fire models.

Also listed in Friedman's survey is the post-flashover version of the Ohio State University model (Sauer, 1983). This model, which addresses flammable walls and ceilings, uses as input measurements made specifically on the OSU apparatus but cannot use heat release data measured on the Cone or flame spread data measured on the LIFT. The model contains adjustable parameters such as the plume entrainment coefficient which affect the prediction of upper layer temperatures. Recently Janssens has modified the OSU model to simulate room corner fires (Janssens, 1993).

For meaningful assessment of the contribution of cabin lining materials to fire spread, models of flame spread on ceilings and at the interface between walls and ceilings need to be developed. Furthermore, because the cabin will not always be horizontal a better understanding and models are needed of flame spread on non horizontal ceilings. These models should also account for additional air flow through the cabin caused by wind blowing through open cabin doors.

We cannot expect the fire spread process in an aircraft cabin to be dictated just by the flammability characteristics of the lining materials or seats and the buoyant plumes generated by the burning materials. Flames and hot gasses from a post crash fire can be blown through an aircraft cabin by external wind. To address the effects of such hot gas flows on cabin lining materials and passengers requires the use of field models. A two dimensional computer code UNDSAFE II developed by DeSouza et. al. (1984) has addressed the effects of ventilation on fire and smoke spread in cabin fires. The fire is modeled as a volumetric heat source in a two dimensional rectangular enclosure that includes seats. The effects of venting at the ceiling and the floor are examined. Since this work a number of three dimensional computational fluid dynamics programs have become commercially available and have been applied to fire problems. One such program, FLOW 3D was applied to an investigation of a fire in King's Cross Underground station in London. The program was able to explain why flames spread so quickly up an escalator rather than impinge on the ceiling as might be expected.

As a further example of the usefulness of computational fluid dynamics in addressing fire problems, the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) has also used FLOW 3D to solve a problem of controlling a wind blown fire plume in a U.S. Navy fire fighter trainer (Forney, 1992). A number of potential solutions were tried on the computer before a specific fence design was chosen. The chosen design was installed and worked as predicted.

Another three dimensional model, JASMINE, (Cox, 1987) has been used on a number of practical smoke movement problems. A more rigorous computational fluid mechanics program, developed at NIST, (Rehm, 1991) has a much finer grid, and includes an algorithm accounting for combustion in each cell. All these codes are costly and require large computer capability.

With the ever increasing speeds and capacities of computers, three dimensional computational fluid mechanics offers the prospect of addressing the problems of the different cabin orientation and wind effects presented by post crash fires. Of course, models mentioned earlier, of flame spread on ceilings still need to be developed and incorporated into the programs.

MODEL VALIDATION

Before computer models can play a significant role in material fire hazard assessment for aircraft cabin lining materials the predictive capability of the models themselves, particularly the flame spread submodels, needs to be addressed. ASTM recently published a standard guide for evaluating the predictive capability of fire models and submodels (ASTM, 1992b). Besides calling for full documentation, the guide calls for a sensitivity analysis to identify the sensitive variables and their acceptable range of variables. The listed methods of evaluation are: comparison with standard tests, comparison with large scale simulations, comparison with documented fire experience, comparison with previously published full scale test data, and comparison with proven benchmark models. Missing from the guide is the need for peer review to confirm that the correct physics has been used within the model.

Instrumentation currently used in large scale experiments to test zone fire models consists largely of thermocouples, pitot-tubes, bidirectional probes, heat flux gauges, gas sampling at a few points, optical smoke measurements and video recording. This is insufficient to test three dimensional computational fluid dynamics predictions of wind effects on the exposure of cabin lining materials. High spatial resolution non-intrusive measurement techniques such as particle image velocimetry or laser doppler velocimetry will need to be explored as ways to quantify the vector flow field in large-scale experiments. Thermal imaging techniques need to be applied to gas and surface temperature measurements.

DATA BASE

Data on the performance of cabin lining materials under controlled test conditions is a key ingredient of fire models for predicting its performance under different scenarios. The newer material flammability test methods produce data that gives an extensive characterization of the material or product. These data are invariably generated as computer files. Unfortunately the format used for storing information has varied among test laboratories thereby limiting the exchange of data and its use in models. A fire data management system (FDMS) has been issued for Beta test and is under further development at NIST. The system can store data from older types of tests such as fire endurance and flame spread tests, and the OSU test (ASTM E 906) as well as the newer tests such as the cone and LIFT (ASTM 1354 and ASTM E 1321).

INTERNATIONAL DEVELOPMENTS

In the field of building fire research and standards new international attention has shifted to scientifically based models, measurement methods and data that are related to real fire conditions (Snell, 1992). The International Organization for Standardization (ISO) Technical Committee 92 Fire Tests on Building Materials Components and Structures has formed a new subcommittee on fire safety engineering to apply fire safety performance concepts to design objectives. Japan has developed a comprehensive alternate method for determining compliance with the fire provisions of their Building Standard Law. The number of approvals granted by this alternate method route in Japan have increased exponentially since completion of the project. Australia is developing a performance based building code utilizing a fire risk assessment model of Vaughn Beck (Beck, 1989). In the United States a fire risk assessment method was released by the National Fire Protection Research Foundation (NFPRF) in 1990 (Clarke, 1990). Although the method was tailored to quantify the fire risk associated with a specific class of products in a specified occupancy it can be used to assess general fire risk of a specified building design. The United Kingdom is developing a code of practice on the application of fire safety engineering principles to building design objectives. This work is forming the basis of the ISO effort. Many European nations are working together on the necessary research to develop modeling approaches to the design of fire safe buildings making use of bench-scale measurement methods.

These are but a few of the efforts underway around the world to develop systematic engineering approaches to building fire safety that provide an alternate if not a replacement for pass/fail fire tests for building materials.

SUMMARY AND CONCLUSIONS

Fire models can play a major role in reducing the number of large scale tests needed to assess the fire hazard of aircraft cabin lining materials under the many fire scenarios that may be encountered but they will not eliminate the need for large scale tests. Measurement methods are available to obtain most of the data to use the models.

A computer stored data base should be developed to collect and exchange the data on materials from both old and new test methods.

Computational fluid dynamics has reached the stage of development where it should be applied to the variety of fire scenarios that present a danger to passengers, thereby indicating the best use of materials with improved fire safety characteristics.

High spatial resolution non-intrusive measurement techniques such as particle image velocimetry or laser doppler velocimetry and thermal imaging techniques should be explored as ways to increase the data that can be obtained from large-scale fire experiments.

International efforts are underway to bring fire safety engineering methods to building fire safety. Aircraft cabin fire safety with its more controlled dimensions, materials, occupancy, and procedures should not be left behind in the application of modern approaches to fire safety.

REFERENCES

ASTM, 1984, "Standard Test Method for Heat and Smoke Release Rates for Materials and Products", American Society for Testing and Materials", ASTM E 906-83, 1984.

ASTM, 1990, "Standard Test Method for Determining Material Ignition and Flame Spread Properties", ASTM E 1321-90, 1990.

ASTM, 1992a, "Test method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter", ASTM E 1354-92, 1992

ASTM, 1992b, "Standard Guide for Evaluating the Predictive Capability of Fire Models", ASTM E 1355, 1992.

Beck, V. 1989, "Rational Design Methods for Building Fire Safety: The Warren Center Project", Fire Safety and Engineering Symposium Papers, University of Sydney, Sydney, Australia, 1989.

Babrauskas, V., Grayson, S. J., 1992, "Heat Release in Fires", Elsevier Applied Science, 1992.

Clarke, F. B. III, Bukowski,R. W., Steifel, S.W., Hall, J. R. Jr, and Steele, S. A., 1990, "The national Fire Risk Assessment Project Final Report", National Fire Protection Research Foundation, Quincy, MA. 1990.

Deitenberger, M. A., 1989, "A Validated Furniture Fire Model with FAST", National Institute of Standards and Technology, Gaithersburg, MD., NIST-GCR-89-564, 1989.

Delichatsios, M. A. and Saito, K., 1991, "Upward Flammability properties: Key Flammability Properties, Similarity Solutions and Flammability Indices", Fire Safety Sciences - Proceedings of the Third International Symposium

De Souza, B.P, Lloyd, J.R., and Yang, K.T., 1984, "Numerical Simulations of the Effect of Ventilation Control on Fire and Smoke Spread in Aircraft Cabins", American Society of Mechanical Engineers paper No. 84-HT-104.

FAA, 1984, "Flammability Requirements for Aircraft Seat Cushions; Final Rule", DOT/FAA, Federal Register, Vol. 49, No. 209, PP 43-188, October 26, 1984.

Forney, G.P, and Davis, W. D., 1992, "Analyzing Strategies for Eliminating Flame Blow-down Occurring in the Navy"s 19F4 Fire Fighting Trainer", National Institute of Standards and Technology, Gaithersburg, MD. NISTIR 4825, 1992.

Friedman, R., 1992, "An International Survey of Computer Models for Fire and Smoke," Journal of Fire Protection Engineering, Vol. 4, No. 3, July, August, September, 1992.

Hill, R.G., Eklund, T. I., and Sarkos, C.P., "Aircraft Interior Panel Test Criteria Derived from Full Scale Fire Tests." Federal Aviation Administration, Report DOT/FAA/CT-85/23, September, 1985.

ISO, 1992, "Fire Test - Reaction to Fire - Rate of Heat Release from Building Products", ISO 5660, 1992.

Janssens, M. L., 1993, " MOSURF: A Modified OSU Room Fire Model for Simulating Corner Fires", Presented at the ASTM International Symposium on Flammability of Furnishings and Contents of Buildings, Miami, Florida, December, 1992,. To be published as a Special Technical Publication by the American Society of Testing and Materials,1916 Race Street Philadelphia, PA.

MacArthur, C. D., 1982, "Dayton Aircraft Fire Cabin Model, Version 3", US Department of Transportation, Atlantic City, New Jersey, DOT/FAA/CT81-69-1, June, 1882, 52pp.

Marcy, J. F., Johnson, R., 1968, "Flaming and Self Extinguishing Characteristics of Aircraft Cabin Interior Materials", Federal Aviation Administration, Report NA-68-30, July 1968.

Mitler, H. E., 1990, " Predicting the Spread Rates of Fires on Vertical Surfaces", 23rd. International Symposium on Combustion, The Combustion Institute, Pittsburgh, PA, p 1715.

Rehm, R. G., Baum, H. R., Lozier, D. W., Tang, H. C., Sims, J. S., "Buoyant Convection in an Inclined Enclosure", International Association of Fire Safety Science, Proceedings of the 3rd. International Symposium, July 1991, Edinburgh, Scotland, Elsevier Applied Science, New York, 1991.

Sarkos, C.P., Hill, R.G., and Howell, W.D., 1982a, "The Development and Application of a Full-scale Test Article to Study the Behavior of Interior Materials during a Post-crash Fuel Fire". AGARD Lecture Series No. 123 on Aircraft Fire Safety , AGARD-LS-123 (June 1982).

Sarkos, C. P., and Hill, R. G., 1982b, Effectiveness of Seat Cushion Blocking Layer Materials against Cabin Fires, SAE Technical Paper Series No. 821,484 presented at the Aerospace Congress and Exposition, October 25-28, 1982.

Sarkos, C. P., 1989, "Development of Improved Fire Safety Standards Adopted by the Federal Aviation Administration", AGARD Propulsion and Energetics Panel 73rd Symposium,, AGARD-CPP-467, May 1989.

Sauer, J. M., and Smith, E.E., 1983, "Mathematical Model of a ventilation controlled compartment fire", Journal of Fire Sciences, Vol. 1, July/August 1983.

Snell, J. E., "Internationalism of Fire Safety Engineering Research and Strategy", International Fire Safety Engineering Conference - The Concept and the Tools, Presented for the Forum for International Cooperation on Fire Research by CSIRO, Sydney, Australia, October, 1992.